IMPACT OF RTFOT AND PAV CONDITIONING PARAMETERS ON VISCOELASTIC BEHAVIOR AND BINDER PERFORMANCE GRADE

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ABSTRACT

This paper presents a sensitivity analysis of two parameters applied for RTFOT and PAV aging on the viscoelastic behavior and performance grade (PG) of an asphalt binder PG 58-22. For the RTFOT, the temperature was varied from the default temperature of 163°C to 143°C and to 183°C. For the PAV, the binder film thickness was varied from default 3.2 mm to 1.0 mm and 5.0 mm. On the virgin binder, as well as on the RTFOT and RTFOT+PAV aged samples, DSR tests were run with a temperature sweep from 46°C to 82°C at a frequency of 1.59 Hz. On the RTFOT+PAV aged samples, BBR tests were carried out at -12°C, -18°C and -24°C. The impact of the mentioned conditioning parameters on $|G^*|$ and δ as well as on the upper and lower PG was investigated.

The results show that the impact of RTFOT temperature on the $|G^*|$ and δ is more distinct for lower DSR temperatures. In general, the effect of a change in RTFOT temperature on the viscoelastic parameters can be considered as small. At 46°C DSR, a change of 1°C RTFOT temperature shifts $|G^*|$ by 2.2% and δ by 0.08°. The PAV binder film thickness has an exponential impact on $|G^*|$ and δ. A reduced RTFOT temperature leads to reduced long-term aging after PAV. Reduced short-term aging due to reduced production temperatures results in significantly reduced long-term aging. The impact of RTFOT temperature and PAV binder film thickness on upper and lower PG were found to be insignificant.

Keywords: asphalt binder, RTFOT, PAV, DSR, BBR

INTRODUCTION

Motivation

Asphalt binder as a product from crude oil refinery is an organic material and is thus susceptible to changes in chemical composition, microstructure and mechanical behavior over its life span (1-5). These changes are generally referred to as aging. Aging of asphalt binder in road construction is divided into short-term aging during transportation, mix production and paving. Short-term aging is characterized by high temperatures, a high specific surface during mix production and thus, evaporation of remaining volatile components and fast oxidation (6, 7). Long-term aging comprises changes in the binder over the in-service life of a pavement layer in the field. It is mainly triggered by slow oxidation and effects of UV-radiation (8). UV-radiation is especially relevant for polymer modified binders (9, 10).

Various lab methods exist that simulate aging to assess the stability of a binder to short-term and long-term aging. Among them, the rolling thin film oven test (RTFOT) (11-13) and the pressure aging vessel (PAV) (14, 15) are validated, standardized and commonly used methods to simulate short-term and long-term aging, respectively.

Two issues seem to be interesting to be looked at more closely for both aging methods:

- In recent years, warm mix asphalt (WMA) with reduced production temperatures has reached a significant share in asphalt mix production. One question of interest is, how the change in production temperatures affects short-term and long-term aging of the asphalt binder. Is a potential benefit due to reduced short-term aging also beneficial for long-term aging?
- Regarding PAV aging, it is known that the binder film thickness in standard PAV (3.2 mm) is significantly higher than the binder film on aggregates in asphalt mixes (16, 17). Although PAV never aimed to simulate a realistic binder film thickness, it is still seen as interesting to understand how the binder film thickness in PAV affects long-term aging of asphalt binders.

Objectives and Approach

From the questions stated above, the following objectives are aimed for within this paper:

- Investigating the impact of RTFOT conditioning temperature on short-term binder aging by varying the RTFOT temperature and test aged samples in terms of dynamic shear rheometer (DSR)
- Investigate the impact of PAV binder film thickness on long-term binder aging by varying the film thickness and test aged samples by means of DSR and bending beam rheometer (BBR).
- Analyze changes of RTFOT temperature and PAV binder film thickness on PG grading of the asphalt binder.
- Investigate the impact of RTFOT temperature on long-term binder aging to find out whether lower production temperature have a potentially beneficial effect on long-term aging.

MATERIALS

One unmodified asphalt binder (PG 58-22, 70/100 pen) was employed for the purpose of this study. The main characteristics of the binder are shown in TABLE 1.

