INFLUENCE OF THE COMPOSTION OF THE ASPHALT MIXTURES ON THEIR FATIGUE PERFORMANCE

Ines Dragon
Dresden University of Technology

ABSTRACT

Since the introduction of the new European Standards for the composition of asphalt mixtures in 2006 an empirical as well as a fundamental material specification can be used in parallel. The difference between the two mix design approaches is that for the empirical specification the characteristics of asphalt mixtures can only be tested indirectly by analyzing the composition of an asphalt mixture and defining a few performance related material properties. In contrast, by using the fundamental specification, the characteristics of asphalt mixtures can be tested directly by performance-based test methods. For asphalt mix design the fundamental specification becomes more and more important. However, there is only insufficient experience available regarding the application of the fundamental specification in Germany. From this reason, the paper presents results of a research that was focused on the investigation of the influence of the bitumen content and the air void contents of the asphalt mixtures on the fatigue life of pavements.

Keywords: fatigue life, performance testing, design of pavement, mixture design

1. INTRODUCTION

A long process of the experience led to the current requirements regarding the asphalt mix design procedure in Germany (Marshall-method), the so called empirical material specification [1, 2]. However, the empirical material specification is insufficient to predict the performance of asphalt used in pavements [3]. Since the introduction of the European standards for asphalt mix design in 2006 the fundamental material specification can be applied as well. In this case, the technical characteristics of asphalt mixtures are based on performance-based test methods (e.g. bending beam test, cyclic compression test, cyclic direct tensile test (DTT), cyclic triaxial test under tensile-/compression and cyclic indirect tensile test (ITT). Although, the fundamental specification becomes more and more important in the European standards, there is only insufficient experience regarding the fundamental specification in Germany available.

Because of the problems described one aim of the research presented in this paper was to determine the influence of the composition of asphalt mixtures on their fatigue performance.

Several asphalt concrete (AC) and stone mastic asphalt mixtures (SMA) were tested within two research projects [4], [5] in order to detect the influence of the compositional characteristics on the performance of asphalt. The investigation was carried out at the Institute of pavement engineering at Dresden University of Technology. Based on the results of ITT (fatigue function and master curve), pavement design calculations were undertaken. The results of the analysis and calculations [4] shall gain knowledge in order to get more experience regarding the application of the fundamental material specification in Germany.

2. MATERIALS TESTED

The research was carried out using an asphalt concrete, grade AC 22 T S [4], and a stone mastic asphalt, grade SMA 11 S [5]. The composition of the asphalt mixtures was varied with regard to the bitumen content. Table 1 shows an overview of the tested asphalt mixtures.

The asphalt mix design was conducted according to the Marshall-Method to the TL Asphalt-StB 07 [1]. At first, this contained the choice of the aggregate mix grading of asphalt mixture variants illustrated in Figure 1. The asphalt identification values of the examined asphalt mixture variants are summarized in Table 2.

The specimens for the ITT were drilled out from asphalt plates. The compaction of asphalt plates were made with the roller compactor according to TP Asphalt-StB 07, Teil 35 [6] and the production of asphalt mixtures in laboratory.

3. INDIRECT TENSILE SWELLING TEST

The material properties (fatigue and master curve) of the asphalt mixtures were determined with the ITT according to AL Sp-Asphalt 09 [7]. The ITT is a relatively simple, rapid and cost-effective test method and were conducted using a servo-hydraulic testing machine. The minimum stress of 0.35 MPa was necessary for a safe position of the specimen during the test. The testing parameters are shown in Table 3.

For the determination of the fatigue curve it was required to carry out per three individual ITT at three different stress amplitudes at a predefined testing temperature and frequency for asphalt mixture. The criterion for the fatigue is defined by the cycles to failure N_{macro} (macro crack) This method was developed by Hopman and is based on the principle of the dissipated energy ratio ER [8] which is defined as a product of the cycles to failure N and the stiffness |E(N)| modulus calculated for N.

$$ER(N) = |E(N)| \cdot N$$

N	cycles to failure [-]
lE(N)l	Stiffness modulus at watched cycles to failure [N/mm²]
ER(N)	Energy ratio [N/mm²]

If ER(N) is represented as a function of N, cycles to failure for the criterion macro crack, N_{macro} can be defined by the maximum of ER(N) (Figure 2).

The elastic horizontal initial strains $\varepsilon_{el,ini}$ measured in the tests and the determined cycles to failure N_{macro} were approximated to the material specific fatigue curve with application of the method of least error squares.

$$N_{macro} = C_1 \cdot \varepsilon^{C_2}$$

N_{macro} cycles to failure [-]

$\varepsilon_{el, ini}$ elastic horizontal initial strains [‰]
C_1, C_2 material specific parameters

The determination of the master curve was made by using multistage-tests at four different temperatures, -10 °C, 0 °C, 10 °C und 20 °C, with variation of the frequency (see Table 3).

