RISK ASSESSMENT OF LOW-TEMPERATURE CRACKING OF ASPHALT – AN EXPERIMENTAL STUDY

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ABSTRACT

Low-temperature cracking occurs when the stresses resulting from thermal shrinkage during cooling exceed the tensile strength of asphalt. Due to the continuous stress relaxation in the binder (bitumen), the risk of low-temperature cracking becomes a function of the loading rate, which is preliminary given by the development of thermal-shrinkage strains controlled by the cooling rate, and the tensile strength of the asphalt mix and the viscosity of bitumen, both increasing with decreasing temperature. However, as regards the tensile strength of the bitumen-aggregate composite, the difference of the thermal dilation between bitumen and aggregate weakens the bitumen-aggregate interaction, causing a decrease of the tensile strength of the composite for low temperatures.

This paper presents recent research work of the Christian Doppler Laboratory for "Performance-based optimization of flexible road pavements" at Vienna University of Technology, focusing on the risk assessment of low-temperature cracking of asphalt. Asphalt mixtures, commonly used for pavement construction, as well as innovative materials, are investigated by means of tensile stress restrained specimen tests (TSRSTs). Hereby, in a first step, the two competing processes, i.e., (i) thermal shrinkage and (ii) stress relaxation resulting from the viscous behaviour of bitumen are studied separately. The combination of the respective results from this tests with the experimental data obtained from the TSRST provides access to the inelastic strains associated with cracking and, hence, to risk of low-temperature failure of asphalt.

As regards the employed testing procedure, the main parameters, such as the cooling rate (defining the rate of loading via thermal shrinkage), the specimen shape, and the mixture characteristics of the tested asphalt, are varied. Respective results and conclusions will be presented at the congress.

1 INTRODUCTION

Low-temperature creep of asphalt provides the stress relaxation capacity in flexible pavements required to avoid cracking as consequence of thermal-shrinkage during cold winter periods. The viscosity of asphalt and, hence, its creep capacity is mainly linked to the rheological behaviour of the used binder material. Low-temperature cracking of asphalt, on the other hand, is controlled by the bitumen, the aggregate, and the properties of the bitumen-aggregate interface. In order to develop a material model, covering the material behaviour of the different constituents, the multiscale approach is employed. Within the developed multiscale model, five scales of observation are introduced (see Fig. 1).

Hereby, at the lowest (bitumen-) scale, with a characteristic length of a few μm, the material is composed of clusters of large-scale molecules (asphaltenes) distributed in the maltene matrix [1, 2]. At the next higher scale, the so-called mastic-scale, the filler, i.e., aggregates with a diameter lower than 125 μm, is introduced. The sand, i.e., aggregate with a diameter lower than 2 mm is considered at the mortar-scale, whereas stone and air voids are introduced at the asphalt scale. The input data for multiscale models, such as shown in Figure 1, are the mechanical properties, the volume fractions, and the shape of the constituents and the interaction between different constituents (asphaltenes, maltenes, filler, …). By means of upscaling of information from one to the next higher scale of observation it is aimed to finally obtain macroscopic material parameters for macroscopic analyses of flexible pavements. For the assessment of the employed upscaling technique, so-called verification experiments are required. In contrast to the identification experiments, providing the input data for the multiscale model, verification experiments are performed on composite materials, such as mastic, mortar and asphalt.

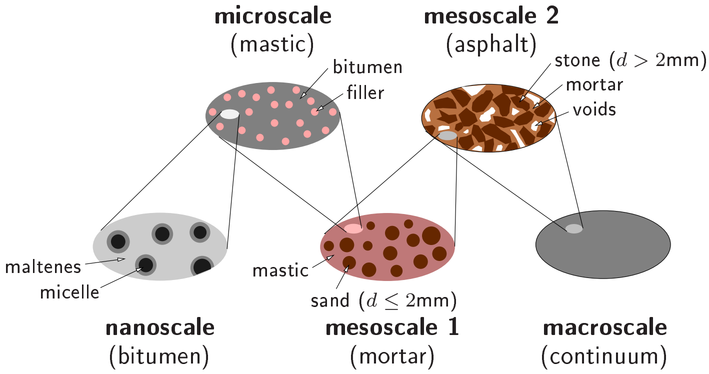


Figure 1: Multiscale model for asphalt comprising five scales of observation [2].

