Binder performance and testing

Performance of asphalt determined by the tensile creep test on binder and asphalt mortar

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Abstract

The performance of an asphalt surface is largely determined by the used binder. Depending on the location, the asphalt road is exposed to wide temperature ranges. Test methods that are commonly used, generally focus either on the cold end, e.g. with the resistance against low temperature cracking addressed by the thermal stress restrained specimen test or at the warm end, e.g. with the resistance against permanent deformation addressed by the cyclic compression test. Until now, no test method to address both competing ends and therefore the whole scope of the application has been established. The tensile creep test (TCT) is a test method which addresses binder or mortar at low temperatures. However, results of this test method may indicate the performance of an asphalt mixture at both high as well as low temperatures. The paper introduces the test method TCT, results of tests on binder and mortar and correlates them with the asphalt's resistance to rutting and cold-induced cracking.

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1. INTRODUCTION

Various methods of testing the response of the functional properties of asphalt are available. For high temperatures, resistance to permanent deformation is examined using cyclic compression tests according to EN 12697-25 [1] or the wheel tracking test. A number of different tensile tests are available at lower temperatures and are described in the standard EN 12697-46 [2].

The functional properties of asphalt are largely determined by the bitumens used. In addition to adhesion, the viscosity of the bitumen has a substantial influence on the performance of the asphalt in the service temperature range.

Well-known test methods for describing the viscosity of bitumens only partially cover the service temperature range, or do not cover it at all. Traditional test methods of addressing viscosity, such as the drawing ball viscometer, are suitable for testing viscosities of up to $1 \cdot 10^8$ mPa·s, which reflects the temperature range for processing the bitumen more than the service temperature range.

With the bending beam rheometer (BBR), 3-point bending tests are conducted on beam-shaped specimens with comparatively small dimensions. The small dimensions of the specimen, combined with the significant influence of the specimen geometry on the test result, as well as the low forces acting on the specimen which therefore only result in minor deformations should be regarded as disadvantages of this test method. Specimens must be prepared very accurately to obtain reliable results. Furthermore, sensitive measuring equipment is needed that has been adapted to the small forces and deformations. The application range of the dynamic shear rheometer (DSR) has been designed for temperatures exceeding 30 °C. Whether the behaviour of bitumen at low temperatures can be directly addressed using this test method will be the subject of future research activities.
The tensile retardation test, unlike the abovementioned methods, can record tensile viscosities of between 100 MPa·s and 10^9 MPa·s which arise during bitumen and mastic tests within the temperature range of from +5 °C to -25 °C. The test principle of the retardation test demands these temperatures, especially when examining bitumen.

The specific feature of the tensile retardation test described here is a constant stress (not a constant load as usually applied by conventional creep tests) that accounts the changing of the tapered cross section in the middle of the specimen during the load.

The results achieved can nevertheless be used to make assertions about behaviour in the service temperature range. The results of tests on paving grade bitumens, wax-modified paving grade bitumens, rubber-modified bitumen and a recycled bitumen that was modified using rejuvenators and “soft” paving grade bitumen are presented. These are followed by the results of tests on asphalt mastic and their relation to the performance of asphalt.

2. TENSILE RETARDATION TEST METHOD

2.1. Test principle

The principle of the tensile retardation test corresponds to that of the tensile creep test (TCT) in EN 12697-46. In the tensile retardation test, a prismatic specimen is statically subjected at a steady test temperature to a sudden application of uniaxial tensile stress which is then kept constant. During the test, the axial strain occurring on the specimen is recorded as a function of time. The material characteristic of tensile viscosity, which describes the flow properties of the specimen, is determined from the recorded time-strain curve using an evaluation method.

The development and verification of the test method, together with the definition of suitable test parameters, are described in the research report [3].

2.2. Test equipment

The test equipment for the tensile retardation test comprises a path measurement system with a resolution of 0.1 µm, a load cell with a resolution of 0.01 N and a step motor transmission unit that can apply changes in length with a resolution of 0.02 µm. The specimen is laid into this equipment and connected at one end to a rigid thrust bearing and to pulling equipment at the other. Friction on the horizontal contact surface of the specimen is minimised by a Teflon layer and the use of graphite flakes, and is negligible considering the amount of tension applied in the direction of tension.

The test equipment is installed in a temperature chamber which controls the test temperature to an accuracy of 0.5 K. The test equipment and temperature chamber are connected by a process computer with real-time multitasking operating system and a program for the simultaneous acquisition of measurement data, control and process visualisation.

The test equipment for the tensile retardation test on bitumen agents and mastic can be integrated in the equipment for tensile and low temperature cracking tests on asphalt specimens, and is available as an accessory.

