Development of an incremental method for mechanistic asphalt concrete pavement deterioration models

Eiad Ramadan[1, a], Hartmut J. Beckedahl[1, b]

[1] *Department of Civil Engineering, University of Wuppertal , Pavement Research Centre, Wuppertal, Germany*

[a] ramadan@uni-wuppertal.de
[b] beckedahl@uni-wuppertal.de

Digital Object Identifier (DOI): dx.doi.org/10.14311/EE.2016.355

ABSTRACT

There exist considerable discrepancies between laboratory and analytical investigation and field performance studies for different modes of deterioration of asphalt pavements. When laboratory determined distress parameters are compared with corresponding field data, the predictions are poor. There are several reasons why this approach has not been as successful as hoped for. One reason is the change in the property of asphalt concrete over time. This is caused by the combined effects of the traffic and the environment. The reasons for the property change of asphalt concrete may be due to a change in air voids, aging of asphalt, seepage of moisture, or a combination of all these effects. As these changes occur over time, the engineering properties of asphalt concrete mixtures also change. To gain considerable confidence on pavement performance modelling and to bring it more closely to the pavement performance seen in the field, a rational design methodology is required. This methodology should take into account the evolution of pavement performance throughout its life time. One obvious choice is the use of incremental method for developing asphalt pavement deterioration models.

The incremental method for the analytical prediction of asphalt pavement deterioration will consist of an integrated set of models, which will be able to predict the progression of deterioration for each mode of distress. The accumulated damage for each deterioration mechanism can be calculated in increments as a function of time and/or damage. The increment spacing will be a function of material property variation caused by climate, time, and/or traffic. Thus the pavement service life is divided into several increments and the calculation input data (material properties, climate, traffic, surface profiles, and layer thickness) as well as the pavement damage will be changed with each new increment.

The priority research objective is the creation and validation of a new incremental method for mechanistic asphalt concrete pavement deterioration models to account for variation in pavement material property and the consequent pavement structural response. The secondary objectives are to modify existing or to develop new analytical pavement performance models.

Keywords: Ageing, Fatigue Cracking, Mechanical Properties, Performance testing, Stiffness

1. Introduction

Up to now in Germany the asphalt road pavement structure is largely designed according to the guidelines of the standardization of pavement structures [RStO 01]. These guidelines are mainly empirically originated from decades of observation of the road constructions and constantly further developed. However, an analytical design is worldwide sought. For this purpose, the guidelines for the analytical design of asphalt pavement structures [RDO Asphalt 09] were in 2009 introduced in Germany. According to German standards [RDO Asphalt 09], the design of asphalt pavements is carried out due to the fatigue behavior of asphalt layers. This behavior will be determined by performance test methods on fresh compacted asphalt samples produced in the laboratory. According to the information of stiffness and fatigue of fresh asphalt, the thickness of asphalt layers is designed depending on the load values, load repetitions and the local conditions. Of course, by the [RDO Asphalt 09] not only the asphalt layers, but also all other construction layers, including subsoil/subgrade, are included in the analytical design. Obviously there is a lack in accounting for realistic changes of layer performances over time because the design process includes only performance data of virgin materials.

The sustainability of the mechanical properties of asphalt depends essentially on the tendency towards aging (bitumen/asphalt), fatigue behavior and stiffness modulus of asphalt layers. During service life asphalt follows an aging process, so that it becomes brittle through oxidation (oxygen, ozone and time), evaporation of light constituents (heat and time) and photo-oxidation (UV radiation and time) and thus leads to a higher stiffness and sensitivity to low temperature. Asphalt aging is influenced by a variety of factors (temperature, air pressure, high-energy radiation, water, humidity, pollutants and salt) and it can leads to early damages under unfavorable conditions. In addition to the aging that arises from environmental influences, asphalt is stressed by the traffic load, which leads over the service life to a fatigue-related decrease in asphalt stiffness. Thereby the pavement loses during the service life the performance value and substantial value.

The aging process thus influences the service life of asphalt pavements. However, the German standards for analytical design of asphalt pavements [RDO Asphalt 09] do not allow accurately enough taking account of changeable asphalt properties due to aging. For reliable prediction of the performance behavior of asphalt pavements and their service life, it is important to consider the changes of performance properties of asphalt with increasing service time (aging). The performance characteristics of asphalt include stiffness, fatigue resistance, permanent deformation resistance, durability, layer adhesion and the resistance to low temperature cracking which simultaneously are affected by load repetitions, ageing, temperature and moisture.

Because the SHRP laboratory long term ageing test method for asphalt mixes [SHRP A-390, 1994] could not represent the in situ long term ageing process, a new lab ageing method had to be developed. As a basis for determining the incremental changes for the damage of asphalt pavements, data of long term pavement performance test tracks (LTPP-database) of the Federal Highway Research Institute (BASt) and many results from laboratory tests on binders and asphalt were utilized. For each asphalt layer, variable binder types consequently, different asphalt types were used for laboratory tests. To determine the incremental changes of binder and asphalt properties, the selected binder and asphalt mixes were aged for different periods, first using accelerated laboratory methods. The laboratory tests which used to determine the mechanical parameters were carried out on binder samples and asphalt samples in the fresh state and those in different aging stages. Subsequently, the laboratory test results were connected, taking into account various stages of aging, with the practical data of LTPP-database.

