Assessing the performance of asphalt mastic by dynamic shear rheometer fatigue testing

Markus Hospodka[1], Bernhard Hofko[1], Ronald Blab[1]
（[1] Vienna University of Technology， Institute of Transportation, Gusshausstrasse 28/E230-3, Austria, markus.hospodka@tuwien.ac.at, bernhard.hofko@tuwien.ac.at, ronald.blab@tuwien.ac.at)

ABSTRACT

Early failure of asphalt pavements is a common issue all around the world. Damages are caused by various reasons like binder or aggregate quality, an inadequate mix design or improper handling in the construction process. The effects of binder, aggregates and mix design have been widely studied and state-of-the-art testing methods are available for both, hot-mix asphalt (HMA) and for each component. An important part in HMA belongs to the asphalt mastic, where no standardized method is available to allow a quality control. Asphalt mastic is the mix of bitumen with aggregates smaller than 63 (125) µm and covers the coarse aggregates as the actual binding component in the mix. This research aims at developing a testing method for asphalt mastic based on fatigue tests. The dynamic shear rheometer (DSR) was found as a suitable device for this purpose. The DSR fatigue test consists of the 8 mm parallel-plate geometry widely used for binder performance grading with a sample height of 3 mm. Instead of a cylindrical specimen shape, a hyperboloid of one sheet is applied. This shape predetermines the point of failure and prevents from adhesion/interface failures between the mastic specimen and the upper or lower DSR stainless steel plate. The specimens are prepared directly in the DSR employing a silicone mould to ensure an exact specimen shape. This test can be applied to all DSR devices without costly changes or additional equipment as long as sufficient cooling capacity and torque can be provided from the DSR.

Keywords: mastic, filler, fines, fatigue, DSR

1. INTRODUCTION

In recent years, damage has increasingly occurred in the case of bituminous top layers, such as the loss of aggregates and decreased fatigue life of the base layers in various parts of Central and Western Europe. These damages can not be attributed either to an unusual climate or a high traffic load. A possible cause of damage is a lack of serviceability of the asphalt mastic (bitumen + mineral fine fraction), like bad adhesion to the aggregates or overall strength. This can be adressed to poor quality of one of the two components, bitumen and added filler or fines. Preliminary work on this subject suggests that the mineralogical composition of the added filler or fines affects the quality of the mastic and thus the adhesion to the coarse aggragates and strength. It can be assumed that a lack of quality of the added filler or fines is responsible for premature damage. Possibly, the use of non-quality-assured fines from the fine and coarse aggregates instead of added filler or mixed filler can be accounted to these damages. This study aims to develop a suitable test to assess the quality of the mastics with regard to durability (fatigue life).

The European Standard EN 12697-24 [1] defines fatigue as „...the reduction of strength of material under repeated loading when compared to the strength of a single load“. Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading below the stress limit untill the state of serviceability limit or total failure is reached.

This effect also occurs in asphalt pavements and affects all asphalt layers. Due to heavy goods vehicle traffic, microcracks occur in the order of fractions of a millimeter. These loads cause tensile stress in the base layer and thus microcracks are formed. In the case of repeated loads, these cracks are propagated upwards and are linked to macrocracks, which are visible. If these cracks finally pass through to the top layer, a cracking pattern typical of fatigue damage occurs. Another form of fatigue damage affects the asphalt surface. The coarse aggregates are glued together by asphalt mastic and under repeated stresses, poor mastic leads to loss of aggregates on the surface. While there are standardized testing methods available for bitumen, aggregates and hot-mix asphalt (HMA), there is no testing method available to assess the durability of asphalt mastic. Thus, several researchers already published their work to account the fatigue performance of asphalt mastic or mortar (bitumen + filler + sand) in different testing setups and maschines, like DSR [2], Annular Shear Rheometer (ASR) [3-6], Dynamic Mechanical Analysis (DMA) [7-9] and Tension Compression Tests [10, 11].

