Binder performance and testing

Durability parameters evaluated on binders recovered from various field sites in Europe

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Abstract

Recently, a number of rheological parameters have been proposed as performance indicators for aging and aging-induced crack formation. These include parameters derived from BBR measurements, as for example delta Tc, or parameters derived from DSR measurements, such as the Glover Rowe parameter, the crossover frequency and parameters related to the shape of Black- and master curves. Delta Tc is defined as the difference between the limiting stiffness temperature (LST) and the limiting slope temperature (LmT). The more negative this difference, LST-LmT, the higher is the risk for aging-induced cracks. The Glover-Rowe parameter is calculated from DSR measurements, more specifically, from the complex modulus and phase angle values taken at 15°C and 0.005 rad/s. This parameter relates also to the ductility recorded at 15°C and at 1 cm/min. In literature, good relations between the various parameters and cracking on field sites have been observed. However, up to now these validations were mainly conducted on North American pavements. The main purpose of this study is to evaluate if the rheological parameters, proposed for US sites, can also be valid for European conditions. Therefore, field test sites from which binders could be recovered were identified. In addition, before taking cores, the road condition, as well as traffic situation was evaluated. From the cores, binder- and void content were determined. And the recovered binders were subjected to a full characterization based on DSR measurements, including 4 mm DSR measurements. The aging state of the binders was further evaluated based on FTIR measurements. Although the original binders were not available, it was possible to draw important conclusions from this study.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

During their service life asphalt constructions are subjected to aging. The binder keeping the aggregates together hardens and becomes more brittle, resulting in an increased risk for different types of crack formation. Aging has been related to a variety of failures, not only to crack formation, also failures such as ravelling and stone loss since (micro)crack formation could also initiate and accelerate these types of damage. Recently, a number of binder parameters have been proposed, including delta Tc, and the Glover-Rowe parameter to determine the tendency for aging and the risk for aging-induced crack formation [1-6]. In addition to the parameters, critical as well as limiting levels have been proposed. And in US, these newly introduced parameters have already been validated in field sections [1-6]. At the moment, however, it is not clear, if these new parameters and their limiting levels are also valid for European pavements and conditions.

In this study, the first objective is to evaluate how bituminous binders age in field sites, when embedded in a road surface, in particular how the rheological properties change and if this is comparable to accelerated aging tests. A second objective is to evaluate if the newly proposed parameters and limiting levels are applicable when looking at European pavements. When trying to find appropriate field sites, it was decided to include sites for which the original binder was not available anymore. This is a choice, limiting the interpretational value, but it allowed more possibilities for finding suitable sections, and for enlarging the sample set. And, instead of the original binder, the recovered binders are compared to a set of reference samples, which were collected in the European market over the years 2012-2014, allowing still a certain way of comparison. Also, sites containing reclaimed asphalt (RA) were included in the sample set. Finally, as it has been demonstrated in literature that there is an aging gradient with pavement depth [7], top surfaces aging more compared to layers deeper below the surface, this approach was adopted when cores were available. In this paper, a few representative sections, selected from the sections investigated so far, are discussed in detail.

2. FIELD SECTIONS

Figure 1 is an overview of the locations, considered so far. The sites indicated with a full line have already been, or are currently under evaluation, this are nine projects in total. And the project in Denmark, consists of three sections so in fact the sample set consists of a total of 11 sections. The sites indicated with dashed lines are possibilities, under consideration, but not yet included. As this project is still ongoing, results will be added continuously as they become available. The sites included at this moment, represent a variety of climatic regions, pavement types, traffic loadings and pavement ages. For some of the sites, limited information on the original binder is available and until now, the original binders as such are not available. For this paper, five representative sites have been selected from the investigated ones, these are highlighted in Figure 1, and these are discussed in detail. In Table 1, information associated with these five selected sites is represented, as well as pictures from the respective road surfaces. The void contents, Table 1, which have been shown to be an important parameter [11], were measured on the cores.

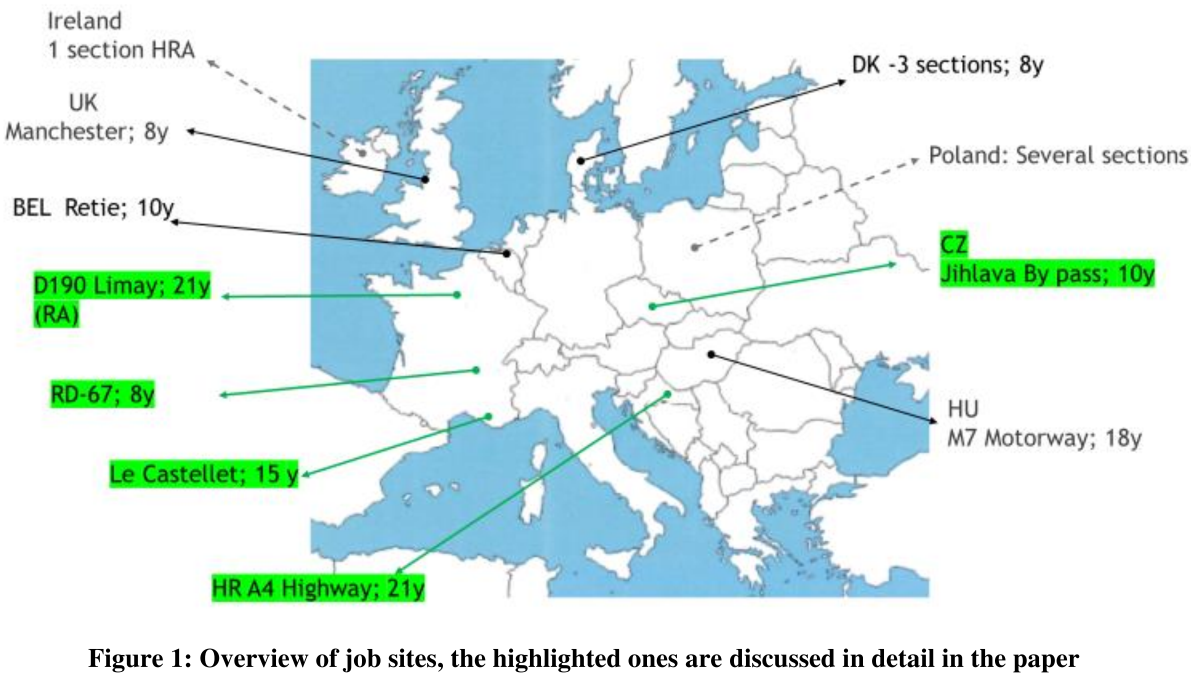


Figure 1: Overview of job sites, the highlighted ones are discussed in detail in the paper

