ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ СОФИЯ

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DEVELOPMENT OF FATIGUE FUNCTIONS FOR ASSESSING THE SERVICE LIFE OF ASPHALT PAVEMENTS AT DIFFERENT INTERLAYER BOND PROPERTIES

B. Hristov[1]

Keywords: *asphalt, shear stiffness, interlayer bond, fatigue, cyclic test, master function*

ABSTRACT

A long service life of asphalt pavements can be achieved through a good and durable interlayer bond. A newly developed test apparatus for cyclic testing of the interlayer bond (CTIB) as well as the extensive experimental procedure are presented in this paper. The methodology for the experimental determination of the bond shear stiffness at different temperatures, normal stresses and shearing frequencies is introduced together with the established master function for the analytical assessment of the shear stiffness. The master function has been implemented into a finite element program in order to calculate fatigue functions for asphalt pavements influenced by different interlayer bonds using the German method for computational design according to [1]. It has succeeded to forecast the fatigue status of asphalt pavements with interlayer bonds of different quality for a service life of 30 years and to make recommendations for the practical use for both new asphalt pavement construction and maintenance.

1. Introduction

The construction of asphalt concrete pavements in Germany usually consists of a surface course, a binder course and a base course. The interlayer bond is the full-surface and

[1] Borislav Hristov, Prof. Dr.-Ing., Department of Engineering, Chair of Transportation, University of Applied Sciences Berlin (HTW Berlin), Wilhelminenhofstraße 75A, 12459 Berlin, e-mail: Borislav.Hristov@HTW-Berlin.de

rigid connection at the interfaces between the individual asphalt layers, which is achieved through a tack coat (e.g. bitumen emulsion). The mechanical behavior of the whole multilayer structure depends on both the material properties of each course and the properties of the interlayer bond. Even if all the asphalt layers possess perfect material properties, the risk of failure of the pavement still remains if the bond at the interfaces is not properly designed. Thus, the durability of the whole structure depends largely on the good quality of the bond between the asphalt layers.

The combined influence of temperature, normal stress and shearing frequency on the bonding properties is still insufficiently researched, despite the numerous studies on this subject. Therefore, work has been undertaken by the authors using a newly developed test apparatus for CTIB and a very detailed testing procedure for determination of the shear stiffness of the interlayer bond.

The main objective of this study is to determine the functional dependency between shear stiffness, temperature, shearing frequency and normal stress in order to implement the established master function in the finite element program SAFEM (Semi-Analytical FE Method). In conjunction with the German method for computational design according to [1] it is aimed to analyze the impact of the interlayer bond on the whole asphalt pavement and to forecast the service life of asphalt pavements at qualitatively different interlayer bonds. Another goal of this work is to make recommendations for the practical use for both new construction and maintenance.

2. Background

The interlayer bond is achieved 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. To ensure a good bond between the asphalt layers, the top surface of the underlying layer should be cleaned before spraying it with a bitumen emulsion and before placing the next layer.

The asphalt concrete pavement is loaded permanently in both a vertical direction by шге vehicle wheel loads and a horizontal direction by braking and acceleration processes, which may fully change the three-dimensional stress state in the entire pavement structure and may lead to horizontal displacements of the layers if a poor interlayer bond is present. Temperature variations also cause additional stresses, which can compromise the functionality of the pavement. The result may be a reduction or a loss of load capacity, premature material fatigue, pothole formation, separation of the layers, delamination of wearing course, slippage cracking, distortion and significantly shorter service life of the entire asphalt construction. When a full bond exists, the asphalt layers act as a unit during load transfer. In this case no relative displacements between the asphalt layers are present. When there is a poor or no bond between the layers, large displacements may appear. Thus, a good interlayer bond contributes to a long service life, driving comfort and road safety.

In Germany the assessment of the interlayer bond in asphalt pavements is currently carried out with a static test according to Leutner [15] by determining the shearing-off force as a criterion for the evaluation of the achieved bond strength, which is regulated in [16]. In many countries there are some similar methods with different test conditions [1 – 4]. Some testing procedures and test devices are improved so that normal stresses can additionally be applied [5 – 9]. The disadvantage of the static tests is that they cannot simulate the real loading state in the pavement due to repeated loads, and therefore they are inapplicable for the accurate description of the bond behavior.

