Effects of fiber reinforcement on the fatigue and rutting performance of asphalt mixes

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ABSTRACT

Fatigue, stiffness and rutting characteristics have a major influence on the pavement performance. For this reason different fibers are currently in use to investigate the impact of loose fiber reinforcement on the performance characteristics of asphalt mixtures. This paper presents tests of the fatigue, stiffness and deformation characteristics of different asphalt mixes. An asphalt base mix AC 22 T S (3 variations) and a stone mastic asphalt SMA 8 S (8 variations) were chosen to determine the effect of fiber reinforcement on fatigue and rutting performance. The test results show the influence of the chosen fibers (cellulose and Polyacrylonitrile PAN) on the material characteristics mentioned. On the one hand the difference between the mastercurves is insignificant concerning fiber use. On the other hand it is obvious that the fibers significantly influence the fatigue behavior. The impact of reinforcement is also illustrated using the German pavement design process. The use of fibers allows a road base layer reduction by up to 6 cm without compromising the safety level. The plastic deformation value can be reduced to 42% depending on fiber type and quantity. Further improvement can be achieved by inserting polymer modified bitumen, which reduces the plastic deformation value to approx. 64%.

Keywords: Design of pavement, Fatigue Cracking, Fibres, Mixture design, Permanent Deformation

1. INTRODUCTION

In Germany, fibers are solely used in stone mastic and porous asphalts due to technological reasons. The fibers prevent drainage of the relatively high bitumen content during transport and paving. Normally cellulose fibers are used.
Several tests with different fibers used in asphalt were conducted to evaluate the performance characteristics. Mahrez [1] observed an improvement of the fatigue resistance. He used glass and polymer fibers. The bitumen content must be increased to ensure good bonding between fibers and asphalt mastic. Chen [2] showed that the optimum bitumen content depends on the type and quantity of the fibers used. Chen [2] also described a better rutting performance by using polyester fibers. The current literature does not provide any information about the economy of fiber use within asphalt mixtures because of the increased bitumen requirement and the costs of the fibers. The precise evaluation of fiber use is possible in the pavement design process. In Germany, the pavement design process [3] is based on cyclic indirect tensile tests [4] to determine the fatigue characteristics and the mastercurve of the asphalt mixtures used. Furthermore, uniaxial compression tests on slim specimens (in dependence on the German guideline TP Asphalt [5]) are the basis for estimating the rutting risk during pavement life.
Fatigue, stiffness and rutting tests were conducted using cyclic indirect tensile tests and uniaxial compression tests to determine the influence of fiber reinforcement on two typical asphalt mixtures: an asphalt base mixture AC 22 T S and a stone mastic asphalt SMA 8 S. After pretests two fiber types (cellulose and polyacrylnitrile) were chosen for the main test phase.

2. ASPHALT MIXTURES

2.1 Materials

An asphalt base mixture AC 22 T S and a stone mastic asphalt SMA 8 S were chosen to determine the effect of fiber reinforcement on fatigue, stiffness and rutting performance. Different variations were defined for each asphalt. The parameters of the asphalt composition are given in Table 1.
Two variations of the asphalt base mixture were reinforced with fibers. On the one hand with cellulose fibers (labeling TMC, fiber length 0.3 – 1.4 mm) and on the other hand with polyacrylnitrile fibers (labeling TMP, fiber length 6.0 mm). The quantity of fibers added was identical for both variations. A variation without any fibers (labeling TM0) was also tested to identify the positive effect of the fibers.
For the stone mastic asphalt, both added fiber quantity and fiber type were variable. For the stone mastic asphalt variations with 0.7 mass-% fiber content the bitumen content was increased to 7.6 mass-% to ensure complete bonding between fibers and asphalt mastic.

Table 1: Asphalt composition

Labeling	Bitumen	Bitumen content [mass-%]	Max. aggregate size [mm]	Fiber type	Fiber content [mass-%]
TM0	50/70	4.7	22	-	-
TMC	50/70	4.7	22	Cellulose	0.5
TMP	50/70	4.7	22	PAN	0.5
SM0 1	50/70	7.3	8	Cellulose	0.3
SM0 2	50/70	7.3	8	Cellulose	0.5
SM0 3	50/70	7.6	8	Cellulose	0.7
SMP 1	50/70	7.3	8	PAN	0.3
SMP 2	50/70	7.3	8	PAN	0.5
SMP 3	50/70	7.6	8	PAN	0.7
SMP 4	PmB 25/55-55A	7.3	8	PAN	0.3
SMP 5	PmB 25/55-55A	7.3	8	PAN	0.5

Additionally, the grading chart for the asphalt base mixtures and the stone mastic asphalts are shown in Figure 1 and Figure 2. Both gradation curves are in accordance with the specifications given in the German guideline TL Asphalt-StB 07 [6]. Only for some sieves values are specified.

