Fatigue Performance of Bituminous Binders Tested by Linear Amplitude Sweep Test

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Abstract. Fatigue cracking is one of the most important phenomena connected to durability of asphalt pavements. The fatigue resistance of asphalt pavements depends on many factors such as asphalt mixture composition and binder properties. Also temperature of asphalt pavement is important, what is directly related to viscoelastic nature of the bituminous binder. The fatigue cracks may occur within the bitumen (cohesive cracking) or at the bitumen-aggregate interface (adhesion cracking). The cohesive cracking resistance can be evaluated by bitumen testing. The Linear Amplitude Sweep (LAS) test has recently been proposed for fatigue characterization of bituminous binders. The LAS test is performed acc. to AASHTO TP 101 standard. This procedure is based on viscoelastic continuum damage approach to predict binder fatigue life as a function of strain level in the pavement. In the research fatigue performance of three types of binders: paving grade, typically polymer modified and highly polymer modified were evaluated. Tests were performed using the LAS method at temperatures: 5 °C, 10 °C, 20 °C, on samples after RTFOT+PAV aging. Obtained results have shown that each group of binders behave in different way which is connected to its internal network or lack of it. Finally, the best fatigue properties have been presented by highly modified bitumen (HiMA). The paper presents description of the LAS method, test results containing comparison of fatigue characteristics of used binders and conclusions.

Keywords: Bitumen · Fatigue · LAS test · VECD · Highly modified bitumen

1 Introduction

The phenomenon of fatigue is one of the most important factors influencing the durability of asphalt pavements. It depends on many factors, e.g. the composition and design of the asphalt mixture as well as the properties of the used bituminous binder. Fatigue cracking may occur within the binder (cohesive cracking) or at the bitumen-aggregate interface (adhesion cracking) (Pereira et al. 2016). Literature describes several methods using DSR for the testing of the fatigue life of bituminous binders. Currently, the most popular one is method developed in 1987 in the USA as a part of the Superpave system. It uses the $|G^*| \cdot \sin\delta$ parameter for the quantitative determination of the bitumen fatigue resistance. The testing is performed in the intermediate

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temperature which depends on the PG grade of a particular binder. The requirements limit the stiffness of the bitumen to the maximum of 5000 [kPa] (for the S grade) and 6000 [kPa] (for the H, V, E grades). The main disadvantage of this specification is that it does not describe in any way the real fatigue phenomena occurring in the binder, such as: higher strains or different level of the frequency of the applied load (Bahia et al. 2001, 2002).

Another widely applied method allowing to specify the fatigue performance of bitumen is time sweep test. The time sweep test consists of the use of a cyclic load application to a binder sample at a constant frequency and a variable strain amplitude. The time sweep test was developed as part of the NCHRP Project 9-10 (Bahia et al. 2001), in order to improve test methodology described in the AASHTO T315 standard. An advantage of the time sweep test is the possibility to evaluate the influence of bituminous binders self-healing phenomena on the fatigue life of asphalt pavement (Pereira et al. 2016), as well as the high correlation with the fatigue tests results of asphalt mixtures (Bahia et al. 2001).

In view of the on-going discussion in the scientific community about the adequacy of using above described methods, in the USA were conducted works in order to develop a new method for the testing of the fatigue life of bitumens. The result of these endeavors is the method described in the AASHTO TP 101-14 standard - *Estimating Damage Tolerance of Asphalt Binders Using the Linear Amplitude Sweep* (abbreviation: LAS), executed with using DSR. It consists a cyclic loading of the tested sample with a constant frequency and a gradually increasing strain amplitude in order to cause accelerated fatigue damage. The test begins with a frequency sweep performed to specify the initial properties of not damaged material. Subsequently, on the same sample the amplitude sweep test is conducted. The frequency sweep is executed at constant shear strain amplitude of 0.1% during the entire test and at a variable frequency, which increases in the range of 0.2–30.0 [Hz]. The amplitude sweep phase begins with 100 initial cycles of sinusoidal loading at the 0.1% strain and at the frequency of 10 [Hz]. The frequency remains unchanged during the entire test. The amplitude increased along with the step every 1% until it reaches the level of 30%. Each level of the amplitude increase includes 100 cycles applying load onto the sample whereby the cumulatively tested material is subjected to 3100 cycles of loading. As the results of the amplitude sweep test complex shear modulus G*, phase angle δ, a shear stress and the accompanying shear strain in the sample are registered. Fatigue characterization – N_f in the LAS test is calculated at the damage level corresponding to the peak stress response.

