Analysis of asphalt mix performance properties considering the discrepancy between mix design and in-field realization (Part I)

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ABSTRACT. In laboratory practice, asphalt mix properties may differ significantly from design specifications. Moreover, due to industrial asphalt mix production, in-field paving and compaction, the asphalt layer properties may vary from pavement design targets. In a study, recently carried out at the Braunschweig Pavement Engineering Centre, Germany, the fluctuations in material properties have been investigated as they may occur considering realistic laboratory conditions and in-field construction conditions.
The results of more than 40,000 control tests performed on newly constructed asphalt pavements were analyzed statistically in order to specify the discrepancies between mix design and in-field realization. As a result, the distributions of the actual binder content, the gradation and the compaction degree were assessed, always in regard to the initial mix design targets. Whereas binder content, grading and layer thickness were found to be normally distributed, the compaction degree follows a Weibull-distribution.
According to published laboratory test results the influence of the observed fluctuations between actually paved material and mix design on the expected pavement performance in terms of resistance against cracking and rutting was evaluated.
To quantify the effect of these fluctuations on the results of pavement design calculations, 5 asphalt base course mixes were produced with varying compositions. For these mixes the material parameters as used for pavement design were established and required layer thicknesses calculated. The study on pavement design and the design results are presented to this Conference in the associated paper Part II.

KEYWORDS: Mix design, site characteristics, performance, material property.

1 INTRODUCTION AND SCOPE

Asphalt mix properties may differ significantly from design targets. The target asphalt mix is designed in the laboratory. Asphalt specimens are produced by compacting the mix in suitable laboratory devices. Mixing and compaction techniques are used which result in specimen properties which are very similar to the properties resulting from plant-mixing and site-compaction (cp. Renken, 2000). However, fluctuations in the asphalt properties and discrepancies between the actual mix and the target mix can not be avoided due to the scatter of laboratory techniques.

In addition, the in-situ asphalt layer properties may vary from pavement design targets due to industrial asphalt mix production, and in-field paving and compaction conditions. In the asphalt mixing plant, the same type of aggregate and the same type of binder is used as determined in the target mix design. Nevertheless, differences in the exact aggregate mineral composition may occur due to the naturally varying properties of natural aggregates in one and the same quarry. Furthermore, several researchers showed that the properties of a specific binder product may vary considerably even for the same binder type and classification (Büchler et al., 2008, 2009). Therefore, the characteristics of the industrially mixed asphalt may differ from the target asphalt mix as specified by type testing.

After mixing, the asphalt mix is transported to the construction site where it is laid and compacted. During the mix process, the hot storage, the transport and the paving the loose hot asphalt mixture is subjected to oxygen, and hence, ages considerably. The compaction process influences void content considerably. Due to the individual steps of asphalt pavement production, further differences to the lab-mixed and lab-compacted material must be taken into account.

In a study, recently carried out at the Braunschweig Pavement Engineering Centre, Germany, the fluctuations in material properties have been investigated, as they may occur considering realistic laboratory conditions and in-field construction conditions.

In-situ pavement layer characteristics were analysed, with special regard to layer thickness, mix design and compaction degree. In order to statistically distinguish the differences in the actual built-in layer thickness compared to the theoretical one a comprehensive database was provided by the Road and Transport Authority of Lower Saxony. The data contain results of check tests from construction sites on highways, federal highways and country roads since 1996. Thus a total number of 40,900 mix analyses and 27,800 core samples of construction projects throughout Lower Saxony are included. Due to the theoretical mix design, groups were established concerning mixture, its type and binder type to classify and evaluate the records.

In a first step the divergences between mix properties as defined in the mix design (type test) were compared with actual paved material (see Chapter 2). Then, the influence of these divergences on the material performance was investigated by means of fundamental laboratory testing (see Chapter 3). For this purpose, asphalt mixtures were composed in the laboratory considering typical divergences from the mix design as found in practice. The findings of these investigations are presented in the following.

In addition, the effect of fluctuations in material properties on the result of a mechanistic pavement design was analyzed and presented to this Conference in the associated paper part II.

