Asphalt mixture performance and testing

Comparison of test results of mortar-dumbbell specimen and asphalt parameter: stiffness and fatigue behavior

Sivapatham Pahirangan[1], Simmleit Norbert[2], Sacihan Hülya[2]
[1]Road Construction and Maintenance, University of Wuppertal, Germany, [2]TPA GmbH, Strabag S.E.

Abstract

Material fatigue is one of the most important causes for failure of asphalt pavements. The structural model of asphalt can be divided into two phases, the aggregate skeleton and the mortar. Mortar is defined as the mixture of fine aggregates, filler, bitumen and additives. As the mortar represents the weakest link in the system of the two-phase-model, it is especially susceptible to fatigue damage. The target of this research and development project is to find out a relationship between the mortar performance and asphalt parameter: stiffness and fatigue behavior, determined on drill cores by means of indirect tension test. Therefore, in this study the fatigue behavior and stiffness of bituminous mortar by means of specially designed mortar specimens (asphalt dumbbell – specimen) have been determined. With rheological measuring by means of DSR, a modern and highly effective technique is found to assess the above mentioned mortar qualities. In Germany no experiences are available with such an investigation on mortar-dumbbell by means of DSR. Due to that, a standard for this test method is not available in Europe. First, the preparation and homogeneity of specimen as well as the repeatability of test method for several type mortars with different type of bitumen have been determined and optimized. The used methods indicate good reproducibility and sufficient accuracy of testing and test evaluation. Furthermore, the gained experiences show that the fatigue behavior and stiffness can be determined in one process compared to the test methods on asphalt drill cores. In addition, the investment for preparation of specimen and the duration of fatigue tests are significantly shorter.

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

Fatigue can occur due to tensile stress, caused by the wheel load. It is well known that every single load generates tensile stresses and causes a decrease of stiffness. These cause over the lifetime exceeding of permissible tensile stress, resulting in initiation of micro cracks at the bottom of the asphalt layer. Finally, the micro cracks propagate to macro cracks resulting in failure of the pavement. Therefore, the fatigue damage is one of the crucial design criteria of asphalt pavement [1].

In most cases of fatigue failure, the interaction between aggregate skeleton and the mortar are destroyed. A single aggregate is an elastic material, much stiffer and stronger than the bitumen or mortar. In the structural model of asphalt, the mortar sticks the aggregates skeleton together and represents the weak link in the system of the two-phase model compared to the aggregates. Thus, the mortar is especially susceptible to failure. Therefore, it is important to investigate the fatigue behaviour and stiffness of mortar. An interfacial failure at the boundaries of the aggregates and bitumen is also possible, but proper aggregate or adhesion promoter can improve this impact. Investigation of bitumen could also be an option, but the bitumen as a mixture with filler (grain size < 0.063 mm) and fines sand (grain size 0.063/0.5 mm) is present in the asphalt mix and only this mix performs.

For dynamic indirect tensile test (ITT) according to European Standard EN 12697-24/26, many experiences are available. However, to gain these material parameters on asphalt specimen a period of 4-6 weeks and an amount of asphalt mix of around 300 kg are necessary. In the case of application of reclaimed asphalt (RAP), the properties of RAP can vary extremely within short time. The test period of 4-6 weeks are too long to determine the asphalt mix properties with new RAP. In most cases, these periods are nearly not available to determine the material parameters such as fatigue properties or stiffness. In addition, in the scope of check tests or quality controls to determine the fatigue behaviour and stiffness modulus more than 20 drill cores (150 mm diameter) are needed. Due to that, new simple test methods are necessary to determine the fatigue properties and stiffness within short time by means of small quantity of sample. Therefore, the objective of this study is to find out a new approach to investigate the fatigue and stiffness of asphalt mortar. Finally, a correlation between fatigue test results determined on mortar specimens and asphalt drill core specimens shall be determined.

2. RESEARCH PROGRAM

Asphalt mortar is a mix of the components filler, fines sand and bitumen. This acts as an extender of the binder by being an active material. Binder serves to stick the aggregates particles. Furthermore, asphalt mortar fills the air voids in the aggregate's skeleton. It is well known that the asphalt mortar also influences many of the asphalt mix properties, such as stiffness, rutting resistance, fatigue, workability and moisture susceptibility [2]. In addition, the investigation of the conventional asphalt mortar characteristics show good correlation to the asphalt performance compared to the investigation of the bitumen [3].