The AASHTO TP 101-14 standard does not specify the referential temperature at which the testing should be conducted. It merely states that the LAS test should be performed at an intermediate temperature specified in accordance with the PG functional type of particular binder. However, correct choice of the test temperature is extremely important because it influences the sample damage mechanism during test (Safaei and Castorena 2016). Researchers Soenen and Eckmann (2000), Soenen et al. (2004) conducted tests of bitumen at different temperatures and noted that when the samples were subjected to cyclic loading in DSR at too high temperature, the binder exhibited mainly viscous properties - edge flow was observed. In turn, during testing at too low temperature, adhesion cracking was occurred. Anderson et al. (2001) made similar observations and defined the transition between the real fatigue cracking and an instability flow of the sample, based on the dependence of the fatigue life with the temperature. Safaei and Hintz (2014) evaluated the influence of temperature on the bituminous binders cyclically loaded at a constant strain amplitude during testing in DSR. The main conclusion from their research was that the test temperatures should be chosen in such way that the dynamic shear modulus corresponding to the test temperature and frequency was in the range from 10 to 60 [MPa] to avoid effects of flow and adhesion loss. Safaei and Castorena (2016) distinguished three mechanisms of sample damage, depending on the test temperature: too low temperature - adhesion loss; too high temperature - bulging of specimens; intermediate temperature - cohesive cracking. The test temperatures for fatigue tests, according to the LAS methodology, should be selected in such way that the tested samples fail by only as a result of cohesive cracking.

2 VECD - Viscoelastic Continuum Damage Theory

The LAS test is based on the VECD - *Viscoelastic Continuum Damage* theory. The main advantage of VECD is possibility to prediction of fatigue life of tested materials at any loading amplitude. Asphalt mixtures and bituminous binders present a well-defined relationship between the amplitude of the applied load and the fatigue life (N_f). This correlation may be described as follows (Monismith et al. 1970):

$$Nf = A \cdot (\gamma)^B \tag{1}$$

where A and B are materials dependent parameters, and γ is strain amplitude.

The VECD theory is based on the Schapery works (Schapery 1975, 1984, 1990). According to that theory for a viscoelastic material, the correlation between the propagation of cracks - D - and the work performed - W - necessary for their occurrence may be described as follows (Kim et al. 2006):

$$\frac{dD}{dt} = \left(-\frac{\partial W}{\partial D}\right)^{\alpha} \tag{2}$$

where: W - work performed (the pseudo strain energy density function); D - damage intensity; t - time; α - materials dependent constant.

In accordance with the AASHTO TP 101-14 standard, the α parameter is calculated according to the formula: $\alpha = 1/m$, where m is the slope of the frequency-shear modulus graph.

In order to estimate the work performed during the occurrence of damages in the sample, the equation developed by Kim et al. (2006) is used, based on the dissipated energy theory:

$$W = \pi \cdot I_D \cdot \gamma^2 \cdot G^* \cdot \sin\delta \tag{3}$$

where: W - dissipated energy; I_D - initial undamaged value of the dynamic shear modulus |G*|; γ - applied shear strain amplitude; G^* - complex shear modulus; δ - phase angle.

Using Eqs. (2) and (3), damage level at time - $D(t)$ (damage accumulation), is calculated as follows (Kim et al. 2006; Johnson 2010; Hintz et al. 2011):

$$D(t) = \sum_{i=1}^{N} \left[\pi I_D \gamma^2 (C_{i-1} - C_i)\right]^{\alpha/1+\alpha} (t_i - t_{i-1})^{1/1+\alpha} \quad (4)$$

where: $D(t)$ - damage accumulation, N - load cycle for which damage accumulation D is calculated, $C(t)$ - material integrity coefficient, described by the equation:

$$C(t) = \frac{G^*(t)}{I_D} \quad (5)$$

The maximum stress - τ_{max} reached by the sample during LAS test is specified as the criterion of the fatigue life. Failure damage level in the sample at this time - $D(f)$ - is described by the correlation:

$$D_f = \left(\frac{C_0 - C_{atpeakstress}}{C_1}\right)^{1/C_2} \quad (6)$$

where: $C_0 = 1$ - initial value of the material integrity; C_1 *and* C_2 - calculation coefficients of the curve fitting (y axis – $log(C_0 - C(t))$, x axis – $logD(t)$).

