Design Of Flexible Pavement Layers

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Abstract

Several research projects realized by the Chair of Pavement Engineering at the Dresden University of Technology aim at the development of an analytical design method comprising a multitude of factors effecting the pavement condition. The stress and strain behaviour of a pavement can be predicted or the remaining life cycle of the pavement structure is calculated by means of such a method. These advantages are especially important regarding warranty claims. The developed dimensioning model is based on the fundamental idea of freely choosing any possible construction (flexible pavement). In this way a particular pavement structure can be set depending on layer thickness and layer material. Furthermore the dimensioning model aims at the optimisation of the pavement construction considering traffic loading and weather-induced factors. Using different materials the particular thickness of each layer is optimised on the basis of failure hypotheses. The described approach is illustrated by a calculation comparing various constructions and examining separately cracking and rutting as the two main reasons for material failure.

On the basis of the calculation example relevant influence parameters (layer thickness, resilient modulus of unbound base layers, material composition) are determined and the general feasibility of the method is shown. The calculation results exhibit a suitable first approximation considering all simplifications made during the approach. In the first place the results are used for a qualitative evaluation of the described parameters.

Additionally the article gives a short overview of the current research work at the Chair of Pavement Engineering at the Dresden University of Technology especially about the research project “Sustainable Development of Pavements”, which was funded by the German Federal Ministry of Education and Research. The determination of material laws for asphalt layers on the basis of dynamic triaxial tests and the calculation and prognosis of cracking and rutting with the finite element method are the main content of this research project. The Chair of Pavement Engineering of the Dresden University of Technology realizes this research project in cooperation with the Institute of Pavement Engineering and Road Design of the Technical University at Brunswick and the German Federal Highway Research Institute. First results will be presented.

1. INTRODUCTION

Several research projects realised by the Chair of Pavement Engineering at the Dresden University of Technology aim at the development of an analytical design method comprising a multitude of factors effecting the pavement condition. The stress and strain behaviour of a pavement can be predicted or the remaining life cycle of the pavement structure is calculated by means of such a method. These advantages are especially important regarding warranty claims.

The developed dimensioning model is based on the fundamental idea of freely choosing any possible construction (flexible pavement). In this way, a particular pavement structure can be set depending on layer thickness and layer material.

Furthermore, the dimensioning model aims at the optimisation of the pavement construction considering traffic loading and weather-induced factors. Using different materials, the particular thickness of each layer is optimised on the basis of failure hypotheses. The described approach is illustrated by a calculation comparing various constructions and examining separately cracking and rutting as the two main reasons for material failure.

On the basis of the calculation example relevant influence parameters (layer thickness, resilient modulus of unbound base layers, material composition) are determined and the general feasibility of the method is shown. The calculation results exhibit a suitable first approximation considering all simplifications made during the approach. In the first place, the results are used for a qualitative evaluation of the described parameters.

The determination of material behaviour of asphalt layers is a very important part of the design process. If these properties are unknown, for example because of the use of new mixtures and/or binders, material testing in the laboratory is necessary. If standard mixtures are used, the material properties can be predicted certainly.

2. FACTORS EFFECTING PAVEMENT CONSTRUCTIONS

The designing method regards three different factors. The factors are

- Traffic loading
- Climatic conditions
- Material data and layer positioning

2.1 Traffic Loading

Traffic loading is one of the factors, which must be predicted. The developed dimensioning model is very customisable regarding different aspects of traffic loading. The axle load cycles are divided into ten categories of loads. According to current definitions, each load category covers the range of two tons. The number of load categories can be selected to fit the needs of each single project.

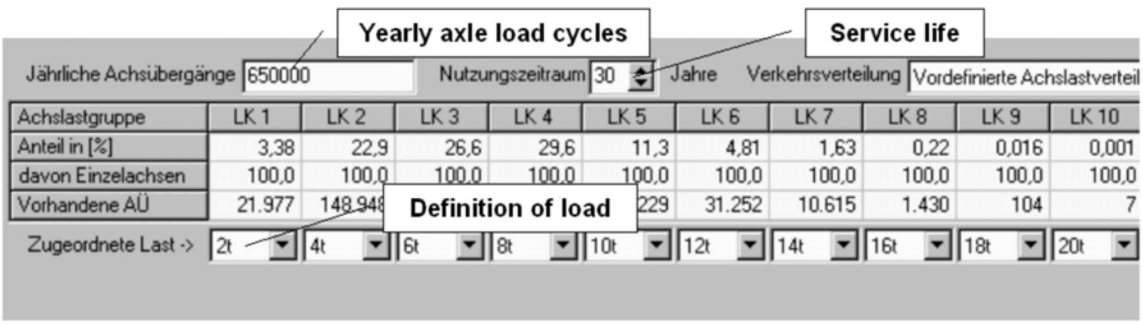

Figure 1: Example of traffic loading data

A typical load configuration can be assigned to each load category describing the positioning of the loads and each value.

With the described information, the load of each axle-load-cycle can be determined and the resulting stresses and strains can be calculated regarding the effects of the exact load value. Only with this way of determining the stresses and strains, the estimation of any kind of rutting or sensitivity for rutting is possible.

The determination of equivalent single axle loads is not necessary anymore. This prevents any inaccuracies caused by the use of the fourth power law.

2.2 Climatic conditions

Constructions with asphalt layers are sensitive regarding the temperature. Asphalt is a thermo viscous material. The material stiffness will change according to the temperature. At temperatures below + 20°C cracking is the main failure criteria. Below + 2,5°C additional thermo induced stresses increase the risk of cracking. If the temperature rises above + 35°C the decreasing stiffness pushes the risk of permanent deformation (rutting) to the foreground.

To consider the climatic conditions 13 temperature curves inside the asphalt layers based on 13 surface temperatures (see Figure 2) are determined. The number of curves can be adapted to the actual climatic conditions. With this method, the temperature at any depth inside the construction can be ascertained.

