Analysis of asphalt mix performance properties considering the discrepancy between mix design and in-field realization – Part II: Effect on asphalt pavement design

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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. The outputs of this part of the study are presented in the paper Part I, which is associated to this paper.

In Part II, which is represented hereafter, the effect of these fluctuations on the mechanistic pavement design result is analysed. Therefore, the design input material parameters in terms of stiffness modulus and fatigue performance were evaluated. For this purpose, 5 asphalt base course mixes were produced with varying compositions according to the expected fluctuations and considering grading, binder content and compaction degree.

In Germany, in addition to the empiric design method of asphalt pavements, a mechanistic pavement design tool based on the linear elastic multilayer theory was recently authorized. Input data needed for the design analysis are related to weather and traffic. The appropriate materials are described in terms of material parameters assessed in fundamental laboratory tests. As a result of this study, the effect of fluctuations in material properties on the resulting design life are specified.

KEYWORDS: mechanistic pavement design, fatigue, stiffness, mix design, material property

1 INTRODUCTION

Usually, German roads are designed according to an empirical design procedure (RStO 2001) where the suitable pavement structure can be selected from a catalogue considering traffic and climate conditions.. As concerns asphalt pavements, the asphalt mix is composed in accordance with mix design specifications, but the mix design is not taken into account in the pavement design. Hence, innovative and new pavement materials can not be considered appropriately in the empiric design approach.

For encouraging the application of innovative pavement materials and innovative design concepts in road pavement design, a mechanistic pavement design procedure based on the classical fatigue design concept was recently established in Germany., The assessment of stiffness and fatigue resistance of the asphalt materials is part of the mix design study and both parameters are used as input in the mechanistic pavement design as decisive material parameters in regard to the required layer thicknesses. Therefore, the result of the mechanistic design in terms of predicted pavement lifetime is especially valid for the mix properties as derived in the mix design study.

However, asphalt mix properties may differ significantly from 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. First, the divergences between mix properties as defined in the mix design (type testing) were compared to properties of actual paved material. Then, the influence of these divergences on the material performance was estimated according to published research results. The findings of these investigations are presented to this Conference in an associated paper Part I.

In the following, the effect of fluctuations in material properties on mechanistic pavement design is discussed. For this purpose, asphalt mixtures were composed in the laboratory considering typical divergences from mix design targets. In detail, base course material of the type AC 22 T S was selected. Binder content, filler content and degree of compaction was varied in order to gain five different sub-types named AC 22-1, AC 22-2, AC 22-3, AC 22-4, and AC 22-5. By Indirect Cyclic Tensile Stress Tests the fatigue resistance of these materials was estimated and used as input-parameters for the mechanistic pavement design.

In subsequent Chapter 2, the design principles applied in Germany are shortly summarized. Chapter 3 presents design results for varied traffic conditions and the varied asphalt base course materials AC 22-1 to AC 22-5.

2 GERMAN PAVEMENT DESIGN

2.1 Empirical design procedure

German roads are usually designed according to the empirical guideline RStO issued last in 2001 (FGSV 2001). According to the specific climate conditions, the local conditions, the structural class and the sub-base of the road, the overall thickness of the pavement is determined in order to guarantee a proper transfer of loads and to avoid frost damage. The structural thickness is selected in function of the actual traffic load. From the daily values of heavy vehicle traffic, the design number of axle loads (related to 10-tonnes equivalent axle load, and corrected by factors considering road width, longitudinal slope, etc.) is calculated for a design period of 30 years and expressed by the number B (“design-relevant load”).

According to the number B, seven structural classes are distinguished, e. g., structural class SV is designed to withstand a number of more than 32 million equivalent axle loads during its design life. According to the construction class, a suitable pavement structure can be selected from the design catalogue as exemplarily depicted in Figure 1. The applied pavement materials fulfil all requirements as defined in the material specifications, like grading, binder content, and binder viscosity, and ranges of tolerance are defined always.. As long as all properties of the used pavement materials meet the mix design requirements, the structural strength of the pavement is guaranteed for the design period.

