Investigation on the Effect of Cooling Medium and Aging Condition on Low-Temperature Properties of Asphalt Binder based on BBR

Di Wang[1], Augusto Cannone Falchetto[2*], Chiara Riccardi[3], Michael P. Wistuba[4], Lily Poulikakos[5] and Bernhard Hofko[6]
([1,2,3,4] Department of Civil Engineering – ISBS, Technische Universität Braunschweig, Braunschweig, 38106, Germany, 1. di.wang@tu-bs.de; 2. a.cannone-falchetto@tu-bs.de*; 3. chiara.riccardi@tu-bs.de; 4. m.wistuba@tu-bs.de)
([5] Empa, Dübendorf, 8600, Switzerland, lily.poulikakos@empa.ch)
([6] Institute of Transportation, Vienna University of Technology, Vienna, 1040, Austria, bernhard.hofko@tuwien.ac.at)

ABSTRACT

The low-temperature properties of asphalt binder are fundamental for designing asphalt mixture in the cold regions. This is especially true for new technologies such as Warm Mix Asphalt (WMA), for which a reduction in the production temperature may potentially lead to substantial benefits in terms long-term aging. Currently, the specification addressing the low-temperature property of asphalt binder is based on creep tests performed with the Bending Beam Rheometer (BBR) in ethanol. Recently, an alternative experimental method was proposed to conduct the tests in air. In this paper, the effect of cooling medium and aging temperatures on the rheological properties obtained from BBR tests is experimentally investigated and modeled. First, BBR tests are performed in both ethanol and air on four PAV long-term aged asphalt binders, which were previously RTFOT short-term aged at three different temperatures (123 ºC, 143 ºC, and 163 ºC). Then, the creep stiffness, $S(t)$, and m-value are computed. Finally, the Huet model is used to compare the effect of cooling medium and aging temperatures on the rheological model parameters. Results indicate that the reduced production temperature of 40ºC significantly affects the material properties at low temperatures, while air leads to higher creep stiffness and poorer relaxation capabilities compared to ethanol.

Keywords: Asphalt Binder, Aging Temperatures, Bending Beam Rheometer (BBR), Cooling Medium, Huet Model

1. INTRODUCTION

Thermal cracking is one of the dominant distresses for asphalt pavement built in regions experiencing a cold climate such as northern America and northern Europe [1,2]. Hence, the low temperature properties of asphalt binder are fundamental for selecting and designing asphalt mixtures. The Performance Grade (PG) specifications were developed by Strategic Highway Research Program (SHRP) during the in 1990's, in order to characterize asphalt binder over the entire service temperature range [3,4]. The Dynamic Shear Rheometer (DSR) [5,6] is used to obtain the high PG at high and intermediate temperatures, while Bending Beam Rheometer (BBR) [7] is selected to determine the low PG at low temperatures [1].

The current BBR procedure consists of simple low temperature creep tests on small asphalt binder beams immersed in an ethanol bath. However, there is still some ongoing scientific debates on this method with respect to the cooling medium used for conditioning. Ethanol can potentially affect the asphalt binder characteristics, while not being entirely representative of the field conditions. Recent studies [8-12] indicate that the results of asphalt binder creep stiffness obtained with the BBR are highly dependent on the conditioning cooling media. It was observed that the creep stiffness in ethanol is about 20% lower than the one measured in potassium acetate (CH_3CO_2K), conventionally used for Direct Tension Tester (DTT) test [8] and in air [9-12]. Nevertheless, these previous studies were restricted to very similar asphalt binders, to a single temperature (low PG+10°C) and only to creep stiffness.

More recently, the use of Warm-Mix Asphalt (WMA) has found increasing application over the years both in Europe and US [13,14]. WMA can be advantageously used to construct asphalt pavements with reduced mixing and compaction temperatures (20°C to 40°C cooler) [14,15] while achieving similar performance and durability in comparison to those prepared with Hot-Mix Asphalt (HMA) [15,16]. In spite of significant research addressing WMA, only a few studies [17-20] consistently attempted to evaluate the effect of different short-term aging temperatures directly on asphalt binders at long-term aging condition while most of the efforts focused on the short-term aging [21-23]. Hence, it is not yet clear if the reduced temperatures involved in the WMA production can ultimately result in an overall reduced material aging in the long-term. In addition, while more work was devoted to the resulting high temperature properties, little was done to investigate such an impact at low temperatures.

