A SINGLE RHEOLOGICAL MODEL TO DESCRIBE LOW TEMPERATURE BEHAVIOUR OF ASPHALT MIXTURRES ASSESSED IN DIFFERENT LABORATORY TEST METHODS

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ABSTRACT

One of the influences of the service life of an asphalt pavement is its low temperature behaviour. To address crack resistance of asphalt pavement exposed to low temperature four test methods are described in the European standard EN 12697-46:
- Thermal Stress Restrained Specimen Test (TSRST),
- Uniaxial Tension Stress Test (UTST),
- Tensile Creep Test (TCT) and
- Relaxation Test (RT).
In the study presented in this paper, a series of low temperature tests are performed on asphalt concrete AC 11, under variation of all test conditions. Based on the results of TCT, the parameters of the Burgers model are calculated and mathematically described in function of temperature and stress. This model is then systematically modified in order to describe the behaviour assessed by all four test methods.
For the TCT the viscosity of the singular damper is decreased in order to explain exponential increase in strain.
Analyzing the RT, it is found, that the singular damper and the singular spring show a damage effect from the moment at the beginning of the test.
In UTST the singular spring generates an increase in stress until the singular damper is damaged exponentially up to the specimen failure.
In TSRST the singular spring generates the increase in stress, until it is damaged and the specimen fails. The singular damper can be neglected for stress calculation.
As a result, essential rheological mechanisms related to low temperature behaviour of asphalt mixtures in static low temperature tests are described by a single model.

Keywords: Low-Temperature, Thermal Cracking, Rheology, crack propagation, Burgers-model

1. INTRODUCTION

One of the essential influences of the service life of an asphalt pavement is its low temperature behaviour. In order to address crack resistance of asphalt pavement, exposed to low temperature, four static test methods are described in the European standard EN 12697-46 [4]:

- Thermal Stress Restrained Specimen Test (TSRST),
- Uniaxial Tension Stress Test (UTST),
- Tensile Creep Test (TCT) and
- Relaxation Test (RT).

In the study presented in this paper, a series of low temperature tests are performed on an asphalt mixture of the type asphalt concrete AC 11, under variation of test conditions. Based on the results of TCT, the parameters of the Burgers model - a combination of elastic elements (springs) and viscous elements (damper) - are calculated and mathematically described in function of temperature and stress. Furthermore the model was expanded by a cryogenic strain element to simulate the results of TSRST [2].

With this model, the so called base model, it should be possible to describe the behaviour assessed by the three other test methods. However, the resulting congruence of the measured and the calculated strain was not satisfying. Therefore the model was systematically modified, assuming that the specimens are always damaged during the tests, independently from the type of test. In order to simulate this damage a decrease in the values of all elements of the burgers model was implemented. This decrease depends on the measured stress and strain, so that the test results directly influence the damage effect.

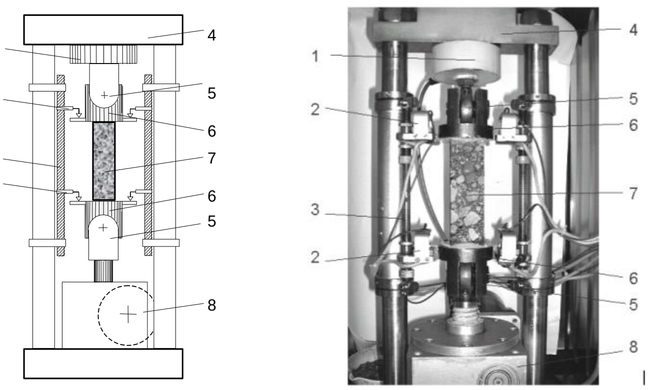
2. TEST EQUIPMENT AND EXPERIMENTAL DATA

2.1. **Test equipment**

The used test equipment is shown in Figure 1, representing the apparatus at the Braunschweig Pavement Engineering Centre (ISBS, Germany) (see e.g. [3]). The frame consists of a base plate of high bending resistance and two columns supporting a stiff crossbeam. A gearbox with stepping motor is fixed to the base plate and can generate movements with an accuracy of 0.05 µm. At the crossbeam the control unit is fixed for controlling the force or displacement applied. In order to avoid radial and/or transversal forces as well as moments in the test specimen, it is placed between the gearbox and the pressure measurement equipment with two gimbal suspensions.

