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The Influence of Ageing on the Fatigue and Healing Properties of Bituminous Mortars

Van den bergh, W.[a,]*, Van de Ven, M.F.C.[b]

[a] *Artesis Hogeschool Antwerpen, Paardenmarkt 92, Antwerpen 2000, Belgium*
[b] *Delft University of Technology, Stevinweg 1, Delft 2628, the Netherlands*

Abstract

For asphalt pavement design in Belgium, healing is taken into account as a standard shift factor, representing the effect of rest periods between loadings of traffic. Because nowadays Reclaimed Asphalt Aggregate (RA) is widely used in hot mixtures, a new validation of the healing factor is needed. Given the lack of test results and a standard healing test for mixtures, a new test method for the evaluation of healing on mortar samples was evaluated using Dynamic Shear Rheology. This paper reports the test settings and results; specific attention is given to DSR stress and strain modes in software and output

Keywords: Bitumen, Bituminous Mortar, Fatigue, Healing, Reclaimed Asphalt

1. Introduction and Importance

Fatigue of the asphalt mixture, determined with cyclic fatigue tests in the laboratory, is an important design parameter in the structural design of asphalt pavements. Examples of fatigue tests are two- or four-point bending tests. The in situ fatigue life of an asphalt mixture is estimated using the result of this laboratory test. However, under real traffic conditions, the pavement is not loaded continuously: between one or more loadings, rest periods appear. During these rest periods, a healing mechanism will recover (micro) damage in the asphalt mixture. Healing during rest periods and lateral wandering of the traffic will result in a longer structural design life for the mixture in situ, compared to the fatigue life determined with a continuous sinusoidal test in the laboratory. The effect of the healing property on the total fatigue life of asphalt mixtures in road design, is expressed by a healing factor. This healing factors is mostly determined in the laboratory as the ratio of the test results of fatigue tests with and without rest periods. So, healing is very important: a higher healing factor will result in a thinner asphalt

* Corresponding author. Tel.: ++32 3 213 79 21; fax: ++32 3 231 86 70.
E-mail address: wim.vandenbergh@artesis.be

layer thickness for the same structural service life or a longer service life at the same asphalt thickness. In Belgium a healing factor of 7.1 is used for standard asphalt mixtures [1]. The value of this factor was determined on asphalt mixtures in the years 70-80 of the last century without the use of RA. In the Netherlands, the value of the healing factor for asphalt mixtures containing RA was discussed since Huurman and Hopman [2] showed that the shift factor of 4 decreased to 1.4 when 60% RA was added to the mixture. This could place the use of RA in a difficult position because of the economic consequences of –in that case- the necessity of laying thicker asphalt layers compared to new asphalt mixtures.

Research [3] has shown that healing can be measured on several ways, but a specified EN-standard test is not available. Moreover, fatigue tests on asphalt mixtures with and without rest periods take long and are expensive. For the asphalt manufacturer in Europe who wants to determine the healing factor of his mixtures linked to road design, the procedure is too cumbersome. There is a need for a simple procedure to determine an adequate but fast way the healing potential of a binder, mastic or mortar. This paper gives a summary of the fatigue and healing results on mortar which were part of a PhD research at the Artesis University College of Antwerp and Delft University of Technology [4]. The objectives of this research was to investigate the influence of the binder of RA on the healing and fatigue behaviour of bituminous asphalt mixtures.

2. Test Methodology and Approach

In asphalt mixtures, the bitumen covers the aggregates such as stone, sand and filler and binds them together. The binder will form a thin film with various thicknesses around the aggregates. Little and Jones [5] reported that the different types of failure (cohesive or adhesive failure) in asphalt mixtures were strongly related to the binder (bitumen) film thickness and the nature of the mastic: mixtures with thin films will show adhesive failure while mixtures with a thicker bitumen film (or mastic film) will show cohesive failure. Healing and fatigue can be considered in the asphalt mixture or in its components: the binder or a mixture of fractions of the aggregates and the binder (mastic or mortar). In this study, the fatigue and healing was evaluated within the mortar. An asphalt mixture can be considered as a mixture of aggregates with dimensions larger than 0.5 mm, coated with a thin binder film about 5 μm and bound by bituminous mortar. The mortar is defined as the mixture of filler and aggregates with dimensions smaller than 0.5 mm, and the binder. The binder quantity in the mortar is the volume of the binder in the asphalt mixture decreased with the volume of the binder that coats the aggregates larger than 0.5 mm with 5 μm thickness.