In this paper, the effect of cooling medium and different short-term aging temperatures on the low temperature properties of asphalt binder is investigated. First, BBR measurements in both ethanol and in air are performed on four sets of short- and long-term aged asphalt binders with different short-term aging temperatures. Then, creep stiffness, $S(t)$, and m-value are calculated and evaluated in both cooling media. Finally, the rheological Huet model [24] is fitted to the creep stiffness and the values of the model parameters are used to quantity evaluate the effect of cooling medium and aging temperatures.

2. MATERIALS AND TESTING

Four different 70/100 pen-graded [25] asphalt binders, which were provided by the RILEM Technical Committee 252-CMB project, were used in this study. These binders are part of a large inter-laboratory study [26]. The virgin binders were identified as B501_virgin to B504_virgin. The binders were then short-term aged with the RTFOT [27] at three different temperatures: 123ºC, 143ºC, and the standard 163ºC and, next, long-term aged according to the standard PAV procedure [28]. The following rule was used to designate the binders: “Binder type_Aging condition_Temperature of short-term aging”. For example, B501_R&P_123, “B501” (B502, B503, and B504) indicates the type of the virgin binder, “R&P” represents the RTFOT+PAV aging, while “123” (143 and 163) represents the short-term aging temperature used for the RTFOT aging. Based on previous characterization [29], the PG of the four asphalt binders is PG 70-22, PG 70-22, PG 70-22 and PG 64-22, respectively.

BBR creep tests [7] were performed to obtain the low temperature properties of the different binders. Creep stiffness, $S(t)$, its inverse creep compliance, $D(t)$, the relaxation parameter m-value were computed according to the current standard [7]. In order to evaluate the effect of different aging temperatures and cooling medium on the low temperature properties of asphalt binder, BBR tests were performed both in ethanol [7], and in air [9-12] for all the asphalt binders. All tests were conducted on three replicates at two temperatures: low PG+10°C and low PG+4°C.

3. EXPERIMENTAL RESULTS

Table 1 and 2 present the experimental results of *S*(60s), *m*(60s) and coefficient of variation (CoV) for binder type B504 as a mean value of three replicates. Figure 1 provides a visual comparison between the tests performed in ethanol and air for the entire set of binders with the bar charts.

TABLE 1 BBR experimental results for all asphalt binders *S*(60s)

Asphalt Binder	*T* [°C]	Ethanol		Air		*S*(60s)
		S(60s) [MPa]	CoV [%]	*S*(60s) [MPa]	CoV [%]	Diff. [%]
B504_virgin	low PG +10ºC	106	2.2	130	4.4	18.5
	low PG + 4ºC	234	1.3	364	4.1	35.7
B504_R&P_123	low PG +10ºC	129	2.7	175	3.3	26.3
	low PG + 4ºC	318	1.9	402	5.1	20.9
B504_R&P_143	low PG +10ºC	159	2.8	205	1.5	22.4
	low PG + 4ºC	362	1.7	453	0.5	20.1
B504_R&P_163	low PG +10ºC	182	3.9	228	1.9	20.2
	low PG + 4ºC	390	4.1	494	2.8	21.1

TABLE 2 BBR experimental results for all asphalt binders *m*(60s)

Asphalt Binder	*T* [°C]	Ethanol		Air		*m*(60s)
		m(60s) [MPa]	CoV [%]	*m*(60s) [MPa]	CoV [%]	Diff. [%]
B504_virgin	low PG +10ºC	0.400	2.1	0.320	4.4	-25.0
	low PG + 4ºC	0.301	3.6	0.240	5.3	-25.4
B504_R&P_123	low PG +10ºC	0.384	0.8	0.309	6.3	-24.3
	low PG + 4ºC	0.294	1.7	0.237	3.2	-24.1
B504_R&P_143	low PG +10ºC	0.362	5.8	0.291	7.8	-24.4
	low PG + 4ºC	0.296	4.4	0.228	4.0	-29.8
B504_R&P_163	low PG +10ºC	0.351	1.2	0.283	4.1	-24.0
	low PG + 4ºC	0.273	3.1	0.216	4.8	-26.4

It can be observed that there is a substantial increase in *S* (60) and a decrease in *m*-value when asphalt binder is conditioned and tested in air. The difference ranges between 18.5% and 35.7% depending on temperature and binder type for creep stiffness; in some case of *m*-value differences up to a maximum 29.8% can be found.

