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PERFORMANCE-BASED ASPHALT MIX AND PAVEMENT DESIGN

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Abstract

Prediction and optimization of in-service performance of road pavements during their live time is one of the main objectives of pavement research these days. For flexible pavements the key performance characteristics are fatigue and low-temperature, as well as permanent deformation behavior at elevated temperatures. The problem facing pavement designers is the need to fully characterize the complex thermo-rheological properties of hot mix asphalt (HMA) over a wide temperature range on the one hand, while on the other also providing a realistic simulation of the traffic- and climate-induced stresses to which pavements are exposed over their design lives of 20 to 30 years. Where heavily trafficked roads are concerned, there is therefore an urgent need for more comprehensive test methods combined with better numerical forecast procedures to improve the economics and extend the service lives of flexible pavements under repair and maintenance programs.

This papers therefore focus on performance-based test methods on the basis of existing European standards that address effective mechanical characteristics of bituminous materials and which may be introduced into national requirements within the framework of European HMA specifications. These test methods comprise low temperature tests, i.e. the tensile stress restrained specimen test or the uniaxial tensile strength test, stiffness and fatigue tests, i.e. the four point bending beam test or the uniaxial tension compression test, as well as methods to determine permanent deformation behavior by means of dynamic triaxial tests.

These tests are used for the performance-based mix design and subsequently implemented in numerical pavement models for a reliable prediction of in-service performance, which, in combination with performance-based tests, enables a simulation of load-induced stresses and mechanogenic effects on the road structure and thus improved forecasts of the in-service performance of flexible pavements over their entire service lives.

Keywords: hot mix asphalt, performance test, mix design, mechanical pavement design

1. INTRODUCTION

For the optimization of flexible road pavements recent research efforts have been focused both on the setup and implementation of performance-based test methods for hot mix asphalt (HMA) as well as on their implementation in valid performance prediction models. While performance-related or empirical tests count for material characteristics that have been found to correlate with fundamental engineering properties that predict performance (e.g. wheel-tracking properties, Marshall properties), performance-based tests describe fundamental engineering properties predicting performance, and appearing in primary performance prediction relationships.

By January 2007 new harmonized European Standards (EN) for the design and testing of road asphalt materials were introduced in all CEN member countries within the European Union. Generally these EN standards distinguish, on the one hand, between the empirical mix design approach and, on the other hand, the fundamental, performance-based approach, which is comparably new. Although both approaches aim in realizing well-performing, structurally optimized pavements, an important advantage of the performance-based approach is the fact that it is based on the laboratory assessment of physically sound material parameters.

These key performance parameters of HMA include (i) complex material stiffness, (ii) fatigue resistance under repeated load cycles (iii) resistance to cracking at low temperatures and (iv) resistance to rutting due to thermal deformation. These material parameters can be used for specifying the mix properties within an advanced type testing procedure required to meet customized quality standards for materials defined in tender documents as well as for mix design [1].

In the European HMA test standard series EN 12697-xx key performance HMA properties are address by different performance tests as summarized in Table 1. To identify the rutting behavior at elevated temperatures cyclic axial load tests with or without confining pressures (TCCT Triaxial Cyclic Compression Test or UCCT uniaxial Cyclic Compression Test) are specified. The low temperature behavior is tested by means of the so-called Tensile Stress Restrained Specimen Test (TSRST) and a Uniaxial Tensile Strength Test (UTST). For characterizing the stiffness and fatigue of asphalt mixtures different tests are described in the European standards, including bending tests (e.g. two point 2PBBT or four point 4PBBT) and direct and indirect tensile tests, but without favoring a particular type of testing device. Further the European HMA specification EN 13108-1 offers different categories for these performance-based HMA properties, which may be introduced as so called fundamental HMA requirements into the national specifications.

Table 1. European test standards for performance-based requirements

asphalt course	stiffness	material fatigue	low temperature performance	permanent deformation
Surface	x	(x)	x	x
Binder	x	(x)	x	x
Base	x	x	(x)	(x)
test procedure	2-Point-Bending test with trapezoidal specimen (2PB-TR) 2-Point-Bending test with prismatic specimen (2PB-PR) 3-Point-Bending test (3PB) 4-Point-Bending test (4PB) Cyclic indirect tensile test (CIDT) Direct tension-compression test (DCT)	Cyclic indirect tensile test (CIDT) 4-Point-Bending test (4PB)	Temperature Stress Restrained Specimen Test (TSRST) Uniaxial tension stress test (UTST) Uniaxial Cyclic tension stress test (UCTST)	Triaxial cyclic compression test (TCCT) Uniaxial cyclic compression test (UCCT)
EN standards	EN 12697-26	EN 12697-24	EN 12697-46	EN 12697-25

x…performance characteristic mandatory, (x)…additional performance characteristic

Such performance-based HMA specifications, however, require more complex and expensive mix design and type testing procedures. But in combination with these European performance-based HMA specifications mechanistic models allow a more reliable prediction of in-service performance of HMA pavement structures. The objectives of these advanced pavement design models are to enable the simulation of thermo- and load-induced stresses and mechanogenic effects and thus improved forecasts of the in-service performance of flexible and semi rigid pavements.

Following the key performance-based test methods and their possible implementation in mechanistic pavement design models as well as enhanced mix design procedures are discussed in more detail.

2. LOW TEMPERTURE BEHAVIOR

2.1. Background

Traditional studies on pavement performance and modeling have generally concentrated on classical fatigue cracking that consider failure to initiate at the bottom of the bituminous base course induced by a large number of "small" repeated traffic-loadings [2, 3]. But this simple approach does not always fit the reality, because two different mayor types of crack damage occur in flexible pavements: cracks that start at the bottom of the bituminous base course and grew upwards, generally named fatigue cracks, and surface cracks that are initiated on top of the pavement. There are always combined effects of critical thermal and load stresses that lead to distress. Thermal stresses are induced by a series of temperature fluctuations within the pavement structure and play a dominant role in the phenomenon of fatigue cracking, and further by a single event, when temperature drops within a very short time. Thermal induced stresses in combination with traffic loading may exceed the critical tensile strength and lead to surface-initiated top-down cracking along the wheel paths.

In the field of low-temperature and fatigue behavior the research activities have been focused on the development of appropriate test methods, to better understand and to identify the fracture mechanisms by means of laboratory experimentation and to further assess the risk of temperature and fatigue cracking for different bituminous materials, which are exposed to stress and temperature.