4. TEST RESULTS

4.1 Fatigue curve

The fatigue curves of the AC mixtures are shown in Figure 4. Figure 5 illustrates the fatigue curve of the SMA mixtures.

The figures provide visual confirmation that the fatigue curves move up with increasing bitumen content (Figure 4). However, this could be observed only up to certain (optimal) bitumen content which depends on the gradation of the mixture. If the bitumen content increases further the allowed cycles to failure are decreasing for the same elastic strain level. Hence, lower number of cycles to failures are calculated to N_{macro} for the fatigue curve for the AC with a bitumen content of 6.5 M.-% and for a strain level of $\varepsilon_{el,ini}$ < 0.18 ‰ than for the AC with a bitumen content of 5.5 M-.% (Figure 4).

Figure 5 preludes, that the fatigue curve of the SMA with bitumen contents of 6.8 M.-% und 7.4 M.-% are almost on top of each other, but "over" the fatigue curve with a bitumen content of 6.2 M.-%. It can be concluded, that the optimal bitumen content regarding the fatigue resistance is between 6.8 M.-% und 7.4 M.-%.

4.2 Master Curve

Figure 6 6 shows the stiffness modulus values for frequency of 10 Hz at temperatures of 10 °C and 20 °C for the AC and the SMA in dependence of the bitumen content.

It can be recognized, that that the stiffness modulus rise with an increasing bitumen content up to a certain (optimal) bitumen content at the asphalt base mixtures. If the bitumen content increases further the stiffness moduli are decreasing again. This trend for the other AC mixtures investigated in [4] as well. From this reason it can be assumed other asphalt mixtures would behave in the same way. The bitumen content of the SMA varies between 5.6 M.-% and 7.4 M.-% [5]. The stiffness moduli for the SMA mixtures with contents of 5.6 M.-% and 6.2 M.-% are nearly the same (Figure 6) for defined temperatures. A further increase of the bitumen content leads to a decrease of the stiffness modulus. Provided that, the SMA performs in the same manner as the AC, the SMA with a bitumen content of 5.0 M.-% will show a lower stiffness compared to the SMA with a bitumen content of 5.6 M.-%. Therefore, by regression of the stiffness modulus for each mixture and temperature condition the optimal bitumen content can be determined (highest stiffness modulus value) (Figure 6).

Figure 7and Figure 8 show the dependence of the stiffness modulus on the air void content V and the bitumen saturation level VFB (voids in the mineral aggregate filled with bitumen) for the same temperatures. The air void content decreases and the bitumen saturation level increases with rise of the bitumen content. An optimal air void content as well as optimal bitumen saturation level exist for every mixture and can be defined by highest stiffness modulus value.

5. PAVEMENT DESIGN CALCULATIONS

Finally, the effects of the bitumen and air void content on the fatigue life of asphalt pavement were investigated using the German mechanistic empirical pavement design procedure RDO Asphalt 09 [9].

The calculations were carried out for two critical locations of the pavement. For the AC the tensile strains were used at the bottom of the asphalt layer in the load axis. The proof of the resistance against fatigue cracking for the SMA was made at a distance of 130 cm to the load axis on top of the asphalt layer.

Among other things the tensile strain values in a pavement depend on the temperature condition within the pavement and the traffic loading. The traffic loading is simulated by an axle load frequency distribution at the calculation based of the RDO Asphalt 09 [9]. A frequency distribution of the temperature distribution of the pavements over the year was taken into account the calculation process. The predefined axle load transitions were super positioned with the frequencies of occurrence of the temperature and the traffic loading for the determination of the available cycles to failure. The calculation of the permitted cycles to failure with regard to the criterion fatigue cracking was made by the constitution with available tensile strains into the fatigue curves of the respective asphalt mixture. A fatigue crack occurs if the available cycles to failure and the permitted cycles to failure are the same. This corresponds to a fatigue status of 100 %. If the fatigue status is smaller than 100 % then the proof is fulfilled for a predefined pavement life.

5.1 Assumptions

For the pavement design calculations the following assumptions were taken:

- 32 million axle repetitions of the heavy vehicle traffic; axle load frequency distribution "federal motorway-long distance traffic" [9]; see Figure 9
- temperature distribution corresponded to the standard frequency distribution in accordance with the temperature zone 3 [9]; see Figure 10
- predefined pavement life: 30 years
- Thickness of the frost resistant pavement structure: 90 cm
- Pavement structure:
  - Different AC 22 T S mixtures from [4], see chapter 2:
    4 cm asphalt surface course (standard asphalt)
    8 cm asphalt binder course (standard asphalt)
    22 cm asphalt base course (AC)
    56 cm subbase
  - Different SMA 11 S mixtures from [5], see chapter 2:
    4 cm asphalt surface course (SMA)
    8 cm asphalt binder course (standard asphalt)
    22 cm asphalt base course (standard asphalt)
    56 cm subbase
- layer adhesion 100 %: between bound layers; layer adhesion 0 %: between bound layers and unbound layers

5.2 Results

The fatigue life of the pavements expressed by fatigue status (see introduction of chapter 5) with different asphalt mixtures is compared. Therefore the fatigue life of the pavements was compared with each other. So they are relatively regarded and the fatigue status of the pavement with the AC (5.5 M.-% bitumen content) and the fatigue status of the SMA (7.4 M.-% bitumen content) correspond to a value of 100%. The relative fatigue status was calculated for the other pavements with different asphalt mixtures Figure 11.