The system is placed in a thermostatic cabinet with temperature control. The temperature range extends from – 40 °C to +40 °C with an accuracy of ± 0.3 °C. The temperature of the test specimen is measured indirectly by means of a temperature sensor positioned in the middle of the cross-section of a dummy of the same cross-section as the specimen. As the steel frame is exposed to the same thermal changes as the examined specimens, it reacts with thermal shrinkage and expansion. Thus, the correct measuring of the actual strain of the specimen requires a basis with constant length at various temperatures. Therefore, two measurement bases with thermal indifference made of carbon fibres help to measure the real deformation of the test specimen and to counterbalance the thermal strain of the test equipment. Figure 1 shows a principle sketch and a photo of the test device.

During the test the force is recorded by a load cell fixed to the cross beam (1, Figure 1) whereas the specimen length of the specimen is measured by 4 displacement transducers (2, Figure 1).



1 load cell
2 displacement transducer
3 thermal indifferent measurement base
4 crossbeam
5 gimbal suspension
6 adapter
7 specimen
8 gear box with stepping motor

Figure 1: Layout of a test device used for conducting static low temperature tests.

The specimen is fixed centrally within two adapters with a two-component epoxy resin adhesive. After curing of the adhesive, the specimen is put between the gimbal suspensions of the test device. At ISBS, prismatic specimens are used with the dimensions 40 x 40 x 160 mm³ for asphalt mixes with a maximum grain size of 11 mm. The specimens are sawn from asphalt plates compacted in the laboratory.

2.2. Experimental data

2.2.1. Tensile Stress Restrained Specimen Test

The tensile stress restrained specimen test (TSRST) is a cooling test in which temperature is reduced at a constant rate. After the installation of the test specimen it is brought to an initial temperature without inducing any stress. During the test the temperature is reduced by e.g. dT = -10 K/h, while the deformation of the specimen is restrained. This will generate a rising cryogenic tensile stress until the tensile force reaches the material's tensile strength and the specimen fractures. The used test results are depicted in Figure 2 for asphalt concrete AC 11 for four different cooling rates. For the following modelling the whole curve progression and not only the results at the fracture point are used.

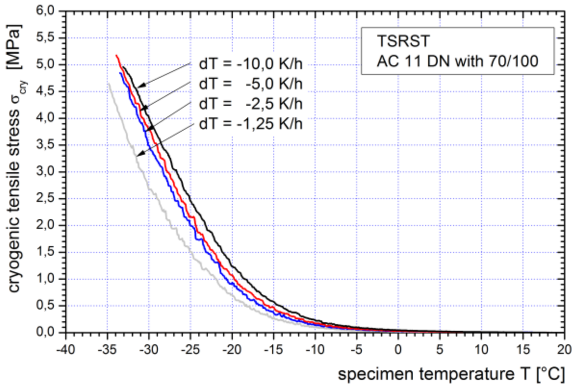


Figure 2: TSRST results for AC 11 with four different cooling rates [2].

2.2.2. Uniaxial tensile stress test

The tensile strength of asphalt mixtures is a critical factor in cracking resistance. During the uniaxial tensile stress test (UTST), the asphalt specimen is loaded by a tensile displacement until fracture occurs, and strength is determined from the maximum load and the specimen dimensions.
After stress-free cooling of the specimen to the test temperature (+25 °C, +5 °C, -10 °C or -25 °C), a constant deformation rate dε is applied. The test is stopped as soon as the applied load has reached a maximum and fracture occurs. In Figure 3 the results of the tests for the temperature of -10 °C and four different strain rates dε are shown. For modelling it is insufficient to use the results at the fracture point or maximum only, but the whole curve of progression is needed.