2 DIVERGENCES BETWEEN MIX DESIGN AND PAVED MATERIAL

2.1 German Quality Control System

In Germany, mix design in the frame of type testing is performed empirically based on volumetric design principles. Material composition of any asphalt mix type is defined according to the technical specifications (FGSV, 2007a), where suitable ranges for binder type and binder content, grading, and void content are defined, based on impact compaction of specimens. Initial type testing is realized by the supplier of the asphalt mix, and the resulting data are provided to the public applicant.

The mix design result is used for asphalt production in plant. When the asphalt is paved on the construction site, mix samples are taken directly from the paver for quality control of a public contracting entity. Hence, mix composition is controlled as it is delivered to the construction site and found in the back of the truck. Moreover, a public contracting entity also checks the final pavement by drilling cores of the pavement and by analyzing them with respect to the parameters given in Table 1 (FGSV, 2007b). The parameters found in quality control tests must not exceed the design targets from type testing and a tolerance range (Table 1). If design targets are not achieved, the fee for the production works is reduced.

Table 1: Mix design targets of selected asphalt mix types for primary roads (FGSV, 2007a) and allowed tolerances to the value given in type testing of the paved layer (FGSV, 2007b).

<table>
<tr><th colspan="2" rowspan="3">Hot mix asphalt type</th><th colspan="2">Binder content [M.-%]</th><th colspan="2">Content of fines [M.-%]</th><th colspan="3">Void content [Vol.-%]</th><th>Comp. degree [%]</th></tr>
<tr><th rowspan="2">Range</th><th rowspan="2">Tol.</th><th rowspan="2">Range</th><th rowspan="2">Tol.</th><th colspan="2">Specimen</th><th colspan="2" rowspan="2">Paved layer</th></tr>
<tr><th>Range</th><th>Tol.</th></tr>
<tr><td rowspan="2">Asphalt concrete for base layers</td><td>AC 32 T S</td><td rowspan="2">≥ 3.8</td><td rowspan="2">±0.6</td><td rowspan="2">2 - 9</td><td rowspan="2">+7.0; -3.0</td><td rowspan="2">5-10</td><td rowspan="2">± 2.0</td><td rowspan="2">-</td><td rowspan="8">≥ 97</td></tr>
<tr><td>AC 22 T S</td></tr>
<tr><td rowspan="2">Asphalt concrete for binder layers</td><td>AC 22 B S</td><td>≥ 4.2</td><td rowspan="6">±0.5</td><td rowspan="2">3-7</td><td rowspan="6">±3.0</td><td rowspan="2">3.5-6.5</td><td rowspan="2">± 2.0</td><td rowspan="2">-</td></tr>
<tr><td>AC 16 B S</td><td>≥ 4.4</td></tr>
<tr><td rowspan="2">Asphalt concrete for surface layers</td><td>AC 11 D S</td><td>≥ 6.0</td><td>5-9</td><td>2.5-4.5</td><td rowspan="2">± 1.5</td><td>≤ 6.5</td></tr>
<tr><td>AC 8 D S</td><td>≥ 6.2</td><td>6-12</td><td>2.0-3.5</td><td>≤ 5.5</td></tr>
<tr><td rowspan="2">Stone Mastic Asphalt</td><td>SMA 11 S</td><td>≥ 6.6</td><td rowspan="2">8-12</td><td rowspan="2">2.5-3</td><td rowspan="2">± 1.5</td><td rowspan="2">≤ 5.0</td></tr>
<tr><td>SMA 8 S</td><td>≥ 7.2</td></tr>
</table>

2.2 Divergences derived from quality control tests

In the following, the discrepancies in material properties are investigated, as they may occur between mix design targets and results from in-field quality controls. This analysis is based on data from the Traffic and Road Works Authority of Lower Saxony, who provided the results of a number of 40 900 quality control tests for the paved asphalt mixtures, and a number of 27 800 cores drilled of the pavement for quality control of the void content after compaction.

2.2.1 Binder content

Exemplarily, Figure 1 shows the distribution of the binder content (black dots) of a number of 1 446 asphalt binder course mixes of type AC 16 B S, with a nominal binder content of 4.2 % according to the mix design. The frequency of occurrence of the binder content is represented by a normal distribution described by a mean value of B_{Mean} = 4.24 %, and a standard deviation of s_B = 0.262 %.

