A5EE-382

DAMAGE AND HEALING TEST PROTOCOLS FOR THE EVALUATION OF BITUMINOUS BINDERS

Ezio Santagata, Orazio Baglieri, Davide Dalmazzo, Lucia Tsantilis
Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture - Politecnico di Torino - Torino - Italy

ABSTRACT

Based on the analysis of the behaviour of a wide range of bituminous binders employed for paving applications, the Authors have developed in the past specific test protocols for the assessment of damage and healing properties. In the case of damage behaviour, reference is made to a parameter, called Relative Crack Propagation Amplitude (RCPA), which is based on dissipated energy data. Healing properties are evaluated by referring to the Relative Healing Index (RHI), which depends upon loading frequency and duration of rest periods.

In order to illustrate the significance of such parameters and related test protocols, in this paper the Authors provide results which show the effects of several factors on fatigue and healing response such as binder type, ageing, and polymer modification.

Keywords: bituminous binders, rheology, damage, healing

1. INTRODUCTION

One of the most common distresses occurring in asphalt pavements is fatigue cracking (1), which is taken into account both in pavement design and in the selection of base materials and mixtures (2,3). In particular, care must be taken in evaluating the fatigue resistance of bituminous binders, in which cracks actually form and propagate (4-6).
As postulated within the currently accepted approach, the development of fatigue cracks results from the combination of two competing phenomena: microcrack damage, due to repeated stress application, and healing, which may occur during rest periods (7,8). As a consequence, it is essential to thoroughly understand both mechanisms and to define appropriate laboratory tests which can be used for a true performance-related selection and characterization of the binders.
In such a context, the Authors have developed in the past specific test protocols for the assessment of damage and healing properties of bituminous binders. In the case of damage behaviour, reference is made to a parameter called Relative Crack Propagation Amplitude (RCPA), derived from time sweep test data processed by means of the dissipated energy ratio (DER) approach (9). Such a parameter provides a measure of the extension of the crack propagation phase expressed in relative terms and can be interpreted as a “fatigue ductility” indicator.
Another parameter, the Relative Healing Index (RHI), was introduced to evaluate healing potential of the materials (10). RHI is calculated from repeated time sweep tests with an intermediate rest period and depends upon loading frequency and rest time.
In order to illustrate the significance of the abovementioned procedures, in this paper a set of experimental results, which show the effects of several factors such as binder type, ageing, and polymer modification on the damage and healing properties of different materials, are reported and discussed.

2. MATERIALS AND TESTING

2.1 Bituminous binders

Materials employed in the experimental investigation presented in this paper included three different bituminous binders, two neat bitumens (PG64-16 and PG 58-22 respectively) and one polymer-modified binder (PG76-22). The neat binders, belonging to the same pen grade (70/100), were sampled from two different refineries located in the north-west of Italy, each of which operates on crudes of various origins.
The polymer-modified binder was originated from the PG58-22 base bitumen, by adding a high percentage of styrene-butadiene-styrene (SBS) according to the undisclosed processing scheme adopted by the plant which provided the material. As can be noted, modification with SBS upgraded the base binder only in the high temperature range (the maximum pavement design temperature raised from 58 to 76°C), whereas low temperature performance was not significantly affected.
The PG64-16 binder was tested in its original state (O), after RTFOT (R) and after PAV (P) treatments. This allowed to evaluate the effects on fatigue and healing properties due to short- and long-term ageing respectively.
The PG58-22 and PG 76-22 binders were tested after PAV only. Such a choice was dictated by the need of limiting total testing time and optimizing laboratory operations. As known, long-term ageing is considered the more significant condition for fatigue testing of binders, because of the intrinsically long-term nature of damage phenomena.
By comparing the results obtained on long-term aged materials, the influence of binder origin and polymer modification was directly assessed.

2.2 Fatigue and healing tests

Binders were tested by means of a Dynamic Shear Rheometer (DSC) with the purpose of evaluating both their damage behavior under continuous oscillatory shear stress (fatigue tests) and their capability to recovery a part of damage after load removal (healing tests).
The instrument used for testing was a Physica MCR 301 DSR from Anton Paar Inc., an air bearing stress-controlled device which can also operate in the strain-controlled mode through a feedback controlled loop. The DSR is equipped with a permanent magnet synchronous drive (minimum torque = 0.1 μNm, torque resolution < 0.1 μNm) and an optical incremental encoder for measurement of angular rotation (resolution < 1 μrad). A 8-mm parallel plate sensor system was used with a 2-mm gap between the plates.
Fatigue tests were carried out applying a continuous sinusoidal load to binder specimens in the stress-controlled mode and iso-stiffness conditions. An initial complex modulus of 15 MPa was selected in order to avoid spurious effects such as edge fracture and instability flow (11,12). Iso-stiffness temperatures adopted for measurements are reported in Table 1. They were determined by subjecting each material to a preliminary temperature ramp carried out in the strain-controlled mode with a strain amplitude of 0.01%, a frequency of 10 Hz and a temperature rate decrease of 1°C/10 min.

Table 1 : Iso-stiffness temperatures used for fatigue tests

Binder code	**Description**	**Iso-stiffness temperature [°C]**
PG64-16 (O)	Neat, Unaged	14.0
PG64-16 (R)	Neat, Short-term aged with RTFOT	15.8
PG64-16 (P)	Neat, Long-term aged with PAV	20.3
PG58-22 (P)	Neat, Long-term aged with PAV	23.0
PG76-22 (P)	Polymer-modified, Long-term aged with PAV	18.0

Before running fatigue tests, the pre-moulded specimens were heated at 50°C for three minutes, in order to improve the bond at the binder-steel interfaces, thus preventing adhesive ruptures. They were then conditioned at the test temperature for one hour. The oscillatory shear stress, set at 250 kPa amplitude and 10 Hz frequency, was imposed to the sample until complete failure, identified by 100% shear strain.