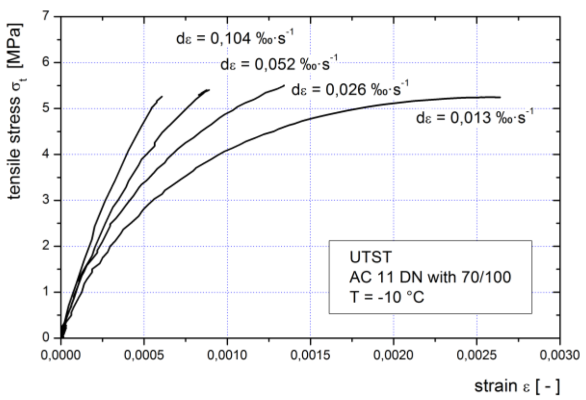


Figure 3: UTST results for AC 11 at -10 °C and different strain rates [2].

The results in generally show that the increase of strain rate will change the behaviour from a ductile to a brittle fracture. This includes an increase in reaching the tensile strength. At -25 °C only brittle fractures can be observed without any influence of the strain rate.

Furthermore the behaviour changes with test temperature. At higher temperatures (+20 °C and +5 °C) ductile fractures can be observed while lower temperatures will result in brittle fractures.

2.2.3. Relaxation test

For the relaxation test (RT) the specimen is cooled down stress-free to test temperature, ranging from +25 °C down to -25 °C. After reaching the test temperature, a starting stress σ_0 is applied spontaneously by applying a specific strain. In the following process the strain is kept constant, while the stress decreases.
This relaxation process depends on test temperature and lasts from some seconds (+20 °C) up to more than 48 hours (end of data recording) at -25 °C.
In Figure 4 three relaxation curves at -10 °C with different start stresses are shown.

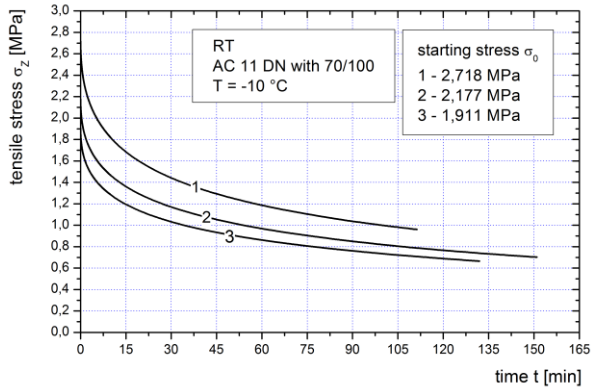


Figure 4: RT results for AC 11 at -10 °C and different starting stresses [2].

At the test temperatures +20 °C and +5 °C the relaxation process decreases down to zero stress. For the temperatures of -10 °C and especially -25 °C an amount of stress up to 50 % of the stress at the beginning remains after the test has been stopped (48 hours).

2.2.4. Tension Creep Test

In the tension creep test (TCT) the specimen is cooled down stress-free to test temperature (usually +25 °C, +5 °C, -10 °C or -25 °C). After reaching the test temperature, a constant stress σ_Z is applied spontaneously. In the following process the resulting strain is recorded up to 8 hours.
The increase of strain (creeping) depends on the applied stress. Higher stresses result in a faster increase of strain so that the end of test (8 hours) is not reached in any case.
Figure 5 shows 8 retardation (creep) curves at -10 °C test temperature with different constant stresses.