In this paper, the tensile stress restrained specimens test system (TSRST) is reviewed in the context of the multiscale model depicted in Figure 1. By considering different types of asphalt mixtures, the TSRST represents a verification experiment at the asphalt scale. The complex material behaviour of asphalt during TSRST testing, including thermal-shrinkage, low-temperature creep, and fracture, requires special consideration of the different phenomena involved. Experimental technique, allowing distinguishing between the different phenomena, will be presented in this paper.

In the following section, the motivation of TSRST testing is given. Moreover, additional experiments required to separate different types of material behaviour are briefly described. Thereafter, first test results are presented, allowing to describe four different material characteristics, i.e., elastic response, thermal dilation, low-temperature creep, and fracture. The incorporation of this information within the proposed multiscale model closes the paper.

2 MOTIVATION & EXPERIMENTAL PROGRAMME

Low-temperature cracking of flexible pavements result from thermal-shrinkage during cooling, inducing tensile stress in the asphalt. The TSRST was developed in order to simulate this situation in flexible pavement layer. While the deformation of the specimen is restrained, the temperature is reduced by a pre-specified cooling rate. The temperature decrease results in a continuous change of material properties, resulting from the temperature-dependence of the mechanical behaviour of bitumen. Accordingly, for the interpretation of TSRST results, the effect of the temperature on material parameters describing asphalt behaviour is required. Hence, in addition to the TSRST, unrestrained thermal-shrinkage tests (TST) and relaxation tests (RT) are performed. While the TST provides the coefficient of thermal expansion (α_T) as a function of the temperature, relaxation tests are performed at different temperatures, providing the effect of the temperature on the relaxation capacity of asphalt. Finally, the stress rate in the TSRST specimen is obtained from

$$\dot{\sigma}(T) = E(T) \cdot (\dot{\varepsilon} - \dot{\varepsilon}^{relax} - \dot{\varepsilon}^{crack} - \dot{\varepsilon}^{T}), \quad (1)$$

where $\dot{\varepsilon} = 0$ and $\dot{\varepsilon}^{T} = \alpha_T(T)\dot{T}$.

$\dot{\varepsilon}^{relax}$ in Equation (1) is associated with the relaxation capacity of asphalt. During TSRST testing, $\dot{\sigma}(T)$ is continuously monitored, finally giving access to the inelastic strains associated with cracking (ε^{crack}). Hereby, E(T) is determined from the instantaneous material response at the beginning of the relaxation tests.

In order to assess the risk of low-temperature cracking, the stress induced by thermal shrinkage is compared with the respective tensile strength. The latter is determined by uniaxial tensile strength tests (UTST). These tests are performed with constant strain rate and isothermal conditions. Hence, in contrast to the TSRST, $\dot{\varepsilon} = \text{constant}$ and $\dot{\varepsilon}^{T} = 0$.

Combining the results of the TSRST and the UTST, two parameters describing the risk of low-temperature cracking, i.e., the tensile strength reserve and the critical cracking temperature can be determined (see Figure 2). Moreover, based on $\varepsilon^{crack}(T)$ provided by both test methods, the state of damage in the asphalt can be associated to bitumen, aggregate, and for interface failure. Respective assumption introduced by the multiscale model will be reified by these test results.

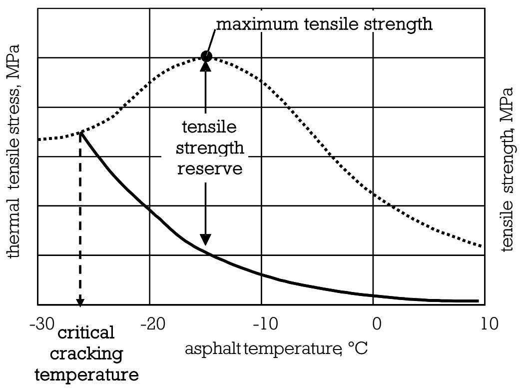


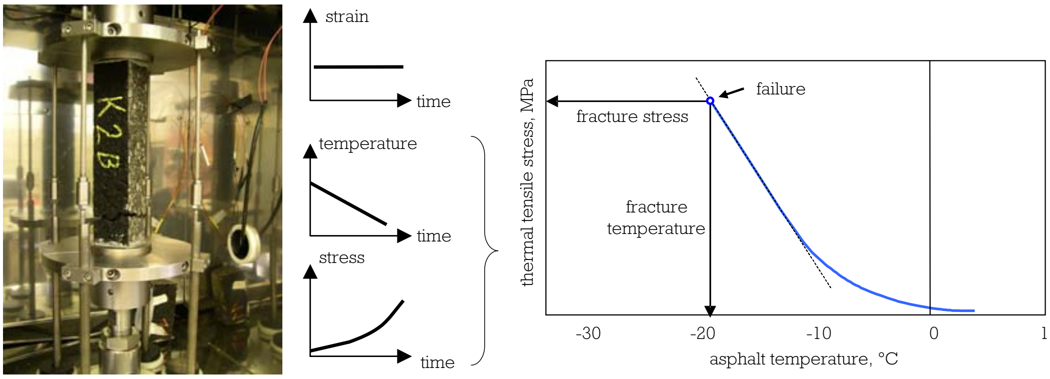
Figure 2: Superposition – tensile strength reserve.