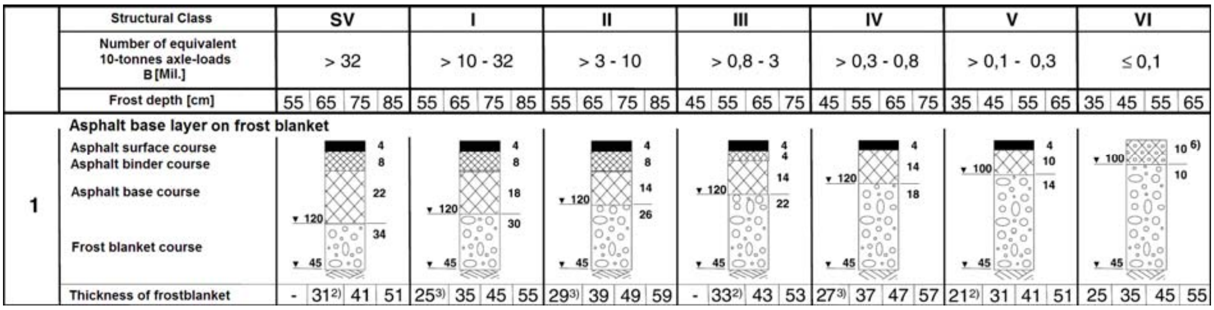


Figure 1. Extract from the German empirical design catalogue (FGSV 2001)

2.2 Mechanistic design procedure

A mechanistic pavement design procedure for asphalt pavements was recently issued in Germany (FGSV, RDO-Asphalt, 2008). Classical fatigue theory is introduced as the design principle, where fatigue damage at the bottom asphalt layer is avoided by limiting the stress at the bottom of the asphalt base course. To calculate the stresses and strains, linear elastic multilayer theory is applied. Herein, the road pavement is divided into homogeneous sub-layers. Each sub-layer is described by the parameters thickness, elastic modulus, Poisson's ratio and bonding to the underlying layer. Hence, the properties of the pavement materials are directly considered in the design process.

Due to the iterative mechanistic design approach, the actual traffic conditions and the temperature conditions in the pavement can be considered in more detail. Heavy vehicle load exposure is represented by a number of 11 load classes representing axle loads between 2 tonnes and 22 tonnes. The frequency distribution of a load class is selected in regard to the road category (SV for heaviest loads; I, II, III, … for lighter loads).

Temperature exposure occurring during the year is represented by a number of 13 surface temperature classes. Each surface temperature is associated with a temperature development within the pavement, which can be calculated by classical law of heat transfer. As a result, 13 typical pavement temperature distributions were derived, each with a specific annual distribution of frequency. A typical distribution of the frequency of occurrence can be seen in Figure 2. Thus, every asphalt sub-layer can be associated with a constant temperature. For each surface temperature class, the layer properties of the individual sub-layers are kept constant which allows the calculation of the horizontal bending tensile strain ε at the bottom of the asphalt layer. For one specific geometrical pavement model, the design process covers a total number of 143 individual models, resulting from 13 temperature cases times 11 load cases.

Results of Indirect Cyclic Tensile Stress Tests (IDT) are used to estimate the number of load cycles which can be endured without any material failure. From these tests a fatigue equation is derived incorporating the parameter *a* and the exponent *k* (cp. Chapter 3.2). Any difference from laboratory test to real pavement conditions is covered by a shift factor SF as well as a safety factor F. For each of the 143 calculated strain values ε, the maximum allowed number of load cycles is calculated from Equation 1.

$$zul\,N = \frac{SF}{F} \cdot a \cdot \varepsilon^{k} \qquad (1)$$

where:	zul N	maximum number of load cases
	a	material parameter, determined by regression from fatigue tests
	ε	elastic strain (layered elastic theory)
	k	material parameter, determined by regression from fatigue tests
	SF	shift-factor (for IDT SF = 1 500)
	F	safety-factor (here F = 1.5)

Hypothesis of MINER is used to estimate accumulation of fatigue damage (Equation 2). Resistance to fatigue macro cracking is given as long as the sum of the partial damages is less than or equal to one.

