Determination and evaluation of the remaining substance of flexible pavement (asphalt) constructions after long-term traffic loading

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ABSTRACT

The aim of this research project is to develop a procedure that is able to estimate the monetary value of asphalt pavements already in use for a typical life time of 15 years regarding given conditions like traffic and climate. Basic coherences for a subject related estimation of the structural material value as well as its monetary evaluation on the basis of an analytic prognosis procedure are made. The necessary material properties (deformation and fatigue parameters) are determined by laboratory tests.

Several sections of federal highways in Germany with different asphalt constructions were investigated. Drill cores were used to determine the deformation characteristics and the fatigue functions. Therefore indirect tensile tests were performed. The same test specimens were used to perform multistage tests (E-modulus) with a frequency of 10 Hz. The test program comprises four temperatures and three tension levels. The fatigue behaviour of the test specimens was tested with a frequency of 10Hz and at only 20°C at three tension levels each.

One possibility for the estimation of the remaining life time is based on a calculation procedure. With this procedure the evaluation of the asphalt construction on the basis of material parameters (deformation characteristic values, fatigue parameters, climatic data and volume of traffic) is possible and results in necessary layer thicknesses and the rutting sensibility of the asphalt layers (deviatoric stresses). In reversal of this procedure the moment when cracking starts and thus the end of the service life can be estimated.

An instrument therewith is available that enables to predict the remaining time until failure of flexible pavement constructions at any time. With this knowledge an optimal pavement management is possible.

To confirm this evaluation method (respectively predictions concerning the behavior of the states of fatigue can only be made by further testing) further drilling cores are at present being examined applying the same test program as described in this project.

The successively obtained results, pavement design calculations and evaluation of remaining substance are presented and discussed in this paper.

1 INTRODUCTION

In the future, German road construction will be less dominated by new construction and more so by maintenance. This requires specific maintenance strategies. For this purpose, so-called “Pavement Management Systems” have been developed in recent years, the basis of which is an objective, network-wide evaluation of the current road conditions in order to identify weak points in time, and to establish priority rankings for upcoming maintenance measures.

The determination of the remaining service life of pavements is absolutely essential for the drawing up of emergency plans and the planning of maintenance measures. Currently, no suitable method for forecasting the remaining life time of asphalt pavements is available (structural damage). For this reason, the development of a suitable method for forecasting the remaining service life of asphalt pavements was necessary for Germany. In this context, traffic exposure, pavement age, climatic conditions and the properties of the materials used had to be considered [1].

The publication is partly based on the research project FA 4.199, “Vergleichende Bewertung der Restsubstanz von Asphaltbefestigungen nach langjähriger Verkehrsnutzung” [1], which was commissioned by the German Federal Ministry of Transport, Building and Urban Affairs. This research project was developed in collaboration with the University of Stuttgart Institute of Roads and Transportation, Chair for Road Planning and Construction Studies

2 METHODS FOR THE FORECAST OF THE REMAINING SERVICE LIFE

For the development of a forecast method for the determination of the remaining service life of asphalt pavements, a computational design program for asphalt pavements which had been developed at Technical University of Dresden was used. Based on this method, the computer program PaDesTo by Kiehne (2008) [2] was developed. With this program it is possible to estimate the maximum tolerable number of load cycles up to the point of pavement failure. The failure criterion for the asphalt package is the fatigue of the asphalt base course. Furthermore, the remaining service life of existing travelled on pavements can be ascertained in context with the traffic forecast and results of the laboratory tests.