Mortar samples, cylindrical test specimens as developed and evaluated by Huurman [6], were manufactured with different ageing state (virgin and long-term aged by Rotating Cylinder Ageing Tests RCAT) and composition (normal and increased high volume of binder). Despite possible differences in ageing process between practice and laboratory ageing, it was decided in this project to age the mortar by RCAT during 168 hours, instead of standard time 144 hours [7] as mentioned in the EN15323. This extended ageing period for RCAT was chosen in order to obtain a reasonable ageing level of the binder in the mortar. For the virgin and laboratory aged mortar, a typical binder for dense asphalt was used (penetration: 44 dmm; R&B: 51.2 °C).

Fatigue and healing controlled-stress tests were performed with the AR2000ex Dynamic Shear Rheometer in oscillation (shear) mode at 15 °C and 10 Hz. The applied torque and the resulting rotation were measured as well as the phase angle. No standard tests were available for healing tests on cylindrical mortar specimens. A special procedure was defined as follows. A time slot of 12 seconds were defined with two steps: 30 cycles of loading (10 Hz) and a rest period of 9 seconds (90 cycles). This time slot is repeated until the failure definition.
Before starting the experiments with mortar, preliminary tests were done with the rheometer. These preliminary tests were necessary to ensure that the test device is measuring the correct deformation given a certain load. Furthermore problems with the correct counting of the number of load repetitions were solved.

3. Sample Preparation

3.1. Composition and Ageing of the Mortar

For the mortar mixture design, the mixture design of a typical asphalt mixture for base layers in Flanders was taken as reference. The mortar is composed by a part of the total amount of binder and the aggregates smaller than 0.5 mm. In order to define the binder content of the mortar, the following assumptions were proposed:

- all aggregates and filler particles are coated with a thin binder film of 5 μm. A part of this binder is absorbed. In this work, the dry mortar mix is composed by aggregates smaller than 0.5 mm and the filler. In this case, the binder volume which coats the aggregates, with dimension larger than 0.5 mm, must be subtracted from the total binder content;

- the binder volume which is not part of the volume for wetting and absorptions is taken into account as 'free binder'. This volume is the total amount of binder decreased with the binder volume that coats the aggregates;
- mortar glues the coated aggregates larger than 0.5 mm together.

The mortar composition is defined as the bituminous mixture of the dry aggregate passing the sieve of 0.5 mm (a), the filler (f) and the reduced bitumen content (b_R). The reduced bitumen content is defined as the total bitumen volume in the mixture minus the bitumen that coats the aggregates larger and equal than 0.5 mm. The binder volume used as coating is calculated as 5 µm thickness on all surfaces of filler and aggregates. The specific surfaces are estimated by using the method developed by Hveem-Edwards ([8], [9]). In this method the factors are based on the dimension of the aggregate which is equivalent to the opening of the sieve (sieve size). The aggregates are represented as spheres.

Two types of mortar compositions were selected: a) the composition as mentioned above – this is defined as the mortar present in the asphalt mixture and b) the composition with double of mass content of binder. The aggregates of the coarse and fine aggregate fractions are dried and sieved separately. Only the fractions passing the sieve of 0.5 mm are used for mortar production. A dry mortar mixture is manufactured by blending the dried and sieved fractions of the aggregates (180 °C) and the filler (100 °C), in a ratio which is representative for the asphalt mixture. In a preheated bowl, first the dry mixture is mixed after which the hot binder (165 °C) is added. The mortar is mixed manually during 1 to 3 minutes to ensure a homogeneous mixture at maximum 180 °C. No additional short term ageing was used after the production of the virgin mortar.

For the short and long term ageing of the mortar with double amount of binder, the RCAT device (EN 15323) was selected since also the manufacturing and ageing of mastic is described in this standard. Approximately 500 ml of mortar was aged in the RCAT-device, first by short term ageing regime (4 hours at 163 °C using air flow) succeeded by long term ageing regime (168 hours at 90 °C using oxygen flow). For the long term ageing condition by RCAT the ageing time was extended to 168 hours in order to obtain an aged binder, with similar penetration as a mean standard RA-binder. A statistical survey done by Van den bergh [4] indicated that the binders of RA-samples, used in Flemish asphalt mixtures in 2009, have a penetration of 20.3 dmm (with s = 5.9 dmm; n=108). After long term ageing, the cylinder was closed with a stopper and heated to 170 °C within 1 hour in order to collect the mortar in a bucket for storage. One mortar type was composed by using a genuine RA-binder (penetration 18 dmm) together with new aggregates, similar as for the other mortars. Since it is not known what the effect of extraction and recovery process on the aggregates is, in relation to the adhesion, it was decided to use virgin aggregates and filler in the same composition and by the same mixture process as mentioned above. In this way, the effect of the aged binder can be evaluated since the composition of this mortar and its virgin aggregates and filler are equal. These five mortar compositions are given in Table 1.