2. APPROACH

The 4-Point Bending-Beam Test (4PBB) according to EN 12697-24 [1] is one of the standardized fatigue tests for HMA. Since the aim of this paper is the development of a fatigue test for asphalt mastic, the 4PBB test is described in more detail for a better understanding of fatigue. In the 4PBB test, a prismatic beam is supported at 4 points and is dynamically loaded at the two inner bearings. The sample is pulled upwards and pushed downwards until a defined deformation/strain is reached in the center of the beam. The force required for the predetermined strain is measured and the dynamic modulus is calculated continuosly. Therefore, the 4PBB test is a strain-controlled test. Due to the increasing number of load cycles during the test progress, the beam becomes weaker and the dynamic modulus is getting lower. When the dynamic modulus reaches half of its initial value at the beginning of the 4PBB test the fatigue criterion is met. Tests have to be carried out at 3 different strain levels with at least 6 samples each level to account for the limited statistic certainty. This results in at least 18 samples that have to be tested. Including the mixing of HMA, sample fabrication and preparation for testing, it takes about 3 weeks to complete all necessary steps for one single HMA. Thus, the 4PBB test is a time consuming test and it is also not applicable to the testing of mastic or mortar.

This paper aims to find a fatigue testing method suitable for asphalt mastic applicable on a device that is already available in most of the commercial laboratories of pavement engineering. The dynamic shear rheometer (DSR) was found as a suitable device with good availability due to the fact that it is used for binder grading.

3. DEVELOPMENT OF THE FATIGUE TEST

3.1. DSR loading mode & fatigue failure criterion

DSR are capable of applying oscillatory stress- and strain-controlled loads on small specimens. Deciding between stress- and strain-controlled loading modes, the stress-controlled mode is in favour because it is more comparable to what happens on site. Thinking about a heavy goods vehicle driving on an asphalt pavement, the induced stress is unchanged and the strain is a function of the stiffness of the material. Under strain-controlled loading mode stiffer materials are subjected to higher stress levels than materials with lower stiffness. Changing the loading mode also requires changing the fatigue criterion. While 50% of the initial modulus is used as a criterion for strain-controlled tests, the true failure of the specimen is applied to stress-controlled tests. **Figure 1** shows a typical fatigue curve under stress-controlled loading mode obtained by DSR within this paper.

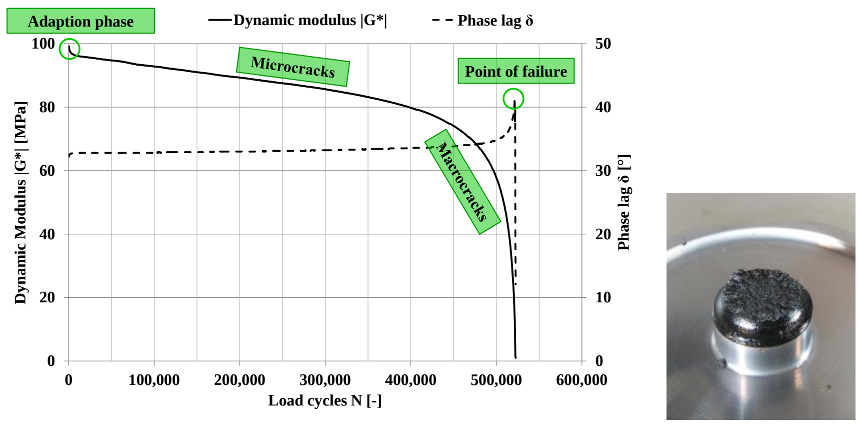

FIGURE 1 left: Fatigue curve under stress-controlled loading mode right: fatigued specimen

A fatigue curve obtained by stress-controlled testing consists of four typical phases: Phase (1) is the adaption phase dominated by thixotropy [12] and little heating of the specimen caused be energy dissipation (both casues a reversible loss of stiffness). Phase (2) consist of a continuous propagation of microcracks. In Phase (3) these microcracks are linked to macrocracks until in Phase (4) these macrocracks are linked to a yield line. Finally, the specimen breaks due to fatigue failure. The failure is reflected in both, dynamic modulus and phase lag. In this study, the point of failure is determined by the sudden drop of the phase lag as shown in **Figure 1**.