Considering binder contents of 3.8 to 4.2 %, the normal distribution overestimates the frequency of occurrence, while it is slightly underestimated for binder contents of 4.2 to 4.7 %. The dashed vertical lines indicate the tolerance as given in Table 1. Hence, more than 90 % of all mixtures considered meet the requirements for the binder content.

In Table 2 the mean values and standard deviations of other selected mixtures are summarized. For each asphalt type the nominal binder content with the highest frequency in the data base was chosen for the evaluation. In general, the mean binder contents are observed to be slightly higher than the nominal binder contents according to the mix design (except for stone mastix asphalt mixtures). The highest standard deviations are found for the base course mixtures. With decreasing nominal grain size D, the standard deviation decreases as well.

2.2.2 Filler content

Filler, as defined in this study, is defined as fine aggregates below a grain diameter of 0.09 mm. Figure 2 shows the distribution of the filler content measured for the delivered asphalt mixtures of the type AC 16 B S having a nominal binder content of 4.2 % and a nominal content of fines of 6.0 %.

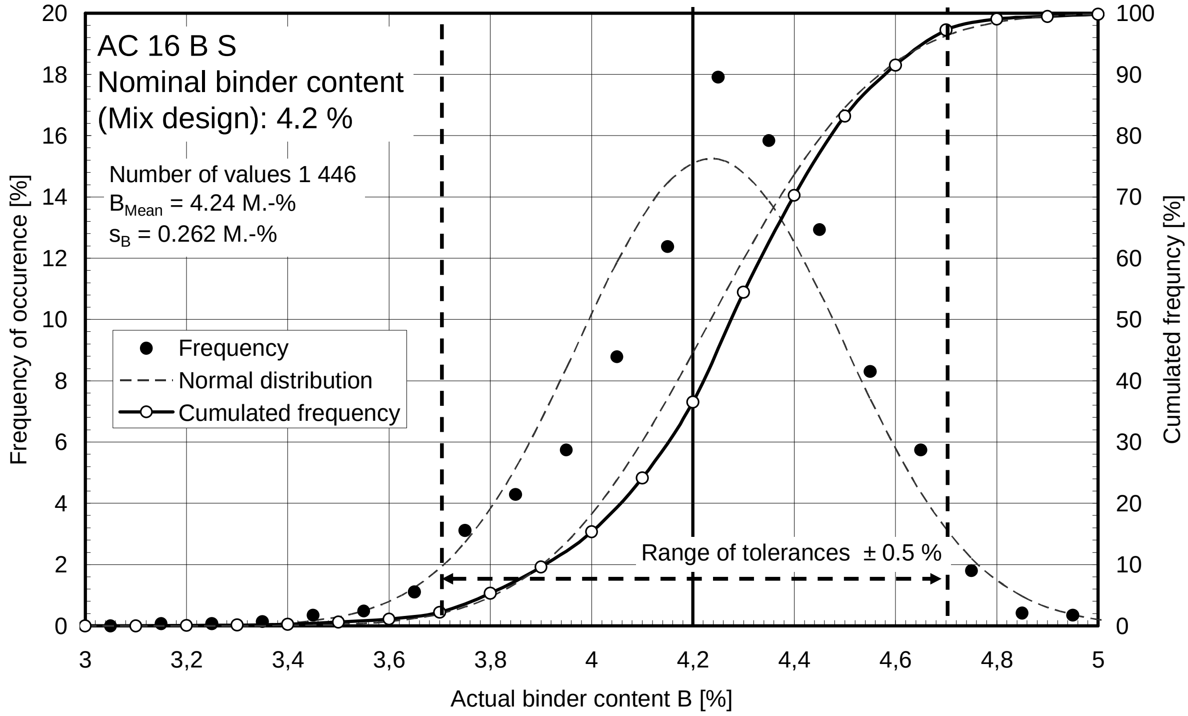

Figure 1. Binder content distribution of asphalt mix type AC 16 B S (nominal binder content of 4.2 % according the mix design) for a data base of 1 446 values.

