Bitumen fatigue performance evaluation - with or without RAP - a real challenge

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ABSTRACT

Bitumen plays an important role in asphalt pavement fatigue. For normal paving grade bitumen fatigue performance generally improves with increasing penetration. However, this general rule does not hold for special binders like high stiffness binders, polymer modified bitumen and Multigrade bitumen. An estimation of the fatigue performance becomes even more difficult when part of the bitumen comes from reclaimed asphalt pavements (RAP). Evaluation of bitumen fatigue performance and the effect of RAP bitumen on bitumen fatigue performance are the main topics of this paper.

The fatigue performance of 10 binders was investigated with a DSR time sweep test at constant strain amplitude. The binders were tested with and without bitumen that was recovered from RAP. Addition of up to 40 % RAP bitumen has various but little effect on the fatigue performance of standard paving grade bitumen but for the better performing bitumen products the shear strain amplitudes corresponding to a fatigue life of 10^6 cycles decreases significantly. When all 10 bitumen products - with known significant differences in fatigue performance - are considered, a good correlation with asphalt fatigue performance as measured with the 2-point bending test is observed.

The DSR time sweep test method is not a practical tool to asses fatigue performance of bitumen as it takes a long time to complete the tests and reproducibility is poor. A number of binders have been tested according to the recently developed Linear Amplitude Sweep (LAS) test to investigate if this test has potential as practical test method to evaluate fatigue performance of bitumen.

Some of the results presented in this paper are from a research project that has been carried out in collaboration between ENTPE in Lyon, EIFFAGE and BP. This research addressed the influence of asphalt mix design parameters on the mechanical response of bituminous mixtures produced with RAP. Scope and some of the main findings and conclusions of this work have already been presented at different international congresses and in a number of scientific publications.

Keywords: Ageing, Durability, Fatigue Cracking, Performance testing, Reclaimed asphalt pavement (RAP) Recycling

1. INTRODUCTION

Bitumen plays an important role in asphalt pavement fatigue. For asphalt mixtures with normal paving grade bitumen (NPG) from straight distillation fatigue performance generally improves with increasing penetration of the bitumen. However, this general rule does not hold for special binders like high stiffness binders (HSB), polymer modified bitumen (PMB) and Multigrade bitumen. An estimation of the fatigue performance becomes even more difficult when part of the bitumen comes from reclaimed asphalt pavements (RAP). Evaluation of bitumen fatigue performance and the effect of RAP bitumen on bitumen fatigue performance are the main topics of this paper.

The fatigue performance of a number of bitumen products are investigated with a DSR time sweep test at constant strain amplitude. The binders are tested with and without bitumen recovered from RAP. The DSR time sweep test method is not a practical tool to asses fatigue performance of bitumen as it takes a long time to complete the tests and reproducibility is poor. A number of binders (without bitumen recovered from RAP) are therefore also tested according to the recently developed Linear Amplitude Sweep (LAS) test to investigate if this test has potential as practical test method to evaluate fatigue performance of bitumen. The binder fatigue test results are compared with the asphalt fatigue performance as measured with the 2-point bending test.

The results presented in the first part of this paper are from a research project that has been carried out in collaboration between École Nationale des Travaux Publics de l'État in Lyon (ENTPE), EIFFAGE Infrastructures and BP. This research project addressed the influence of asphalt mix design parameters on the mechanical response of bituminous mixtures produced with RAP and has been the subject of a PhD thesis [1].

2. TESTING OF BITUMEN FATIGUE PERFORMANCE

In Europe there is no standardized test procedure to assess the fatigue performance of bituminous binders. In many published studies of the last 15 years fatigue behaviour of bituminous binders is characterized with a DSR in high frequency oscillation mode [2, 3, 4, 5, 7]. This method is usually referred to as a DSR time sweep test. At sufficiently high stiffness level bitumen exhibits fatigue damage which is observed by a progressive decrease in stiffness with time (number of load cycles). A relative new method to assess the fatigue performance of bituminous binders is the linear amplitude sweep (LAS). This method [9, 10, 11] uses the results of a frequency sweep and a strain sweep to calculate the coefficients of a fatigue law.

The failure mechanism within a DSR bitumen sample depends on temperature and under certain conditions also the gap settings [6]. At sufficiently low temperature the sample shows pure fatigue which suddenly appears independently of the gap settings and with no change in sample shape during the test. Above a certain (critical) temperature, which is different for each bitumen grade, the sample shows both fatigue and ductile failure. In this stage the behaviour depends on the gap. The larger the gap the faster the failure appears. The sample radius decreases during the test and cracks can be observed at the edge of the sample. Further increase of temperature leads to pure ductile behaviour of the sample. To observe pure fatigue failure it is therefore important to test at high enough stiffness level. According to [2] fatigue tests for bituminous binders should be performed at a stiffness level of between 10 and 50 MPa. Equipment compliance limits the maximum stiffness.

