Asphalt mixture performance and testing

# The impact of VAPro ageing on material characteristics and calculated life time of a surface course asphalt mixture

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Abstract

Ageing of bitumen leads to increased stiffness and brittleness. Thus, the ageing behavior of bitumen has a large impact on the fatigue behavior and the durability of asphalt pavements. To asses ageing of bitumen in the laboratory RTFOT is the standard for short-term-ageing and with additional PAV for long-term-ageing. In the last decades more and more methods have been developed to study the ageing of asphalt mixtures. The paper presents the results of a joint research project using the Viennese Ageing Procedure (VAPro) for ageing a surface course asphalt mix. Aim of the project is to validate the VAPro with regard to the in-situ ageing. Studying a 19 years old test track and the samples taken there after different exposure time, offers the possibility to validate the VAPro ageing. Additionally, it was determined that only the top 1 cm of the surface course suffers considerably ageing. All these findings are combined with the results of the laboratory tests. This paper focuses on the impact of VAPro on the fatigue and stiffness performance determined using the CY-IT at three different stages – (1) unaged test specimen (2) 72 hours VAPro aged and (3) 144 hours VAPro aged. It is a well-known fact that fatigue and stiffness characteristics have a major influence on the pavement performance. Thus, the described investigations concerning the material characteristics are completed with pavement design life calculations concerning top down cracking due to fatigue of the asphalt surface course mixture. The calculations cover different settings concerning the layer bond and the fact that only the upper part of the surface course layer will sustain changes of the material characteristics due to ageing.

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# 1. INTRODUCTION

The design life calculations for asphalt pavements in Germany currently only take into account the fatigue status on the bottom side of the asphalt base layer. There the greatest tensile strain occur in case of sufficient interlayer bond. In the future, top down cracking should also be considered in the mathematical dimensioning of the pavement life time. Thus, the changes in the material properties of the used asphalt mixtures as a result of bitumen ageing are of particular importance for the design life calculation. The aim of the research project is therefore to describe the changed material properties due to bitumen ageing and the effect on the design life of the asphalt wearing course. A method was selected in which the asphalt was aged overall. The design life calculations were carried out with a FE program in order to be able to take into account the interlayer bond and different ageing approach.

# 2. AGEING OF BITUMEN AND ASPHALT IN THE LABORATORY

The ageing of bitumen has a large impact on the stiffness and fatigue performance and thus the durability of asphalt pavements. The ageing of bitumen and asphalt can be simulated in the laboratory using various methods. The ageing procedures relevant for this research project are briefly described below.

## 2.1. RTFOT and PAV

Commonly bitumen are aged in the laboratory by means of the standardized combined procedures of the RTFOT (Rolling Thin Film Oven Test) [1] and PAV (Pressure Ageing Vessel) [2] to simulate long-term ageing. The disadvantage of this approach is that only pure bitumen is aged and interaction phenomena between the aggregates and bitumen are not taken into account during ageing.

Within this research project both, the RTFOT and the PAV test were performed on the bitumen in order to estimate the ageing of the bitumen achieved with VAPro (Viennese Ageing Procedure – see section below). The bitumen from the VAPro-aged asphalt was recovered for this purpose. The BTSV method [3] among other methods was used in order to establish the possibility to make comparisons. The BTSV method was developed and applied for different aged bitumen by the project partners at the Braunschweig Pavement Engineering Centre, Technische Universität Braunschweig.

## 2.2. VAPro

The VAPro (Viennese Ageing Procedure) was developed in 2014 as an optimised lab procedure for long-term oxidative ageing of asphalt mix specimen by the project partners at the Institute of Transportation, Vienna University of Technology [4].

VAPro offers the possibility of ageing compacted hot mix asphalt specimen using compressed air enriched with reactive oxygen species (ROS), i.e. ozone and nitric oxides, at a temperature of +60°C and a pressure of ~0.5 bar. This means, VAPro applies conditions that occur in the field and uses highly oxidant gases to achieve ageing of the binder. These ROS occur in the field as well, just in lower concentrations. Usually, each specimen used for the tests described below was aged for 72 hours (1xVAPro-aged). Former studies [4] showed that these conditions lead to an ageing-level of the binder comparable to RTFOT+PAV-ageing. In order to assess the influence of VAPro on the material characteristics a second set of specimens was aged for 144 hours (2xVAPro-aged) within the project.

# 3. ASPHALT MIXTURE AND SAMPLE PREPARATION

A stone mastic asphalt (SMA) with a nominal aggregate size of 11 mm and a bitumen PG 76-22 (5.6 mass.-%) was used for the investigations. The grading curve is shown in Table 1.

The SMA was compacted in the laboratory using a segmented roller compactor. The asphalt slabs were of dimensions 260 mm x 500 mm x 70 mm. The samples had a diameter of 100 mm and a height of 40 mm. Eight specimens were cored out of each slab. Subsequently, the front faces of the cylindrical specimens were cut off plane-parallel.