Several devices have been developed over the years, which make the initiation of shear stresses in the specimens possible via cyclic loads with or without interaction of normal loads [16 – 21]. All testing devices differ in terms of testing procedure, type of load (force-controlled or position-controlled testing procedure), testing temperature and normal stresses. At TU Dresden, [21] have used a shear apparatus for cyclic shear tests with static normal force. The detailed testing procedure includes temperatures ranging from -10 °C to 50 °C, frequencies in the range of 1 Hz to 15 Hz and normal stresses ranging from 0 to 1,1 MPa. The purpose of the project has been to find a "bonding factor" for good and poor bond.

A new improved apparatus for CTIB has been designed at the Department of Pavement Engineering at TU Dresden. Its purpose is to simulate as accurately as possible the real load conditions which exist on in-service asphalt pavements. An extensive testing procedure has been created to take into account the interactions of repeated traffic loading, acceleration and braking processes as well as weather-related effects.

3. Experimental program

3.1. Preparation of Double-Layered Asphalt Specimens

The layer combination of surface course binder course and binder course on base course was produced in the laboratory for the cyclic tests described in this work. Two-layered asphalt slabs (320 mm × 260 mm) were prepared in the roller sector compactor using a compression program with position-controlled pre-compression and force-controlled main compression. The slabs of the lower course were first produced and stored at room temperature (RT) for 24 hours. Before applying the bitumen emulsion, the slabs surfaces were cleaned with a brush. The bitumen emulsion was then applied uniformly using a flexible foam roller with the desired amount. The coated slabs were left at RT for at least two hours until the complete "breaking" of the bitumen emulsion [10]. The hot bituminous mixture of the upper course was then laid and compacted. Four cylindrical specimens of a diameter of 100 mm were drilled from one double-layered asphalt slab. The asphalt specimen was fixed inside two steel adapters with the aid of a two-component epoxy adhesive. 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 (Fig. 1). The four half-shells were fastened together with eight screws. Each sample was stored at RT for at least 24 hours until the complete hardening of the adhesive.

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Figure 1. Specimen preparation for CTIB

Two types of bitumen emulsion were used to produce the interlayer bond: the polymer modified cationic C60BP1-S from two different manufacturers and the cationic C40BF1-S with solvents. The bond was created using respective amounts of 200 g/m^2, 300 g/m^2 and 400 g/m^2 bitumen emulsion and at three roughness combinations of layer surfaces, namely fine, normal and rough. The experimental program also included an interlayer bond at three degrees of contamination of the surface of the underlying layer with silt (clean, middle contamination with 180 g/m^2 and high contamination with 360 g/m^2).

3.2. New Apparatus for Cyclic Testing of the Interlayer Bond

The new test apparatus was designed to apply cyclic shear force in the vertical direction and static normal force in the horizontal direction (Fig. 2) and was mounted in the temperature chamber of a servo-hydraulic testing machine. The test sample was inserted in the jowls A and B. Half of the sample was in jowl A and the other half was in jowl B. The gap between the jowls was the same as it was between the steel adapters of the sample (1,0 mm). The steel adapters were fastened in the jowls with 24 screws to avoid any movement of the sample in the test apparatus. The sinusoidal position-controlled shear cyclic loading was applied to one layer of the specimen through jowl B. The second half of the specimen was held unmovable in vertical direction by jowl A. The normal pressure was applied on the back of the asphalt specimen (jowl A) by a piston rod through a steel plate. To counteract the normal pressure, the specimen was blocked at the front surface through a second steel plate held by a socket which was fastened to jowl B. The mechanical model of the test apparatus is also shown in Fig. 2. The vertical shear displacement was measured using two sensors, which were attached to jowl B. The horizontal motion of jowl A was also measured by two sensors, which were mounted horizontally on it. The mechanical model of the test apparatus can be seen in Fig. 2 (right).

