Monetary evaluation of the reduced service life of asphalt pavements caused by the interlayer bond

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Abstract. The sustainability of asphalt pavements is highly depending on the quality of the interlayer bond (IB) between the different asphalt layers. In this project a complicated apparatus for cycling testing of the interlayer bond has been developed in order to determine the shear stiffness at the interface between asphalt layers taking into account the combined effect of varying and repeated traffic loading, acceleration and braking processes and temperature. A universal master function for analytical assessment of the IB shear stiffness has been established for any IB condition using the experimental results. Another function for completely fatigued IB has been developed as well. Both functions have been implemented into a finite element program to estimate the fatigue status of asphalt pavements for different bond qualities over a service life of 30 years using the German method for computational design according to RDO Asphalt 09. It has been succeeded to make a monetary evaluation of the reduced service life of asphalt pavements caused by interlayer bonds of different quality and to assess the construction cost penalty.

1. Introduction and background

Asphalt pavements in Germany usually consist of a surface course, a binder course and a base course. If the thickness of the asphalt base course is more than 17 cm, it is produced and compacted in two layers. The asphalt layers are bonded together through a tack coat (e.g. cationic bitumen emulsion) which ensures the interlayer bond. The whole asphalt concrete pavement is loaded permanently vertically by vehicle’s wheel loads and horizontally by braking and acceleration processes causing high stresses in tangential and radial direction \cite{11}. The temperature variation also cause additional stresses. In order to allow the transmission of shear stresses between the individual layers of the asphalt pavement, the interlayer bond (IB) should be produced as a full-surface and rigid connection between them. The effect of the interlayer bond has to be generated through the interlocking of the aggregate particles at the interface, the friction between the surfaces of the two asphalt layers and the adhesion between the asphalt binder of the two layers and the applied tack coat. These three factors act simultaneously when transferring shear stresses across the layer interface but will in different proportions, depending on the asphalt mixes, the temperature, the normal pressure, the frequency, the type and quantity of the bitumen emulsion, the roughness of the layer’s surfaces and the contamination of the underlying layer’s surface.

The three-dimensional stress state in the entire pavement structure changes dramatically if the interlayer bond is missing or if it is too flexible. As a result, a reduced service life can be expected due
to premature material fatigue. This is the reason to strive for the production of the best possible rigid interlayer bond in order to ensure that all layers act as a unit during the load transfer and to reduce the relative displacements, which occur at the layer interface between the layers, to the lowest possible values.

The results presented in this paper are based on the results of IGF project No. 17634 BG "Cyclic Shear Stiffness and Shear Fatigue Testing for Evaluation and Optimization of Interlayer Bond in Asphalt Pavements", supported by the Association of Industrial Research Communities (AIF) and the German Asphalt Institute (DAI) in cooperation with the Pavement Engineering Centre (ISBS) at the TU Braunschweig.

The main objective of this study is to computationally estimate the effect of the combination of qualitatively different interlayer bonds on the service life of the asphalt pavement using the developed universal master function for analytical assessment of the shear stiffness. It is then aimed to make a monetary evaluation of the reduced service life of asphalt pavements and to assess the construction cost penalty.

2. Experimental program

2.1. Double-layered asphalt specimens and apparatus for cyclic testing of the interlayer bond
Two-layered asphalt slabs with dimensions 320 mm x 260 mm were prepared in the lab with a roller sector compactor. The slabs of the underlying course were produced and stored at room temperature (RT) for 24 hours. The bitumen emulsion was then applied uniformly using a flexible foam roller. The coated slabs were left at RT for at least two hours until the complete breaking of the bitumen emulsion. The hot bituminous mixture of the upper course was then laid and compacted. Four cylindrical specimens with a diameter of 100 mm were drilled from one double-layered asphalt slab. The asphalt specimen was fixed inside two steel adapters, which consist of four steel shells (figure 1, a). The gap between the two steel adapters was set to 1.0 mm and the interface of the specimen was precisely adjusted to fit in this gap.

The test apparatus used for the tests applies cyclic shear force in the vertical direction (jowl B) and varying static normal force in the horizontal direction (jowl A) and was mounted in the temperature chamber of a servo-hydraulic testing machine (figure 1, b). The test sample was inserted and fixed in the jowls A and B, so that half of the sample was in the vertically unmovable jawl A and the other half was in B (figure 1, c).