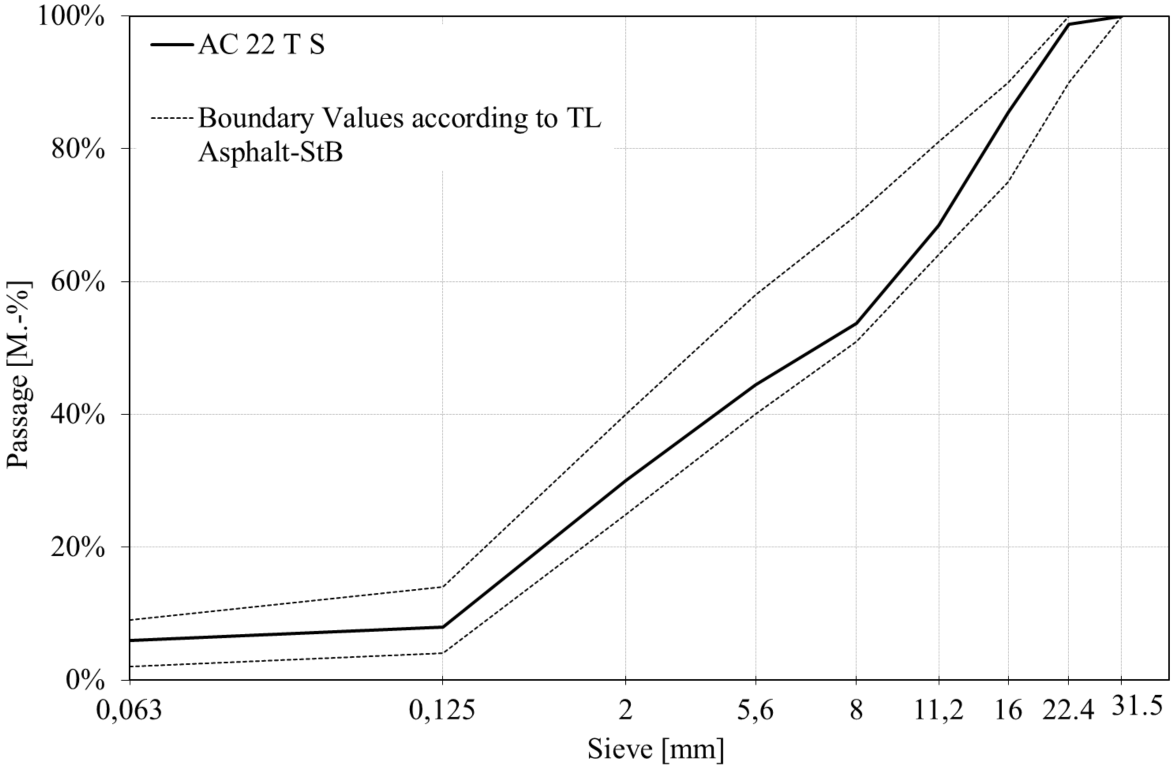

Figure 1: Grading chart for the three asphalt base variations AC 22 T S

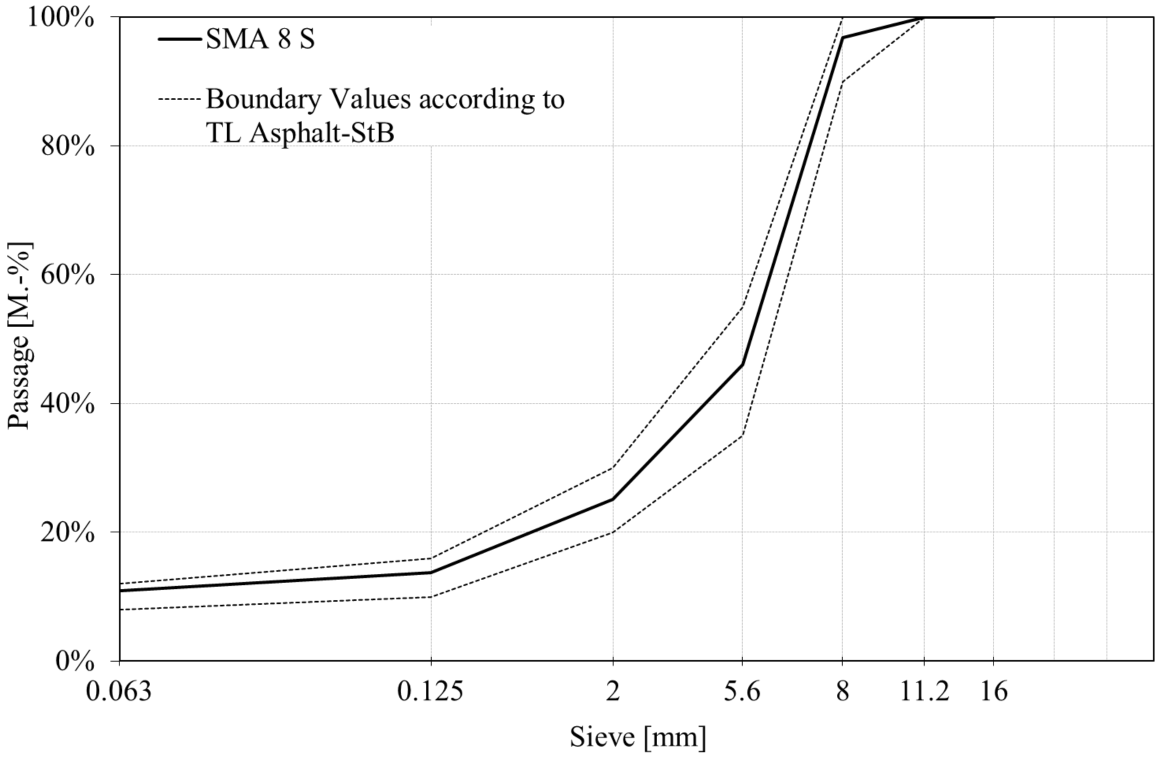

Figure 2: Grading chart for the eight asphalt surface course variations SMA 8 S

2.2 Specimen Preparation

For the cyclic indirect tensile tests (CITT) circular specimens are required. Therefore, all asphalt mixtures were produced in an asphalt mixing plant to ensure even mixing.

Afterwards, asphalt slabs with a dimension of 320 by 260 by 40 respectively 60 mm were manufactured using a segmented roller compactor. Thereafter, the specimens were cored out of the slabs. The diameter of the specimen is 150 mm for the asphalt base mixtures and 100 mm for the stone mastic asphalts. The samples were cleaned and dehumidified. Further, the air void content and the dimensions of each specimen were determined. This was done since it is known that the air void content greatly affects the results of the CITT. The air void content for the asphalt base mixtures was found to be between 5.2 and 6.2 vol.-% and between 1.5 and 3.9 vol.-% for the stone mastic asphalt which is in line with the test requirements.

For the uniaxial compression tests (UCT) slim cylindrical specimens (d=150 mm, h=300 mm) are required. The UCT was only performed on the stone mastic asphalts to estimate the rutting performance. Asphalt slabs with a dimension of 400 by 500 by 180 mm were manufactured using a segmented roller compactor. Thereafter, the specimens were cored out of the slabs. The samples were cut to the required length, cleaned and dehumidified. The dimensions of each specimen were determined.

3. LABORATORY TESTS

3.1 Cyclic Indirect Tensile Test (CITT)

The CITT is a practical test using circular specimens with a constant stress ratio horizontal/vertical = 1/3 in the center of the specimen. In the case of the CITT, the resultant horizontal deformations are measured for the cylindrical specimen which is loaded by two diametrically arranged compressive forces applied via curved loading strips. The horizontal displacement of the sample was measured using two LVDTs.
The loading strips had a width of 12.7 mm for specimens with a diameter of 100 mm and a width of 19.1 mm for specimens with a diameter of 150 mm. So the load application angle is 0.252 rad constantly.