Table 1 Summary of the mortar batches for fatigue and healing tests

Mortar I.D.	Mortar composition (m/m%)				State
	Filler f	Aggregate < 0.5 mm a	Binder b_R	(f+a)/ b_R m/m	Unaged , Aged or RA
MO02/03	16.4	51.6	32	2.13	Unaged
MO04	16.4	51.6	32	2.13	Aged
MO05	20.1	64.4	15.5	5.45	Unaged
MO06	20.1	64.4	15.5	5.45	Aged
MO07	20.1	64.4	15.5	5.45	Unaged using RA-binder

3.2. Sample Preparation

Instead of the plate-plate geometries, a specific set-up with clamps for cylindrical mortar specimens was used (see Figure 1) as described and developed in the former LOT-project ([6], [10]).

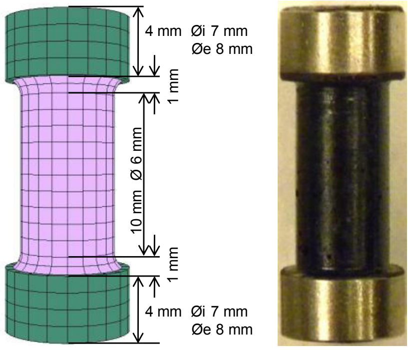


Figure 1 Example of FE-model (left: Huurman, [6]) and the test specimen (right)

The mortar samples are manufactured using a Teflon mould. A detail of the mould is shown in Figure 2.

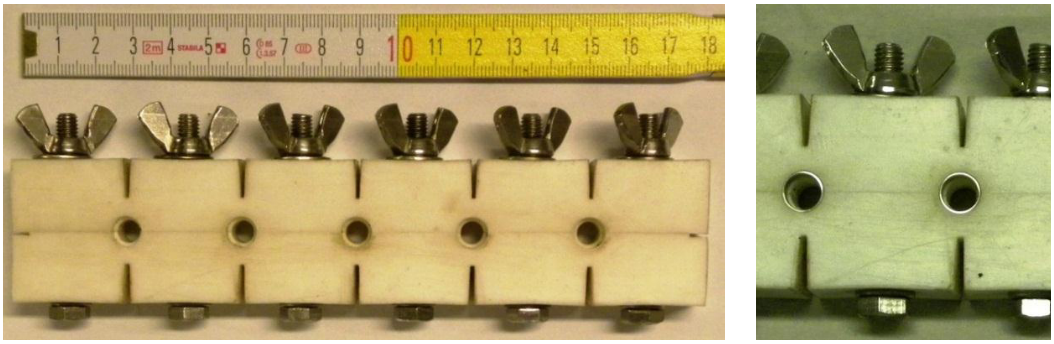


Figure 2 Teflon mould (left) and detail with metal ring (right)

Before filling the mould with mortar, the mortar is heated to 180 °C in sealed cans and homogenised by shortly mixing the mortar. The mortar is casted in the heated mould with a small spoon and is slightly over-filled. For the aged mortars, the mortar is gently pushed in the cavity with a thin bar. During the filling process, the mortar is continuously heated on a hot plate and mixed to ensure homogenisation. After the last specimen is casted, the mould is placed in the oven at 180 °C during 5 to 10 minutes to allow possible air voids to escape. Then the mould is visually checked: more mortar is added until the upper ring is filled. Afterwards the mould is cooled down first to ambient temperature and then in a refrigerator to -10 °C for storage in order to avoid distortion of the sample, for example creep, during at least 2 hours. Before testing, the samples are set in the specific clamp device. The upper clamp is fitted on the DSR-loading shaft. The bottom clamp is fixed on the (non-moveable) base plate of the DSR. This special setup is illustrated in Figure 3, with opened doors of the Environmental Test Chamber (ETC).