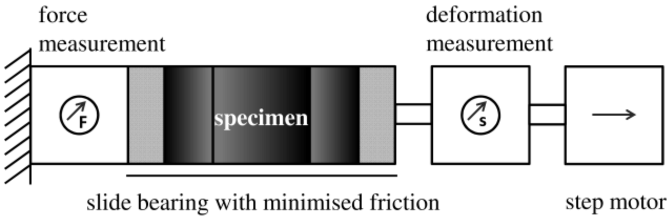

Figure 1: Schematic of the test set-up

2.3. Test specimen

The test specimen dimensions are shown in Figure 2. The geometry of the dumbbell test specimen with a smaller cross section at its centre enables the strain that occurs under tensile load to be concentrated on a specific area.

The tensile zone has an initial cross-section of 1000 mm². The ends, which have an area of 1600 mm², offer more contact surface for the adapter plates, also enabling high tensile forces to be applied to the specimens. The comparatively large dimensions and associated quantities of test material result in a very manageable process for producing specimens and inserting them in the test equipment. The test results achieved are extremely reliable, particularly in view of the required load control and the large initial cross-section of the specimen.

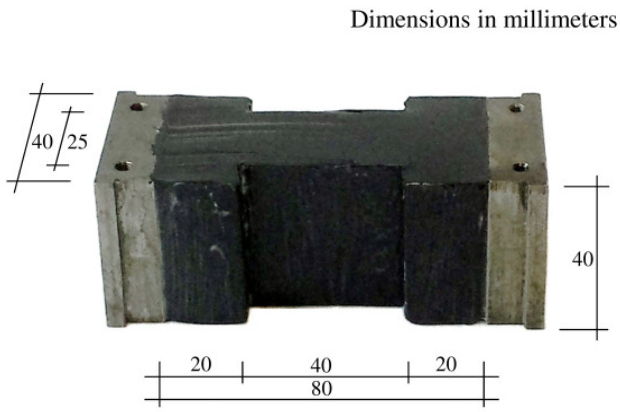

Figure 2: Test specimen with adapter plates

2.4. Producing test specimens

Portions of around 120 g of bitumen and 120 ml of asphalt mastic should be prepared to allow for apportioning supplements and the necessary superelevation of the test specimen during production.

The bitumen should be gently heated, and a temperature selected that permits the bitumen to be easily stirred while also not forming bubbles when the test specimens are cast. As a rule, bitumen subsamples used to produce the test specimens are obtained from a larger container. The reproducibility of the subsamples can be easily assessed using the ring and ball softening point test method.

Both bitumen and filler components are heated to produce the mastic. The bitumen share is apportioned on scales and put in a pan. The filler components are added to the pan according to the formulation, mixed well with the bitumen and tempered for 30 minutes in the furnace. After stirring the mastic again, the test specimens are cast.
The multiple part mould for the test specimens should first be coated with a release agent, whereby only the adapter plates are thoroughly degreased and inserted into the specimen mould.
The heated and homogenised bitumen or asphalt mastic is cast with some excess quantity into the mould. The filled specimen mould is left to cool at room temperature and is then stored overnight at 5 °C. Potential influences on test results are balanced out and comparable results achieved by using the same period of time (cycle) for the work steps of specimen preparation, specimen production, specimen storage and subsequent testing throughout the test programme.

2.5. Testing

By smoothing and levelling the top surface with a hot spatula, the test specimen is cut to size, shaped and then held in place in the test equipment by the adaptor plates. The test specimen is then tempered without stress at test temperature for 150 minutes. Following tempering, load is applied. This application of tensile load is adapted in terms of stress and duration to the test temperature and type of specimen.

Table 1. Test conditions

Test temperature [°C]	Tension Bitumen [MPa]	Tension Mastic [MPa]	Time of strain [Min]
+ 5	0.010	0.100	60
- 5	0.100	0.100	120
- 15	0.250	0.250	240
- 25	0.250	0.500	480

The stress applied which is constant in relation to the changing, tapered cross-section in the tensile zone results in the test specimen expanding. The force to be applied is permanent calculated and readjusted as a function of the cross-section in the middle of the specimen.
Based on the constant volume and the effective length of the test specimen the necessary force for a constant stress over the ever-changing cross section is calculated by

$$F_{\Delta l} = \sigma \cdot \frac{V_o}{L_0 + \Delta l} \text{ [N]} \tag{1}$$

where: $F_{\Delta l}$ = force [N]; σ = constant, uniaxial tensile stress [N/mm²]; V_o = volume of the specimen; L_0 = effective length of the test specimen = 60 mm (const.); Δl = the change in length over the observation period [mm]

The constant stress is a significant difference to various well known types of conventional creep tests. After a consolidation phase, a linear course of expansion sets in over time during the further application of load and is used to evaluate the test.

Note: For reasons of intelligibility equations (1) and (2) offer different but equivalent units [N/mm²] and [MPa] for the stress σ.