2.2. Test Methods

Low-temperature cracking of flexible pavements results from thermal-shrinkage during cooling, inducing tensile stress in the asphalt. In order to simulate the situation in flexible pavement layers the following test methods on asphalt specimens according to the European Standard EN 12697-46 are employed [1, 4]:

(i) Tensile Stress Restrained Specimen Test (TSRST): while the deformation of the specimen is restrained, the temperature is reduced by a pre-specified cooling rate;

(ii) Uniaxial Tensile Strength Test (UTST): in order to assess the risk of low-temperature cracking, the stress induced by thermal shrinkage is compared with the respective tensile strength;

The target parameters, which are found by TSRST, are the fracture temperature (T_{crack}) and the corresponding fracture stress (σ_{crack}). An illustration of the test procedure of the TSRST is given in Figure 1.

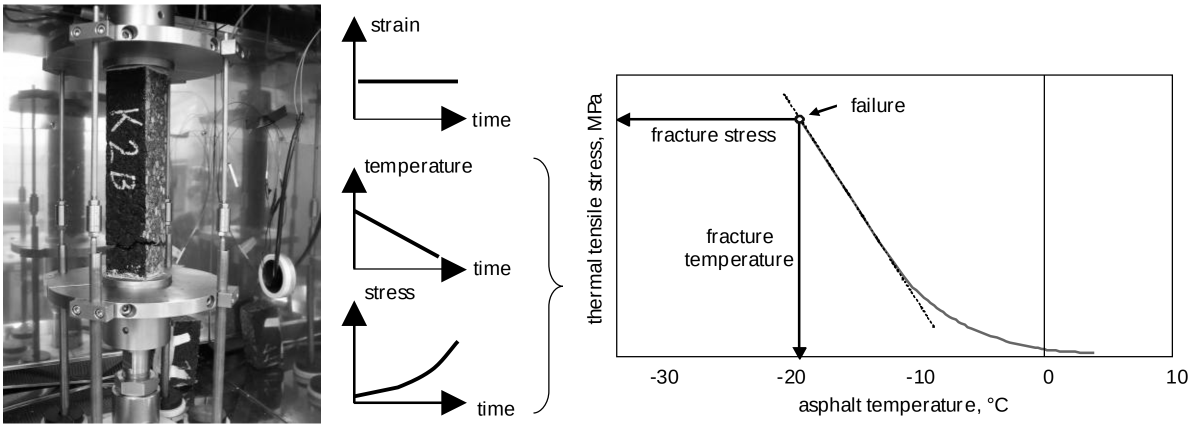

Figure 1 . TSRST: experimental setup and illustration of result [4]

The UTST is an isothermal process at specified temperatures (e.g. +10, +5, -5, -15 and -25°C). After stress-free cooling of the asphalt to the testing temperature, the UTST is performed by applying a constant strain rate (1 mm/min) until the specimen fractures.

Combining the results of TSRST and UTST the tensile strength reserve (Δβ) is found, a “traditional” target parameter for low-temperature cracking (Figure 2).

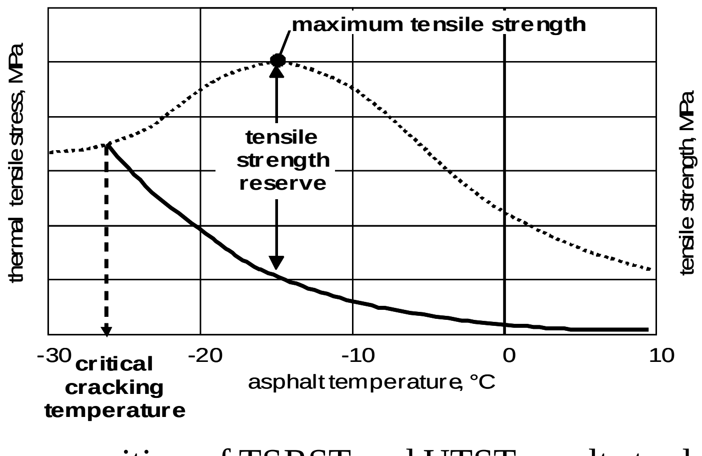

Figure 2. Superposition of TSRST and UTST results to derive tensile strength reserve [4]

2.3. Application in Numerical Modeling

In consequence these key material parameters are used to predict thermal induced stresses in pavement structures, e.g. in a first step on the basis of a simple rheological Maxwell model [5], describing the two concurring processes in flexible pavements during cooling: thermal shrinkage and viscous stress relaxation. Figure 3 shows the results of a Finite Element (FE) simulation of the thermal and load induced stress situation in typical flexible pavement structure consisting of a stone mastic (SMA) wearing course and a bituminous base layer (AC), that is cooled down from -10°C to -20°C in five hours and then loaded by a 57,5 kN tire (110 kN axle) load. Further more the stress and strain situation around an open joint is studied at the edge of the SMA layer.

