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Evaluating and Modelling the Effect of Carbon Fiber Grid Reinforcement in a Model Asphalt Pavement

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ABSTRACT: Laboratory and modeling results on a special type of carbon fiber grid placed at different depth in model asphalt pavements are presented. The purpose was to obtain design information regarding the position of the grid to reach optimum effect. Two completely different types of asphalt pavements were investigated: asphalt concrete and mastic asphalt. Depending on the different application range of these materials, the test program was slightly different in each case. In case of asphalt concrete, special focus was devoted to the question of rutting performance with the Model Mobile Load Simulator MMLS where the asphalt layer was placed on a rubber pad foundation in order to increase bending effects. Test results are discussed and compared with dynamic FE modeling using ABAQUS. In addition, interlayer shear properties were investigated with the layer parallel direct shear test LPDS based on the Leutner device. The evaluation of the complex modulus in the coaxial shear test CAST developed by EMPA is also presented. In case of mastic asphalt, rutting and cracking resistance were considered varying the mesh width of the grid. Here, MMLS and LCPC rutting tests were performed. As for cracking resistance, the influence on bottom up cracking regarding bridge deck application at freezing temperature was evaluated with a special mechanical stretching bench that enabled to study a model system with a mastic asphalt placed on a bituminous waterproofing membrane.

1 INTRODUCTION

Reinforcement of asphalt pavements with grids has attracted much attention and has triggered international initiatives such as the European Cost 348 REIPAS (Rathmayer 2006). Nowadays, a considerable variety of different products is available and still under development raising questions of appropriate testing and modeling. In this investigation emphasis was given to testing and evaluation of the following three cases:

- *Carbon fiber grid reinforcement against traffic induced fatigue distress of hot mix asphalt (HMA):* The effect of carbon fiber grid reinforcements, placed at different positions between two layers of HMA, was analysed. Furthermore, the influence of pretreating the surface of the bottom pavement layer by surface milling was investigated. The experimental results were qualitatively confirmed by finite element modelling, as shown in section 2
- *Carbon fiber grid reinforcement against low temperature cracking of mastic asphalt (MA):*The mechanical behaviour of two layered MA specimens under horizontal repeated loading at low temperatures was investigated. The carbon fibre grid reinforcements were placed between the pavement layers. The most important findings are presented in section 3.
- *Carbon fiber grid reinforcement against rutting of mastic asphalt (MA):* The influence of the carbon fibre grid reinforcements on rutting behaviour of two-layered MA-specimens at different test temperatures was investigated. These results are summarised in section 4.

2 REINFORCEMENT AGAINST TRAFFIC INDUCED FATIGUE DISTRESS OF HMA

2.1 *Experiments*

Five two-layered specimens were produced using asphalt concrete AC 8 S for testing with the Model Mobile traffic Load Simulator MMLS. The AC 8 S layers of the specimens were compacted with a vibration roller compactor. Length, width and height of the specimens were 1800 x 870 x 60 mm. The first specimen (K1) was composed of two asphalt layers without grid reinforcement and served as reference. The other specimens were reinforced by carbon fibre grids either applied at the bottom side of the bottom asphalt layer (specimen K2) or in between the asphalt layers (specimens K3, K4, K5). The bottom asphalt layer of specimen K5 was produced at excess thickness of 5 mm (total thickness 25 mm). Before applying the reinforcement grid, these additional 5 mm were milled off with a hand miller, resulting in a final thickness of 20 mm. In order to simulate the compliance of the subbase, the specimens were supported by a cellular rubber pad. Details regarding the MMLS specimens and carbon fibre grids are given in Figure 1 and Table 1. The theoretical fiber cross-section of carbon fiber, according to 50 mm^2/m, and the elasticity modulus of the carbon fibre grid are 160 GPa (carbon fibre) and 47 GPa (glass fibre). The coated matrix of fibre grids is SBS (Styrene-Butadiene-Styrene) polymer modified bitumen.