2.6. Evaluation of the tensile retardation test

At constant tensile stress and a constant test temperature, the tensile viscosity of the bitumen specimen can be determined in simplified form from the course of the time-strain curve in the linear range using the gradient in the time-strain curve.

$$\lambda_Z = \frac{\sigma}{\dot{\varepsilon}} = \frac{\sigma}{\frac{\Delta l}{\Delta t \cdot L_0}} \text{ [MPa·s]} \tag{2}$$

where: λ_Z = tensile viscosity of the bitumen [MPa·s]; σ = constant, uniaxial tensile stress [MPa]; $\dot{\varepsilon}$ = gradient in the linear range of the time-strain curve considered [1/s]; Δl = the change in length over the observation period [mm];
Δt = time of the strain observed [s]; L_0 = effective length of the test specimen = 60 mm (const.)

The individual test results are transferred to a diagram with logarithmic scaling (with base 10) of the ordinate for tensile viscosity and linear scaling of the x-axis for test temperature. Using this scaling, the tensile viscosity curve can be specified as a function of the test temperatures with a regression line in the form:

$$\lg(\lambda_Z) = b\,(T) + a \tag{3}$$

where: lg = common logarithm; a = tensile viscosity at 0 °C; b = gradient of regression line; T = test temperature [°C]

The gradient b of the regression line indicates the temperature sensitivity of the bitumen.

3. TESTS

3.1. Tests on paving grade bitumens

The results of tests on five types of paving grade bitumens from the same manufacturer are portrayed in Figure 3. The ring and ball softening points of the paving grade bitumens are also specified. The diagram produces plausible results. The tensile retardation test provides a differentiated picture of the bitumen viscosities.
Every point denotes the result of one retardation test. The regression lines fan out slightly, as can be seen on the regression line gradients. All five types display different degrees of similar behaviour across the temperature range.
All regression lines show a very high coefficient of determination (R^2 > 0.999). Temperature differences for the same viscosity are also reflected in the temperatures of the bitumens softening points.

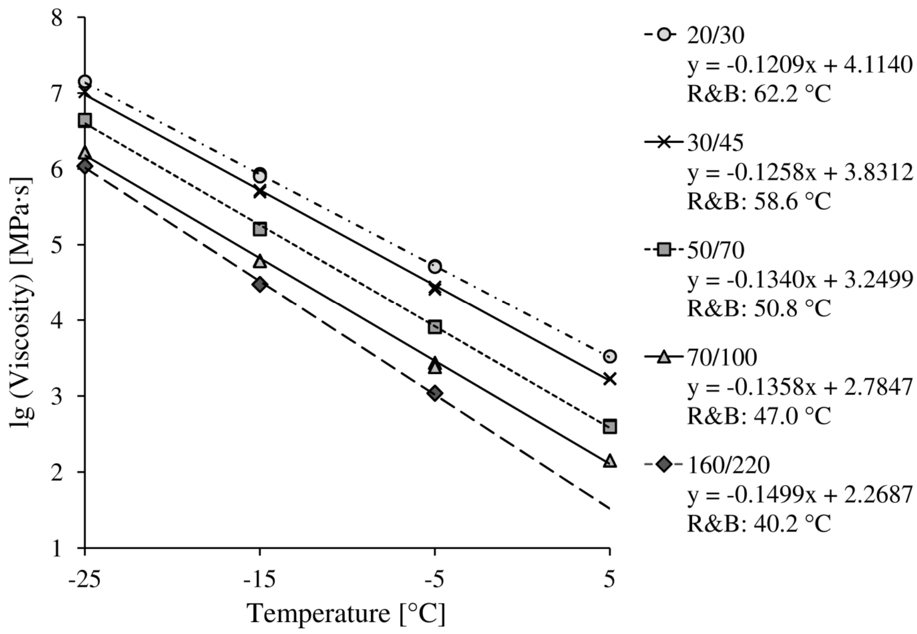

Figure 3: Paving grade bitumens

3.2. Tests on wax-modified paving grade bitumens

A FAD (fatty acid derivative) and FTP (Fischer-Tropsch paraffin) were selected for wax modification. Both modifications are used to lower the production and processing temperatures of asphalt. A "soft" paving grade bitumen (70/100) and a "hard" paving grade bitumen (20/30) were each modified using 2 % of the additives by weight. The addition of FTP and FAD alter the viscosity of the bitumens. The viscosities determined in the tensile retardation test are shown in Figure 4.