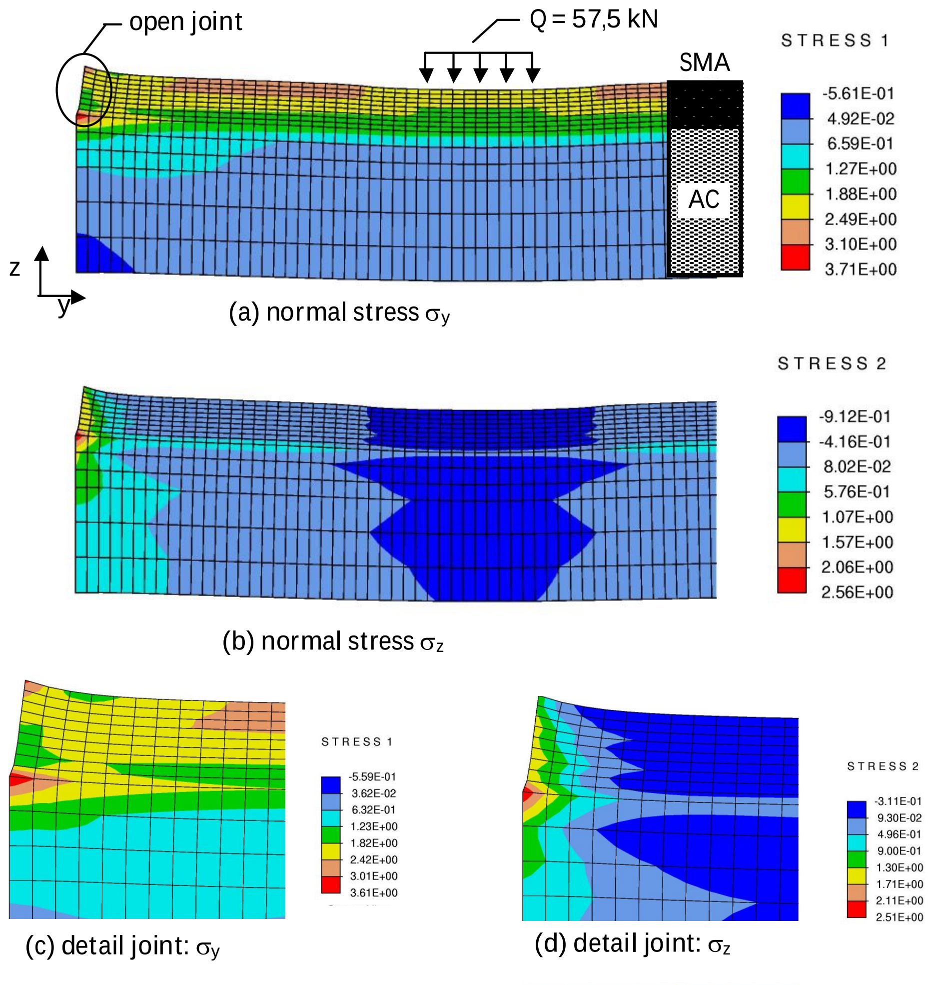

Figure 3. FE simulation of thermal and load induced stresses in a flexible pavement structure after cooling from -10°C to – 20°C in five hours [1]

The computations show clearly that at low temperatures the tensile strains at the top of the pavement in a distance of app. 0.6 to 0.9 m from the load axis are higher than those occurring at the bottom of the flexible pavement underneath the load. These may lead to top down cracking if the actual tensile strength is reached. However, the stress situation at the layer interface at the joint between the SMA and the AC layer is even higher and may reach the fatigue strength and induce crack propagation.

2.4. Implementation in the Mix Design Process

Furthermore the TSRST is a useful test method to optimize the low temperature behavior of HMA within a mix design procedure. Figure 4 shows the results of cooling tests on four different HMA types (stone mastix asphalt SMA with steel slag, asphalt concrete AC binder and AC base course) to optimize a flexible pavement structure. The results show that the low temperature behavior is considerably dependent on the bitumen type and only moderately on the bitumen content and the asphalt type (grading curve). However, as regards the lowest achievable fracture temperature for each HMA type an optimum bitumen content exists.

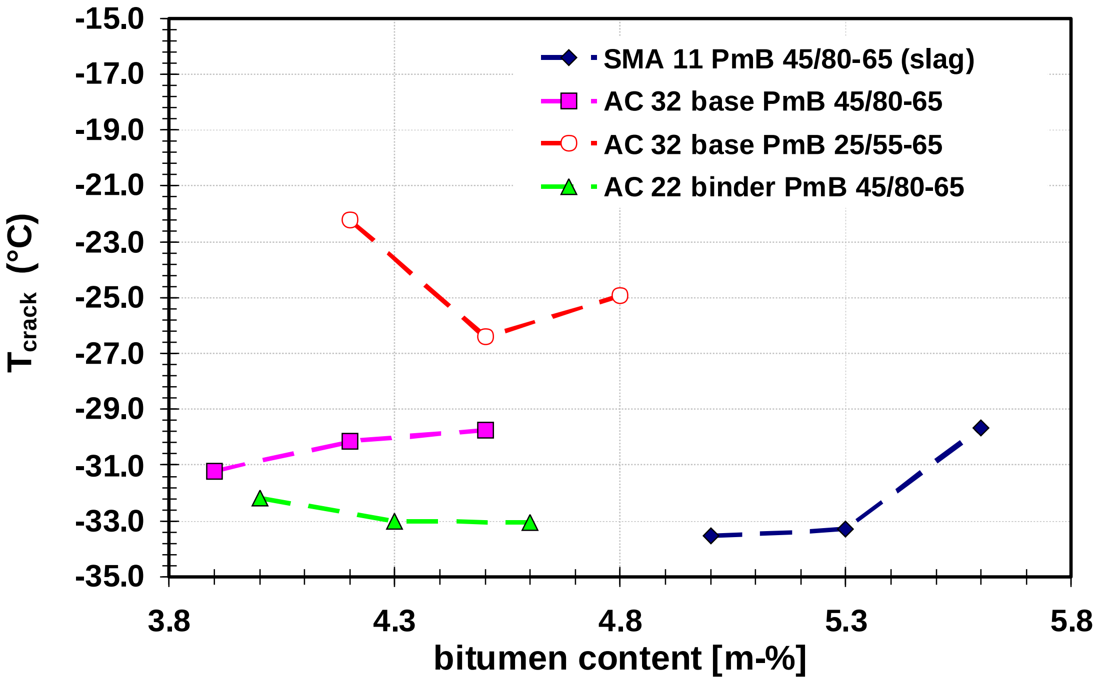

Figure 4. TSRST fracture temperature vs. bitumen content

3. STIFFNESS AND FATIGUE BEHAVIOR

3.1. Background

Stiffness and fatigue testing, where a repeated stress is applied on a test specimen, has been a major topic in pavement engineering since decades. Latest research is known from the Association of European Laboratories RILEM and the US Strategic Highway Research Program (SHRP), where a sophisticated layout of different test methods for asphalt concrete design and testing has been developed and which has started a broad discussion on new ways to further optimize fatigue testing procedures and interpretation of test results. Presently two European Standard EN 12697-24 (fatigue) and EN 12697-26 (stiffness) specifies the methods for characterizing the stiffness and fatigue of asphalt mixtures by different tests, including bending tests and direct and indirect tensile tests, but without favoring a particular type of testing device [1, 3]. However, a single test method for type testing will be imposed on European level in the next future.

3.2. Test Methods

All different types of EN test methods are used to derive basically two material characteristics: the material's stiffness, expressed by the variation of the complex asphalt modulus (E*(T)) over time, and the long-term fatigue behavior, expressed by the number of permissible load repetitions (N_{perm}).

The initial stiffness modulus E*(T) of the unloaded material can be determined on the basis of specimen geometry and load impulse and simultaneous measurement of the resulting strains by strain sensors. The stiffness is calculated from the quotient of the applied maximum stress and the resulting maximum strain, which is time-shifted by the corresponding phase displacement angle (φ) as a result of the viscoelastic material behavior of asphalt (Figure 5).

Traditional fatigue criterion of asphalt concrete is linked to the number of load-cycles giving half the initial stiffness. The comparison of modulus and the number of load repetitions is plotted as so-called "Wöhler" curve. The Wöhler curve gives important information for the derivation of fundamental relationships between mix composition and stiffness properties and serves as input for material and pavement structure optimization.