$$\sum_{MINER} = \frac{vorh\ldots N_a}{zul\ldots N_a} + \frac{vorh\ldots N_b}{zul\ldots N_b} + \frac{vorh\ldots N_c}{zul\ldots N_c} + \ldots.. + \frac{vorh\ldots N_n}{zul\ldots N_n} \leq 1 \qquad (2)$$

Note: Any effects of the sub ground and of the unbound base layers on the design result are left disregarded in this study. Information on these factors are found in the German pavement design guide (FGSV, RDO Asphalt, 2008), and in Werkmeister et al. (2006), and Kayser & Wellner (2009).

3 PAVEMENT DESIGN ANALYSES

For the pavement design analyses in this study, four road sections located in Lower Saxony, Germany, are considered. A motorway section BAB 2 (structural class SV acc. RStO (FGSV 2001)) and 3 federal road sections B 4 (structural classes I), B 1 (structural class II), and B 248 (structural class III) are covered. For these road sections, the average daily traffic and the percentage of heavy vehicles as measured during the year 2005 are summarised in Table 1.

3.1 Empirical pavement design

By assuming an average increase of heavy traffic and considering a design period of 30 years, the number of equivalent 10-tonnes axle loads is calculated. By applying the empirical design procedure (FGSV 2001), the roads can be classified into the structural classes SV for the motorway section and I, II and III for the federal road sections. For the B numbers see Table 1. As concerns the climatic conditions of Lower Saxony, the frost depth is 75 cm (65 cm for the B 248 section).

A suitable design pavement can be selected from the empirical design catalogue exemplarily represented in Figure 1. For the motorway section BAB 2 the structural layers are derived as follows:

- Asphalt surface course: 4 cm
- Asphalt binder course: 8 cm
- Asphalt base course: 22 cm
- Frost blanket course: 41 cm (= 75 cm (frost depth) – 34 cm (Asphalt courses))

Table 1: Input for design analysis and results of the empirical design procedure

Road section	**Motorway**	**Federal road**		
	BAB 2	**B 4**	**B 1**	**B 248**
vehicles per 24 hours	82,838	15,908	7,968	6,470
heavy traffic percentage [%]	22.1	18.7	7.7	6.4
annual increase of heavy traffic [-]	0.03	0.02	0.01	0.01
design period [a]	30	30	30	30
Pavement design input:				
Number of equivalent 10-axle loads [Mil.]	156.2	16.1	3.0	2.6
Structural class	SV	I	II	III
Frost depth [cm]	75	75	75	65

The construction materials used must fulfil the requirements according to the relevant specification documents. As concerns the asphalt mix design, the actual performance quality of the asphalt mix is not further specified for the empirical design procedure.

3.2 Fluctuations in material properties

In the empirical design, any fluctuations in material properties are left disregarded. However, such fluctuations may influence pavement life significantly. In the frame of this study, the potential discrepancy between the mix properties as defined in the mix design and as realized on the construction site was analyzed. For this purpose, , 5 variations of asphalt base course material of the type AC 22 were mixed and compacted in laboratory, as this is the most common base course asphalt material in Germany. The variations cover potential fluctuations as observed in real pavement construction projects. From this Table 1 summarises the material properties of the 5 asphalt mix variations.

For the assessment of potential fluctuations, 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 contained results of check tests from construction sites on highways, federal highways and country roads since 1996. A total number of 40,900 mix analyses and 27,800 core samples of construction projects throughout Lower Saxony were included. Details on the statistical analysis to derive potential material fluctuations are published in the associated paper Part I.