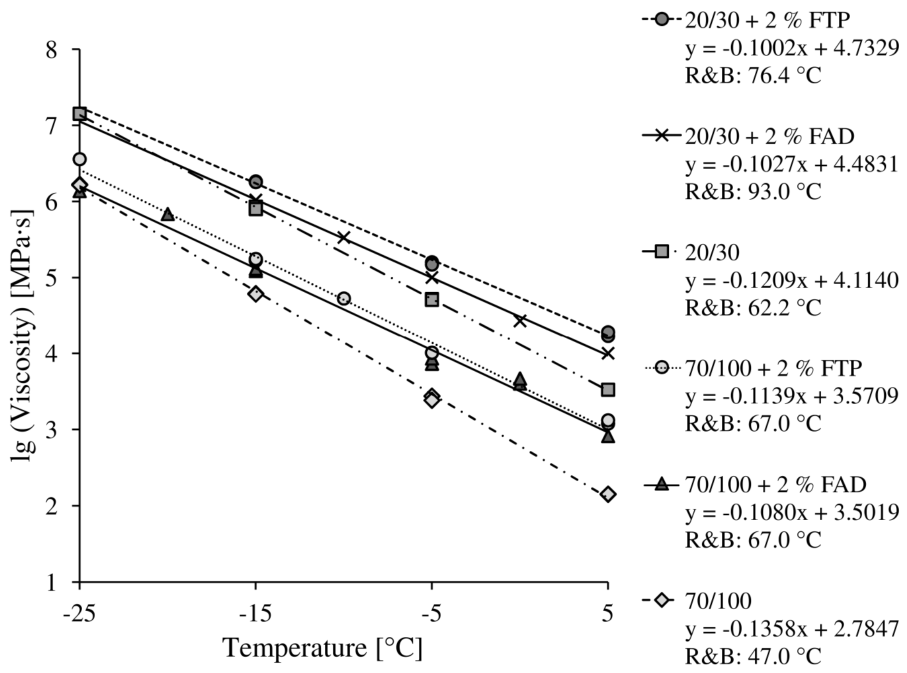

Figure 4: Wax-modified paving grade bitumens

Unlike with paving grade bitumens, the ring and ball softening point here does not represent an accurate characterisation of bitumen viscosity. The changes in viscosity resulting from the additive are clearer with the 70/100 bitumen both in terms of increased viscosity and altered temperature sensitivity. The equation for the regression lines shows higher viscosity for all modifications in the 50 °C range. This is coupled with the observation that types of asphalt with “wax-modified” bitumen show greater resistance to deformation. The change in viscosity can also be expressed in terms of the equiviscous temperature. In the case of 20/30 paving grade bitumen, modifications for the temperature range around 0 °C shift viscosity by 3 K to 6 K. At 6 °C, the FTP modified 20/30 paving grade bitumen has the same viscosity as the non-modified bitumen at 0 °C. The climatic conditions at the place of installation and traffic load must be taken into account when assessing this change in bitumen viscosity with respect to the functional properties of the asphalt layer produced with it. The modification of “hard” bitumen using wax and paraffin should be seen as critical in application areas with frequent temperatures of around 0 °C.

3.3. Tests on rubber-modified bitumen

Rubber-modified bitumens are an alternative to polymer-modified bitumens, which are increasingly provided for use in stone mastic asphalt. The results of tensile retardation tests on three bitumens are presented in Figure 5: a 50/70 paving grade bitumen, a polymer-modified bitumen and one produced through modification with crumb rubber.
This bitumen should be classified as type GmB 25/55-55 under the recommendations on rubber-modified bitumen and asphalt, E GmBA [4].
By way of comparison, the characteristic curve of a conventional polymer-modified 25/55-55 bitumen (designation in accordance with EN 14023 [5] is also depicted in this figure. The regression lines for the bitumen show that the rubber-modified bitumen is less temperature-sensitive and has higher tensile viscosity at high service temperatures. Compared to the regression lines, similar behaviour can be seen for all three bitumens at very low temperatures.