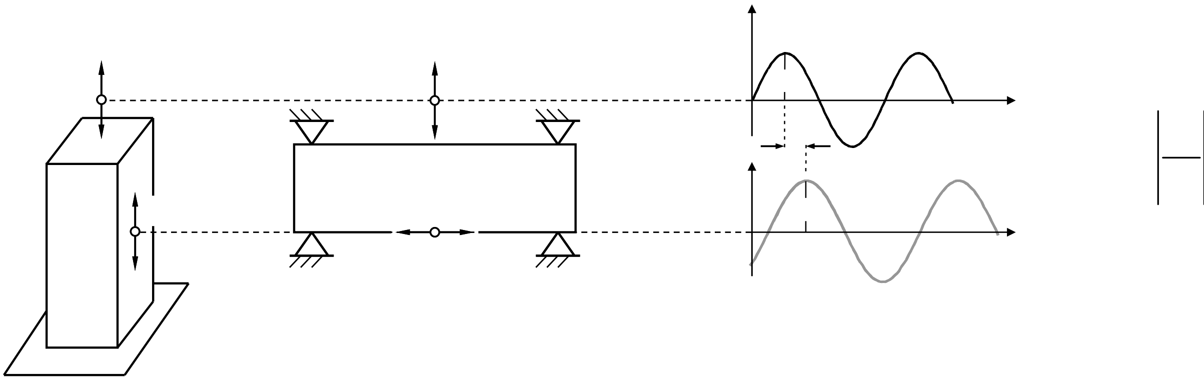

Figure 5. Stiffness modulus (E*) and phase angle (φ) [1]

From the EN test methods following two methods were selected to perform stiffness and fatigue tests on asphalt mixtures:

(i) the four-point bending-beam-test (4PBBT) (Figure 6a) and
(ii) the direct tension-compression test (DTCT). (Figure 6b).

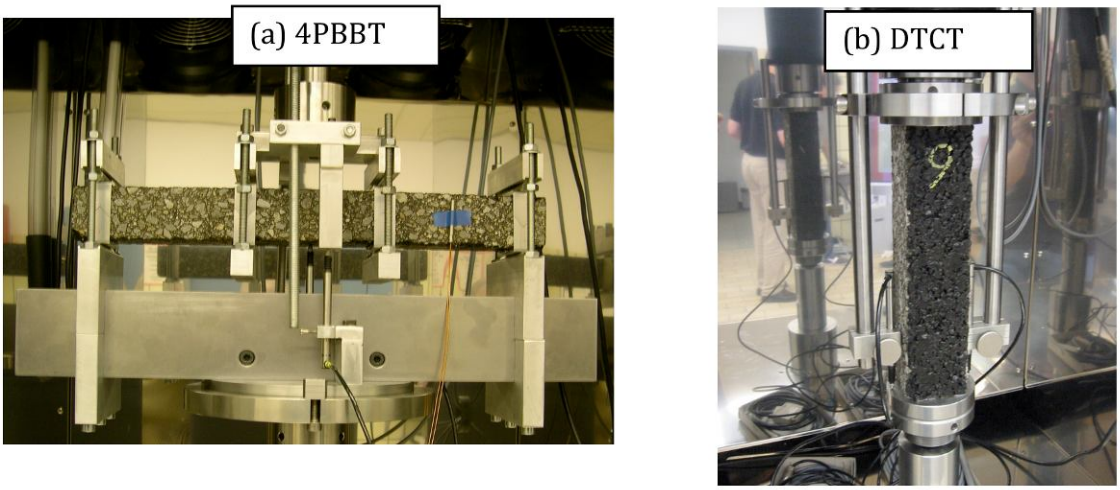

Figure 6. 4PBBT & DTCT equipment used for stiffness and fatigue testing [1]

Figure 7 shows typical results of stiffness measurements on a SMA 11 used for wearing courses that were performed at different temperatures and loading frequencies. Results are the master curve of the complex stiffness modulus E* at reference temperature of e.g. 15° C (Figure 7a), and the frequency independent representation of the loss modulus E’’ and the conservation modulus E’ in a so-called Cole-Cole diagram (Figure 7b).

Consequently, these test results describing the temperature and frequency dependent material response of asphalt can be used to compute thermal and load induce stresses and strains in the asphalt layers by means of a numerical pavement model.

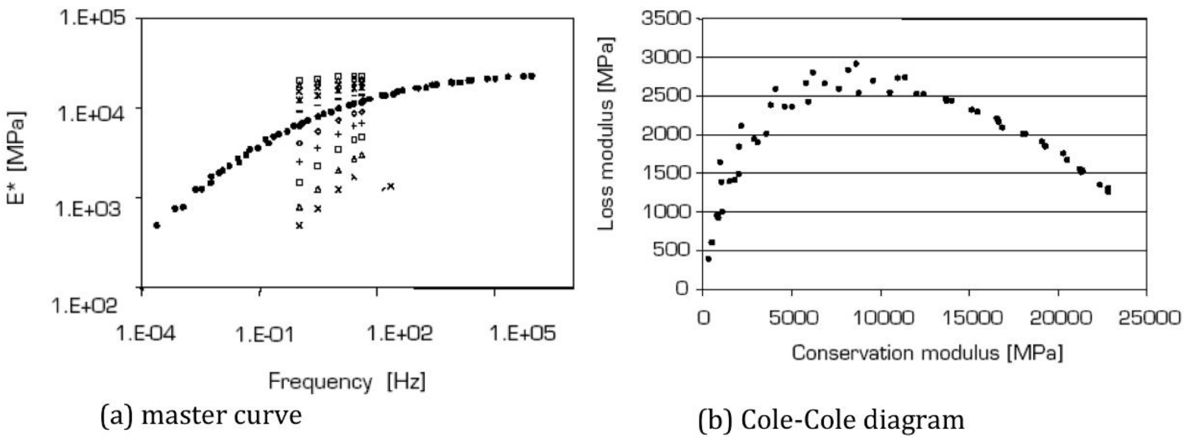

Figure 7. Stiffness master curve of SMA 11 derived form a 4PBBT [1]

For the prediction of the fatigue damage long term tests under repeated dynamic loading are performed. Such tests can be carried out under stress or strain controlled conditions providing typical fatigue curves as given for example in Figure 8 for hot mix asphalt (HMA) AC 22 at 10 Hz and 20 °C. From such curves the permissible load repetitions (N_{perm}) are obtained to describe the theoretical life time within an analytically based pavement design method on the basis of fatigue laws.