Table 1. Characteristics of the investigated field sections

Nr.	Information	Photographs
1	RD 67, 8y, South France BBMs 0/10 R30, WMA No cracking, Binder type: 50/70 + RA Binder w%: 5.3% + 0.4% WMA additive. (3.9% fresh binder, 1.4% RA binder) Voids 12.3% range 10.2-16.4	
2	Jilhava Bypass 10y, Czech Republic SMA 11 S No damage Binder type: PmB 45/80-50: Penetration 25°C: 69 dmm, R&B: 51.5°C Binder w%: 6.3 + fibers Voids: 7.3% range 5.3-8.1	
3	Le Castellet 15y, South France, racetrack BBMc 0/10 Some cracking: longitudinal at joints & transverse cracking Binder type: PmB 25/55-65 Penetration: 51 dmm Binder w%: 5.84% Voids: 6.8% range 3.4-11.6	
4	A4 Highway, 21y, Croatia, AC 11 surf Fatigue damage & reflective cracks Binder type: 50/70 Penetration 25°C: 64 dmm R&B: 49.5°C Fraass: -17°C Binder w%: 5.8 Voids: 2.5% range 2.4-2.6	
5	Limay D290, 21y, France AC 10 reclaimed asphalt, from the surface layer. Cracking is visible, probably fatigue. Binder type: No data Binder w%: 4.9 Voids: No data	

3. EXPERIMENTAL

3.1. Binder recovery and the binder reference set

Wearing courses were studied. Asphalt cores were cut into thin slices and afterwards the slices from the same depth (and different cores) were recovered together. The slices of the top surfaces were typically 0.5cm. For all the sections, except the reclaimed asphalt, the cores were cut in at least two slices, in one case even in four slices, the number and thickness of these is indicated in Table 2. Binder recovery was conducted according to EN12697-3, with trichloroethylene as the solvent.

Table 2. Overview of the binder recoveries of the field sites

Section	Nr of layers and thickness
1	3: Top (< 1cm), Middle (1-2cm), Bottom (> 2cm)
2	4: Top (< 0.5cm), 2nd (0.5-1cm), 3rd (1-2cm), Bottom (> 2cm)
3	3: Top (< 0.5cm), Middle (0.5-1cm) Bottom (> 1cm)
4	3: Top (< 0.5cm), Middle (0.5-1cm) Bottom (> 1cm)
5	Wearing course

A set of binders, 50/70 and 70/100 grades, collected in the period 2012-2014, from the main European bitumen producers, was used as reference set for the recovered binders. It consists of nine 50/70 and four 70/100 binders. These binders have been evaluated by conventional tests (penetration, R&B) and FTIR before aging, after RTFOT and after RTFOT+PAV. Rheological tests (8mm and 25mm plates) and BBR measurements were conducted before aging and after RTFOT+PAV.

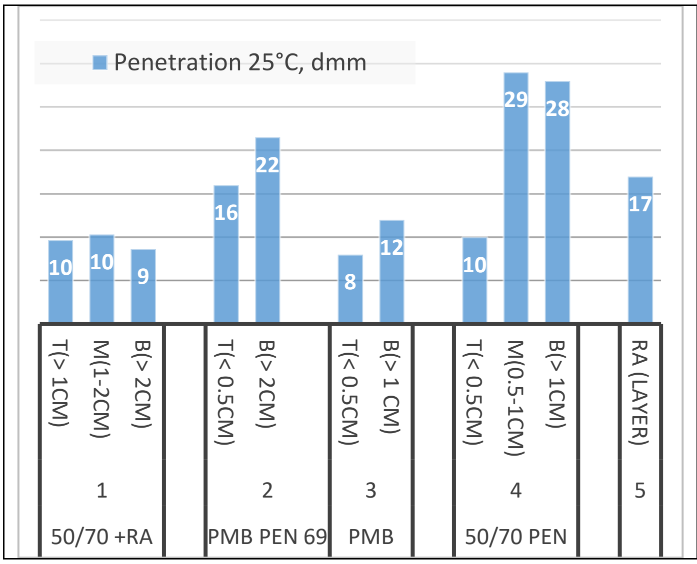
3.2. Characterization tests

Rheological tests were conducted with Anton Paar rheometers, for the 25mm, 8mm plate tests an MSCR500 was used, and for the 4mm plate tests an MCR 101. A description of the sample loading procedure and rheometer calibrations for the 4mm plates tests can be found in [8]. Isotherms were recorded from +12°C to -30°C, from the highest to the lowest temperatures, in steps of 6°C, in a frequency range 10Hz to 0.01Hz. The strain was set to 0.0002 for all temperatures and all frequencies. At each temperature an equilibration period of 20 minutes was used. The time for testing the frequency range was also almost 20 minutes. So, in this procedure, the samples were for about 40 minutes at each of the tested temperatures. The 8mm tests were performed from 0 to 50°C, in steps of 10°C, in the same frequency range as the 4mm tests, at a strain of 0.0005. The 25mm plates were tested from 50°C to 90°C, also in steps of 10°C, at the same frequency ranges, and at a strain of 0.001 for 40°C and 50°C, and a strain of 0.01 at higher temperatures. For the 8mm and 25mm plates equilibration times were 10 minutes.
A Cannon BBR was used, according to EN14771, with ethanol as the cooling medium.
FT-IR tests were conducted using a Nicolet IS 10 with a diamond cell and an attenuated total reflection setup. Binders were first heated, and a drop of material was poured on the diamond cell and investigated.
The bulk density of the cores was measured by gamma rays according to EN 12697-7.