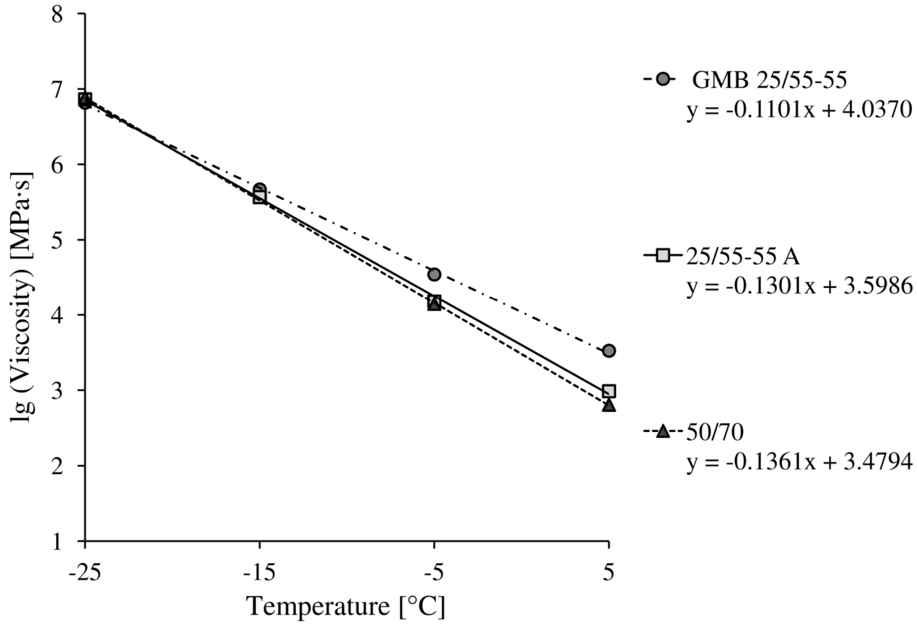

Figure 5: Rubber-modified paving grade bitumen

3.4. Tests on recycled bitumen and rejuvenators

The recycled bitumen was made of reclaimed asphalt from the wearing course of a stone mastic asphalt pavement. No precise details of the reclaimed asphalt are available. Generally, however, a polymer-modified 25/55-55 bitumen is used for stone mastic asphalt. A sufficient quantity of the bitumen was extracted from the reclaimed asphalt. Two rejuvenators were used to modify the recycled bitumen. Rejuvenator 1 (R1) is described by the manufacturer as a renewable raw material obtained from pine and other wood as a by-product of the paper industry. The manufacturer of Rejuvenator 2 (R2) has not provided any description for its properties.
The viscosities determined for the recycled bitumen (rB) record the sum of several influences. These are the thermal stress of the bitumen during the production of the asphalt mix, the ageing of the bitumen over the lifetime of the asphalt construction, interactions with the asphalt aggregates and stress caused by the trichlorethylene solvent during the extraction, recycling and subsequent homogenisation of the subsamples which were needed to obtain a sufficient sample mass. The quantities of the R1 and R2 rejuvenators added were estimated using the ring and ball softening point of the bitumen/rejuvenator mix. The target quantity for the required amount of rejuvenator added was a ring and ball softening point of 57 °C, which simultaneously corresponds to the ring and ball softening point for 25/55-55, one of the bitumen tested. There was a 7.5 % addition of rejuvenator R1 and 6.0 % of rejuvenator R2. The viscosities determined using the tensile retardation test are shown in Figure 6. As a guide, the tensile viscosities of a 25/55-55 bitumen are also provided in the figure. It can be seen that the estimate of the required amounts of rejuvenator additives was only moderately successful using the ring and ball softening point criterion. The temperature sensitivity of both variants of the rejuvenated recycled bitumen, expressed as the gradient of the regression lines, is lower compared to the 25/55-55 bitumen. The gradient of the regression lines shows that tensile viscosities of the variants of the rejuvenated recycled bitumen are

greater in the high service temperature range (approx. 50 °C), causing greater deformation resistance in the asphalt manufactured with it.
The modifications shown here represent the case of 100 % recycling, where there is complete mixing of the bitumen made of reclaimed asphalt with the rejuvenators.

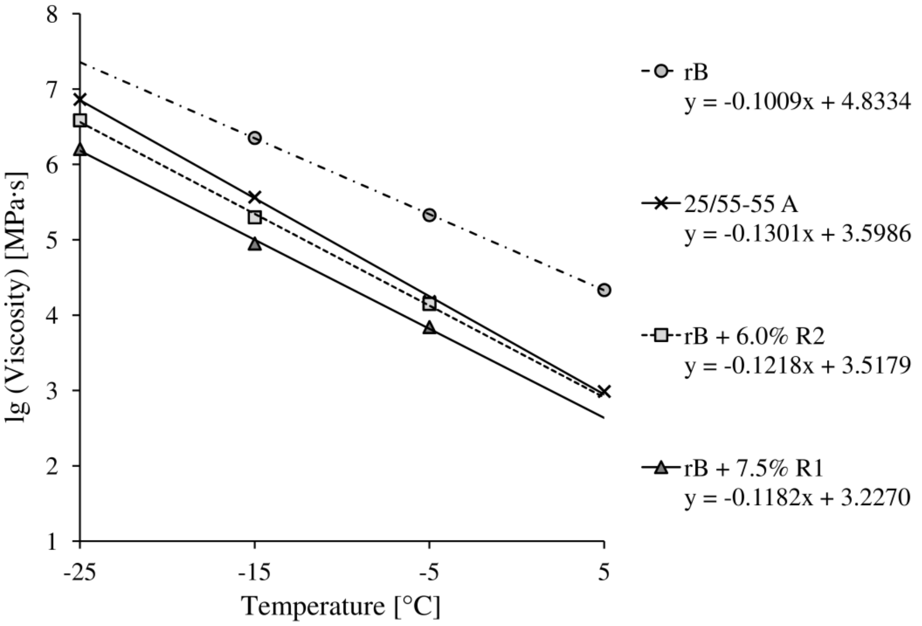

Figure 6: Rejuvenators

When recycling reclaimed asphalt, a similar effect can be achieved in the resultant bitumen using "soft" added bitumen as when using rejuvenators. For the tensile retardation tests, the recycled bitumen (rB) was mixed with paving grade bitumens types 70/100 and 160/220. The target quantity for the mixing ratio of rB and added bitumen is a tensile viscosity that corresponds to 30/45 paving grade bitumen, which is used as a basis here in view of the expected high amounts of additive. Unlike with the use of rejuvenators R1 and R2, there are not only regression equations for the recycled bitumen and target quantity from past tensile retardation tests, but also for the two added bitumens. The necessary mixing ratio of recycled bitumen and added bitumen can therefore be very well calculated from the tensile viscosity levels at 0 °C (equation with two variables and one side condition). The following mixing ratios are calculated for a tensile viscosity of 3.8 MPa·s at 0 °C:

40 % recycled bitumen + 60 % added 70/100,
60 % recycled bitumen + 40 % added 160/220.