![Figure 1. Sample preparation for CTIB (a), test apparatus for CTIB (b) and mechanical model (c).](image)

2.2. Experimental procedure
The whole experiment was conducted at four different temperatures starting at a temperature of $T = -10^\circ\text{C}$, normal stress $\sigma_N = 0.9$ MPa, shearing frequency $f = 10$ Hz and a maximal shear displacement $s_{w,\text{max}} = 0.03$ mm and ending at $T = 50^\circ\text{C}$, $\sigma_N = 0.9$ MPa, $f = 10$ Hz and $s_{w,\text{max}} = 0.15$ mm. A figure of
the whole procedure is shown in [9]. At each temperature the specimen was loaded with five normal stresses. Six frequencies at the corresponding number of load cycles changed successively during each normal pressure. The whole procedure of simultaneous and consecutive process runs was fully automated.

3. Master functions for assessment of interlayer bond shear stiffness

The regression for the development of a universal master function for the shear stiffness $G_s$, which takes into account the combined influence of temperature, normal stress and frequency was the sigmoidal function. The derivation of the master function is described detailed in [9].

$$G_s = G_{s,\text{min}} + \frac{G_{s,\text{max}} - G_{s,\text{min}}}{1 + e^{m(c \ln \sigma_N + d)}}$$

where $m$ is the temperature-frequency equivalence (Hz); $G_{s,\text{min}}$ is the minimal shear stiffness (MPa/mm); $G_{s,\text{max}}$ is the maximal shear stiffness (MPa/mm); $a$ and $b$ are regression parameters, both functions of the normal stress.

For parameter $a$ it was found, that the logarithmic function showed the best fit, while for parameter $b$ it was the linear function.

The sigmoidal master functions for calculating the shear stiffness at the two interfaces of road pavements (surface course – binder course and binder course – base course) were inserted into the Semi-Analytical Finite Elements Method program SAFEM [12], in order to investigate the fatigue of the whole asphalt pavement influenced by the interlayer bond.

The determination of the fatigue curves for the interlayer bond was undertaken at the Technical University of Braunschweig. It was stated, that the increase in the normal stress $\sigma_N$ causes generally an increase in the remaining shear stiffness over the entire service life of the road pavement as well as a higher number of load cycles until complete fatigue. The fatigue curves approached the same value range at all three temperatures for each normal stress, which leads to the conclusion that the functions of the completely fatigued interlayer bonds are independent of the temperature [9]. Under these assumption, a linear relationship (10) of the shear stiffness and the normal stress between the average values of the completely fatigued interlayer bonds was determined, namely

$$G_s = 42.82 \cdot \sigma_N + 4.025$$

Using this function, the service life of the completely fatigued interlayer bond (CFIB) was calculated in the Semi-Analytical Finite Elements Method program SAFEM.

4. Results

4.1. Effect of different interlayer bond combinations on the service life of asphalt pavements

The extensive experiments have shown that the shear stiffness between two asphalt layers never exceeds a shear stiffness of 100 MPa [16]. The interlayer bond is thus significantly weaker than it is considered in the German calculation model of RDO Asphalt 09.

In order to investigate the effects of the reduced (flexible) interlayer bond on the fatigue behavior of asphalt pavements, calculations according to the RDO Asphalt 09 method were performed using SAFEM. For this purpose, five different interlayer bond configurations were defined for the layer boundaries between surface and binder course, between binder course and base course as well as between base course and base course:

1) Full interlayer bond (FIB): theoretical case, which was not proven to exist in the experiments. Upper and lower asphalt layer are firmly connected. It is assumed for the dimensioning calculation according to RDO Asphalt between asphalt layers.
2) Good Case (GC): experimentally established best shear stiffness on laboratory-produced test specimens.
3) Bad Case (BC): smallest shear stiffness, which was determined on laboratory-produced test specimens.
4) Completely fatigued interlayer bond (CFIB): determined in long-term tests normal-stress-dependent, temperature-independent shear stiffness [9].
5) Completely missing interlayer bond (CMIB): theoretical case, which was not proven to exist in the experiments. Upper and lower asphalt layer slide on each other.

Though cases 1) and 5) were not proven to exist in the experiments, they are shown in the figures for orientation and comparison. The results have been produced for a standard asphalt pavement construction according to Table 1, line 1 of the RStO 2012 for a dimensioning-relevant load B corresponding to loading class Bk100. The “Good Case” interlayer bond configuration was set as a reference value for the 100% fatigue status of the asphalt pavement for a service life of 30 years.

For the calculations, following assumptions were made for all possible interlayer bonds (figure 2).

The realistic service life of asphalt pavements was calculated between 15 and 65 years (figure 3).