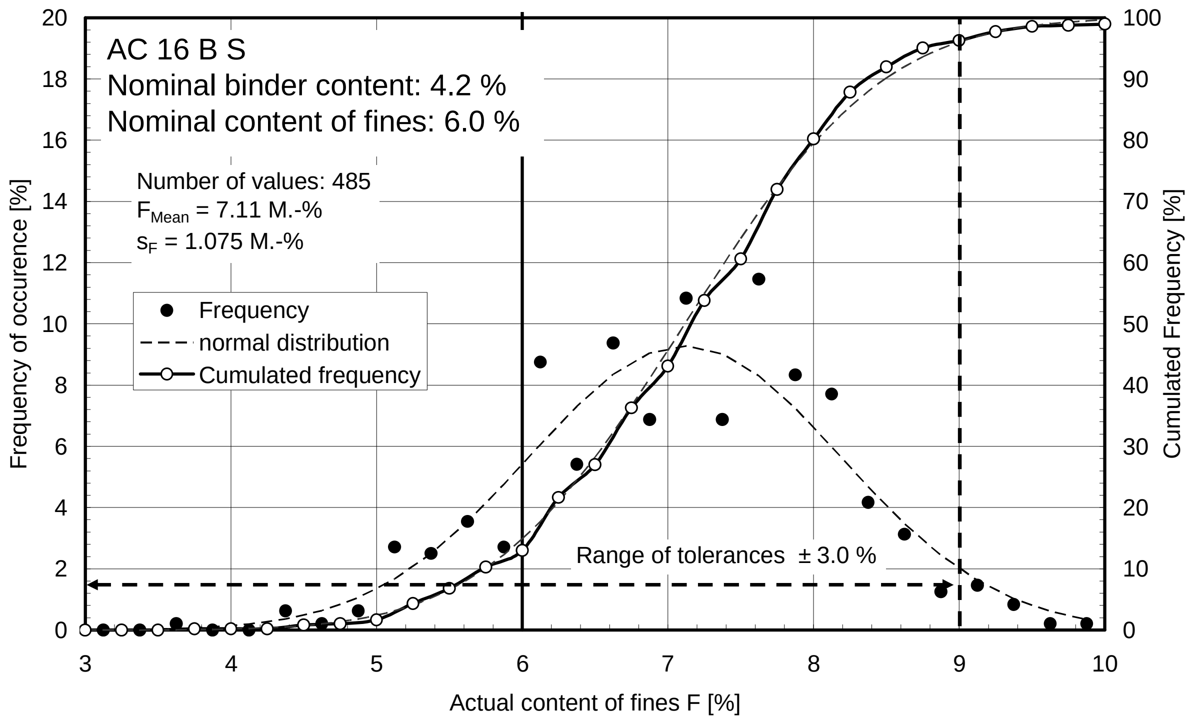

Figure 2. Distribution of content of fines of asphalt mix type AC 16 B S (nominal binder content of 4.2 % and a nominal content of fines of 6.0 %) for a data base of 485 values.

As indicated by the polygon of cumulated frequency of occurrence, the content of fines follows a normal distribution. This is observed for 95 % of all asphalt mixtures, as shown by the range of tolerance. The mean values and standard deviations of other mixtures are added to Table 2. It is generally observed that the mean content of fines is higher than the nominal value. Especially as concerns the base course asphalt mixes, the content of fines exceeds the nominal value by more than 30 %.

Table 2: Mean values and standard deviations of binder content and filler content of selected asphalt mixes.