A realistic aging process was proved during fundamental investigations. Thus functional relationships for the incremental changes of binder and asphalt properties were created on the experimental and numerical basis. These functional relationships were developed for further application in an incremental method.

This paper focuses on the investigation of changes in stiffness and fatigue behavior due to the aging of asphalt and/or load repetitions, thereby concentrating on the possible impacts in relation to the design and the prediction of the service life of asphalt pavements. Furthermore, the influence of asphalt aging is presented on changes in binder and asphalt properties.

2. Aging of Asphalt

In order to obtain a solid basis for estimating the incremental changes of the performance properties of asphalt and/or material parameters, the aging of asphalt was carried out for different aging stages. The internationally recognized method for asphalt aging SHRP (Strategic Highway Research Project) was used at first to simulate the in situ aging of asphalt. Here the asphalt type AC 22 TS (50/70) was undergone to short- and long-term oven aging according to [SHRP A-390, 1994]. It was found that the used aging method according to SHRP is not able to reflect with sufficient accuracy the in-situ aging of asphalt. Therefore, a new aging process the "Wuppertal Aging Process (WAP)" was developed for the aging of asphalt mix. To develop the "Wuppertal Aging Process (WAP)", the investigation results of the ongoing in-situ aging of asphalt by [Potschka, Tappert, 1987], [Potschka, Schmidt, 1990], [Radenberg, Louis, 1999], [IGSV, 1996] and [Nafe, 2011], in particular based on the increase in the softening point were utilized. From the specific value of the in-situ aged bitumen 50/70, the relationship (regression curve) was determined through regression analysis between the service time of asphalt base layer (AC 32 T with 50/70) and softening point, needle penetration respectively (see Fig. 1).

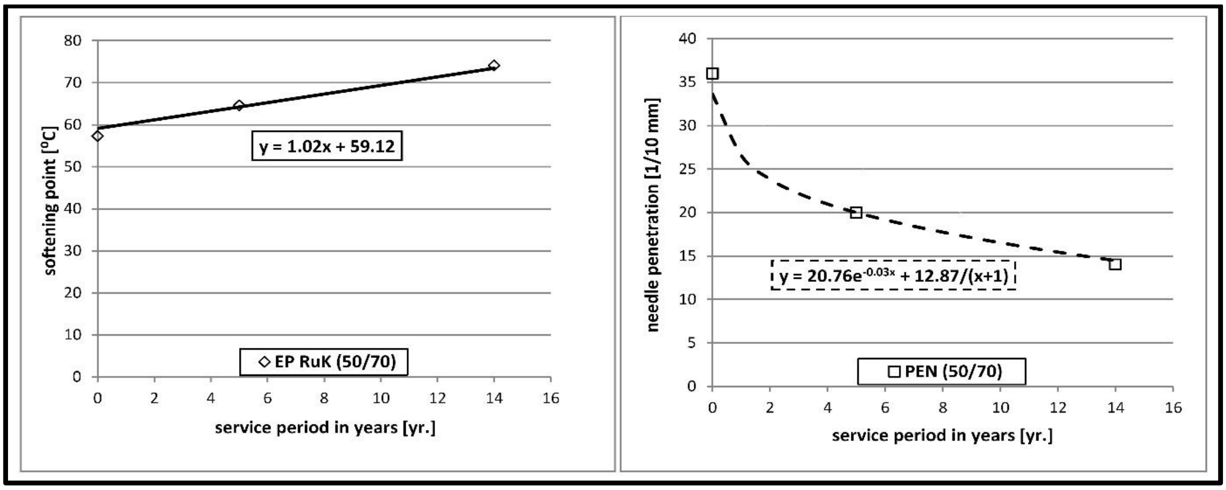

Fig. 1: Relationship between service time of asphalt base layer (AC 32 T with 50/70) the softening point (left), and needle penetration (right)

The main objective of the developmed "Wuppertal Aging Process" (WAP) was to simulate the in-situ aging of asphalt in lab. In this case an AC 22 TS with 50/70 Pen bitumen was defined as reference asphalt. Here, asphalt base course mixtures AC 22 TS (50/70) were undergone to different aging stages of WAP. To achieve the desired aging stages, which correspond to the in situ aging, the aging period was diversified in lab. At each aging stage, the final asphalt mix was extended equally at a thickness of 20 kg/m^2 on preheated plates and stored in oven with fresh air supply at a constant temperature (135 ± 1) °C. To ensure an equal aging of the asphalt mix, different turning intervals were established. From aged asphalt base course mixtures in different lengths, sample asphalt paving slabs were prepared. Subsequently, for each aging stage the binder was regained and its specific values were compared with the test results of the aforementioned research works. Here, with aging of the asphalt mix AC 22 TS (50/70), aging stages with 6, 18, 40 and 64 h exposure durations were achieved, which simulate in situ equivalent service durations of about 3, 14, 42 and 54 years respectively (see Fig. 2 and Tab. 1). For comparability of performance properties at all aging stages, same compaction degree/air void contents/volumetric properties had to be provided for all asphalt test samples (asphalt slabs).