4. RESULTS

4.1. Conventional properties

Conventional (pen, R&B) parameters were tested for the recovered binders, and in Figure 2 penetration values at 25°C of the various samples are represented. This test was conducted since for most sites the penetration class of the original binder was known, and in two cases also the exact penetration value. And, it was also a quick first indicator for differences between top and bottom samples. In one case there was not enough binder to conduct a penetration test, section 2-top part, and in this case the penetration was calculated from the rheological data, according to [9]. The data demonstrate that the binders have hardened a lot, compared to the initial state, also the bottom parts. The penetration levels observed in the recovered binders were compared to the average penetration of the reference binder set, after laboratory aging. This comparison indicates that binders have either aged to penetration levels corresponding to RTFOT+PAV, or have gone beyond and obtained an even lower penetration value. For the first section, the starting binder was already a mix of 50/70 and RA binder, this can explain why this binder has become so hard.



Average penetration after RTFOT: (25°C, dmm)

50/70 binders	33.4	Range: 23-40
70/100 binders	45.8	Range: 38-50

Average penetration after RTFOT+PAV: (25°C, dmm)

50/70 binders	20.1	Range: 15-24
70/100 binders	26.8	Range: 23-28

Figure 2: Penetration levels of recovered binders and changes related to laboratory aging tests

4.2. Rheological data

For the 4mm data, a repeatability check was made as this is still a rather new method of measuring low temperature properties. Randomly some samples were repeated, as is shown in Table 3. The repeatability for the phase angle was calculated as the difference between two values or as the standard deviation in case of more data. For G* the coefficient of variation, COV is reported, calculated as the standard deviation, divided by the average, expressed in percent. The so obtained repeatability was enough for further use. There were also some concerns about the overlap between data recorded with 4mm and 8mm plate tests. At 0°C, the average difference (COV) was around 20%, the 8mm plates always being lower in stiffness compared to the 4mm plate data. When comparing the values at 10°C, the average difference in COV was reduced to values below 10%, acceptable for further use. It seems that the binders were already too stiff at 0°C for 8mm plate testing, and rheometer machine compliance effects were already present.

Table 3. Repeatability of 4mm plate tests

Sample	Nr. of repeats	Δ phase, °	COV-G*, %
1-top	3	0.2	3.3
2-bot	2	0.1	8.4
4-top	2	0.2	7.5
4-bot	2	0.2	5.5
5-RA	2	0.4	1.6

There are many possibilities of representing rheological data: In Figure 3, Black diagrams are represented, as a check for changes in the shape of these curves, related to changes in the temperature susceptibility. This representation is often used to show the effects of laboratory aging. In Figure 3 frequency sweeps at 50°C are also plotted to visualize differences in stiffness. The data show that for section 1, all the slices have almost exactly the same rheological behaviour, in stiffness and in the Black curve. Section 2, 3 and 4, show a clear difference in the stiffness of top and bottom slices, and for section 4 this is combined with a slight change in the shape of the Black curve. For section 2 &3 there is almost no change in the shape of the Black curve. For section 5, as this was the rap binder, only one curve was available, this is not shown in Figure 3. Section 2 and 3 were constructed using PmBs and the polymer presence can be observed from the Black curve. In this paper, the effect of the PmBs is not further analysed, this will be discussed at a later stage, once more PmB sections have been studied.

In Figure 4, the same graphs are represented for one of the standard reference binders, before and after RTFOT+PAV aging. This binder is maybe not the one used in the sections, but it is shown, to give an idea of how the same parameters change due to laboratory aging. In this case there is a clear difference in the stiffness, as was also observed for some of the recovered sites, but this stiffness difference is combined with a clear shift in the Black curve. For the reference binders, 4mm data were not recorded.

From the frequency temperature sweeps master curves were constructed, and various aging-related parameters were calculated. These are summarized in Table 4, with a short description explaining how they were calculated.