As Figure 11 shows, the fatigue performance of the pavement improves with an increasing bitumen content of the asphalt base mixtures AC which is indicated by a decrease of the fatigue status. Hence, the pavement fatigue life increases. However, this observed up to certain (optimal) bitumen content only. With a further rise of the bitumen content the fatigue life of the asphalt pavement decreases. This relation also was found for other AC mixtures as well [4]. It is suspected that this trend is valid for asphalt mixtures with other type and grades as well. On the other side, it can be concluded that with further increase of the bitumen content the resistance to fatigue cracking either decreases again or rises not significantly. This can be confirmed by the results of the pavement design calculations with the SMA mixes (Figure 11). The fatigue status value decreases up to the examined bitumen content of 7.4 M.-%. Therefore the fatigue life rises. The fatigue status values of the pavements with a SMA (6.8 M.-%- and 7.4 M.-% bitumen content) are almost equal (100 % and 104 %). Nevertheless, it was found that optimal bitumen content is existing with regard to the fatigue performance. Because the bitumen is the most expensive component in an asphalt mixture, the bitumen content should not be increased further if no significant improvement of the fatigue resistance can be expected.

In Figure 12 and Figure 13 the fatigue status values of the pavements are shown in dependence of the air void content V and of the bitumen saturation level VFB. With rise of the bitumen content V is reduced in an asphalt mixture and the VFB increases. This leads to an improvement of the fatigue life. The improvement was observed up to a certain (optimal) air void content and bitumen saturation level only. A further decrease of the air void content or increase of the bitumen saturation level caused by a rise of the bitumen content leads either to a reduction or to an insignificant improvement in the fatigue life of the asphalt pavement. Hence, the optimal air void content and the optimal bitumen saturation level of the asphalt mixtures to improve the fatigue life of a pavement can be determined by regression of the calculated fatigue status for each mixture to get the lowest fatigue status.

Very high optimal bitumen content was established for the AC investigated within this research [4]. Because it was suspected that this mixture with the high bitumen content is no longer economic, it was necessary to carry costs analysis for the individual AC variants supplementary. For the cost analysis the following assumptions were taken:

- A modification of the layer thicknesses of the asphalt base course was carried out with the respective asphalt base mixtures in accordance with RDO Asphalt 09 [9] so that the fatigue status was ≤ 100 % respectively for the asphalt pavement life of 30 years.

- The determination of the material and production costs for the asphalt base variants was made for 1 m² of asphalt base course in the required layer thickness.
- At the laydown asphalt base course 100 % degree of compaction are reached.
- The maximum lift thickness is 14 cm; the costs for the lay down per layer of the asphalt base course are constant.
- The material and production costs of the most economy variant correspond to 100%.

Figure 14 shows the relative material and production costs. The asphalt base mixture variant with 5.5 M. % bitumen content corresponds to 100%. An optimal bitumen content was found with regard to the material and production costs for the pavement with a mixture with 4.6 M.-% bitumen content and with regard to the fatigue behaviour for the pavement with a mixture with 5.2 M.-% bitumen content. Hence, the optimal bitumen content regarding the fatigue behaviour of the pavement is 0.6 M. % higher than the optimal bitumen content with regard to the material and production costs. This can be explained by the lower required layer thickness of the variants with a better fatigue behaviour which is compensated by the increasing materials costs due to the rising bitumen content for 1 ton of asphalt base mixture.

For the asphalt base mixture with respect to the pavement fatigue life the following comparison (Figure 14) with regard to the material and production costs versus the optimal bitumen content can be established. In this case, an optimum bitumen content of 4.6 M.-% could be found.

6. CONCLUSIONS AND OUTLOOK

The results of the laboratory tests and pavement design calculations showed that in terms of the pavement fatigue life for each asphalt mixture an optimal bitumen content, air void content as well as bitumen saturation level exists.

Based on the results of the pavement design calculations for the pavements examined it was found that the fatigue performance of an asphalt mixture is both determined by its fatigue curve and by the stiffness. Figure 4 prelude that the asphalt base mixtures with 4.5 and 6.5 M.-% bitumen content have a similar position of the fatigue curve. Which one of the two causes the better fatigue performance of the asphalt pavement depends on the stiffness of the AC. The AC with 6.5 M.-% bitumen content at the temperatures of 10°C and 20°C has lower stiffness modulus than the mixture with 4.5 M.-% bitumen (see Figure 6). Therefore, a lower fatigue status was the result for the mixture with the lower bitumen content at the calculations of the fatigue life (see Figure 11 on the left).