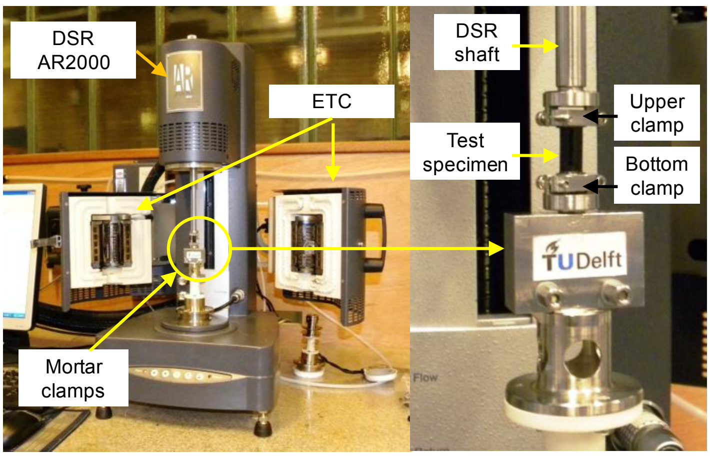


Figure 3 General view of the DSR device (left) and the specimen position between the clamps (right)

4. Preliminary tests concerning Dynamic Testing by means of Dynamic Shear Rheometer

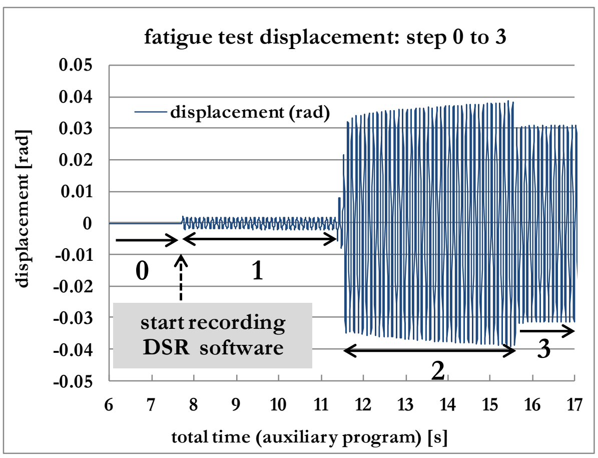
DSR-tests on bitumen are typically performed using a strain level as input. But in most of the cases the rheometer is stress-controlled: when a specific strain is required, the motor of the apparatus will perform a force, stepwise, until this strain is achieved. It is very important that the controlling of the amplitude of the force and the deflection is accurate; the result of a fatigue and healing test is directly related to this accuracy and expressed as a function of these parameters (fatigue life – strain level). When a higher torque deflection level is applied, than required, measured or not by software, this can affect the result, especially when the measurements are performed outside the linear visco-elastic region. The result of the fatigue and healing test is in that case unreliable. In the experimental program for fatigue and healing tests, an AR2000ex Rheometer of TA Instruments is used. This rheometer is stress-controlled. All fatigue and healing tests were conducted in sinusoidal oscillation mode at 10 Hz and 15 °C. In order to record the real deflections and applied force, an auxiliary program was run simultaneously with the DSR test. These raw data are not adjusted by correction factors, but give an idea of the signal of the applied torque and the corresponding deformation. For fatigue tests with the DSR, two loading methods can be used: torque-controlled and displacement-controlled mode. Often fatigue tests are conducted in strain-controlled mode. In these preliminary tests, the accuracy of the DSR during fatigue tests in both modes was evaluated.

4.1. Software settings in function of the exact number of loading cycles

Fatigue and healing are commonly expressed as a function of number of cycles and duration of rest periods. An exact calculation of the number of cycles and an accurate control of the specific loading settings are essential in order to evaluate fatigue and healing performance. For an oscillation test, the software of the AR2000 gives two options: a standard oscillation and a continuous oscillation. When the standard oscillation is chosen, as in the LOT-project, each loading period during which the data is captured is followed by a period of 0.5 s without oscillation: this means a short and unwanted rest period during fatigue. When the option ‘continuous oscillation’ is chosen, this short period is not present, thus a continuous fatigue test is performed. An auxiliary data recording program was provided to record the raw signals of the DSR: normal force, torque and displacement. Preliminary tests were done on a plastic ABS-tube at ambient temperature in order to evaluate the number of cycles, the time needed to obtain the defined values of torque and displacement. During a fatigue test it was observed that the input setting for loading cycles differs from the real performed settings: for instance an input of 3 s loading at 10 Hz results in 35 cycles instead of 30 cycles. It was observed that the frequency was correct (10 cycles per second), but that the total loading period was extended: instead of 3 seconds the total loading period was 3.5 seconds. Also, when 30 cycles were set, 35 cycles were performed actually. For standard fatigue and healing tests it is necessary to count the real applied cycles. In order to perform 30 cycles fatigue (3 s, 10 Hz) the software input was adapted so the exact number of loading cycles was achieved for each test.