Asphalt mix	for base courses		for binder courses		for surface courses		
	AC 32 T S	AC 22 T S	AC 22 B S	AC 16 B S	AC 11 D S	SMA 11 S	SMA 8 S
Nominal binder content [%]	3.6	3.6	4.0	4.2	5.9	6.5	7.0
Mean of actual binder content [%]	3.66	3.71	4.04	4.24	5.90	6.42	6.99
Standard deviation s_B [%]	0.354	0.343	0.300	0.262	0.253	0.243	0.222
Number of values [-]	3 046	677	1 406	1 446	1 180	4 812	870
Nominal content of fines [%]	6.1	6.7	8.0	6.0	7.5	9.0	10.0
Mean of actual content of fines [%]	7.12	8.99	8.15	7.11	7.81	9.16	9.87
Standard deviation s_F [%]	0.967	1.054	1.061	1.075	1.177	1.053	1.144
Number of values	449	101	597	485	378	1 876	461

2.2.3 Degree of compaction

Degree of compaction is defined as the quotient of the bulk density of the sample cored from the road structure divided by the bulk density of the reference specimen as derived from mix design. As shown in Figure 3, the degree of compaction follows a Weibull distribution. It is observed, that about 90 % of the analysed asphalt courses do not meet the requirements. Highest frequency of occurrence is given for a value of 101.1 % degree of compaction. However, the expected degree of compaction is about 98.9 %.

In Table 3, the results of the statistical analysis with respect to the degree of compaction are summarized for selected asphalt mixtures. Surface courses in general show low degrees of compaction. This observation is less distinct for base or binder courses, which is explained by the layer thickness. A thick layer is less susceptible for bad weather conditions (low temperature, high winds, rain), as more energy is stored in the thick layer and more time is available for the compaction process if compared to a thin surface layer.

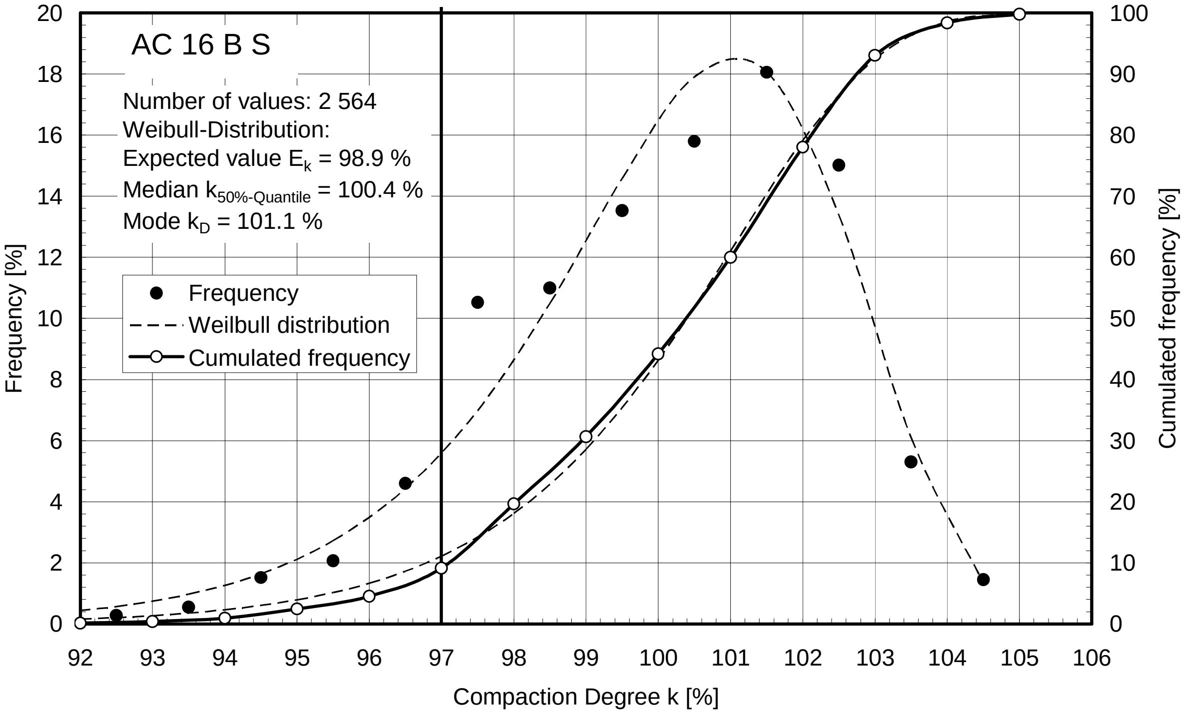

Figure 3. Distribution of the compaction degree measured in quality control tests on 2 564 AC 16 B S courses.