Higher stiffness of the asphalts cause smaller elastic strains in the asphalt pavement and with it a rise of the number of permitted cycles to failure at the same loading. Thus it is recommended that asphalt mixtures should have a minimum stiffness to limit the size of the tensile strains at the bottom/top of the asphalt pavement preferably. With regard to the behaviour at low temperatures it can be required to limit the stiffness of asphalt mixtures by maximum values. A possible suggestion would be to define a range for the master curve which is dependent on the traffic loading. For the fatigue curves a similar approach would be possible. Hence, limits could be defined in which the fatigue curves should be arranged depending on the traffic loading. Furthermore, it is anticipated that no requirements regarding material properties are necessary anymore in future. Instead, performance requirements regarding the pavement durability or permitted traffic loading should be defined.

Construction aspects as well cost-effectiveness should be taken into account within the asphalt mix design (determination of the optimal bitumen content). In addition, asphalt surface courses and asphalt binder courses must be optimized regarding other performance properties as well. Asphalt binder courses must show a high resistance against plastic deformations. Asphalt surface courses need to have a high fatigue resistance as well as a high resistance against wearing and plastic deformation. In this context, the optimization regarding the fatigue resistance and the plastic deformation at the same time is a compromise, because the improvement of the plastic deformation resistance can lead to a lower fatigue life of the pavement. As an example, the asphalt surface mixtures tested [5] are showing this performance. While the optimal bitumen content is about 7 M.-% regarding the resistance to fatigue cracking for the SMA, the optimal bitumen content with regard to the stiffness is between 5.5 M.-% and 6.0 M.-% (10 °C and 20 °C). An optimization problem will arise in the context of consideration of all these criteria. For this reason it is recommended to continue the research.

7. ACKNOWLEDGEMENTS

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Table 1: Asphalt mixtures tested

Asphalt type/grade	Bitumen grade	Bitumen content
AC 22 T S	50/70	3.5 M.-%; 4.5 M.-%; 5.5 M.-% 6.5 M.-%
SMA 11 S	25/55-55	5.6 M.-%; 6.2 M.-%; 6.8 M.-%; 7.4 M.-%

Table 2: Properties of the asphalt mixtures tested

Asphalt grade	Bitumen grade	Bitumen content B [M.-%]	Maximum density φ_m [g/cm³]	Bulk density φ_b [g/cm³]	Air void content V [Vol.-%]	Bitumen saturation level VFB [%]
AC 22 T S	50/70	3.5	2.683	2.392	10.8	43,2
AC 22 T S	50/70	4.5	2.638	2.454	7.0	60,9
AC 22 T S	50/70	5.5	2.595	2.477	4.6	74,6
AC 22 T S	50/70	6.5	2.554	2.486	2.7	85,7
SMA 11 S	25/55-55 A	5.6	2.487	2.381	4.3	75,4
SMA 11 S	25/55-55 A	6.2	2.465	2.382	3.4	81,2
SMA 11 S	25/55-55 A	6.8	2.442	2.375	2.8	85,2
SMA 11 S	25/55-55 A	7.4	2.420	2.360	2.5	87,4

Table 3: Test parameters for the ITT according to AL Sp-Asphalt 09 [6]

Test parameters	Unit	Fatigue performance	Stiffness modulus
Temperature	°C	20.0 (AC 22 T S) 5.0 (SMA 11 S)	-10.0 / 0.0 / 10.0 / 20.0
Frequency	Hz	10	0.1 /0.5 / 1 / 3 / 5 / 10
Permitted elastic horizontal initial strains	‰	0.05 to 0.30	0.05 to 0.10

