Thin Bonded Overlays with Carbon Reinforcement for Concrete Pavements

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Abstract. Here a possible alternative joint design in plain concrete pavements was investigated. The basis for this is to cover the concrete pavement with a thin jointless carbon reinforced concrete layer (CRC layer) of 50 to 70 mm as the top concrete. In the process, the classic joints already present in the lower concrete layer are also covered. The carbon reinforcement with a very high load capacity is intended to generate a finely distributed crack pattern in the upper concrete layer, thus preventing the penetration of moisture and other fluids into the joint area. This method thus represents an alternative to conventional joint sealing. Such a construction method is applicable both in the context of repair and new construction measures. In addition to tests on the cracking behaviour of CRC for concrete pavements, the main focus was on tests on large scale composite beams (classic jointed lower concrete + CRC layer). The focus was on the effects of static and cyclic bending on the material behaviour of the CRC over the moving joints in the lower concrete and the bond behaviour of lower and carbon reinforced concrete. The influence of differently designed bond breakers on the crack formation in the joint area was also considered.

1 Introduction

Of the approx. 13,000 km of German highways about one third are constructed as concrete pavements. These in turn are almost exclusively Jointed Plain Concrete Pavements (JPCP). If the pavement surface is extensively damaged, the entire superstructure is usually replaced. This is a considerable economic and ecological expense, not least because of the material costs and the traffic disruptions caused by the repair. Apart from large-scale and smaller repairs, regular maintenance is required for the sealed joints. These have to be replaced about every 12 years and represent the main weak point of the pavement. Within the scope of rehabilitation measures, it would be therefore beneficial to completely cover the joints with an overlay.

Laboratory tests were carried out to determine whether it is possible to repair large areas of damaged pavement while at the same time bridging the joints with a 50 -70 mm thick carbon concrete overlay (CRC overlay). The concrete overlay, reinforced with carbon mesh, is intended to seal the joints while maintaining their function by forming a fine crack pattern in the joint area. For this, the damaged concrete is first milled off so that only structurally sound concrete remains. After cleaning the milled surface, the CRC overlay is concreted using the lamination process (see Figure 1).

2 Carbon Reinforced Concrete (CRC)

Carbon Reinforced Concrete (CRC), as a form of Textile Reinforced Concrete (TRC), is composed of a matrix of (fine) concrete and reinforcement made of carbon, which, analogous to steel in reinforced concrete, compensates for the low tensile strength of the concrete. This reinforcement can be in the form of bars or meshes of carbon rovings (strands consisting of many thousands of individual filaments) [1].

Since the characteristic material and bond properties of CRC differ from those of regular reinforced concrete, the existing design models are not transferable in terms of load-bearing capacity and mechanisms. Under uniaxial tensile loading, the stress-strain behaviour is very similar to that of reinforced concrete. However, since the carbon reinforcement has no plastic capacity, the plastic

Fig. 1. Schematic construction of a jointless CRC overlay on a deteriorated JPCP adapted from [2]

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deformation state does not occur in CRC. Overall, the load-bearing behaviour of CRC and TRC in general is considerably more influenced by the bond behaviour of reinforcement and concrete. For more detailed information refer to [3] and [4] among others. The four basic failure mechanisms of CRC are tearing of the filaments without extraction from the matrix or the roving, full bond loss (roving pullout out of the matrix), telescopic failure (outermost filaments are pulled out first) and delamination of concrete matrix and reinforcement [5]. For further explanations of the bond behaviour refer to [6] and [7] among others. The most important properties that make CRC particularly suitable for use in thin overlays are its high tensile strength (2000 - 6000 Mpa [8]), high specific stiffness, high chemical resistance and its high resistance to alkaline environments [9,10]. Further, the low creep tendency and high temperature resistance must be mentioned [6]. Thus, building components made of CRC have a high durability and enable thin components that need a concrete cover of only a few millimetres [1]. In addition, there is potential to reduce both transport costs and CO₂ emissions due to the low weight and the lower volume of concrete required [10, 8]. It should be mentioned that carbon fibres are currently comparatively expensive with a price of approx. 16 €/kg. However, the high price of carbon fibres is relativized by the interplay of the above-mentioned properties and resulting consequences [9].