4.2. Displacement controlled mode

A displacement controlled fatigue-healing test was done on a mortar sample at 15 °C and 10 Hz with controlled displacement of 0.03 rad (strain in the sample 0.72 %). The auxiliary program recorded simultaneously the raw data. Since the auxiliary program is started separately to the AR2000 software, the time-scales are different. In general, a displacement controlled fatigue test with the AR2000 consists of 4 important steps. These steps are illustrated in Figure 4 for the displacement signal (left) and for the torque signal (right).



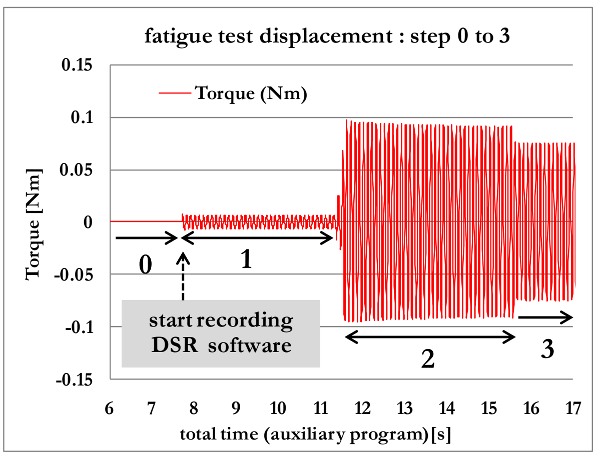


Figure 4 Displacement and Torque signal for displacement controlled test

- step 0: this step is not part of the defined fatigue procedure but is the time between the start of the auxiliary program and the start of the AR2000 procedure just before testing. Within this period also the controlling of the DSR from software to hardware is considered;
- step 1 (7.7 to 11.4 s): the DSR performs a very small constant displacement loading and torque during 3.7 s;
- step 2 (11.4 to 15.4 s): the DSR performs a high and increasing displacement loading during 4 s, which is at the start even higher than required in the software (see further). The torque decreases;
- step 3 (15.4 s to end fatigue period): the DSR performs the required displacement (input 0.03 rad) during the defined fatigue period decreased with the periods of step 1 and step 2. The torque decreases in order to keep the displacement constant at 0.03 rad.

The small displacements during step 1 do not have consequences for the fatigue damage process. However, since this period is calculated as part of the total fatigue process, these cycles should be rejected afterwards as fatigue cycles. For healing tests (discontinuous loading tests) these cycles must be subtracted from the number of fatigue cycles. In Figure 5, these output data of the DSR are shown together with the step indication as mentioned earlier. The deformations of the second step are too high and are variable. This will lead to inaccurate results and an uncontrolled first fatigue period which is not considered in the further calculation, such as determining the fatigue behaviour in relation to the strain levels. Moreover, during a discontinuous fatigue test ("healing" test) this error is introduced in every fatigue cycle. It is recommended to investigate the influence of these insufficiencies on the interpretation of the fatigue behaviour extensively when strain-controlled fatigue tests are used.

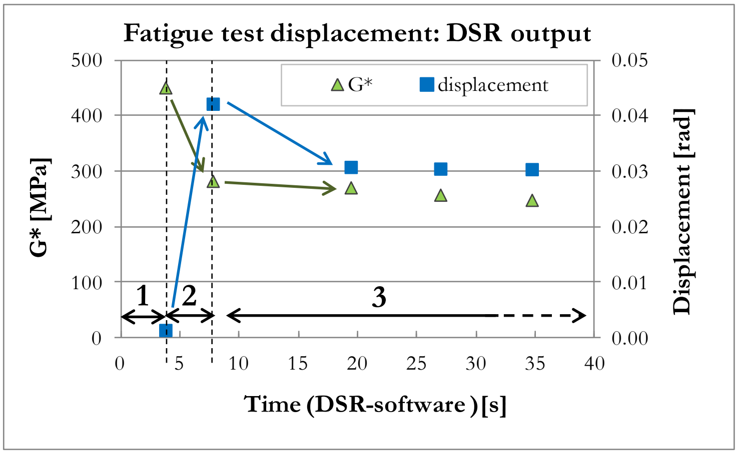


Figure 5 DSR software output data

4.3. Stress (torque) controlled fatigue tests

In a stress controlled test it was observed that after the first loading cycle the torque was performed very accurately, as shown in Figure 6. During the first cycle, the loading torque increases without exceeding the required torque. From the second loading cycle, the torque remains constant during the whole fatigue test. This observation was confirmed in several tests so it can be concluded that a stress (torque) controlled fatigue and healing test is preferable to a strain (deformation) controlled test procedure for this DSR.