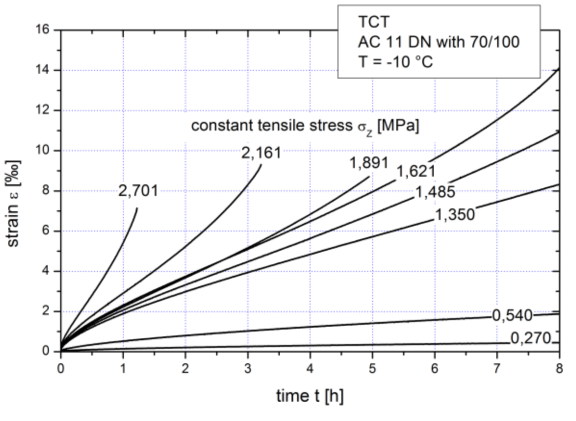
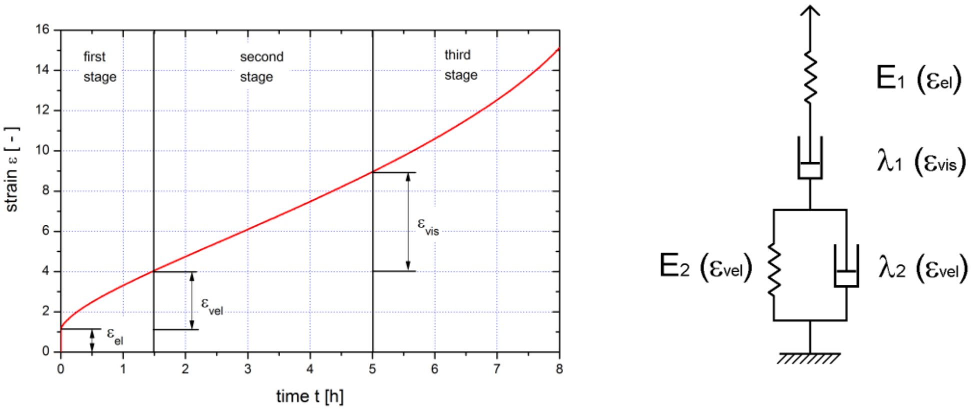


Figure 5: TCT results for AC 11 at -10 °C and different constant stresses [2].

Especially the tension creep test can be used for the burgers model. In this model two linear elastic springs (E_1 and E_2) and two linear viscous dampers (λ_1 and λ_2) are combined as shown in Figure 6. On the basis of the resulting strain in the

TCT the parameters of the four elements of the burgers model can directly be calculated. Figure 6 shows the conversion of the strain to the corresponding elements.



(a) (b)

Figure 6: Resulting strain of a TCT (a) and direct conversion into the elements of the burgers model (b).

3. BASE MODEL

Arand et al. [1] determined the dependency of the parameters in the burgers model for TCTs from temperature and stress. Büchler [2] united this dependency mathematically, as shown in Equation 1 and Table 1.

$$\lambda_{1,2} = 10^{(a_0+a_1\cdot T+a_2\cdot T^2)+\left(b_0+b_1\cdot e^{T/b_2}\right)\cdot\sigma} \quad \text{respectivly} \quad E_{1,2} = 10^{(a_0+a_1\cdot T+a_2\cdot T^2)+\left(b_0+b_1\cdot e^{T/b_2}\right)\cdot\sigma} \qquad \textbf{Eq. 1}$$

Table 1: Factors a_0, a_1, a_2, b_0, b_1 and b_2 to describe the stress and temperature dependency of the parameters in the burgers model

Burgers-Parameter	a_0	a_1	a_2	b_0	b_1	b_2
E_1	2,49858	-0,06540	-	0,0	1,92035	11,93873
E_2	2,10912	-0,06696	-	0,0	1,23597	15,49257
λ_1	6,41250	-0,05704	0,00187	-0,22554	-0,34084	5,00908
λ_2	5,85220	-0,09893	0,00242	-0,11814	-0,86968	7,71826

In order to describe TSRST behaviour the burgers model has to be expanded by a cryogenic strain element ε_T, depending on the thermal strain coefficient α and the temperature rate dT, as given by Equation 2.

$$\varepsilon_T = \alpha \cdot dT \qquad \textbf{Eq. 2}$$

In theory this expanded burgers model should be able to simulate all results of the four different test methods.
However, in reality clear deviations are observed, as illustrated in Figure 7 by an example of a TCT at ±0°C and a stress of 0,547 MPa.

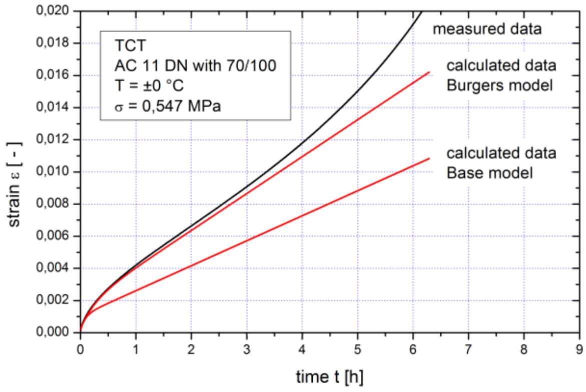


Figure 7: TCT – measured strain and calculated strain by burgers model and base model.