3 Materials

3.1 Concrete

For the investigations, a distinction was made between concrete for the CRC overlay and concrete representing the existing pavement (JPCP layer).

The concrete used for the JPCP layer, was chosen in accordance with the applicable German guideline TL Beton-STB 07 [11] and represents an in Germany commonly used pavement concrete. This concrete fulfilled the following requirements:

- Compressive strength class C30/37
- exposure class XF4
- maximum grain size 22 mm
- moisture class WS
- min. 420 kg/m³ cement content.

For the CRC layer, a typical pavement concrete according to [11] and [12] was modified to make it suitable for use in CRC (see Table 1). This mainly concerned the consistency, which was adjusted to very soft (slump 490 - 550 mm) by using a PCE based superplasticiser. In addition, the concrete was produced as exposed aggregate concrete for its positive effects on noise emission and skid resistance. This resulting in the typical maximum grain size of 8 mm, which is also advantageous in combination with the mesh size of the reinforcement used (see Chapter 3.2).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>[g/m²]</td>
</tr>
<tr>
<td>density</td>
<td>[g/cm³]</td>
</tr>
<tr>
<td>Centre distance of rovings</td>
<td>[mm] lengthwise 21</td>
</tr>
<tr>
<td>Mesh size</td>
<td>[mm] lengthwise 18</td>
</tr>
<tr>
<td>Strand gauge</td>
<td>[tex] lengthwise 3200</td>
</tr>
<tr>
<td>Cross section</td>
<td>[mm²/m]</td>
</tr>
</tbody>
</table>

### Table 1. Concrete mix design [2]

<table>
<thead>
<tr>
<th>Materials</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>CEM I 42.5 N (sd) 430 kg/m³</td>
</tr>
<tr>
<td>w/c-ratio</td>
<td>0.42</td>
</tr>
<tr>
<td>Rhine sand 0/2 mm</td>
<td>–</td>
</tr>
<tr>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Basalt 2/8 mm</td>
<td>–</td>
</tr>
<tr>
<td>70%</td>
<td></td>
</tr>
<tr>
<td>Grading curve</td>
<td>A/B 8</td>
</tr>
<tr>
<td>Air-entaining agent</td>
<td>Highly concentrated 0.09 % by mass of cement</td>
</tr>
</tbody>
</table>

### Table 2. Carbon reinforcement [2]

**3.2 Carbon reinforcement**

The laboratory tests were carried out with a reinforcement mesh made of carbon rovings (see Table 2 and Figure 2). It had a strand gauge of 3200 tex which equals a weight of 3200 g/km [13]. It was impregnated with epoxy resin and had a cross-section of 85 mm²/m in both directions. In combination with the overall width of the carbon mesh this resulted in a mesh size (distance between rovings) of 18 mm lengthwise and crosswise (see Figure 2).

Since the actual bond properties between textile and concrete were determined in the course of the project, the following criteria regarding load-bearing capacity and processing were taken into account in the selection of the textile:

- Sufficiently large mesh size to ensure penetration by aggregates (approx. three times of the largest grain diameter, smaller if concreting in layers is possible),
- sufficient stiffness (allows for laminated installation),
- Sufficient flexibility to allow rolling up (possible use with concrete paver),
- Sufficient reinforcement cross-section for load-bearing capacity.
A mesh size of at least three times the largest grain diameter could not be maintained. Preliminary tests showed, however, that good penetration could be achieved. Also, rolling up was not possible. The required flexibility competed with the required stiffness for installation, which at this moment was the overall more important factor. In addition, the choice was limited by the available textiles at the time.

4 Bond behaviour of CRC overlay and retained JPCP layer

The aim of the static and cyclic bending tests was to investigate the crack development, as well as the joint bridging capacity of the CRC layer bonded with the retained JPCP layer. For this purpose, drill cores were also taken from the beams after the tests under cyclic load.