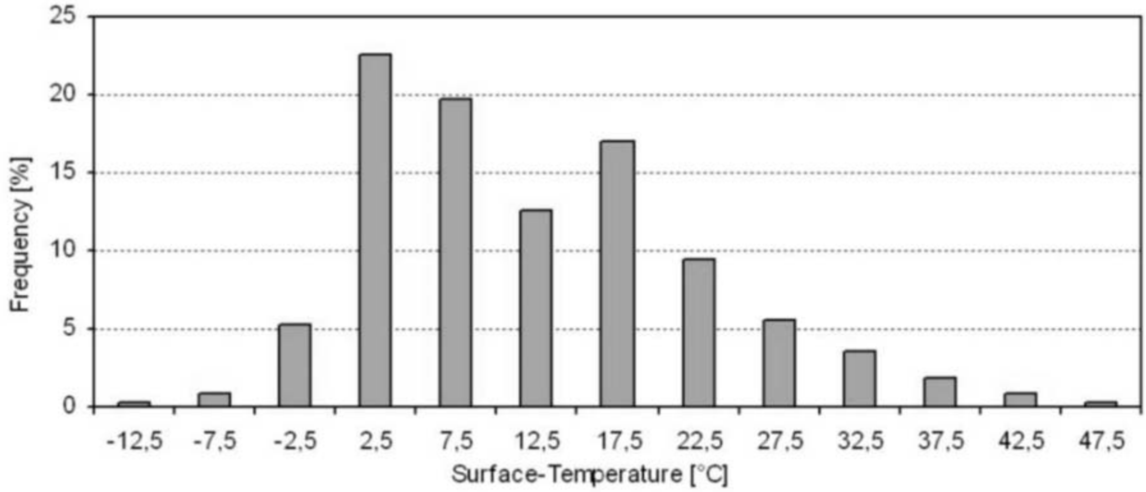

Figure 2: Example of surface temperatures specific for the northern part of Germany

In addition to the surface temperatures the frequency of the specified surface temperature has to be provided. The combination of this frequency and the number of load cycles per year indicates the number of load cycles per year for each surface temperature.

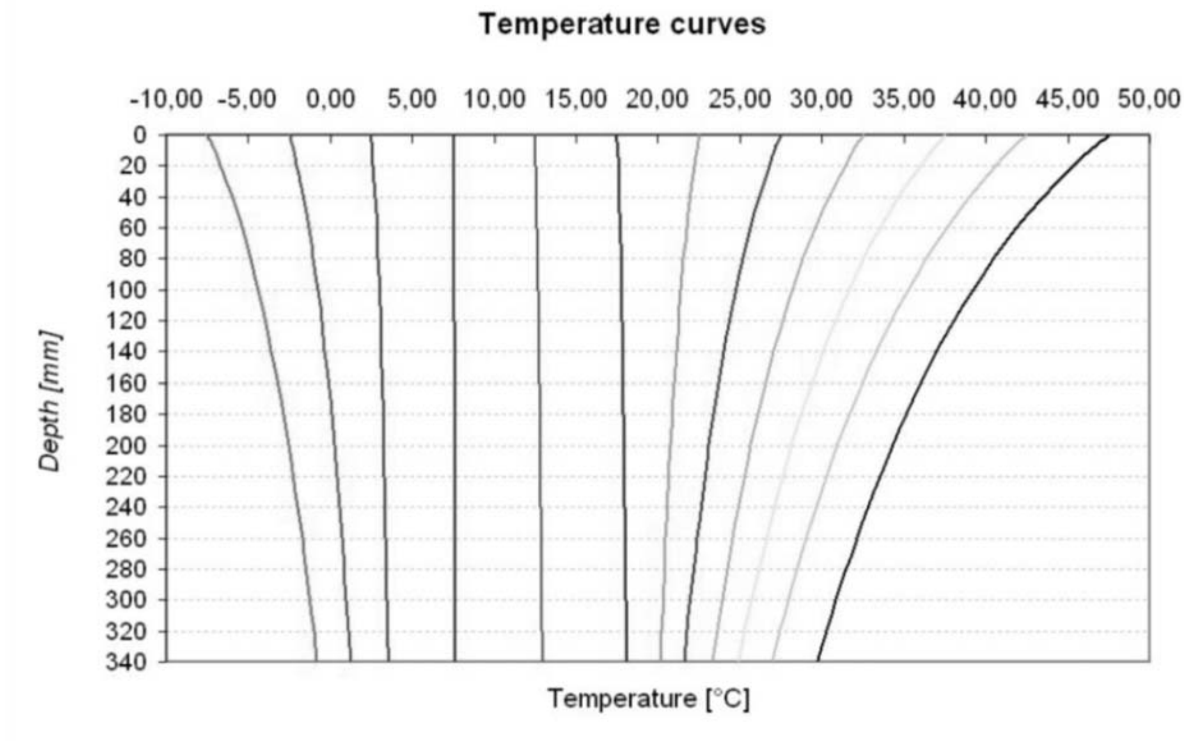

Figure 3: Temperatures curves for several surface tempeartures

2.3 Mechanical behaviour of asphalt mixtures

The prediction of material properties by using the method of FRANCKEN and VERSTRAETEN is possible (if no testing results are available). This method is able to predict the resilient modulus of asphalt materials on the basis of mixture data. Compared with tests the results of this method fits sufficiently if German standard mixtures are used. The required parameters are binder content, bitumen density, bulk density, maximum specific density and the needle penetration. In combination with the asphalt temperature the resilient modulus of the specific asphalt layer can be calculated. The Poisson's ratio is calculated with the regression equation developed by WITCZAK and MIRZA depending on the asphalt temperature.