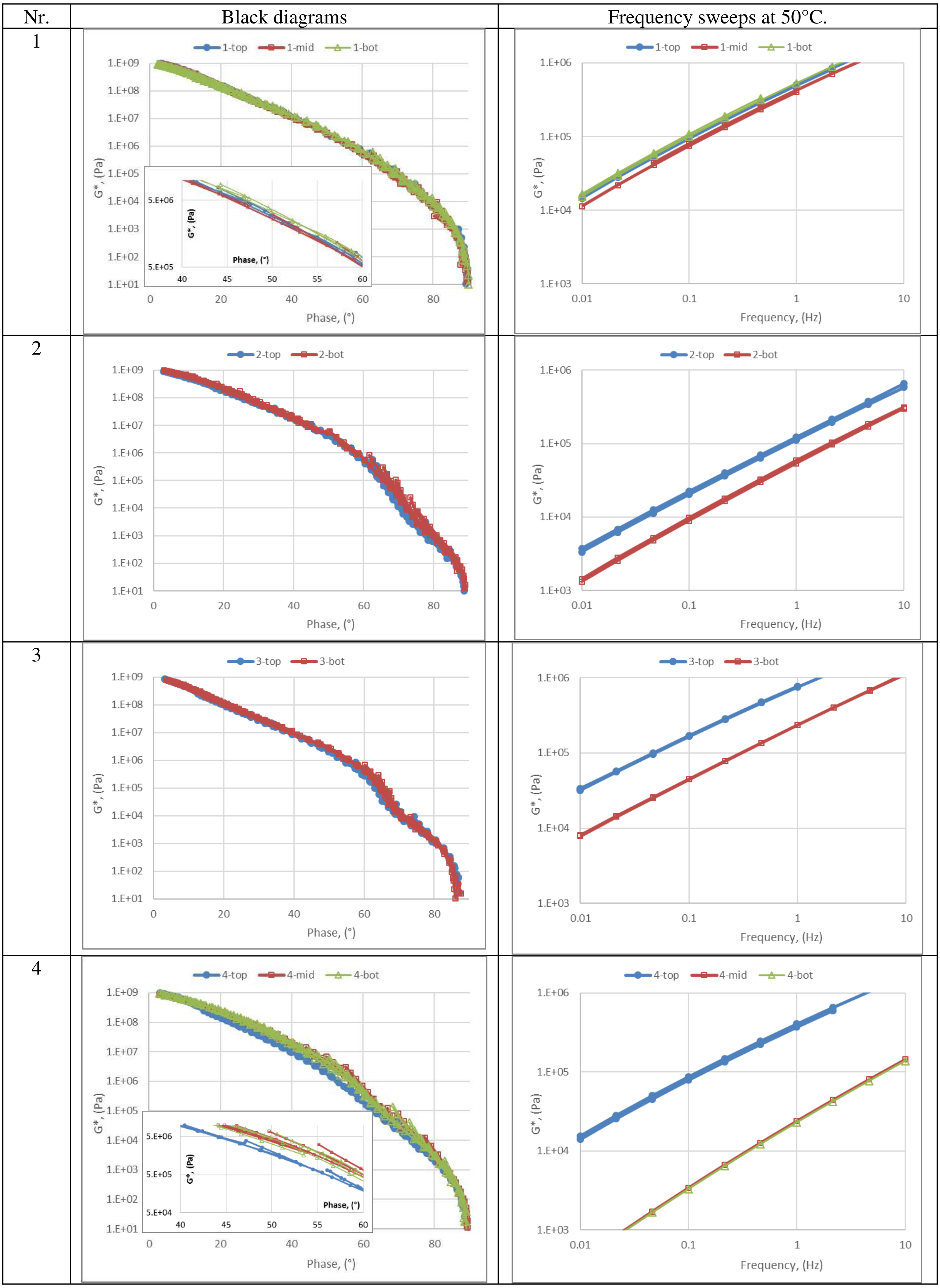


Figure 3: Overview of the rheological properties of recovered binders from the first 4 sections

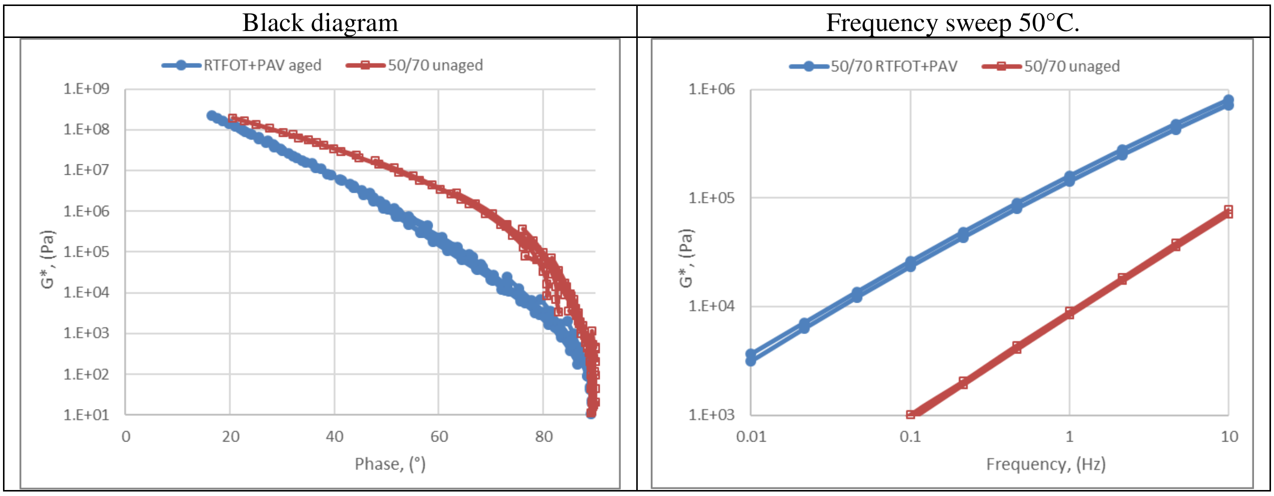


Figure 4: A Black diagram and a frequency sweep at 50°C, for a standard 50/70 binder before and after laboratory aging

Table 4. Summary of the rheological parameters calculated from master curves

Parameter	Description
Glover – Rowe (G-R)	Master curves were constructed from the 8mm plate data, using the Rhea software. (Abatech). To calculate the G-R parameter, the reference temperature of the master curve was set to 15°C, G* and phase angle at 15°C and 0.005 rad/s were calculated. $G-R\ parameter = \frac{G^*(\cos\partial)^2}{\sin\partial}$
LST LmT	The low temperature properties LST and LmT were determined from master curves constructed with 4mm and 8mm data. The Rhea software allows to transform dynamic data, G*(ω) into transient G(t) data. When calculating G(60s) and m(60s) at a certain temperature, the reference temperature was always set to this temperature, and only 4 isotherms, the one at the temperature of interest, including 3 above this temperature were used. Data of G(60s) and m(60s) were determined at temperature intervals of 6°C. LST and LmT were determined following a procedure explained in ASTM D7643-16, LST as the temperature where G(t) is 143MPa and LmT as the temperature where m = 0.275, in correspondence to [5,6].
Delta Tc	LST-LmT
Crossover parameters	Three crossover parameters were determined from the master curves constructed with the 8mm plate tests, at a reference temperature 0°C: The crossover frequency was calculated using the Christensen - Anderson model (CA); which can be obtained using the Rhea software. The crossover temperature and stiffness were both calculated at a frequency of 10 rad/s using the appropriate tool in Rhea.
R-index	Calculated using log (1 GPa / the cross-over stiffness)

A distinction can be made between on one hand, parameters only determined by the temperature susceptibility, but independent of the stiffness levels, such as the R-index, the phase angle at a fixed stiffness level, the crossover stiffness, and also delta Tc. On the other hand, there are the parameters that vary with the binder stiffness, and binder grade, such as G-R, crossover frequency and temperature. In this project, very good correlations were obtained between data of the second group; for example, log(G-R) gave a linear correlation coefficient (R^2) of 0.95 to log(crossover frequency) and of 0.99 to the crossover temperature. Therefore, only selected graphs are presented.

In Figure 5, G* is plotted versus phase angle, at the Glover-Rowe test conditions (15°C, 0.005 rad/s) for the various samples. The two lines represent two levels of G-R; the warning limit at 180kPa and the limiting level at 600 kPa [13]. The same trends as observed before are obvious; for the samples from section 1, there is no difference for the different slices, while section 2, 3 and 4 show a difference. In this graph the same data obtained on the reference set of binders is also plotted, before and after RTFOT+PAV aging. It is quite clear that all the recovered binders have aged, and some even beyond the level of what is obtained after the standard laboratory aging. The RA binder is somewhere in the range of the data after laboratory aging. The data also show that there is a large difference between the aging of the various reference binders, in the original state they can be collected in a small circle, indicated in blue, while after aging this area has stretched out to an elliptical area, shown in red. Some binders are already in the damaged zone after only one aging cycle. For the binders from the various field sites, the top part of binder 1, 3 and 4 are in the damaged zone, G-R above 600 kPa, and for binder 1 and 3 also the bottom part is in this region.