It is therefore of outmost importance that the input parameters (material parameters, climatic data, traffic loads) are determined as accurately as possible, for the reliability of the statements (tolerable number of load cycles to failure of the pavement). For example, it is necessary that the fatigue functions of the used asphalt mixes, which can be determined by laboratory tests, are available as material parameters. A suitable laboratory test for the testing of fatigue behaviour (crack formation) of asphalt mixes is the Indirect-Tensile-Test. However, the results of the Indirect-Tensile-Tests do not allow for a direct conclusion with respect to the fatigue load cycles in situ, meaning in the pavement. For this reason, fatigue models for the estimation of the fatigue load cycles of pavements which consider the results of the fatigue tests are necessary. Therefore, a fatigue model was implemented in the PaDesTo program, to allow for the design of asphalt pavements in respect to the failure criterion fatigue (crack formation at the underside of the asphalt base course).

3 PROCEDURE

The results of the laboratory tests performed on the drill core samples from the asphalt of the 10 test tracks (hereinafter referred to as TT), formed the basis of the research project for the evaluation of the remaining substance of pavement (asphalt) constructions. In this publication, the test results of six of the selected TT are presented.

The specimens were produced from asphalt drill cores in the laboratory. First, the general material characteristics such as density and the complex E-Modulus, determined by Indirect-Tensile-Tests, for the asphalt wearing course (ADS), the asphalt binder (ABi) and the asphalt base course (ATS) samples were determined. In the second step of the research, the fatigue conditions for the ATS-mixes were determined. In order to determine the cryogenic tensions for the ATS-mixes, cooling tests were necessary. The tests were conducted at the Braunschweig Pavement Engineering Centre (ISBS) of the Technical University Braunschweig. Based on the laboratory test results, a computational evaluation of the number of load cycles up to the point of fatigue cracks occurring was performed with the PaDesTo program in order to determine the time of failure (TOF) of the pavements. The definition of the selection criteria for the individual TT was an essential prerequisite for the comparability of results. The following selection criteria were defined for each TT:

- Pavement structure in accordance with RStO 86/89, line 1 (asphalt on base course without binder (ToB),
- long-term traffic usage (between 10 and 16 years),
- high traffic load: Cumulative load > 10.000.000 equivalent passes of 10 ton axle loads for construction classes SV and I and > 5.000.000 equivalent passes of 10 ton axle loads for the construction classes II and III,
- high proportion of heavy vehicles (> 15 %).

Table 1 lists the six selected TT of existing pavement designs in tabular form. Drill cores were taken from the pavements in and next to the wheel track.

Table 1 – Pavement design of the 6 TT

test track	ADS [mm]	ABi [mm]	oATS [mm]	uATS [mm]	sub-base
A	40	80	80	100	FSS
B	40	80	100	120	FSS
C	40	80	-	140	FSS
D	40	90	-	140	FSS
E	40	80	-	120	FSS
F	40	90	120	100	FSS
ADS: Asphalt wearing course, ABi: Asphalt binder, oATS: upper Asphalt base course, uATS: lower Asphalt base course, FSS: base course without binder					

4 EXECUTION OF THE LABORATORY TESTS

The resistance to plastic deformation and resistance against fatigue essentially influence the usage behaviour of asphalt pavements. The deformation characteristics and strength properties of asphalt can be characterised by the three mechanical properties:

- Stiffness
- Plastic deformation behaviour
- Fatigue behaviour

These properties are essential for the analytical design of asphalt pavements.

In this context, in Germany the asphalt composition is mainly optimised with regard to the resistance against plastic deformation. Resistance to cracking is often only taken into account insufficiently. Both fatigue cracks, due to repeated traffic exposure, and rutting are the most commonly observed damages to asphalt pavements.

As mentioned earlier, the tests for fatigue behaviour and the determination of the E-

Modulus of asphalt can be conducted in a laboratory by means of the Indirect-Tensile-Test. The principle of the Indirect-Tensile-Test will not be discussed in detail here.