The use of this method is suitable for standard asphalt mixtures only. If the material behaviour is unknown, for example because of the use of special polymer modified binders, material testing in the laboratory is necessary. Former research projects and especially the current research project "Sustainable Development of Pavements", which was funded by the German Federal Ministry of Education and Research, extensive experiences were made in the estimation of the mechanical behaviour of asphalt mixtures. If the resilient modulus is determined by laboratory testing mostly dynamic triaxial tests or ITS-Test (Indirect Tensile Strength) are used at Chair of Pavement Engineering of the Dresden University of Technology. Former research work has shown, that the resilient modulus measured in laboratory tests fits well to the values predicted with the method of FRANCKEN and VERSTRAETEN.

The stress-to-strain relationship under sinusoidal loading in the temperature range from – 20 °C to + 50 C is an essential part of current triaxial tests. The state of the art universal testing machine allows static and/or dynamic load functions for the axial loading (from 1,5 N/mm² tensile stress tor 1,5 N/mm² compressive stress) as well as the radial pressure (up to 1,5 N/mm²). At these tests, any desired phase angle between axial and radial loading can be enforced. Cylindrical specimen with 150 mm in diameter and 300 mm in height are used. During the specimen production asphalt plates (500 x 400 x 180 mm) are manufactured in the slap-form compactor. In the second step cores with 150 mm in diameter are drilled and finally prepared for the testing machine. For the determination of the resilient modulus, the measured values from the radial LVDT and magnetic-axial-deformation-measurement-system (see Figure 5) are analysed.

Figure 4: **Universal Triaxial Testing Machine with climatic chamber**

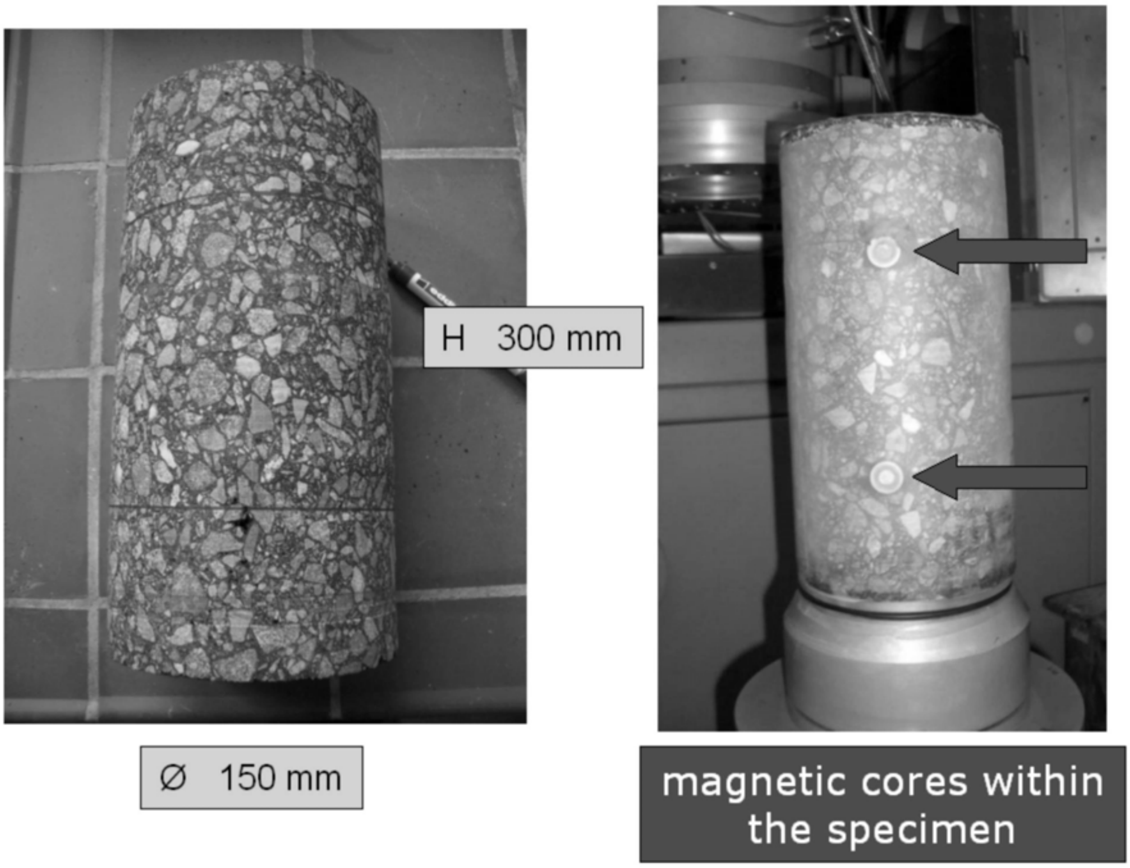

Figure 5: **Specimen for the Triaxial Tests**

The stress-to-strain relationship, which has been determined in the triaxial tests, can be used for the back-calculation with the FE-Program for pavement materials and layers, developed at the Dresden University of Technology. The following figure shows the vertical compressive stresses during a triaxial test at one forth of the specimen. The specimen-deformations and the displayed stresses are scaled with different values in figure 6.