3. BITUMEN FATIGUE PERFORMANCE EVALUATION WITH DSR OSCILLATION TEST

3.1 Test program

Most of the bitumen products that are included in the research project about the mechanical response of bituminous mixtures produced with RAP [1] are assessed for their fatigue performance with DSR time sweep tests. Configuration and main test conditions are:

- Plate-Plate configuration
- 4 or 8 mm roughed plates
- 2 mm gap
- Test temperature 10 °C
- Test frequency 25 Hz
- Constant strain amplitude

In this study fatigue life is defined as the number of load cycles at which the norm of complex shear modulus (|G*|) (further in this paper referred to as complex shear modulus) has become 50% of its initial value. To be able to develop the relation between shear strain amplitude (γ) and fatigue life (N) each binder is tested at minimum three different strain amplitude levels. 20 bitumen products - with and without recovered binder from RAP – have been tested. Details of binders that have been tested are given in table 1.

These binders are used in asphalt mixes with different amounts of RAP. The asphalt mixtures are evaluated for their fatigue performance according to EN 12697-24 (Appendix A) [12]. Configuration and main test conditions are:

- Two point bending / trapezoidal specimen
- Test temperature 10 °C
- Test frequency 25 Hz
- Constant strain amplitude

In accordance with the test norm fatigue life is defined as the number of load cycles at which the norm of complex modulus (|E*|) has become 50 % of its initial value. To be able to develop the relation between strain amplitude (ε) and fatigue life (N) each asphalt mix is tested at different strain amplitude levels. Details of asphalt mixtures that have been tested are given in table 1.

Table 1: Details of tested bitumen products (B) and asphalt mixtures (A)

Bitumen	**Amount of recovered bitumen from RAP*1 / Amount of RAP*2**		
	0 %	20%	40%
10/20	B	B+A	
15/25	B+A		B+A
35/50	B+A		B+A
35/50 + 2.5 % SBS	B	B+A	
35/50 + 4.5 % SBS	B	B+A	
35/50 + 2.0 % PPA	B	B+A	
35/50 B	B	B+A	
35/50 B + 2.5 % SBS	B	B+A	
70/100	B+A		B+A
Commercial PMB	B	B+A	
*1: In bitumen; *2: In asphalt mixture			

3.2 Test results

Some typical test results for a standard bitumen grade (i.e.70/100) are presented in Figure 1. The graphs show the complex shear modulus against time (i.e. number of test cycles) for three different strain amplitude levels. Main findings and observations from the DSR time sweep tests are:

- Initial complex shear modulus of the binders is between 20 and 200 MPa.
- Complex shear modulus of some binders undulates at the beginning and/or end of the test which influences the determination of initial complex shear modulus and/or cycles to failure.
- Complex shear modulus of some binders increases during the test.

- For most binders the initial complex shear modulus decreases with increasing strain level. This is especially so for the (highly) modified bitumen which are tested at relatively high strain levels (i.e. up to 6.6 %).
- Test reproducibility is poor for most binders.

All binders included in this study showed at least one of these phenomena. There are several possible reasons that - to some extend - can explain these phenomena like for example measuring outside the linear domain, steric hardening, equipment compliance, change in motor performance and insufficient expansion compensation. However, the influence on the test results remains uncertain. Observations from other studies and information on repeatability and reproducibility for the RILEM Round Robin on bitumen fatigue testing are reported in [7].

The shear strain amplitudes corresponding to a fatigue life of 10^6 cycles (γ_6) for the bitumen products without RAP are shown in figure 2. The differences between the standard grades from straight distillation (i.e. 35/50 and 70/100) and the air rectified hard binders (i.e. 10/20 and 15/25) are small (i.e. $0.5 \leq \gamma_6 \leq 0.8$). The Multigrade bitumen (35/50 B) and the polymer modified bitumen (PMB) show improved fatigue performance (i.e. higher values for γ_6).