TABLE 1 Binder Characteristics

Parameter	Value
Penetration @ 25°C [1/10 mm]	91
Softening Point Ring & Ball [°C]	46.0
PG [-]	58-22

TEST PROGRAM

RTFOT

Simulation of short-term aging of the asphalt binder was carried out by RTFOT according to (18). To study the effect of temperature on short-term aging, three different temperatures were applied, 143°C, 163°C and 183°C, respectively.

PAV

Simulation of long-term aging of the asphalt binder was realized by PAV according to (19) at a temperature of 100°C. Five binder film thicknesses were employed in the study to analyze the effect on long-term aging.

TABLE 2 shows the variations in RTFOT temperature and PAV film thickness that were considered within the study. The film thicknesses of 1.0 mm, 2.0 mm, 3.3 mm, 4.0 mm and 5.0 mm correspond to 15 g, 30 g, 50 g, 61 g and 76 g of binder per PAV pan respectively.

TABLE 2 Variation of RTFOT Temperature and PAV Binder Film Thickness

RTFOT Temperature [°C]	143	163	183
Binder film thickness [mm]			
1.0	x	x	x
2.0		x	
3.3	x	x	x
4.0		x	
5.0	x	x	x

DSR

The rheological properties – complex modulus |G*| and phase lag δ – of the virgin and aged binder samples at high temperatures were obtained by DSR tests according to (20) at 1.59 Hz and a temperature sweep from 46°C to 82°C with 6 K steps. The samples were tested with 25 oscillations at each temperature. The majority of the test was carried out with triple repetition.

BBR

BBR tests were run on all PAV aged samples according to (21) to measure the stiffness and relaxation capability at low temperatures. Samples were tested at -12°C, -18°C and -24°C.

RESULTS AND DISCUSSION

Complex Modulus and Phase Lag at High Temperatures (DSR)

The complex modulus |G*| and the phase lag δ from DSR tests are presented and discussed in this section to analyze the effect of conditioning parameters in RTFOT and PAV on the high temperature behavior of the binder.

All DSR tests for the virgin binder and the RTFOT aged samples were run with triple repetition. The PAV aged binders were tested with triple repetition for samples “RTFOT aged at 143°C” and “RTFOT aged at 183°C”. The PAV aged binders from samples “RTFOT aged at 163°C” were tested only once, since it was found that the scattering of results is similar regardless of the conditioning temperature in RTFOT.

Impact of RTFOT Conditioning Temperature

FIGURE 1 shows the impact of the RTFOT temperature on complex modulus in the left diagram and on the phase lag in the right diagram. Two DSR temperatures were chosen for the presentation in the diagrams: 46°C and 82°C, respectively. The diagrams contain the mean values of three repetitions and error bars indicating the standard deviation.

Regarding the complex modulus, the diagram shows the relative change in |G*| compared to the virgin binder. A value of 0 would indicate that no change in |G*| was derived. At all test temperatures, there is a linear trend between RTFOT temperature and change in |G*|. At lower temperatures (46°C) the impact of a change in the aging temperature is more severe than for higher temperatures (82°C). A change of 1°C RTFOT temperature leads to a change of 2.2% in |G*| at 46°C and 1.4% at 82°C.

For the phase lag (right diagram), similar trends can be found. The diagram shows the absolute change in phase lag between virgin and RTFOT aged binder. A value of 0 would indicate that no change in the phase lag occurred. Again, the effect of RTFOT temperature is stronger for lower temperatures. At 46°C a change of 1°C RTFOT temperature leads to a change of 0.08° in phase lag, at 82°C this change is only 0.01°.

Taking into account mean value and standard deviation of the RTFOT aged sample at 163°C (standard aging conditions), a t-test was carried out to investigate which change in RTFOT temperature will lead to significant changes in the behavior of the respective aged binder: At 46°C significant changes in |G*| can be expected when the RTFOT temperature changes by more than 33°C and in δ when the RTFOT temperature changes by more than 12°C. At 82°C, significant changes in |G*| may occur when the RTFOT temperature changes by more than 10°C and in δ when the RTFOT temperature changes by more than 11°C.