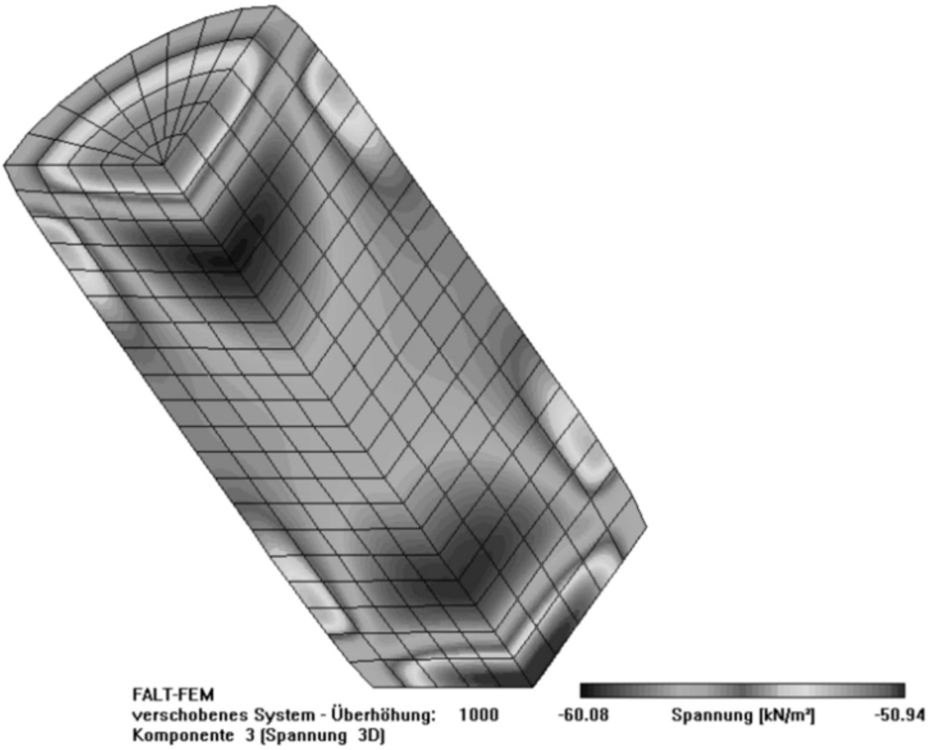

Figure 6: Result of the back calculation of triaxial tests with the FE-Method

The main focus for the triaxial tests is on the analysis of mixture response to permanent deformation beside the estimation of resilient modulus and Poisson's ratio. Figure 7 shows dynamic creep curves of several dynamic triaxial tests at 50 °C.

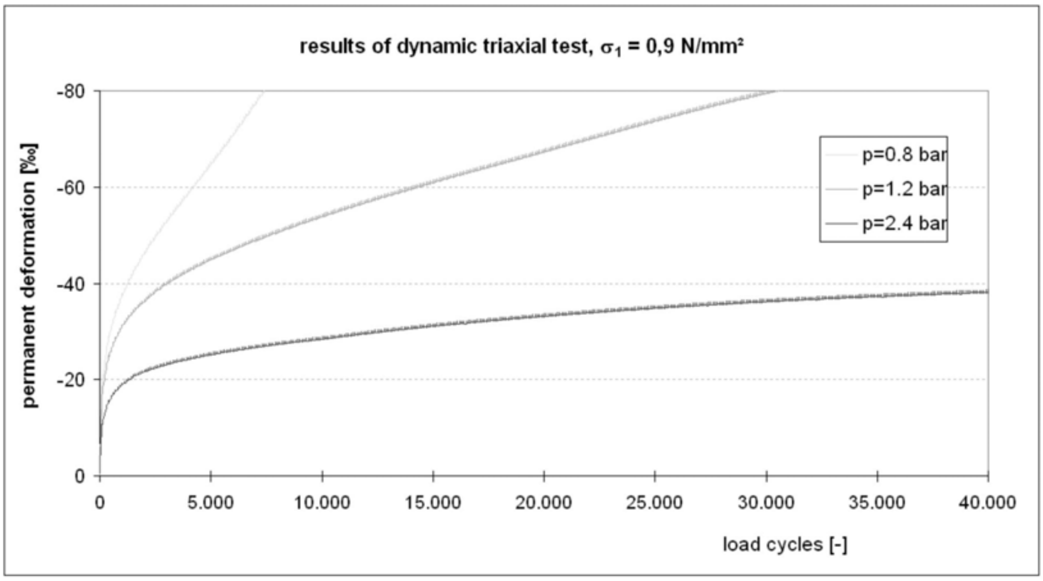

Figure 7: Dynamic creep curves of triaxial tests with different confining pressures

By the evaluation of several test results a method for the prediction of rutting is under development at present time. Until now no tertiary flow (no turning point in the dynamic creep curve) has been observed within dynamic triaxial tests. Therefore the best fitting will be achieved with following regression equation:

$$\varepsilon_{pl} = a \cdot N^k$$

With:

ε_{pl}	[‰]	plastic strain, irrecoverable and time-independent
N	[-]	number of load cycles
a, k	[-]	regression constants a and b, which ignore the tertiary zone of material deferability

Beside to the estimation of resilient modulus and the Poisson's ratio the analysis of fatigue is significant. The fatigue law is an important part to determine the tolerable load cycles. In the developed design method a fatigue law can be assigned to each set of material parameters. For standard asphalt mixtures the HEUKELOM fatigue law is used. According to HEUKELOM the maximum number of tolerable axle load cycles was determined by following equation:

$$N = \frac{10^{2,633(\lg E+1)}}{(\gamma \cdot 10\sigma)^5}$$

With:

N	[-]	number of tolerable load cycles
E	[MN/m²]	Young's modulus of the concerning asphalt layer
σ	[MN/m²]	tensile stress at the bottom of the asphalt
γ	[-]	safety factor (against cracking)

For other materials, for example if asphalt layers with special polymer modified binders are used, material testing in the laboratory is necessary. The ITS-Test (Indirect Tensile Strength) will be used for fatigue testing. The following figure shows the results of fatigue testing of two different asphalt mixtures (asphalt base course).