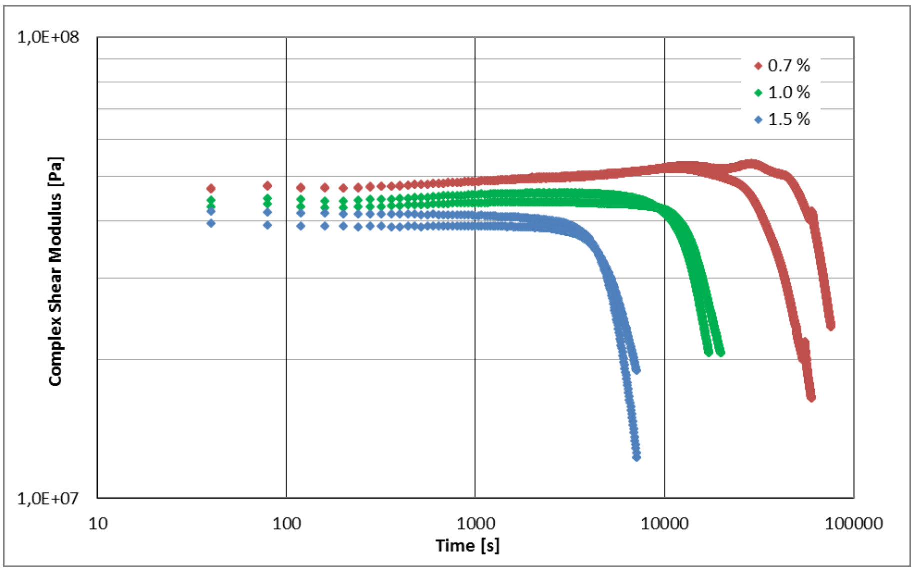

Figure 1: DSR fatigue curves 70/100 bitumen

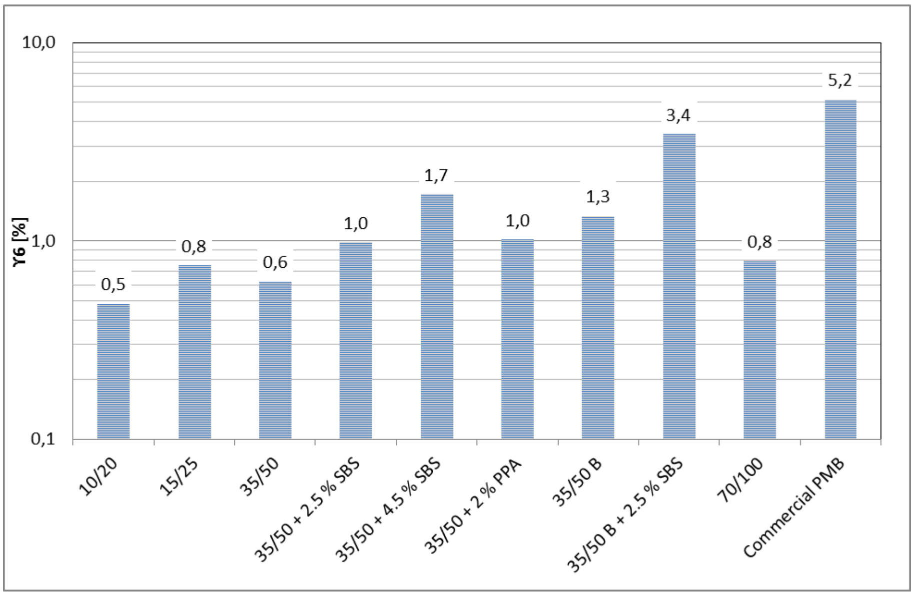

Figure 2: Fatigue performance of bitumen products without RAP

Bitumen recovered from two different batches of RAP is also tested for fatigue performance. The γ_6 results are respectively 0.42 and 0.44 %. The effect of RAP bitumen on the fatigue performance of the bitumen products is shown in figure 3. Addition of 20 or 40 % RAP bitumen has various but little effect on γ_6 for bitumen with $\gamma_6 \leq 1.0$ % (i.e. mainly standard paving grades) but for the better performing bitumen products γ_6 decreases up to 40 % when 20 % RAP bitumen is added.

Figure 4 shows the correlation between the fatigue performance of the tested bitumen products and the corresponding asphalt mixes. There is a clear trend when all data is considered. However, when looking at the more commonly used grades, for which $\gamma_6 \leq 1.0$ %, the trend becomes less obvious.