4.1 Determining the E-Modulus

18 drill cores were taken as samples from each TT and made into specimens for the determination of the E-Modulus. Indirect-Tensile-Tests were performed at a frequency of 10 Hz, at three different temperatures and three different tension levels for all asphalt mixes (ADS, ABi, ATS), to determine the E-Modulus. Force-controlled, harmonic sinusoidal fatigue stress without load break at lower stress of 0,035 N/mm² was applied to the specimens. Thereafter, the asphalt mix samples which had been taken from the wheel track were given the designation _R, and the asphalt mix samples taken from next to the wheel track were given the designation _N (e.g. ATS_R and ATS_N). When examining the E-Modulus values of the ADS it becomes clear (Figure 1), that based on a TT, the E-Moduli of nearly all tested specimens of the ADS_R are higher than the E-Moduli of the specimens of the ADS_N. Presumably, the cause for the higher E-Moduli of the ADS_R is the higher compaction that occurs due to the many roll-overs and the resultant lower void content of the ADS_R compared to the ADS_N.

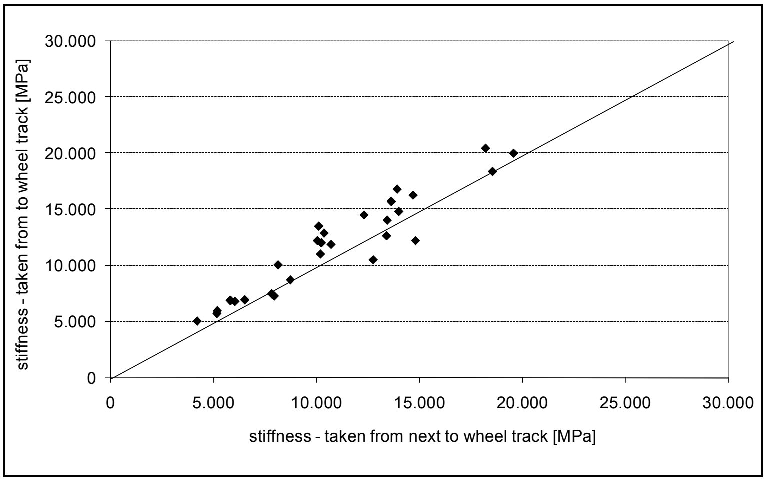

Figure 1 – Comparison of the E-Moduli of ADS_R and ADS_N

Furthermore, it was detected that on average values of the E-Moduli of the lower ATS_R compared to the ATS_N are approximately 4 to 8 % lower (Figure 2). The cause of these differences could be incipient damage of the ATS by microcrack formation and a resultant drop of the E-Modulus. The damage caused at the underside of the asphalt course by microcrack formation results in an increase of the elastic strains in these areas (decrease of the E-Modulus); in turn, this results in the decrease of effective stiffness of the total ATS. For example, studies performed on the LINTRACK test tracks at the TU Delft (Molenaar 2007) [3] showed that with a decrease of the E-Modulus in the range of 30 – 50 %, significant damage, in terms of crack formation in the respective asphalt courses, was observed. It can be concluded that different states of fatigue of asphalt base courses (here: ATS_R compared to ATS_N) should already be detectable when comparing the E-Moduli.

Based on the results of the fatigue tests at the lower ATS, the E-Modulus was determined before the start of the test. Figure 2 shows the ratio of the E-Moduli for the ATS (ratio of E-Moduli of the ATS_R and ATS_N).