Figure 4 shows the combination cases BC-BC-BC, BC-BC, GC-GC-GC and GC-GC. A reduction of the service life by 25...30% results solely from the existence of a third interface. Thus, the consideration of three instead of only two interfaces shows the clear effect of the interlayer bond on the service life of the whole asphalt pavement. The two Bad Case interfaces (BC-BC) lead to the same service life of the asphalt pavement (43 years) as the three Good Case interfaces (GC-GC-GC) which is a service life prolongation of 13 years in comparison with three Bad Case interfaces (BC-BC-BC). Two BC interfaces reduce the whole pavement’s service life with 13 years compared to the existence of two Good Case interfaces (GC-GC).

Figure 5 shows that almost the same service life has been estimated when using the Bad Case bond with three interfaces (BC-BC-BC) as it is in the case with two interfaces of Completely Fatigued Interlayer Bond (CFIB-CFIB). When adding an interface with completely fatigued bond to the base course (CFIB-CFIB-CFIB) approximately 47% service life reduction was calculated compared to the reference variant BC-BC-BC. This finding clearly shows again what effect an additional interface has on the service life reduction of asphalt pavements.
A comparison between three varieties of interface quality has been undertaken (figure 6). The results of the combination of two Bad Case interfaces with one Completely Fatigued Interlayer Bond show that CFIB between binder and base course or between both base courses causes similar service life reductions. As soon as there are two interfaces with Completely Fatigued Interlayer Bond (BC-CFIB-CFIB), a significant reduction of the service life is observed. In this case, the service life of the asphalt pavement is expected to be only 17 years.

The variant with completely fatigued interlayer bond, calculated in both combinations (binder on base course and base on base course) hardly shows a change in the estimated service life compared to the variant with a completely fatigued interlayer bond at all three interfaces. This leads to the conclusion, that the interfaces between binder course and base course and between base course and base course are the relevant ones with respect to the fatigue of the asphalt courses.

Figure 3. All calculated fatigue curves normalized to BC-BC-BC (three interfaces).

Figure 4. Comparison between three instead of two interfaces under otherwise identical conditions.
Figure 5. Comparison between variants Bad Case and Completely Fatigued Interlayer bond.

Figure 6. Further comparison between variants Bad Case and Completely Fatigued Interlayer bond.

4.2. Monetary evaluation

Further investigation was undertaken, whether a monetary assessment, based on the calculation results, is possible in case that completely missing bond between the layers is stated after completion of the asphalt pavement. The German "Recommendations for the execution of construction contracts when using RDO Asphalt 09" were used for this assessment. In the example presented in figure 7, it is aimed to find out what effect the lack of bond between binder and base course can have. The mathematical estimation shows a service life reduction of 5 years or 17%.
The monetary evaluation can be made using the recommendations for the execution of construction contracts (figure 8). The red-edged area is presented enlarged in figure 9.

**Figure 8.** Construction cost penalty depending on the service life reduction. A service life reduction of 17% would result in a construction cost penalty of 8% (figure 9).

**Figure 9.** Construction cost penalty at a service life reduction of 17%.

Figure 10 shows that in case of a completely fatigued interlayer bond at both relevant interfaces, a service life reduction of 13 years or 43% is calculated. The monetary evaluation is shown in figure 11.
Such service life reduction would result in a very high construction cost penalty of about 34%, which would possibly necessitate the replacement of the defective asphalt pavement.

![Figure 10](image1.png)

**Figure 10.** Service life reduction in the absence of IB between binder and base course and between base and base course.

![Figure 11](image2.png)

**Figure 11.** Construction cost penalty at a service life reduction of 43%.

5. Conclusions

In this work, it has been succeeded to determine the shear stiffness at the interface using a newly developed test apparatus and an extended test procedure. Universal master functions for the analytical assessment of the shear stiffness $G_S$ have been established and implemented in the finite element program SAFEM to estimate the influence of the interlayer bond on the service life of asphalt pavements. This function takes into account the influence of temperature, shearing frequency and normal pressure.

Using the finite element calculations and applying the German method for computational design according to RDO Asphalt 09 fatigue curves for a full/rigid (FIB), a good (Good Case), a most achievable (Bad Case), a completely fatigued (CFIB) and a completely missing (CMIB) interlayer bond have been established for an exemplary assumed asphalt pavement.

Based on the calculation results, a monetary evaluation has been done and a methodology for a construction cost penalty according to the service life reduction of asphalt pavements caused by interlayer bonds of different quality has been developed.
The detailed calculations presented in this paper show that a computational service life assessment on the basis of results from performance testing of both the interlayer bond and the asphalt properties represent plausible and promising possibilities for estimating the quality of new as well as existing asphalt pavements.

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