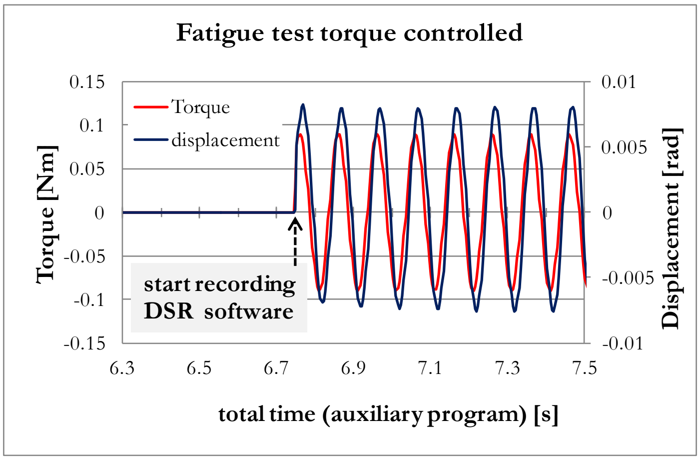


Figure 6 Raw signals during stress-controlled test

5. Test settings for Dynamic Testing by means of Dynamic Shear Rheometer Fatigue and Healing Tests

Based on the observations mentioned above, it was concluded that the AR2000 only performs accurate fatigue and healing tests in the torque controlled oscillation mode. The mortar fatigue and healing tests were performed for different torque levels at 15 °C and 10 Hz, beyond the lineair visco-elastic region; this is shown in Table 2.

Table 2: Torque settings for fatigue (continuous) and healing (discontinuous) test (with n=number of test results)

Mortar ID	Mortar type	Fatigue test Torque [mNm]	n	Healing test Torque [mNm]	n
MO02/03	Unaged	25, 30, 40, 50	18	25, 30, 40, 50	09
MO04	Aged	40, 45, 50, 60, 75	17	40, 45, 50, 60, 75	09
MO05	Unaged	30, 40, 50, 65, 75	10	50, 65, 75	05
MO06	Aged	80, 90, 105	06	90, 105	05
MO07	RA-mortar	90, 105, 115	05	90, 105, 115	08

The effect of rest periods on the fatigue life is calculated as a healing factor by the Equation 1:

$$H = \frac{N_{discontinuousloading}}{N_{continuousloading}} \qquad (1)$$

For fatigue tests, an oscillating torque is applied on the upper clamp inducing a sinusoidal angular rotation and a shear strain in the mortar sample. During testing, both the angular rotation (also called displacement) and the applied torque are measured. The DSR application software calculates their average peak values and their phase lag. Data was collected every 10 seconds. The average peak values for torque, angular rotation and phase lag are calculated over a period of 3 preceding seconds. The fatigue life is defined as the maximum in the curve of the stiffness multiplied with the number of cycles versus the number of cycles, as given in Figure 7 .

Since it is not feasible for the AR2000 to perform tests with a single cycle followed by a rest period and since a minimum required time is needed to transfer the recorded data, the loading period was set to 30 cycles followed by a rest period of 90 cycles for healing tests. Every 12 seconds the data was recorded after the loading period. The number of loading cycles to failure of the sample was defined and determined as described above. For all mortar types, fatigue and healing curves were determined. In Figure 8, the fatigue results are given for mortars MO02/03 (virgin) and MO04 (aged by RCAT for 168 hours) in relation to the applied sample shear stress (stress at the outer edge of the sample).

