Design of bituminous pavements in Austria - a mechanistic approach

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ABSTRACT

The objective of pavement design is to develop pavement constructions, which are able to resist appearing traffic loads and climatic conditions during the intended life time. The concerning regulations and standards in Austria are based on semi-analytical models to describe the mechanical response to these loads. As, thereby, standard constructions are derived for 7 load classes and 8 pavement types, neither actual data concerning traffic load, nor performance related material characteristics like stiffness or fatigue behavior of the hot mix asphalt (HMA) used can be considered leading to significant design reserves. Hence, a mechanistic design approach for bituminous pavements in Austria was developed, recently, and is expected to be released as a new national standard. Thereby, statistically derived model parameters or actually measured input parameters (traffic loads, HMA stiffness behavior, HMA fatigue behavior) or a combination of both are taken into account. The possible consideration of the advantages in mechanical behavior of modern bituminous mixtures not only allows more economic design results but also leads to the efficient use of bitumen, a crude oil product with decreasing availability.

Keywords: Design of pavement, Economics, Fatigue Cracking, Stiffness

1. INTRODUCTION

The objective of pavement design is to plan pavements, which are able to resist appearing loads during the intended life time. This implies that stresses and strains within the constructions emerging in the bituminous layers due to traffic and climatic conditions do not exceed certain limits. Failure due to fatigue is commonly regarded as relevant for pavement design. Hence, criterions describing the fatigue behavior exist, which link the technical life time to significant stresses or strains within the construction appearing, in general, either as tensile load at the bottom of the bituminous base course or as compressive load at the top of the subgrade. For bituminous layers, for example, single cracks emerging at the bottom of the base course and growing to the surface are regarded as relevant for the structural fatigue of the pavement. At the surface, these single cracks lead to so-called alligator cracking and, hence, decreasing bearing capacity of the pavement construction.

The design of bituminous pavements in Austria is regularized by the national standard RVS 03.08.63 [1] that provides a design catalogue specifying standard constructions for 7 load classes and 8 pavement types. Traffic relevant parameters like the average annual daily truck traffic (AADTT) are taken into account to chose one of these standard constructions, which are derived considering generally valid physical and mechanical principles to describe the reaction of the pavement on external loads (e.g. traffic, climatic conditions) on the basis of semi-analytical models [2-4].

This design approach allows for a simple and fast selection of the pavement construction to be built. As a design catalogue of standard constructions is provided, significant restrictions regarding the consideration of mechanical properties of the used material as well as the detailed composition of the traffic arise implying that significant design safety factors have to be ensured.

2. MECHANISTIC DESIGN OF BITUMINOUS PAVEMENTS

To meet the demand for a design method able to take performance related material behavior of modern HMA types into account, a new mechanistic design method for bituminous pavements in Austria is introduced [5], which not only allows for reducing necessary safety factors, and hence more economic pavements. Additionally, the implementation of a performance related description of material characteristics should stimulate innovation regarding the development of new binders and bituminous mixtures meeting the demands of modern asphaltic roads.

2.1 Design approach

The design process is performed according to the limit state of serviceability. Hence, the number of load cycles the pavement is able to resist, N_{res} (resistance), is related to the expected number of passages during the design life, N_{imp} (impact), by

$$\frac{N_{imp}}{N_{res}} \leq 1 \qquad (1)$$

The expected number of passages, N_{imp}, depends on the number of heavy good vehicles (HGV) predicted to pass the pavement expressed as AADTT (average annual daily truck traffic), a factor V related to the distribution of vehicles to several lanes, a factor S respecting the loading distribution of vehicle tracks within one lane, the design life n in years and a growth factor z, yielding

$$N_{imp} = AADTT \cdot V \cdot S \cdot 365 \cdot n \cdot z \qquad (2)$$

with

$$z = \frac{q^n - 1}{n(q - 1)} \qquad (3)$$

where q = 1 + p/100, and p denotes the annual traffic growth rate in %.

The number of load cycles the pavement is able to resist, N_{res}, is determined on the basis of general physical and mechanical principles, which describe the response of the pavement construction to load due to traffic and climatic conditions. Thereby, design levels for the input parameters (traffic load, mechanical stiffness and fatigue behavior) depending on the availability of traffic data or experimental results are introduced allowing for a more economic design as necessary safety factors may be reduced with increasing accuracy of the determination of the input parameters.