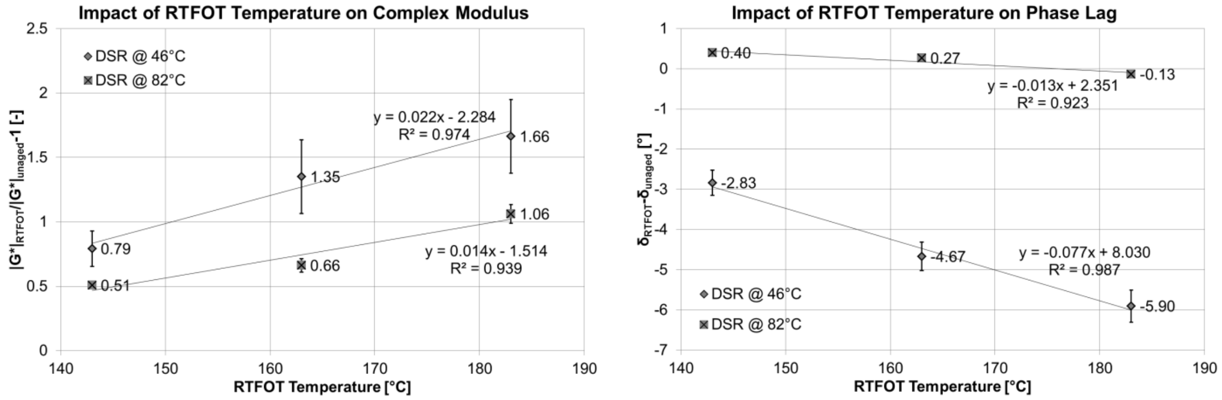

FIGURE 1 Impact of RTFOT Temperature on Complex Modulus (left) and Phase Lag (right)

Impact of PAV binder film thickness

FIGURE 2 presents the effect of the binder film thickness in PAV pans on the high temperature behavior of RTFOT+PAV aged samples. PAVs were carried out on samples from RTFOT aging at different RTFOT temperatures. The left diagram shows relative changes in |G*| compared to |G*| of the respective RTFOT aged sample. The right diagram shows the absolute change in δ compared to the respective RTFOT aged sample. A value of 0 would indicate that no change in |G*| occurs between RTFOT and PAV aging. Since the largest changes were found to occur at lowest DSR temperature, only results from DSR tests at 46°C are shown here. Similar trends can be seen for higher test temperatures but with smaller impact of the binder film thickness.

Two essential findings can be made from the data depicted in FIGURE 2:

- There is no significant difference that can be traced back to the RTFOT temperature when comparing data from PAV aged samples to the respective samples from RTOFT aging. The change in binder behavior from short-term to long-term aging does not seem to be affected by the RTFOT temperature.
- There is a strong impact of the binder film thickness on the long-term aging in PAV. As shown in the left diagram, there is an exponential trend. This seems to be rational since an increase in the binder film thickness will bring the long-term aged |G*| asymptotically towards the short-term aged |G*|. A reasonable explanation for this trend towards the short-term aged stage is that during a standard PAV with a duration of 20 h, only a thin layer of the sample is actually aged. The binder below this layer stays on RTFOT-aged level. Increasing binder film thickness does not increase the layer of aged binder after PAV, it only increases the mass of binder below this layer that is still at an RTFOT-aged level after PAV aging. Thus, increasing binder film thickness leads to decreasing aging of the complete sample. In the theoretical case of indefinite binder film thickness, the binder behavior after RTFOT+PAV aging would be equal to the behavior after RTFOT. Analogue statements can be made about the phase lag.

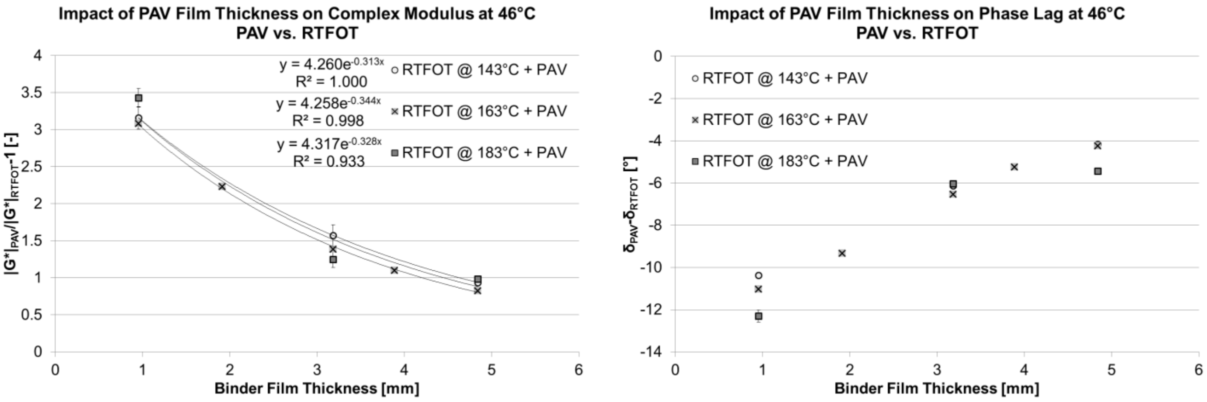

FIGURE 2 Impact of PAV Film Thickness on Complex Modulus (left) and Phase Lag (right) – RTFOT aged binder vs. PAV aged binder