On the one hand, the air void content has a significant influence on the material characteristics. On the other hand, the required flow rate for the ageing according to the VAPro procedure is heavily dependent on the air void content. Thus, it was necessary to find an optimum air void content, which was adjusted to 8.4 % by volume.

**Table 1. Grading curve of the SMA**

| Sieve size [mm] | Passing [%] |
|---|---|
| 0.063 | 6.7 |
| 0.125 | 9.5 |
| 0.25 | 12.3 |
| 0.5 | 15.9 |
| 1.0 | 20.3 |
| 2.0 | 27.2 |
| 4.0 | 30.9 |
| 8.0 | 46.7 |
| 11.2 | 89.8 |
| 16.0 | 100 |

## 4. LABORATORY TESTS

The material characteristics (stiffness and fatigue performance) of the SMA for the three ageing conditions were determined using the cyclic indirect tensile test (IT-CY). The IT-CY is regulated by the German guideline TP Asphalt-StB Part 24 (fatigue) and Part 26 (stiffness) and by the European standard EN 12697 Part 24 [5] and Part 26 [6].

The IT-CY is a practicable test in terms of sample preparation and test procedure. The stress ratio between horizontal and vertical stresses of the cylindrical specimen is almost constant over the specimen diameter (approximately 1/3). During the test, the resultant horizontal deformations of the cylindrical specimen are measured, which is loaded by two diametrically arranged compressive forces applied via curved loading strips. The horizontal deformation of the sample is measured using two Linear Variable Differential Transformer (LVDTs). The loading strips had a width of 12.7 mm for specimens with a diameter of 100 mm. Thus, the load application angle is 0.252 rad.

### 4.1. Stiffness tests

In order to determine the stiffness performance described as mastercurve (stiffness at various temperatures/frequencies) loading was applied with a sinusoidal waveform and without any rest periods. Five loading frequencies between 0.1 Hz and 10 Hz were chosen. Depending on the loading frequency, a limited number of load cycles between 10 and 110 was applied on the specimen. In order to avoid damages on the specimen, the stresses were adjusted accordingly so that the initial elastic strain did not exceed 0.075 ‰. The average elastic strain of five load cycles was determined and thus, the stiffness modulus could be computed. Test temperatures ranged from -10 and 5 to 20°C. All tests were performed as multistage tests with temperature-frequency-sweeps. Finally, three specimens of each ageing condition were tested by the same procedure.

### 4.2. Fatigue test

For the determination of the fatigue performance of the asphalt mixes, loading had a sinusoidal waveform without any rest periods and the loading frequency was 10 Hz. The lower stress level was 0.035 MPa (contact stress) and the upper stress level was varied three times to achieve initial elastic strains between 0.05 ‰ and approximately 0.30 ‰. At least 1000 load cycles had to be applied to achieve $N_{macro,}$ which is the number of load cycles at crack formation. The initial elastic strain is determined as an average value of five load cycles between 93 and 97 after overcoming the initial phenomena of specimen adapting to the stresses applied. The test temperature was 20°C and the number of load cycles at crack formation $N_{macro}$ was chosen as the fatigue criterion. Rowe [7] developed a method by detecting the number of load cycles at the time of crack formation based on the concept of dissipated energy.

## 5. TEST RESULTS

### 5.1. Stiffness performance

Using the determined test values, the master curve can be described using Equation 1 and Equation 2 from the German technical test specification [8] depending on the temperature and the frequency.

$$|E^*| = |E^*|_{-\infty} + \frac{|E^*|_{+\infty} - |E^*|_{-\infty}}{1 + e^{(\dot{z}_1 \cdot x^* + \dot{z}_0)}}$$

Equation 1

$|E^*|$ = absolute value of the complex stiffness modulus [MPa]
$|E^*|_{+\infty}$ = limit value of the stiffness modulus at very low temperature and/or high loading frequencies [MPa]
$|E^*|_{-\infty}$ = limit value of the stiffness modulus at very high temperature and/or low loading frequencies [MPa]
$x^*$ = value on the abscissa axis of the master curve, determined by temperature-frequency equivalence [Hz]
$\dot{z}_0, \dot{z}_1$ = material parameters of the master curve [-]

$$x^* = \frac{\phi \cdot \left(\frac{1}{T + 273{,}15} - \frac{1}{T_0 + 273{,}15}\right) + ln(f)}{ln(10)}$$

Equation 2

$x^*$ = value on the abscissa axis of the master curve, determined by temperature-frequency equivalence [Hz]
$\phi$ = material-specific parameter [-]
T = temperature for the calculated stiffness modulus [°C]
$T_0$ = reference temperature (temperature for which the master curve is to be determined, usually 20°C) [°C]
f = loading frequency [Hz]

The determined master curves for the three ageing conditions of the SMA are given in Figure 1. The changes in the functional parameters of the master curves can be seen in Figure 3. There is no significant difference in the determined master curves depending on the ageing conditions. Independently, the progression functions of the material parameters (see section 5.3) were set up for the planned service life calculations. This is an interesting observation, since former studies showed that VAPro-aged specimens exhibit a significantly higher stiffness due to increased binder ageing [4][9]. However, these studies were carried out with asphalt concrete (AC) and porous asphalt (PA) mixtures. It is possible that the larger binder film thickness in an SMA leads to decreased ageing susceptibility or that the dominant stone-stone interaction in SMA mixtures prevent an observable increase in stiffness due to binder oxidation.