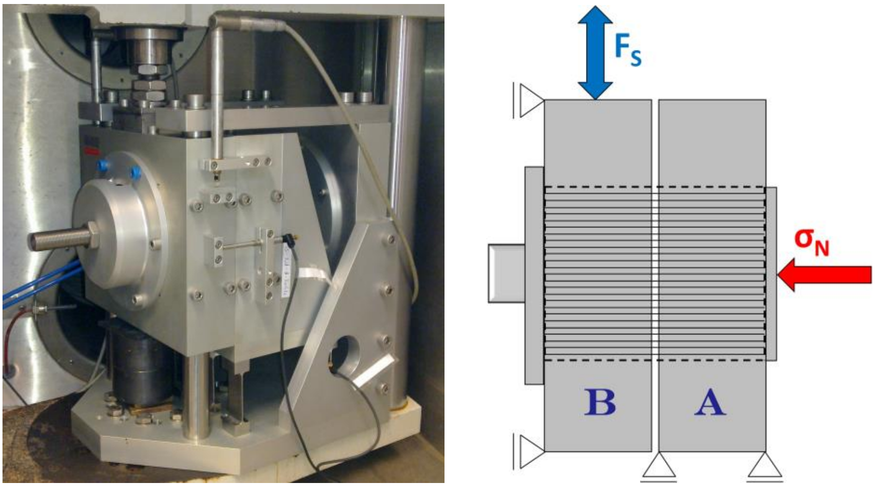

Figure 2. Newly developed test apparatus for CTIB (left) and mechanical model (right)

3.3. Testing Procedure

The cyclic tests were carried out in the form of an extensive test procedure to include all factors that influence the interlayer bond. The whole experiment was conducted at four different temperatures. At each temperature the specimen was loaded with five normal stresses.

Six frequencies at the corresponding number of load cycles (LC) changed successively during each normal pressure. The whole procedure of simultaneous and consecutive process runs was fully automated and no manual interference was required. In order to be able to test two specimens within one day, a program with a temperature excess was developed to reach the five targeted test temperatures within the asphalt specimen in a shorter time. The duration of the whole procedure for one specimen lasted 11 h 43 min.

4. Functions for shear stiffness assessment

4.1. Development of a Master Function

All data obtained in the course of the experiment was recorded in log files. Only the data from the last five cycles at the end of each shearing frequency were used for the calculation of the shear stiffness in order to exclude the initial deviations at the beginning. The shear strain is calculated as follows:

$$\tan \gamma_s = \frac{\tau_s}{G_s} . \tag{1}$$

For small shear angles $\tan \gamma_s \approx \gamma_s$. The shear strain can be determined as the ratio of the shear displacement s_w to the gap between the steel adapters $d_s = 1{,}0$ mm (Fig. 1).

$$\tan \gamma_s = \gamma_s = \frac{s_w}{d_s} . \tag{2}$$

The shear stiffness is therefore

$$G_s = \frac{\tau_s}{\gamma_s} = \frac{\tau_s}{\left(\dfrac{s_w}{d_s}\right)} \tag{3}$$

with

$$\tau_s = \frac{F_s}{A} , \tag{4}$$

where F_s is the shear force amplitude (N);

γ_s – shear strain (-);

τ_s – shear stress, MPa;

A – cross section at the interface, mm^2;

s_w – shear displacement amplitude, mm;

d_s – gap between steel adapters, mm;

G_s – shear stiffness, MPa/mm.

For the analytical assessment of the shear stiffness, it was necessary to develop a universal master function, which takes into account the combined influence of temperature, normal stress and frequency. First, the relationship between the shear stiffness and the temperature-frequency equivalence was established at the four normal stresses from the average values of at least three tests for every particular test case (Fig. 3). The regression used for the master curves which approximated the experimental values most accurately was the sigmoid function. This function approaches asymptotically the minimum and the maximum values of the shear stiffness. The temperature-frequency equivalence as described in AL Sp-Asphalt 09 was computed as follows:

$$m = \log(\alpha_T \cdot f) = \log\left[\frac{1}{e^{-\frac{E_a}{R}\cdot\left(\frac{1}{T+273{,}15}-\frac{1}{T_R+273{,}15}\right)}}\cdot f\right]. \tag{5}$$

The master function for the shear stiffness G_s was found to be

$$G_s = G_{s,\min} + \frac{\left(G_{s,\max} - G_{s,\min}\right)}{1+e^{(m\cdot a+b)}}, \tag{6}$$

where m is the temperature-frequency equivalence, Hz;

$G_{s,\min}$ – minimal shear stiffness, MPa/mm;

$G_{s,\max}$ – maximal shear stiffness, MPa/mm;

α_T – shift factor (-);

f – frequency, Hz;

T – test temperature, °C;

T_R – reference temperature (20 °C);

E_a – activation energy, J/mol;

R – universal gas constant, J/mol·K.