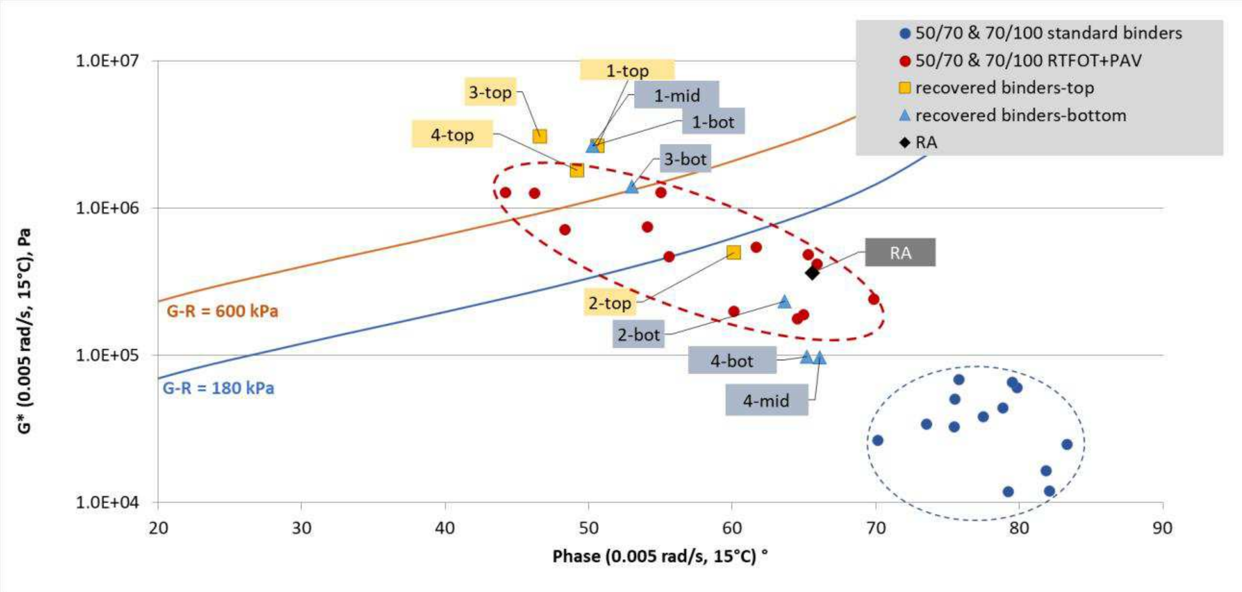


Figure 5: Phase angle versus G* at 0.005 rad/s and 15°C

In Figure 6, LST is plotted versus LmT, and the line of equality, for which delta Tc is zero is indicated, as well as the line for which delta Tc is -5°C. A delta Tc of -5°C has been proposed as the cracking limit [1]. For the field samples LmT and LST were determined based on 4mm data. A number of observations can be made: Only for section 1, top and bottom part are almost equal, for all other sections there is a difference. This difference is largest for section 4. The change from bottom to top parts, for sections 2, 3 and 4 are as expected, top parts have moved to less negative temperatures, and a more negative delta Tc. Or, LmT has changed more compared to LST. For all the field samples, the highest limiting temperature for low temperature cracking, is reached by LmT, all samples are m-controlled. With respect to the cracking sensitivity, for low temperature cracking, the top parts of sections 1 and 3 have LmT temperatures reaching respectively -2.3 and -1.3 °C. This corresponds to a low temperature PG grade of -10°C, a temperature that is not so low anymore. Regarding aging induced cracking, the limiting level for delta Tc of -5°C is reached for sections 1 & 3, and the top parts of section 4. Data from the reference set were also added to this graph, but these have been determined based on BBR measurements, and not on DSR tests. As this can induce a shift in the data, they should be considered as an indication. And, instead of the 13 reference binders used previously, only 6 reference samples are included, these 6 binders are the ones with the smallest and largest changes due to laboratory aging. When comparing the lab aged and the field aged data, it seems that the recovered binders have moved more in the levels of LST and LmT as what is seen for laboratory aged samples.

To evaluate if the change in the shape of the Black curve is similar for field aged as for lab aged binders, one more plot was made. In Figure 7, the crossover stiffness, a parameter only related to the shape of the Black or master curve, was plotted versus the stiffness at a fixed frequency and temperature, a parameter that is obviously very dependent on the stiffness level. In figure 7 the same data for the reference set of binders are also indicated, again the full set of 13 binders. When comparing the recovered binders to the original reference binders, it seems that all top parts, and all bottom parts, have moved outside of the crossover stiffness region formed by these original binders. So, there is a change in the shape of the Black curves in the same direction as seen in laboratory aging. When comparing the recovered binders to the lab aged reference binders, most samples, including the RA, are in the same region as observed for the aged reference binders. But section 1 and the top part of section 3 have, when looking at the stiffness levels, the Y-axis, aged beyond the levels reached by the reference set. While none of the recovered binders has changed beyond the crossover stiffness levels, the X-axis, compared to the reference binder set. At least, this indicates that there could be a difference between field and lab aging in the ratio of stiffening versus changing the shape of the Black curve but this will need some more confirmation.