Table 3: Expected value, Median, Mode and Frequency of values failing the requirement for the compaction degree of selected asphalt courses.

Asphalt mix	for base courses		for binder courses		for surface courses		
	AC 32 T S	AC 22 T S	AC 22 B S	AC 16 B S	AC 11 D S	SMA 11 S	SMA 8 S
Expected value E_k	99.2	99.1	99.2	98.9	99.2	99.2	99.1
Median $k_{50\,\%}$	101.7	101.3	101.3	100.4	99.1	99.7	99.2
Mode k_D	102.2	101.9	101.8	101.1	99.6	100.2	99.8
Frequency of values below requirement of $k \geq 97$ %	3 %	4 %	3 %	10 %	13 %	9 %	16 %
Number of values	4 946	902	2 868	2 564	1 537	5 082	1 409

3 INFLUENCES OF PROPERTIES ON PERFORMANCE CHARACTERISTICS

3.1 Resistance against fatigue cracking

3.1.1 Influence of binder content

The influence of the binder content on the fatigue resistance is well documented in literature and exemplarily shown in Figure 4, where the results are represented of 3-point-bending tests on specimens made from an asphalt concrete mix AC 19 (Harvey & Tsai, 1996). In general, fatigue resistance is increased by increasing binder content.

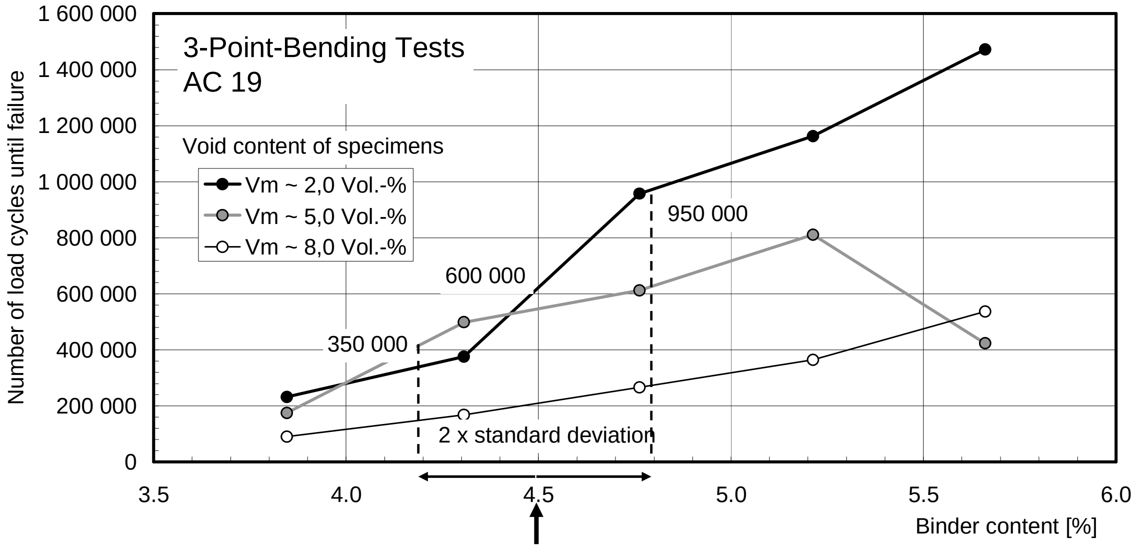

Figure 4. Influence of binder content on fatigue resistance (Harvey & Tsai, 1996).

Mollenhauer et al. (2009) studied the influence of binder content on fatigue resistance of AC 11 surface mixtures and SMA 11 mixtures based on Uniaxial Cyclic Tensile Stress Tests (UCTST) according to prEN 12697-46. It was found that a varying binder content of ± 0.25 % for the AC 11 induces a variation of the fatigue life of about ± 25 % if compared to the fatigue life of mixtures with the mean binder content. A variation of the fatigue life of about ± 25 % to even 50 % was found for SMA 11 mixtures. For AC 16 and AC 22 mixtures, as investigated in this study, a binder content variation of 0.3 % was found. Again a variation of the fatigue life of about ± 25 % to 50 % was observed.