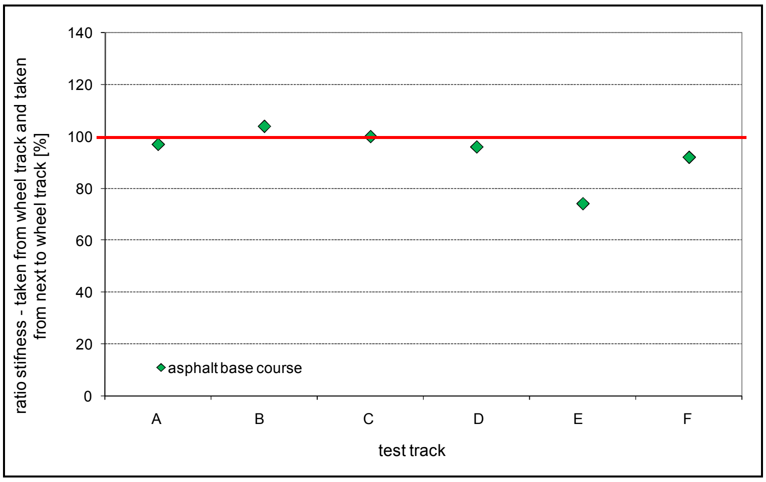

Figure 2 – Ratios of the E-Moduli next to and in the wheel track
for the lower ATS of the TT A to F

Significantly different E-Moduli could be determined for the E-Moduli of the ATS_R and ATS_N for the TT E. In this context, a markedly higher decrease in stiffness could be detected for the ATS_R during the resting period of the pavements compared to the ATS_N. For all other TT the value of the E-Moduli of the ATS_R and ATS_N was of similar scale (< 10 %). In this context, a range of variation of the E-Moduli value ± 10 % can be rated as too low to expect significant effects on the fatigue behaviour. The variations determined in respect to the stiffness of ± 10 % are probably due to installation. For example, the layer thicknesses and degrees of compaction of the ATS_R and the ATS_N can fluctuate, whereby the fatigue (crack formation behaviour) of the ATS due to traffic and other effects is interfered with. Hereby, slight shifting/torsion (in the sense of change in steepness) may occur in the fatigue functions, which are not necessarily caused by material fatigue due to traffic. By means of comparison of the E-Moduli values of the ATS for the individual TT, the following was expected when determining the fatigue conditions:

- The E-Modulus of the ATS_R for TT E was identified as being 25 % lower than the ATS_N E-Modulus. For this reason, compared to the ATS_N, a lower fatigue resistance of the ATS_R is expected. As a result of the different E-Moduli of the ATS_R and ATS_N for the TT E, differences should also occur for the course of the cryogenic tensions.
- Based on the low range of variation of the stiffness, no significant differences in respect to the fatigue behaviour are expected for the remaining TT for the ATS_R and ATS_N.

4.2 Determination of fatigue functions

As already outlined in Section 3, the fatigue conditions for the ATS could be determined by Indirect-Tensile-Tests within the framework of the research project. The determination of the fatigue conditions was performed by individual tests at three different top loads (stress amplitudes). The test temperature was set at 20 °C and the loading frequency at 10 Hz.

For the determination of the material-specific fatigue functions, the number of load cycles to reach the point of macro cracking occurring was established. Strain based fatigue functions could be determined for all tested asphalt mixes in correlation with the initial elastic lateral strain. Furthermore, the stress based fatigue functions were determined.

The analysis of the fatigue tests showed that the values derived from the comparison of the E-Modulus values of the ATS_R and ATS_N, were, as a matter of principle, confirmed with respect to the fatigue behaviour of asphalt mixes. In this context, a direct comparison of the strain based fatigue functions of the ATS_R and the ATS_N (equal pavement design) is only possible if both E-Moduli have the same value. However, in the case of a comparison of the fatigue behaviour by means of strain based fatigue functions, the different strains which potentially occur in the ATS at equal load level, due to the different grades of stiffness, must be considered. This comparison can be performed with the aid of the design method described in the draft of the RDO-Asphalt (FGSV 2008) [4]. Alternatively, it is possible to determine comparative statements in respect to the fatigue resistance of the ATS_R and ATS_N, based on the stress based fatigue functions (for one temperature level - here 20 °C), provided a similar status of stress occurs in the pavement.

No significant difference can be determined for TT A, B, C, D and F, neither for the value of the E-Modulus, nor for the comparison of the strain and stress based fatigue functions of the ATS_R and ATS_N. The slightly different orientation in the fatigue functions is presumably due to installation.