Literature review shows a lot of research works carried out on asphalt mortar to determine the influence on performance behaviour [4, 5, 6, 7 and 8]. In this study, the mortar properties were determined by means of the test method developed at the Technical University of Delft (TU Delft) [4 and 8]. TU Delft applied this test method mainly to optimise the ravelling failure of the porous asphalt caused by fatigue in mortar and adhesive zone. In this study, this test method was enhanced to apply for dense asphalt with a high viscosity bitumen.

2.1. Fatigue

Fatigue cracks in asphalt layer is a complex phenomenon and due to that, a clearly accepted test method to describe the fatigue properties is not available. Therefore, fatigue tests are determined worldwide by means of several test methods. According to European Standard (EN 12697-24/26), several bending tests (2-, 3- and 4-point) and dynamic indirect tensile tests are used to determine the fatigue properties of asphalt specimen.

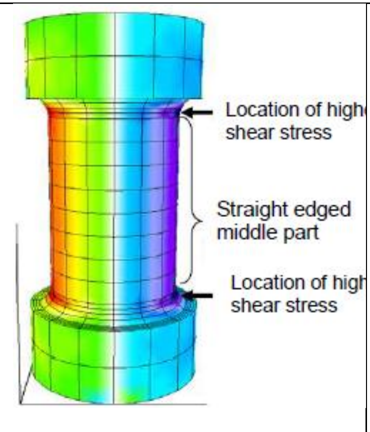
For the determination of the fatigue properties of bitumen or mortar, the most commonly used equipment is the plate-plate system of Dynamic Shear Rheometer (DSR). However, the experience of this test method shows not enough reliability yet. Therefore, in this study a new approach to describe fatigue behaviour of asphalt mortar applied and checked the reliability.

2.2. Fatigue Test on mortar-dumbbell Specimen

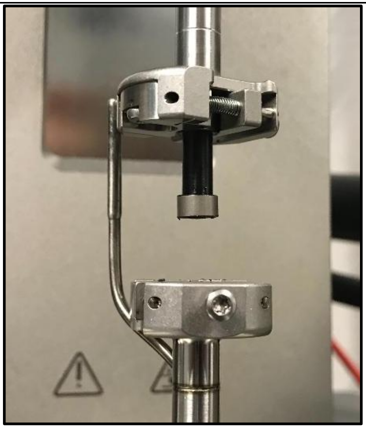
The main part of this study is to draft a test method to determine a fatigue property and stiffness for mortar specimen. Through the literature study, DSR under stress and torque-controlled mode shows as a proper method to determine the fatigue test on mortar specimen [8]. DSR with rheological measuring system provides a modern and highly effective technique to assess the mortar qualities. Worldwide, nearly no experiences are available with such investigation on mortar-dumbbell produced with high viscosity mortar. Due to that, a standard for this test method is not available.

In this study in total, DSR shear fatigue tests at a temperature of +10 °C and at a frequency of 10 Hz were carried out on four different asphalt mortars. The mortar-dumbbell specimens were loaded by a sinusoidal torque. During the test, the applied torque and the rotational deformation of the specimen measured. In addition, the phase angle between the torque signal and the displacement recorded. The chosen torque for the fatigue test was reached over a preload stage within 300 seconds to avoid abrupt shearing of the specimen. The test results did not consider the applied load cycle during the preload stage. The specimen was loaded until it cracked and the type of cracks can be described as shear failure. In a FE-model simulation, a transfer function for shear stress and shear strain in specimen could be determined, Figure 3. Therefore, as input values the applied torque and measured rotational deformation used subject to the geometry of the dumbbell specimen. The FE-model confirms that shear deformation, G*, is induced in the DSR shear tests. The highest shear stress was determined along the curved edge in the narrowing area of the steel ring [4].

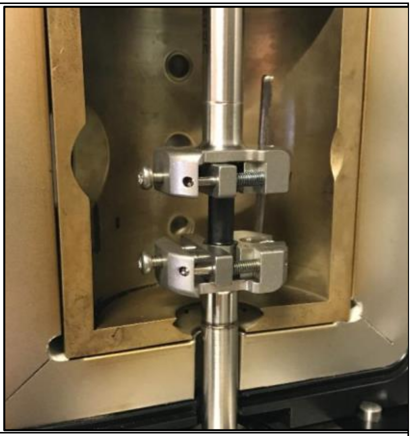
A clamps set-up SCFB 11.5-15 used to hold the sample in DSR during the fatigue tests, Figure 1. The clamps hold only the sample at the two steel rings at both ends and do not touch the mortar. A bond between ring and mortar-dumbbell was ensured during the whole fatigue test. The mortar-dumbbell had never loosed from the ring.