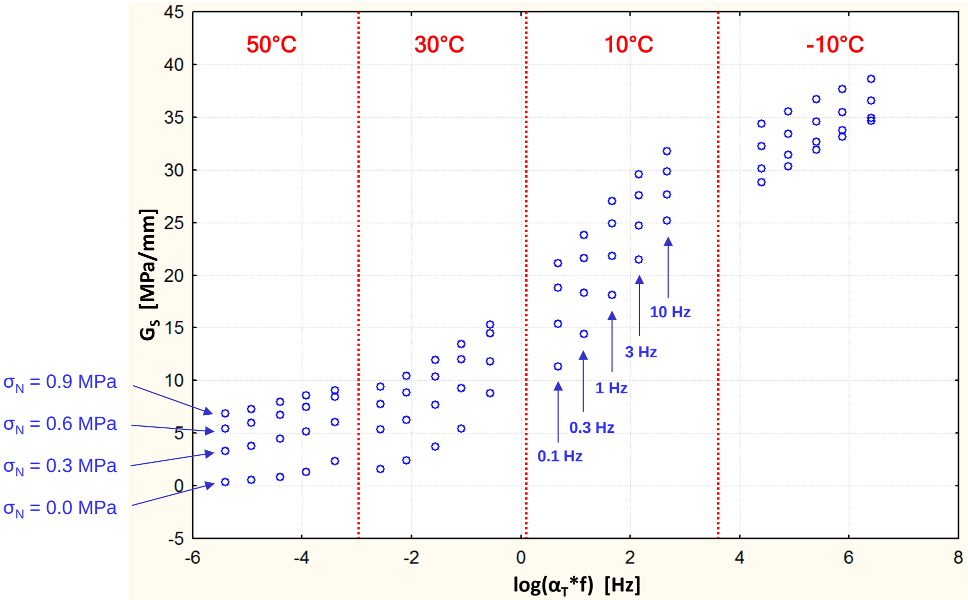

Figure 3. Functional dependence between the shear stiffness and the temperature-frequency equivalence at four normal stresses

The regression parameters, **a** and **b,** are both functions of the normal stress. For parameter **a** the logarithmic function showed the best fit, while for parameter **b** it was the linear function.

Using the master function for G_s (6), the shear stiffness of the interlayer bond can be calculated for any arbitrary temperature, frequency and normal stress.

4.2. Shear Stiffness of Completely Fatigued Interlayer Bond

From the experimentally determined fatigue curves it was found that the increase in the normal stress 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 (Fig. 4). 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.

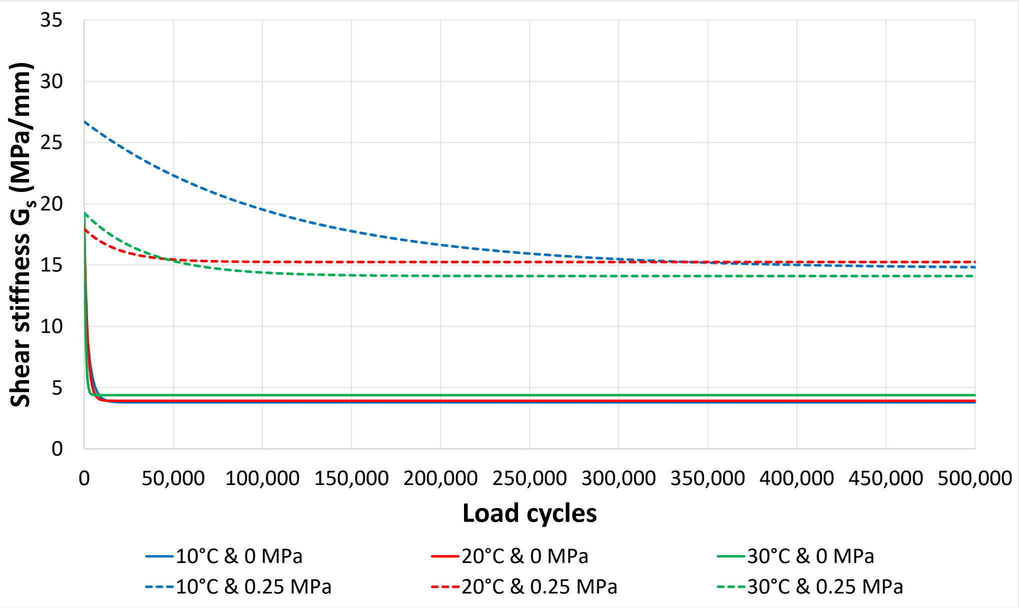

Figure 4. Fatigue curves for the interlayer bond at two normal stresses and three temperatures