While the upper figure, FIGURE 2 compared changes between RTFOT and PAV aged binder, FIGURE 3 compares changes between virgin and PAV aged binders. By the data in FIGURE 3, the impact of RTFOT temperature and PAV binder film thickness on the complete short-term and long-term aging process can be assessed.

Similar to FIGURE 2, the change in |G*| follows an exponential trend, which proves the strong impact of the binder film thickness in PAV. Different from FIGURE 2, here the RTFOT temperature has a clear impact on the change of |G*|. A higher temperature used for short-term aging, leads to a stronger increase in stiffness after PAV compared to the virgin binder. While the impact of the binder film thickness is not affected by RTFOT temperature (similar exponent of regression function for all samples) the offset of the regression function changes with RTFOT temperature. To give an example at standard PAV conditions (3.3 mm PAV binder film thickness corresponding to 50 g of binder), a change from 163°C to 183°C RTFOT temperature results in a 22% higher |G*|. On the other hand, a reduction from 163°C to 143°C RTFOT temperature leads to 23% lower |G*|. Again, similar trends can be observed for the phase lag.

From these results, it can be stated that the temperature that occurs during short-term aging has a significant effect on long-term aged binder behavior.

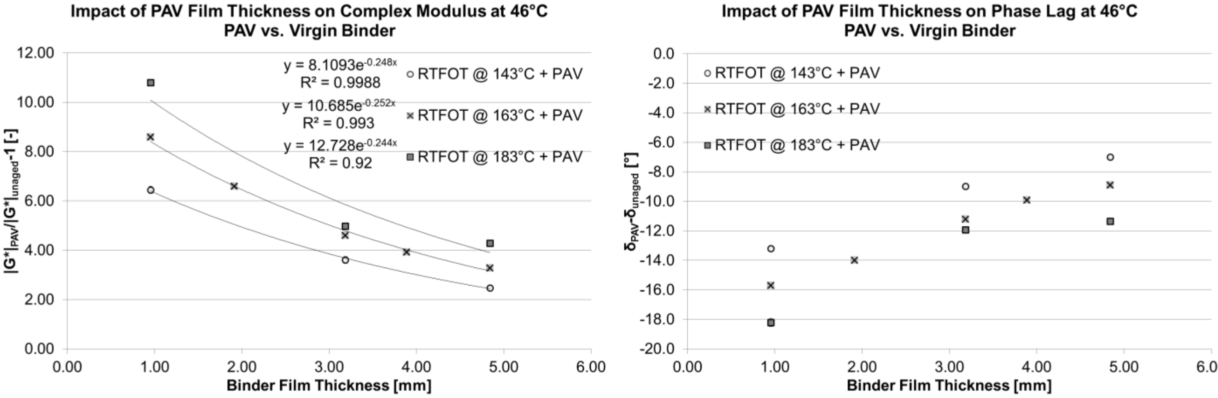

FIGURE 3 Impact of PAV Film Thickness on Complex Modulus (left) and Phase Lag (right) at 46°C – RTFOT aged binder vs. virgin binder

Performance Grading (PG)

Results from DSR and BBR testing were also analyzed regarding changes in the SUPERPAVE Performance Grading. The impact of RTFOT temperature on upper PG and the impact of RTFOT temperature and PAV binder film thickness on the lower PG are shown in FIGURE 4 and FIGURE 5, respectively. For both PGs, the continuous values were calculated from the results of DSR and BBR tests.

From the data in FIGURE 4, the tested binder would represent an upper PG of 64°C. However, DSR testing of the unaged binder sample resulted in an upper PG of 58°C. Thus, the binder is labeled PG 58-22.