The differences of the 5 asphalt mixes are as follows:

- AC 22-1: according to the mix design (standard compaction properties),
- AC 22-2: according to the mix design, but less compacted than AC 22-1,
- AC 22-3: according to the mix design, but stronger compacted than AC 22-1,
- AC 22-4: “worst-case mix”: low binder content, less fine aggregates, standard compaction properties,
- AC 22-5: “best-case mix”: high binder content, more fine aggregates, standard compaction properties

Table 2: Mix design characteristics of the generated AC 22 variants

Characteristics of asphalt mixtures		**AC 22-1**	**AC 22-2**	**AC 22-3**	**AC 22-4**	**AC 22-5**
binder type				50/70		
binder content (mix design)	B [M.-%]		3,6		3,2	4,3
binder content (actual)	B [M.-%]		3,9		3,4	4,4
maximum density	ρ_m [g/cm³]		2,537		2,567	2,522
softening point ring and ball	$T_{R\&B}$[°C]		57,1		55,2	54,4
reference bulk density (Marshall method)	ρ_{bdim} [g/cm³]		2,401		2,352	2,425
void content (reference specimen)	V [%]		3,4		6,5	1,9
Characteristics of specimens						
compaction degree (actual)	k [%]	99,9	97,0	101,2	100,5	99,9
void content (actual)	V [Vol.-%]	5,5	8,2	4,3	7,9	4,0

From these mix properties the stiffness modulus was calculated by the method established by Francken & Verstraeten (1974). The result of this calculation is depicted in Figure 2. For the use in the German mechanistic design procedure the stiffness moduli as calculated for a loading frequency of f = 10 Hz are applied. For the multi-layer elastic model, the stiffness of the various layers are calculated according to their mean temperature for each of the 13 surface temperature cases. By using multi-layer elastic theory the bending strain ε at the bottom of the asphalt base course is calculated.

For deriving the fatigue characteristics needed for the mechanistic design procedure, Cyclic Indirect Tensile Stress Tests (IDT) were conducted (comp. Werkmeister et al., 2006). Thereby, a cylindrical specimen is loaded with a sinusoidal compressive force applied vertically to the lateral area of the specimen. This provokes a stress contribution with a horizontal tensile loading of the specimen. By measuring the evolution of the horizontal diameter, sinusoidal strain reaction can be derived from the test. In the fatigue test the specimen is loaded in controlled force-mode until failure. Nine single IDT are evaluated by plotting the number of load cycles until failure $N_{failure}$ versus the measured strain difference of the sinusoidal strain signal at the beginning of the test. As depicted in Figure 3, the test results can be fitted by a power-law function. Parameter a and exponent k are directly applied in the pavement design calculation (cp. Equation 1).

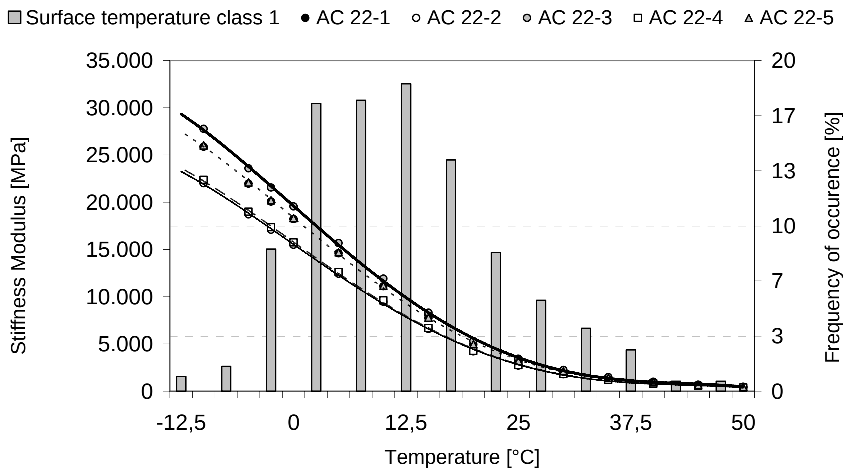
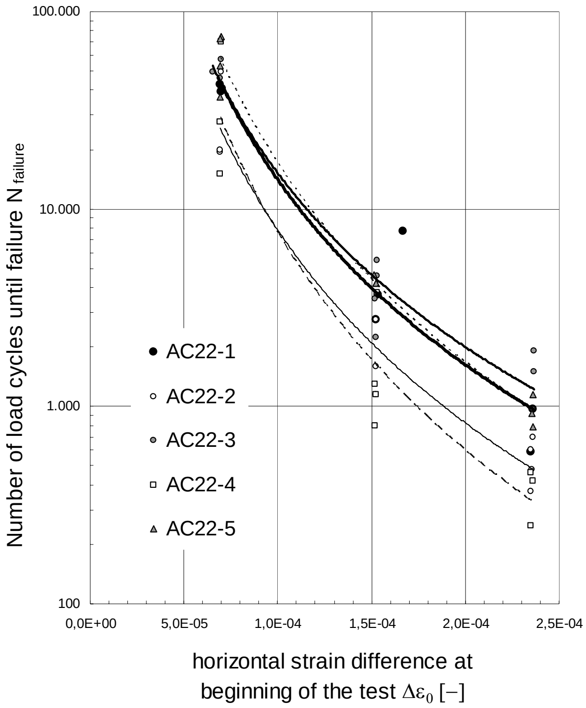
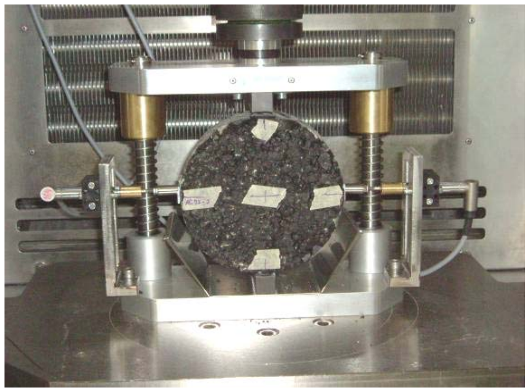