3.1.2 Influence of degree of compaction

The influence of the degree of compaction on the fatigue resistance was evaluated by Leutner et al. (2000) using the UCTST. For three different asphalt mixtures, i. e. AC 11, SMA 11, and AC 16, Figure 5 shows the resulting fatigue lives in function of the degree of compaction. It is observed, that a reduction of the degree of compaction from 100 % to 97 % reduces the fatigue life by more than 50 %.

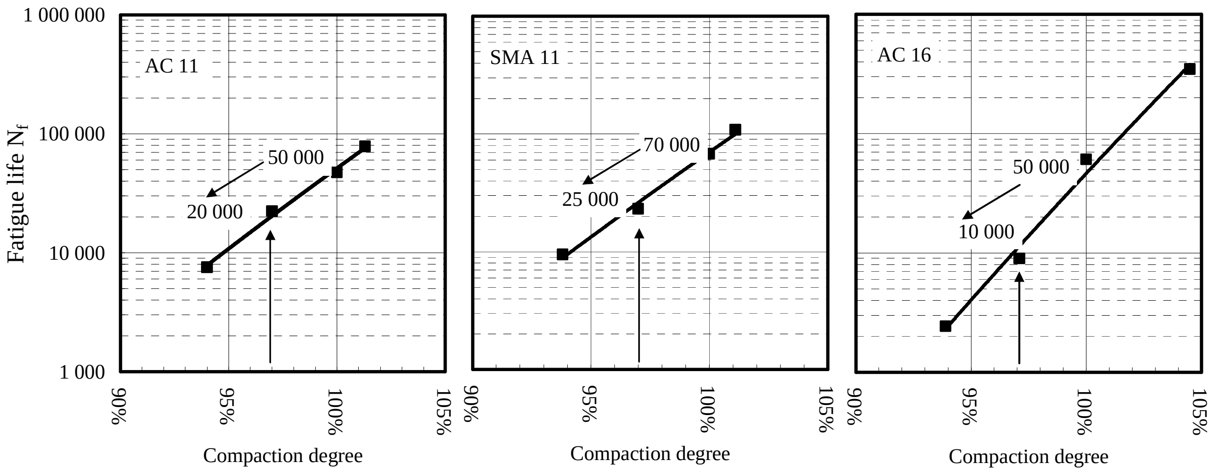

Figure 5. Influence of the compaction degree on the fatigue resistance (data source: Leutner et al., 2000).

3.2 Rutting resistance

3.1.1 Influence of binder content

In Figure 6, the influence of the binder content on rutting resistance is represented. In general, an increase in the binder content results in higher axial strains. Considering the standard deviations of the binder content according to Table 2, the measured strain varies between ± 10 % for SMA 11 mixtures up to ± 17 % for AC 11 mixture. However, the results on AC 22 mixtures indicate, that some mixtures seem to be less effected by binder content variations.