For the upper PG (FIGURE 4), two ways of obtaining the continuous PG were chosen. In the linear case, the |G*|/sin(δ) values were interpolated between each test temperature in a linear way. This linear interpolation was used to calculate the exact temperature at which 2,200 kPa was reached (continuous upper PG (linear) in FIGURE 4).

Since the |G*|/sin(δ) vs. temperature curve shows a power-law trend with high coefficient of correlation ($R^2>0.99$ for all samples) of the following form:

$$\frac{|G^*|}{\sin(\delta)}(T) = a \cdot T^b \tag{1}$$

where T is the test temperature, the respective curves were fitted with a power-law regression and the exact temperature at which 2,200 kPa was reached, was obtained from the regression (continuous upper PG (power-law) in FIGURE 4).

The method using the linear interpolation show a smaller impact of the RTFOT temperature on the upper PG with a slope of 0.038 compared to the method using power-law regression with a slope of 0.073. At the standard RTFOT temperature of 163°C, both methods result in similar continuous upper PGs. Using the linear interpolation, to change the upper PG by 1°C, the RTFOT temperature would need to change by 27°C. For the power-law regression a change of 14°C of the RTFOT temperature is necessary to change the upper PG by 1°C. Thus, it can be stated that the upper PG is relatively insensitive to inaccuracies in the RTFOT temperature.

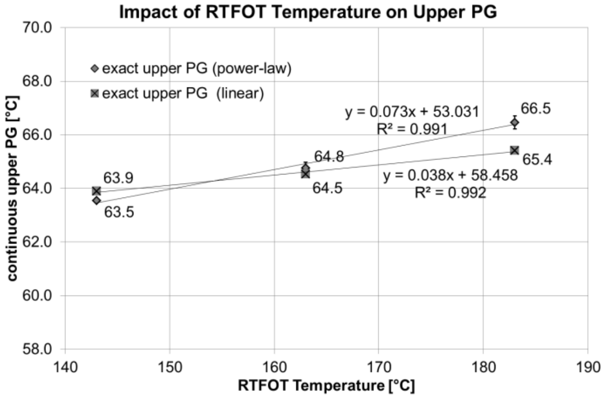

FIGURE 4 Impact of RTFOT Temperature on Upper PG

For the continuous lower PG derived from RTFOT+PAV aged samples that were tested in the BBR, the standard benchmark values of stiffness S ≤ 300 MPa and m-value ≥ 0.3 were employed. Since the evolution of S and m-value vs. BBR test temperature is linear, the continuous lower PGs shown in FIGURE 5 were derived by linear interpolation of S and m-values between the BBR test temperatures.

The left diagram in FIGURE 5 presents the impact of RTFOT temperature and PAV binder film thickness on the lower PG with regard to the stiffness S. There is a consistent impact of the binder film thickness for all RTFOT temperatures. A change of 1 mm in binder film thickness shifts the lower PG by 0.24°C to 0.33°C, whereas a change 10 g of binder in a PAV pan (corresponding to a change of 0.6 mm binder film) leads to a change of the lower PG by 0.15°C to 0.21°C. From these data, the impact of the binder film thickness on the lower PG seems to be rather insignificant.

No consistent statement can be made for the impact of the RTFOT temperature. Results from RTFOTs at 143°C and 183°C are on the same level and produce slightly worse lower PGs than RTFOTs at 163°C.

The right diagram in FIGURE 5 shows the impact of aging conditioning parameters on the lower PG with regard to the m-value. The impact of the binder film thickness is more distinct than for stiffness. A change of 1 mm in film thickness changes the lower PG by 0.28°C to 0.56°C. When a change in the binder mass in a PAV pan is taken into account, a change of 10 g of binder shifts the lower PG by 0.18°C to 0.36°C. The higher the RTFOT temperature is, the stronger is the impact of the binder film thickness. Although the impact of the binder film thickness on the lower PG is more pronounced for the m-value than for the stiffness, it can still be seen as rather insignificant.

Looking at the impact of RTFOT temperatures, again, no clear statement can be made. RTFOTs at 143°C lead to the lowest PGs, which seems to be rational. But the ranking of RTFOTs at 163°C and 183°C is not consistent, since the higher RTFOT temperature leads to a better low temperature PG.