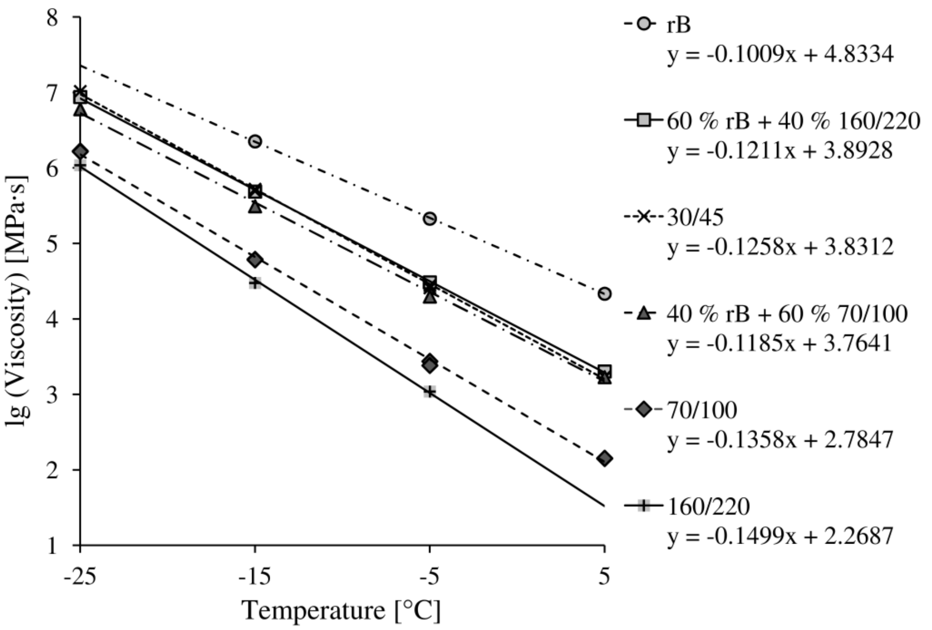

Figure 7: "Soft" bitumens as rejuvenators

Using these mixing ratios, added bitumen and recycled bitumen were mixed and test specimens produced for the tensile retardation tests. The results of the tests are shown in Figure 7. It can be seen that known viscosity characteristic curves can be used to extrapolate viscosity characteristic curves that reflect mixing ratios.
The regression line of the 30/45 paving grade bitumen was very well reproduced by the various proportions of different added bitumen. The regression line for the 60 % rB + 40 % 160/220 variant is almost congruent with the regression lines of the 30/45 paving grade bitumen. A reduction in tensile viscosity and change to the temperature sensitivity is achieved by adding soft bitumen.
The modifications shown here represent the case of a common recycling rate where the added bitumen is completely mixed with the bitumen made of reclaimed asphalt.

3.5. Tests on asphalt mastic

The test method is equally suitable for addressing the tensile viscosity of asphalt mastic. Higher tensile stress is applied here due to the stiffening effect of the fillers in asphalt mastic. There is additionally the potential to raise the test temperature for asphalt mastic rich in filler and thus very stiff. The usual evaluation and presentation of the tensile retardation test easily enable test results in the warm service temperature range to be taken into consideration in the regression lines without this impairing the validity of results.