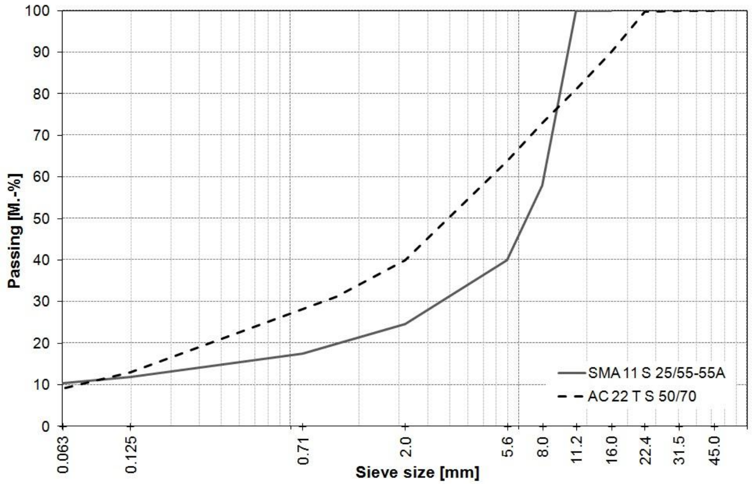


Figure 1: Gradations of the asphalt mixtures tested

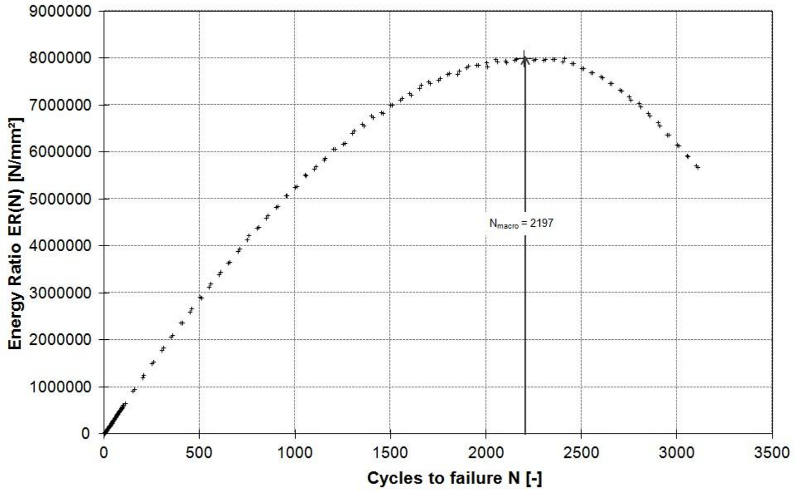


Figure 2: Example of the determination of the cycles to failure for the criterion macro crack N_{macro} [7]

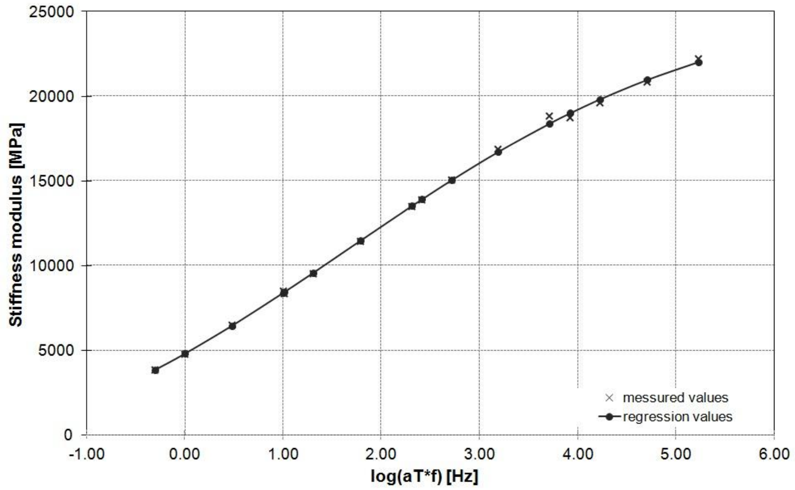


Figure 3: Example of a master curve of an asphalt mixture

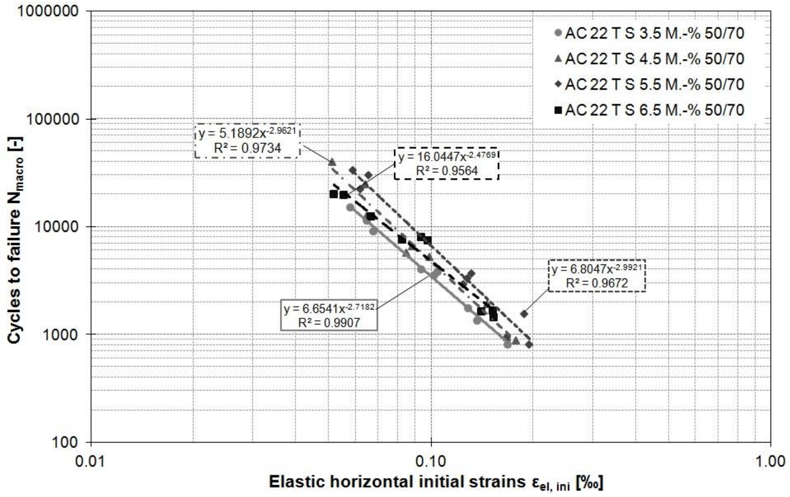


Figure 4: Fatigue curve of AC 22 T S, test temperature 20 °C and frequency 10 Hz [4]

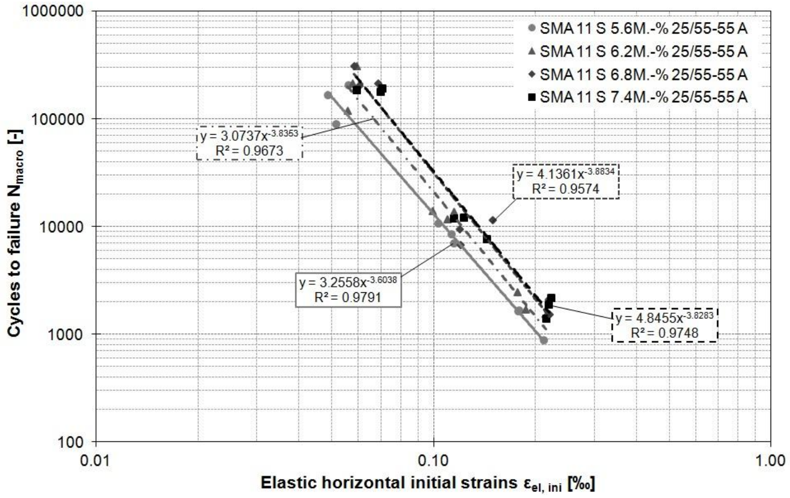


Figure 5: Fatigue curve of SMA 11 S, test temperature 5 °C and frequency 10 Hz [5]