Creep stiffness increases while the relaxation parameter decreases with the aging temperatures; therefore, it may be hypothesized that a reduced production temperature might lead to a lower stiffness and higher relaxation capability. Overall, based on simple statistical multiple comparisons, for both creep stiffness and *m*-value it appears that a difference in 20°C in the aging temperature is not necessarily resulting in a significant effect on the rheological properties of the asphalt binder. In addition, when the reduction temperature is only 20°C, the maximum difference of creep stiffness is 13.1%, with an average of 9.8%; however, this percentage reaches a maximum of 27.0% with an average percentage of 20.6% when the production temperature is 40°C lower than the conventional HMA binder. This suggests that an overall softening effect takes place with the reduction of production temperatures with the potentially decreased brittleness of the materials. Hence, WMA technology may potentially result in substantial benefits in terms of long-term aging when the reduction in temperature reaches 40°C.

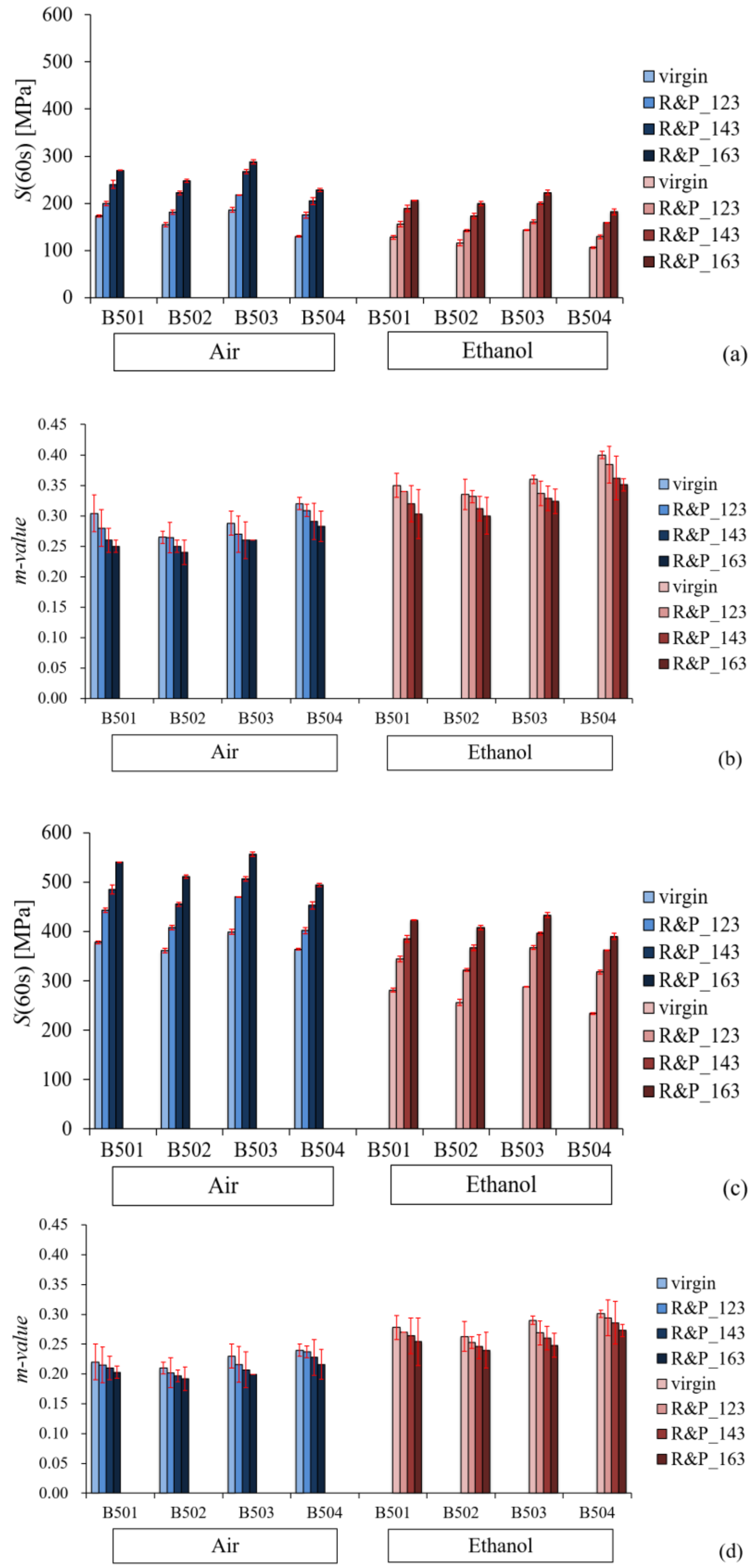

FIGURE 1 (a) *S*(60s) at low PG+10°C, (b) *m*-value at low PG+10°C, (c) *S*(60s) at low PG+4°C, (d) *m*-value at low PG+4°C