3.3. Preparation of asphalt mastic samples

Depending on grading curve, air void and binder content, HMA is categorized into asphalt concrete (AC), stone mastic asphalt (SMA), mastic asphalt (MA) and porous asphalt (PA). The ratio of binder to filler/fines is different within these mix designs. A mixing ratio of 1 part binder to 1.5 parts of filler/fines by weight (m/m) is chosen to obtain a ratio almost similar to the ratio used in AC. In preliminary tests mixing ratios of up to 1:2.5 have been tested where rations from 1:2.0 show a decreasing repeatability. This can either be accounted to bad mixing quality or the grain shape. The higer the filler/fines content the higher is the interaction level between each single grain. The higher the interaction level the more prone is a poured DSR specimen to the exact position of each grain. Both, the filler or fines and the binder are heated up to 180°C in a thermal chamber. The next step is to pour the binder into the metal can with the filler/fines inside and it is then steered with a metal or glas rod until a homgenious asphalt mastic is obtained. A temperature controlled heat gun is used to maintain the temperature during mixing. The mastic samples are immediately stored in a fridge at 5°C to avoid settling of particles after mixing. Two different fillers (limestone and quarzite) have been tested in this study. Both of them with a maximum grain size of 125 µm. It is important to keep a certain maxiumum grain size when comparing fillers or fines because of the sensitivity to fatigue tests. As a binder a 70/100 paving grade bitumen with a PG 58-28 is used. It is known from literature that the stiffness of a binder has an impact to the fatigue life of the mastic. This behaviour is not accounted in this paper, but is part of the ongoing project.

3.3. Test parameters & sample geometry

While a temperature sweep is applied during binder grading the fatigue test is carried out at one single temperature only. The temperature is selected according to the creep stiffness of the mastic. The higher the creep stiffness is, the higher the applicable temperature can be chosen for the fatigue test. It is necessary to maintain a certain minimum stiffness at test temperature to avoid creep deformation. In this study and in accordance to other researchers a test temperature of **10°C** is selected [12-32]. Fatigue performance testing requires a high number of load cycles until fatigue failure. It is recommended to select a high frequency to conduct these tests in a limited time to to be economical. For that reason a testing frequency of **30 Hz** is selected in this study. With 30 Hz it is possible to perform 108,000 load cycles within one hour. It is possible to choose even higher frequencies as far as an appropriate DSR is available. However, higher frequencies cause higher dissipated energy and thus, more friction heating to the mastic sample.

There are two different parallel-plate testing geometries used for binder grading, PP08 and PP25. The numbers determine the diameter of the specimen and are applied to the upper (PP25) and lower temperature testing range (PP08) according to AASHTO M 320 [33]. Due to the fact that bitumen is a highly temperature-dependent material and DSR are limited in its applicable torgue, **PP08** has to be used for fatigue testing. In preliminary tests the standard specimen geometry shape (diameter 8 mm, height 2 mm) used for binder grading have also been used for fatigue tests. After extensive pretests, it can be concluded that a cylindric specimen shape (even with a height of 3 mm) is not suitable for fatigue testing due to the fracture behaviour. In all these tests performed, the specimens failed either as pure interfacial/adhesion failure (picture 1 in **Figure 2**) or in a combination of adhesion and cohesion failure (picture 2 in **Figure 2**). However, several researches published work employing a cylindric specimen shape for fatigue testing of pure binder or mastic [12, 13, 15-19, 21-23, 25-30, 32, 34, 35]. Some researches came to the same conclusion regarding the disadvantageous use of a cylindric specimen shape for fatigue testing.