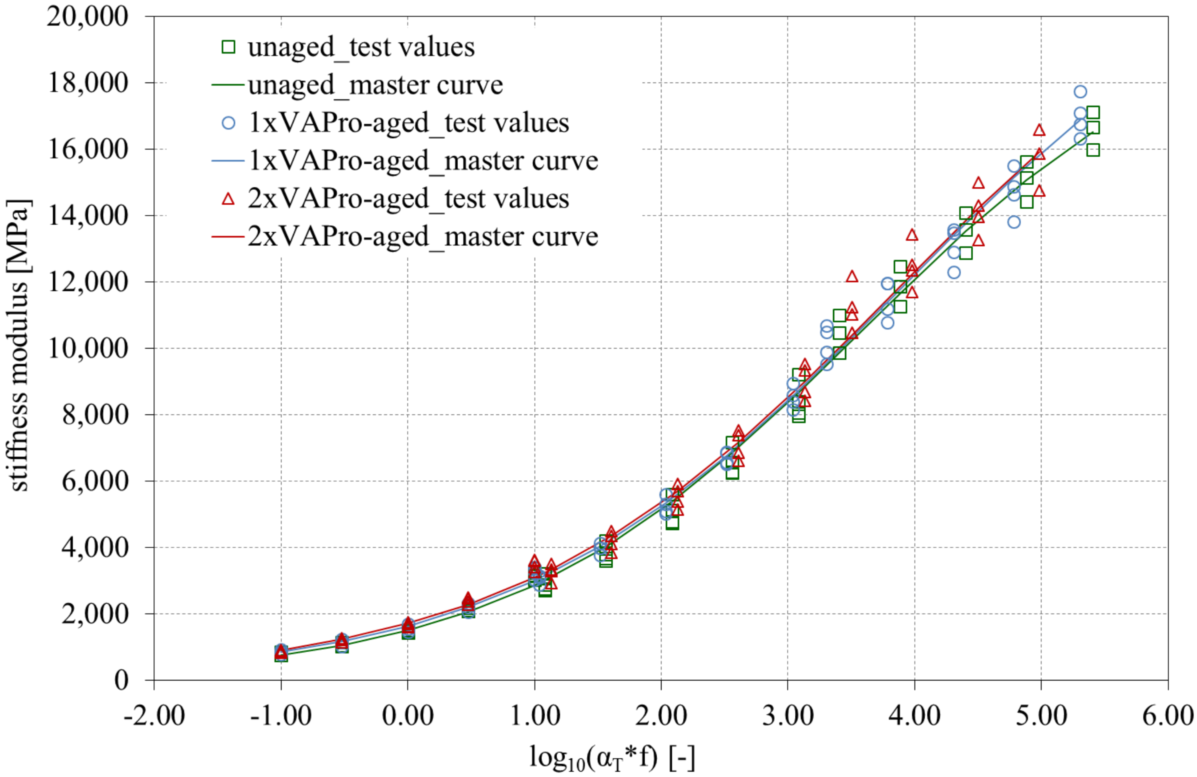


**Figure 1: Master curves and test values of the three ageing conditions of the used SMA**

## 5.2. Fatigue performance

In order to illustrate the fatigue performance, the moment of macro crack formation is plotted as a function of the initial elastic strain. Each fatigue function is based on the results of at least nine IT-CY s. As a result, material-specific fatigue functions can be determined using Equation 3:

$$N_{macro} = K_1 \cdot \varepsilon_{el}^{K_2}$$

Equation 3

$\varepsilon_{el}$ = initial elastic strain [‰]
$N_{macro}$ = number of load cycles at macro-cracking [-]
$K_1$, $K_2$ = material parameters [-]

The single test values and the fatigue functions for the three ageing conditions given in Figure 2 show a very low test scatter. The fatigue performance of the 1xVAPro-aged SMA increased as a result of the impact of VAPro compared to the unaged asphalt mixture.

No distinction can be made between the two states 1xVAPro-aged and 2xVAPro-aged, since the fatigue functions are almost identical. Due to its high bitumen content and splintered grading curve, SMA has a thicker bitumen film compared to the asphalt concrete of the same maximum aggregate size. It can be assumed that the bitumen film thickness has a significant influence on the ageing of compacted asphalt specimen with VAPro. Further studies are planned to investigate that phenomenon. It can be ruled out that an especially age-resistant bitumen was used, since the changes due to RTFOT and PAV were in the usual order of magnitude.