By solving the system of equations consisting of the expressions: (2), (3) and (4) the final equation describing the fatigue performance can be described as follows:

$$N_f = \frac{f(D_f)^k}{k(\pi C_1 C_2)^\alpha} (\gamma_{max})^{-2\alpha} \quad (7)$$

where: f - frequency [Hz]; k - calculation coefficient, described with the equation: $k = 1 + (1 - C_2)\alpha$, D_f – failure damage level, γ_{max} – maximum set strain.

Applying the VECD theory, it is possible to calculate the number of cycles to failure of the sample for any selected strain amplitude. In this way, it is possible to predict the fatigue life of the tested bitumens at any level of pavement loading.

3 Highly Polymer Modified Binders - HiMA

The HiMA binders are the new type of bitumen modified by more than 7% m/m of SBS block polymers. Such a high quantity of SBS causes that the volume proportions between bitumen and polymer after the modification process are reversed and the final binder is characterized by the reversed bitumen-polymer phase. The volume advantage of the polymer network and its physical continuity gives the binder its unique properties, more similar to the properties of an elastomer than bitumen. One of the main characteristics of the new binder is the significant improvement of the flexibility and high tolerance to increasing tensile strains, as well as the other properties which result from it - fatigue performance, resistance to cracking etc. (Błażejowski et al. 2016). The research and the implementation works of new bituminous binders showed that they are products with above standard functional properties (Błażejowski et al. 2016). Full-scale testing conducted since 2009 on the experimental track in the US (NCAT Pavement Test Track) indicated that the pavement designed with the use of highly modified bitumen is extraordinarily resistant to rutting and fatigue cracking (Timm et al. 2013; West et al. 2012). Due to its properties, highly modified bitumen are particularly suitable for use in situations requiring very high durability, e.g.: asphalt pavements subject to high stresses and strains, courses requiring high resistance to low temperatures, asphalt base courses with very high fatigue durability, e.g. for perpetual pavements.

4 Experimental

4.1 Materials and Test Methods

The goal of this studies was to checked and compared fatigue properties of three different type of bitumens. Fatigue characterization of the binders was conducted using the LAS test in accordance with the AASHTO TP 101-14. All binders were aged in the standard RTFOT and PAV prior to testing. Tests were performed at three temperatures: 5 °C, 10 °C, and 20 °C to allow for assessment of the effect of temperature on fatigue resistance.

The following types of binders were used in the test program:

- Paving grade bitumen 50/70
- Polymer modified bitumen PMB 45/80-55 (SBS polymer content 3–4% m/m)
- Highly polymer modified bitumen PMB 45/80-80 HiMA (SBS polymer content ~7.5% m/m) –polymer - bitumen reversed phase binders.

Table 1 provides a summary of the bituminous binders used.

Table 1. Summary of the bituminous binders used

Properties	Unit	Bitumen type		
		Paving grade 50/70	PMB 45/80-55	PMB 45/80-80 HiMA
Penetration at 25 °C	[0.1 mm]	56	70	59
Softening point	[°C]	50.0	65.9	94.4
Elastic recovery at 25 °C	[%]	–	89	94
Performance grade	[–]	64–22	70–28	94–28
FCCT, G*sinδ = 5000 kPa	[°C]	21.3	14.1	11.7
FCCT, G*sinδ = 6000 kPa	[°C]	19.4	12.5	10.1
Jnr 3.2 kPa^{-1} MSCR test, 64 °C (samples after RTFOT)	[kPa^{-1}]	2.49	0.63	0.02