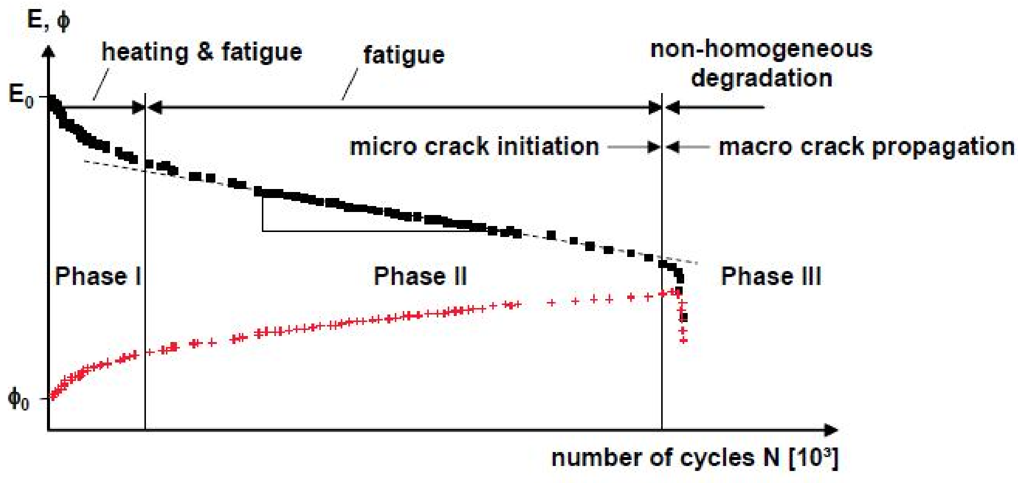

Figure 8. Phases of AC 22 fatigue curve from a strain controlled 4PBBT [1]

3.3. Implementation in Pavement Design

Stiffness master curves of HMA and fatigue curves are main input parameters for mechanistic methods of thickness design for flexible and semi rigid pavements.

But within the described laboratory fatigue tests such as the DTCT or the 4PBBT inside the asphalt specimen a more or less uniaxial stress or strain condition prevails. However, the stress condition in a flexible pavement during the passing of a wheel is a 3-dimensional (3D) and rather complex one. For reliable life time predictions a transformation of the computed 3D stress situation into an equivalent uniaxial stress situation as simulated during the fatigue tests in the laboratory is therefore necessary. This can be achieved either by means of so-called “shift factors”, which relate the allowable load repetitions derived from the laboratory fatigue tests with the fatigue damage observed in the field on the basis of empirical correlations, or by means of a material strength hypothesis, that enables the stress/strain transformation on an analytical, theoretical basis. The later is utilized within the Austrian pavement design method (Figure 9).

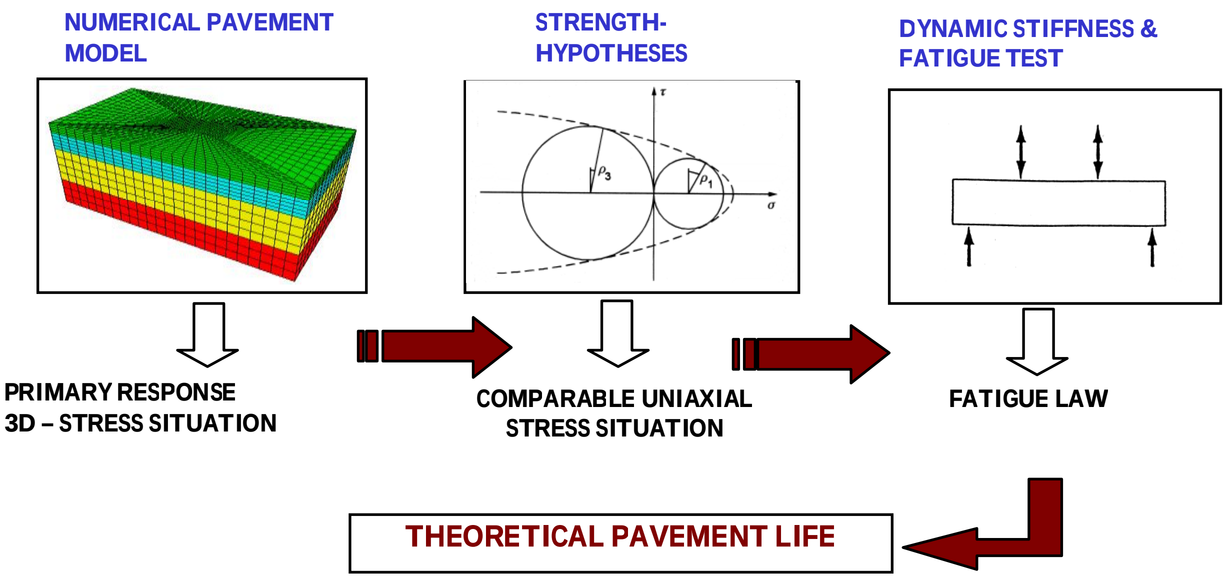

Figure 9. Flexible pavement design method based on numerical modeling and laboratory testing [1]

3.4. Implementation in the Mix Design Process

Although HMA fatigue are most time consuming and expensive performance tests they provide substantial information for pavement design and the optimum binder content of the HMA base layer, where the maximum tensile strains due to traffic loading occurs. Figure 10 gives an example of the effect of higher binder content on the fatigue of HMA. At specific strain levels (ε) permissible number of load cycles (N_{perm}) significantly increase with higher binder content. This may lead to a rich-bottom mix that is defined as having a binder content that is up to 0.5 m-% higher than the optimum binder content according to the traditional Marshal mix design. Rich-bottom design increases the fatigue life of the pavement structure when compared to the conventional pavement structure. Fatigue tests in combination with economic analysis can prove a cost-effective design for pavement structures with higher HMA binder content of the base layer.