Tab. 1: In situ equivalent service durations of artificially aging stages (AC 22 TS) with respect to the specific values of 50/70 Pen bitumen

aging period		fresh	0 h	6 h	18 h	40 h	64 h
50/70	R&B [°C]	50.3	57.9	62.0	73.9	101.7	113.9
	Pen. [1/10 mm]	51	28	22	14	6	4
Equivalent service duration (in situ) in years[1)]		-	0	3	14-15	42-43	54-56

[1)] Regression $R\&B = 1.024 * yeras + 59.115$

Regression $Pen = 20.7638 * e^{-0.0301396*years} + \frac{12.8681}{yeras+1}$

Based on the theoretical service durations of asphalt base course by [RStO 12] and [RPE-Stra 01, 2001] the service duration of 42 years for the asphalt base layer with AC 22 TS (50/70) was assumed. Thus, the 6 h, 18 h and 40 h-aging stages were selected. For aging of asphalt mixes of intermediate layer and base layer, the 18 h and 40 h-aging steps were performed.

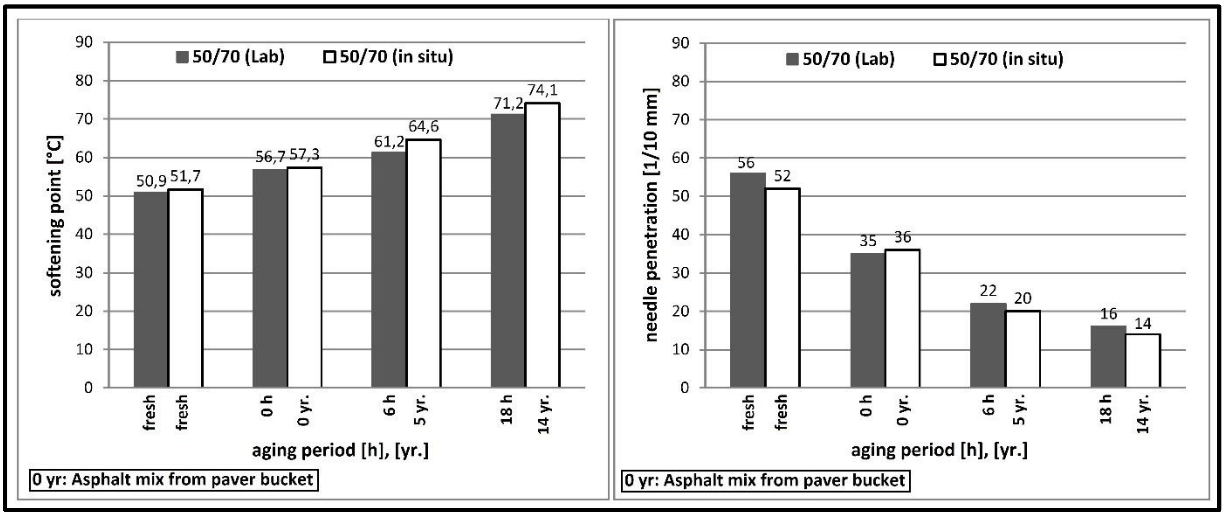

Fig. 2: Comparison of test results of the softening point (left) and the needle penetration (right) in proportion of the in-situ aging (AC 32 T) and WAV aging (AC 22 T S)

The 40 h aging have not been performed on asphalt surface course mix (SMA 11 S) as it is according to [RPE-Stra 01, 2001] for the theoretical service duration of asphalt wearing surface, which is built from a stone matrix asphalt for a construction class SV by [RStO 01], a temporary value of 16 years is specified. As a result, the 18 hour-aging stage is used for the long-term aging, and the 6 hour aging stage for the short-term aging of the surface course mixes.

3. Investigation program

At investigations, two mixes, which differ only by the sort of binder, were tested for each asphalt layer. It is concerned with an AC 22 T S (each with 50/70 and 25/55-55 A), an AC 16 B S (each with 25/55-55 A and 40/100-65 A) and a SMA 11 S (each with 25/55-55 A and 40/100-65 A).

In order to achieve a practical compaction during the production of test specimens, unaged asphalt slabs (0h-aging stages) were prepared from the selected asphalt mixtures based on the [TP Asphalt-StB, Part 33]. The compaction of asphalt slabs was done with a roller segment compactor, which can simulate the compaction operations of asphalt in practice. At each aging level of the examined asphalt types, Marshall specimens were prepared according to [TP Asphalt-StB, Part 30], to determine the compressibility according to [TP Asphalt-StB, Part 10 B] and thus, the compression temperature was adapted in order to achieve equal volumetric properties for all aging stages. In an analogous manner to the unaged asphalt slabs preparation, for each of asphalt types, asphalt slabs from the differently aged asphalt mixes with the previously determined compression temperatures were produced. .

From these produced asphalt slabs (unaged and aged), cylindrical cores and prismatic specimen were drawn. To determine asphalt properties, asphalt investigations of stiffness, fatigue behavior, low-temperature behavior, deformation behavior and adhesion behavior were carried out.

To determine the fatigue resistance and the dynamic stiffness, indirect tensile test in according to [AL Sp asphalt 09] was applied. Here, the indirect tensile test of each used asphalt type was performed with a dynamic universal testing machine. In order to assess the resistance of asphalt to low temperature cracking, uniaxial tension tests and thermal stress restrained specimen test (TSRST) on the two asphalt types of wearing surface were carried out according to [TP A-StB 1994]. To investigate the resistance to permanent deformation and respectively the stability, the wheel tracking test was performed according to [TP Asphalt-StB, Part 22] on the asphalt sample slabs of intermediate layer and wearing surface.