4.2 Influence of the Test Temperature on the Sample Damage Mechanism During LAS Test

Safaei and Castorena (2016) described three mechanisms of sample damage depending on the temperature at which the measurements are taken: adhesion loss, bulging of specimens and cohesive cracking. The temperature in the LAS test should be selected so that the product of the initial value of the complex stiffness modulus and the phase angle specified at the frequency of 10 [Hz] is in the linear viscoelasticity range of the tested binder. Acc. to Safaei and Castorena works, the $|G^*|_{LVE}$ range for cohesive cracking should be between $10 < |G^*|_{LVE} < 60$ [MPa]. However, it should be noted that this range does not have to correct for all type of binder, especially for PMB or HiMA. The HiMA binders are characterized by a significantly lower stiffness, what can be observed of the FCCT comparison in Table 1 or the |G*| comparison in Table 2.

Table 2 shows the results of $|G^*|_{LVE}$ taking into account the mechanism of sample damage, depending on the test temperature for three tested bitumens.

Table 2. Relationship between $|G^*|_{LVE}$, test temperature and failure mechanism

Test temperature [˚C]	5˚C	10˚C	20˚C
		|G*|LVE [MPa]	
Paving grade50/70	**69.2**	**40.6**	**13.4**
PMB 45/80-55	**50.7**	**27.9**	10.2
PMB 45/80-80 HiMA	**38.9**	**23.2**	4.9

Adhesion loss	Cohesive cracking	Instability flow

According to data presented in Table 2, the way in which the sample is damaged depends on the test temperature. Only at the temperature of 10 °C the damage of all of the tested samples occurred as the result of cohesive cracking.

4.3 Obtained Parameters and Discussion

The LAS test begins with a frequency sweep test conducted to specify the initial properties of the tested material. The result of this measurement is the α parameter which describing the initial characteristics of the tested material. In Table 3 values of the α parameters which were obtained at three test temperatures for the tested bituminous binders are presented.

Table 3. α parameters obtained from frequency sweep test at three temperatures

Test temperature [°C]	5 °C	10 °C	20 °C
	α parameters		
Paving grade 50/70	2.779	2.489	1.999
PMB 45/80-55	2.377	2.139	1.730
PMB 45/80-80 HiMA	2.511	2.286	1.917

The value of the α parameter decreases along with the increase of the test temperature. This relationship is present in case of all tested bitumens, regardless of the degree of SBS polymer modification.

The AASHTO TP 101-14 standard as the fatigue criterion for the tested materials specifies the moment during the amplitude sweep test when the maximum shear stress occurs in the sample is registered - τ_{max}. Figure 1 presents changes of shear stress occurring in the tested samples, depending on the test temperature.

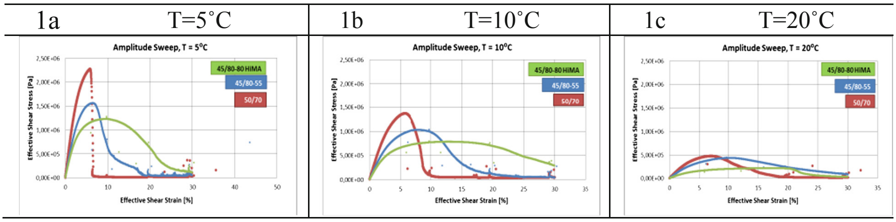

Fig. 1. Diagrams of shear stress-shear strain dependence of test temperatures for three bitumens

The lower the test temperature, the higher values of the shear stress in the samples. On the presented graphs three types of binders can easily be recognized. In the case of the stress-strain curve for the paving-grade bitumen 50/70 and PMB 45/80-55 it is possible to easily indicate the moment of testing when the level of stress occurring in the sample reaches the maximum value. In case of PMB 45/80-80 HiMA, that point is not clearly visible. In case of that bitumen, also no sudden decrease in the stress can be seen after the maximum value is reached, as it happens in case of the paving-grade bitumen 50/70 and PMB 45/80-55. Such behaviour of PMB HiMA means that they are not damaged in the used test conditions and that it is able to transfer the applied load continuously. A similar correlation was observed by other researchers (Wesołowska and Ryś 2018).