4. MODELING AND ANALYSES

The rheological Huet [24] model which consists of an assembly of two parabolic elements and one spring combined in series, was used to better understand the effect of cooling media and aging temperatures. Figure 2 illustrates the constitution of Huet model.

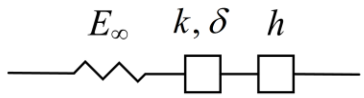

FIGURE 2 Huet model [24]

The creep compliance, $D(t)$, is expressed according to the following equation:

$$D(t) = \frac{1}{S(t)} = \frac{1}{E_\infty}\left(1 + \delta\frac{(t/\tau)^{k}}{\Gamma(k+1)} + \frac{(t/\tau)^{h}}{\Gamma(h+1)}\right) \tag{3}$$

Where $S(t)$ is creep stiffness; E_∞ is glassy modulus; h and k are exponents such that $0<k<h<1$; δ is dimensionless constant; Γ is the gamma function and τ is characteristic time, associated with the relaxation time of the material. Parameters, k and h are commonly in the range of 0.08~0.3 and 0.3~0.8, respectively, although lower values were found as reported in a different research [30]; stiffer materials are associated with lower values of these parameters [24,28]. The fitting of Huet model was performed on the low temperature creep stiffness obtained at low PG+10ºC. Figures 3 shows the model fitting for asphalt binder B504_R&P_143 and B501_R&P_143 in ethanol and air as an example, other binders displayed similar trends. As can be seen from Figure 3, the Huet model fits the experimental creep stiffness obtained in ethanol and in air with two different binders reasonably well. The corresponding model parameters for binder B504 are listed in Table 3.

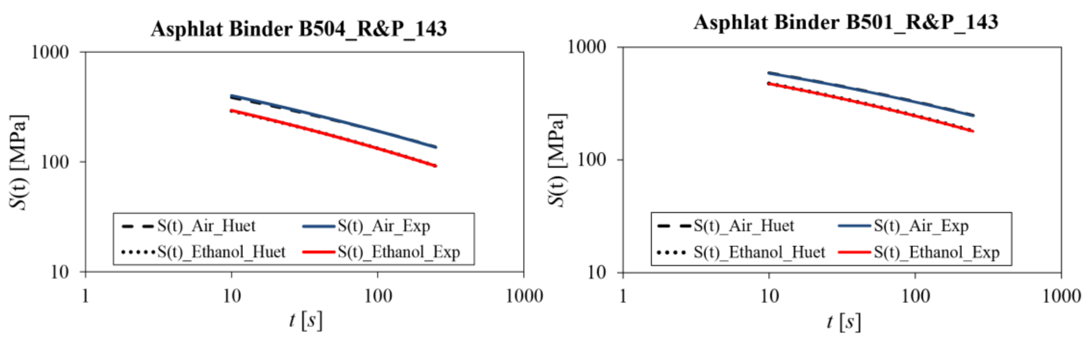

FIGURE 3 Huet model fitting of $S(t)$ in ethanol and air at T=low PG+10°C

TABLE 3 Huet model parameters of $S(t)$ in ethanol and air at T=low PG+10°C for asphalt binder B504

Asphalt binder	Cooling medium	E_∞ (MPa)	δ	k	h	log(τ_0)	R^2
B504_virgin	Ethanol	3000	2.37	0.23	0.80	2.01	0.998
	Air	3000	1.68	0.20	0.56	2.09	0.996
B504_R&P_123	Ethanol	3000	4.86	0.24	0.80	1.67	0.999
	Air	3000	4.31	0.22	0.62	2.43	0.997
B504_R&P_143	Ethanol	3000	5.26	0.24	0.80	1.83	0.996
	Air	3000	4.80	0.21	0.62	2.46	0.994
B504_R&P_163	Ethanol	3000	6.70	0.27	0.80	1.97	0.994
	Air	3000	5.30	0.22	0.64	2.51	0.999