The curve calculated by the base model differs from the measured strain. The reason can be found in a smoothing effect by describing the parameters of the burgers model functionally. This can effect broad deviations for single test results, as shown in Figure 7. This effect has to be considered in view of all four test methods. Another handicap of the base model is, that the disproportionately increase at the end of the test cannot be calculated.

So far, the verification for the remaining three test methods leads to the following results:

- The results of the relaxation tests are verified qualitatively. That means the shape of the relaxation curve can be described, but there is no complete congruence. The effect of smoothing has to be explored more in detail.
- Describing the results of the TSRST the shape of the curves can be described in a qualitative way, but there are more differences than the effect of smoothing.
- The results of the UTST cannot be described in a satisfying. For this test method, further effects have to be explored.

4. MODIFICATION

As the application of the base model doesn't show a satisfying congruence, it has to be modified. The modification is executed on each element of the burgers model in the same way.
At first, there has to be introduced a factor d_1 to eliminate the possible effect of smoothing. The second factor d_2 shall reduce the value of the spring or damper in dependency of an influence value which has to be specified. Every parameter of the burgers elements will be modified in the following way:

$$\text{Modified Burgers parameter}(\sigma, T, \text{influence value}) = \frac{\text{Burgers parameter}(\sigma, T)}{d_1 \cdot d_2^{\text{influence value}}} \qquad \textbf{Eq. 3}$$

Considering this modification 8 additional coefficients d_1 to d_8 have to be determined for each test. These coefficients stay constant for one individual test and in ideal case for one test method. Furthermore it is to be tested, if all coefficients are indispensable.

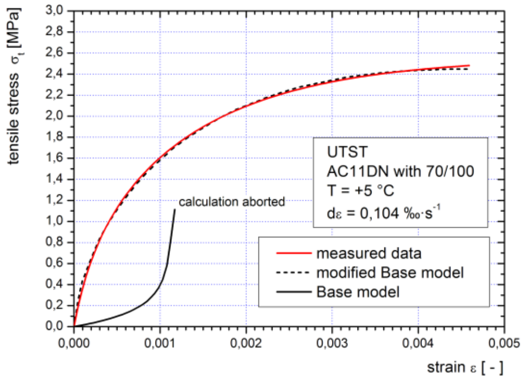
Consequently, all the four elements of the burgers model are modified as described by Equation 4:

$$E_1 \Rightarrow \frac{E_1}{d_1 \cdot d_2^{\varepsilon}}, \quad \lambda_1 \Rightarrow \frac{\lambda_1}{d_3 \cdot d_4^{\varepsilon}}, \quad E_2 \Rightarrow \frac{E_2}{d_5 \cdot d_6^{\varepsilon}} \text{ and } \quad \lambda_2 \Rightarrow \frac{\lambda_2}{d_7 \cdot d_8^{\varepsilon}} \qquad \textbf{Eq. 4}$$

with E_1, E_2 = spring (functionally described dependency from temperature and stress)
λ_1, λ_2 = damper (functionally described dependency from temperature and stress),
d_1 to d_8 = coefficient
ε = influence value, in this case: resulting strain in a TCT

The test methods TSRST, UTST and RT are modified in analogy.

In figure 8 the impact of the modification is shown exemplarily for a UTST and a TSRST. The coefficient of determination exceeds 0,99 in nearly all regressions.



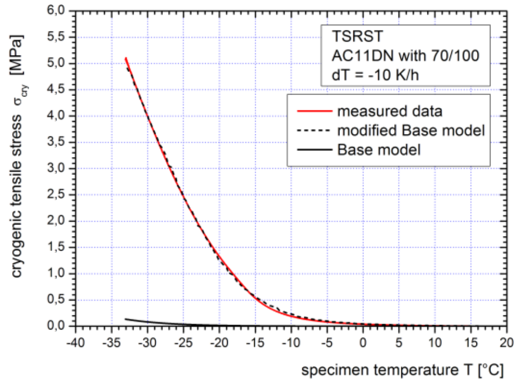


Figure 8: Impact of the modification of the Base model for a UTST (left) and a TSRST (right).