A significant difference in the E-Modulus values of the ATS_R and ATS_N can be detected for TT E. Here, due to the different levels of material fatigue, the stiffness of the lower ATS_R is markedly lower (approximately 25 %) than the stiffness of the ATS_N. It is for this reason, that a comparison of the stress based fatigue functions is appropriate. Figure 3 shows, that the ATS_R of the TT E has a significantly lower fatigue resistance than the ATS_N. Furthermore, it is observed that the correlation coefficients R^2 of the fatigue functions for the ATS_R tend to be lower than those of the ATS_N (Figure 4). In this context, the lower correlation coefficients of the fatigue functions of the ATS_R could be an indication of advanced material fatigue or change in material.

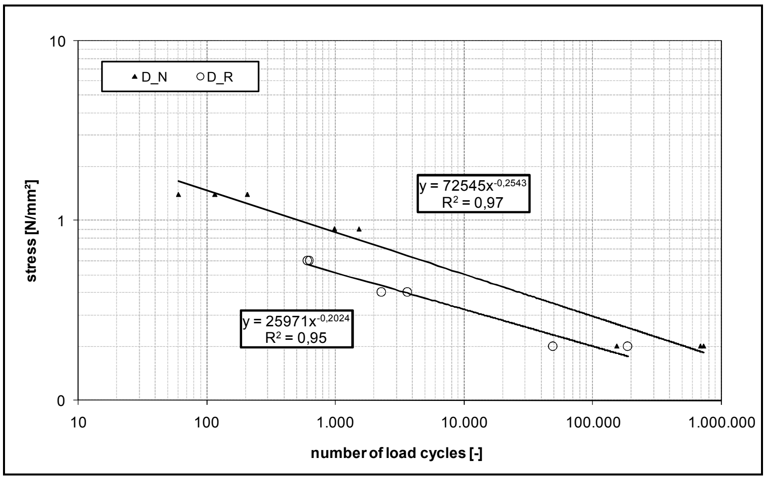

Figure 3 – Stress based fatigue functions
for the ATS_R (ER) and ATS_N (EN) of TT E

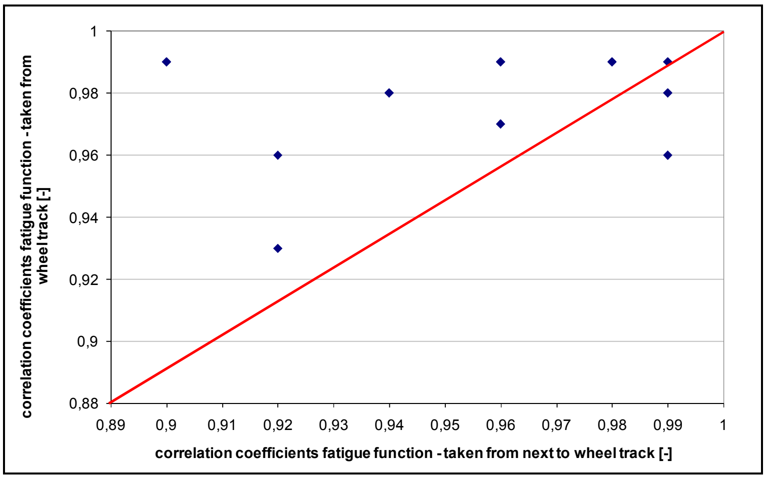

Figure 4 – Comparison of the correlation coefficients R² of the fatigue functions for the ATS_R and ATS_N

4.3 Cryogenic stresses

For the determination of tensile stress which can occur at low temperatures due to hindered thermal expansion, cooling tests in accordance with the German Technical Test Procedure “Behaviour of Asphalt at Low Temperatures” [5] were conducted. The tests were conducted at a cooling rate of 10 K/h.