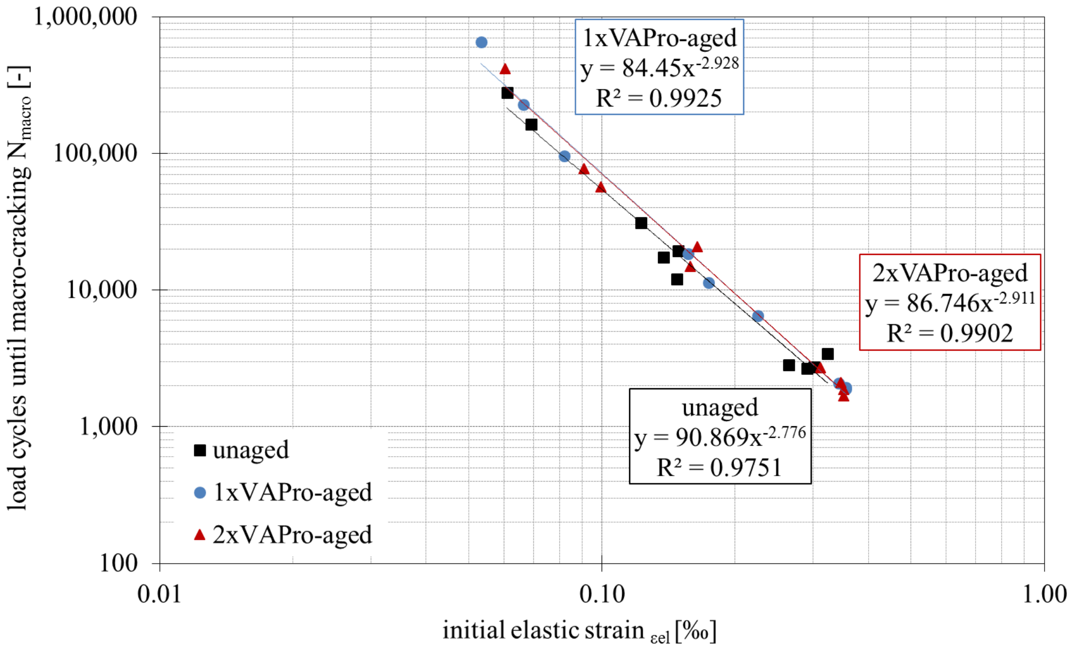


**Figure 2: Fatigue performance of the three ageing conditions of the used SMA**

## 5.3. Progression functions of the material parameters

Since the master curve and thus the corresponding parameters $|E^*|_{-\infty}$, $\phi$, $z_0$ and $z_1$ change only slightly as a result of VAPro-ageing, the parameters remain almost the same over the assumed life time of 15 years for the SMA. Thus, the intermediate values for each year were interpolated linearly.