Considering the input parameters, the linear elastic multi layer analysis according to Burmister [6] and the modified shear stress hypothesis according to Leon [7, 8] are applied to determine resulting stresses and strains. Thereby, twelve temperature periods – providing nearly constant climatic conditions during each period – are introduced (see Section 2.3).

Considering a fatigue criterion (see Section 2.5) the number of load cycles N_{ijk} the pavement is able to resist can be determined for each axle i of each vehicle j and each temperature period k. While the corresponding damage C_{ijk} yields

$$C_{ijk} = \frac{1}{N_{ijk}} \tag{4}$$

the average damage C_{res} is provided by

$$C_{res} = \sum_{i} \sum_{j} \sum_{k} p_j \cdot p_k \cdot C_{ijk} \tag{5}$$

with p_j as the appearance probability of vehicle j on the HGV traffic volume and p_k as the relative duration of temperature period k during one year. Hence, the number of load cycles the pavement is able to resist, N_{res}, is reading as

$$N_{res} = \frac{1}{C_{res}} \tag{6}$$

2.2 Relevant traffic load

Information about the volume and composition of heavy traffic is essential for reliable pavement design. In Austria, detailed information about the volume of heavy traffic on highways is available from records gained from automatic road toll stations, while other roads are monitored by frequently conducted traffic counting. While these data is obtained regularly, distributions of vehicle types, gross weights and axle loads are determined only sporadically and point-wise (e.g. weight-in-motion measurements). Hence, three traffic design levels according to Table 1 can be distinguished.

Table 1: Traffic design levels for consideration of traffic load [5]

Traffic design level	HGV volume	Probability of appearance of HGV types	Distribution of HGV gross vehicle weights	Distribution of HGV axle loads
1	*available*	*not available*	*not available*	*not available*
2	*available*	*available*	*not available*	*not available*
3	*available*	*available*	*available*	*available*

While traffic design level 1 implies that only HGV traffic volume data from road tolls or traffic volume counting is available and characteristic distributions of vehicle types, gross weights and axle loads representative for the heavy traffic in Austria can be applied (see [5] for details), the actual distribution of HGV types within the considered road section is accessible from detailed traffic counting at traffic design level 2 and only characteristic distributions of gross weights and axle loads have to be used. At traffic design level 3, actual data of traffic volume, vehicle gross weight and axle load distributions from e.g. weight-in-motion measurements are needed. Hence, traffic loads can be taken into account as realistic as possible and, therefore, safety factors can be reduced to a minimum, since no derived characteristic distributions have to be applied.

2.3 Consideration of subgrade bearing capacity and HMA temperature

Subgrade bearing capacity strongly depends on local climatic and hydrological conditions. Hence, 4 periods within a year with differing subgrade modulus are distinguished. While the bearing capacity reaches a maximum in winter, when the soil is frozen, the subgrade modulus decreases to a minimum in spring, when the ice in the soil is thawing.

The bearing capacity of unbound layers depends on the quality of the material it is made of, its thickness and the modulus of the layer beneath. Therefore, functions are given, which provide the bearing capacity depending on these parameters.

Due to the climatic conditions in Austria, fluctuations of the temperature in bituminous layers occur leading to varying

HMA stiffness during a year. Hence, a temperature model based on long-term analysis of wind speed as well as air and HMA temperature (presented in [4]) is introduced to the design method. This model distinguishes 12 temperature periods during a year with nearly constant climatic conditions and provides realistic temperature distributions within the bituminous layers for each of these periods.

2.4 Realistic consideration of HMA stiffness behaviour

Due to the fact that the stiffness behavior of the pavement layers plays a crucial role when it comes to determine resulting stresses and strains in the pavement construction the applied assumptions to determine HMA stiffness $S_{mix}(T,f)$ strongly influences the design result. To estimate the temperature, T, and frequency, f, dependent $S_{mix}(T,f)$ (in MPa) a Hirsch-type material model [5, 9] is used (see Equation (7) and (8)). Thereby, the volumetric composition of the mixture (in terms of voids in the mineral aggregate, VMA (in vol-%), and voids filled with binder, VFB (in vol-%)) and the binder shear stiffness, $|G^*_{bin}|(T,f)$, (in MPa). The parameters a, b, c and d depend on the type of bitumen used (unmodified or polymer-modified bitumen) and the assumed failure probability (as an indicator for the provided safety factors) and were derived from the results of around 1500 stiffness tests conducted on mixtures typically used in Austria (see [5] for details).