Figure 5 illustrates the determined cryogenic tensile stress. This is illustrated for ATS_R (example: TT_R) and for the ATS_N (example: TT_N). First, it is evident that different levels of cryogenic stress occurred for the ATS-mixes of the individual TT. Furthermore, it becomes clear that the lowest level of cryogenic stress, of all tested mixes, was determined for the ATS_R of the TT E (E_R), which indicates a high state of fatigue (damage) in the asphalt mix. Similarly, in this context the difference between the cryogenic stress values of the ATS_R and ATS_N must be examined (Figure 6). It becomes clear that the largest difference between the cryogenic stresses for the ATS_R and the ATS_N could be determined for TT E. All other ATS_R and ATS_N behaved in a similar manner with respect to the cryogenic stress profile, whereby during the cooling tests for the majority of the ATS_R, compared to the ATS_N, lower cryogenic stresses were measured.

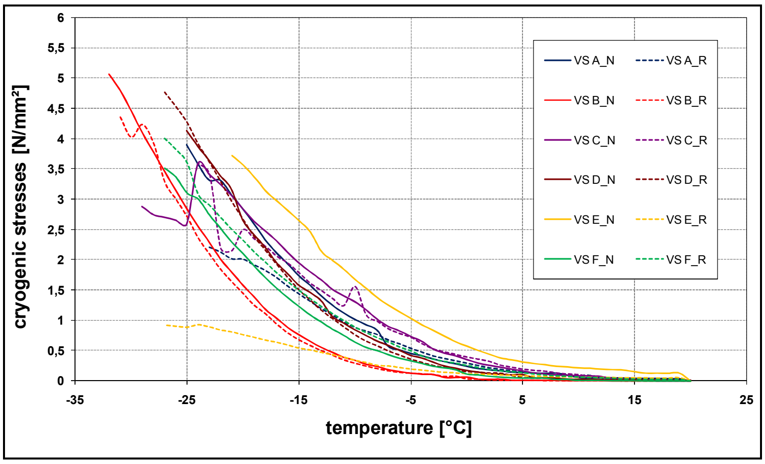

Figure 5 – Course of cryogenic stresses of the ATS_R and ATS_N

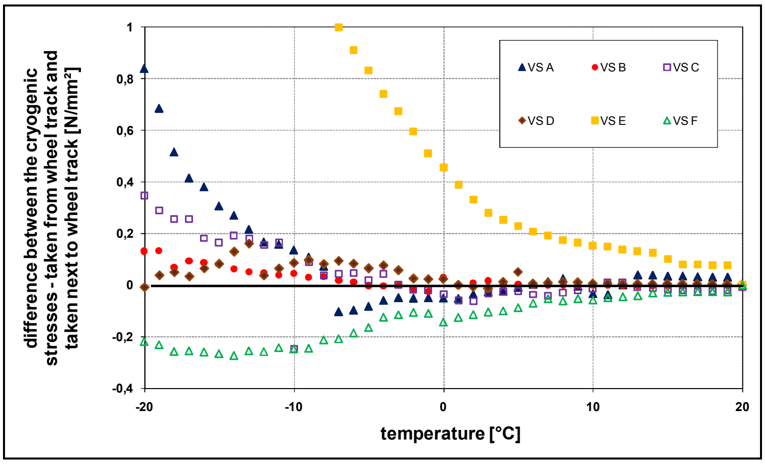

Figure 6 – Difference between the cryogenic stresses of ATS_R and ATS_N

5 CALCULATION FOR THE DETERMINATION OF THE TIME OF FAILURE (TOF)

5.1 Preliminary observations

The tensile strain at the underside of the ATS was used as a design criterion for the asphalt, based on which, the point in time (number of load cycles) of crack formation occurring on the underside of the asphalt can be predicted. The time of failure (TOF) is defined by the occurrence of macro cracks on the underside of the ATS. Not only are the E-Modulus values of all asphalt layers, determined in laboratory tests, incorporated into the calculations but also the stated fatigue functions of the ATS. In this context, the calculated TOF value corresponds to the end of service life of asphalt pavements by application of fatigue models.