The loading has a sinusoidal wave form without any rest periods and a frequency of 10 Hz for the determination of the fatigue characteristics. 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 0.3‰. The test temperature was 20°C. The number of load cycles until crack formation 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. The moment of macro crack formation is combined with the initial elastic strain. Each fatigue line is based on the results of at least nine CITTs. As a result, material-specific fatigue lines can be determined using Equation 1

$$\varepsilon_{el} = K_1 \cdot N^{K_2} \qquad (1)$$

where ε_{el} = initial elastic strain; N = number of load cycles until macro-crack; and K_1, K_2 = material parameters.

For the determination of the mastercurve (stiffness at various temperatures/frequencies) the loading again has a sinusoidal wave form without any rest periods. Five loading frequencies between 0.1 Hz and 10 Hz were chosen. Only a limited number of load cycles between 10 and 110 (depending on the loading frequency) was applied on the specimen to determine the stiffness modulus. Test temperatures were -10, 5 and 20 °C and the specimen were used multistage. Three specimens have been tested for each asphalt.

3.2 Uniaxial Cyclic Compression Test (UCCT)

The UCCT is a well-known test. We used our triaxial test apparatus to measure the elastic and permanent vertical deformations of the slim specimens at different locations during the test scheme. External linear variable differential transformers (LVDTs) and an internal contactless system were used to measure the axial deformations. The external system could be used to measure permanent deformations over the whole sample height and to define the termination criteria of the test. The internal system uses polarized magnets and coils. This measurement system consists of six magnets with a diameter of 20 mm that had to be placed in the specimen. Small holes were drilled into the specimen. Afterwards, the magnets were glued into the specimen using bitumen. Using this system, it is possible to measure the vertical elastic and permanent deformations in the mid-height of the specimen. The average distance between two magnets is 150 mm.
The permanent plastic strains measured with the internal contactless system were used to examine the graphs of the eight stone mastic asphalts visual. The loading (σ_{max} = 0.35 MPa) has a sinusoidal wave form without any rest periods and a frequency of 10 Hz. 170,000 load cycles at a test temperature of 50°C were applied to the specimen. For each asphalt, at least two specimens were tested with the UCCT and the strain values have been averaged.