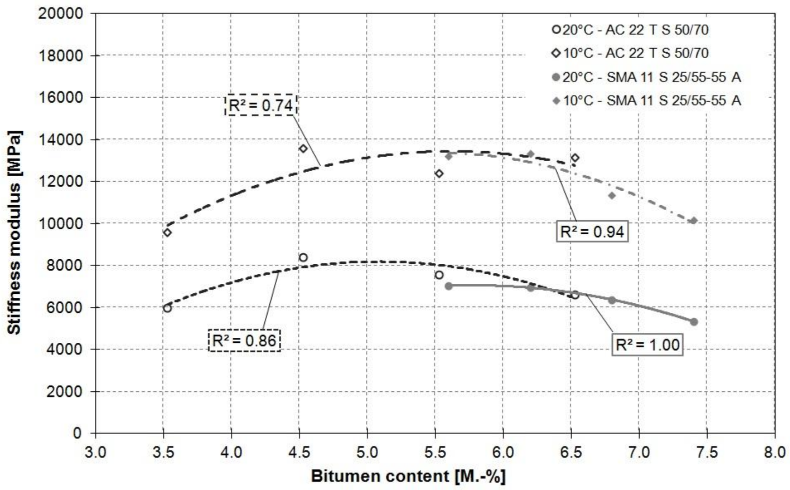


Figure 6: Stiffness modulus of AC 22 T S and the SMA 11 S into dependence of bitumen content, frequency f = 10 Hz, temperature 10 °C and 20 °C [4, 5]

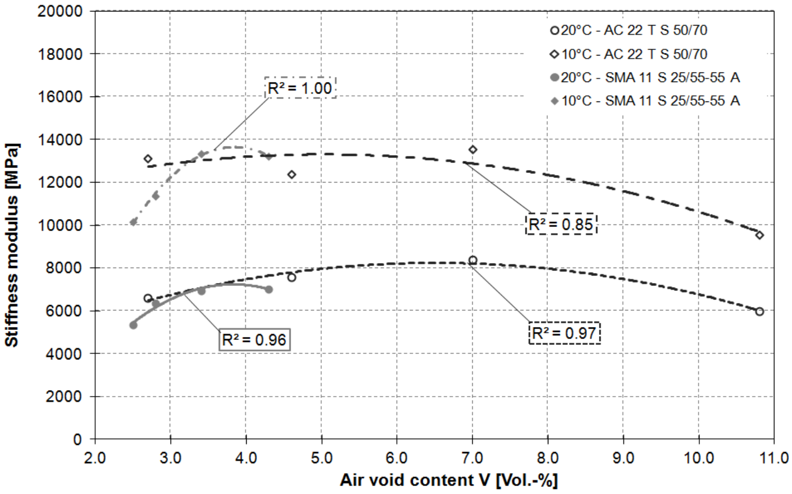


Figure 7: Stiffness modulus of AC 22 T S and SMA 11 S into dependence of air void content V, frequency f = 10 Hz, temperature T = 10 °C and 20 °C [4, 5]

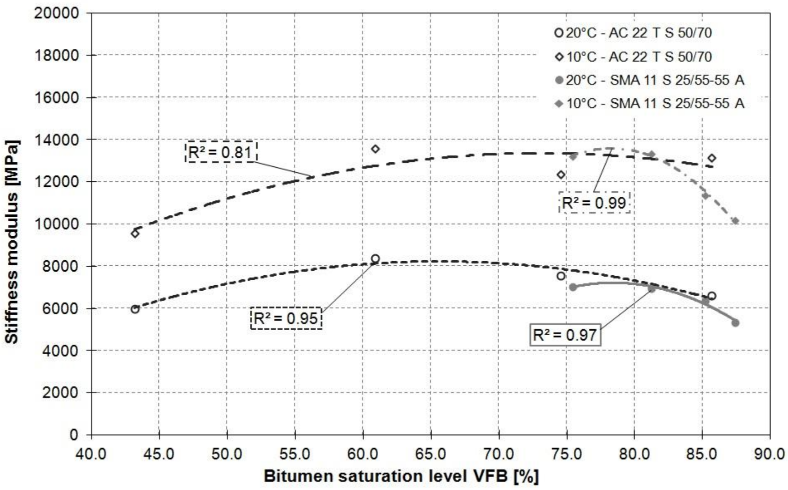


Figure 8: Stiffness modulus of AC 22 T S and SMA 11 S into dependence of bitumen saturation level VFB, frequency f = 10 Hz, temperature T = 10 °C und 20 °C [4, 5]