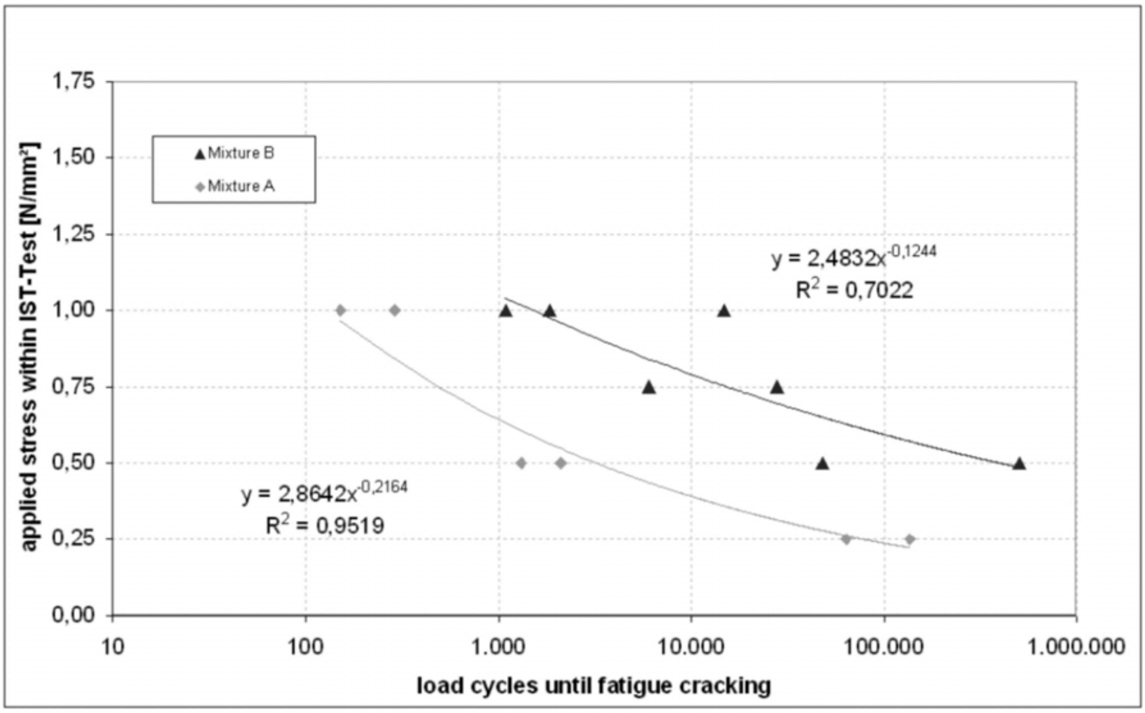

Figure 8: Results of Fatigue Tests determined with the ITS-Test

It's obvious, that both materials have different tolerable load cycles until fatigue cracking. In detail mixture A can resist about 500 load cycles at an applied stress of 0,75 N/mm². Compared to this mixture B can resist about 16.000 load cycles. In total the number of tolerable load cycles of mixture B is about 32 times higher. This different material behaviour is caused by different mixture compositions. At mixture A an unmodified Bitumen 50/70 was used. Compared with this the Bitumen 50/70 of mixture B was modified with a special additive.

3. DESIGNING PROCESS

3.1 Composition of layers

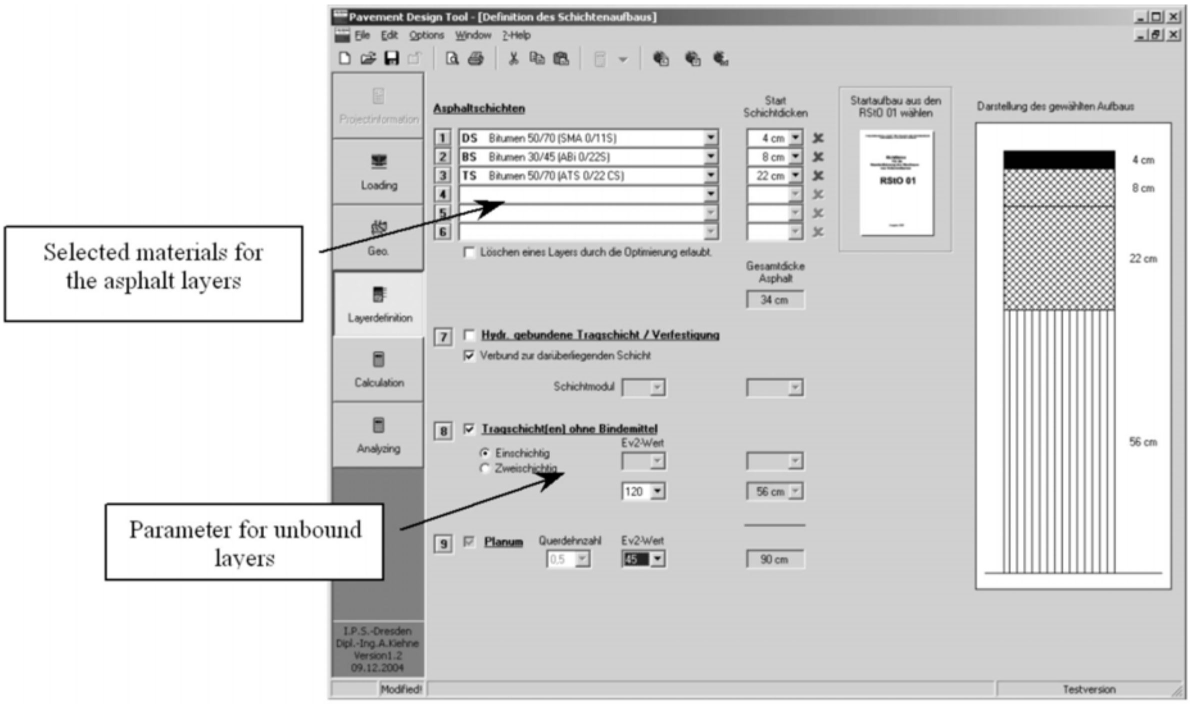

Figure 9: Composition of layers

By selecting a material for one of the six possible asphalt layers, the pavement construction can be defined step by step. All parameters needed for the calculation are determined by this selection. Only the thickness has to be adjusted to complete the design of the asphalt layers.

The number of unbound granular layers, the thickness and the bearing capacity for each unbound layer must be specified. The last step is to select the bearing capacity for the underground.