4 TEST PROCEDURE & EQUIPMENT

In order to avoid errors on test results arising from the use of different test equipment, all experiments mentioned in the previous section, i.e., (i) unrestrained thermal dilation test, (ii) relaxation tests, (iii) TSRST, and (iv) uniaxial tensile tests, are performed employing the same testing equipment. In the following, the test procedure, allowing to perform this variety of tests, are briefly described.

4.1 Test procedures

For the tensile stress restrained specimen test (TSRST) a beam specimen is mounted in a load frame, which is enclosed in a cooling chamber. During the experiment the length of the specimen is kept constant and the temperature is decreased with a constant cooling rate. Any movement of the specimen as consequence of thermal shrinkage is monitored by LVDTs, activating a screw jack, which stretches the specimen back to its original length. This process continues until the tensile stress exceeds the tensile strength and, hence, the specimen fractures. While different cooling rates are possible, the standard procedure starts at 20°C and has a cooling rate of 10°C/h [3]. An illustration of the test procedure of the TSRST is given in Figure 3.



(a) (b)

Figure 3: TSRST: (a) experimental setup and (b) illustration of result from TSRST.

In contrast to the TSRST, for the TST the asphalt specimen is not restrained. This test allows to derive the thermal expansion (α_T). Test parameters such as the start temperature and the cooling rate are the same as for the TSRST.

The relaxation test is conducted at constant temperature (isothermal condition). Relaxation time (τ) and stiffness (E) are monitored at the considered testing temperatures. The test is performed in three steps: first, the specimen is cooled to the testing temperature (stress-free). Thereafter, a strain increment is applied, giving access to the instantaneous (elastic) material response. In the third step, the strain is kept constant and the relaxation of stress is monitored. In order to avoid damage of the specimen, the stresses induced by the strain increment in step three may not exceed 30% of the tensile strength of asphalt at the considered temperature. Commonly, the relaxation test is performed at +20, +5, -10 and -25°C [3].

Similar to the RT, the UTST is conducted at specified temperatures: +20, +5, -10 and -25°C. After stress-free cooling of the asphalt to the testing temperature, the tensile strength test is performed by applying a constant strain rate (1 mm/min) until the specimen fractures [3].

4.2 Test Equipment at the Christian-Doppler Laboratory

In order to eliminate errors arising from the use of different equipments, all four experiments described in the previous subsection are performed in the same testing machine. This electromechanical testing machine consists of a load frame, a screw jack, a computer data acquisition and control system, a climate chamber, a temperature controller, 4 LVDTs (linearly variable differential transducers), and a specimen-alignment stand (ref. also to [4, 5]). The climate chamber allows to control the temperatures within T= ±40°C (accuracy of ±0,5°C). The LVDTs are placed outside of the climate chamber (accuracy of 0,2%). In order to avoid a strong influence of temperature changes on the measurement device, the top and bottom plates and the measurement rods are made of invar steel. A beam or cylindrical specimen can be mounted in the load frame. The diameter can vary between 40 and 60 mm and the length between 150 and 300 mm. Figure 4 shows the setup of the employed testing equipment.