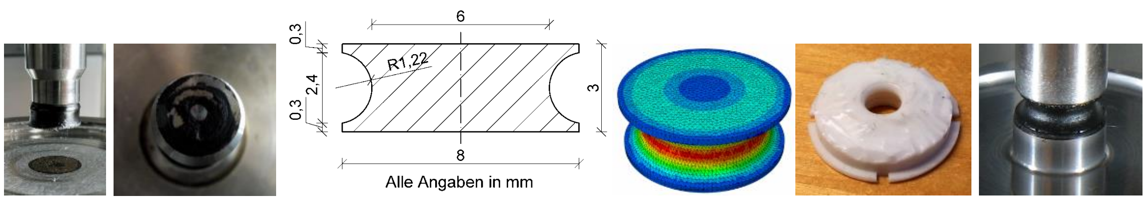

FIGURE 2 Failure types, hyperboloid shape, FE model, silicone mould, alt. solution

A solution has been found in a redesigned specimen geometry (picture 3 in **Figure 2**). This geometry is based on the PP08 testing geometry with a specimen height of 3 mm and a predetermined point of failure in the middle of the height. Higher specimens are not recommended due to the limited cooling capacity of the DSR (thermal gradient). The predetermination is realised by circular necking of the original diameter of 8 mm down to 6 mm. A small platform of 0.3 mm at both ends of the hyperboloid avoids unfavourable stress concentrations in the edges. In literature, researches solved that issue with other specimen shapes like dog-bone or even larger cylinders with clamps or terminals at both ends [14, 20, 24, 27]. These specimen shapes requires a DSR with a temperature-controlled chamber instead of a temperature-controlled hood. This leads to expensive, additional equipment not common or even not available for standard DSR setups employed for binder grading.

Picture 4 in **Figure 2** also shows the shear stress distribution in the hyperboloid where the stress goes from higher (red) to lower levels (blue), calculated by finite element analysis software Abaqus. With this geometry it is possible to obtain true cohesion failure within the mastic specimen.

3.4. Specimen preparation in the DSR

The specimen preparation has to be carried out directly in the DSR because it is not possible to trim a hyperbolid shape by hand. A reusable silicone mould is employed to ensure an accurate specimen. The silicone mould is made out of two-component silicone and is temperature-resistant of up to 180°C (picture 5 in **Figure 2**). Thus, it is possible to pour the molten mastic sample directly into the silicone mould loaded in the DSR. The loading of molten samples guarantees an ideal bonding between mastic and the smooth stainless steel surfaces of the DSR. It is optional to remove excess mastic at the top of the mould because it has no impact to the fatigue test. The silicone mould is removed after a cooling period of at least 10 minutes resulting in an accurate specimen shape (picture 6 in **Figure 2**).

4. RESULTS

4.1. Hyperboloid – A challenging specimen shape

It must be noted that the dynamic modulus calculated by the DSR software (Anton Paar RheoCompass) is not the true dynamic modulus of the mastic sample being measured. This issue is related to the hyperboloid specimen shape. Parallel-plate tests are usually run with cylindric specimen shapes and therefore, all the calculations within the DSR software are based on a cylindric shape with a diameter of 8 mm and a sample height of 3 mm. Equalling Ø6 and Ø8 mm gives a correction factor of 3.2. Hence, a cylindric specimen with Ø8 mm is expected to be 3.2 times higher in dynamic modulus than a cylindric specimen with Ø6 mm. Oscillatory shear tests on a bitumen 70/100 with the same conditions as applied for the fatigue tests (10°C, 30 Hz sample height of 3 mm) on both, Ø8 mm cylindric shape and hyperboloid resulted in a correction factor of 2.4. This means that the dynamic modulus of the Ø8 mm cylindric specimen is not as high as expected from calculations or vice versa, the hyperboloid is stiffer than expected. It is highly likely that the contributing diameter of the hyperboloid is higher than 6 mm because of the circular necking. Probably, this correction factor is varying depending on the grading curve and grain shape of the filler/fines as well as the grading or (polymer-) modification of the binder. This issue will be looked into in future work.