FE-model, visualization of stress distribution [4]



DSR clamps set-up SCFB 11.5-15



Clamped mortar-dumbbell specimen

Figure 1: DSR test set-up with clamped mortar-dumbbell Specimen and the distribution of stress

3. PRODUCTION OF THE TEST SPECIMEN

3.1. Asphalt mortar

Mortar is defined as the mixture of fines sand (size 0.063/0.5 mm), filler (size < 0.063 mm) and bitumen. In the literature, several ratios for the bitumen and filler or sand content suggested. However, in this study, the amount of bitumen, filler and fines of sand selected subject to the composition of the asphalt base course mix (AC 22 T S), which was used for the production of the drill core. The asphalt mix (AC 22 T S) was composed according to the European Standard. The tables below give the information of properties of the asphalt base course mix (AC 22 T S) and of the composition of the asphalt mortar [Tables 1 and 2].

Table 1: Properties of the Asphalt Mix (AC 22 T S)

	filler (0-0.063)	fine aggregate (0.063-0.125)	fine aggregate (0.125-2.0)	Coarse aggregate (> 2.0)	Bitumen content	Void Content	Voids filled with binder
	[% by mass]					[% by mass]	[%]
AC 22 TS	8.9	2.4	20.4	68.2	4.5	5.0	68.4

Four different asphalt mortars were produced with similar bitumen and aggregates used to prepare the drill cores. Thereby only the bitumen used varied. One type of bitumen (PEN 30/45) from four different refineries was used. The selected refineries deliver nearly the total bitumen to the market of the north part of Germany. The fines of the sand between 0.063 mm and 0.5 mm was gained by means of sieving. In addition, the necessary bitumen and aggregates of RAP material were obtained by means of extraction of RAP in an automatic apparatus called asphalt analysator. After the extraction, vacuum evaporator according to European Standard was used to move the solvent. By means of sieving the filler and fines (sand) were separated for further use.

Table 1: Composition of asphalt mortar [% by mass]

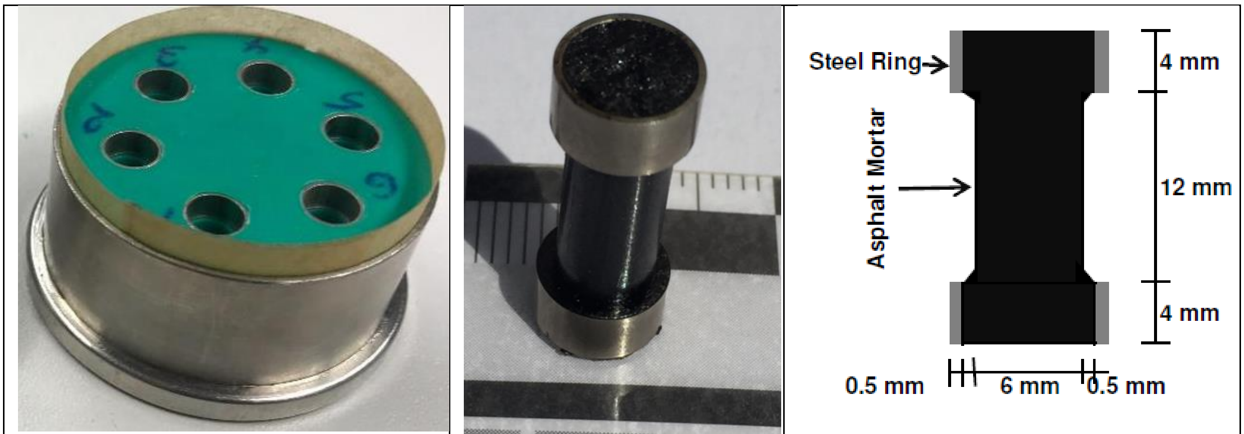
Filler-lime stone (0-0.063 mm)	20.5 %	Filler	36.4 %
Filler -RAP	15.9 %		
Fines of fine aggregates/sand lime stone (0.063-0.5 mm)	21.5 %	Fines of fine aggregates	44.8 %
Fines of fine aggregates/RAP (0.063-0.5 mm)	23.3 %		
Bitumen (30/45)	11.6 %	Bitumen	18.8 %
Bitumen in RAP	7.2 %		
Total	100 %		100 %