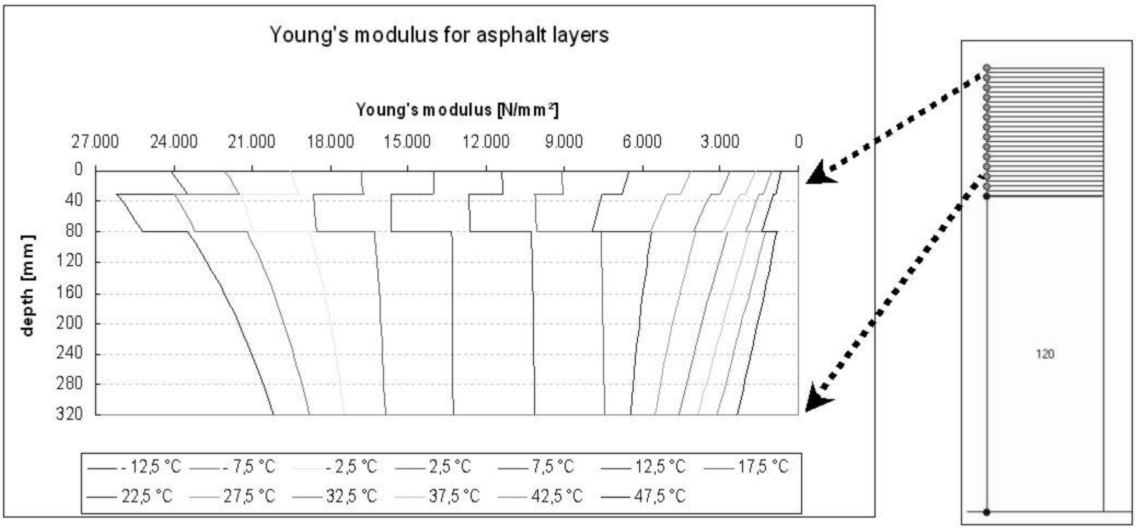

Figure 10: Young’s modulus for asphalt layers

This selection is the basis to build the model for the calculation. The asphalt layers will be divided into sub layers with 1 cm thickness each and linear elastic behaviour will be assumed (μ= 0,35). The Young’s modulus is calculated regarding the temperature of the sub layer. The modulus for each unbound layer was calculated according to the evaluation of the plate-bearing test. The material parameters for the model are determined separately for each temperature curve.

3.2 Calculations

Asphalt Layers

Stresses and strains within the layers are calculated separately for each load category and for each temperature gradient.

The calculation will be done in two steps. The first is to calculate all temperature states in combination with all selected load categories. These combinations can reach the number of 130 or more depending on the number of load categories and the number of surface temperatures. Because of the short calculation time of a calculation according to the multi layer (course) theory, this first step is executed with this calculation method.

The second step is performed using the finite element method to examine for example critical temperature states by using material specific calculation models. This part of the analysis needs more time to be calculated.

In case of complete adhesion of the asphalt layers the highest values for the tensile stresses occur on the bottom of the asphalt base.

For each result the number of tolerable axle load cycles are determined and compared with the existing load cycles of the according load category. The results are accumulated by the hypothesis of MINER.

Accumulated damage:

$$\frac{N_a}{N_{Ba}} + \frac{N_b}{N_{Bb}} + \frac{N_c}{N_{Bc}} + \ldots \frac{N_z}{N_{Bz}} \leq 1$$

With:

$N_{a\ (b,\ c,\ \ldots)}$	[-]	number of existing load cycles in state a (b, c, …)
$N_{Ba\ (Bb,\ Bc,\ldots)}$	[-]	number of tolerable load cycles in state a (b, c, …)

If the sum of the MINER-Term is equal to 1 the fatigue cracking of the asphalt layers starts. Figure 11 shows the progress of the sum of MINER for the service life that was supposed to be 30 years. The MINER value of 1 is equal to the 100 percent of figure 11. This pavement construction will start cracking after 21,5 years of service. Intensive maintenance must be expected.

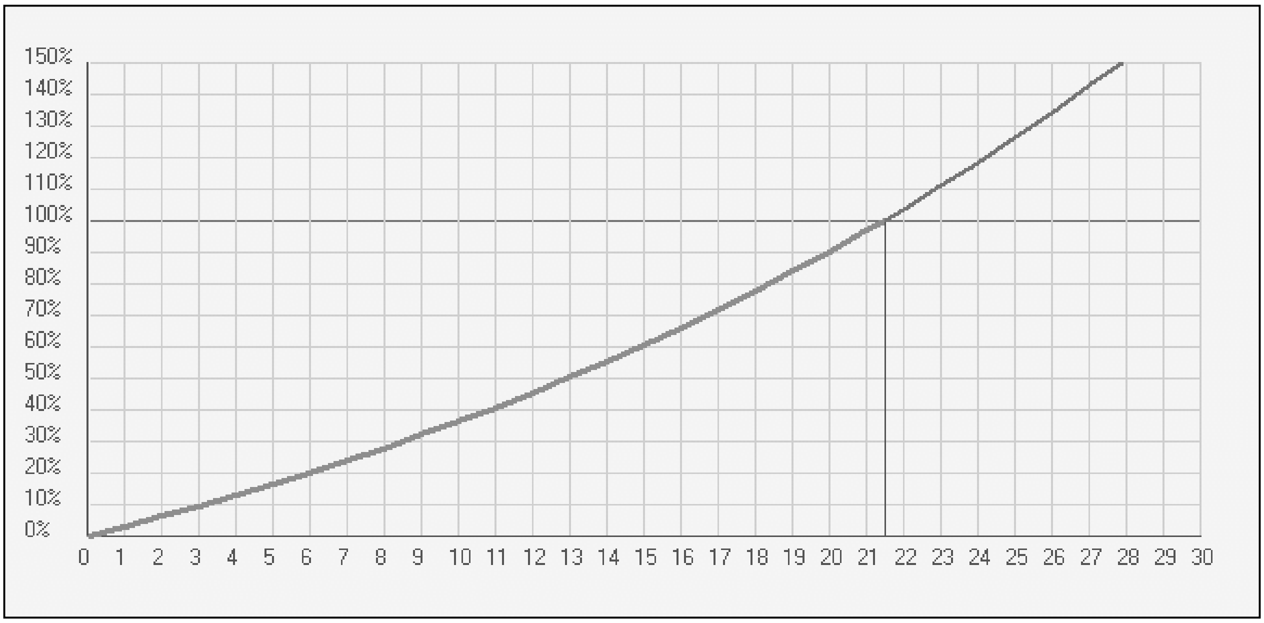

Figure 11: Example for cracking within the service life (after approximately 21,5 years)