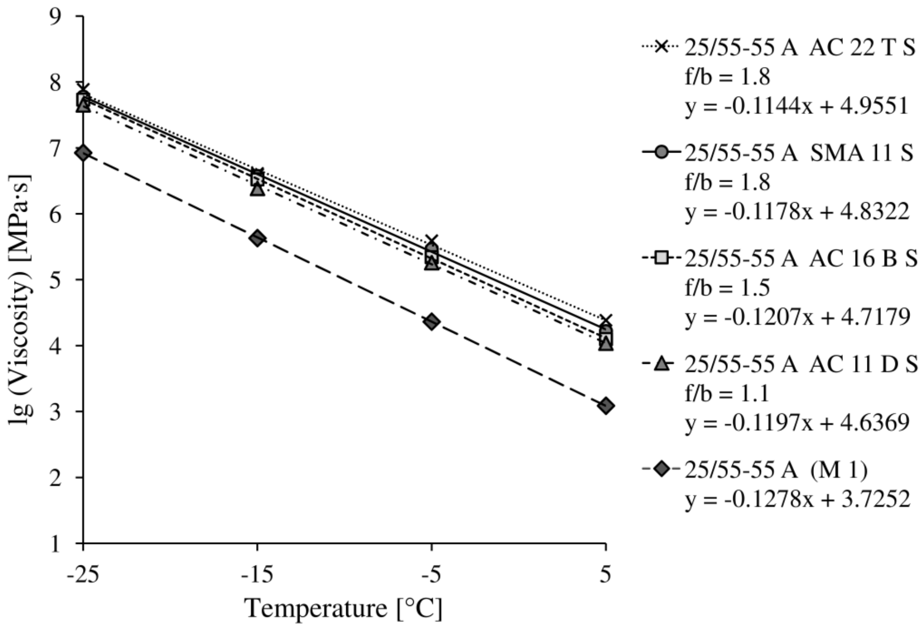

Figure 8: Asphalt mastic retardation

The FE 07.225 [6] and FE 07.0235 [7] research projects on the influence of quality differences in polymer-modified bitumens of the same type examined whether the deformation behaviour and low temperature behaviour of the asphalt produced from the bitumens can be extrapolated from their rheological properties. Both research projects were broadly designed, each taking into consideration three polymer-modified bitumens of the same type from four manufacturers that were then used in three or four types of asphalt. Identical bitumens and aggregates were used in both research projects. After the conclusion of the projects, adequate quantities of some bitumens were still available for bitumen and mastic studies using the tensile retardation test. The results are presented, permitting a comparison of a bitumen with different types of asphalt or rather mastic (Figure 8) and a comparison of different bitumens with one type of mastic (Figure 9). The designation of the bitumen manufacturers corresponds to the designation from the two aforementioned research projects. The mastic formulations for the tensile retardation tests were prepared on the basis of the initial type tests on asphalt formulations documented in the final reports. Limestone was likewise used as external filler and diabase as the own filler of the crushed sand fraction. With respect to the asphalt tests in the two research projects identical bitumens and comparable fillers were therefore used to produce the asphalt mastic. The presentation of the tensile viscosities of the various asphalt mastic with one bitumen shows that the mastic viscosities are 9 to 12 times greater than the viscosities of the bitumens.
The filler/bitumen ratio (f/b) of the corresponding types of asphalt can also be seen in the sequence of the regression lines. The different regression lines for the AC 22 T S and SMA 11 S mastic despite the same filler/bitumen ratio show that the test method also addresses the different proportions of the own diabase filler and the added limestone filler.

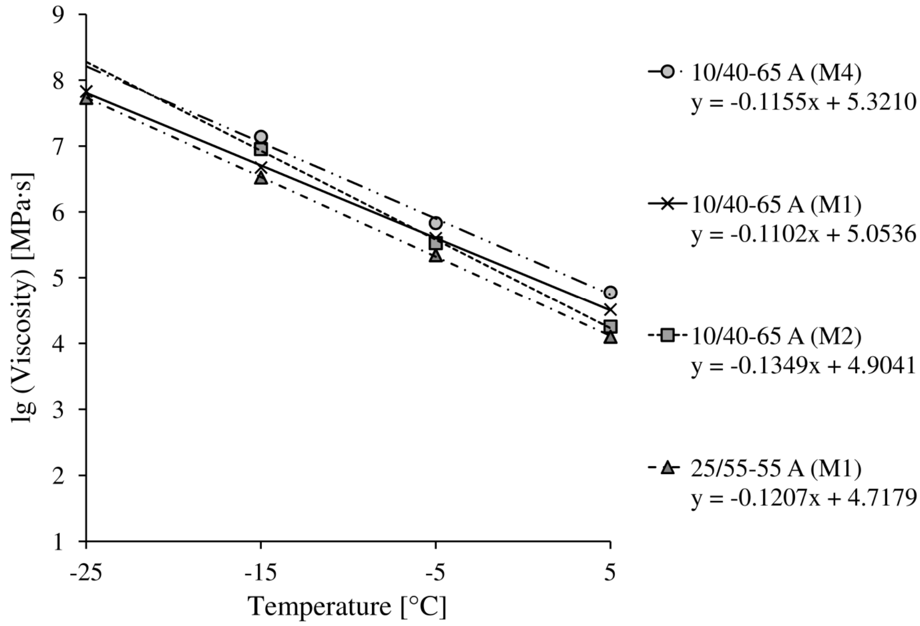

Figure 9: AC 16 B S asphalt mastic retardation

Figure 9 shows the tensile viscosities of a mastic formulation for AC 16 B S with different bitumens. Three of these bitumens are of the same type (10/40-65), but from different manufacturers (M1, M2 and M4). In FE 07.225, the AC 16 B S asphalt mix was, among other things, tested for resistance against permanent deformation using the uniaxial cyclic compression test on Marshall test specimens. The following parameters were principally defined for the assessment:

n_w = number of load cycles at turning point [-]
ε_w = strain at the turning point [‰]
ε^*_w = strain rate at turning point [‰ / 10^4·n]

The resistance against low temperature cracking of the AC 16 B S asphalt mix was examined in the FE 07.0235 research project, also using the thermal stress restrained specimen test (TSRST) according to EN 12697-46. The value calculated here is the failure temperature $T_{failure}$ [°C]. The significant characteristic values to describe the deformation behaviour and low temperature behaviour for an AC 16 B S are compiled in the following table.