The fatigue life criterion – N_f of the tested materials can be specified as sample damage level corresponding to the peak stress response - τ_{max}. Masad et al. (2001) shown that the strain level in the bituminous binder working in the pavement is about 50 times higher than the strain level in the asphalt mixture. Because of that, it is recommended to calculate the fatigue parameter for the two strain levels: γ = 2.5% and γ = 5.0%. Figure 2 shows a comparison of fatigue characteristics of the tested binders, conducted at three test temperatures.

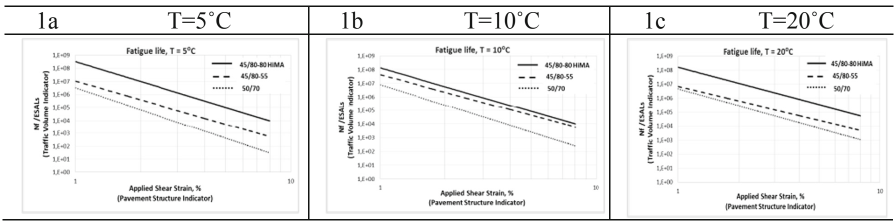

Fig. 2. Variation of fatigue life for three bitumens at different test temperatures

Comparison of the fatigue curves of the tested bitumens, shown that the highly modified bitumen PMB 45/80-80 HiMA is characterized by the best fatigue properties for both applied strain: $\gamma = 2.5\%$ as well as $\gamma = 5\%$. Regardless of the tested temperature, this bitumen withstands the largest number of load cycles to destruction. A fundamental role in this behaviour of HiMA binders is the predominance of the polymeric phase over the bitumen phase as well as the continuity of the elastomer network, which substantially enhances the tensile strength of the binder. As expected, the weakest fatigue properties was obtained for the paving-grade bitumen. Modified bitumen PMB 45/80-55 is characterized by intermediate properties.

Bahia and Teymourpour (2014) proposed to include the results of the fatigue life obtained with the LAS test as an additional property in the classification of bituminous binders in the PG system. They suggested a division of the obtained results in relation to the thickness of the asphalt layer in which a particular binder has to be used. Table 4 presents a classification of the tested bitumens in relation to their usefulness for a particular traffic grades, for each test temperature.

Table 4. Bitumens classification based on LAS test results, acc. to additional PG classification

Test temperature [°C]	Nf at 2.5% for asphalt layer > 4″			Nf at 5.0% for asphalt layer < 4″		
	5 °C	10 °C	20 °C	5 °C	10 °C	20 °C
Paving grade 50/70	H	V, E	V, E	*	*	*
PMB 45/80-55	V, E	V, E	V, E	*	V, E	H
PMB 45/80-80 HiMA	V, E	V, E	V, E	V, E	V, E	V, E

* *result out of classification*

Analyzing the data from the Table 4, it can be stated that in case of pavements in which the thickness of the asphalt layer exceeds 4″ (the so-called strong pavements), the tested binders meet the requirements for Very Heavy/Extreme grades. In the case of pavements in which the thickness of the asphalt layer will not exceed 4″ (the so-called weak pavement), only the PMB 45/80-80 HiMA meets the requirements for the Very Heavy/Extreme grades at all test temperatures. This confirms the results obtained at the NCAT Pavement Test Track which proved that the pavement of a reduced thickness designed with using HiMA is resistant to fatigue cracking (Timm et al. 2013; West et al. 2012). The paving-grade bitumen 50/70 shows too weak fatigue properties for the strain $\gamma = 5.0\%$ and does not meet the fatigue criteria in any of the set temperature values. PMB 45/80-55 tested at 10 °C shows properties appropriate for the Very Heavy/Extreme grades. However, at other temperatures it shows significantly weaker fatigue performance.

5 Summary and Conclusions

- The presented results clearly show that the PMB 45/80-80 HiMA is characterized by the best fatigue properties. As expected, the weakest fatigue properties is obtained for the paving-grade bitumen 50/70. The PMB 45/80-55 has shown intermediate properties.

- The LAS test results confirm the previous research conducted by ORLEN Asfalt (Błażejowski et al. 2016) regarding the functional properties of HiMA binders. It has been found that PMB 45/80-80 HiMA may successfully be used in pavement construction which require very good fatigue properties.
- The test temperature is significant importance for the obtained results of the fatigue life and for the mechanism of sample damage during the LAS test. For that reason the way in which the temperature is chosen should be clearly specified.