Under the assumption that the fatigue is normal stress but not temperature dependent, a linear relationship of the shear stiffness and the normal stress between the average values of the completely fatigued interlayer bonds was determined.

5. Results and recommendations

The results show that the shear stiffness of the interlayer bond is significantly smaller than is taken into account in the calculation model of [1].

In order to investigate the effects of the reduced interlayer bond on the fatigue behavior of asphalt pavements, the finite element program SAFEM [11] has been used to perform calculations according to the German method for computational design over the service life of 30 years. For this purpose, five different interlayer bond configurations were established for both layer combinations of surface course on a binder course, and a binder course on a base course (Fig. 5):

1) Full interlayer bond:
    - theoretical bond;
    - upper and lower asphalt layers are fully fixed together;
    - used for dimensioning according to [1] between asphalt layers.
2) "Good Case" (good bond): best measured interlayer bond.
3) "Bad Case" (poor bond): worst measured interlayer bond.
4) Completely fatigued interlayer bond: normal stress-dependent, temperature-independent bond determined in long-term tests.
5) Completely missing interlayer bond:
    - theoretical bond;
    - upper and lower asphalt layers glide smoothly against each other.

The "Good Case" was set as the reference value for the 100 % fatigue for a service life of 30 years.

Table 1. Relative results for the calculated interlayer bond configurations

Interlayer bond configuration	Relative downtime			
	Reference „Complete interlayer bond"		Reference „Good Case"	
	Percent	Referred to 30 years	Percent	Referred to 30 years
Full interlayer bond	100,00 %	30,00 years	181,03 %	54,31 years
Good Case	55,24 %	16,57 years	100,00 %	30,00 years
Bad Case	42,18 %	12,65 years	76,36 %	22,91 years
Completely fatigued interlayer bond	28,66 %	8,60 years	51,88 %	15,56 years
Completely missing interlayer bond	14,53 %	4,36 years	26,30 %	7,89 years

For pavement maintenance, the "Bad Case" values should be applied when calculating the asphalt pavement fatigue for the case of existing adhesion between the asphalt layers, with the interlayer bond being not experimentally tested.

If the layers are not bonded together (broken interlayer bond), and only the effects interlocking and friction are present, then the fatigue function for the completely fatigued interlayer bond should be used. For pavement maintenance, if the interlayer bond is experimentally tested and the fatigue function is calculated, the values of the fatigue gradient may appear to be higher than the calibration values and thus the service life of the asphalt pavement may exceed 30 years.