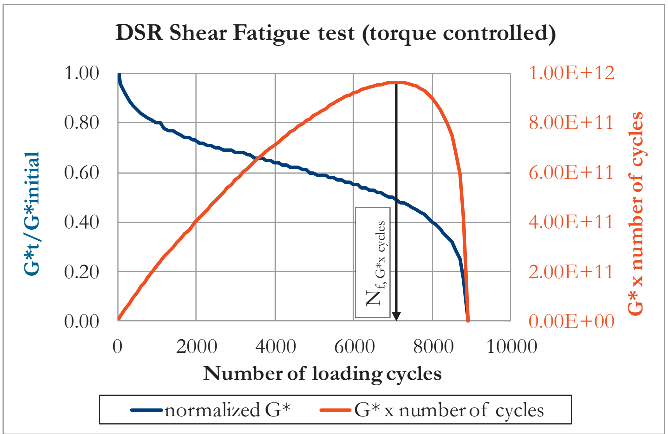


Figure 7 Fatigue life definition of fatigue and healing tests

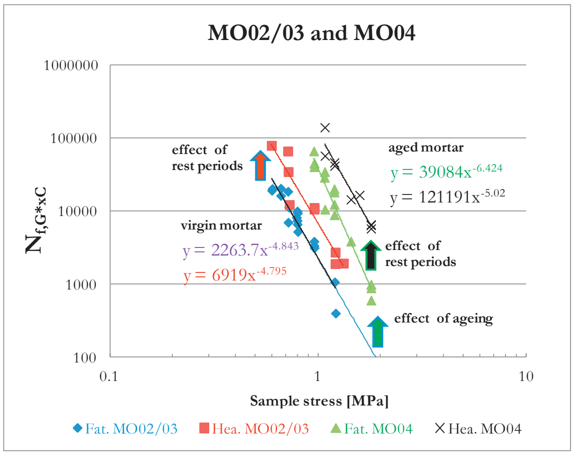


Figure 8 Fatigue and healing results for virgin MO02/03 and aged MO04 mortars

6. Results of Fatigue and Healing Tests

The results show a good fit on a log-log scale between the shear stress and the fatigue life N_{f,G^*xC}. The coefficients of determination of the fatigue relationships for the continuous ("fatigue") and discontinuous ("healing") tests are summarized in Table 3. The results illustrate that at an equal stress level the fatigue life increases when rest periods are introduced (discontinuous oscillation). Also at equal stress levels, ageing of the mortars increases the fatigue life.

Table 3 Fatigue and healing curves for mortar (stress-controlled)

Mortar type	Fatigue curve		Healing curve	
	$Nf_{,G^*xC}$	R^2	$Nf_{,\ G^*xC}$	R^2
MO-02 /03	$N_f=2263.7\ \tau^{-4.843}$	0.90	$N_f= 6919\ \tau^{--4.795}$	0.90
MO-04	$N_f=39084\ \tau^{-6.424}$	0.96	$N_f= 121191\ \tau^{-5.02}$	0.94
MO-05	$N_f=15031\ \tau^{-5.07}$	0.95	$N_f=57906\ \tau^{-5.649}$	0.998
MO-06	$N_f=627132\ \tau^{-6.678}$	0.93	$N_f=3218257\ \tau^{-7.06}$	0.87
MO-07	$N_f= 482991\ \tau^{-6.366}$	0.93	$N_f= 468872\ \tau^{-5.43}$	0.92

In order to evaluate the effect of rest periods quantitatively the fatigue life with and without rest periods are compared. This comparison must be done under equal loading conditions, for example the same sample stress or number of loading cycles. The healing factors are calculated as the ratio of number of loading cycles in discontinuous mode to number of cycles in continuous mode until fatigue occur (equation 1). The sample stress is defined for $N_{f,G*xC}$=7000 cycles in continuous loading condition. This number of cycles is a common result of the fatigue and healing tests. Next, this sample stress is used to calculate the number of loading cycles for the tests with rest periods. In Table 4, the healing factors are given for equal fatigue life (upper table) and for equal sample stress (table below).

Table 4 Healing factors of mortar in function of equal Nf,G*xC (above) and constant sample stress (below)

Mortar	Type	Loading Condition	$N_{f,G*xC}$	Sample stress [MPa]	Factor H
MO02/03	Virgin	Continuous	7000	0.79	3.0
		Discontinuous	21157	0.79	
MO04	RCAT90	Continuous	7000	1.31	4.5
		Discontinuous	31608	1.31	
MO05	Virgin	Continuous	7000	1.16	3.5
		Discontinuous	24713	1.16	
MO06	RCAT90	Continuous	7000	1.96	4.0
		Discontinuous	27777	1.96	
MO07	RA-mortar	Continuous	7000	1.94	1.8
		Discontinuous	12706	1.94	
MO02/03	Virgin	Continuous	1000	1.18	3.1
		Discontinuous	3081	1.18	
MO04	RCAT90	Continuous	13500	1.18	3.9
		Discontinuous	52807	1.18	
MO05	Virgin	Continuous	500	1.96	2.6
		Discontinuous	1305	1.96	
MO06	RCAT90	Continuous	7000	1.96	4.0
		Discontinuous	27777	1.96	
MO07	RA-mortar	Continuous	6700	1.96	1.8
		Discontinuous	12241	1.96	

For the virgin and laboratory-aged mortars it is clear that ageing results in a higher healing factor. When the mortar is composed with a higher binder content, the effect of rest periods is larger. For the non-aged mortar MO05, which is a typical mortar as expected in a dense asphalt mixture for base layers, this factor is 3.5. Ageing of this mortar seems to increase this factor (from 3.5 to 4.0), although it is emphasized that this is a laboratory long term aged mortar. The effect of rest periods for the RA-mortar MO07 is small compared to the other mortars (healing factor 1.8). At equal sample stress, the healing factor increases when mortar is aged in the laboratory: the mortar, which contains the RA-binder shows the lowest healing factor.
The results indicate that mortar, which is aged in the laboratory, shows different healing properties than the field aged mortar although the fatigue relations are about the same.