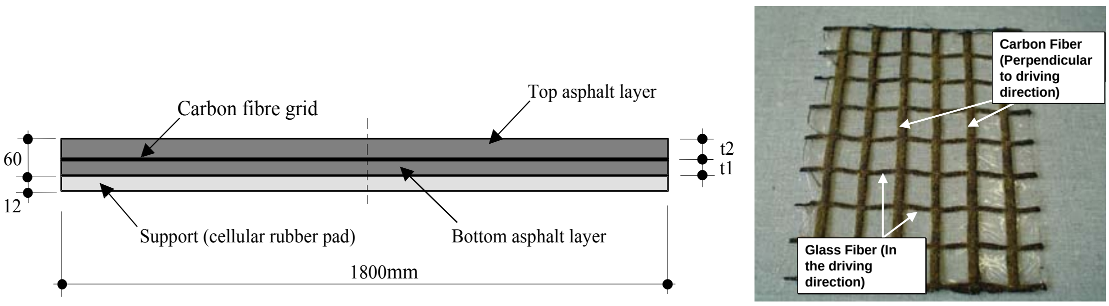

Figure 1. Longitudinal cross section of the asphalt concrete specimens for MMLS testing and Carbon fibre grid (units in mm)

Table 1. Asphalt concrete specimens, system characteristics

Specimen-Code	Specimen Size [mm]	Surface Treatment Bottom Layer	Thickness t1 Bottom Asphalt Layer [mm]	Thickness t2 Top Asphalt Layer [mm]	Grid Position
K1	1800 x 870 x 60	No	30	30	No Reinforcement
K2		No	30	30	Bottom Side of Bottom Asphalt Layer
K3		No	20	40	Between Asphalt Layers
K4		No	30	30	Between Asphalt Layers
K5		Milled	20	40	Between Asphalt Layers

In order to measure the strains on the bottom of the specimens during MMLS testing, strain gauges were applied. The vertical surface displacements of the specimens (rut depths) were measured in a selected cross section of the specimens with a special profilometer. The traffic simulator MMLS was positioned on top of the specimen as shown in Figure 2. The combination of test parameters (tire width 80 mm, tire diameter 300 mm, tire load 2.1 kN) corresponds approximately to the vertical tire load of a regular truck. The test temperature was $25^{\circ}C$.

Average permanent strains in the longitudinal strain gauge under the wheel path after ca. 0.5 Mio. cycles at 25°C showed that a reinforcement grid placed below or within the neutral plain of the specimen, leads to a reduction of the horizontal strains in the rutting zone. Comparing the average strains in specimen K2 (grid reinforcement on bottom side of bottom layer) with the values from specimens K3, K4 and K5 (grid reinforcement between asphalt layers) demonstrated that the carbon fibre grid reinforcement must always be placed between two pavement layers. It was also found that the application of the carbon fiber reinforcement between sub grade and asphalt base does not make sense.

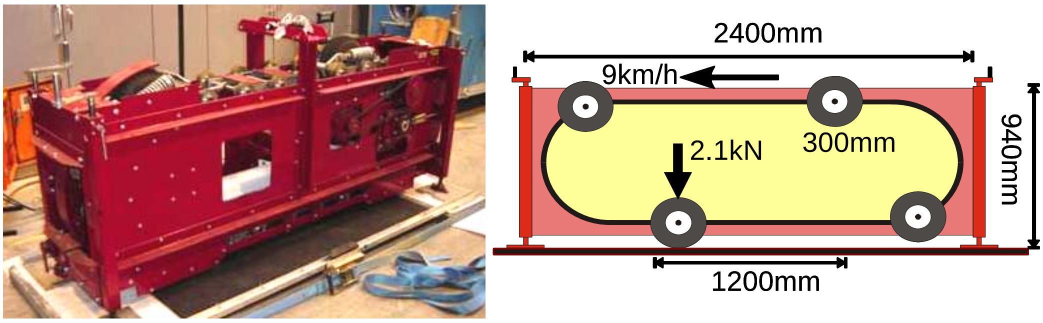

Figure 2. Model Mobile traffic Load Simulator MMLS, positioned on top of the specimen.

Interlayer shear properties were determined with the layer parallel direct shear test LPDS based on the Leutner device according to Swiss standard SN 670461, except for the test temperature of 25°C, which was equal to the temperature of the MMLS tests.