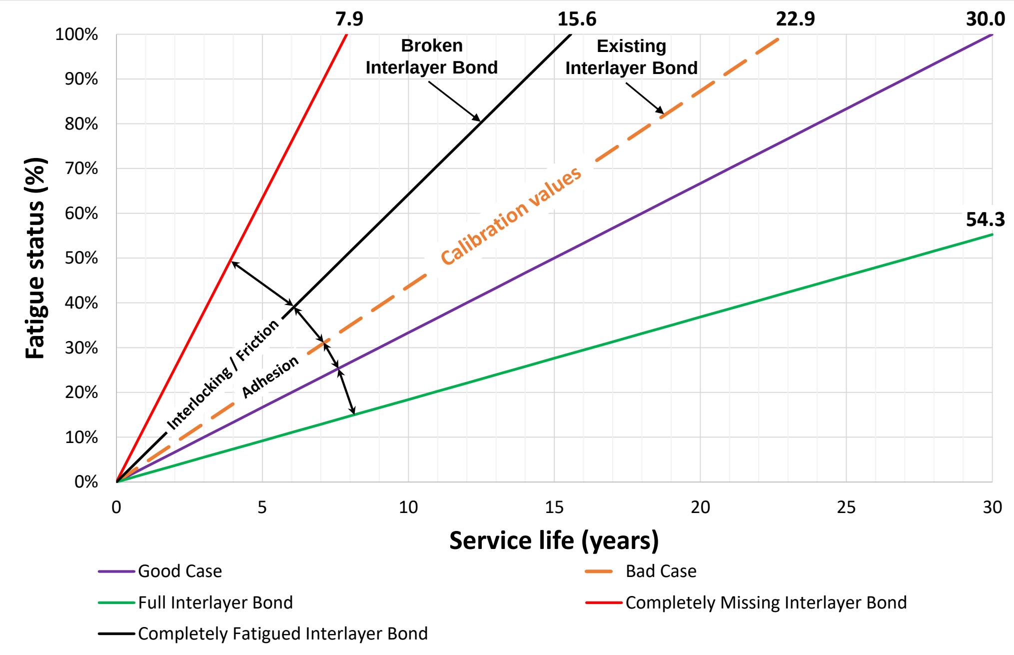

Figure 5. Fatigue functions for asphalt pavements affected by different interlayer bond properties for new construction and maintenance

6. Conclusions

A new test apparatus and an extended test procedure have been developed to determine the shear stiffness at the interface at different temperatures and normal stresses under sinusoidal repeated shear loading conditions-for-varying frequencies.

A master function for the analytical assessment of the shear stiffness G_s has been developed. The regression which approximates most accurately the experimentally determined shear stiffness values is the sigmoid function. This function takes into account the combined influence of temperature, normal pressure and shearing frequency, and the calculated shear stiffness agrees well with the experimentally assessed one.

The master function with the respective regression parameters for five different bond qualities has been implemented in the SAFEM finite element program to calculate the fatigue behavior in accordance with the German method for computational design. Thus, it is possible to predict how the interlayer bond affects the whole asphalt pavement structure. Fatigue functions for a full, good, poor, completely fatigued, and completely missing interlayer bond have been derived to define the most important fatigue cases for new pavements and pavement maintenance. As a reference value for 100 % fatigue, the pavement with good bond between the asphalt layers ("Good Case") has been determined for a service life of 30 years. If a broken interlayer bond is determined on a core sample when performing pavement maintenance activities, the fatigue function for the asphalt pavement with completely fatigued interlayer bond should be used. In the case of an existing bond between the asphalt layers of the core sample, and on condition that this bond is not experimentally tested, the use of the calibration values is recommended. Verification through experimental testing and computation of the fatigue function using the RDO Asphalt 09 method and the finite element program SAFEM may result in higher values than the calibration ones.

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РАЗРАБОТВАНЕ НА ФУНКЦИИ НА УМОРА ЗА ОЦЕНКА НА ЕКСПЛОАТАЦИОННИЯ СРОК НА АСФАЛТОВИ НАСТИЛКИ ПРИ РАЗЛИЧНИ СВОЙСТВА НА МЕЖДУСЛОЕВАТА СВЪРЗКА

Б. Христов[1]

Ключови думи: *асфалт, коравина на срязване, междинна връзка, умора, циклично изпитване, основна функция*

РЕЗЮМЕ

Дългият експлоатационен живот на асфалтовите настилки може да се постигне чрез добра и издръжлива междинна връзка. В тази статия е представен новоразработен тестов апарат за циклично изпитване на междуслойната връзка (CTIB), както и обширна експериментална процедура. Въведена е методологията за експериментално определяне на якостта на срязване на връзката при различни температури, нормални напрежения и

[1] Борислав Христов, проф. д-р инж., Катедра по пътно строителство, Университет за приложни науки Берлин (HTW Berlin), Вилхелминенхофщрасе 75А, 12459 Берлин, e-mail: Borislav.Hristov@HTW-Berlin.de

честоти на срязване заедно с установената основна функция за аналитична оценка на коравината на срязване. Главната функция е внедрена в програма с крайни елементи, за да се изчислят функциите на умора за асфалтови настилки, повлияни от различни междуслойни връзки, като се използва немският метод за проектиране съгласно [1]. Прогнозира се състоянието на умора на асфалтови настилки с междуслойни връзки с различно качество за експлоатационен живот от 30 години и са направени препоръки за практическа употреба както при изграждането, така и при поддръжката на нови асфалтови настилки.