The specimens for the tests under cyclic load were based on the composition of JPCP commonly used in Germany in order to represent the material behaviour in situ as accurately as possible (see Figure 4). Therefore, a total specimen height of 270 mm was chosen. With the selected layer thicknesses of the CRC layer of 50 mm and 70 mm, the layer thicknesses of the JPCP layer resulted in 220 mm and 200 mm respectively. The width of 500 mm and length of 1800 mm were given by the boundary conditions of the test setup. The length was also used for the test specimens under static load (see Figure 5). Here, however, a width of 240 mm was chosen due to the limitations of the test setup. The height of the JPCP layer was set to 150 mm resulting in a total height of 200 mm and 220 mm.

The transverse expansion joint of the JPCP was simulated in all tests by a 20 mm wide notch. For the cyclic tests, the usual dowelling of the expansion joint was also carried out as can be seen in Figure 4. For this purpose, two dowel bars made of powder-coated steel and with a diameter of 25 mm were installed at a distance of 250 mm on dowel holders so that they were halfway up the finished beams.

The bond joint between the JPCP layer and the CRC layer was roughened by creating an exposed aggregate concrete surface by using a surface retarder. Roughening by milling, as common in practice, was not possible here due to the comparably small specimen surface.

Some specimens were equipped with a bond breaker above the expansion joint, which was supposed to favour the formation of fine cracks under tensile load and prevent reflection cracking [15, 16]. Lengths of 300 mm and 600 mm were selected and an aluminium-laminated bitumen coating and 0.3 mm thick PE foil were used as bond breaker materials.

4.1. Static bending tests

The purpose of the bending tests under static load was to investigate the general crack development in the CRC layer while bonded to the JPCP. The focus was on the influence of different bond breaker materials and their length but also on the influence of CRC layer thickness and number of reinforcement layers on the cracking and bond behaviour.

The specimens were subjected to a 4-point bending test with a deformation speed of 1 mm/min (see Figure 5). The supports were spaced 750 mm apart which resulted in 525 mm unloaded length on both sides of the beams, which were intended to simulate long bond lengths in situ. The loading points were spaced 250 mm apart. The
machine travel, force and, at points, the strains on the carbon concrete surface in the centre of the beam (via strain gauges) were recorded. The test specimens were loaded until failure. The tests were evaluated regarding the general crack pattern and the influence of the CRC layer thickness, number of reinforcement layers and bond breaker. One to three test specimens were examined per configuration.

Since the crack widths generally decrease with an increasing number of cracks under constant load, the largest possible number of cracks was considered beneficial for the overall objective.

4.1.1. General crack formation behaviour and failure mechanisms

All test specimens showed the same general cracking behaviour (see Figure 5). Shear cracks formed over the entire beam height from the support in the direction of the loading points. All further cracks ran between these cracks. Horizontal, slightly curved cracks often formed in the compression area between the loading points. Where the cracks occurred above the bond breaker, they did not continue beyond the CRC layer. In most cases, one crack was visible at each edge of the bond breaker. As deformation progressed, spalling of the CRC layer occurred immediately above the supports. Depending on the design of the CRC layer, different crack patterns (number, width, and course) developed.

The majority of the test specimens failed due to tearing of the reinforcement. Whereby the tests were terminated when tearing of the rovings was clearly audible. There was no evidence of reinforcement pull-out in any of the cases. The tests could not always be terminated before complete breakage occurred. This was the case for 31 % of the test specimens. Tearing of the reinforcement alone thus caused 69% of the specimens to fail. In addition, delamination of the reinforcement from the matrix occurred in 47 %, but it was never the decisive failure mechanism.

4.1.2. Influence of the CRC layer thickness

Overall, no pronounced difference in crack formation between 50 and 70 mm CRC layer thickness could be found on the specimens (see Figure 6). The specimens compared were equipped with a 300 mm long bond breaker of PE foil and two reinforcement layers. For 50 mm layer thickness, 13 cracks occurred on average, of which 8.5 occurred above the bond breaker. For 70 mm, there were 14 cracks, 6 of which were above the bond breaker.

In general, a higher number of cracks at the same load is associated with smaller crack widths. Since it was not possible to determine the number of cracks at the relevant service load levels, it is not possible to make a concrete statement in this regard.

4.1.3. Influence of the bond breaker

In order to assess the influence of the bond breaker, a distinction must be made between the comparison of material and length. Specimens were either without bond breaker or equipped with a 300 mm or 600 mm long bond breaker.