The parameters of the Huet model provide additional understanding of the effect of cooling media and aging temperatures. First, the Huet model parameters show a significant difference when compared with respect to the cooling medium. In ethanol, the shape parameter δ is significantly higher, with maximum 29.1%, than the one deduced from the fitting parameters in air. An overall larger characteristic time, τ, is obtained for the measurements in air. As previously mentioned, this parameter is associated with the time of the system to relax; therefore, this suggests that materials tested in air may have poorer relaxation properties. Overall, the parameters of the Huet model confirmed the trend observed from the curve of creep stiffness and *m*-value. The cooling medium strongly affects the experimental measurements resulting in stiffer and brittle materials when air is used in place of the conventional ethanol bath in the BBR.

In addition, the parameters have a similar variation trend in both ethanol and in air, hence, it can be derived that the experimental results are also highly dependent on the materials type. Among the long-term aged asphalt binders, with the decreasing of aging temperatures, all the parameters shown an overall decreasing trend in both cooling media. According to table 3, a significant decrease was obtained for the shape parameter δ while only slight differences were observed for the other parameters. For a reduced production temperature of 20 ºC, δ decreases to 21.5% and 9.4% in ethanol and air, respectively; when an aging reduction of 40 ºC is applied, the decreasing percentage reaches 27.5% and 18.7%, respectively. This confirms that the potential use of WMA technology with a production temperature of 40°C can positively affect the low temperature property of asphalt binder; on the other hand, testing in air appears to have a smaller impact on the model parameters, suggesting a smaller sensitivity of the measurements in comparison to ethanol.

5. SUMMARY AND CONCLUSION

In this paper, the effects of different aging temperatures and cooling medium on the low temperature properties of asphalt binder were investigated. BBR tests were conducted on four asphalt binders which were long-term aged after a short-term aging process at three different temperatures. Ethanol and air were used as cooling media. Creep stiffness and *m*-value were calculated, and a simple rheological model was used for the analysis of one of the binders. Based on the results obtained in the present study it can be stated that a maximum difference of 27% in the low temperature response of the material can be observed when a reduction of 40 ºC is imposed during the short-term aging process. This is confirmed both by the experimental results and by the parameters of the rheological model, suggesting the use of WMA technology, may be ultimately beneficial for the long-term performance of asphalt materials at low temperature.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the asphalt binders suppliers and the members of the RILEM Technical Committee 252-CMB.

REFERENCES

[1] Moon, K. H., Marasteanu, M. O., and Turos, M. Comparison of Thermal Stresses Calculated from Asphalt Binder and Asphalt Mixture Creep Tests. Journal of Material in Civil Engineering, (25), 1059-1067, 2013.

[2] Marasteanu, M. O., et al. Investigation of Low Temperature Cracking in Asphalt Pavements. National Pooled Fund Study Phase II. Research Report 2007-43, Minnesota Department of Transportation (MN/DOT), Saint Paul, 2012.

[3] D.A. Anderson, T. Kennedy, Development of SHRP Binder Specification, Journal of the Association of Asphalt Pavement Technologies, (62) 1993 481-507.

[4] AASHTO M320, Standard Method of Test for Performance Graded Asphalt Binder, American Association of State Highway and Transportation Officials, 2016.

[5] AASHTO T315, Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR), American Association of State Highway and Transportation Officials, 2012.

[6] EN 14770-08. Bitumen and bituminous binders - Determination of complex shear modulus and phase angle using a Dynamic Shear Rheometer (DSR). European Committee for Standardization. 2012.

[7] AASHTO T313, Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR), American Association of State Highway and Transportation Officials, 2012.

[8] AASHTO T314. Standard Method of Test for Determining the Fracture Properties of Asphalt Binder in Direct Tension (DT). American Association of State Highway and Transportation Officials, 2012.

[9] Cannone Falchetto, A., Turos, I., Marasteanu, M. O., Investigation on Asphalt Binder Strength at Low Temperatures, Road Materials and Pavement Design, Vol. 13(4), 2012, 804-816.

[10] Marasteanu, M. O., Cannone Falchetto, A., Turos, M., Le, J-L., Development of a Simple Test to Determine the Low Temperature Strength of Asphalt Mixtures and Binders, IDEA Program Final Report NCHRP 151, 2012.