3.2. Mortar-Dumbbell Specimen

As specimen, a specially designed mortar-dumbbell has been used. Specification or a European Standard are not available to produce this specimen. The mortar-dumbbell has a height of 20 mm and a diameter of 6 mm in the column. 4 mm height stainless-steel rings covered the ends of the mortar-dumbell. The steel rings contribute to better clamping during the test in the testing apparatus DSR. The diameter of the specimen in the ring area is 7 mm; it means diameter increase from 6 mm to 7 mm, Figure 2. For production of nine Specimen, around 250 g mortar were produced. The amount of necessary mortar is very little, compared to the amount of asphalt mixes used for fatigue and stiffness tests.

Bitumen is temperature sensitive and heating the bitumen to high temperature always causes an ageing. Ageing of bitumen can influence the test results significantly. A standard preparation method for mortar and specimen production was established. Therefore, several preliminary mortar and specimen production as well as specimen testing were carried out. The reproducibility and the testing accuracy became better with increasing experiences.

The workability of the mortar is dependent on the viscosity of bitumen and ratio of the bitumen and mineral aggregates. The higher the viscosity of bitumen and the higher the ratio of mineral aggregates to bitumen, the less workable the resulting mortar will be. The extracted bitumen of asphalt mortar (30/45+RAP-Bitumen) showed a softening point ring and balls around 62 [°C] and penetration value of around 19 [1/10 mm]. These characteristics indicates on high viscosity. In addition, the ratio of mineral aggregates to bitumen (4.3:1) is also very high. As a result, the workability of mortar was very difficult. To produce a homogeneity and pourable asphalt mortar, a mixing temperature between 210-230 °C was necessary. According to European Standard, the mixing temperature of mastic asphalt with a paving grade bitumen PEN 30/45 is between 220 and 230 °C.



Silicone mould for mortar-dumbbell preparation	Mortar-Dumbbell specimen	Geometry of mortar-dumbbell specimen

Figure 2: Mortar Dumbbell Specimen and the Geometry

First, the virgin and extracted (RAP) bitumen were heated to 180 °C in a container and mixed. The necessary amount of filler and fine sand were also prepared and pre-heated to a temperature of 180 °C. The mixing was carried out by slowly adding the filler and fines of sand while being stirred with a conventional stirrer in a container. After reaching the temperature of 210 °C, for an additional 15 minutes the mix was stirred to ensure homogeneity. After that, for 30 minutes the mix was placed in the vacuum degassing oven to remove air bubbles. The mortar was stirred again while heating the mortar to a temperature of 230 °C to get the mortar more viscous. Finally, the mortar was carefully poured into the pre-heated (180 °C) silicone mould to an overtopping of 5 mm. Immediately after the filling, the mould was put in a freezer for five minutes to avoid the sink of aggregates and placed for one hour in room temperature. The overtopped mortar was removed and the mould was put in a refrigerator for 12 hours.

Homogeneity of the distribution of filler, fines sand and bitumen in the mortar-dumbbell specimen was verified by means of micrograph evaluation in the top and bottom layer of the specimen. While the pouring, a needle was used to stick the mortar into the mould. By this way, the homogeneity could be improved significantly and the air voids in the mortar-dumbbell could be reduced. However, in some cases, air voids were still there and the specimen with relatively large air voids was not considered. In common, specimen with air voids could be identified very easy by means of outlier test. In addition, the cracks in the specimen with large air voids occurred always at the position of air voids. Furthermore, it is well known, that asphalt is an inhomogeneous material. The inhomogeneity always shows differences in mechanical properties. In this study, the mortar-dumbbell with discontinuity showed also differences in stiffness resulting in lower load cycles compared to samples with less or no air voids.