Test specimens with 50 mm CRC layer thickness and two reinforcement layers were considered. With regard to the length, on average 11.5 cracks were found over the
entire beam length without a bond breaker. With PE foil on average 13 cracks with 300 mm bond breaker length and 13.5 cracks with 600 mm bond breaker length occurred. However, it was found that above the bond breaker, a somewhat higher gradient could be determined, from 8.5 to 11.5 cracks on average (see Figure 7). It was noticeable that with increasing bond breaker length less force could be absorbed until failure. The measured machine force at the time of failure dropped from 246.8 kN to 203.0 kN.

This behaviour was also seen on test specimens with a laminated bitumen coating above the joint area. While 11.5 cracks occurred overall without a bond breaker, 14 with 300 mm long bond breaker and 11.5 with 600 mm bond breaker length, the maximum load fell from 230.2 kN to 199.8 kN (600 mm bond breaker length) after an increase to 237.2 kN (300 mm bond breaker length).

4.1.4. Influence of reinforcement layers

When considering the influence of the reinforcement layers, it was shown that an increase in the reinforcement layers had a positive effect on the number of cracks (see Figure 8). All specimens were equipped with 300 mm long bond breaker made of PE foil and they had a 50 mm thick CRC layer.

With the increase from one to two reinforcement layers, the number of cracks increased by 5.5 cracks from 3 to an average of 8.5 cracks above the bond breaker and by 10 cracks from 3 to 13 cracks on the entire beam.

4.1.5. Summary

While the use of a bond breaker proved to be advantageous in terms of crack formation, only a small influence of the used length on the number of cracks could be determined. However, the load-bearing capacity decreased with increasing bond breaker length. An influence of the bond breaker material could not be determined. With increasing number of reinforcement layers, an increase in the number of cracks could be shown. Furthermore, no influence of the CRC layer thickness on the crack formation could be determined. Tearing of the reinforcement was the main failure mechanism, in some cases in combination with delamination of reinforcement and concrete matrix. The bond joint outside the bond breaker always remained intact in the tests.

4.2. Bending tests under cyclic loading

The aim of the tests under cyclic loading was to simulate the effects of the service load in situ on the cracking and bond behaviour of the CRC layer bonded to the JPCP layer. Particular focus was placed on the crack bridging capacity of the CRC overlay.

The relevant load scenario was the combination "traffic load + rapid cooling", which resulted in a stress ratio of \( \sigma_{\text{netz}}/\sigma_{\text{top}} = 2.2 \text{ MPa} / 3.4 \text{ MPa} = 0.65 \) and a utilization rate of the CRC overlay of \( \sigma_{\text{top}}/\sigma_{\tau} \approx 0.61 \). For the detailed determination of these values refer to [14, 17].

The tests were carried out in a hydraulically controlled testing rig in a 4-point bending test. The test specimens were exposed to the load at a frequency of 5 Hz at +20 °C for 5 x 10^6 load cycles. Continuously recorded was the strain above the expansion joint on the overlay surface. At regular intervals the relative dynamic Young's modulus (RDYM) based on ultrasonic transit times was determined.

4.2.1. Cracking behaviour

No delamination, spalling or other changes in the surface of the CRC overlay or the JPCP layer were observed on

Fig. 7. Influence of the bond breaker length on the average number of cracks; two reinforcement layers

Fig. 8. Influence of the reinforcement layers on the average number of cracks; 300 mm bond breaker length, bond breaker material PE
any of the tested beams. On all beams one to three cracks occurred within the first 50,000 load cycles. The crack width of 0.10 - 0.30 mm remained relatively constant until the end of the test. The cracks mostly ran across the entire width of the test specimens and were only limited to the edges of the beams in individual cases. If a bond breaker was used the cracks occurred on top of it (example see Figure 4). If no bond breaker was used, only one crack occurred approximately in the middle of the beam (reflection cracking). The number and location of cracks observed here was similar to the observations under static load at service load level (results not presented here). A continuation of the cracks from the CRC overlay into the JPCP layer was not observed.