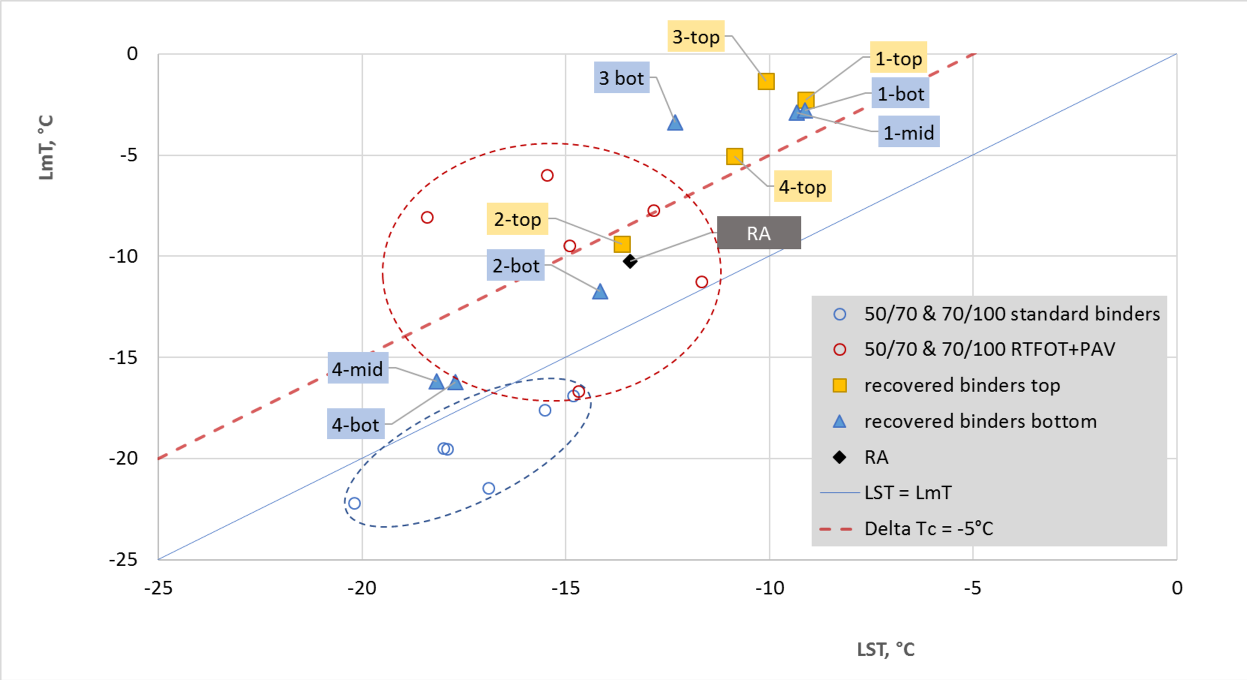


Figure 6: Plot of LST versus LmT

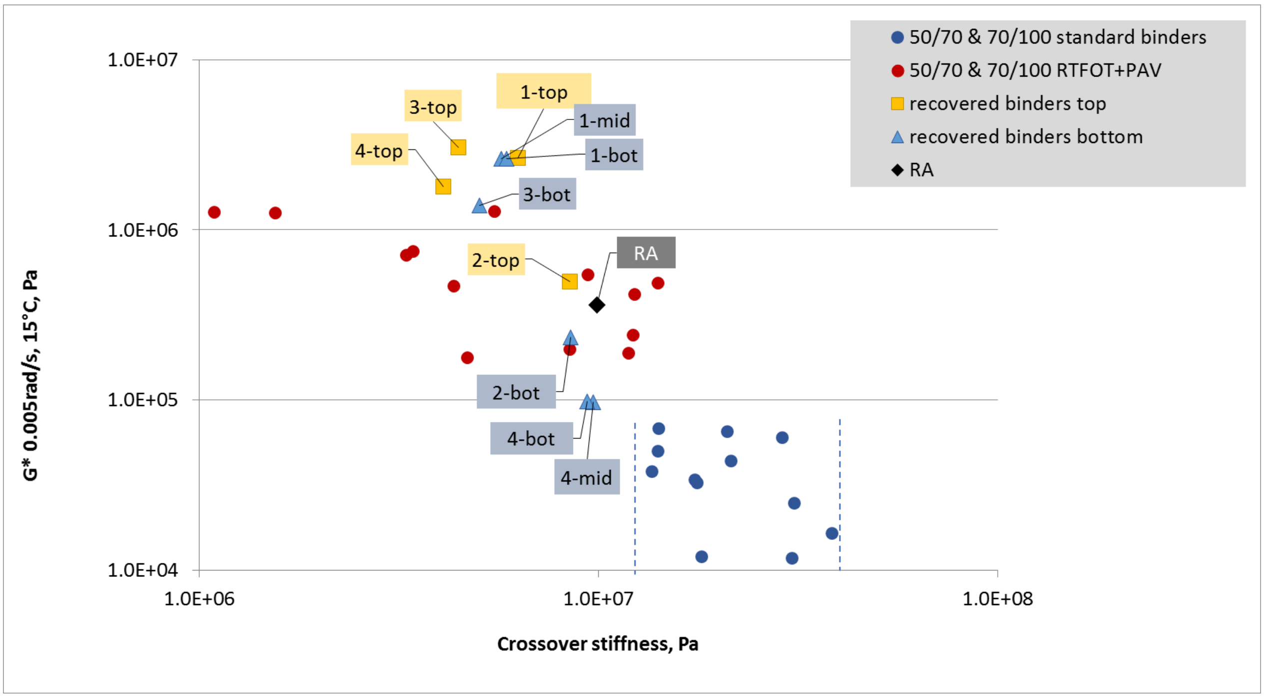


Figure 7: Crossover stiffness versus the stiffness at a fixed temperature and frequency

4.3. FT-IR results

The main changes related to aging, as observed by FTIR, correspond to an increase in the C=O and S=O absorption. In this study, aging indices were quantified following a procedure explained in [10]. For the signals at 1700 cm^{-1} and at 1030 cm^{-1}, the integration limits proposed in ref. 10, gave also the best fit for these spectra. Only for the CH2,CH3 bending, the start and endpoints of the integrated area were slightly shifted from the proposed limits in ref. 10. Indices were calculated by dividing the area of respectively C=O and S=O, by the area of the CH2, CH3 bending absorptions. The absorptions related to the presence of polymer were present in section 2 & 3, but these will be summarized at a later stage, when more sections with SBS binders become available. Typical absorption spectra are illustrated in Figure 8.

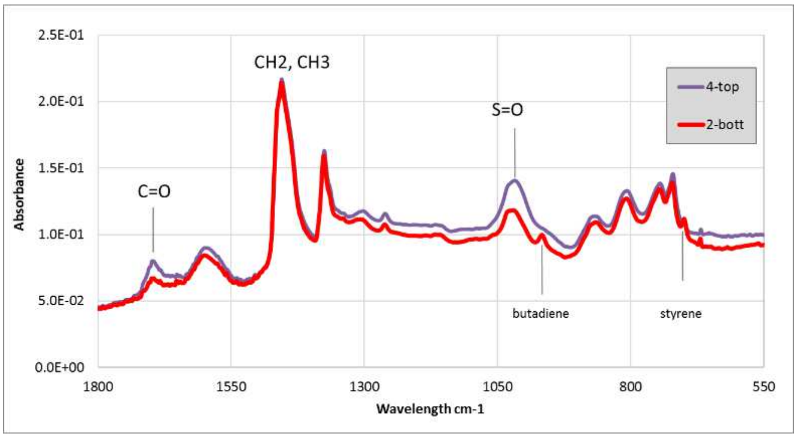


Figure 8: Typical spectra for the recovered binders.