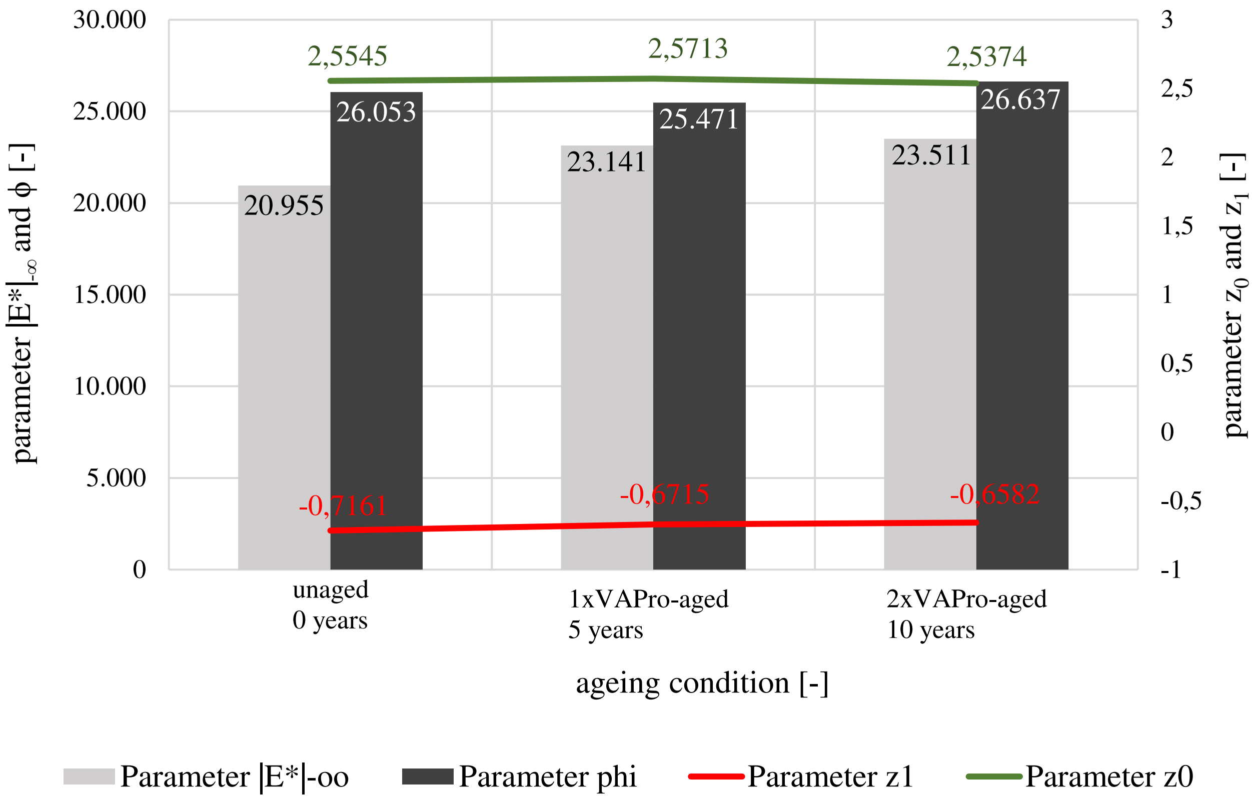


**Figure 3: Progression functions of the stiffness performance of the SMA**

In order to being able to carry out detailed life time calculations, the progression functions of the material parameters (stiffness and fatigue performance) were set up as a function of the ageing condition. The Parameter $K_1$ and $K_2$ of the fatigue function given in Figure 4 can be modelled with a square function in dependence of the ageing condition and the assumed life time respectively.

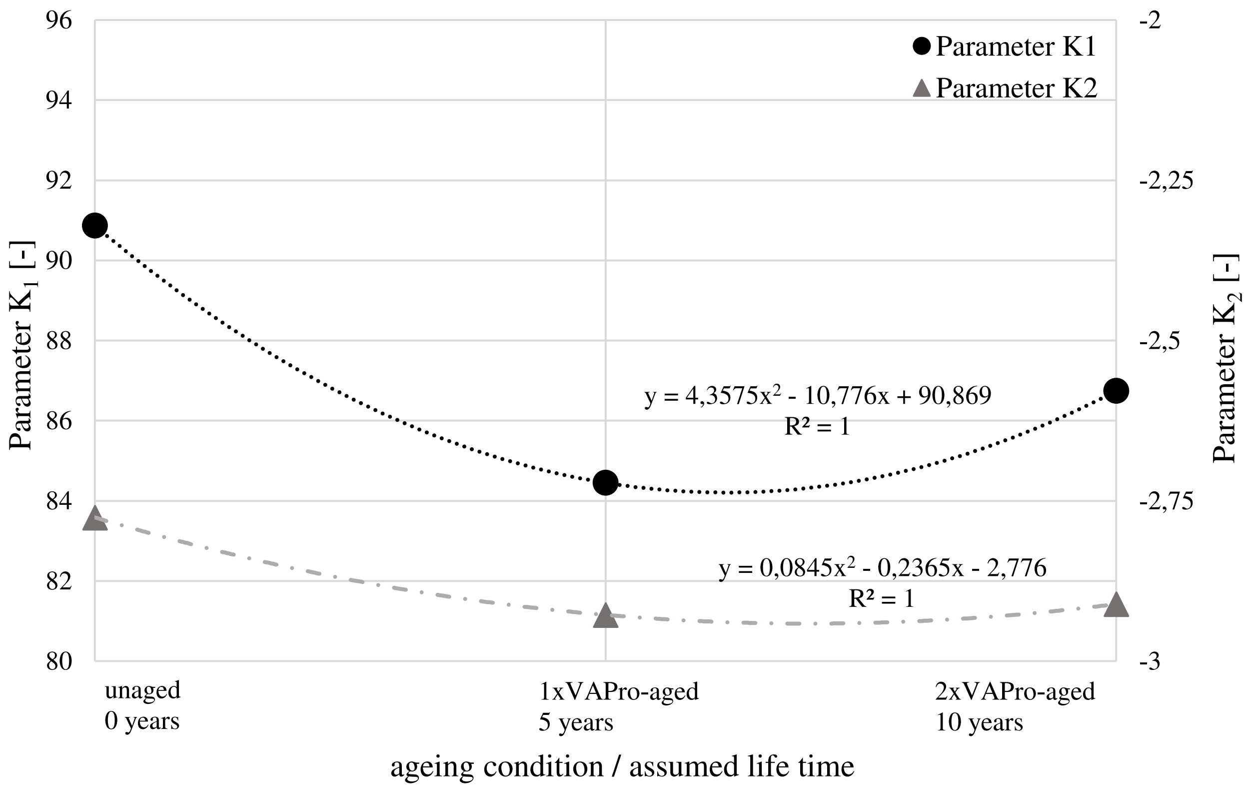


**Figure 4: Progression functions of the fatigue performance of the SMA**

## 6. PAVEMENT DESIGN LIFE CALCULATIONS

### 6.1. Approach and Description of the calculation method

Mathematical dimensioning according to the RDO - Asphalt 09 [10] is intended in order to determine the necessary thickness of base courses within the frost-proof foundation. Local conditions, characteristics of the base course and construction material, and traffic loads on the existing subsoil/substructure are considered. The procedure according to RDO – Asphalt 09 should serve to prevent structural damage to the foundation during the planned period of use. Maintenance for top and binder courses may still be necessary. The planned period of use should be determined beforehand (e.g. 30 years).