Figure 2. Stiffness modulus as a function of temperature for a frequency of f = 10 Hz as calculated according to Francken & Verstraeten (1974) and frequency of occurrence of the surface temperature class 1 for the analyzed pavements.





	a	k	R^2
AC 22-1	4,912 E-09	-3,114	0,933
AC 22-2	8,269 E-10	-3,244	0,954
AC 22-3	3,018 E-08	-2,925	0,956
AC 22-4	1,779 E-11	-3,657	0,914
AC 22-5	6,953 E-10	-3,347	0,986

Figure 3: Results of Cyclic Indirect Tensile Stress Tests and derived fatigue functions used in this study.

3.3 Mechanistic pavement design results

Pavements in the four road sections were mechanistically designed by varying only the asphalt base course material according to the potential material fluctuation. The results of the design calculations are summarized in Table 3

The results of mechanistic design is compared to empiric design in Figure 4. For the asphalt base course materials AC 22-1, AC 22-3 and AC 22-5 the sum of Miner reaches values below 1, indicating a longer actual service life than 30 years. On the other hand, the sum of Miner, calculated for AC 22-2 and AC 22-4 exceeds the value 1, and hence, early fatigue failure is expected.

Table 3: Results of the mechanistic design procedure on four pavement structures by varying the asphalt base course material

Asphalt base course	Layer thickness according to the empirical design (see Figure 1)								Results of mechanistic design			
	Σ Miner [-]				theoretical service life [a]				required thickness [cm]			
	road section				road section				road section			
	BAB2	B4	B1	B248	BAB2	B4	B1	B248	BAB2	B4	B1	B248
AC 22-1	5,02	1,60	0,73	0,87	9	22	37	33	33	21	13	14
AC 22-2	12,26	3,99	1,85	2,32	4	11	20	17	40	26	18	18
AC 22-3	4,22	1,29	0,56	0,63	10	26	43	41	32	20	12	12
AC 22-4	12,53	4,53	2,35	3,24	4	10	17	13	37	26	18	19
AC 22-5	4,01	1,36	0,66	0,85	11	25	39	34	31	20	13	14