In Figure 9, carbonyl and sulfoxide indices are plotted for the recovered binders and for the reference binders. For the selected reference binders, using the integration procedure proposed in [10], negative values were obtained for the carbonyl index before and after RTFOT, since there was in fact no carbonyl signal. Except for one binder, the first one, this binder already had a carbonyl absorption even in the original state. But, for the comparison to the recovered binders it can be disregarded since this sample was not used in the sections investigated so far. When comparing the indices of reference and recovered binders, the data show that all the recovered binders are aged, also the bottom parts, and when considering the C=O absorptions, they are aged to a level beyond RTFOT, indicating that field aging has taken place. In addition, most of the top parts are aged more as what would be expected after RTFOT + PAV, from FTIR observations. A similar observation can be made for the sulfoxide indices, but as these could be influenced by residual filler, they were not considered in this paper. The error bars were derived by a repeatability check on one of the binders, in this case 6 spectra were taken and analysed. The coefficient of variation (standard deviation/average *100) of these 6 repeats was used as the error bar in each direction in Figure 9.

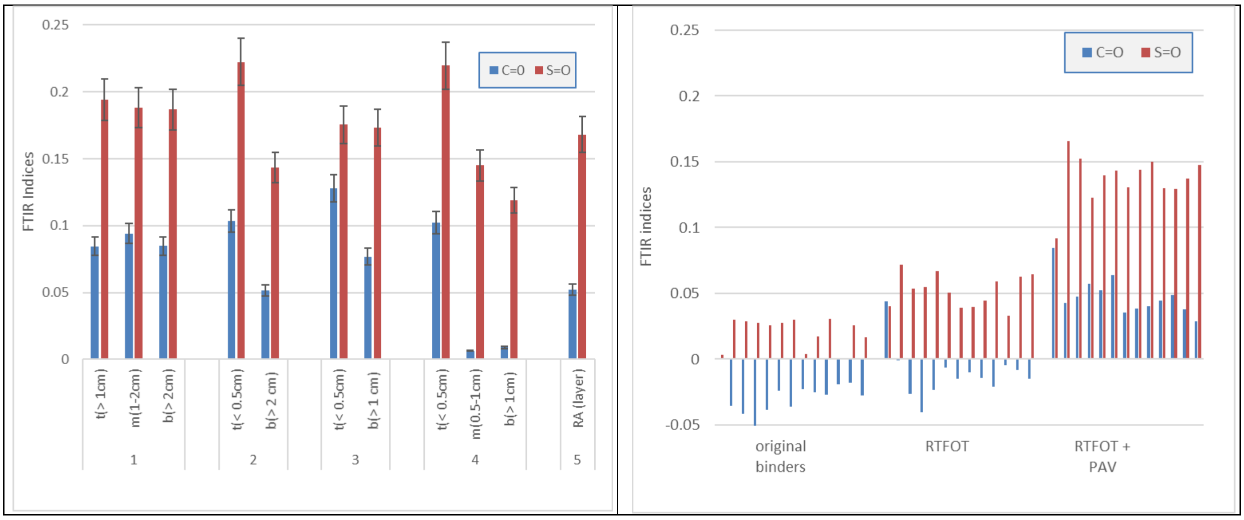


Figure 9: Carbonyl and sulfoxide indices for recovered and lab aged binders

5. DISCUSSION

In this study, five field sections have been investigated. For four sections, asphalt cores were taken, while one section consisted of reclaimed asphalt. For the asphalt cores, binder recovery was conducted after slicing the cores in thin layers, and these binders were investigated separately. This revealed that for three out of four sections there was a difference in the degree of aging between the top and the lower layers. For the first section, there was no difference, not in the rheological properties and not in FTIR spectroscopy, between three different layers from this section.

When comparing this to the mixture properties, it seems that the section that is aged homogeneously is the one with the highest air voids percentage, 12.3% in this case, while the section with the largest difference between top and bottom part, section 4, was the section, with the lowest percentage of air voids, 2.5%. The high void content of section 1 could make the whole asphalt layer more permeable, resulting in the bottom asphalt layer being much more accessible to oxygen than when the void content is much lower (e.g. section 4). Another consequence is that, over time, dense and moderately dense mixes (with air voids in the range of 6% -7%) develop a stiff top surface and softer layers below. This in turn may be interesting to analyse, in particular how it could induce stresses and strains, or influence external stresses and strains, possibly in combination with temperature gradients.

Regarding damage prediction, from the 5 sections that were studied, three showed damage in the form of cracking. Unfortunately, one of these was the RA sample, so it was not possible to investigate the aging of the top part separately. Therefore, the RA section is not included in the damage evaluation. For the other four sections, based on delta Tc and G-R parameters of top parts, sections 1, 3 and 4 have values located in the damaged zones as proposed in literature. For section 1, no cracking has been reported, there is some ravelling, but only in front of the roundabout and related to braking cars, which it is not considered to be a general damage phenomenon of this section. More importantly, this section contained RA, which could possibly explain the values seen on the recovered binders. For section 3 some cracking was observed; some longitudinal cracks close to the joint, combined with some transverse cracking. In fact, as traffic is very limited on section 3, it is a race track, these cracks are either low temperature or aging induced. For section 4, damage is clear, some of this is related to reflective cracking, and some could be due to fatigue or aging induced. For section 2, no damage has been reported. From the four observed sites, in fact section 2, 3 and 4 are in line with the expectations from the binder properties, when considering the top parts. At the moment, the damage evaluation is still qualitatively, a close evaluation of possible crack mechanisms and a quantification of the damage would be very helpful. Possibilities to perform such evaluations are under consideration.

Regarding the binder types, two sections were constructed based on PmBs, while three were based on unmodified binders, and from these one was a combination of fresh and RA binder. In this study, binder parameters such as delta Tc, G-R, crossover parameters, were calculated and used in comparisons. But, it is not fully clear if for polymer modified binders the same parameters, or limiting levels could be used, and if the polymer modification could have an influence on these rheological parameters [12].