4. TEST RESULTS

4.1 Fatigue characteristics

The fatigue characteristics of asphalt mixtures can be described using fatigue lines (see Equation 1) which illustrate the relationship between initial elastic strain and the load cycles until macro-cracking. The fatigue lines of the three asphalt base variations are shown in Figure 3. It is obvious that the fibers significantly influence the fatigue characteristics. For variation TMC, an increase in fatigue life in comparison to TM0 (without any fibers) can be observed. Using PAN fibers (TMP) considerably increases fatigue life even more.

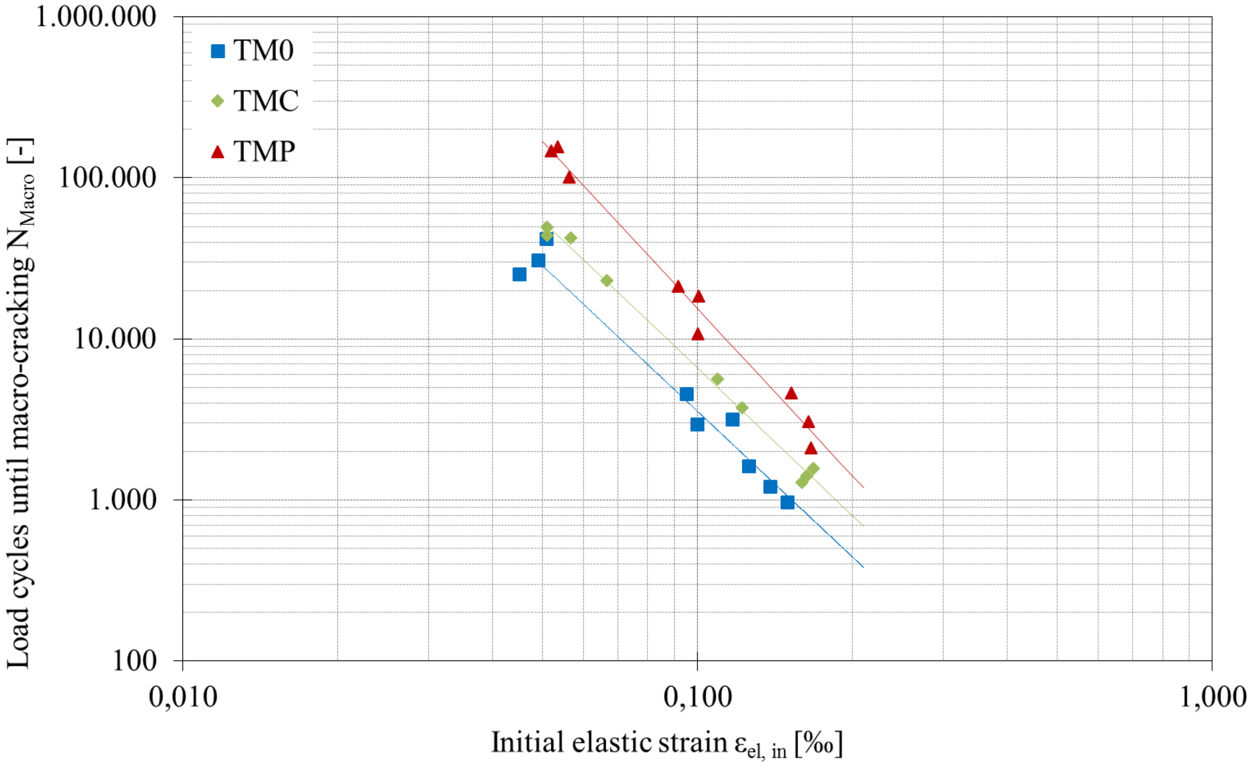

Figure 3: Fatigue of the three asphalt base variations

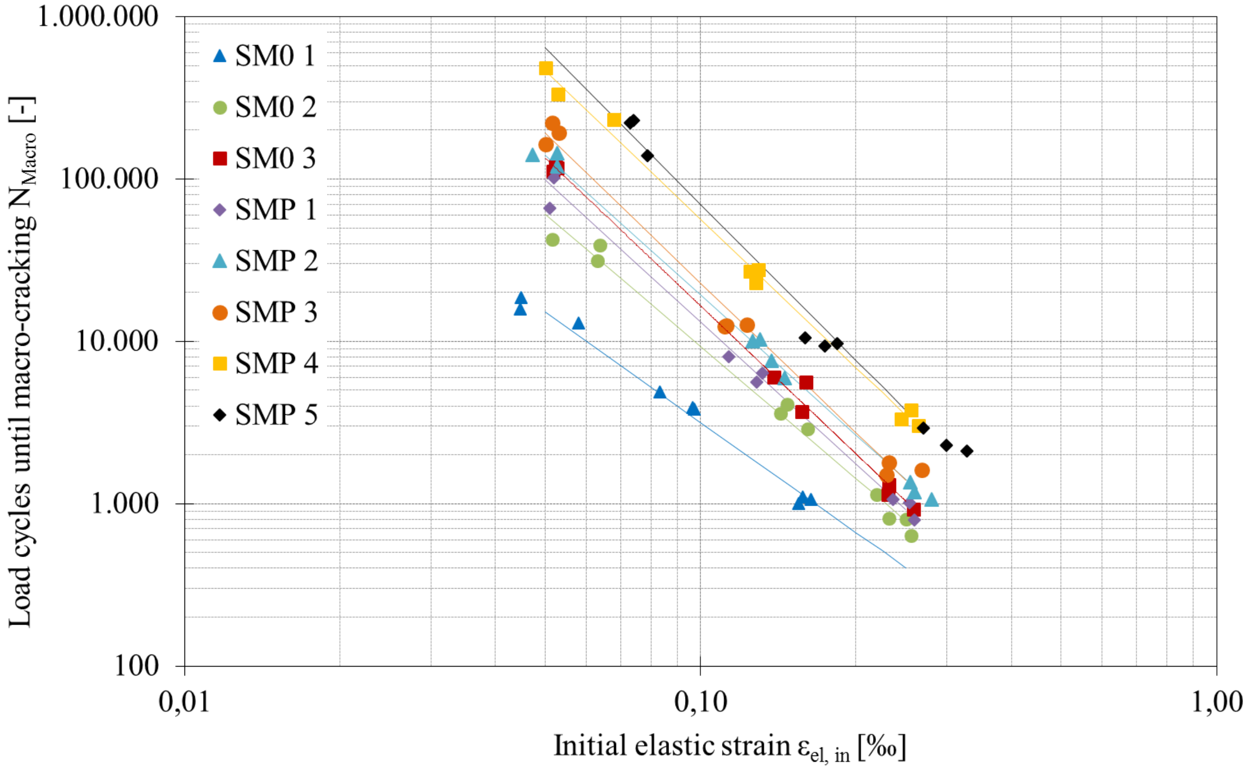

Figure 4: Fatigue characteristics of the eight asphalt surface course variations

The effect of the fibers on the fatigue characteristics of stone mastic asphalt is less pronounced compared to the asphalt base mixtures presented above. Figure 4 gives the fatigue lines of the eight stone mastic asphalt variations. There is a clear difference between the fatigue line of SM0 1 and other stone mastic variations with grade 50/70 bitumen. Furthermore, the fatigue lines of SMP 4 and SMP 5 are significantly improved because of the polymer modified bitumen PmB 25/55-55A used.

It must be noted that differences in the material life time concerning fatigue are not only based on the fatigue lines but also on the stiffness. Therefore, the mastercurves / stiffness are also examined.

4.2 Stiffness

The mastercurves of the three asphalt base variations are presented in Figure 5. The highest stiffness values are determined for TM0 followed by the values for TMC. The lowest values are measured for TMP. Overall, the differences between the three variations are insignificant. Especially at high temperatures or low frequencies the stiffness values are almost similar.
The mastercurves of the eight stone mastic asphalt variations are shown in Figure 6. It is obvious that the differences between the variations with grade 50/70 bitumen are very small. Only the mastercurves of the two variations with polymer modified bitumen PmB 25/55-55A (SMP 4 and SMP 5) show deviant stiffness values especially at normal and low temperatures compared to the asphalts with grade 50/70 bitumen. It can be concluded that the fibers have only a minor effect on the mastercurve of an asphalt.