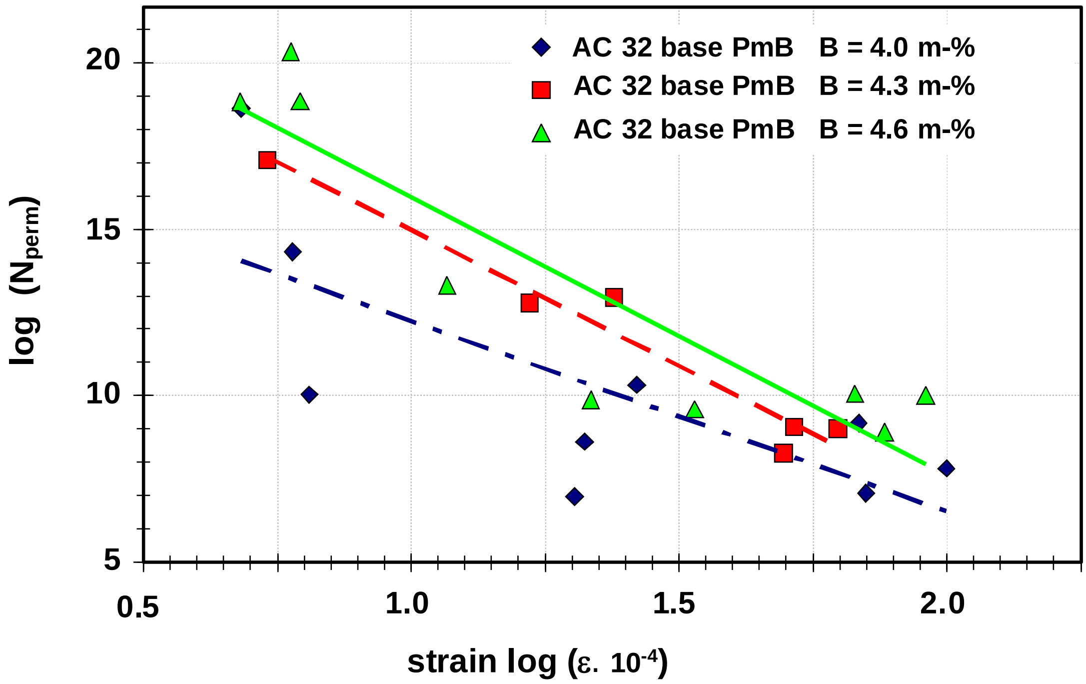

Figure 10. Fatigue curves of AC 32 base HMA type vs. binder content

4. PERMANENT DEFORMATION BEHAVIOR

4.1. Background

Currently one of the main challenging topics in flexible pavement research is the fundamental description of the performance behavior of bituminous mixtures at elevated temperatures. For a better understanding of the permanent deformation behavior tests that realistically simulate in-situ stress conditions and traffic loads are necessary. Permanent deformation can be related to the material characteristics of HMA at hot temperatures in combination with deviatoric stresses and strains under load application. Therefore pavement surface and binder course are most susceptible to permanent deformation. Dynamic or repeated axial load tests with or without confining pressures (unconfined or confined), where these triaxial stress conditions are simulated are considered as most reliable test methods to characteristics the resistance to permanent deformations of bituminous mixtures.

4.2. Test method

The triaxial cyclic compression test TCCT was implemented into the series of harmonized European Standards for testing of HMA to assess the resistance to permanent deformation at high temperatures (rutting). The standard test procedure consists of a cyclic dynamic axial loading $\sigma_A(t)$ to simulate a tire passing a pavement structure and a radial confining pressure σ_c to consider the confinement of the material within the pavement structure. The axial loading σA(t) can either be shaped as a sinusoidal function (Figure 11a) or a block-impulse (Figure 11b).

The standard states that the confining pressure σ_C can either be held constant or oscillate dynamically without providing more specific information. However, The TCCT recommended for performance testing is loaded by a sinusoidal axial at a constant confinement loading, respectively.

Figure 12 shows a triaxial testing cell used for permanent deformation tests on HMA. A servo-hydraulic regulated and programmable machine with two independent servo-channels is necessary one to drive the axial loads and the other one for confining pressure. It is possible to run both static tests, i.e. creep tests, and dynamic tests even with dynamic, oscillating confining pressure.

The axial strain $\varepsilon_N = \varepsilon_{ax}(n)$ is determined for the complete test and drawn in a load-cycle-strain diagram with linear scale for both axes. The resulting creep curve shows two characteristic phases: a primary non linear and a secondary creep phase with a quasi-constant incline of the creep curve. The creep rate f_c in micrometer per meter per load cycle (µm/m/n) can now be determined as incline of the linear approximation function that is fitted to the quasi-linear part of the creep curve (Figure 13).

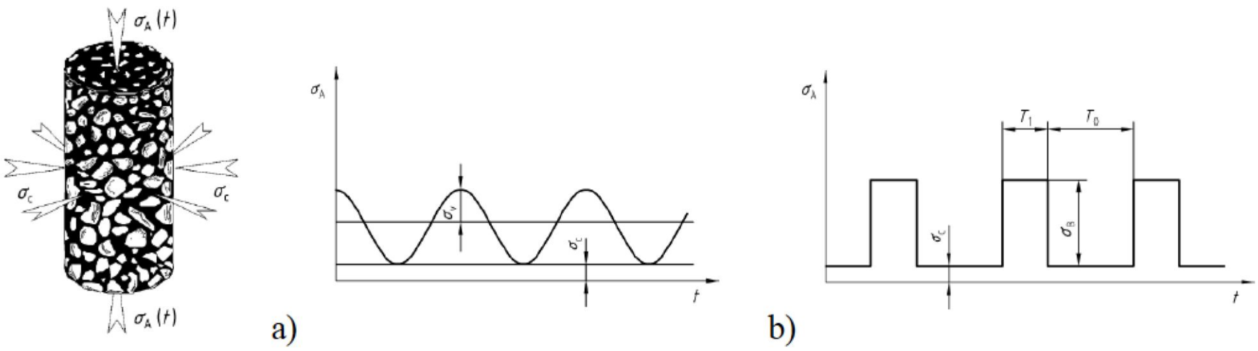

Figure 11. Loading conditions in the TCCT
a) sinusoidal shaped axial loading and b) block-impulses as axial loading, both with constant confining pressure [EN 12697-25, 2005]