5.2 Design input parameters

The results of the Indirect-Tensile-Tests in terms of fatigue functions of the ATS and the E-Moduli were the input parameters used for the PaDesTo program. As an example, Figure 7 shows the E-Modulus characteristic curve of the ABi_R of TT E (red line). The second line (blue/green) represents the E-Modulus characteristic curve of the same ABi_R of TT E based on the E-Modulus estimation procedure by Francken and Verstraeten. It becomes clear that the E-Modulus of the ABi_R of the TT E is relatively low as a result of the fatigue process with low temperatures, compared to the values determined by the Francken/Verstraeten method.

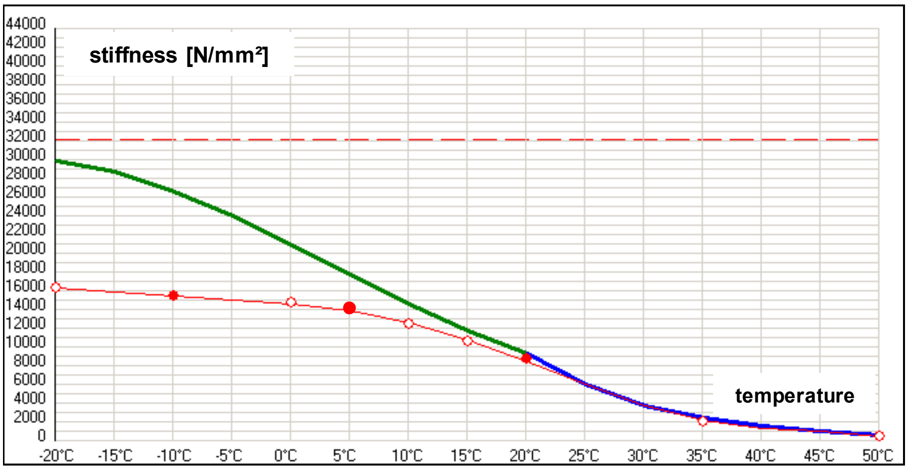

Figure 7 – E-Modulus characteristic curve for ABi_R of TT E

Table 2 lists the traffic loads endured so far on the TT in terms of equivalent passes of 10 ton axle loads. For example, the load borne on TT E amounts to approximately 15,8 million equivalent passes of 10 ton axle loads. Furthermore, an annual average increase in heavy goods traffic of 3 % up to the end of the intended service life of 30 years was calculated for all TT.

Table 2 – TT traffic loads endured in terms of equivalent passes of 10 ton axle loads

test track	endured traffic loads [Mio] (equivalent passes of 10 ton axle loads)
A	11
B	19
C	15
D	14
E	15,8
F	11

The layer modulus located at the layer below the asphalt without binder was valued at 150 N/mm². Furthermore, parameters in respect to the thickness of the asphalt layers are required for the calculations of the TOF of the different TT. Table 1 lists the layer thicknesses applied for the individual TT. Based on the construction class and geographic location parameters (frost action zone) of each TT which are contained in the database, the resultant thicknesses of frost-proof pavement structure were determined.

5.3 Analysis of results

After determination of all necessary input parameters, the “state of fatigue” of the pavements was determined with the program PaDesTo, taking various factors of safety into consideration. In this context, the state of fatigue expresses the “consumption” of the service life in accordance with the traffic load to be expected for the selected service life. It can be assumed that a state of fatigue of 100 % indicates the TOF of a pavement from the perspective of fatigue crack formation.

The determined TOF are shown in Figure 8 for the TT E. In this context, a separate analysis of the TOF (in and next to the wheel tack) for TT E was performed due to the extremely different fatigue behaviour of the ATS_R and ATS_N, as determined in the laboratory tests. Figure 8 shows that for TT E, the asphalt pavement in the wheel track (E_R) has a higher status of fatigue than the pavement next to the wheel track (E_N). This means that crack formation occurs earlier for the ATS_R, compared to the ATS_N, at equal traffic load.