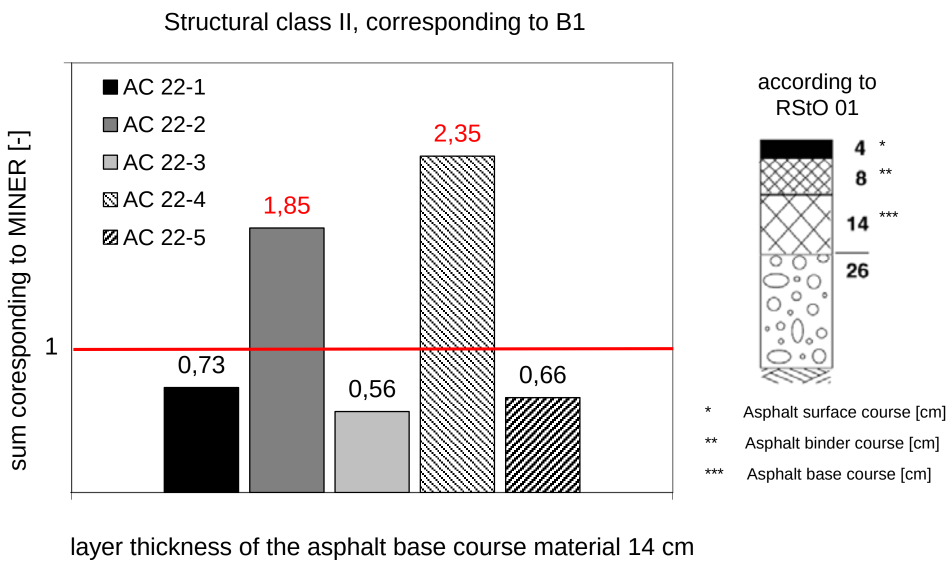


Figure 4. Design fatigue life, expressed by Miner's law, for different asphalt base course materials AC 22-1 to AC 22-5 and for an assumed design life of 30 years.

Differences can also be expressed in terms of design life time, as shown in Figure 5. The variant AC 22-2 with a low compaction degree reduces life time by a factor between 62 % and 48 % compared to the mix design material AC 22-1. A better compaction will lead to a longer life, as indicated by the results for AC 22-3 where the theoretical life time is improved by 11 % up to 25 % compared to AC 22-1. The theoretically life time of variant AC 22-4 (low binder content) is shortened between 55 % and 65 % while AC 22-5 (high binder content) is extended between 2 % and 28 %.

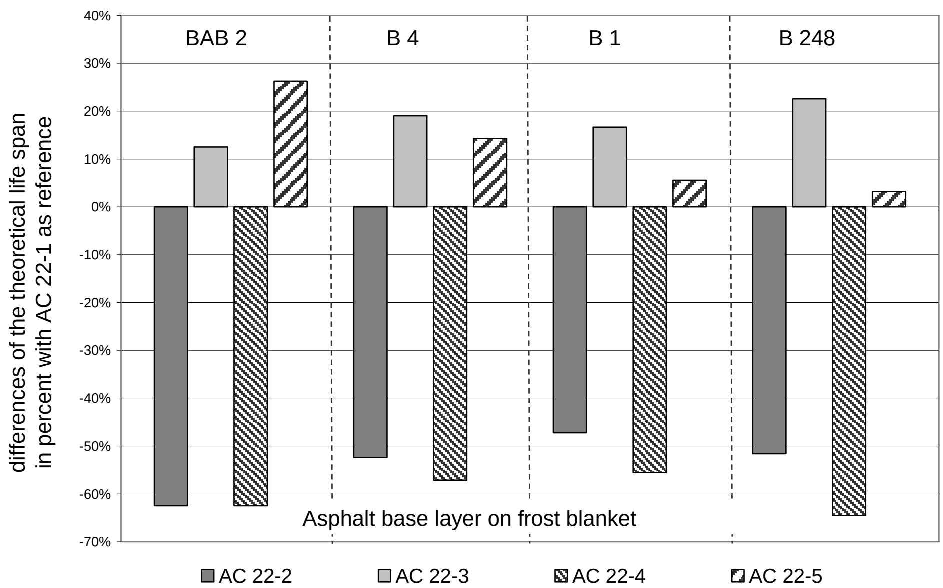


Figure 5. Differences of the theoretical life time in percent of the AC 22 variants.