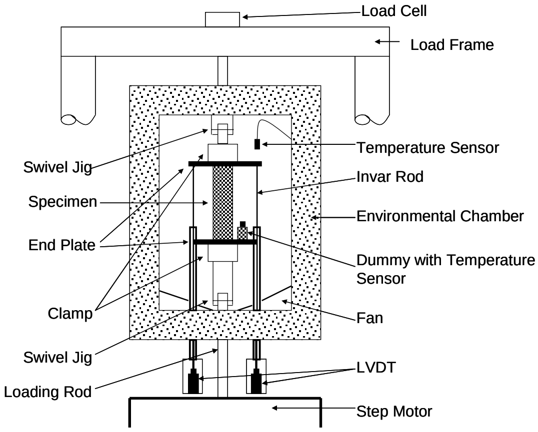
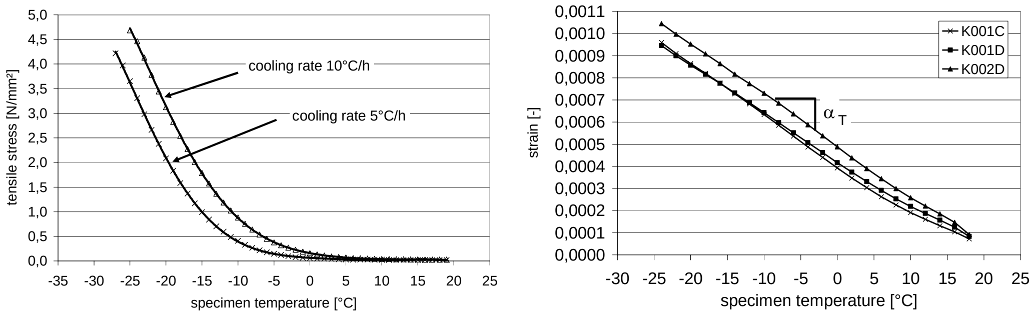


Figure 4: Illustration of setup of the employed testing equipment at the Christian-Doppler Laboratory.

5 FIRST TEST RESULTS

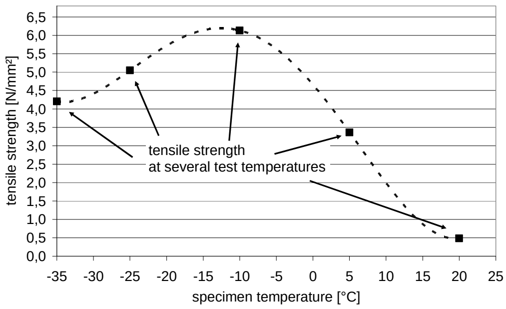
In this section, first results obtained from testing of AB 11, an asphalt concrete used for wearing courses commonly used in Austria, are presented.

Figure 5a shows the influence of the cooling rate, 5 and 10°C/h were chosen, for TSRST testing of AB 11. The lower the cooling rate, the more relaxation time is provided and, hence, the lower is the temperature at failure of the specimen. Moreover, the linearity of the stress-temperature curve at lower temperatures indicates that the influence of stress relaxation decreases with decreasing temperature. Figure 5b shows the result of shrinkage tests. This result gives access to the α_T as a function of the temperature. For the tested AB 11, α_T is more or less constant over the tested temperature range, with $\alpha_T = 2{,}2 \cdot 10^{-5}$ [1/°C]. Figure 6a shows the results of AB 11 subjected to tension tests at different temperatures (+20, +5, -10, -25 and -35°C), which allows to allocate a tensile strength curve (dotted line in Figure 6b). The maximum tensile strength is obtained for T = -12°C. After combination of the two results the tensile strength reserve and the maximum cracking temperature are obtained and illustrated in Figure 6b.

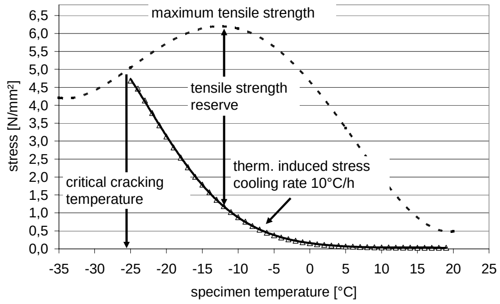


a.) b.)

Figure 5: Results from testing of AB 11: (a) TSRST and (b) shrinkage test to derive α_T.



a.)



b.)

Figure 6: Testing of AB 11: (a) UTST and (b) comparison between TSRST and UTST results.

6 CONCLUSION & OUTLOOK

For risk assessment of low-temperature cracking of asphalt the results of the TSRST and UTST are not sufficient. In addition to the TSRST and the tensile test, determination of the thermal expansion coefficient and the relaxation behaviour of asphalt by additional experiments are proposed in this paper. Based on these data, the inelastic deformations leading to low-temperature cracking can be derived.

In the future different asphalt mixture, commonly used for pavement construction, as well as innovative materials will be investigated using these four test methods. Hereby the TSRST will be performed with two different cooling rates (5 and 10°C/h). The uniaxial tensile test and the relaxation test will be performed at +20, +5, -10, -25 and -35°C, providing information over a wide temperature range. Respective results will be presented at the congress.

Finally, all test results will serve as input data to verify the employed upscaling scheme developed within the multiscale model for asphalt. Recent development an upscaling of creep, thermal, and strength properties can be found in [6].

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