The adhesivity between aggregate and bitumen is a crucial criterion for evaluating the durability of asphalt against impacts of traffic and weather. Although the adhesion behavior (adhesivity) is not a primary criterion for dimensioning pavement structure of asphalt roads [Beckedahl 2007], however, a poor adhesivity leads to a serious and irreparable material damage of asphalt layers.

To determine the adhesion behavior between aggregate and bitumen, the rolling bottle test was used according to [TP Asphalt-StB, Part 11]. Here, the adhesion behavior between building materials, which were employed in used asphalt mixes, was investigated. It concerns limestone and the bitumen 50/70, and the polymer-modified bitumen 25/55-55 A respectively. Furthermore, it concerns diabase and the polymer-modified bitumen 25/55-55 A, and the highly-polymer-modified bitumen 40/100-65 A respectively. Aggregate of the particle size class 8/11 were used for all investigations according to [TP Asphalt-StB, Part 11]. The experiment was carried out in each case with a rolling period of 6, 24, 48 and 72 hours. To investigate the adhesion behavior taking into account the aging between aggregate and binder, a bitumen-coated aggregate was initially aged with the WAV under equal conditions of the previously performed aging stages. During the aging process, the high temperature of 135 °C resulted in drainage of the bitumen from the aggregate. Thus a uniform coating of bitumen for rolling bottle test was not guaranteed. Therefore, the used fresh binders were aged with rolling thin film oven test (RTFOT) according to [DIN EN 12607-1]. This RTFOT-aged bitumen is intended to reflect the short-term aging in the context of stresses caused by asphalt mixing process and asphalt paving process. For each used rock type, aggregate of the particle size class 8/11 was enveloped with the RTFOT-aged binder, and then tested with rolling bottle tests for adhesion behavior.

In order to investigate the binder characteristics, softening point [DIN EN 1427], needle penetration [DIN EN 1426] and Fraass breaking point [12593 DIN EN] were determined on the used fresh binders. In addition, performance test methods such as bending beam rheometer (BBR) [DIN EN 14771], dynamic shear rheometer (DSR) [EN 14770] and force ductility method [DIN EN 13589] were used. To determine the incremental changes in the binder characteristics, the above mentioned binder tests were carried out on the recovered binder according to [DIN EN 12697-3] for each aging stage of all investigated asphalt types.

4. Investigation results

The following results of the carried out investigations are exemplary shown.

In considering the test results to the softening point and respectively, the needle penetration is clear that an aging-related hardening /brittleness of the binder is recorded with increasing asphalt aging (see. Fig. 3). Here, a significant decrease in needle penetration on all examined binder types due to asphalt production (0 h) is recognized. Thus it is evident that the asphalt production has a significant impact on the bitumen aging. The values of softening point and needle penetration show that the exactly same binder in different asphalt types leads to different results. Furthermore, it can be seen that this behavior is systematic for several aging stages (see. Fig. 3). Based on this fact, it can be derived that asphalt types through various factors (such as binder content, binder film thickness, types of rock, particle size distribution, and particle maximum size) have a decisive influence on the aging behavior of a binder. This must be, however, yet to be verified by systematic studies.

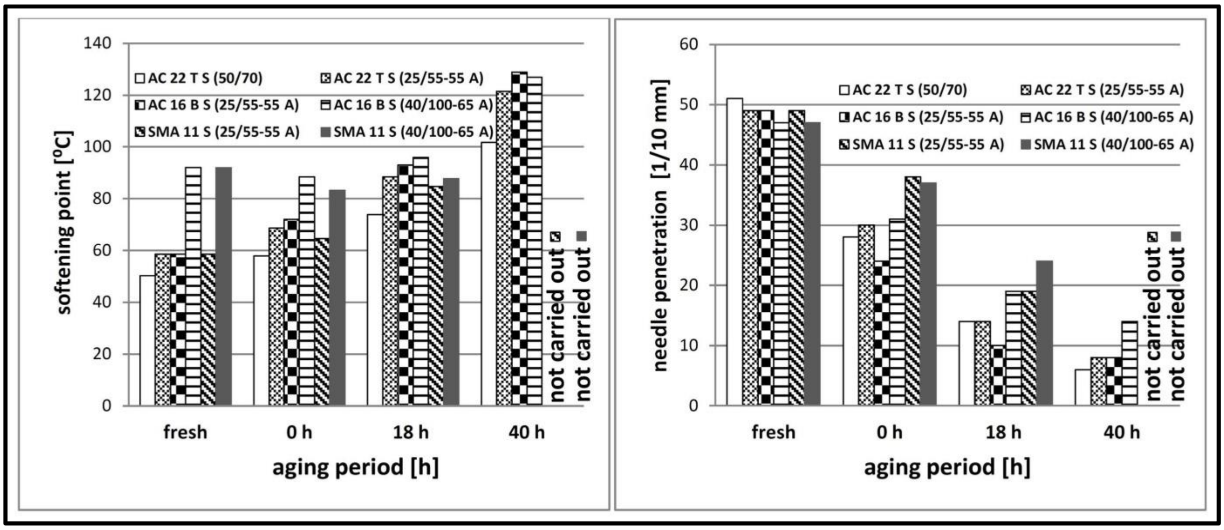

Fig. 3: Influence of asphalt aging on the softening point (left) and on the needle penetration (right) compared to the respective base bitumen

The test results for the low temperature behavior of bitumen show that asphalt aging and/or bitumen aging, adversely affects the low temperature behavior. As expected, the investigations of Fraass breaking point show that, with advancing asphalt aging an increase in the breaking point of the used bitumen will occur, and thus an increase in low-temperature sensitivity (see Fig. 4). Due to the significant hardening or the brittleness of the binder, which is recovered at 40 h-aging stages, Fraass breaking points could not be determined. In addition, BBR test revealed (test temperature -16 °C) for 40 h aging stage that the results (S (60s) > 300 MPa and/or m-value (60s) < 0.30) no longer lay in the favorable ranges (see Fig. 4). This state is attributed to the strong aging-related brittleness of binders.