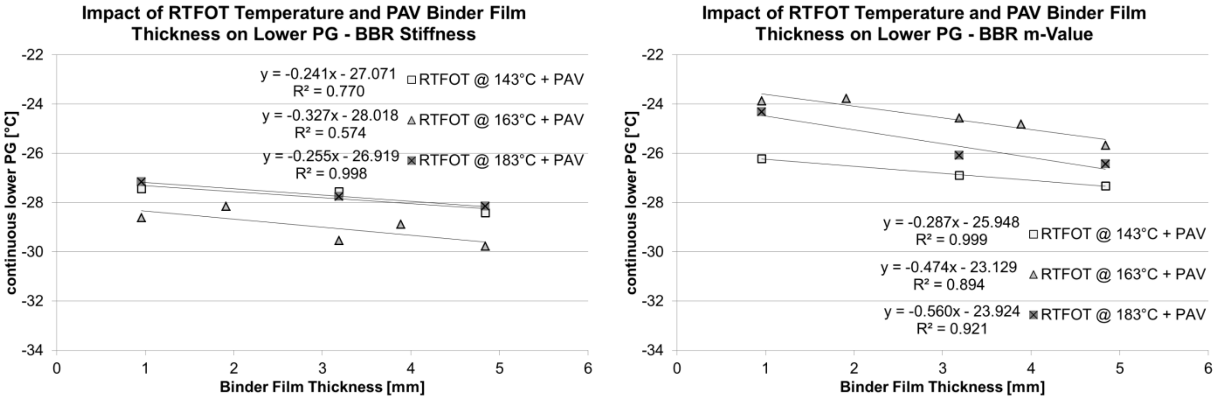

FIGURE 5 Impact of RTFOT Temperature on Lower PG with Regard to BBR Stiffness (left) and m-Value (right)

SUMMARY AND CONCLUSIONS

This paper presents a study on the impact of two essential parameters in RTFOT and PAV on the viscoelastic behavior and PG of an asphalt binder PG 58-22 (70/100 pen). For the RTFOT, the temperature was varied from the default temperature of 163°C to 143°C and to 183°C. For the PAV, the binder film thickness was varied from default 3.2 mm to 1.0 mm and 5.0 mm. On the virgin binder, as well as the different RTFOT and RTFOT+PAV aged samples, DSR tests with a temperature sweep from 46°C to 82°C were carried out. The frequency was fixed at 1.59 Hz. On the RTFOT+PAV aged samples, BBR tests were carried out at -12°C, -18°C and -24°C. The impact of the mentioned conditioning parameters on |G*| and δ as well as on the upper and lower PG were investigated. From the results, the following conclusions can be drawn:

- In general, the impact of a change in the RTFOT temperature on the complex modulus and phase angle is higher for lower test temperatures. At change of 1°C RTFOT temperature leads to an increase of 2.2% |G*| or 0.08° phase lag at 46°C. At 82°C, this change is only 1.4% |G*| and 0.01° phase lag, respectively.
- Based on a t-test it can be stated that significant changes in |G*| will occur, when the RTFOT temperatures changes by more than 33°C at a DSR temperature of 46°C and by more than 10°C at 82°C. For the phase lag, the necessary changes in RTFOT temperatures are 12°C at a DSR temperature of 46°C and 11°C at 82°C. Thus, the impact of the RTFOT temperature on the viscoelastic behavior seems to be small.
- The PAV binder film thickness has an exponential impact on |G*| and the phase lag.
- An impact of the RTFOT temperature can also be detected after PAV long-term aging. A change in the RTFOT temperature from 163°C to 183°C brings an increase in |G*| by 22% and a reduction from 163°C to 143°C brings a decrease in |G*| by 23%. Similar trends can be observed for the phase lag. From these data, it can be concluded that a change in the production temperature of asphalt mixes does not only have an effect on short-term aging. Reduced short-term aging due to reduced production temperatures results in significantly reduced long-term aging.
- The impact of RTFOT temperature on upper PG is rather insignificant. The upper PG changes by 1°C when the RTFOT temperature is changed by 27°C. Analogue statements can be made about the impact of PAV binder film thickness on the lower PG. A change of 10 g binder per PAV pan shifts the lower PG by up to 0.36°C in the worst case. Thus, RTFOT and PAV seem to be rather robust to changes in the two investigated parameters.