$$\left|S_{mix}\right|(T,f)=\frac{p_c}{145{,}0377}\left[a\left(1-\frac{VMA}{100}\right)+145{,}0377\cdot 3\left|G^*_{bin}\right|(T,f)\left(\frac{VFB\cdot VMA}{10.000}\right)\right]+\frac{(1-p_c)}{145{,}0377}\left[\frac{1-\dfrac{VMA}{100}}{a}+\frac{VMA}{VFB\cdot 145{,}0377\cdot 3\left|G^*_{bin}\right|(T,f)}\right]^{-1} \qquad (7)$$

with

$$p_c=\frac{\left(b+\dfrac{VFB\cdot 145{,}0377\cdot 3\left|G^*_{bin}\right|(T,f)}{VMA}\right)^{c}}{d+\left(\dfrac{VFB\cdot 145{,}0377\cdot 3\left|G^*_{bin}\right|(T,f)}{VMA}\right)^{c}} \qquad (8)$$

So, HMA stiffness design levels are introduced to be able to consider the stiffness behavior of the bituminous mixture actually used. According to Table 2, three levels can be distinguished, where the level of detail increases with increasing experimental effort, while necessary safety factors decrease.

Table 2: Stiffness design levels for consideration of realistic mechanical behaviour [5]

Stiffness design level	HMA volumetric composition	$\|G^*_{binder}\|(T,f)$ conducted in DSR tests (EN 14770)	HMA stiffness S_{min} @20°C (EN 13108-1)
1	*available*	*not available*	*not available*
2	*available*	*available*	*not available*
3	*available*	*not available*	*available*

As only the volumetric composition of the bituminous mixture used is known at stiffness design level 1, $|G^*_{bin}|(T,f)$ is approximated by the mechanical behavior in terms of a mastercurve at a reference frequency of 8 Hz (corresponding to a vehicle speed of 80 to 100 km/h) of a characteristic model binder, which was derived from an experimental dataset of around 1600 dynamic shear rheometer (DSR) test results, to determine $S_{mix}(T,f=8Hz)$ from Equation (7) and (8). Thereby, $|G^*_{bin}|(T,f=8Hz)$ for two bitumen types can be distinguished: (i) an unmodified bitumen (based on paving grade bitumen *pen 70/100*), and (ii) a polymer-modified binder (based on *PmB 45/80-65*). Since only the volumetric composition of the HMA mixture actually used is considered, significant safety factors have to be ensured.

With the stiffness behavior $|G^*_{bin}|(T,f=8Hz)$ of the actually used bitumen conducted in DSR tests according to EN 14770 [10] and the volumetric composition of the mixture at hand at stiffness design level 2, the Hirsch-type model in Equation (7) and (8) can be applied to estimate HMA elastic modulus $S_{mix}(T,f=8Hz)$. Thereby, the mastercurve should be evaluated at a reference frequency of 8 Hz as well.

Is the minimum stiffness modulus S_{min}@20°C (according to EN 13108-1 [11]) conducted in four point bending beam stiffness tests at 20 °C (according to EN 12697-26 [12]) declared by the manufacturer (according to EN 13108-20 [13]), stiffness design level 3 can be applied. S_{min}@20°C (in MPa) is used to adjust the temperature dependent results of the Hirsch-type model by multiplying Equation (7) by

$$F_S = \frac{S_{min}@20°C}{S_{mix,p}} \tag{9}$$

where $S_{mix,p}$ is a statistically verified stiffness (in MPa).