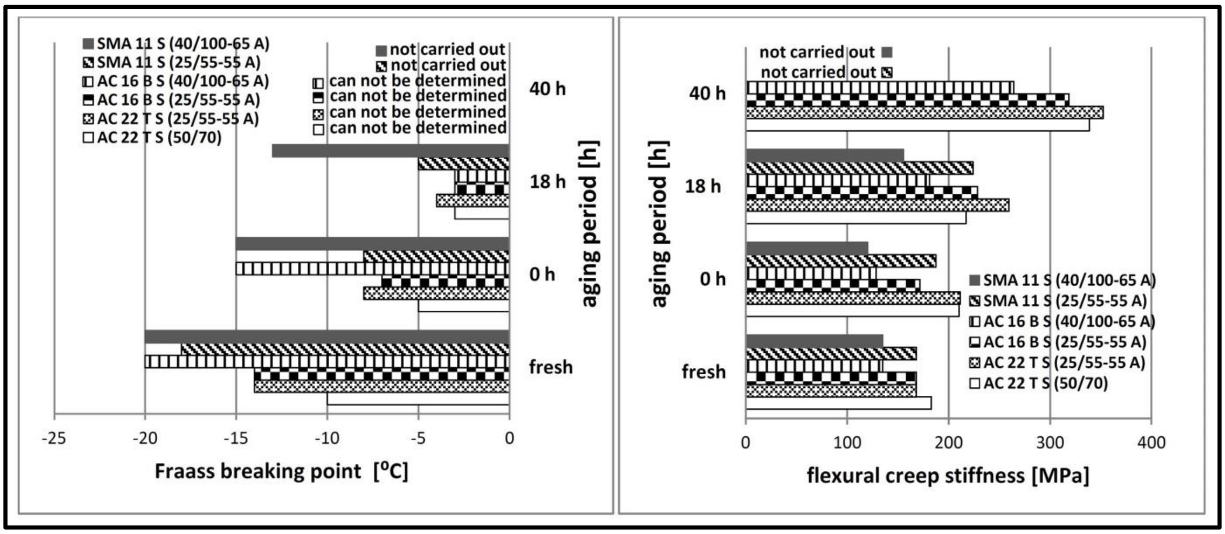

Fig. 4: Influence of asphalt aging on the Fraass breaking point (left) and on the flexural creep stiffness at -16 °C (right) compared to the respective base bitumen.

The investigations of the dynamic shear rheometer showed that a systematic influence of asphalt aging on the binders´ deformation behavior can be ascertained. With the increase of asphalt aging and respectively bitumen, the complex shear modulus (G*) increases while the phase angle (δ) decreases (see Fig. 5). Moreover, the specific value (G*/ sin δ) increases with the increase of aging, which is equivalent to the raise of the resistance against permanent deformation in comparison with the base bitumen.

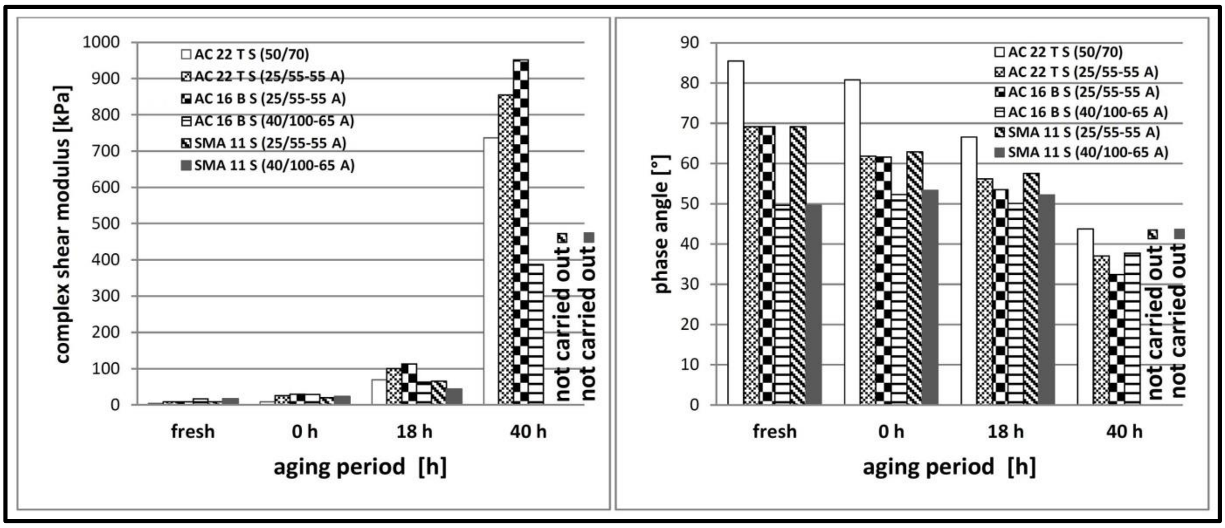

Fig. 5: Influence of asphalt aging on the complex shear modulus at 60 °C (left) and on the corresponding phase angle (right) compared to the respective base bitumen