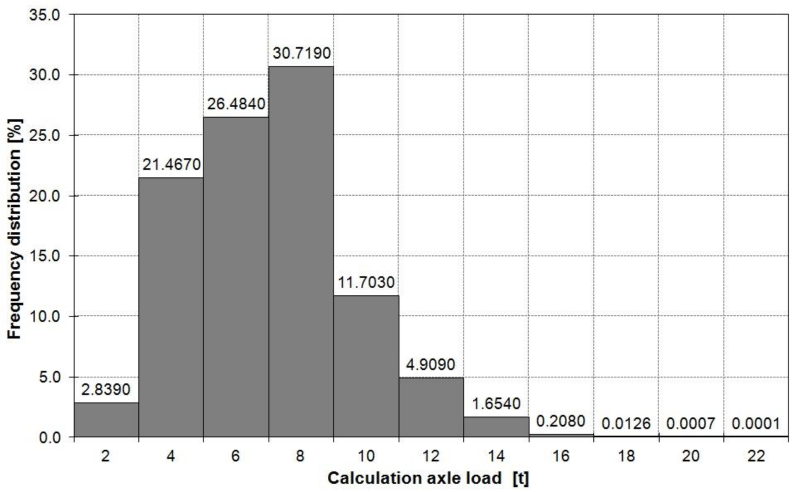


Figure 9: Axle load frequency distribution “federal motorway-long distance traffic” [8]

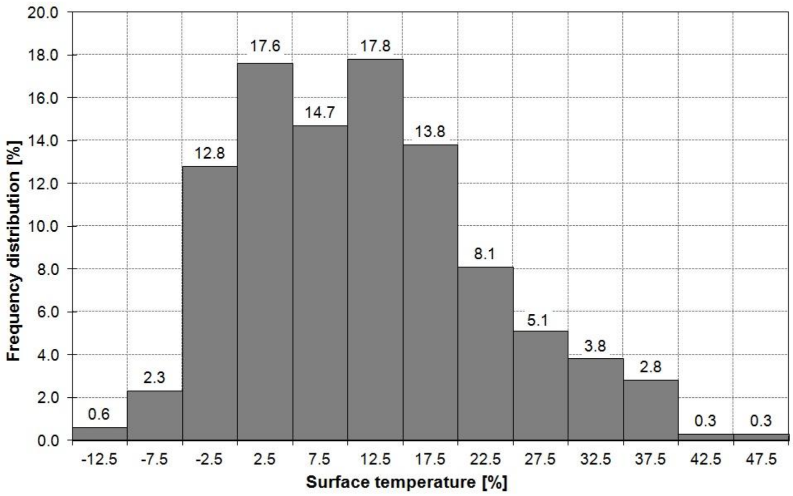


Figure 10: Standard frequency distribution – temperature zone 3 [8]

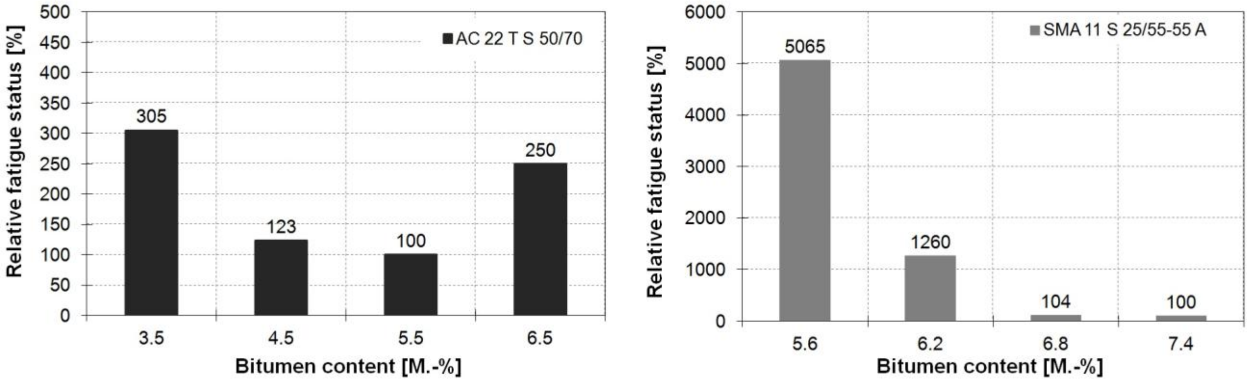


Figure 11: Fatigue status of AC 22 T S (on the left) and SMA 11 S (on the right) in a relative representation into dependence of the bitumen content [4, 5]