2.5 Consideration of HMA fatigue behaviour

The fatigue behavior of HMA – or in other words – the correlation between the number of load cycles N a pavement is able to resist and the stress induced by traffic loading for each axle i of each vehicle j and each temperature period k can be described by

$$N_{ijk} = \frac{k_1(T)}{F(\varepsilon_6)} \cdot \left(\frac{S_{mix,k}(T,f)}{\sigma_{e,ijk}} \right)^{k_2(T)} \tag{10}$$

with the temperature dependent elastic modulus of the mixture $S_{mix}(T,f)$, an equivalent one-dimensional stress state σ_e according to Leon (see [5, 7, 8] for details) and the fatigue parameters $k_1(T)$, $k_2(T)$ and $F(\varepsilon_6)$. While $k_1(T)$ and $k_2(T)$ are defined as

$$\begin{aligned} k_1 &= 10^{-(0.0077\times T^2 - 0.4859\times T + 17.602)} \\ k_2 &= 0.0015\times T^2 - 0.0875\times T + 6.1803 \end{aligned} \tag{11}$$

with the temperature T (in °C), the parameter $F(\varepsilon_6)$ depends on the performance-based fatigue parameter ε_6 according to EN 12697-24 [14] and can be determined by

$$F(\varepsilon_6) = 1.6833 - 0.5256 \cdot \left(\frac{\varepsilon_6}{100} \right). \tag{12}$$

Figure 1 shows the derivation of ε_6 from fatigue tests on HMA specimen (AC22 binder PmB 45/80-65) on the basis of four point bending beam test according to EN 12697-24 [14]. The results of single tests performed at 3 different strain levels (a minimum of 6 tests at each strain level) are analyzed in terms of a Wöhler curve, that provides ε_6 as strain (in µm/m), at which a prismatic specimen is able to resist 10^6 load cycles. Thus, a higher value for ε_6 implies a greater resistance against fatigue failure. According to EN 13108-1 [11], minimum requirements regarding the performance-based material behavior are defined. For bituminous base courses in Austria, ε_6 has to fulfill either $\varepsilon_6 \geq 130$ µm/m or $\varepsilon_6 \geq 190$ µm/m depending on the expected traffic load, when performance-related parameters are postulated.

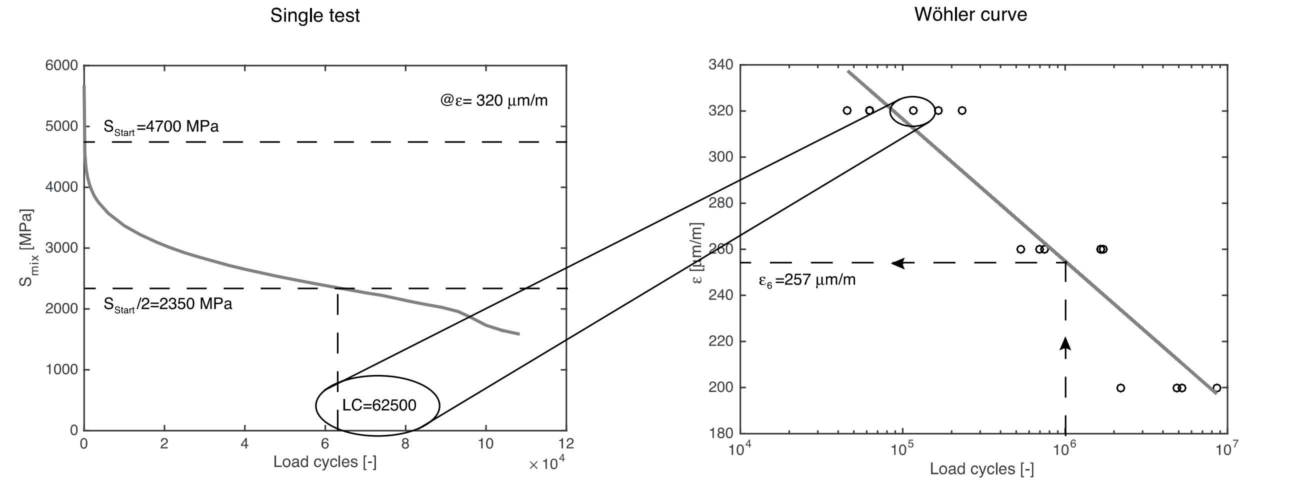

Figure 1: Derivation of ε_6 on the basis of four point bending beam fatigue tests at 20°C and 30 Hz

3. COMPARISON OF STANDARD AND MECHANISTIC PAVEMENT DESIGN

Using mechanistic pavement design allows for a detailed description of input parameters. Hence, necessary safety factors can be decreased, while technical lifetime, which can be taken into account for economic efficiency evaluation, can be increased. To illustrate that the results of the currently used pavement design method according to RVS 03.08.63 [1] and the new mechanistic approach should be compared.