In excerpts, the results of indirect tensile tests for determining the temperature and frequency-dependent stiffness modulus function (stiffness modulus master curve) are shown in figure 6 (left). It turns out that the asphalt stiffness rises with increasing the load frequency as well with decreasing test temperature. At test temperatures > 0 °C, the frequency-dependent stiffness modulus functions are significantly shifted towards higher stiffness. In the temperature range < 0 °C, the change of asphalt stiffness results in dependence of aging no uniform picture.

According to the performed rolling bottle test, the degree of bitumen coverage of the stressed aggregate particles reduces continuously with aged bitumen over the entire duration of the experiment (see Fig. 6, right). Thus, the affinity between bitumen and aggregate worsens by using aged bitumen compared with the base bitumen.

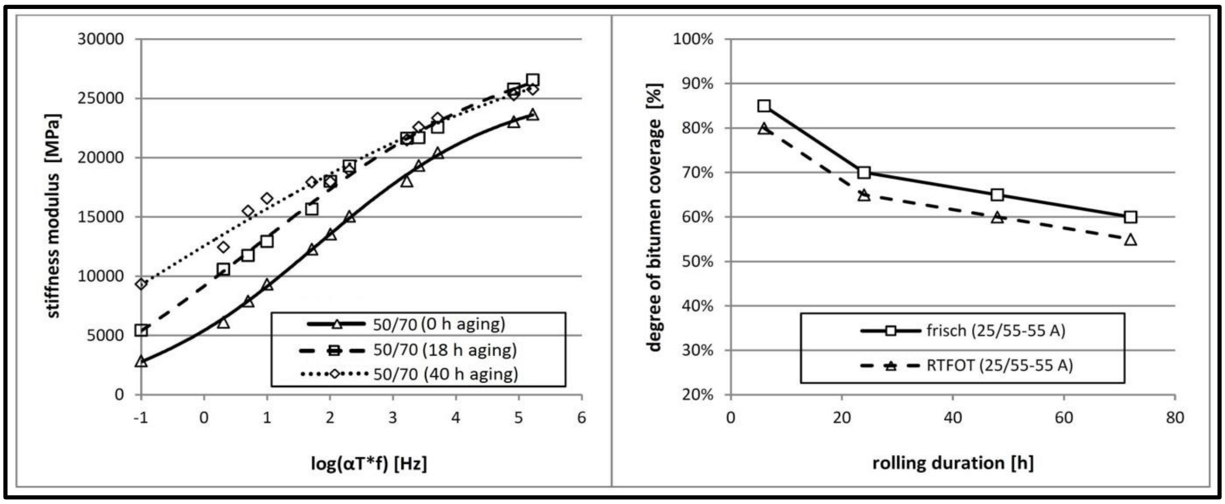

Fig. 6: Stiffness modulus master curves for the asphalt base layer AC 22 TS (50/70) depending on asphalt aging (left), rolling bottle test (right): Effect RTFOT-aged bitumen (limestone + 25/55-55 A)

The results of wheel tracking tests indicate that the stability of asphalt (resistance to permanent deformation) is clearly improved with increased aging. This can be recognized by means of the rut depth after 20,000 overrollings and /or the trend of the rut depth (see Fig. 7, left). The improved deformation behavior is here attributed to the over-proportionate increase of stiffness at high temperatures due to aging.

Investigation results of low temperature behavior of asphalt show that the curve trend (of uniaxial tension test and thermal stress restrained specimen test) shift with the increased aging in the direction of higher temperatures (see Fig. 7, right). Thus, aging affects negatively on the low temperature behavior of the tested asphalt types.