With increasing temperature and stirring time, the thermal loading of bitumen increases normally. To evaluate the quantity of thermal loading, the bitumen properties SP Ring and Balls and penetration were determined for the virgin bitumen mix (30/45+RAP Bitumen) and extracted bitumen of asphalt mortar. The determined test results show an increase of SP R&B (≤ 6 °C) and decrease of PEN values (≤ 4 (1/10 mm)). These values are lower, compared to the change of bitumen properties after RTFOT ageing, Table 2. As consequence, a high ageing of bitumen during the mortar production at a temperature of 230 °C can be eliminated.

Table 2: Comparison of Bitumen Ageing while the Mortar Production and RTFOT

	SP R&B [°C]	Penetration [1/10 mm]
Mix of the bitumen (30/45+RAP Bitumen)	60.0 – 63.0	20 -23
Extracted bitumen from asphalt mortar	65.0 -66.0	19 - 20
RTFOT- Mix of the bitumen (30/45+RAP Bitumen)	66.7 – 69.0	13 - 17

3.3. Curing and Stabilization

According to the European Standard (EN 12697-24) the asphalt specimen needs curing time before performing the test. The stiffness and fatigue resistance of asphalt specimen shall stabilize during the curing time and increase. To confirm this assumption fatigue tests were carried out for samples with different curing and stabilization period. Therefore, the specimen were stored for 1 day, 2 days, 4 days and 14 days before testing.

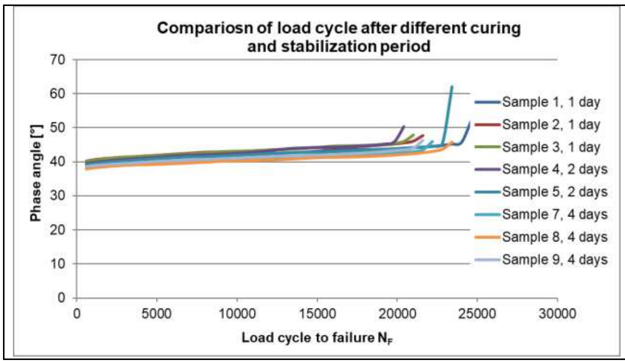


Figure 3: Comparison of load cycle after different curing and stabilization period (1-4 days)

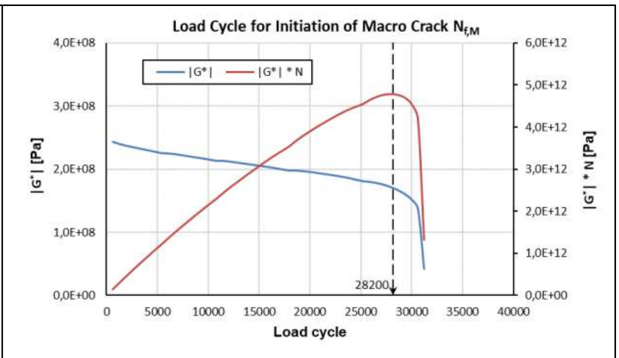


Figure 4: Determination of point of macro cracks initiation (Transition point)

Figure 3 shows the test results of samples stored for 1-4 days. Influence of the curing days between 1 day and 4 days could not be determined. The test results determined on samples after curing period of 14 days show in mean an increase of 11 % of load cycle to failure. As consequence, in this study the fatigue test for all variants have been determined on samples with curing and stabilization period between 1 and 4 days. The stabilization time of the temperature after placing in DSR before test start was 30 minutes.

4. ANALYSING OF TEST RESULTS

Several analytical methods are available to describe the fatigue behaviour. The classical criterion of fatigue failure is the number of load cycle (N_f) until the crack of the sample or the stiffness modulus decrease to 50% of the initial value. The stiffness modulus after 100 load cycles is characterised as initial stiffness modulus. These models are very simple, do not need any complicated analyses and are widely accepted [1]. However, in common the fatigue crack is reached when the density of micro cracks reaches the critical value and changes to macro cracks. This transition point can be calculated by means of multiplication of shear modulus with the number of corresponding load cycles, Figure 4. It is well known that the specimen can still bear a number of load cycles after reaching the point of macro cracks. This point of fatigue failure can be calculated by means of behaviour of deflection angle subject to the load cycle. Furthermore, the point of fatigue failure can be also calculated by forward and backward extrapolation of the measured displacement [4]. In common, the slope of the phase angle proceeds very flat and increases exponential before fatigue failure arise, Figure 5.