From the MMLS specimens K1, K3 and K4, three Leutner-specimens (double layered cylinders with a diameter of 150 mm) were cored and tested, each from the trafficked and non-trafficked zone (e.g. inside and outside the wheel track). From each zone of the MMLS specimen K5 (with milled interlayer interface) six Leutner-specimens were cored and tested. Prior to testing the specimens were conditioned at 25°C in a climatic chamber during 8 hours.

The Leutner shear tests led to a dramatic decrease of the interlayer shear strength of the specimens from the wheel track zone from 20.3 kN (for K1) to 6.0 kN (for K4). This can be explained by successive loosening of the interface between the asphalt layers in presence of the reinforcement. 0.5 Mio. cycles, acting on the only 60 mm thick specimens, supported by the soft cellular rubber pad, produced vibrations with high horizontal stresses and strains that caused debonding in the boundary layer. The high values of the interlayer shear force of specimen K5 outside (18.3kN) and inside (17.7kN) the wheel track confirm that appropriate pre-treatment (e.g. milling) of the contact zone between the pavement layers improves the interlayer shear bond and therefore increases the efficiency of the carbon fibre grid reinforcement significantly.

2.2 *Numerical Analysis*

In order to verify the experimental investigations, the specimens K1 to K4 were numerically modelled. For the asphalt concrete specimens, tested with the MMLS, a four layer finite element model was used. Calculation and visualisation was conducted with the software package ABAQUS. The traffic load was simulated as a moving vertical stress distribution under the wheel and adjusted to the wheel load of the MMLS traffic simulator. For this study elements of type C3D8R (8 point prismatic element with reduced integration), linear elastic material properties and the explicit dynamic solver were chosen. For the boundary conditions, the bottom of rubber pad layer was vertically fixed and the lateral sides of FE model have no boundary fixation. The carbon hanks of the reinforcement grid were implemented as rebar-elements in an asphalt layer of 4 mm thickness. Each finite element calculation was performed for one tire cycle taking into account the E moduli for the asphalt (1000MPa), for the supporting cellular rubber pad (0.19 MPa) and for the carbon fiber grid in the longitudinal (47'000MPa) and transversal direction (160'000MPa) assuming a grid spacing of 20mm and fiber cross section of 50mm^2/m. The selected E-modulus of asphalt corresponds to the value determined in laboratory tests at a temperature of 25°C and a frequency of 0.5 Hz. Figure 3 shows the loaded elements of the model.

Table 2 presents the longitudinal strain amplitudes on the bottom of the specimen under the wheel path, normalized to the K1 values. It can be noticed that the results of the experimental and numerical analysis are in qualitative agreement based on relative comparisons. The quantitative discrepancy indicates that the numerical model represents an idealised situation (perfect interlayer bond, linear elasticity).

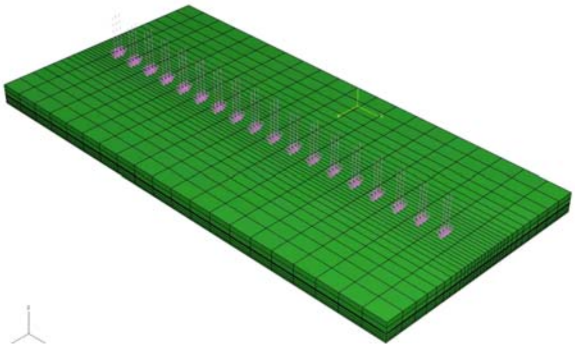

Figure 3. Finite element - modelling, loaded elements of MMLS-specimen K3.

Table 2. Longitudinal strain amplitudes below wheel path on the bottom of the specimen (units in mm/mm).

Specimen Code	Experiment	Finite Element Modelling
K1	1	1
K2	0.7212	0.4545
K3	0.9038	0.4756
K4	0.9904	0.6324

3 REINFORCEMENT AGAINST LOW TEMPERATURE CRACKING OF MASTIC ASPHALT

3.1 *Experiments*

The specimens had a length, width and height of 2600x500x70 mm, see Figure 4, and consisted of two mastic asphalt (MA) layers of 35 mm thickness each, bridging a gap of 10 mm width. Between the bottom MA layer and the two concrete supports a SBS polymer bitumen flexible sheet for waterproofing was installed. Carbon fibre grid reinforcement was placed in between the MA layers. The carbon fibres of the grid were oriented in longitudinal direction perpendicular to the gap. Table 3 provides an overview of the specimen characteristics.