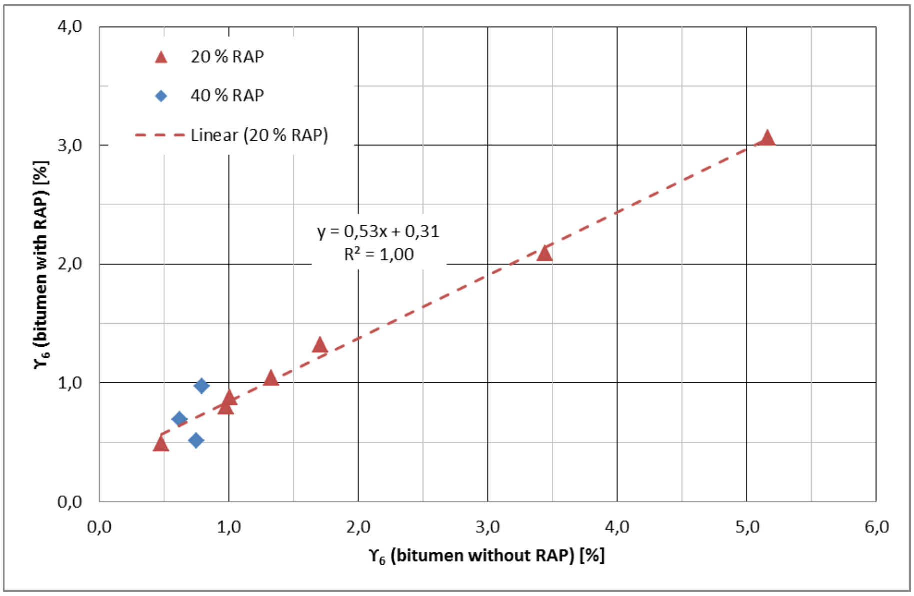

Figure 3: Influence of RAP on bitumen fatigue performance

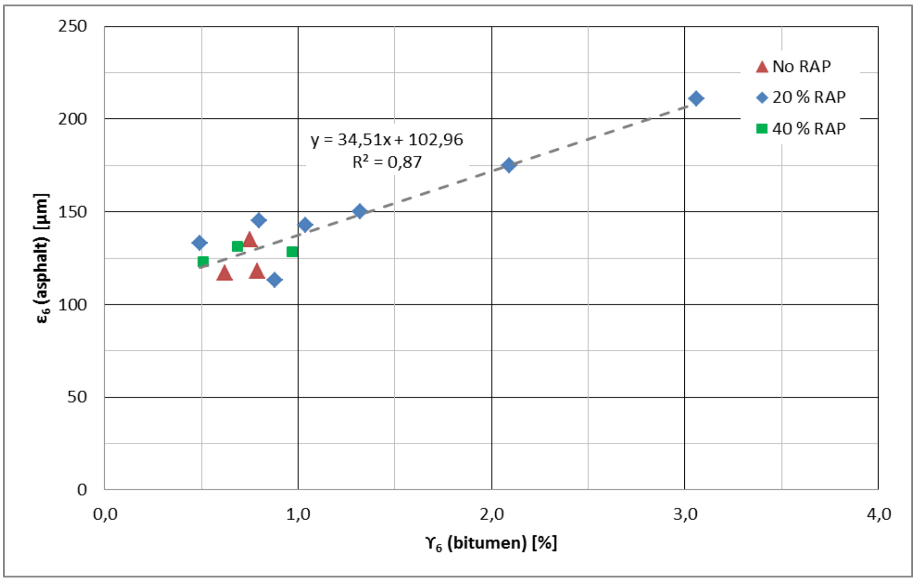

Figure 4: Correlation between bitumen and asphalt mix fatigue performance (Trend line includes all data)

4. BITUMEN FATIGUE PERFORMANCE EVALUATION WITH LAS TEST

4.1 Test program

A relatively new method to evaluate the fatigue performance of bitumen is the linear amplitude sweep (LAS) test. The LAS test procedure used for this study is based on AASHTO TP 101-12-UL [11]. Analysis of the test results is based on complex theory and a number of assumptions which not all may be valid. The LAS procedure includes following three main steps:

- Performing a frequency sweep at a defined temperature.
- Performing a continuous strain amplitude sweep at the same temperature as for the frequency sweep.
- Calculation of the coefficients for the fatigue law:

$$N_f = A \times \gamma^{-B} \tag{1}$$

With:

N_f = Number of cycles to failure
γ = Amplitude of applied strain
A, B = Coefficients

Coefficient A is obtained from the continuous strain amplitude sweep data. The calculation of A is based on viscoelastic continuum damage (VECD) theory adapted from Kim, et al [8]. Coefficient B is calculated from the frequency sweep data. It is directly related to the slope of the storage modulus against log frequency.

The LAS tests are performed with five bitumen products from the research project, i.e. 10/20, 15/25, 35/50, 35/50 B and 70/100. For these binders, the γ_6 values are estimated according to equation (1), based on parameters A and B obtained from LAS tests. These γ_6 values are then compared with those obtained with the time sweep tests. Configuration and main test conditions for the LAS tests are:

- Plate-Plate configuration
- 8 mm plates
- 2 mm gap
- Test frequency
  - Frequency sweep from 0.2 to 30 Hz
  - Continuous strain amplitude sweep at 10 Hz frequency
- Strain amplitude
  - Frequency sweep at 0.1 % strain amplitude
  - Continuous strain amplitude sweep from 0 to 30% (within 3,200 cycles)
- Test temperature varied (between 8.0 and 40.8 °C)

First all samples are tested at a set temperature of 16 °C and at a temperature where the complex shear modulus of the bitumen is 30 MPa - called iso-modulus temperature. The iso-modulus temperature is determined from results of temperature sweeps that are carried out between 5 and 25 °C at a frequency of 10 Hz in the linear-viscoelastic (LVE) domain. Testing at different temperatures introduce uncertainty into the interpretation of the test results.

Another approach to evaluate and assess the fatigue behaviour is to test at a defined level of the phase angle - called iso-phase angle. By testing at iso-phase angle the ratio between viscous and elastic behaviour is the same for all binders. The bitumen samples are first tested at an iso-phase angle of 45° where loss and storage modulus (i.e. viscous and elastic behaviour) of the bitumen are equal. The binders are also tested at a lower iso-phase angle of 35° where elastic behaviour dominates.

In the field fatigue failure is a long term problem and usually not observed on new road pavements. Different binders have different ageing performance which will influence their long term fatigue performance. It therefore makes sense to assess the fatigue performance of bitumen in an aged state. To investigate the influence of ageing on the fatigue performance the binders are also tested after short term ageing with the rolling thin film oven test (RTFOT) and after long term ageing with the pressure ageing vessel (PAV). Due to time constraints the aged bitumen samples are only tested at an iso-phase angle of 35°.