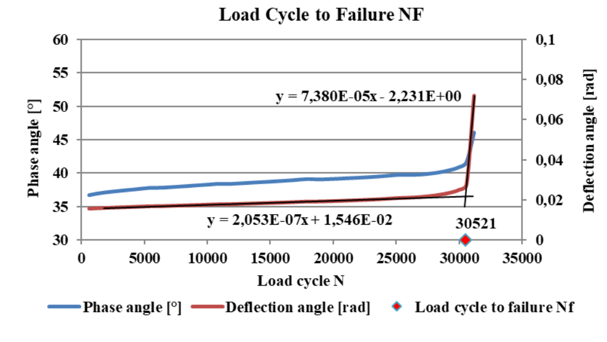


Figure 5: Determination of load cycle to cracks

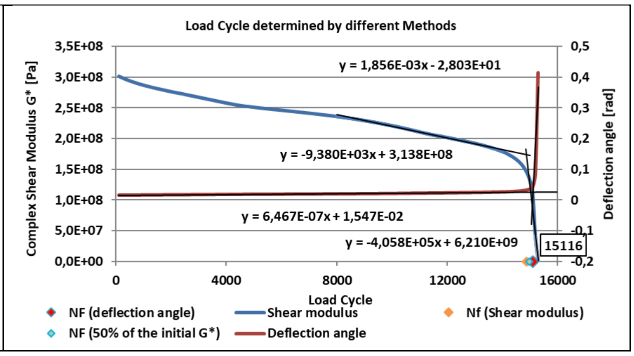


Figure 6: Comparison of load cycle determined by different methods

4.1. Determination of Fatigue Line

The above-mentioned methods for determination of fatigue behaviour used mostly for the characterisation of asphalt fatigue and not for the mortar. To find out the proper method, the load cycles to failure were determined by means of the above-mentioned three methods and compared. The method based on the deflection angle shows better mathematical correlation and selected for the further determination.

Fatigue line, also known as Woehler line was used to describe the fatigue properties. Therefore, several specimens loaded with three levels torque between 70 Nmm and 150 Nmm until failure. Minimum three specimen tested for each level of torque. The levels of the torque were chosen so that the gained average of load cycles of a series were close to 10^3 and 10^6. The determined load cycles to failure (N_f) were plotted versus the corresponding shear strain on a log-log scale. Shear strain is a mechanical parameter. Asphalt is a heterogeneous material. Due to that, the mechanical parameter such as shear strain is a proper parameter to describe the physical condition of the tested specimen. Based on measured deflection angle and calibration factors determined by means of F+E Models the corresponding shear strain was calculated. The calibration factor is depending on the stress concentration in the mortar-dumbbell. In some cases, the cracks occurred in the narrowing area of the steel ends. In this case the determined load cycle has multiplied with a material constant $k_1 = 1.1$ [4]

Figure 7 shows the determined fatigue test results of four asphalt mortar variants. For each variant, using the single fatigue results, fatigue lines were generated. By means of regression analysis, an equation for each fatigue line was determined. The coefficient of fatigue line equation can be considered as material parameter to describe the fatigue behaviour [Eq. 1].

$$N_{f,B} = k_3 \times \gamma_{f,0}^{k_4} \qquad \text{[Eq.1]}$$

$N_{f,B}$ [1] Load cycle to failure
γ [1] Shear strain
k_3 [1] Material parameter
k_4 [1] Material parameter

The calculated coefficients of determination (R^2) by means of regression analysis show values between 95.1 % and 99.1 %. Value for R^2 of one indicates that the equation of regressions analysis fits perfectly in the data considered. It means, the closer the value to one, the better relationship is available. In common, a reliable model shows value of R^2 higher than 90 %. Due to that, the gained fatigue tests results of all variants indicate on very high correlation between the load cycle to failure and material parameter, shear strain. Thus, the fatigue test used is a very reliable method to characterise the mortar properties subject to the resistance against fatigue cracks.

Asphalt Mortar variants produced with bitumen delivered by different refineries show significant differences in the fatigue behaviour. The variant B1 shows the lowest and the variant S3 the highest load cycle to failure. The variants N2 and T1 range between the tests results of the variants B1 and S3. Due to that, the asphalt pavement with the bitumen from the Refinery S3 will have significantly long lifetime compared to the asphalt pavement with bitumen from refinery B1.