4.2. Repeatability of the developed fatigue test

Tests are required to have a good repeatability and comparability to guarantee a wide spread application. **Figure 8** shows the repeatability of 10 fatigue tests at a shear stress level of 400 kPa of both, dynamic modulus at the beginning of each fatigue test and the fatigue strength expressed as the number of load cycles until failure. The dynamic modulus is obtained after 10 seconds, which is equal to 300 load cycles. While EN 14770 [36] for standard DSR tests presets the comparability of the dynamic modulus to 10 %, there is no value given for the repeatability. It has to be accounted that this comparability is based on a round-robin test with a cylindric specimen shape. Because there is no repeatability given, the mean ±5 % is shown in **Figure 3**. The 50% (median) and 95 % confidence interval of the standard error (SEM) is calculated to look into the quality of the obtained fatigue strength. With a probability of 95 % the true fatigue strength is between 188,000 and 212,000 load cycles. This is about ±6 % of the mean. It can be seen that both, dynamic modulus and fatigue strength show a good repeatability. This proves that the hyperboloid specimen shape can be prepared very accuratly and the entire DSR setup is suitable for fatigue testing.

4.1. Comparison of mastic samples

For the determination of the fatigue strength of a mastic sample and for the comparsion to other samples it is necessary to fit a logarithmic stress-cycle (S-N) curve (Wöhler curve) into the fatigue test results obtained of at least three different shear stress levels. **Figure 4** shows S-N curves of two different mastic samples. Both curves are fitted to the mean values of three single fatigue tests at four different shear stress levels, respectively. Both S-N curves show an excellent coefficient of determination of R^2=0.99.

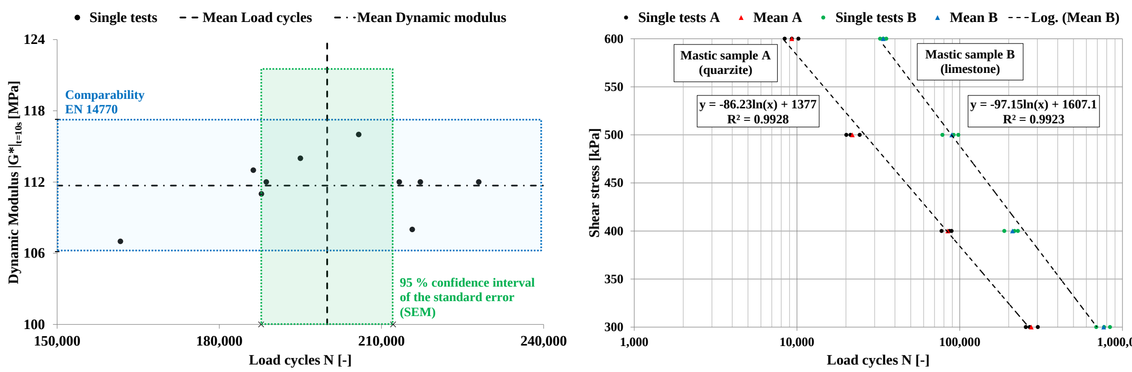

FIGURE 3 left: Repeatability test with hyperboloid shape at 10°C, 400 kPa right: Stress-cycle curves of two different mastic samples

5. CONCLUSIONS & OUTLOOK

5.1. Conclusions

This study shows that a standard DSR equipped with components used for binder grading (temperature-controlled hood, PP08 geometry) is capable of fatigue testing of asphalt mastic. Therefore, no costly changes are necessary. The developed hyperbolid specimen shape with predetermined point of failure gives a good repeatability. This makes it possible to compare the fatigue durability of different mastic samples with S-N curves at different shear stress levels.