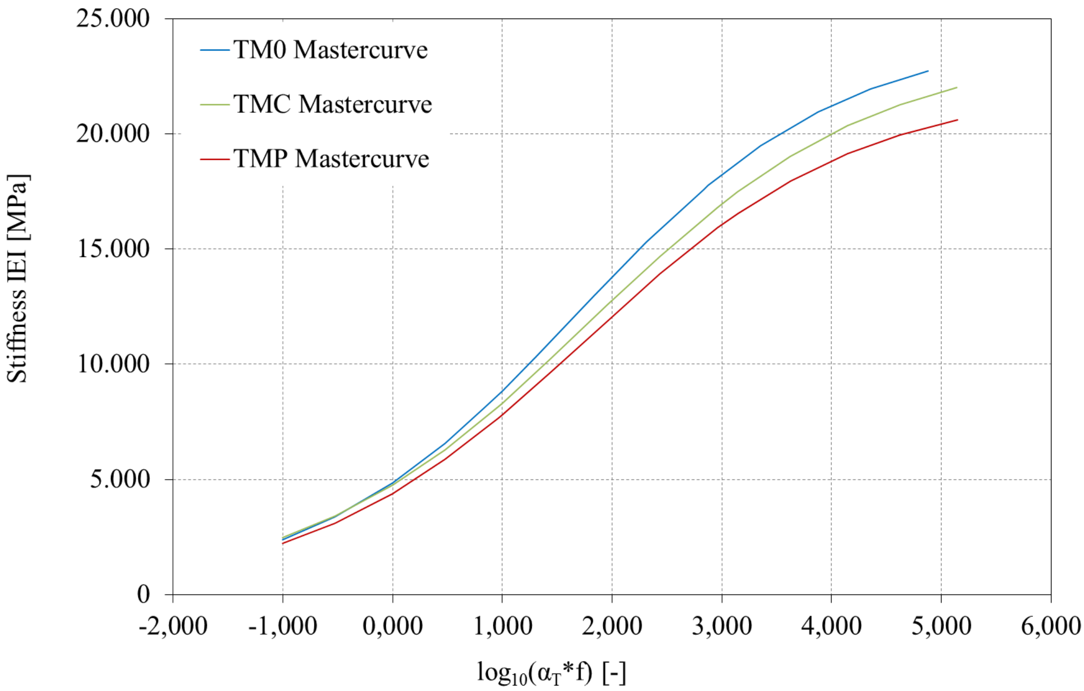

Figure 5: Mastercurves and single stiffness values of the three asphalt base variations

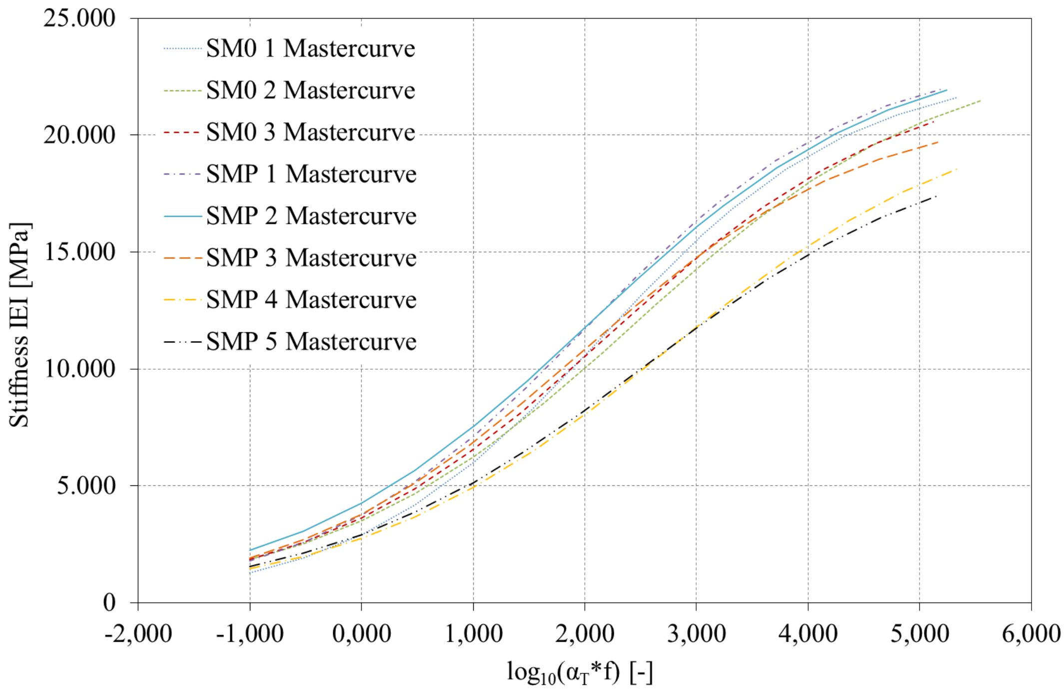

Figure 6: Mastercurves of the eight asphalt surface course variations

4.3 Rutting Performance

In addition to the fatigue characteristics, the rutting of an asphalt pavement also influences the life time and, consequently, the maintenance intervals. The rutting performance was not determined by calculating the rut depth, for example. In fact, the rutting tendency for all stone mastic asphalts was examined by conducting UCCT on slim specimens. The lines of the vertical plastic strains for the asphalts are given in Figure 7**:**. It can be concluded that both the fiber content and the type of fiber influence the plastic deformation values significantly. Variation SM0 1 failed before the target number of load cycles was achieved. For the variations with cellulose fibers (SM01, SM0 2 and SM0 3), the improvement concerning vertical plastic strain is around 30% compared to SM0 1. The difference of the plastic vertical strain between mixtures with cellulose and PAN fibers (SM0 1 and SMP 1) is approx. 13%. A larger amount of fibers has a positive effect on the plastic strain values. The strain values for SMP 3 are approx. 37% lower than those for SM0 1.
The strain values for SMP 4 and SMP 5 are again lower than for the other 6 variations, which is justified by the polymer modified bitumen used. Furthermore, the PAN fibers also have a positive effect on the plastic deformations. So it can be concluded that the stone mastic asphalt should contain PAN fibers and polymer modified bitumen if high loading is expected.