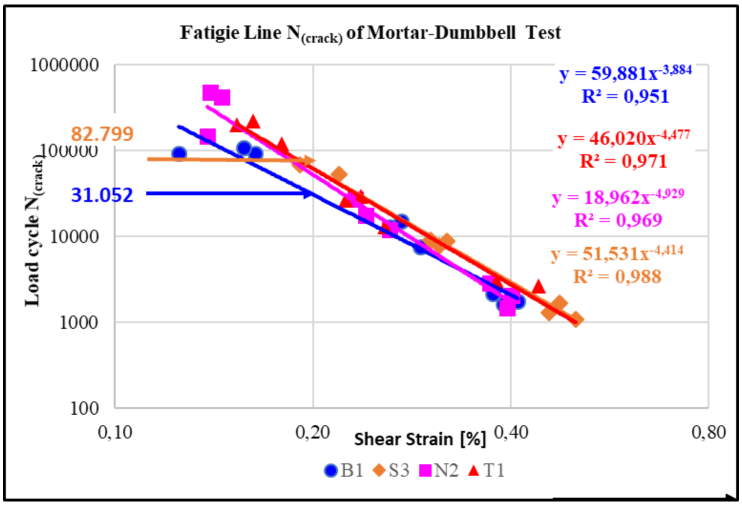


Figure 7: Fatigue line $N_{(crack)}$ of mortar test

4.2. Comparison of the test results of mortar-dumbbell and asphalt specimen

The fatigue behaviours of asphalt mixes (AC 22 T S) were determined by means of dynamic indirect tensile test (ITT) according to European Standard EN 12697-24 (Annex E) /26 (Annex F). For these test methods, many experiences are available. Figure 8 shows the determined test results of four different asphalt mixes. The variant S3 shows high load cycle to failure and the variant B1 shows the lowest load cycle.

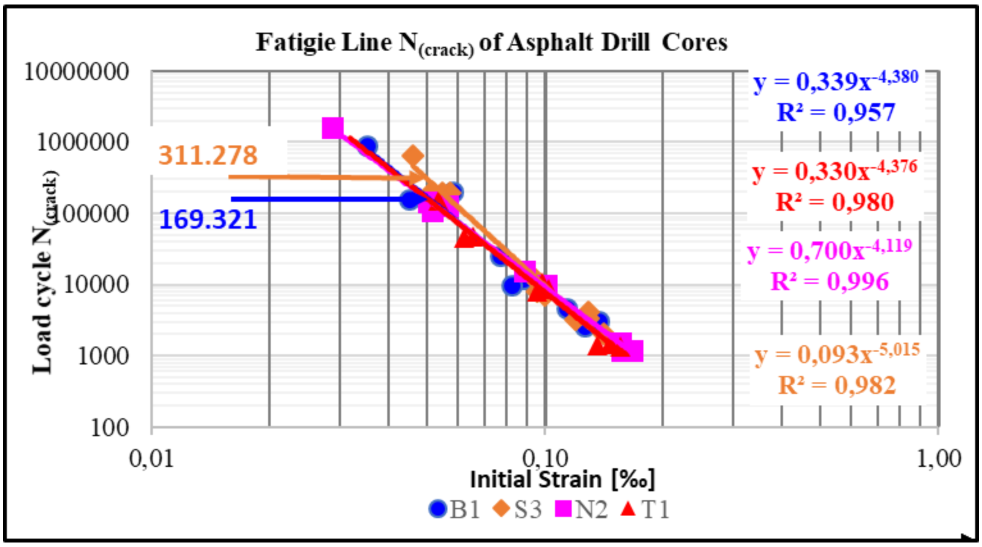


Figure 8: Fatigue behaviour of asphalt drill cores, ITT

To determine the relationship between the test results of asphalt drill cores and mortar-dumbbell, load cycle to failure of drill cores and mortar-dumbbell compared. Load cycles to failure of drill cores were calculated at the different initial strains and the load cycles to failure of mortar-dumbbell at different shear strains.

Figure 9 shows the comparison of the determined test results. The numbers of load cycles calculated for the asphalt drill cores are plotted versus the load cycle determined on mortar-dumbbell in a log-log scale. For each variant, a trend line was generated. Following, for each variant an equation by means of regression analysis was determined. Apparently, a mathematical correlation between the tests results can be determined. The coefficient of determinations indicates on very high correlation between the test results of asphalt drill cores and mortar-dumbbell investigations, although in total two different test methods used. The calculated coefficients of determination (R^2) confirm the relationship.