6. CONCLUSIONS

In the objectives of this paper, the question if laboratory aging tests can predict field aging was one of the topics. With respect to this question, the following conclusions can be made:

- The trends observed in field aging and in laboratory aging tests are the same. There is an increase in G-R, delta Tc becomes more negative, crossover frequency and crossover temperature change in the expected directions.
- When comparing the recovered binders to laboratory aged standard binders, sometimes especially in top parts, more aging is observed in the field as that obtained after the standard short plus long term aging tests. This may indicate that longer laboratory aging times may reflect field aging better.
- For all the field aged binders, the highest limiting temperature for low temperature cracking, determined by 4 mm DSR tests, is reached by LmT, all samples are m-controlled.

Another objective was to investigate if parameters like delta Tc or Glover Rowe can be related to crack formation in the field. For this question a definite conclusion is not possible yet, in this project only four sites were suited to be investigated for damage parameters, as the RA site was not included in this part. But still important conclusions can be taken from these tests:

- The whole asphalt surface course has aged, for the four sections from which cores were evaluated, the bottom parts are all aged, more than would be expected from only RTFOT.
- The analysis also shows that if a thick asphalt course is recovered in one step, the degree of aging will be an average and the aged top part will be diluted by less aged bottom parts. This can be positive for the use of RA, as the RA binder, studied from section 5 indicates. But when trying to set aging related limits, it is important to measure the actual aging levels, a recovery in slices seems more appropriate. Possibly a recovery of the top 0.5cm could be enough.
- Whether the surface course is aged homogenously or not, is related to the void content of the mix; In this study, the surface course for which top and bottom parts were equally aged, was the one with the highest air voids content, and the site with the largest difference between the top and bottom part, was the most dense asphalt mix, studied so far.
- It seems that also dense mixes can have a considerable degree of aging in the top parts.

As already mentioned, this project is still on going and more field sites will be added. In addition, the plan is also to follow up some of the already tested sites and possibly investigate them again, for example when distresses would become obvious or after a longer service period. Hopefully this will allow us to give clear answers to the questions that started in this project.

ACKNOWLEDGEMENTS

The authors would like to thank all the people who worked to get cores from jobsites, and who made this research possible: Rosine Confais (Colas IDFN), Aziz Mohamedi (Colas Auvergne Rhone alpes), Velimir LAckovic (Colas Croatie), Jean Paul Dupuy et Dalibor Benes (CZ), Franck Ainaud (Colas Midi mediterranée)

REFERENCES

[1] AAPTP PROJECT 06-01; A Laboratory and field evaluation to develop test procedures for predicting non-load associated cracking of airfield HMA pavements, December 2010, AMEC Project No. 09-119-00948, Downloaded from: https://www.eng.auburn.edu/research/centers/ncat/files/aaptp/Report.Final.06-01.pdf

[2] R.M. Anderson, G.N. King, D.I. Hanson and P.B. Blankenship, Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking, AAPT, 2011, P 651

[3] G.M. Rowe, Prepared Discussion following the Anderson AAPT paper ref. 4, AAPT, Vol. 14 80, pp. 649-662, 2011.

[4] G. King, M. Anderson, D. Hanson, P. Blankenship, Using Black Space Diagrams to Predict Age-Induced Cracking, 7th RILEM International Conference on Cracking in Pavements, A. Scarpas, N. Kringos, I. Al-Qadi, A. Loizos (Editors), Mechanisms, Modelling, Testing, Detection, Prevention and Case Histories, Springer, DELFT, 2012 DOI: 10.1007/978-94-007-4566-7_44

[5] G. Reinke, A. Hanz, R.M. Anderson, M. Ryan, S. Engber, D. Herlitzka, Impact of re-refined engine oil bottoms on binder properties and mix performance on two pavements in Minnesota, E&E conference 2016, Prague DOI: 10.14311/EE.2016.284

[6] R. Hajj, A. Filonzi, A. Bhasin, TECHNICAL REPORT 0-6925-1, Improving the Performance-Graded Asphalt Binder Specification: Final Report, May 2019, Downloaded from: http://library.ctr.utexas.edu/ctr-publications/0-6925-1.pdf

[7] M. J. Farrar, T. F. Turner, J-P. Planche, J. F. Schabron, P. M. Harnsberger, Evolution of the Crossover Modulus with Oxidative Aging. Transportation Research Record: Journal of the Transportation Research Board. First Published January 1, 2013, DOI: 10.3141/2370-10

[8] J. Gražulytė, H. Soenen, J. Blom, A. Vaitkus, J. Židanavičiūtė & A. Margaritis (2019): Analysis of 4-mm DSR tests: calibration, sample preparation, and evaluation of repeatability and reproducibility, Road Materials and Pavement Design, DOI: 10.1080/14680629.2019.1634636

[9] RNJ Saal, JWA Labout. Rheological properties of asphalts. rheology. New York: Academic Press Inc.; 1958. p.363–400 DOI:10.1016/B978-0-12-395695-8.50014-8

[10] A. Dony, L. Ziyani, et al. MURE National Project: FTIR spectroscopy study to assess ageing of asphalt mixtures, E&E Congress 2016, Prague, Czech Republic, DOI:10.14311/EE.2016.154

[11] X. Lu, H. Soenen, O-V Laukkanen, Aging of bituminous binders in asphalt pavements and laboratory tests, p 273 280, Bearing Capacity of Roads, Railways and Airfields – Loizos et al. (Eds) © 2017 Taylor & Francis Group, London, DOI: 10.1201/9781315100333-40

[12] R.M. Anderson, Delta Tc - Concept and use, in “Past, Present, and Future of Asphalt Binder Rheological Parameters”, Transportation Research Circular E-C241, January 2019, p 22-44. Downloaded from: http://onlinepubs.trb.org/onlinepubs/circulars/ec241.pdf

[13] J. S. Daniel, F. Yin, A. E. Martin, E. Arámbula-Mercado, D. Newcomb, J-P. Planche, A. Pauli, H. Farrar, S. C. Huang, G. Reinke, and A. Hanz, Transportation Research Circular E-C234 (2018), from http://www.trb.org/Main/Blurbs/178080.aspx. last accessed 2019/11/21