With regard to the occurring crack pattern, it can be summarised that the number of cracks increased with increasing length of the bond breaker, whereby the crack width remained almost unchanged. The number of reinforcement layers and the thickness of the CRC layer, on the other hand, had an effect on the crack widths but not on the number of cracks. It was also shown that in the comparison of the layer thicknesses chosen here, a CRC layer of 70 mm thickness compared to 50 mm had only a very small positive effect on the crack widths. An influence of the bond breaker materials was not discernible.

4.2.2. Ultrasonic measurements

Ultrasonic measurements can be used to show structural damage in concrete as a result of cyclic loading, which manifests itself primarily as micro cracks. With increasing load cycles, these increase in number and crack area, which results in a change in the stiffness of the concrete structure and thus in the Young’s modulus [18]. This can be represented by the relative dynamic Young’s modulus (RDYM). More detailed explanations can be found in [17].

The ultrasonic transit times were measured both on the side surface of the composite beams in the CRC layer and on the top of the CRC layer. As the measurement depth for the latter measurement extended through the CRC layer a few centimetres into the JPCP layer, the condition of the bond joint could be recorded. The comparison of the ultrasonic transit times for the CRC layer and the bond joint showed no indication of any impairment of the bond joint beyond the formation of micro cracks in the CRC overlay.

Outside the cracked areas the RDYM decreased relatively evenly across the entire beam length (see Figure 9). In these cases the RDYM dropped on average to 89 % of the initial value with a standard deviation of 6 %. This drop of 11 % on average is thus in the same order of magnitude as the development of the RDYM for JPCP under cyclic loading previously determined in own projects (RDYM drop about 15 %) [19]. Most of the RDYM degradation occurred within the first 250,000 load cycles. This general behaviour was also observed in the less loaded areas near the beam ends. An influence of the configuration of the CRC layers on the RDYM was not recognisable. This was also true for the areas with cracks. However, in these the RDYM decreased significantly more to an average of 52% (standard deviation of 16%)

(see Figure 9). A correlation of the measured crack widths with the measured values of the RDYM could not be established. If cracks occurred this was always reflected in the behaviour of the RDYM. In addition, the drop of the RDYM occurred within 50,000 to 250,000 load cycles, indicating a formation of detectable macro cracks that extend over the entire CRC layer thickness within these load cycles.

![Fig 9. Example of the change of the relative dynamic Young’s modulus on beams with cracks considered for the CRC layer; adapted from [20]](image)

4.2.3. Accompanying investigations

Following the cyclic loading, drill cores were taken which were used for shear tests and tensile tests under centric load to determine the acting bond forces. The coring locations were selected individually for each beam based on the measurement data recorded during the tests and the visual appearance after the tests. Eight drill cores were taken from cyclically loaded and cyclically little to unloaded beam areas. Four cores were used for each test type. Two each were taken from loaded and little to unloaded areas. In the loaded beam areas, the cores were taken next to the bond breaker.

The aim of the shear tests was to determine the shear strength of the bond joint of CRC layer and JPCP layer in order to be able to draw conclusions about a possible delamination of those layers. The drill cores had a diameter of 150 mm and the full beam length. The tests were carried out according to [21] with a loading rate of 50 ± 2 mm/min using a shear frame. The shear plane was the bond joint and the specimens were loaded until complete failure.

The influence of the bond breaker (material, length), the reinforcement layers and the layer thickness of the CRC layer on the shear strength of the bond joint were evaluated, as parameters for the damage of the bond between both concrete layers.

Since in Germany there are no requirements for the shear strength of the bond joint between the retained concrete and overlay, the condition of the bond joint could only be assessed qualitatively. In practice, it is assumed
that the bond between the two concrete layers under shear load is sufficient if the roughness of the bond joint is ample without air pockets or other disturbances. In addition to the qualitative assessment of the bonded joint, the focus of the evaluation was therefore primarily on the influence of the above-mentioned parameters on the shear strength under cyclic loading.