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References

Anderson DA, Le Hir YM, Marasteanu M, Planche J-P, Martin D, Gaauthier G (2001) Evaluation of fatigue criteria for asphalt binder. Transp Res Rec 1766:48–56

Bahia HU, Hanson DI, Zeng M, Zhai H, Khatri MA, Anderson RM (2001) Characterization of modified asphalt binders in Superpave Mix Design. NCHRP Report 459. TRB, National Research Council, Washington, D.C., USA

Bahia HU, Teymourpour P (2014) Linear amplitude sweep test: binder grading specification and field validation. In: Presentation on Binder Expert Task Group Meeting, Baton Rouge, LA, USA

Bahia HU, Zhai H, Zeng M, Hu Y, Turner P (2002) Development of binder specification parameters based on characterization of damage behavior. J Assoc Asphalt Paving Technol 70:442–470

Błażejowski K, Wójcik-Wiśniewska M, Peciakowski H, Olszacki J (2016) The performance of a highly modified asphalt for long-lasting asphalt pavements. Transp Res Procedia 14:679–684

Hintz C, Velasquez R, Johnson CM, Bahia HU (2011) Modification and validation of linear amplitude sweep test for binder fatigue specification. Transp Res Rec 2207:99–106

Johnson CM (2010) Estimating asphalt binder fatigue resistance using an accelerated test method. Ph.D. thesis, University of Wisconsin – Madison, USA

Kim YR, Little DN, Lytton RL (2006) A simple testing method to evaluate fatigue fracture and damage performance of asphalt mixtures. J Assoc Asphalt Paving Technol 71:176–206

Masad E, Somadevan N, Bahia HU, Kose S (2001) Modelling and experimental measurements of strain distribution in asphalt mixes. J Transp Eng 127:477–485

Monismith CM, Epps JA, Kasianchuk DA, McLean DB (1970) Asphalt mixture behavior in repeated flexure. Institute of Transportation and Traffic Engineering, University of California, Berkeley, USA

Pereira A, Micaelo R, Cidade MT, Quaresma L (2016) Evaluation of different methods for the estimation of the bitumen fatigue life with DSR testing. RILEM Bookseries. https://doi.org/10.1007/978-94-017-7342-3_81

Safaei F, Castorena C (2016) Temperature effects of linear amplitude sweep testing and analysis. Transp Res Rec 2574(1):92–100

Safaei F, Hintz C (2014) Investigation of the effect of temperature on asphalt binder fatigue. In: International Society for Asphalt Pavement Conference, pp 1491–1500

Schapery RA (1975) A theory of crack initiation and growth in viscoelastic media. Analysis of continuous growth. Int J Fract 11:549–562

Schapery RA (1984) Correspondence principle and generalized integral for large deformation and fracture analysis of viscoelastic media. Int J Fract 25:195–223

Schapery RA (1990) A theory of mechanical behavior of elastic media with growing damage and other changes in structure. J Mech Phys Solids 2:215–253

Soenen H, De La Roche C, Redelius P (2004) Predict mix fatigue tests from binder fatigue properties measured with a DSR. In: 3rd Eurasphalt and Eurobitume Congress, Vienna, Austria

Soenen H, Eckmann B (2000) Fatigue testing of bituminous binders with a dynamic shear rheometer. In: Proceedings of the 2nd Eurasphalt and Eurobitume Congress, Barcelona, Spain

Timm DH, Robbins MM, Willis JR, Tran N, Taylor AJ (2013) Field and laboratory study of high-polymer mixtures at the NCAT test track. Draft Report, National Center for Asphalt Technology, Auburn University, USA

West R, Timm DH, Willis JR, Powell B, Tran N, Watson D, Brown R, Robbins M, Vargas-Nordcbeck A, Nelson J (2012) Phase IV NCAT pavement test track findings. Draft Report. National Center for Asphalt Technology, Auburn University, USA

Wesołowska M, Ryś D (2018) Analysis of the fatigue life of neat and modified bitumens using linear amplitude sweep test. Roads Bridges Drogi I Mosty 17:317–336