5.2. Outlook

This paper is limited to one binder and two different fillers. Further tests with different binders and filler/fines are still ongoing. Another aim of this project is to determine the impact of different temperatures on the fatigue strength of mastic. As soon as the fatigue strength of several fillers/fines is found, a correlation analysis with 4PBB results will be carried out. The actual state of the developed fatigue test does no allow any kind of weathering. Because fillers/fines can have a high water susceptibility, it is important to find a suitable solution for takeing the water susceptibitily in the fatigue test into account in the future.

6. REFERENCES

1. CEN, *EN 12697-24: Bituminous mixtures – Test methods for hot mix asphalt – Part 24: Resistance to fatigue*. 2012: Brussels.
2. Kim, Y.R., D.N. Little, and I.J. Song, *Effect of mineral fillers on fatigue resistance and fundamental material characteristics - Mechanistic evaluation.* Bituminous Paving Mixtures 2003, 2003(1832): p. 1-8.
3. Van Rompu, J., et al., *New fatigue test on bituminous binders: Experimental results and modeling.* Construction and Building Materials, 2012. **37**: p. 197-208.
4. Di Benedetto, H., Q.T. Nguyen, and C. Sauzéat, *Nonlinearity, Heating, Fatigue and Thixotropy during Cyclic Loading of Asphalt Mixtures.* Road Materials and Pavement Design, 2011. **12**(1): p. 129-158.
5. Van Rompu, J., et al., *New fatigue test on bituminous binders and mastics using an annular shear rheometer prototype and waves propagation.* Advanced Testing and Characterisation of Bituminous Materials, Vols 1 and 2, 2009: p. 69-79.
6. Delaporte, B., et al., *New procedure to evaluate fatigue of bituminous mastics using an annular shear rheometer prototype.* Pavement Cracking: Mechanisms, Modeling, Detection, Testing and Case Histories, 2008: p. 457-467.
7. Kim, Y.-R. and H.-J. Lee, *Evaluation of the effect of aging on mechanical and fatigue properties of sand asphalt mixtures.* KSCE Journal of Civil Engineering, 2003. **7**(4): p. 389-398.
8. Kim, Y.R., D.N. Little, and R.L. Lytton, *Fatigue and healing characterization of asphalt mixtures.* Journal of Materials in Civil Engineering, 2003. **15**(1): p. 75-83.
9. Kim, Y.R., D.N. Little, and R.L. Lytton, *Use of dynamic mechanical analysis (DMA) to evaluate the fatigue and healing potential of asphalt binders in sand asphalt mixtures.* Journal of the Association of Asphalt Paving Technologists, Vol 71, 2002: p. 176-206.
10. Taylor, R. and G. Airey, *Influence of surface interactions between bitumen and mineral fillers on the rheology of bitumen-filler mastics.* 2008.
11. Cardone, F., et al., *Influence of mineral fillers on the rheological response of polymer-modified bitumens and mastics.* Journal of Traffic and Transportation Engineering (English Edition), 2015. **2**(6): p. 373-381.
12. Shan, L.Y., et al., *Separation of Thixotropy from Fatigue Process of Asphalt Binder.* Transportation Research Record, 2011(2207): p. 89-98.
13. Ameri, M., et al., *Fatigue performance evaluation of modified asphalt binder using of dissipated energy approach.* Construction and Building Materials, 2017. **136**: p. 184-191.
14. Mukandila, E.M., W.J.v.d.M. Steyn, and T.I. Milne, *Modelling of cohesion and adhesion damage of seal based on dynamic shear rheometer testing.* International Journal of Pavement Engineering, 2016: p. 1-12.
15. Shan, L., et al., *Effect of load control mode on the fatigue performance of asphalt binder.* Materials and Structures, 2015. **49**(4): p. 1391-1402.
16. Santagata, E., et al., *Fatigue properties of bituminous binders reinforced with carbon nanotubes.* International Journal of Pavement Engineering, 2014. **16**(1): p. 80-90.
17. Liao, M.-C., G. Airey, and J.-S. Chen, *Mechanical Properties of Filler-Asphalt Mastics.* International Journal of Pavement Research and Technology, 2013. **6**(5): p. 576-581.