REFERENCES

1. Hofko, B., F. Handle, L. Eberhardsteiner, M. Hospodka, R. Blab, J. Fuessl, and H. Grothe, *Alternative Approach Toward Aging of Bitumen and Asphalt Mixes.* TRB 94th Annual Meeting Compendium of Papers, 2015: p. 15.
2. Hofko, B., L. Eberhardsteiner, J. Füssl, H. Grothe, et al., *Impact of maltene and asphaltene fraction on mechanical behavior and microstructure of bitumen.* Materials and Structures, 2015: p. 1-13.
3. Mouillet, V., J. Lamontagne, F. Durrieu, J.P. Planche, and L. Lapalu, *Infrared microscopy investigation of oxidation and phase evolution in bitumen modified with polymers.* Fuel, 2008. **87**(7): p. 1270-1280.
4. Stulirova, J. and K. Pospisil, *Observation of Bitumen Microstructure Changes using Scanning Electron Microscopy.* Road Materials and Pavement Design, 2008. **9**(4): p. 745-754.
5. Rebelo, L.M., J.S. de Sousa, A.S. Abreu, M.P.M.A. Baroni, A.E.V. Alencar, S.A. Soares, J. Mendes, and J.B. Soares, *Aging of asphaltic binders investigated with atomic force microscopy.* Fuel, 2014. **117**: p. 15-25.
6. Galal, K.A. and T.D. White, *SHRP PG classification and evaluation of in-service asphalts after eight years.* Progress of Superpave (Superior Performing Asphalt Pavement): Evaluation and Implementation, 1997. **1322**: p. 135-150.
7. Im, S. and F.J. Zhou, *Laboratory short-term aging protocol for plant-mixed and laboratory compacted samples.* Construction and Building Materials, 2015. **89**: p. 1-12.
8. Chipps, J.F., R.R. Davison, and C.J. Glover, *A model for oxidative aging of rubber-modified asphalts and implications to performance analysis.* Energy & Fuels, 2001. **15**(3): p. 637-647.
9. Wu, S.P., L. Pang, and G.J. Zhu, *The Effect of Ageing on Rheological Properties and Chemical Conversions of Asphalts.* Advances in Fracture and Damage Mechanics Vii, 2008. **385-387**: p. 481-484.
10. Feng, Z.G., S. Xu, Y.B. Sun, and J.Y. Yu, *Performance Evaluation of SBS Modified Asphalt with Different Anti-aging Additives.* Journal of Testing and Evaluation, 2012. **40**(5): p. 728-733.
11. Migliori, F. and J.F. Corte, *Comparative study of RTFOT and PAV aging simulation laboratory tests.* Asphalt Mixture Components, 1998(1638): p. 56-63.
12. Bahia, H.U., H.C. Zhai, and A. Rangel, *Revisions of the superpave binder specifications to include modified binders.* Materials and Construction: Exploring the Connection, 1999: p. 657-663.
13. Naskar, M., K.S. Reddy, T.K. Chaki, M.K. Divya, and A.P. Deshpande, *Effect of ageing on different modified bituminous binders: comparison between RTFOT and radiation ageing.* Materials and Structures, 2013. **46**(7): p. 1227-1241.
14. Bahia, H.U. and D.A. Anderson, *The pressure aging vessel (PAV): A test to simulate rheological changes due to field aging.* Physical Properties of Asphalt Cement Binders, 1995. **1241**: p. 67-88.
15. Puello, J., N. Afanasjeva, and M. Alvarez, *Thermal properties and chemical composition of bituminous materials exposed to accelerated ageing.* Road Materials and Pavement Design, 2013. **14**(2): p. 278-288.
16. Khedaywi, T.S. and E. Tons, *Aggregate rugosity and size effect on bituminous mixes.* Testing of Conventional and Unconventional Aggregates and Soils, 1998(1619): p. 26-36.
17. Jung, Y., H. Lee, M.J. Lee, S. Choi, and Y.H. Cho, *Concept of Film Thickness Applied to a*

New Approach for Polymer Concrete Mix Design for Airport Pavement Repair. Transportation Research Record, 2014(2440): p. 103-109.

18. ASTM, *ASTM D2872-12e1: Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)*. 2012, ASTM International: West Conshohocken, PA.
19. ASTM, *ASTM D6521-13: Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)*. 2013, ASTM International: West Conshohocken, PA.
20. ASTM, *ASTM D7175-08: Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer*. 2008, ASTM International: West Conshohocken, PA.
21. ASTM, *ASTM D6648-08, Standard Test Method for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)*. 2008, ASTM International: West Conshohocken, PA.