5. VERIFICATION OF THE MODIFIED MODEL

5.1. **TSRST**

The resulting stress is chosen as the influencing value, so that a possible damage is considered by the calculated stress. For the coefficients d_1 to d_8 the values of the damper λ_1 increase, so that the damper has no effect on the test results. As a conclusion the damper λ_1 is not necessary and can be dispensed in the model.
The values of the damper λ_2 change little while the values of the springs E_1 and E_2 are important. At the end of the tests, the values of E_1 decrease (see Figure 9) which can be interpreted as a damaging effect of E_1.

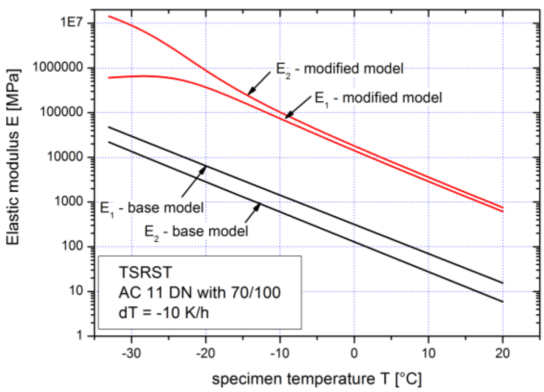


Figure 9: TSRST - values of the springs E_1 and E_2 in the base model and the modified model, dT = -10 K/h.

In Figure 10 the individual strains of each element in the modified model are shown. The overall strain can be represented by the spring E_1 (elastic part). The spring becomes harder with falling temperature. Fracture corresponds to the fracture of the specimen.

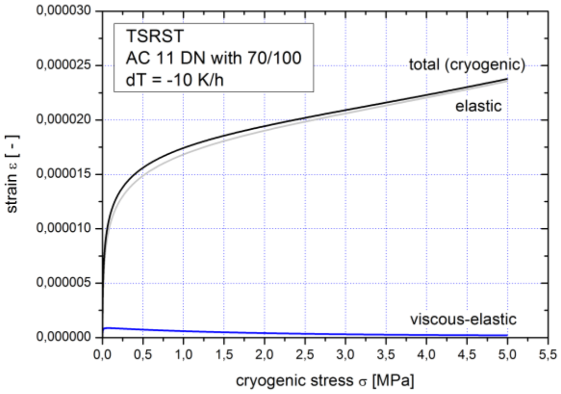


Figure 10: TSRST - individual strain values for the elements of the modified model, dT = -10 K/h.

5.2. UTST

Again the resulting stress is chosen as the influencing value.
The modified model is represented by slightly damaged values for the springs E_1 and E_2. The values of the two dampers λ_1 and λ_2 fall logarithmically over the resulting stress (see Figure 11). Strain increases disproportionally before fracture.

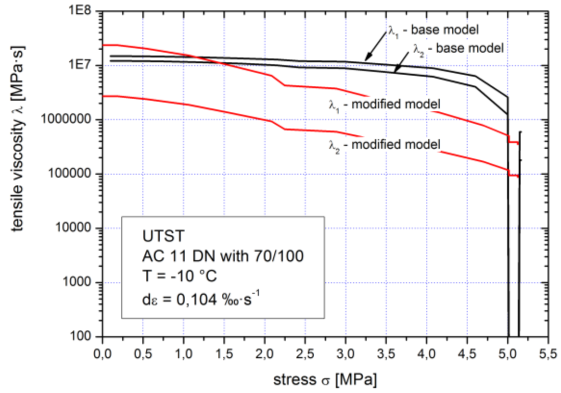


Figure 11: UTST - values of the dampers λ_1 and λ_2 in the base model and the modified model, T = -10 °C, dε = 0,104 ‰/s.

Figure 12 shows the individual strain values of the elements in the modified model. With the beginning of the disproportional increase of strain, the damper λ_1 is damaged.