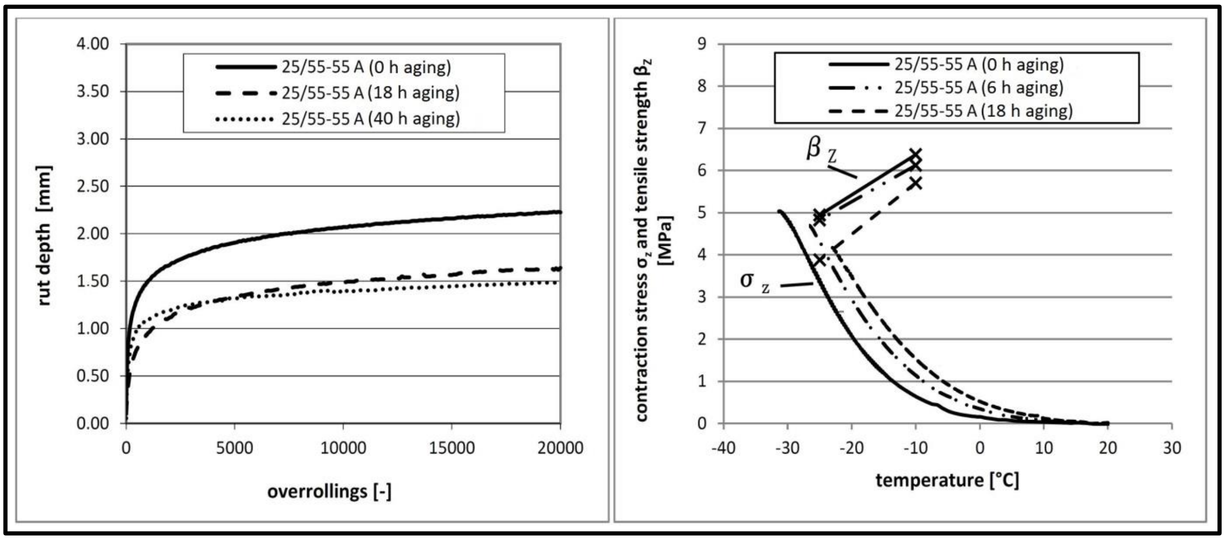

Fig. 7: Behavior of rut depth of asphalt type AC 16 B S (25/55-55 A) and low-temperature behavior of asphalt type SMA 11 S (40/100-65 A) before and after aging respectively

Based on the results of fatigue tests, functional relationships between the stiffness modulus and the number of load cycles could be derived depending on the asphalt aging. Thus, the incremental change of the Stiffness modulus could be determined during the service life. For each aging stage of the tested asphalt types, the averaged stiffness trend was calculated from three test specimens (spec.) for each load level until reaching the number of fatigue load cycles N_{makro} (number of load cycles until macrocrack formation). The stiffness moduli, which are measured during the three fatigue tests, must be depicted on a normalized number of load cycles in order to calculate the average of them. The normalization of a number of load cycles occurred on the basis of the relied fatigue criterion for determining the fatigue load cycles. Here, the number of load cycles until macrocrack formation N_{makro} [Hopman et al., 1989] was applied as fatigue criterion based on the concept of dissipated energy [Van Dijk, 1975]. To calculate the normalized number of load cycles $N_{norm,i}$, the number of load cycles N_i until macrocrack formation was divided by Nmakro for each tested specimen. Subsequently, the stiffness modulus E_i, which is measured at a number of load cycles N_i, was assigned to the normalized number of load cycles $N_{norm,i}$. Thus, the stiffness curves of the three specimens for each aging stage were equally stretched and then reached the normalized number of fatigue load cycles with a value of one. Thus, the averaged stiffness curve of each aging stage could be determined from the three stiffness curves at the normalized load cycles. Similarly, the average of the stiffness curve until reaching the number of cycle to failure $N_{failure}$ could be formed for each aging stage. During normalization, the recorded number of load cycles N_i until the specimen failure and the maximum reached number of load cycles $N_{failure}$ were utilized. In Figure 8, the averaged stiffness curves until N_{makro} and/or $N_{failure}$ with the corresponding regression functions are exemplified for the three aging stages of an asphalt type and for a load level.

Figure 8 shows an aging-related and over-proportionate stiffness increase, which wears with increasing load repetition. Thus, the asphalt aging has an advantageous effect on the fatigue behavior until a certain number of load cycles. At this number, the asphalt aging causes by an increasing load repetition a decline to the initial stiffness of the unaged asphalt.

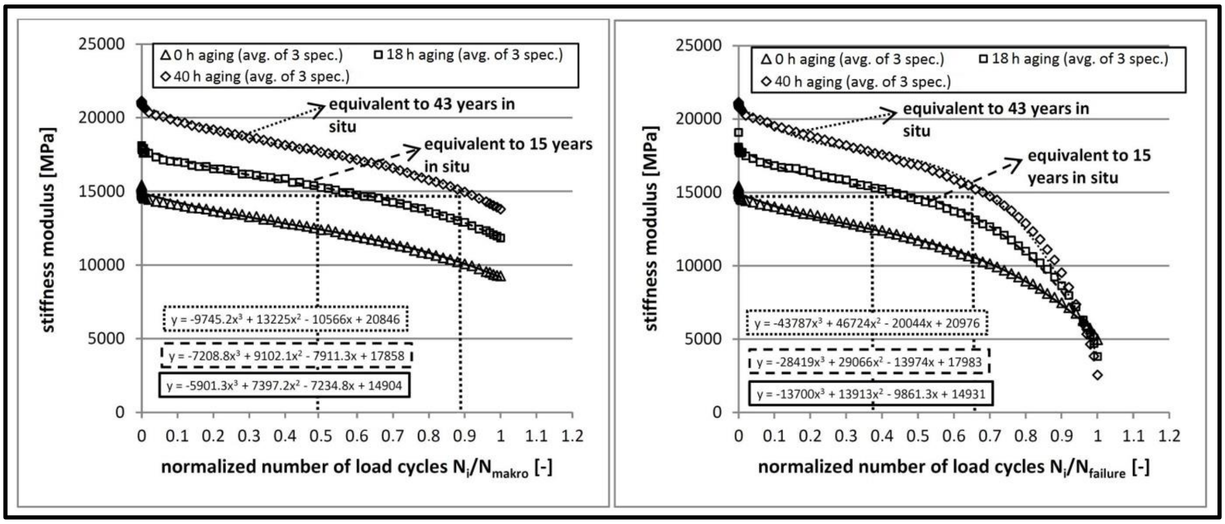

Fig. 8: Averaged stiffness curve until N_{makro} (left) and $N_{failure}$ on the normalized number of load cycles in the fatigue tests (low load level, T = 10 °C, f = 10 Hz), AC 22 T S (50/70)

Using the regression functions (see Fig. 8), the stiffness modulus could be calculated for the percentages of the normalized number of load cycles N_i /N_{makro} and/or N_i /$N_{failure}$ (for the percentage utilization of the service life) at each aging stage. Figure 9 shows the relationships between stiffness development and asphalt aging, also between stiffness development and percentage utilization of the service life N_{makro} (left) and/or $N_{failure}$ (right).