4.2 Test results

The LAS results at a test temperature of 16 °C are summarized in table 2. The values of complex shear modulus and phase angle at 10 Hz are obtained from the frequency sweeps. The ranking of the binders is based on the value of γ_6. As expected the complex shear modulus decreases and phase angle increases when moving from hard to soft grades. Only binder 35/50 B, which is a "GEL" type Multigrade bitumen with known lower complex shear modulus than comparable Pen grade, does not fit this trend. The complex shear modulus varies from 13.5 MPa to 66.6 MPa and the phase angle varies from 27.3° to 46.6°. The ranking based on the value for γ_6 seems to be related to complex shear modulus and phase angle with best performance for the hardest Pen grade (i.e. 10/20) and worst performance for the softest Pen grade (i.e. 70/100). Again 35/50 B shows different (i.e. better) performance than the comparable Pen grade.

Table 2: LAS results at a temperature of 16 °C

Binder	**Frequency sweep [10 Hz, 0,1% strain]**		**LAS parameters**		**Estimated γ_6**	**Ranking**
	G* [MPa]	δ [°]	A [-]	B [-]	[%]	
10/20	66.6	27.3	6.83E+06	-5.640	1.41	1
15/25	55.4	30.9	2.06E+06	-4.907	1.16	2
35/50	29.3	39.8	1.53E+05	-3.599	0.59	4
35/50 B	14.4	37.3	8.57E+05	-4.347	0.97	3
70/100	13.5	46.6	7.34E+04	-3.065	0.43	5

The LAS results at iso-modulus of 30 MPa are summarized in table 3. The test temperature decreases when moving from hard to soft Pen grades, except for binder 35/50 B with known lower complex shear modulus than comparable Pen grade. At the test temperatures the complex shear modulus of all binders is close to the target value of 30 MPa. The values for phase angle vary from 33.3° to 39.9°. The ranking based on the value for γ_6 seems related to phase angle with best fatigue performance for 35/50 B, followed by 10/20 and then generally decreasing when moving to softer Pen grade.

Table 3: LAS results at iso-modulus of 30 MPa

Binder	**Test temperature**	**Frequency sweep [10 Hz, 0,1 % strain]**		**LAS parameters**		**Estimated γ_6**	**Ranking**
	[°C]	G* [MPa]	δ [°]	A [-]	B [-]	[%]	
10/20	23.0	32.1	33.7	1.54E+06	-4.661	1.10	2
15/25	20.7	31.2	35.4	5.72E+05	-4.165	0.87	3
35/50	16.4	28.0	39.9	1.20E+05	-3.522	0.55	5
35/50 B	9.9	29.1	33.3	2.73E+06	-4.967	1.22	1
70/100	10.7	28.8	38.9	1.44E+05	-3.691	0.59	4

The LAS results at iso-phase angle of 45° are summarized in table 4. The test temperature decreases when moving from hard to soft Pen grades, except again for the Multigrade bitumen (35/50 B). At the test temperatures the phase angle of all binders is close to the target value of 45°. The ranking based on the value for γ_6 is identical as for the LAS tests at iso-modulus at 30 MPa but the differences in γ_6 are smaller. As for some binders the complex shear modulus might be too low (i.e. less than 10 MPa) to observe pure fatigue [6] it was decided to test the binders also at lower iso-phase angle.

Table 4: LAS results at iso-phase angle of 45°

Binder	**Test temperature**	**Frequency sweep [10 Hz, 0,1 % strain]**		**LAS parameters**		**Estimated γ_6**	**Ranking**
	[°C]	G* [MPa]	δ [°]	A [-]	B [-]	[%]	
10/20	35.2	6.69	45.5	3.25E+05	-3.401	0.72	2
15/25	28.8	12.0	44.1	2.20E+05	-3.386	0.64	3
35/50	20.6	15.2	45.6	8.52E+04	-3.088	0.45	5
35/50 B	25.7	3.72	45.8	6.36E+05	-3.598	0.88	1
70/100	14.5	16.0	44.1	8.36E+04	-3.246	0.47	4

The LAS results at iso-phase angle of 35° are summarized in table 5. The test temperature decreases when moving from hard to soft Pen grades (including 35/50 B). At the test temperatures the phase angle of all binders is close to the target value of 35°. The values for complex shear modulus vary from 21.9 MPa to 46.0 MPa, which is within the recommended range for binder fatigue testing (i.e. 10 to 50 MPa). The ranking based on the value for γ_6 is identical as for the LAS tests at iso-modulus at 30 MPa but the differences in γ_6 are smaller.