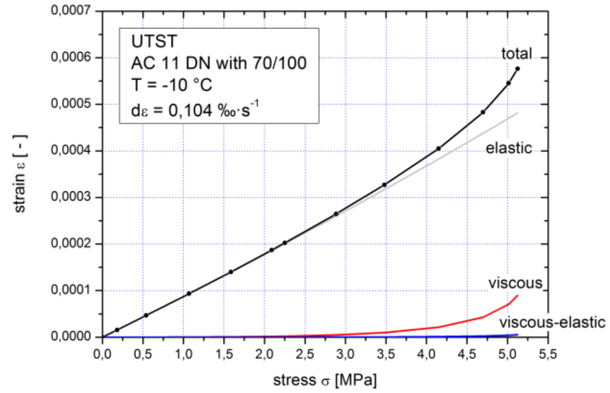


Figure 12: UTST - Individual strain values for the elements of the modified model, T = -10 K/h, dε = 0,104 ‰/s.

5.3. RT

For covering relaxation test results, the resulting (decreasing) stress was used as the influencing value. This modification results in hardly any change in the values for E_2 and λ_2. But the values of λ_1 decrease much at the start of the test (see Figure 13). This was interpreted as a damaging effect caused by the (nearly) spontaneous increase of stress. With a decrease in test temperature the values of E_1 decrease at the starting point. Only this partially strong decrease in values will allow for estimation of the measured relaxation.

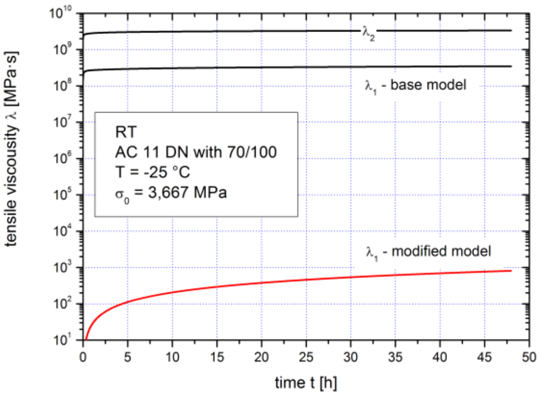


Figure 13: RT - values of the damper λ_1 and λ_2 in the base model and the modified model (λ_1 only), T = -25 °C, σ_0 = 3,667 MPa.

The individual strain values of the elements show that the relaxation process is realized only by the spring E_1 and the damper λ_1 (see Figure 14). This is equivalent to the Maxwell model.

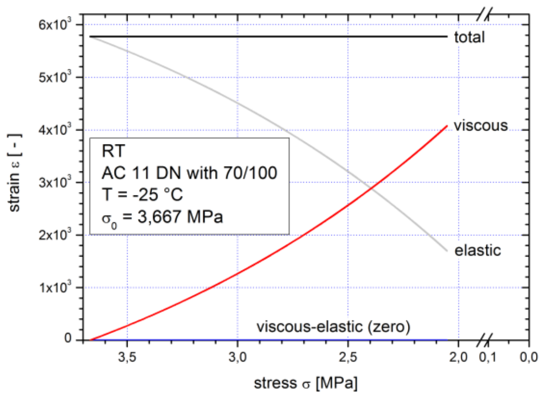


Figure 14: RT - individual strain values for the elements of the modified model, T = -25 °C, σ_0 = 3,667 MPa.

5.4. TCT

For consideration of the increasing strain in the third stage of TCT, the resulting strain used as is the influencing value. Parameter E_1 was changed, and damper λ_1 was modified in order to cover the disproportional increase in strain.

In Figure 15 the individual strain values of the elements can be observed. The elastic strain values stay constant, while the viscous-elastic strain values increase up to the maximum stress of the spring E_2. The viscous part displays the increase in strain including the disproportional increase at the end of the test.