The life time of the entire structure is based on the asphalt base layer according to RDO Asphalt 09. Within the project, the life time of the asphalt wearing course of 15 years was considered additionally. Therefore, the planned life time of the SMA was 15 years. Different to the RDO Asphalt 09, the stresses and strains were not determined with the multi-layer theory but with the FE program SAFEM [11]. So, it was possible to consider the interlayer bond in detail.

In addition, the interlayer bond between the asphalt layers was varied. In principle, the following four states of the interlayer bond are defined.

1. complete bond equivalent to a monolithic construction
2. no bond between the layers enabling free movement
3. the best interlayer bond determined in laboratory tests – good case (GC)
4. the worst interlayer bond determined in laboratory tests – bad case (BC)

State 1 and state 2 do not occur in-situ and are not taken into account in the following calculations. It is to be assumed that the in-situ occurring layer bond lies in between the so-called good or bad case [12].
For the calculations, the climate and traffic approaches of RDO Asphalt 09 were used, but the calculations were carried out with the FE program.

### 6.2. Calculation parameters

A common German pavement structure for a federal road was chosen for the calculations (see Figure 5 for the layer thicknesses).

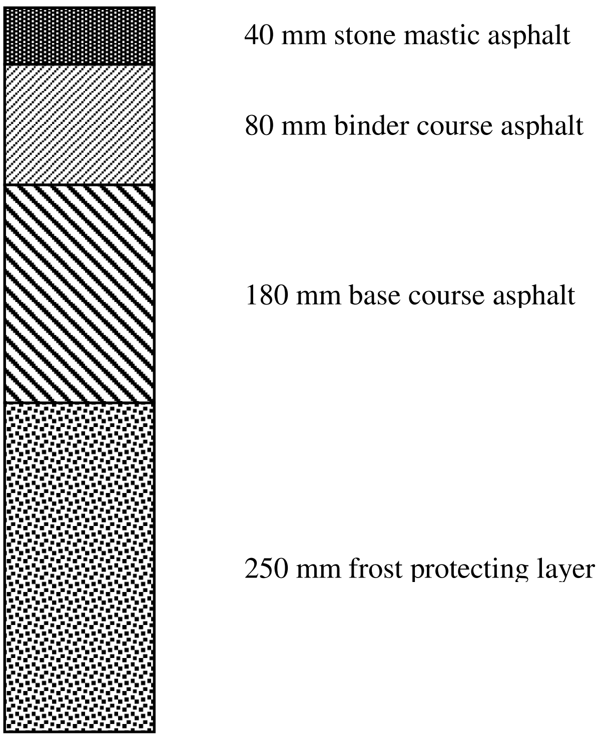


**Figure 5: Layer arrangement of the Road construction for the pavement design life calculations**

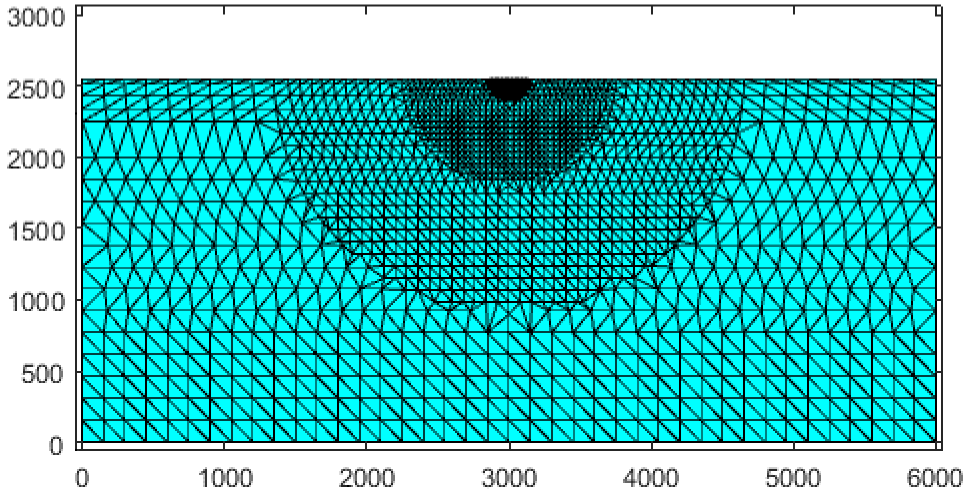


**Figure 6: FE mesh**

Figure 6 shows the used FE mesh. The number of axle transitions for each year of the planned life time of 15 years are given in Table 2. The axle transitions include an annual increase of 3%. A total of 30.5 million axle transitions occur over a period of 15 years.