Table 5: LAS Results at iso-phase angle of 35°

Binder	Test temperature	Frequency sweep [10 Hz, 0,1 % strain]		LAS parameters		Estimated γ_6	Ranking
	[°C]	G* [MPa]	δ [°]	A [-]	B [-]	[%]	
10/20	24.0	26.4	35.5	8.87E+05	-4.357	0.97	2
15/25	20.7	31.2	35.4	5.72E+05	-4.165	0.87	3
35/50	12.9	43.1	35.1	2.96E+05	-4.068	0.74	5
35/50 B	12.5	21.9	34.8	1.61E+06	-4.742	1.11	1
70/100	8.0	46.0	35.1	3.07E+05	-4.209	0.76	4

Figure 5 shows the frequency sweep curves at iso-modulus (30 MPa) and iso-phase angle (35°). The shapes of the curves clearly show the influence of test conditions on material behaviour. For iso-modulus test conditions the slope of the curves differ what signifies different frequency dependent behaviour. For iso-phase angle test conditions the curves run almost parallel with - as expected - an offset for complex shear modulus.

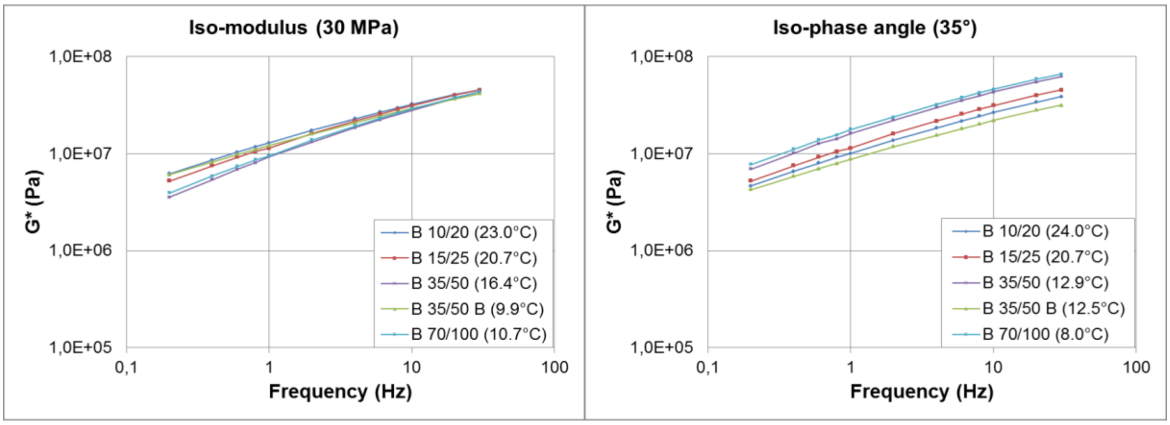

Figure 5: Frequency sweeps curves at iso-modulus and iso-phase angle

Figure 6 shows the results of the continuous strain amplitude sweeps (i.e. effective shear stress against effective shear strain curves) at iso-modulus (30 MPa) and iso-phase angle (35°). It can be seen that for iso-modulus test conditions all binders show the same behaviour within the linear viscoelastic region and up till about 10 % strain. Above a strain of 10 % the curves start to differentiate. At iso-phase angle test conditions the binders show different behaviour from the start of the strain sweep. This shows again the influence of the test conditions on the behaviour of the binders.

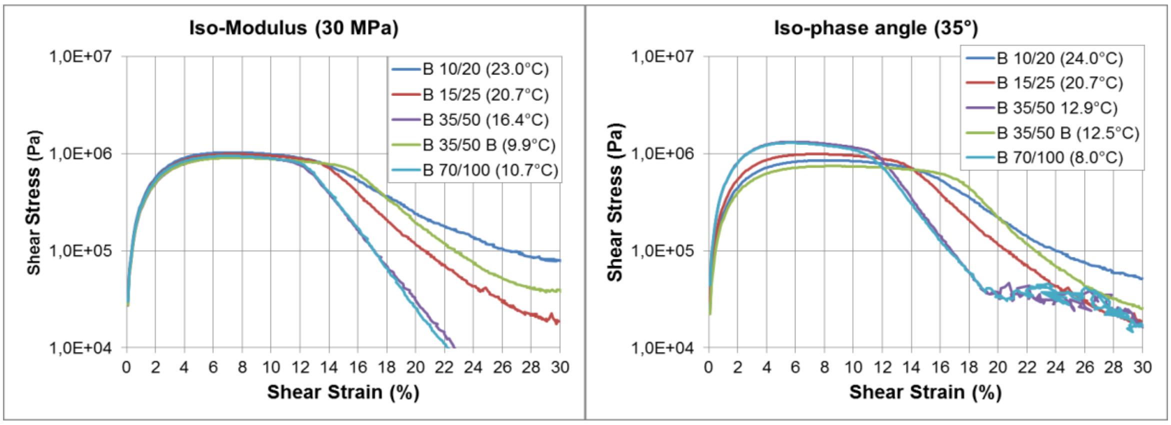

Figure 6: Continuous strain amplitude sweep curves at iso-modulus and iso-phase angle

The results at iso-phase angle (35°) after short time aging with RTFOT and after long term aging with RTFOT and PAV are shown in tables 6 and 7. At first sight it appears that complex shear modulus decreases with progressive ageing. However, during the RTFOT hardening and PAV ageing processes the chemical structure of the molecules evaluate and their balance leads to a progressive move from a “SOL” type distribution to a “GEL” type distribution [13]. This generally results in binders with lower phase angle at a certain level of complex shear modulus than the original binder (or lower complex shear modulus at a certain value for the phase angle). As a consequence – for the aged binders – it is necessary to increase the test temperature to obtain a phase angle of 35°. Ageing has the highest effect on the test temperature for 35/50 B (i.e. +8.1 °C after RTFOT and +22.5 °C after RTFOT+PAV). These (different) changes in test temperature make interpretation of the results complex. After RTFOT the ranking based on the value for γ_6 is identical as for the fresh binders. There are some changes in ranking after RTFOT+PAV indicating the influence of ageing performance on the results of fatigue performance evaluations.