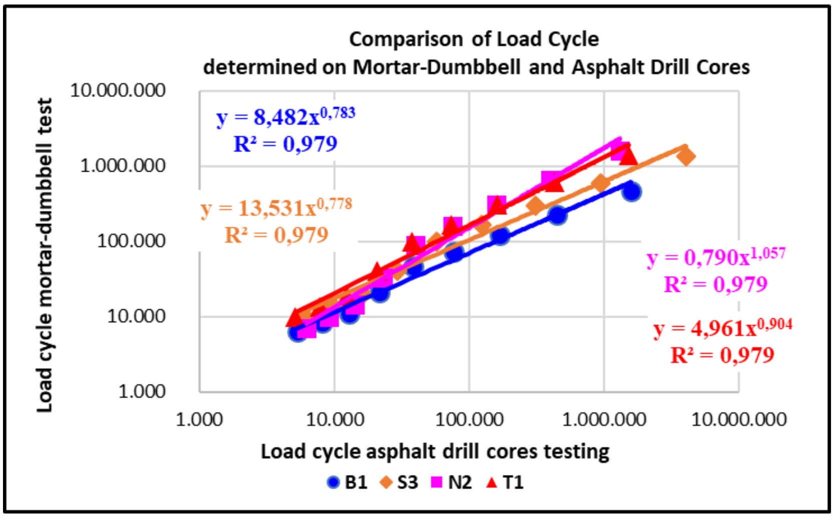


Figure 9: Comparison of load cycle of asphalt drill cores and mortar-dumbbell

5. SUMMARY

In this study, fatigue behaviours of asphalt mortars by means of DSR were determined. Worldwide, apart from Netherlands, nearly no experiences are available for fatigue test on such a "mortar-dumbbell" specimen in DSR shear testing. During the fatigue test the specimen mortar-dumbbell was loaded by a sinusoidal torque until the specimen cracks. The specimens were tested at three different torques to gain load cycles between 10^3 and 10^6 and to generate fatigue line with respect to different shear strain.

The determined test results for four different asphalt mortar types show significant differences in fatigue behaviour and mechanical parameter such as shear strain. Furthermore, the determined fatigue test results were compared with the fatigue test results of asphalt drill cores. The specimen's mortar-dumbbell have been produced with similar bitumen and aggregates like the asphalt mix used to prepare the drill cores.

The determined fatigue test results of the investigated variants show very high coefficient of determination. The comparison indicates on good relationship between the fatigue behaviour of mortar and asphalt specimen. Due to that, the determined test results are not at random. At the TPA GmbH rather worldwide, mortar fatigue testing on mortar-dumbbell is still in an early stage and provides promising approach. Further investigation and optimization, as well as validation and repeatability for different asphalt mix types are necessary to consider as input values in the pavement design process.

REFERENCES

[1] Sivapatham P., Influence of the Compaction Degree of Asphalt Mix on Performance Behavior of Asphalt Pavement (original in German language), University Of Wuppertal, Transportation Engineering, Issue 11, 2012

[2] Pippich J., The influence of filler in asphalt, (original in German language), *Journal: Bitumen 4/81*, Hamburg, Germany 1981

[3] Qiu H, Tan X, Shi S, und Zhang H, Influence of Filler-Bitumen Ratio on Performance of Modified Asphalt Mortar by Additive, Wuhan: Springer, 2013.

[4] Liantong Mo, Damage Development in the Adhesive Zone and Mortar of Porous Asphalt Concrete, Road & Railway Engineering Section, TU Delft, 2009

[5] K.H. Moon, A.C. Falchetto, et.al., Mechanical Performance of Asphalt Mortar Containing Hydrated Lime and EAFSS at Low and High Temperatures, Material, Basel, Swiss 2017

[6] Hospodka,B. Hofko und R. Blab, Developement of test method for determination of durability of asphalt mortar, (original in German language) , Wienna, Austria 2015

[7] W.G. Buttlar, Bozkurt, D, Al-Khateeb, G.g. Waldhoff, A.S., Understanding Asphalt Mastic Behavior through Micromechanics, Transportation Research Record 1681, Paper No. 99-1229, pp. 157-169, 1999

[8] M. Huurmann, Report 7-07-170-1, Lifetime Optimisation Tool, LOT, Main Report, TU Delft 2008.