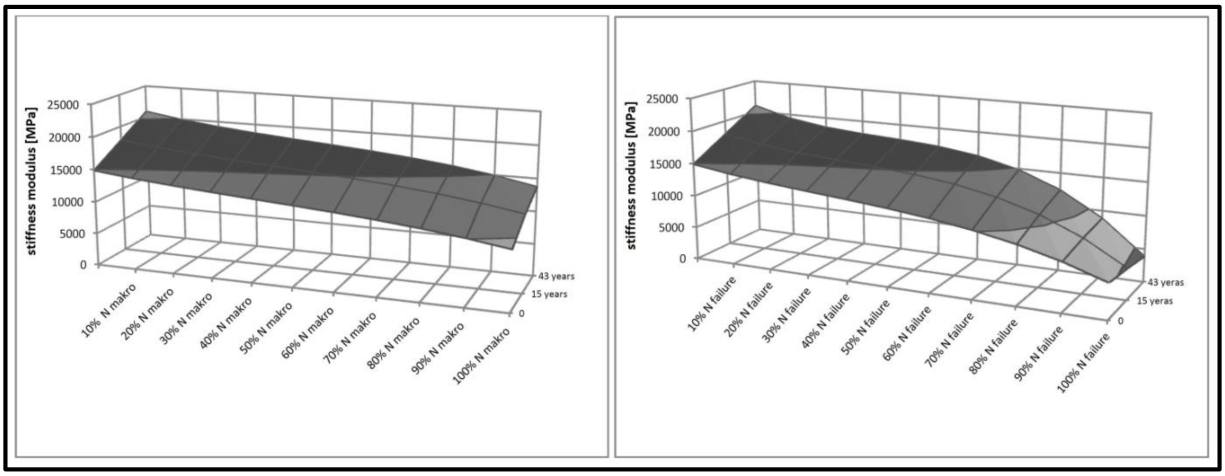

Fig. 9: Stiffness development of AC 22 T S (50/70) depending on asphalt aging and the percentage utilization of service life N_{makro} (left) and $N_{failure}$ (right), fatigue test (low load level, T = 10 ° C, f = 10 Hz)

Based on these three-dimensional representations, the stiffness development of asphalt could be determined at any point of time and any number of load cycles until reaching the fatigue load cycles N_{makro} or $N_{failure}$. In addition, the fatigue life can be determined, at which the stiffness of the aged asphalts and the initial stiffness of the unaged asphalt are the same. This cognition is therefore of crucial importance because it attached a great importance to the determination of a remaining service life of asphalt pavement (see for this purpose: [RSO Asphalt 14]). Using the fatigue criterion N_{makro}, figure 9 shows that after a service and / or aging period of 15 years, it can be already 55% of service life (N_{makro}) exhausted due to fatigue, the stiffness at this point will not be lower than the stiffness in the beginning of service life. After 43 years of service and utilization of 90% service life N_{makro}, the stiffness increase due to aging and the stiffness reduction due to fatigue may cause no change compared to the beginning of service life. The discrepancy is less sharply defined by using the fatigue criterion $N_{failure}$. After a service period of 15 and 43 years, 45% and 70% of service life can be exhausted respectively, although the asphalt stiffness is respectively not less than its state in the corresponding new building. This shows that the determination of the remaining service life, especially those that are based solely on bearing capacity measurements, is still currently subject to a great uncertainty.

The opposing stiffness developments in asphalt (fatigue, aging), as well as the stiffness increases, which usually occur with increasing service time in unbound layers and subsoil / subgrade, with associated changes in the bearing and stress behavior should all be considered in [RDO Asphalt 09]. Moreover, the shift factors SF of the [RDO Asphalt 09] should be checked and verified on the basis of corresponding functional relationships.

5. Summary

As a basis for determining the incremental changes for the damage of asphalt pavements, practice data of LTPP-database of the Federal Highway Research Institute (BASt) and many results from laboratory tests on binders and asphalt were utilized. For each asphalt layer, variable binder types consequently, different asphalt types were used for laboratory tests. To determine the incremental changes of the binder and asphalt properties, a new, multi-stage aging process was developed, with which it was possible to simulate several years of service life of asphalt.

In summary, it can be concluded from the test results that the aging leads to a significant change in the binder and asphalt properties. On the one hand, the stability and fatigue resistance improve. On the other hand, the aging negatively affects low-temperature behavior and durability. Based on the combination of the laboratory test results with the practical data, the functional relationships for the incremental changes of the binder and asphalt properties could be created. These functional relationships have been implemented programmatically for the application of the incremental method and used for fundamental investigations. Thus, an essential contribution to the development of a new calculative prediction method for the service life of asphalt pavement has been made. An essential finding is however, that the consistently high asphalt stiffness over the service life does not permit clear inferences about the remaining service life. Asphalt stiffness increase over the service period indicates a relatively high residual service life, while asphalt stiffness loss over the service period indicates a relatively low residual service life.

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