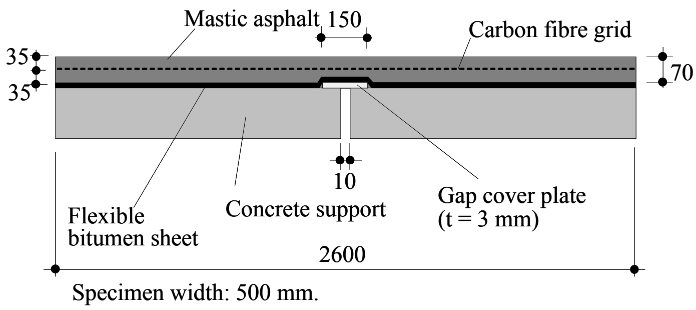

Figure 4. Longitudinal cross section of MA specimens for low temperature tests (units in mm)

Table 3. Mastic asphalt specimens, system characteristics

Specimen Code	Mix	Grid Spacing [mm]	Thickness of MA Bottom Layer[mm]	Thickness of MA Upper Layer [mm]
K6	MA11	20	35	35
K7		40	35	35
K8		No Grid	35	35

In order to investigate the behaviour of the specimens under repeated horizontal opening and closing of the gap at low temperature (-5°C), a special test equipment available at Empa, the so called Joint Movement Simulator JMS, was used (Figure 5). One side of the specimen was fixed on the concrete support, the other side was moved with a spindle motor in horizontal direction. The repeated loading was applied deformation controlled at constant testing temperature. The average speed of the gap opening was 5 mm/h. The gap opening was measured as distance between the concrete supports at both sides of the specimen with the LVDT deformation sensors W1. The horizontal deformation of the MA in the gap zone was measured with two LVDTs W2 that were mounted at half height of the bottom MA layer in front and at the back side of the specimen. For qualitative investigation of the longitudinal strain distribution, vertical marker lines were laterally painted on the specimen in a distance of 20 mm (Figure 5). Table 4 contains the test conditions and some test results. The basis length L2 of 150mm (K6), 250mm (K7, K8) was used for calculating the strains in the MA from W2 data.

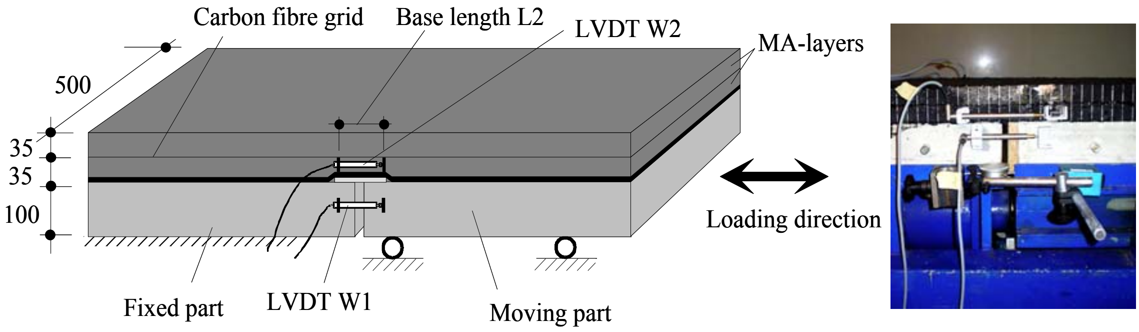

Figure 5. Schematic of the joint movement simulator JMS (units in mm) and detailed view

Table 4. Mastic asphalt specimens, system characteristics and test results

Specimen Code	Maximal Gap Opening *W1* [mm]	Number of Load Cycles [kN]	Maximal Strain *W2/L2* in MA [%]	Maximal nominal Stress in MA [MPa]	E-Modulus *E* [MPa]
K6	1	6	0.0883	1.295	*1466*
	2	4	0.1713	2.121	1238
	3	4	0.2527	2.421	958
	4	1	0.3413	2.538	743
	5.984 (failure)	1 (failure)	*0.547*	*3.267*	684
K7	1	6	0.075	1.157	*1543*
	2	4	0.138	1.858	1342
	3	4	0.198	2.319	1168
	4	2	0.268	2.870	1070
	4.78 (failure)	1 (failure)	*0.360*	*3.138*	871
K8	3.58 (failure)	1 (failure)	*0.244*	*2.849*	*1167*