18. Hintz, C. and H. Bahia, *Understanding mechanisms leading to asphalt binder fatigue in the dynamic shear rheometer.* Road Materials and Pavement Design, 2013. **14**(sup2): p. 231-251.
19. Stimilli, A., et al., *Effect of Healing on Fatigue Law Parameters of Asphalt Binders.* Transportation Research Record, 2012(2293): p. 96-105.
20. Mo, L.T., et al., *Research of Bituminous Mortar Fatigue Test Method Based on Dynamic Shear Rheometer.* Journal of Testing and Evaluation, 2012. **40**(1): p. 84-90.
21. Liao, M.C., J.S. Chen, and K.W. Tsou, *Fatigue Characteristics of Bitumen-Filler Mastics and Asphalt Mixtures.* Journal of Materials in Civil Engineering, 2012. **24**(7): p. 916-923.
22. Soenen, H., C. de La Roche, and P. Redelius, *Fatigue Behaviour of Bituminous Materials: From Binders to Mixes.* Road Materials and Pavement Design, 2011. **4**(1): p. 7-27.
23. Shen, S., et al., *A Dissipated Energy Approach to Fatigue Evaluation.* Road Materials and Pavement Design, 2011. **7**(1): p. 47-69.
24. Liu, G., et al., *Influence of organo-montmorillonites on fatigue properties of bitumen and mortar.* International Journal of Fatigue, 2011. **33**(12): p. 1574-1582.
25. Shen, S.H., H.M. Chiu, and H. Huang, *Characterization of Fatigue and Healing in Asphalt Binders.* Journal of Materials in Civil Engineering, 2010. **22**(9): p. 846-852.
26. Shan, L., et al., *Application of Thixotropy to Analyze Fatigue and Healing Characteristics of Asphalt Binder.* Transportation Research Record: Journal of the Transportation Research Board, 2010. **2179**: p. 85-92.
27. Martono, W., H.U. Bahia, and J. D'Angelo, *Effect of Testing Geometry on Measuring Fatigue of Asphalt Binders and Mastics.* Journal of Materials in Civil Engineering, 2007. **19**(9): p. 746-752.
28. Planche, J.-P., et al., *Evaluation of fatigue properties of bituminous binders.* Materials and Structures, 2004. **37**(5): p. 356-359.
29. Bonnetti, K., K. Nam, and H. Bahia, *Measuring and Defining Fatigue Behavior of Asphalt Binders.* Transportation Research Record: Journal of the Transportation Research Board, 2002. **1810**: p. 33-43.
30. Anderson, D.A., et al., *Evaluation of fatigue criteria for asphalt binders.* Asphalt Binders 2001, 2001(1766): p. 48-56.
31. Smith, B. and S. Hesp, *Crack Pinning in Asphalt Mastic and Concrete: Regular Fatigue Studies.* Transportation Research Record: Journal of the Transportation Research Board, 2000. **1728**: p. 75-81.
32. Bahia, H.U., et al., *Non-linear viscoelastic and fatigue properties of asphalt binders.* Journal of the Association of Asphalt Paving Technology, Vol 68, 1999, 1999: p. 1-34.
33. AASHTO, *AASHTO M 320-10: Standard Specification for Performance-Graded Asphalt Binder*. 2010, American Association of State and Highway Transportation Officials: Washington, D.C.
34. Ortiz, O.J.R. and F.E.P. Jimenez, *Studying asphalt binder fatigue pattern by using a dynamic shear rheometer.* Ingenieria E Investigacion, 2011. **31**(1): p. 47-55.
35. Epps, J.A., et al. *Influnce of Mixture Variables on the Flexural Fatigue Pproperties ofAsphalt Concrete*. 1969.
36. CEN, *EN 14770: Bitumen and bituminous binders - Determination of complex shear modulus and phase angle - Dynamic Shear Rheometer (DSR)*. 2005: Brussels.