Table 6: Results at iso-phase angle (35°) after RTFOT

Binder	**Temperature**	**Frequency sweep [10 Hz, 0,1 % strain]**		**LAS parameters**		**Estimated γ_6**	**Ranking**
	[°C]	G* [MPa]	δ [°]	A [-]	B [-]	[%]	
10/20	30.2	18.4	35.1	1.29E+06	-4.477	1.06	2
15/25	26.8	23.7	35.1	1.19E+06	-4.450	1.04	3
35/50	16.7	38.5	34.3	4.40E+05	-4.343	0.83	5
35/50 B	20.6	12.3	35.2	2.73E+06	-4.765	1.23	1
70/100	11.3	38.5	35.0	6.31E+05	-4.428	0.90	4

Table 7: Results at iso-phase angle (35°) after RTFOT+PAV

Binder	**Temperature**	**Frequency sweep [10 Hz, 0,1 % strain]**		**LAS parameters**		**Estimated γ_6**	**Ranking**
	[°C]	G* [MPa]	δ [°]	A [-]	B [-]	[%]	
10/20	40.8	10.0	35.0	1.45E+06	-4.575	1.08	3
15/25	34.8	14.6	35.2	1.63E+06	-4.553	1.11	2
35/50	23.3	24.2	34.7	1.05E+06	-4.487	1.01	4
35/50 B	35.0	4.6	35.3	3.98E+06	-4.856	1.33	1
70/100	19.2	20.1	35.4	7.56E+05	-4.444	0.94	5

Figure 7 shows the results of the strain sweeps (i.e. stress-strain curves) at iso-phase angle (35°) for both the fresh and aged binders. These curves provide further insights in the influence of ageing on the failure behaviour of the binders. When comparing these curves it can be observed that the shape of the curve changes with ageing. The plateau gets longer and the drop in shear stress after the plateau becomes more gradual. This indicates that the shear susceptibility changes due to ageing. However, there is probably also an (unknown) effect of the (increasing) test temperature.

4.3 Comparison with time sweep test results

When comparing the γ_6 results of the LAS tests with the γ_6 results of the time sweep tests it appears that - for the five binders that are tested - the results are in the same range (i.e. 0.4 - 1.4 %) but none of the LAS data sets (i.e. test conditions) show correlation with the results of the time sweep tests. The rankings for the different tests and test conditions are summarized in table 8.

Table 8: Fatigue performance rankings

Binder	**Time sweep**	**LAS**			
	[10°C; 25 Hz]	[16°C]	Iso-modulus [30 MPa]	Iso-phase angle [45°]	Iso-phase angle [35°]
10/20	5	1	2	2	2
15/25	3	2	3	3	3
35/50	4	4	5	5	5
35/50 B	1	3	1	1	1
70/100	2	5	4	4	4