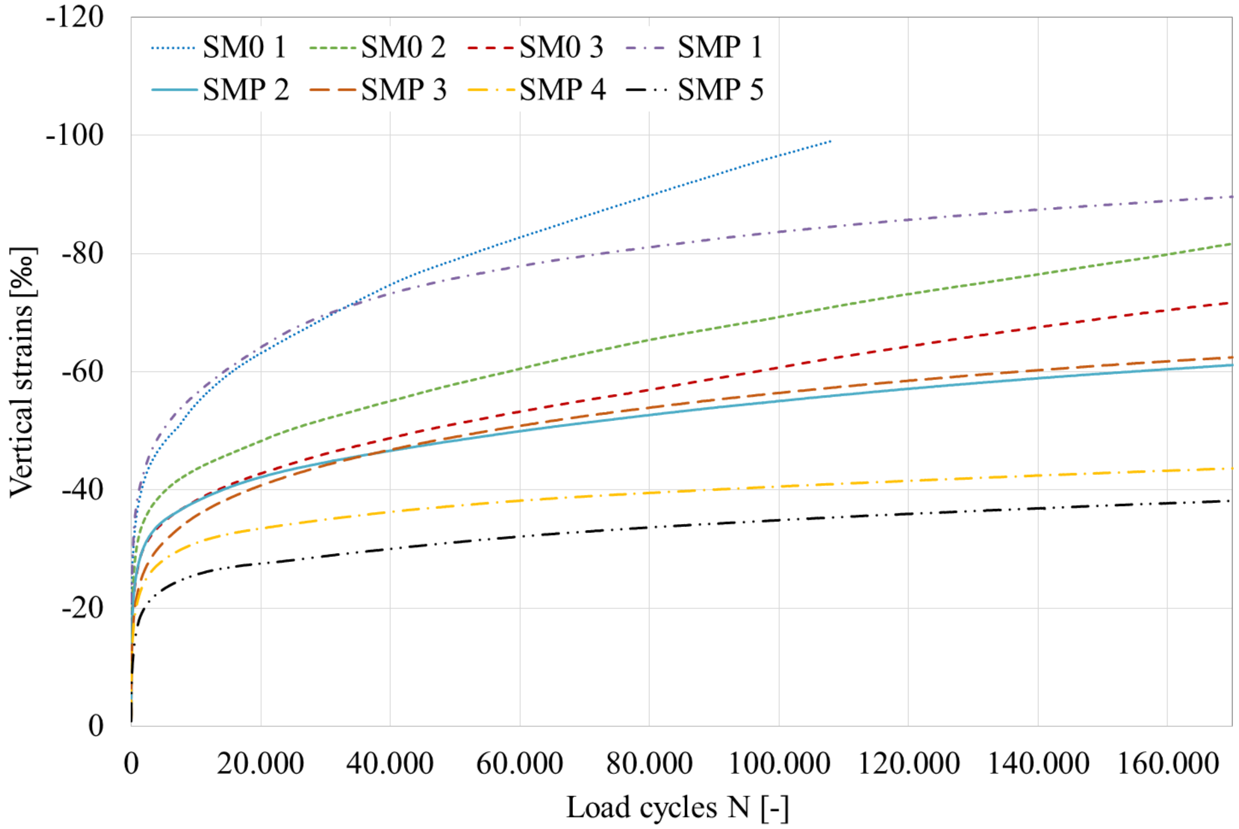

Figure 7: Vertical plastic strains of the eight asphalt surface course variations during UCCT

5. CALCULATION RESULTS

It is possible to evaluate the effect of fibers on the material characteristics by using the pavement design process that is defined in the German guideline RDO Asphalt 09 [3].
Therefore, a common pavement was chosen which is able to resist high loadings and a large amount of traffic. The layers and thicknesses of the pavement are given in Figure 8. A daily heavy vehicle traffic of 1000 is assumed for the calculations.