7. Conclusions

In this work a new healing test procedure was introduced using the dynamic shear rheometer. The test device and the used specimens are based on the work done by Huurman [6] and Mo [10].
Preliminary tests with the DSR showed that, when using this DSR device, strain-controlled tests are not reliable for fatigue and healing tests and that the number of cycles deviates from software input. Therefore, a stress-

controlled test for fatigue and healing was designed for this study and the number of loadings was checked and altered by means of an auxiliary program. Torque-controlled continuous and discontinuous tests at 15 °C and 10 Hz at different torque levels were done on five types of mortar. Virgin and aged mortars were manufactured. One mortar contained an extracted binder from reclaimed asphalt aggregate. For each mortar the fatigue life is determined by using the number of cycles when the peak in the G*x number of cycles curve is reached (failure). Laboratory ageing of the respective mortars does affect the fatigue properties negatively: at an equal stress level, the number of loading cycles to failure for aged samples is higher than that of unaged samples.
Healing factors were calculated as the ratio of number of loading cycles to failure with rest periods to number of loading cycles to failure without rest periods. Healing factors between 1.8 and 4.5 were found when the same sample stress was considered between samples tested in continuous and discontinuous loading mode. For a typical mortar for base layers, the healing factor is 3.5; artificial ageing of this mortar promotes this effect up to 4.0. Considering equal sample stresses, the laboratory aged mortar MO-06 and the RA-mortar MO07 show similar fatigue properties. The healing factor of the RA-mortar is lower than for the artificial aged mortar. For a RA-mortar with the same composition, but manufactured with a real RA-binder, the healing factor is 1.8 (instead of 4.0 as for the laboratory-aged mortar). This could indicate that RA mortar, when it is used as a part of new mixtures, affects the healing properties negatively and that laboratory ageing overestimates the healing property of binders.

8. Acknowledgments

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9. References

[1] COST333 (1999). “Transport Research, Cost 333: Development of New Bituminous Pavement Design Method”, *Final Report*, ISBN 92-828-6796-X, Brussels.
[2] Huurman, M., Hopman P. (2003). “The influence of RAP on healing and fatigue in StAC ”, *report of NPC (in Dutch)*, Utrecht, The Netherlands.
[3] Qiu, J. (2008). *Self-healing of asphalt mixes: Literature Review*, Report 7-08-183-1, Delft University of Technology.
[4] Van den bergh, W. (2011). “The Effect of Ageing on the Fatigue and Healing Properties of Bituminous Mortars”, *PhD. Thesis*, Delft University of Technology, Delft, The Netherlands, ISBN 978-90-8570-784-4.
[5] Little, D., Jones, D. (2003). “Chemical and Mechanical Processes of Moisture Damage in Hot-Mix Asphalt Pavement”, *TRB report Moisture Sensitivity of Asphalt Pavements: A National Seminar*, San Diego, CA, Transportation Research Board.
[6] Huurman, M. (2007). “Lifetime Optimisation Tool –Main Report”, *Report 7-07-170-1*, Delft University of Technology, Laboratory of Road and Railway Engineering, Delft, The Netherlands.
[7] Verhasselt , A. (2002). “*Long term ageing – simulation by RCAT ageing tests”*, 9th ISAP congress 2002, Copenhagen, Denmark.
[8] Hveem, F.N. (1974). “*Mix design method for asphalt concrete MS-2”*, The Asphalt Institute, College Park, Md., USA.
[9] Roberts F.L., Kandhal, P.S., Brown, E.R., Lee, D. and Kennedy, T.W. (1996).” *Hot Mix Asphalt Materials, Mixture Design and Construction”,* Second Edition, National Asphalt Pavement Association, Lanham, MD.
[10] Mo, L. (2009). “Damage development in the adhesive zone and mortar of porous asphalt concrete”, *Phd thesis*, Delft University of Technology, Delft, The Netherlands.