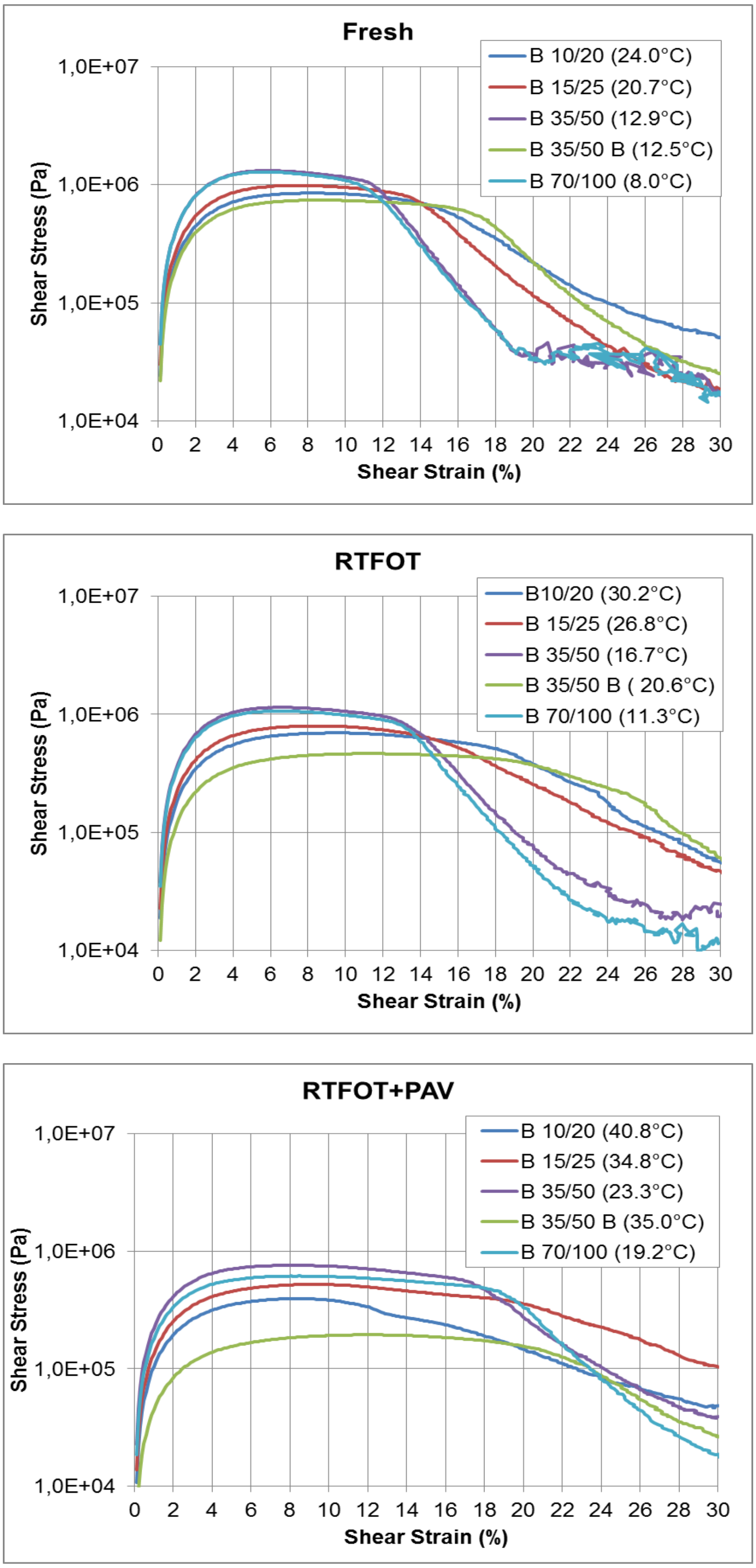

Figure 7: Strain sweep curves at iso-phase angle (35°) for fresh and aged binders

5. CONCLUSIONS

5.1 Time sweep tests

Test reproducibility is generally poor. The influence of phenomena like increasing complex shear modulus during the test and undulating complex shear modulus at the beginning and/or end of a test cannot be quantified. It takes very long (i.e. weeks rather than days) to assess the fatigue performance of a single binder.

The differences in γ_6 results for the standard grades from straight distillation (i.e. 35/50 and 70/100) and the air rectified hard binders (i.e. 10/20 and 15/25) are too small to be able to differentiate in product performance. Highest γ_6 values are found for the Multigrade bitumen (35/50 B) and the PMBs. Only when all 10 bitumen products - with known significant differences in fatigue performance - are considered a good correlation with asphalt fatigue performance is observed.

The addition of RAP bitumen has various but little effect on the fatigue performance of standard paving grade bitumen, but for the better performing bitumen products γ_6 decreases up to 40 %.

5.2 LAS tests

Although the LAS test can be easily performed with standard DSR equipment in a relatively short time, it is based on complex theory and a number of assumptions which not all may be valid. It is normally performed at a set temperature or at iso-modulus. Additionally, it can also be performed at iso-phase angle test conditions, for which the ratio between viscous and elastic behaviour is the same for all binders.

At a set test temperature of 16 °C, the best fatigue performance is found for the hardest Pen grade bitumen and the worst performance for the softest Pen grade bitumen. This is not in line with what is experienced in practice. At iso-modulus test conditions best fatigue performance is for the Multigrade bitumen (35/50 B). The performance seems to be related to phase angle (i.e. best performance for binder with lowest phase angle). At iso-phase angle test conditions the ranking based on the value for γ_6 is identical as for the LAS tests at iso-modulus but the differences in γ_6 are smaller. The performance seems to be related to the complex shear modulus at the test temperature (i.e. best performance for binder with lowest complex shear modulus). Testing at different temperatures introduces uncertainty into the interpretation of the test results.

Aged bitumen samples are only tested at an iso-phase angle of 35°. After RTFOT the ranking is identical as for the fresh binders. There are some changes in ranking after RTFOT + PAV indicating the influence of ageing performance on the results of fatigue performance evaluations. Test temperature for aged bitumen samples needs to be adjusted to also test these products at an iso-phase angle of 35°. These (different) changes in test temperature make interpretation of the results even more complex.

For the five binders that are tested the γ_6 results of the LAS tests are in the same range as the γ_6 results of the time sweep tests but none of the LAS data sets (i.e. test conditions) show correlations with the results of the time sweep tests.

The effect of the addition of RAP bitumen on the fatigue performance has not been evaluated with the LAS test.

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