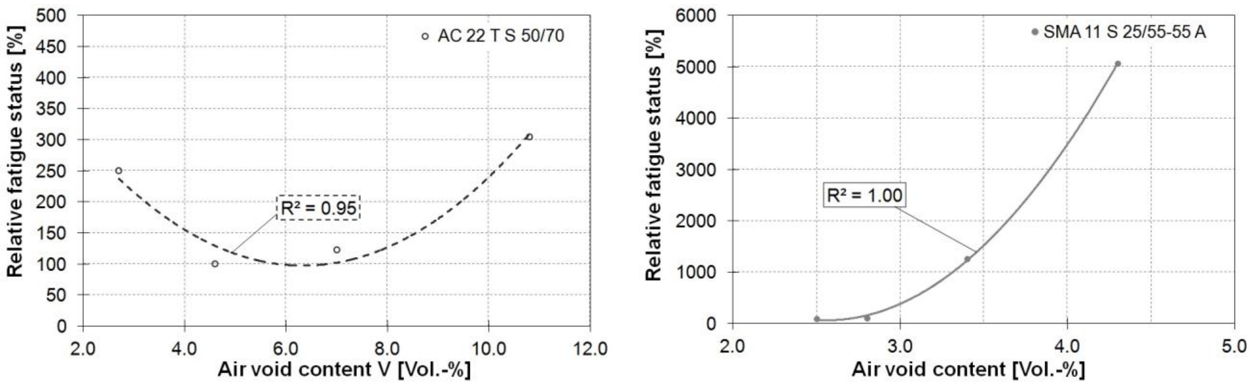
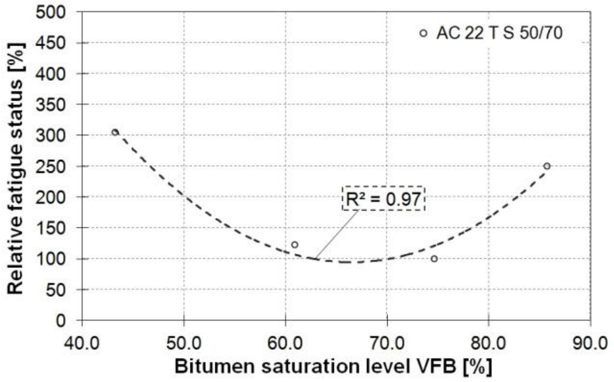


Figure 12: Fatigue status of AC 22 T S (on the left) and SMA 11 S (on the right) in a relative representation into dependence of the air void content V [4, 5]



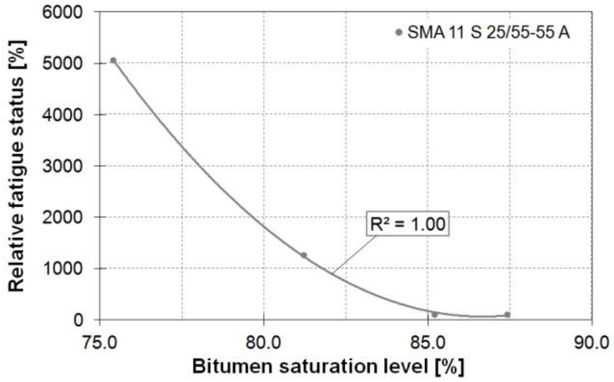


Figure 13: Fatigue status of AC 22 T S (on the left) and SMA 11 S (on the right) in a relative representation into dependence of the bitumen saturation level VFB [4, 5]

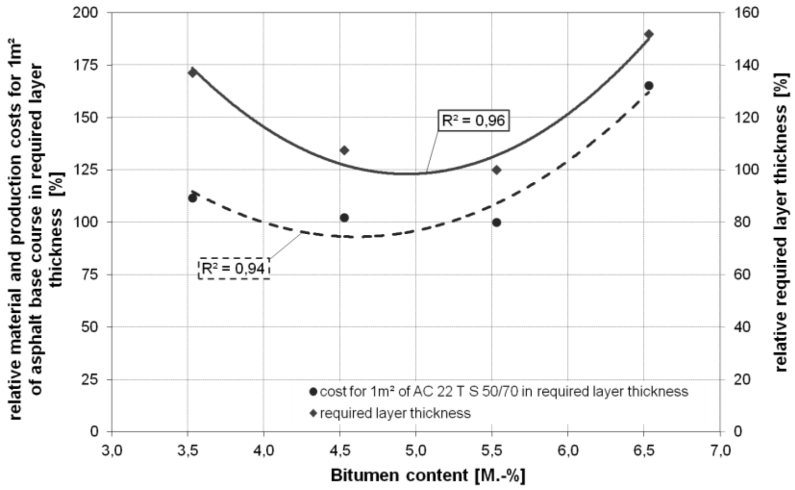


Figure 14: Material and production costs for 1 m² of asphalt base course in the required layer thicknesses (in a relative representation on the left y-axis) and the required layer thicknesses (in a relative representation on the right y-axis) of the asphalt base mixtures into dependence of the bitumen content