Table 2. Characteristic values of AC 16 B S

Type of bitumen	10/40-65	10/40-65	10/40-65	25/55-55
Manufacturer	4	1	2	1
n_w [-]	10.000	10.000	4.013	8.024
ε_w [‰]	19.83	14.83	19.81	15.18
ε^*_w [‰/10^4·n]	6.39	3.08	18.79	3.42
$T_{failure}$ [°C]	-18.1	-22.3	-18.8	-24.0

It is possible from the course of the asphalt mastic regression lines to identify good correlation with the uniaxial cyclic compression test values on the asphalt. The clear differences in gradients of the regression lines for the types of mastic with the 10/40-65 bitumen from Manufacturer 1 and Manufacturer 2 explain the very good and very poor values for the resistance against permanent deformation.

A mastic viscosity can be calculated for the test temperature of the cyclic compression test of 50 °C using the regression equations from the asphalt mastic tests, reflecting the sequence of deformation resistance of the Marshall test specimens in the cyclic compression test. Failure temperatures of between - 18.1 °C and - 24.0 °C were determined in the TSRST on asphalt prisms. The corresponding tensile viscosities calculated using the regression equations in the mastic tests all indicate a figure of approx. $10^{7.5}$ MPa·s, whereby the tensile viscosity values of the mastic for the three 10/40-65 bitumens only differ very slightly. This allows the conclusion to be drawn that an “intrinsic tensile viscosity” can be calculated for bitumen of the same type and with the same filler/bitumen ratios and same filler formulations (added and own), from which a failure temperature can be derived for the asphalt.

4. SUMMARY

Using the test method of tensile retardation, it is possible to directly address the viscosities of bitumens and asphalt mastic at low temperatures. The test method is extremely robust and simultaneously very sensitive. Bitumen modifications and the stiffening effect of different fillers in terms of their type and their proportion in the mastic can be clearly demonstrated and differentiated using the test method.
The regression line for the tensile viscosity of the asphalt mastic, whose value is largely determined by the filler/bitumen ratio and whose gradient is determined by the bitumen, shows whether a specific type of asphalt has both a favourable resistance against low temperature cracking and high resistance against permanent deformation. This enables this test method to be used to evaluate the performance of the asphalt across the entire service temperature range. As such the test method is a very effective tool when designing durable asphalt mixtures.
A suitable bitumen is selected using the gradient of regression lines in tensile retardation tests. Tests on asphalt mastic are then used to optimise the filler/bitumen ratio of the asphalt formulation for the designated use. Since the test method also addresses the differing stiffening effect of diverse fillers, the ratio of own filler to added filler can be determined when designing the asphalt mix so as to create very deformation-resistant mastic formulations that simultaneously demonstrate a favourable filler/bitumen ratio for the low temperature behaviour of the asphalt. It is, however, always necessary to weigh up the extent to which the competing asphalt properties of deformation resistance and resistance against low temperature cracking formation should be prioritised for the intended use, and the ratio that produces an appropriate balance for the given application.

5. OUTLOOK

Remaining bitumens from two research projects [6], [7] were examined for this project. Using these bitumens it was possible to assess some, but not all, types of asphalt from the two research projects. Comparable but not identical fillers were used for the mastic examinations. Despite this, a very clear connection was demonstrated between the tensile viscosities calculated on the bitumen and mastic, the low temperature properties and the deformation resistance at high temperatures calculated on the asphalt. An external research project is planned for a systematic and integrated study of bitumen, mastic and asphalt using the tensile retardation test. The connection between mastic viscosity and failure temperature of the asphalt in the low temperature cracking test described as critical strength must be more closely examined, as should the potential of the viscosity characteristic curves for deriving asphalt stiffness, which flow into the dimensioning calculations of asphalt constructions.
In the draft version of the instructions, the same tempering duration of 150 minutes for all test temperatures is specified for test specimens. The test results achieved with this tempering confirm this uniform approach. It nevertheless appears sensible to check the course of tempering. The temperature can be monitored using thermocouples that are embedded in the test specimens and are connected to a data logger, and which can then be used to derive the adequate tempering time for the relevant test temperatures. Possible effects of the rheological hysteresis of the bitumen and mastic mixes that are attributable to the course of tempering can likewise be recorded using temperature monitoring.

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