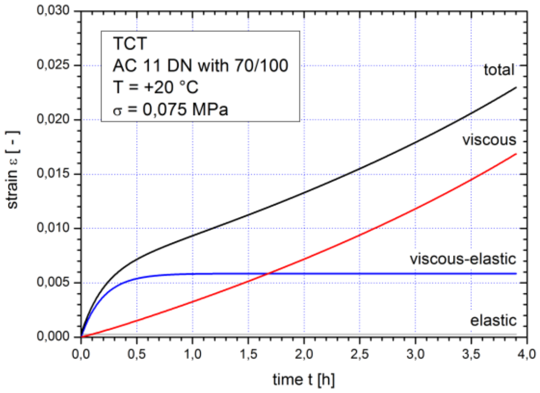


Figure 15: TCT - individual strain values for the elements of the modified model, T = +20 °C, σ = 0,075 MPa.

6. CONCLUSIONS

Low temperature behaviour significantly affects the service life of an asphalt pavement. In the European standard EN 12697-46 four static test methods are described addressing crack resistance of asphalt pavement exposed to low temperature:
- Thermal Stress Restrained Specimen Test (TSRST),
- Uniaxial Tension Stress Test (UTST),
- Tensile Creep Test (TCT) and
- Relaxation Test (RT).

A series of low temperature tests were performed on asphalt concrete AC 11, considering variation of test conditions. Based on the results of TCT, the parameters of the Burgers model were calculated and mathematically described in function of temperature and stress.
The Burgers model was expanded by a cryogenic strain element to describe TSRST. But this expanded and functionally described model (base model) is not suitable to simulate the results of all remaining test methods. Therefore the model was modified.
Every element of the base model was modified in the same way:

$$E_1 \Rightarrow \frac{E_1}{d_1 \cdot d_2{}^{\varepsilon}}, \quad \lambda_1 \Rightarrow \frac{\lambda_1}{d_3 \cdot d_4{}^{\varepsilon}}, \quad E_2 \Rightarrow \frac{E_2}{d_5 \cdot d_6{}^{\varepsilon}} \text{ and } \quad \lambda_2 \Rightarrow \frac{\lambda_2}{d_7 \cdot d_8{}^{\varepsilon}} \qquad \textbf{Eq. 5}$$

with E_1, E_2 = spring (functionally described dependency of temperature and stress),
λ_1, λ_2 = damper (functionally described dependency of temperature and stress),
d_1 to d_8 = coefficient
ε = influence value, in this case: resulting strain in a TCT

For the test methods TSRST, UTST and RT, the resulting stress is the influencing value. The coefficients d_1 to d_8 stay constant for one individual test, in ideal case for the whole test method.

This modification allows an exact simulation of all measured test results. Displaying the values of all elements and their strains the following conclusions can be drawn:

- In TSRST the singular spring generates an increase in stress, until it is damaged and the specimen fails. The singular damper can be neglected for stress calculation.
- In UTST the singular spring generates an increase in stress until the singular damper is damaged exponentially up to the specimen failure.
- Analyzing the RT, it is found, that the singular damper and the singular spring show a damage effect from the moment of the beginning of the test.
- For the TCT, the viscosity of the singular damper decreases, explaining exponential increase in strain.

As a result of this study, essential rheological mechanisms related to low temperature behaviour of asphalt mixtures in static low temperature tests can be described by a single model.

7. REFERENCES

[1] Arand, W., Sörensen, A. und Büchler, S. 1996. Ermittlung der Zugviskositäten von Asphalten mittels Retardations- und Relaxationsversuchen. Schlussbericht, FE 7.161 G 92 C im Auftrag des BMV, Institut für Straßenwesen, Technische Universität Braunschweig.

[2] Büchler, S. 2010. Rheologisches Modell zur Beschreibung des Kälteverhaltens von Asphalten. Schriftenreihe Straßenwesen, Heft 24, Institut für Straßenwesen, Technische Universität Braunschweig.

[3] Eulitz, H. 1987. Kälteverhalten von Walzasphalten. Prüftechnische Ansprache und Einfluss kompositioneller Merkmale. Schriftenreihe des Instituts für Straßenwesen, Technische Universität Braunschweig, Heft 7.

[4] pr EN 12697-46 April 2009. Asphalt – Prüfverfahren für Heißasphalt - Rissbildung und Eigenschaften bei niedrigen Temperaturen. Beuth Verlag GmbH, Berlin.