Figure 8 – Status of fatigue of TT E (next to and in the wheel track) in dependency of period of use

For further considerations in respect to the TOF of TT E, reference is made to the E-Modulus and the fatigue functions of the ATS_R, as the pavement in the wheel track displays a significantly higher status of fatigue compared to the pavement next to the wheel track. For all other TT, the average fatigue function is used for the determination of the TOF, based on equal test results over the cross section of the TT. Table 3 illustrates the expected total service life of pavements.

Table 3 – Expected total service life of the TT

test track	Expected total service life [a]
A	29
B	22
C	22
D	20
E	22,5
F	83

In this context, TT B, C, D and E show the shortest service life compared to TT A and F, for which the longest service life was determined. Furthermore, the low range of the determined total resting periods for TT B, C, D and E becomes clear, whereby these tracks currently show the longest service life (Table 2). In this context, the determined total service life of 83 years for TT F seems to be unrealistic. A much shorter total service life is to be assumed here, too.

6 SUMMARY AND OUTLOOK

The method for the forecast of the remaining service life of asphalt pavements presented here is based on the results of laboratory tests (tests for the determination of the stiffness and fatigue behaviour of asphalt mixes) and on the calculations performed with a design program for road pavements.

In order to determine the time of failure (TOF) of pavements, a computational evaluation of the number of load cycles tolerable until the occurrence of fatigue cracks in the asphalt was performed. Suitable test tracks were selected for this purpose and specimens were extracted. Laboratory tests were conducted on these specimens. By means of the results of the laboratory tests, the complex E-Modulus for all asphalt mixes, as well as the fatigue functions and cryogenic stresses for asphalt base course mixes (ATS) were determined. Based on these results, a computational evaluation of the load cycles tolerable up to the point of fatigue cracks occurring, was performed with the PaDesTo design program, in order to determine the time of failure (TOF) for these pavements. Thus, statements regarding the expected time of failure (TOF) and the remaining service life of the tested test tracks could be made. It must be noted that an estimation of the time of failure (TOF), merely based on comparison of fatigue curves is not possible. On the basis of the test results, it could further be determined that a drop of the E-Modulus (> 20 %) of installed asphalt base courses due to traffic loads was connected with a significant decrease in fatigue resistance.

In the absence of detailed knowledge, a linear gradient of the fatigue status curves was presumed for simplification purposes. However, an exponential gradient is also a realistic possibility. Statements on this can only be made based on results of further field investigations. To this end, drill cores would need to be extracted from the tested test tracks at a later point in time (ideally in 3 to 4 years) and examined in order to subsequently determine the state of fatigue of the pavements. This would make it possible to obtain precise knowledge about the further process of fatigue or crack formation in the studied asphalt pavements. It is for this reason that a continuation of the studies is recommended. However, a prerequisite for this would entail that for comparability purposes no further maintenance measures should be performed on the TT.

REFERENCES

1. Ressel, W. et al. (2007): Vergleichende Bewertung der Restsubstanz von Asphaltbefestigungen nach langjähriger Verkehrsnutzung, Abschlussbericht zum Forschungsprojekt FA 4.199.
2. Kiehne, A. (2008): Dimensionierung von Asphaltbefestigungen, Manuskript zur Dissertation, TU Dresden.
3. Molenaar, A. (2007): Prediction of fatigue Cracking in asphalt pavements: Do we follow the right approach? Transportation Research Record. No. 2001, pp. 155-162.
4. Forschungsgesellschaft für Straßen- und Verkehrswesen (2008): Richtlinien für die rechnerische Dimensionierung des Oberbaues von Verkehrsflächen mit Asphaltdeckschicht (RDO-Asphalt), Entwurf 3/2008, Köln.
5. Forschungsgesellschaft für Straßen- und Verkehrswesen (1994): Technische Prüfvorschriften - Verhalten von Asphalten bei tiefen Temperaturen, Ausgabe 1994, Köln.