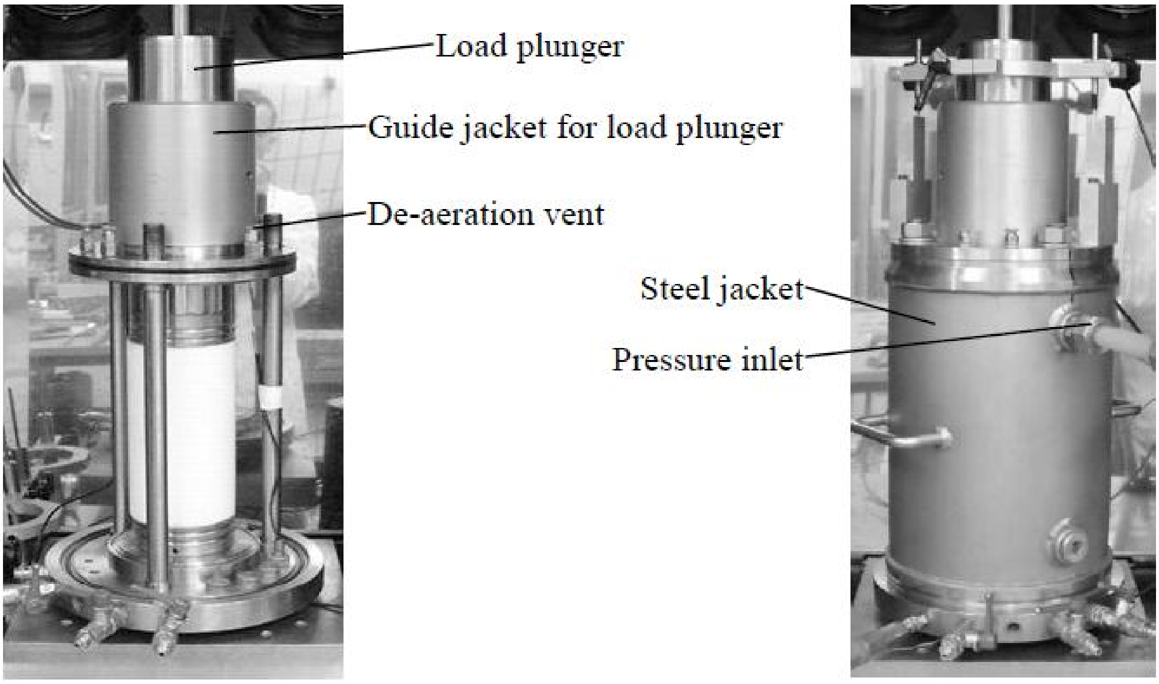

Figure 12. Main elements of a triaxial cell used for permanent deformation tests [1]

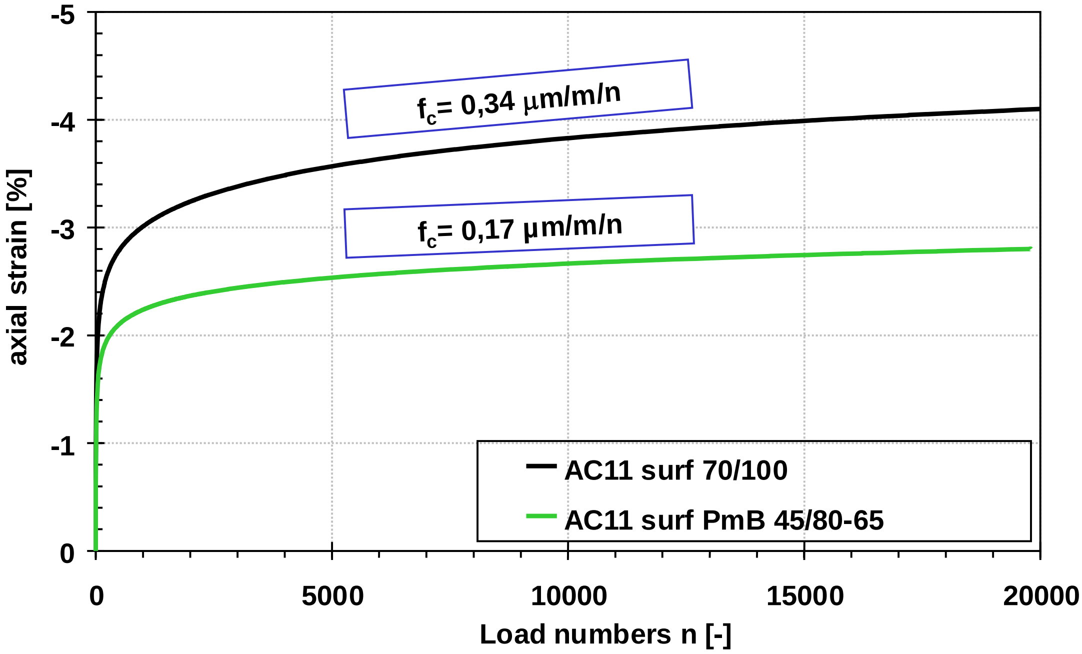

Figure 13. Creep curves for HMA type AC 11 surface with two different of binders

4.3. Prediction Model

For the prediction of permanent deformation in flexible pavement layers in a first step a modified deformation law model can be employed that was described first by Franken et al. [6]. It is based on repeated triaxial compression tests in combination with the linear elastic layer theory, which means that stresses and strains required for this model are calculated or computed on the base of linear-elastic material models. This approach is justified for practical purposes due to the fact that the results obtained from this theory coincide with those from other models, i.e. visco-elastic material models [7].

On the base of TCCT carried out at different temperatures, frequencies and stress combinations, the plastic deformation modulus $|E_p|$ can be derived. It can be expressed, e.g. in relation to the HMA air void content, the evolution of the creep curves and the complex modulus E*. The deformation law derived from the laboratory tests may in consequence be introduced into numerical pavement models to predict permanent deformation.

Figure 14 shows for example the prediction of the permanent vertical deformation ε_p in the cross section of a flexible pavement structure consisting of 0,04 m stone mastic layer (SMA), 0,08 m polymer-modified, high modulus binder layer and 0,12 m conventional asphalt base layer. For the simulation of specific climatic conditions at the site under consideration representative temperature distributions in the flexible layers are considered within the computations. Heavy vehicle traffic is simulated by 4 .10^5 loadings of a 100 kN standard axle load (ESAL). Vehicle speed can be related to the frequency of the dynamic axial loading during the material test, e.g. about 3 Hz for creep speed at a cross section area.