Unbound layers

The unbound layers were treated the same way as the asphalt layers. The number of allowable load cycles was determined by using equation 3. If the number of the existing axle load cycles is lower than the tolerable load cycles, permanent deformations in the unbound layers are almost impossible.

$$N_B = 10^{\frac{1}{0,7}\left(\frac{0,00875 \cdot E_{v2}}{\gamma \cdot \sigma_Z} - 1\right)}$$

With:

N_B	[-]	number of tolerable load cycles
E_{V2}	[MN/m²]	stiffness of the sub-base/sub grade, measured with the plate bearing test
σ_Z	[MN/m²]	vertical (compressive) stress on the top of the unbound layers
γ	[-]	safety factor

The safety of standard pavement constructions, which were used in Germany so far, against permanent deformation of the unbound layers, is about three times higher than the safety of the asphalt layers. A failure of the unbound layers is improbable.

4. EXAMPLE

4.1 Basis data for the construction

- Traffic loading of 525.000 axle load cycles per year from 2 tons to 20 tons.
- Climatic conditions as shown in Figure 2 and 3

Two different pavement constructions have to be compared to select the best variation.

Construction A:

4 cm surface course
    SMA 0/11 S Bitumen 50/70
8 cm binder course
    ABi 0/16 S Bitumen 30/45
16 cm asphalt base
    ATS 0/22 CS Bitumen 50/70
62 cm unbound granular material

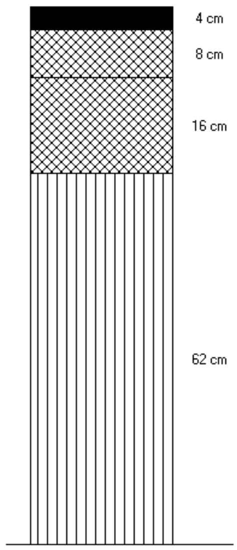

Figure 12: Construction A

Construction B:

4 cm surface course
    SMA 0/11 S Bitumen 50/70
4 cm binder course
    ABi 0/16 S Bitumen 30/45
20 cm asphalt base
    ATS 0/22 CS Bitumen 50/70
62 cm unbound granular material

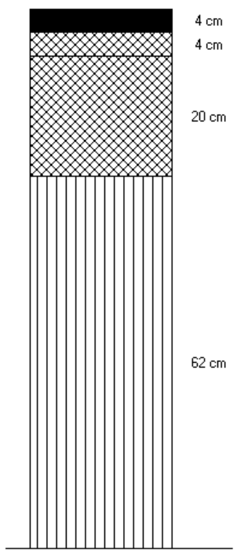

Figure 13: Construction B

4.2 Calculation results

Fatigue cracking

Both constructions show the same MINER value of 0,48 (equivalent to 48 %). This result indicates both constructions to be equal and both constructions are capable to overcome the service life of 30 years.

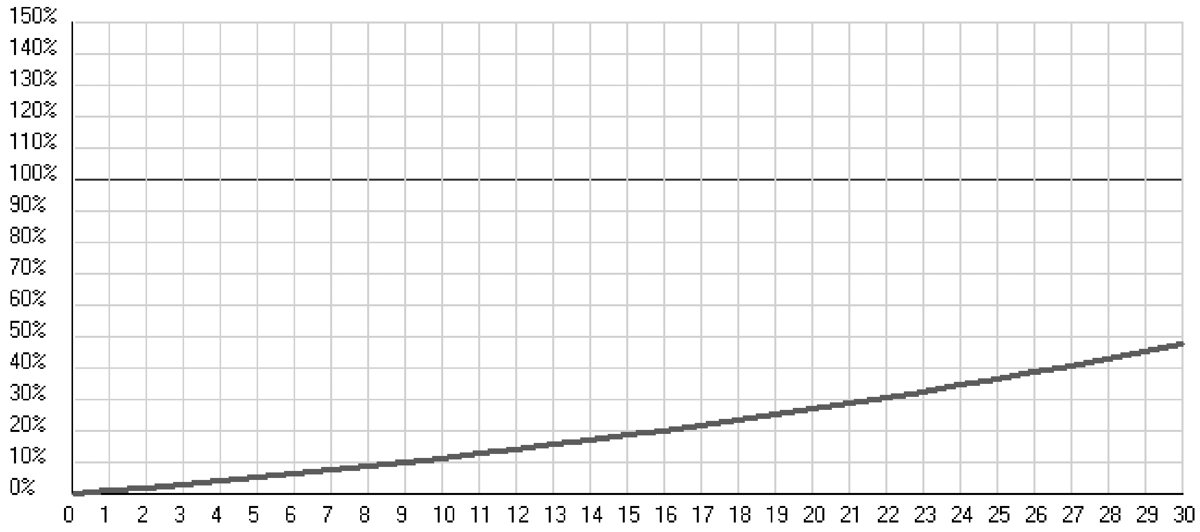

Figure 14: Progress of cracking within the service life

Permanent deformation

Focusing on the permanent deformation differences can be discovered. Because of the different stress-to-strain relationship especially in the surface and binder course the risk of rutting is much higher if construction A is selected (figure 15). If a threshold value of 10 mm rut depth must not be exceeded first maintenance procedures after 16 years are necessary for construction A. Construction B reaches 10 mm rut depth after 24 years and therefore will last 8 years longer in this case than construction A.