3.2 *Analysis of Results*

From Table 4 follows that the application of the carbon fiber grid reinforcement leads to both a stiffening of the MA pavement (increase of the initial E-modulus) and an increase of its failure strain and stress. Table 5 presents a comparison of these parameters for all specimens. The values were taken from *Table 4 (Italic terms)* and are given as percentage of the value for the non-reinforced specimen K8. It follows that carbon fibre grid with narrow spacing leads to a significantly higher failure strain than the grid with a larger grid spacing (224.2% for K6 vs. 147.5% for K7). However the increase of failure stress remained small (114.7% for K6 vs. 110.1% for K7). No increase of initial stiffness was observed (125.6% for K6 vs. 132.25 for K7).

Table 5. Comparison of test results

Specimen Code	Failure Strain [%]	Failure Stress [%]	Initial-E-Modulus [%]
K6	224.2	114.7	125.6
K7	147.5	110.1	132.2
K8 (reference)	100	100	100

4 REINFORCEMENT AGAINST RUTTING OF MASTIC ASPHALT

4.1 *Experiments*

The specimens had a length, width and height of 2000x1200x70 mm, see Figure 6, and consisted of two mastic asphalt layers MA11 of 35 mm thickness each. In between the MA layers of some selected specimens a carbon fiber grid reinforcement was placed. The carbon fibers of the reinforcement grid were oriented in transversal direction perpendicular to the wheel tracking direction. Table 6 presents a summary of the specimen characteristics and the measured rut depths at the end of the MMLS tests.

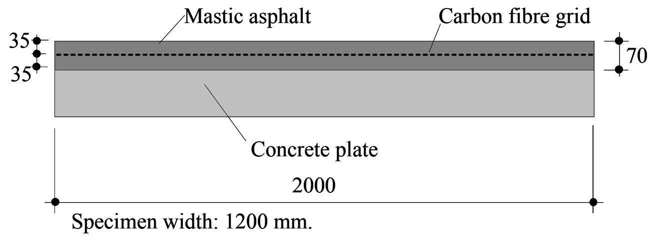

Figure 6. Longitudinal cross section of MA specimens for MMLS rut tests at 45 and 60°C (units in mm)

Table 6. Mastic asphalt specimens, system characteristics and rut depths after MMLS testing

Specimen Code	Grid Spacing [mm]	Number of Cycles	Test Temperature [°C]	Rut Depth [mm]
K9	20	72000	45	4.60
K10	40	72000	45	4.62
K13	20	72000	45	4.78
K11	40	10000	60	11.62
K12	no grid	10000	60	11.34
K14	no grid	10000	60	8.13

From Table 6 follows that the carbon fiber grid reinforcement has no significant positive effect on the rutting behaviour of MA 11 at 45°C and 60°C. The grid structure is not able to prevent plastic deformations (flow) in the MA layer. A reduction of rutting must therefore be achieved by other means, e.g. by using harder binder.

5 CONCLUSIONS

This study demonstrates the following positive properties of carbon fibre grid reinforced in a model hot mix asphalt and mastic asphalt as compared to non reinforced pavements:

- Increased resistance against low temperature cracking
- Increased stiffness of the pavement
- Increased failure strain and stress

However, the grid was not found to improve resistance against plastic deformations in the MA layer during rutting tests with Model Mobile traffic Load Simulator MMLS. It was also found that careful pre-treatement is required in order to reduce the risk of interlayer debonding.

6 REFERENCES

Rathmayer, Hans. 2006. *Reinforcement of Pavements with Steel Meshes and Geosynthetics.* European COST 348 REIPAS

Swiss Standard SN 670461. 2000. *Bituminöses Mischgut: Bestimmung des Schichtenverbundes nach Leutner*