**Table 2. Axle transitions for each year**

| year | axle transitions | year | axle transitions | year | axle transitions |
|---|---|---|---|---|---|
| 1 | 1,642,500 | 6 | 1,904,108 | 11 | 2,207,383 |
| 2 | 1,691,775 | 7 | 1,961,231 | 12 | 2,273,604 |
| 3 | 1,742,528 | 8 | 2,020,068 | 13 | 2,341,812 |
| 4 | 1,794,804 | 9 | 2,080,670 | 14 | 2,412,067 |
| 5 | 1,848,648 | 10 | 2,143,090 | 15 | 2,484,429 |
| **1-5** | **8,720,256** | **6-10** | **10,109,166** | **11-15** | **11,719,294** |

The axle load distribution are combined with the temperature distribution for the pavement design life calculations. This results in 143 different stress combinations. Considering the interlayer bond at least two iteration are required. The computing time with simultaneous use of 2 cores for each variant with constant material conditions was around 140 hours. Due to the long computing times, only selected approaches to the ageing of the asphalt wearing course could be taken into account.

### 6.3. Consideration of ageing in the calculation method

Within the pavement design life calculations, the ageing of the SMA was considered using different approaches. The calculations were carried out for both variants of the interlayer bond (good case - GC, bad case - BC) described in the previous chapter. The verification point for horizontal strains is on the bottom side of the asphalt wearing course layer 140 mm next to the load introduction axis.

1. The material characteristics (unaged condition) did not change over the planned life time of 15 years (current standard case according to RDO Asphalt 09).
2. The planned life time of 15 years was divided into three sections with a duration of five years each. For the first five years the material characteristics corresponded to the unaged condition. The material characteristics of the second five year period corresponded to the condition of 1xVAPro-aged. For the last section of 5 years the material characteristics comply with the condition of two times VAPro-ageing.
3. The material parameters of the entire asphalt wearing course layer changed annually according to the progression function given in section 5.3.
4. The material parameters did not change for the entire asphalt wearing course layer but it did change for the upper 1 cm and 2 cm layers according to Figure 7. For the first 5 years the SMA is applied in unaged condition. For the year 6-10 the upper 1 cm of the SMA is considered with material parameters according to 1xVAPro-aged condition (SMA*). For the years 11-15 the upper 2 cm of the SMA are considered with material parameters according to 1xVAPro-aged condition.
5. The material parameters of the asphalt wearing course layer changed annually in layers as described in sub-item 4 according to the progression function given in section 5.3.

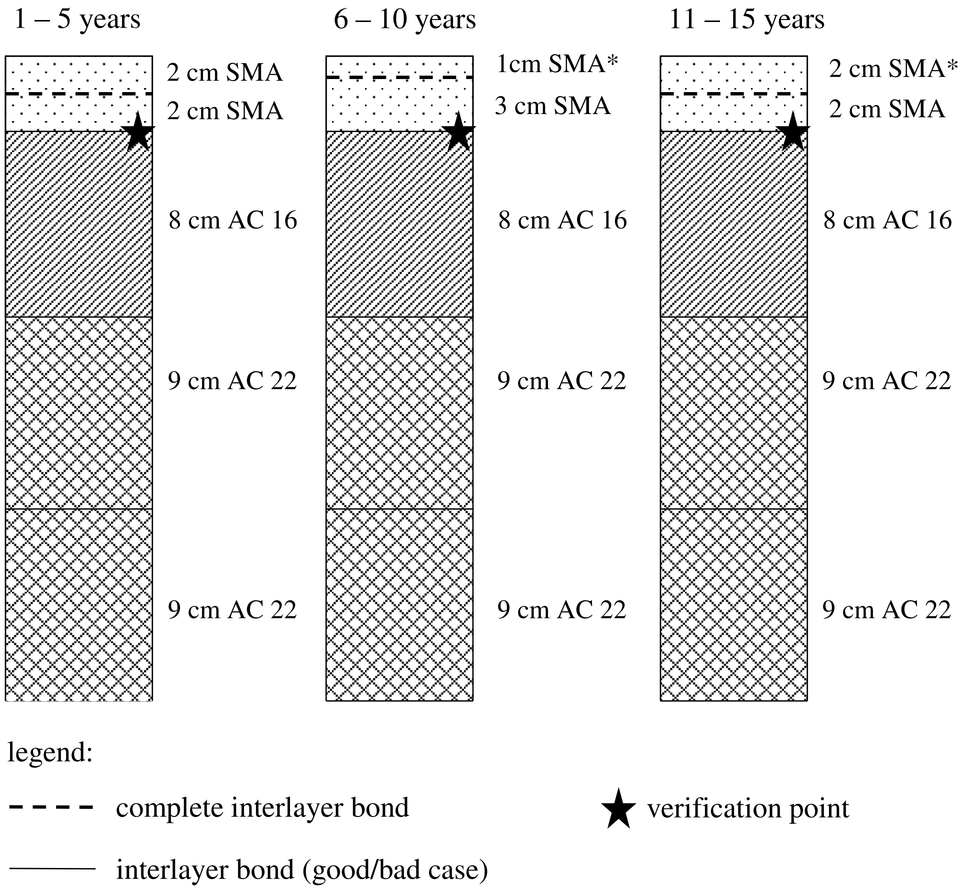


**Figure 7: Layer ageing approach**

### 6.4. Calculation results

The permitted load cycle numbers $N_i$ for the strains corresponding to the 143 stress conditions are determined on the basis of the fatigue functions. The existing load cycle numbers $n_i$ result from the axis transitions as shown in table 2 in combination with the axle load distribution. Thus is possible to determine the damage rates of each stress condition and in general regarding Miner's law [13].