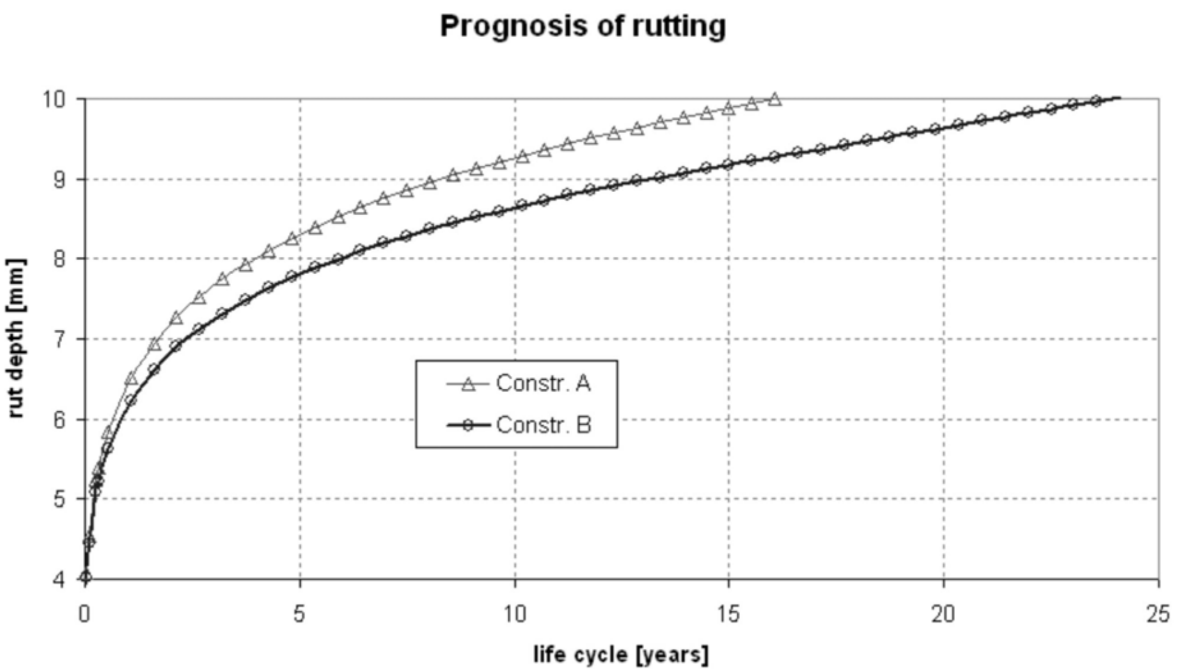

Figure 15: Prognosis of rutting for construction A and B

5. SUMMARY

With the developed design method, the calculation of safety levels of flexible pavement layers (asphalt and unbound layers) is possible. A developed computer program, that uses the multiplayer theory at present time, is available. Different road constructions with different layer thickness, layer stiffness and mixture composition can be evaluated and compared (in this case cracking and permanent deformations). The method is capable to check the possibility of alternative constructions with the same safety level against failure. At present time research work at Chair of Pavement Engineering of Dresden University of Technology aims the estimation of input data/parameters like resilient modulus, resistance against fatigue and plastic deformation behaviour.

6. REFERENCES

1. ALMEIDA, J. R., 1991, *Program FENLAP users guide*, Report No. PR 91010, University of Nottingham, United Kingdom

2. Burmister, D. M., 1943, *The General Theory of Stresses and Displacements in Layered Systems* Journal of Applied Physics, Vol. 2/1943,

3. Kaniklijke Shell labour, 1972, *BISAR Layered systems under normal and tangential surface loads-Users manual*, Amsterdam, Netherlands

4. FRANKEN, L. and J. VERSTRAETEN. Methods for predicting moduli and fatigue laws of bituminous road mixes under repeated bending. In Transportation Research Record 515, pp. 114-123, TRB, National Research Council, Washington, D.C., 1974.

5. HESS, R., 1998, *Calibration of models for preservation of road constructions*. (Diploma thesis in German), Institut für Verkehrswirtschaft, Straßenwesen und Städtebau, Fachgebiet Konstruktiver Straßenbau der Universität Hannover, Hannover, Germany

6. HEUKELOM, W.; KLOMP, A. J., 1964, *Road design and dynamic loading.*, Proceedings of the Association of Asphalt Paving Technologists 33 (1964)

7. JÄHNIG, J., unpublished, *Prognose der Spurrinnenbildung – Untersuchung des plastischen Verformungsverhaltens von Asphalt mit dem Triaxialversuch (Prognosis of rutting – Analsys of the permanent deformation behaviour of asphalt layers)*, Ph. D. thesis, University of Technology Dresden, Dresden, Germany

8. JANSSEN, D., 1985, *Effect of heavy axle loads on rutting of flexible pavement constructions*. Straßenwesen und Städtebau, Fachgebiet Konstruktiver Straßenbau der Universität Hannover, Hannover, Germany

9. KIEHNE, A., unpublished, *Rechnerische Bemessung von Straßenbefestigungen - Entwicklung und Umsetzung eines Verfahrens – (Analytical design methods of pavement structures – development and implementation)*, Ph. D. thesis, University of Technology Dresden, Dresden, Germany

10. MINER, M. A., 1945, *Cumulative damage in fatigue*. Journal of Applied Mechanics, Vol. 12, Nr. 3

11. Forschungsgesellschaft für Straßen- und Verkehrswesen (in German), 2001, *RStO 01 The German pavement design guideline*, Köln, Germany

12. RUBACH, K., 1996, *Influence of asphalt mixtures on the crack resistances in consideration of cryogenic tensile stresses*, Schriftenreihe des Instituts für Straßenwesen Technische Universität Braunschweig Heft 14, Braunschweig, Germany

13. WITCZAK et.all, *Simple Performance Test for Superpave Mix Design*
NCHRP Report 465
Washington, D.C. 2002