No air pockets or other disturbances of the bond joint could be observed on the drill cores. Furthermore, they were free of spalling, cracks or delamination. In some cases, pieces of JPCP and/or CRC concrete broke off. In summary, with cyclic loading, less damage to the bond joint occurred with an increase in the bond breaker length, whereby with bitumen coating as bond breaker material, this effect only occurred from a length of 600 mm. No influence of the reinforcement layers and layer thicknesses on the bond could be determined. All tests showed a varying decrease in shear strength of max. 18 % after cyclic loading.

In addition, centric tensile tests were carried out on 100 mm diameter cores of 100 mm length according to [22] with a loading rate of 0.05 ± 0.01 MPa/s until the cores failed. Essentially, the position of the failure plane (fracture in the JPCP, CRC or in the bond joint) allowed conclusions to be drawn about the weak point of the specimens with regard to cyclic bending. After cyclic loading, approx. 80 % of the cores failed in the JPCP layer, approx. 12 % in the bond joint and 4 % each partially in the JPCP and at the interface of CRC matrix and reinforcement. Without cyclic preloading, a very similar distribution occurred. Consequently, the JPCP concrete can be identified here as the decisive weak point with regard to tensile strength for beam areas with and without cyclic preloading. Even if the bond joint was damaged by the cyclic loading, as indicated by the shear tests, this was not decisive with regard to the tensile load-bearing capacity perpendicular to the bond joint.

Further investigations on water absorption with Karsten-tubes were carried out before the drill cores were taken. They showed an overall increase in water absorption of 9 % to 31 % after cyclic loading. With a bond breaker a slight reduction in water absorption could be achieved (3 - 20 % increase), while increasing the CRC layer thickness from 50 mm to 70 mm caused a reduction of 10 %. Supplementary investigations on drill cores, among others on the penetration behaviour of de-icing salt solutions, showed that under unfavourable circumstances, penetration of liquids into the expansion joint and thus into the JPCP is possible. This is the decisive situation that promotes damage. In order to prevent this, the use of a permanently liquid-tight bond breaker is recommended [2].

5 Conclusions and outlook

The used carbon reinforcement mesh proved to be suitable for use in exposed aggregate concrete with a maximum grain size of 8 mm. In addition, its stiffness due to the epoxy resin impregnation made it easy to install in the correct position. However, the installation on site was not a focus here and must be considered more closely.

In order to achieve the best possible bond to the JPCP layer, the roughness should be carefully adjusted to the concrete used for the overlay. It is estimated that it should not exceed about five millimetres.

Both layer thicknesses investigated (50 mm and 70 mm) showed to be sensible choices. Previous tests on thinner overlays showed an unfavourable ratio of layer thickness and maximum grain size. This made processing and placing the reinforcement properly exceedingly more difficult.

At least two layers of reinforcement should be chosen to create as many and as fine cracks as possible. When choosing more than two reinforcement layers the CRC layer thickness needs to be adjusted to maintain favourable ratio of layer thickness and maximum grain size.

The results show a bond breaker to be necessary to bridge the transverse expansion joint to transfer the joint movement into several fine cracks. Both tested materials (PE foil, aluminium coated bitumen) proved to be suitable. From a practical point of view, the bitumen coating is easier to use, as it adheres to the existing pavement. No significant difference in functionality was found between 300 mm and 600 mm long bond breakers. The bond breaker also appears to be beneficial in preventing liquids from entering the expansion joint through the cracked CRC overlay.

While macro cracks over the entire CRC overlay thickness appeared after 10,000 to 250,000 cycles of service load, the overall bond of the JPCP layer and CRC overlay stayed largely intact for 5 x 10^6 load cycles. The damaged induced by micro cracking was comparable to that of JPCP under cyclic load.

In order to be able to use the presented repair method in practice, further investigations are required with regard to the influence of damages and cracks on durability. In addition the bond behaviour of the CRC overlay and the JPCP layer under pressure and centric tensile load should be researched. Last but not least the functionality in situ should be tested in the form of test tracks.

The results presented here represent an excerpt of the laboratory tests carried out in the research project “Textilbewehrter Oberbeton als Basis für eine fugenlose Oberfläche von Betonfahrbahnen” in cooperation with the Institute of Concrete Structures at the TU Dresden. The authors would like to thank the colleagues at the TU Dresden for the pleasant and productive cooperation.

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