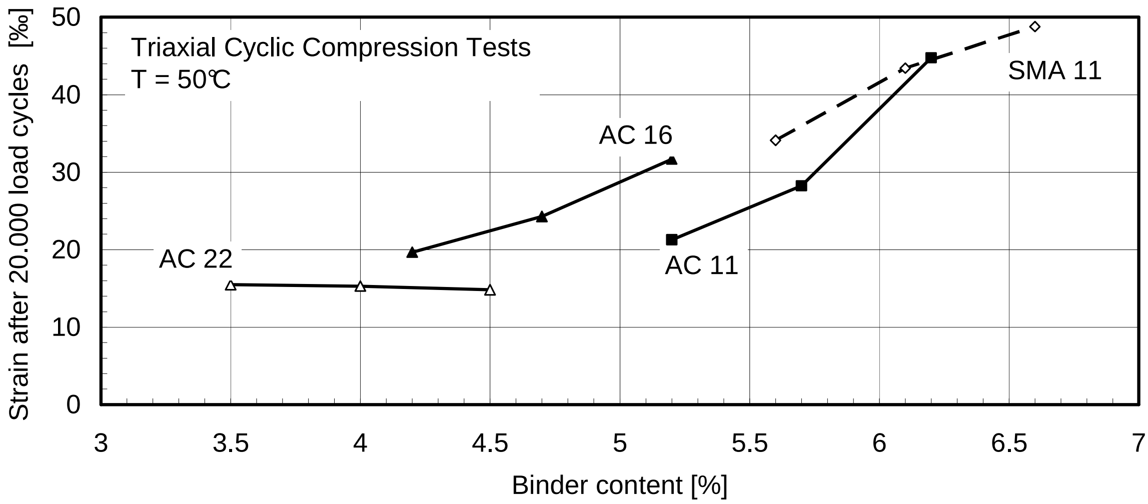

Figure 6. Influence of the binder content on the strain measured in Triaxial Cyclic Compression Tests (data source: Gauer et al., 2000)

3.1.2 Influence of degree of compaction

A variation in the degree of compaction and its effect on permanent deformation is shown in Figure 7 (Leutner et al., 2000). A low degree of compaction results in high permanent deformations. A reduction of 50 % is observed for a degree of compaction of 97 % if compared to the value obtained for a degree of compaction of 100 %.

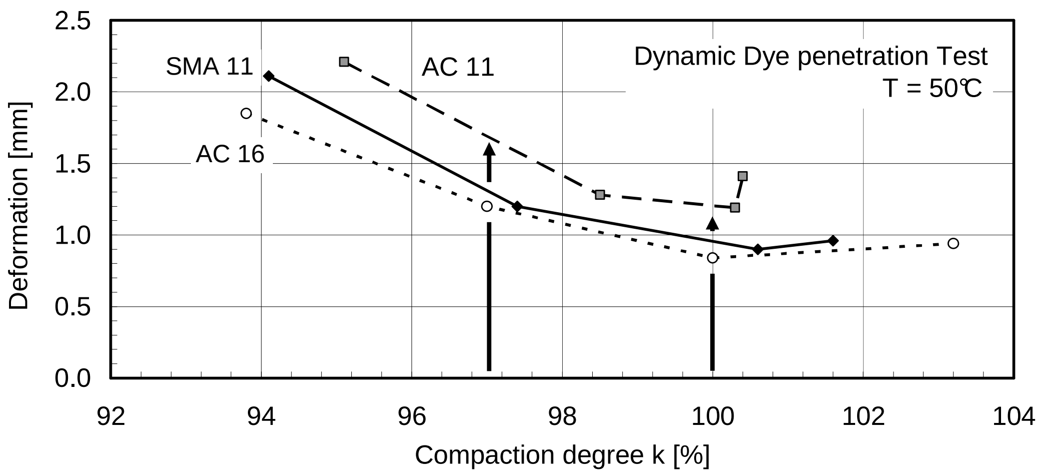

Figure 7. Influence of the compaction degree on the resistance against permanent deformation (data source: Leutner et al., 2000)

4 CONCLUSIONS

Statistical analysis of control test data derived from a huge data base indicates considerable discrepancies between the initial mix design targets and the properties of actual paved road material. Discrepancies in binder content and degree of compaction will consequently effect fundamental pavement performance properties, i. e. fatigue resistance, and rutting resistance. Based on the investigations in this study, the following conclusions can be drawn In Germany:

- It can be assumed, that more than 90 % of asphalt mixtures paved meet the requirements for the binder content. For 10 % of the mixtures, the binder content may differ from design targets by about ± 0.5 %. Mostly, the mean binder contents are observed to be slightly higher than the nominal binder contents according to the mix design.
- A (realistic) variation of the binder content of specimens subjected to cyclic laboratory loading changes the resulting fatigue life by a factor of up to ± 50 %.
- A (realistic) increase of the binder content of specimens subjected to cyclic laboratory loading increases the resulting permanent deformation (rutting resistance) by a factor of up to + 17 %.
- A (realistic) decrease in the degree of compaction from 100 to 97 % of specimens subjected to cyclic laboratory loading shortens the resulting fatigue life by a factor of up to 50 %.
- A (realistic) decrease in the degree of compaction from 100 to 97 % of specimens subjected to cyclic laboratory loading increases the permanent deformation (rutting resistance) by a factor of up to 50 %.

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