[11] Carret, J. C., Cannone Falchetto, A., Marasteanu, M. O., Di Benedetto, H., Wistuba, M. P., Sauzeat, C., Comparison of Rheological Parameters of Asphalt Binders Obtained from Bending Beam Rheometer and Dynamic Shear Rheometer at Low Temperatures, Road Materials and Pavement Design, 16(1), 2015, 211-227.

[12] Riccardi, C., Cannone Falchetto, A., Wang, D., Wistuba, M. Effect of cooling medium on low-temperature properties of asphalt binder, Road Materials and Pavement Design, 18(7), 2017, 1-22.

[13] Chowdhury, A., Button, J. W., A review of warm mix asphalt (No. SWUTC/08/473700-00080-1). Texas Transportation Institute, the Texas A & M University System. 2008.

[14] European Asphalt Pavement Association (EAPA). The Use of Warm Mix Asphalt. EAPA position paper 2010. www.eapa.org. Accessed Feb. 26th, 2017.

[15] Bonaquist, R. F. Mix design practices for warm mix asphalt (Vol. 691). National Cooperative Highway Research Program-NCHRP Report 691. Washington, DC: Transportation Research Board. 2011.

[16] AASHTO R35-15. Standard Practice for Superpave Volumetric Design for Asphalt Mixtures. American Association of State Highway and Transportation Officials, 2015.

[17] Gandhi, T., Rogers, W., Amirkhanian, S. Laboratory evaluation of warm mix asphalt ageing characteristics. International Journal of Pavement Engineering, 11(2), 133-142. 2010.

[18] Rashwan, M. H. Characterization of Warm Mix Asphalt (WMA) performance in different asphalt applications (Doctoral dissertation, Iowa State University). 2012.

[19] Poulikakos, L. D., Hofko, B., Porot, L., Lu, X., Fischer, H., Kringos, N. Impact of temperature on short-and long-term aging of asphalt binders. RILEM Technical Letters 1, 6-9. 2016.

[20] Hofko, B. and M. Hospodka, Rolling Thin Film Oven Test and Pressure Aging Vessel Conditioning Parameters Effect on Viscoelastic Behavior and Binder Performance Grade. Transportation Research Record, 2016(2574): p. 111-116.

[21] Gandhi, T. Effects of warm asphalt additives on asphalt binder and mixture properties (Doctoral dissertation, Clemson University). 2008.

[22] Kim, H., Lee, S. J., Amirkhanian, S. N., Jeong, K. D., Quantification of oxidative aging of polymer-modified asphalt mixes made with warm mix technologies. Journal of Materials in Civil Engineering, 25(1), 1-8. 2012.

[23] Abbas, A. R., Nazzal, M., Kaya, S., Akinbowale, S., Subedi, B., Qtaish, L. A., Effect of Warm Mix Asphalt on Aging of Asphalt Binders. In Proceedings of the TMS Middle East—Mediterranean Materials Congress on Energy and Infrastructure Systems (MEMA 2015) (pp. 55-64). Springer International Publishing. 2015.

[24] Huet, C. Etude par une Méthode d'Impédance du Comportement Viscoélastique des Matériaux Hydrocarbonés. Thèse de Doctorat d'Ingénieur. Faculté des Sciences de l'Université de Paris, 1963. (In French).

[25] EN 1426: Bitumen and bituminous binders—determination of needle penetration. British Standards. European Committee for Standardization. 2007.

[26] Hofko, B., Cannone Falchetto, A., Grenfell, J., Huber, L., Lu, X., Porot, L., Poulikakos, L., You, Z. Effect of short-term ageing temperature on bitumen properties. Road Materials and Pavement Design, 1-10. 2017.

[27] AASHTO T240. Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test), American Association of State Highway and Transportation Officials, 2013.

[28] AASHTO R028. Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV), American Association of State Highway and Transportation Officials, 2012.

[29] Wang, D., Cannone Falchetto, A., Riccardi, C., Schrader, J., Hofko, B., Poulikakos, L., Wistuba, M. Reological Modeling of Asphalt Binder under Different Short and Long-Term Aging Conditions. Washington, DC: 97th Transportation Research Board. 2018. (in press)

[30] Cannone Falchetto, A., Moon, K. H. Micromechanical-Analogical Modelling of Asphalt Binder and Asphalt Mixture Creep Stiffness Properties at Low Temperature. Road Materials and Pavement Design, 16(S1), 111-137, 2015.