Figure 6 summarizes the results of the empiric and mechanistic design calculations. It is observed, that for road section B 1 (structural class II) the variants AC 22-1, AC 22-3, and AC 22-5 are well designed for the aspired design life of 30 years. Road sections BAB 2, B 4 and B 248 (structural classes SV, I and III) show divergences to some extent. In order to achieve the durability of 30 years the design thickness can be changed by iterative design calculations.

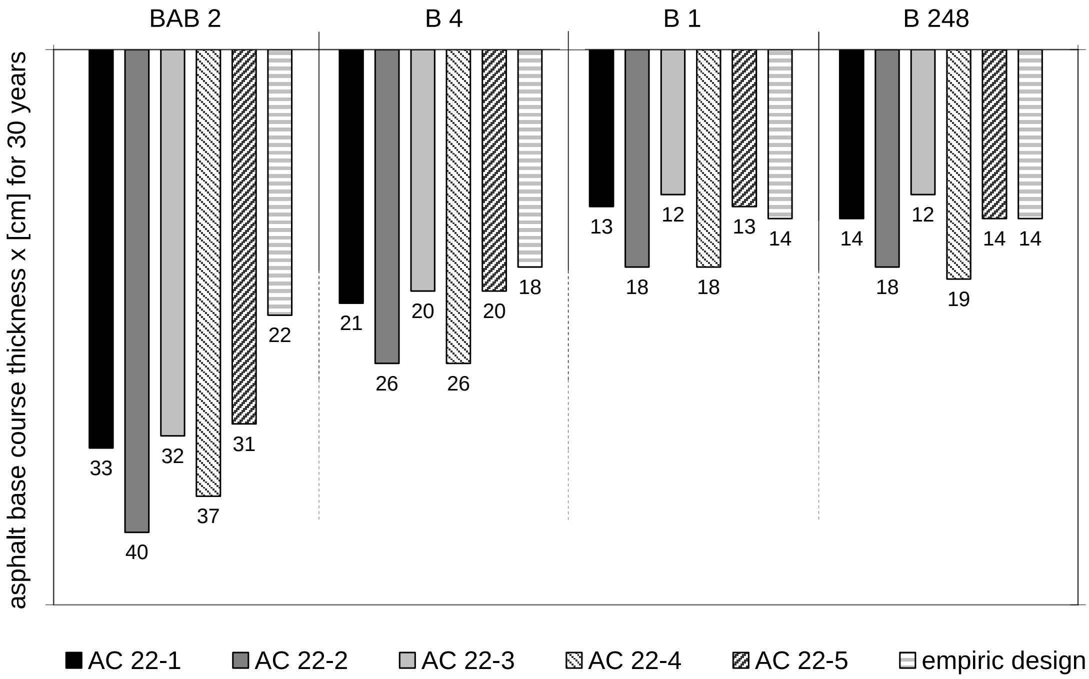


Figure 6. Results of the mechanistic design: Required thicknesses for the asphalt base layer for an aspired design life of 30 years.

4 CONCLUDING REMARKS

Material parameters are important inputs to mechanistic pavement design. They are determined in laboratory tests, usually during mix design tests. However, the actual built-in materials differ in their composition to some extent from design targets. Within a certain range, an increasing binder content and an increase in fines aggregates influences the fatigue resistance in a positive, the deformation resistance in the negative way. The same behavior can be detected with an increase in the binder viscosity at low temperatures. The degree of compaction influences both the fatigue resistance and the deformation resistance.

The mechanistic design process allows the consideration of the specific material properties and potential fluctuations in the material properties. This may influence the design decisions. Materials that exhibit a high quality improve the structural strength of the pavement. Therefore they can be performed with a reduced thickness compared to standard materials. Furthermore, the lifetime prognosis of innovative design procedures and new materials can improvingly be assessed.

ACKNOWLEDGEMENT

The German Federal Ministry or Traffic, Building and Urban Development and the Bundesanstalt für Straßenwesen (BASt) is acknowledged for funding this study. Special thanks go to the Road and Transport Authority of Lower Saxony for providing comprehensive data.

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