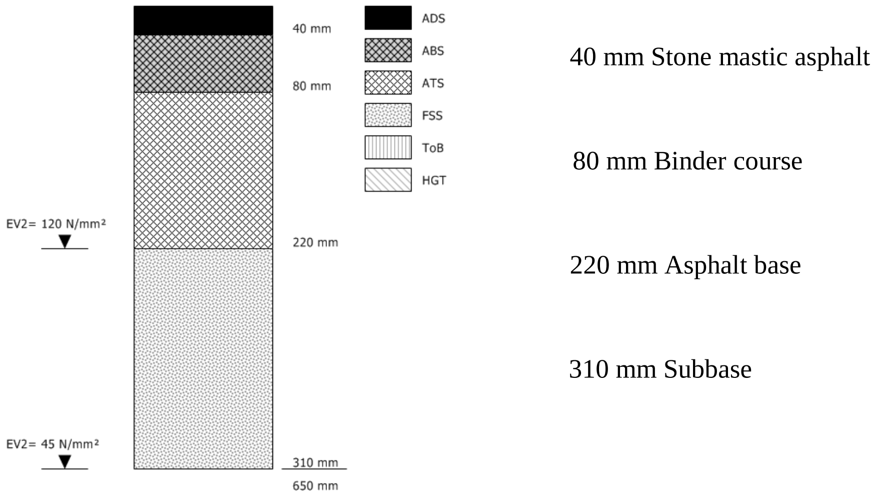

Figure 8: Layer structure of the chosen pavement

The results of the pavement design process are given in Table 2 and Table 3. The pavement design was carried out at two witness points. The first at the bottom of the asphalt base in the loading centerline and the second at the top of the asphalt surface course 165 mm from the centerline. This point was chosen because of the maximum tension value at the top of the surface layer. The fatigue status was calculated for a life time of 30 years.

Table 2 Pavement design process – fatigue status on the bottom of the asphalt base

[%]	TM0	TMC	TMP
SM0 1	114.4	70.3	32.4
SM0 2	112.3	81.8	31.6
SM0 3	110.5	80.6	31.1
SMP 1	109.2	79.6	30.7
SMP 2	106.8	78.0	29.9
SMP 3	109.6	80.0	30.8
SMP 4	118.0	85.8	33.3
SMP 5	116.7	85.0	32.9

Table 3 Pavement design process – fatigue status on the top of the asphalt surface course

[%]	TM0	TMC	TMP
SM0 1	124.2	132.3	142.3
SM0 2	29.1	31.4	34.3
SM0 3	13.0	14.2	15.7
SMP 1	18.0	19.5	21.5
SMP 2	11.6	12.6	13.8
SMP 3	9.2	10.0	11.1
SMP 4	4.1	4.5	5.0
SMP 5	3.0	3.3	3.6

It can be seen from the values of the fatigue status that fatigue cracks will occur in the base layer prior the end of 30 years if mixture TM0 is used. When using mixtures TMC or TMP, a reduction of the layer thickness of 1 cm for TMC and 5.5 cm for TMP is possible without compromising the safety level of the calculation and the life time. This offers a great resource saving potential. The values of the fatigue status on the top of the surface course show that mixture SM0 1 has a poor fatigue characteristic which will lead to cracks in the life time chosen. But normally surface courses will be replaced after approx. 15 years due to different damages.
Table 4 summarize the possible respectively necessary layer thickness change of the asphalt base due to the fatigue status given in Table 2. For TM0 the asphalt base layer thickness must increase 0.5 to 1.0 cm. For TMC a layer reduction between 0.5 and 1.0 cm are possible. For the asphalt base mixture with PAN fibers a layer reduction between 5.0 and 6.0 cm is verified. It must be considered that the asphalt base layer reduction or increase must be compensated in the subbase to ensure a constant value of the frost free pavement structure.

Table 4 Pavement design process – Possible layer thickness reduction of the asphalt base

	TM0		**TMC**		**TMP**	
	layer increase [cm]	**fatigue status [%]**	**layer reduction [cm]**	**fatigue status [%]**	**layer reduction [cm]**	**fatigue status [%]**
SM0 1	1.0	95.9	1.0	98.3	5.5	97.5
SM0 2	1.0	94.2	1.0	96.5	5.5	94.8
SM0 3	1.0	92.8	1.0	95.2	5.5	92.9
SMP 1	0.5	99.9	1.0	93.9	5.5	91.8
SMP 2	0.5	97.8	1.0	92.0	6.0	99.1
SMP 3	1.0	92.0	1.0	94.4	5.5	92.0
SMP 4	0.5	98.9	0.5	93.2	5.0	90.4
SMP 5	0.5	97.9	0.5	92.3	5.5	98.9

Under consideration of the costs of the used fibers also economical evaluation can be undertaken. The PAN fibers are five times more expensive than Cellulose fibers. Therefore it is economical not wise to use PAN fibers even if you can save 6.0 cm of the base layer due to the low prices of base layer mixes in Germany. Using Cellulose fibers and saving 1.0 cm the costs are constant in comparison to TM0 and a layer increase of 1.0 cm. Further economical evaluations for Germany are presented in [8].

6. DISCUSSION AND CONCLUSIONS

This paper investigates the fatigue and rutting characteristics of different asphalt mixtures with and without fiber reinforcement. We further studied the effects of fiber reinforcement on the results of the pavement design process. Our research has shown that the use of fibers allows the reduction of base layers to save resources without affecting the safety level. We could also show that the vertical plastic deformation of the different surface course mixtures highly depends on the used fiber type and quantity.

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