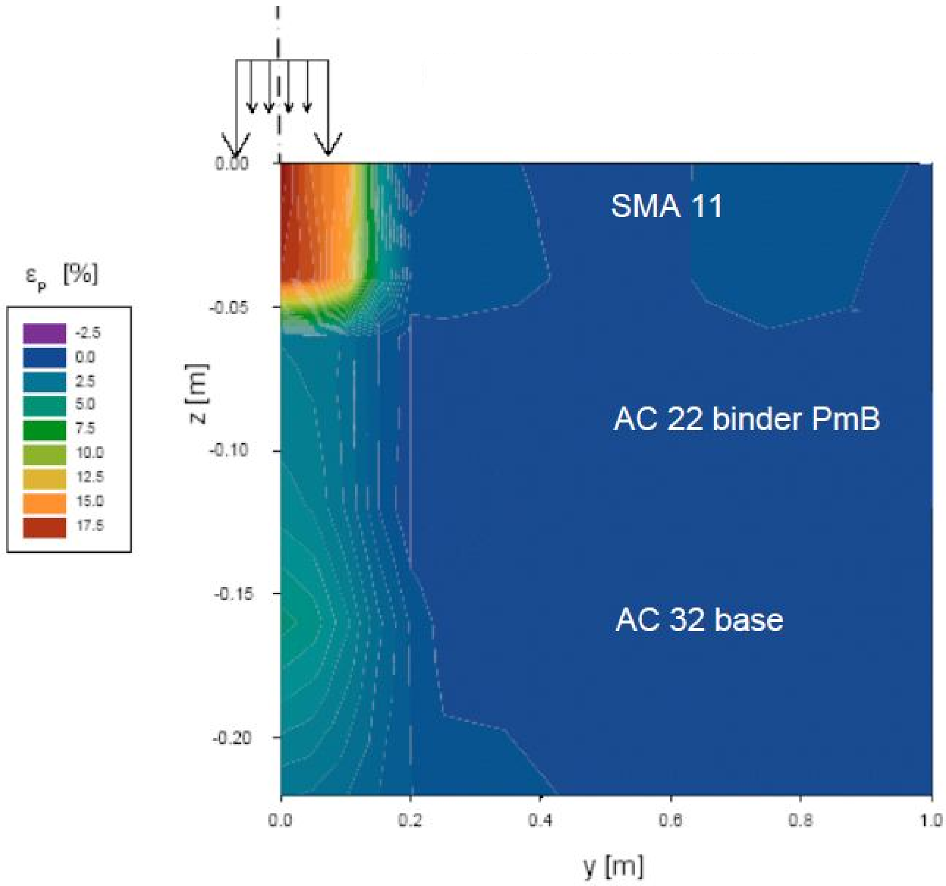

Figure 14. Prediction of plastic deformations in a flexible pavement structure after $4.0*10^5$ ESAL's at creep speed (cross section) [1]

4.4. Implementation in the Mix Design Process

High resistance to permanent deformation is especially important for HMA types used in surface and binder courses. TCCT can be used within the mix design process to identify the optimum binder content in respect to maximum rutting resistance of the HMA. Figure 15 shows the TCCT test results of three different HMA binder types with identical grading curves but made of different rock types (steel slag, steel slag mixed with basaltic stones and limestone). Depicted is the derived creep rate drawn against the HMA binder content. It is demonstrated that both the binder content and the stone type clearly influences the susceptibility of permanent deformation of the mix.

For each HMA type a typical optimum binder content exists, where the creep rate f_c becomes a minimum. According to the previous experience this optimum binder content derived from the performance based TCCT is about 0.3 to 0.1 m-% lower then the binder content found by the traditional Marshal mix design method.

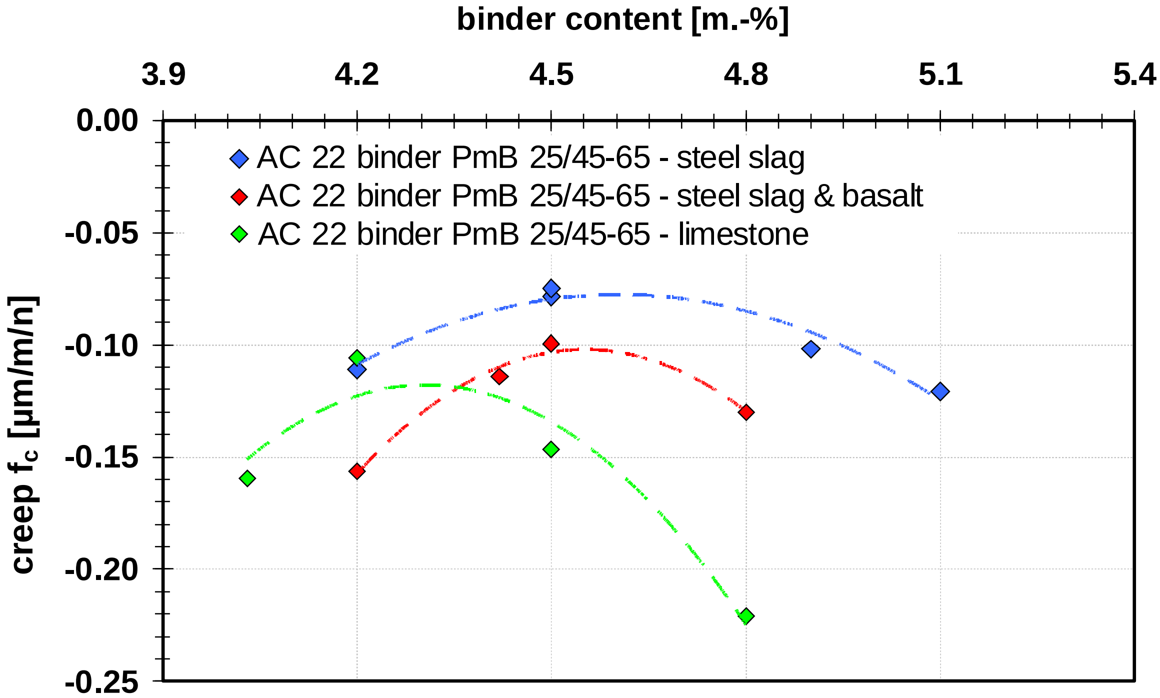

Figure 15. creep rate from TCCT vs. binder content

5. CONCLUSIONS

Road constructions today should last longer and endure high traffic loads under challenging climatic conditions. Moreover, traffic densities, axle loads and tire pressures will continue to increase during the next years and decades. To guarantee a long life cycle of flexible and semi rigid pavement structures the optimization of pavement materials in general and bituminous mixtures in particular is getting more and more important in order to avoid damages and subsequently minimize costs for road construction and maintenance.

Therefore prediction of in-service performance of road pavements during their live time is one of the main challenges of pavement research these days. For flexible pavements the key performance characteristics are fatigue and low-temperature, as well as permanent deformation behavior at elevated temperatures. Enhanced test methods, so called performance based tests, to address these key characteristics are implemented in the latest European standards. So called fundamental requirements for HMA may be specified by the road authorities. These performance tests are used on the one hand to significantly improve the mix design process of bituminous mixtures. On the other hand they provide material input parameters for numerical models that are employed to more reliably predict in-service performance of specific flexible pavement structures.

In combination with enhanced binder tests the implementation of performance-based HMA specifications are the future way to create an innovative road engineering environment in a common Europe.

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