$$\sum_i \frac{\boldsymbol{n_i}}{\boldsymbol{N_i}} = \mathbf{1}$$

Equation 4

$n_i$ = number of load cycles applied at stress $i$
$N_i$ = number of load cycles to failure at stress $i$.

For a better comparability of the calculation results, the determined Miner sums were weighted. For this the Miner sum of ageing approach 1 (unaged material characteristics) in combination with the bad case interlayer bond is defined as a service life of 15 years (see Figure 8). The other service life values were weighted accordingly.

From Figure 8 it can be deduced that there is only a small difference in the weighted service life of the Asphalt wearing course concerning the chosen interlayer bond (good case – GC or bad case – BC). As expected, the values for the ageing approaches using the BC interlayer bond are marginally lower than for using the GC interlayer bond. The figure also shows that unaged material characteristics (approach 1) result in a low weighted service life. Considering the ageing of the asphalt wearing course mixture leads to a prolongation of the service life (approaches 2 and 3). In the case of layer ageing (approaches 4 and 5), the thin aged sublayer is stiffer (see years 6-10 and 11-15 in Figure 7) than the unaged sublayer. This causes a significant reduction in the service life of the entire asphalt wearing course layer.

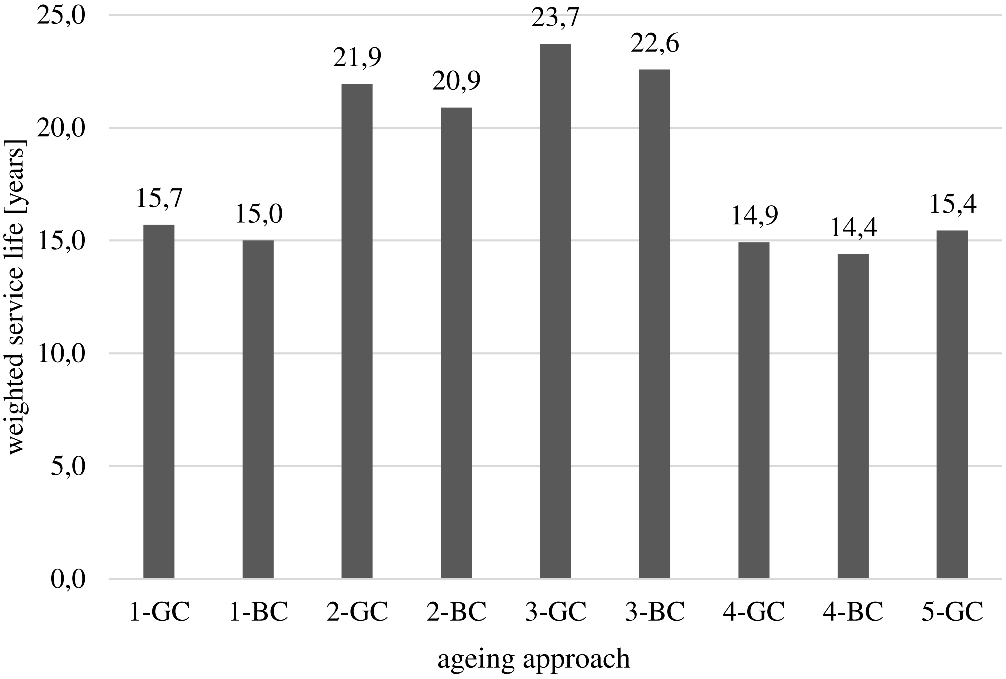


**Figure 8:** ***Weighted service life for different ageing approaches***

## 7. DISCUSSION AND CONCLUSION

The results of the investigations show that it is possible to take into account the material properties for asphalt wearing courses which have changed as a result of ageing in the mathematical dimensioning with regard to top down cracking. A significant increase in the calculated service life with respect to top down cracking of the chosen example can be observed. The summary to 5-year blocks appears to be reasonable when considering the respective computing time without distorting the result. Due to the location of the verification point, the interlayer bond has only a minor influence on the calculated service life. The modelling of layer-by-layer ageing is currently still causing interaction phenomena which require further investigation.
Further studies are planned to investigate the phenomenon, that bitumen film thickness has potentially a significant influence on the ageing of compacted asphalt specimen with VAPro.

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