Thereby, a road section with a traffic volume of AADTT= 2.200 HGVs/24h is considered. The bituminous base course should consist of asphalt concrete AC22 (VMA = 20,4 vol-%, VFB = 63,3 vol-%) with a polymer-modified binder (*PmB 45/80-65*), which fulfills the requirements for $\varepsilon_6 \geq 190$ µm/m according to EN13108-1 [11]. Four point bending beam stiffness and fatigue tests conducted on this material deliver the performance-based parameters S_{min}= 4.500 MPa and $\varepsilon_6 = 250$ µm/m. Assuming a design life of 20 years and an annual traffic growth of 3%, pavement design according to the design catalogue in RVS 03.08.63 results in a pavement construction consisting of a 30 cm thick unbound lower base course, a 20 cm thick unbound upper base course and a 23 cm thick bituminous layer, independent of the used bituminous material.

Using mechanistic pavement design, the traffic information given above allows for applying traffic design level 1, which provides representative distributions for the appearance of HGV types, the gross vehicle weights as well as the axles loads. As the volumetric composition of the HMA and the use of a polymer-modified binder are known, stiffness design level 1 is available and the Hirsch-type model in Equation (7) predicts the temperature-dependent stiffness behavior of the HMA considering a (polymer-modified) model bitumen. The used HMA fulfills the requirements for $\varepsilon_6 \geq 190$µm/m, with which the Parameter $F(\varepsilon_6)$ can be determined. Considering these input parameters, the mechanistic approach predicts a design life of 22 years for the considered pavement construction.

As the performance related material parameter S_{min} is known, stiffness design level 3 can be applied and the stiffness predicted by Equation (7) can be multiplied by F_S. Considering traffic design level 1 as well as $\varepsilon_6 \geq 190$ µm/m, a design life of 25 years is estimated.

The characterization of the fatigue behavior in terms of $\varepsilon_6 = 250$ µm/m allows for taking the fatigue behavior of the mixture actually used into account by determining $F(\varepsilon_6)$. Considering traffic design level 1 and stiffness design level 1, mechanistic pavement design results in design life of 26 years for the examined pavement construction.

The predicted design lives are compared in Figure 2. Applying the mechanistic approach results in an increase of technical lifetime of up to 30 % compared to traditional design methods. Hence, the detailed characterization of material properties leads to a more effective design. Assuming a specific (technical) life span, the consideration of performance-based material properties leads to more economic pavement design in terms of reduced layer thicknesses.

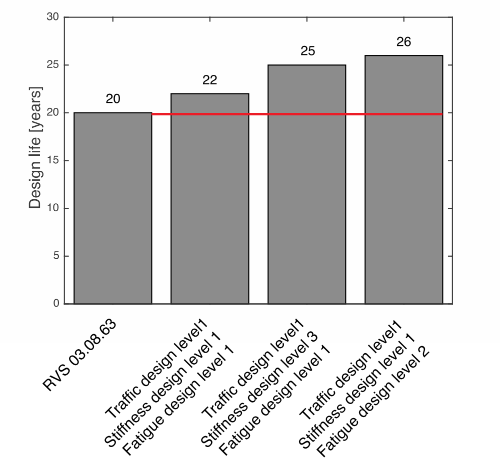

Figure 2: Comparison of design results

4. CONCLUSIONS

Pavement design in Austria is currently based on a design catalogue specifying standard constructions [1], which can be chosen depending on traffic related parameters like the average annual daily truck traffic (AADTT). This approach allows for a simple and fast choice of the construction to be built but is not able to take actual parameters like detailed traffic information (appearance of vehicle types, axle loads,…) or mechanical behavior (stiffness and fatigue properties) of the hot mix asphalt (HMA) used in the bituminous base course into account.

To resolve these limitations, a mechanistic approach for the design of bituminous pavements in Austria was developed. Thereby, design levels for important parameters are introduced, which allow for the consideration of actual details regarding traffic or results of material testing for the road section to be planned. With increasing detail, also the experimental effort related to the identification increases but necessary safety factors decrease allowing for more economic constructions.

The presented approach allows for modern, performance related and economic design of bituminous pavements and is expected to be published as a new Austrian standard.

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