Healing tests consisted in oscillatory loading (carried out at the same temperatures, stress amplitude and frequency of fatigue tests) in which an intermediate rest period was introduced between a first and a second loading phase. The use of a single long healing duration in spite of multiple rest periods follows the past experience of the Authors which successfully adopted this type of test to investigate the correlation between healing properties and chemical characteristics of binders (10). The first loading phase was interrupted when a predefined level of damage was reached by the material, expressed in terms of loss of the initial complex modulus (ΔG_0*); on the contrary, the re-loading phase was prolonged until 100% shear strain.

In the case of PG64-16 binder, four different values of modulus loss were adopted in healing tests, covering a wide damage spectrum which ranges from very low degree of damage to a complete failure of the material.

Specifically, two levels of damage were selected to reproduce failure conditions. The first one refers to the classical 50% stiffness loss criterion. The second one was established according to the Dissipated Energy Ratio (DER) concept (6, 13) and corresponds to the peak value of the DER function when plotted against the number of loading cycles.

The other two levels of damage, related to non-critical conditions, were identified by considering one third and two thirds of the peak DER respectively.

For PG58-22 and PG76-22 binders, only the two levels of damage corresponding to failure conditions were considered.

The length of the rest time was adjusted on the basis of the duration the first loading phase, in order to provide a sufficient time to the material for the recovery of damage during unloading and to limit testing time.

Testing conditions adopted for healing tests are summarized in Table 2.

A minimum of three repetitions were performed for each test and the average values were considered for analysis.

Table 2 : Test conditions used for healing tests

Level of damage before load removal	**1/3 Peak DER**		**2/3 Peak DER**		**Peak DER**		**50% G***	
Binder code	**ΔG_0* [%]**	**Rest time [min]**	**ΔG_0* [%]**	**Rest time [min]**	**ΔG_0* [%]**	**Rest time [min]**	**ΔG_0* [%]**	**Rest time [min]**
PG64-16 (O)	5.8	30	9.1	60	23.9	100	50.0	100
PG64-16 (R)	6.9	60	10.0	100	24.4	200	50.0	200
PG64-16 (P)	9.6	100	13.1	200	27.4	360	50.0	360
PG58-22 (P)	-	-	-	-	22.8	80	50.0	80
PG76-22 (P)	-	-	-		91.9	390	50.0	390

3. EXPERIMENTAL RESULTS

3.1 Fatigue properties

Figure 1 reports the results derived from fatigue tests carried out on all the materials considered in this study. The curves were obtained by plotting the measured values of the storage (G’) and the loss (G”) component of the complex modulus as a function of load repetitions N.

Substantial differences in damage evolution can be observed by comparing the neat bitumens with the polymer-modified binder. In the case of neat materials (PG 64-16 and PG58-22), both G’ and G” curves are characterized by an initial stiffness reduction that takes place at a very low rate followed by a final abrupt decrease leading to failure.

On the contrary, the stiffness of the PG 76-22 binder drops dramatically during the first phase of loading, after which it decreases more gradually over the whole test duration. Such a behavior is probably linked to a structural reorganization occurring within the sample under repeated loads, associated to thixotropy and relaxation phenomena involving the elastomeric network formed by the SBS polymer (9,14). As a result, the classical 50% stiffness loss criterion appears to be not suitable to identify the failure point of this type of material, but different approaches such as those referring to energy-based methods, must be preferred.

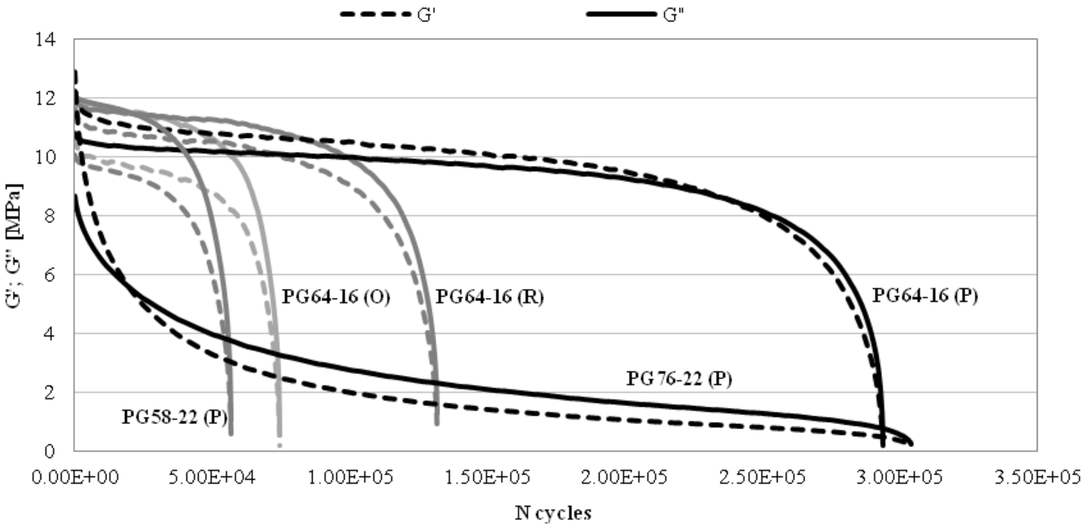

Figure 1 : Plots of storage and loss modulus as a function of loading cycles

Additional observations can be drawn from the analysis of phase angles. As shown in Figure 2, even in this case a clear distinction can be made between modified and unmodified binders. The curves of neat binders exhibit a plateau region, with the phase angle that remains quite constant for an extended portion of the test, and then suddenly raise in the final loading phase. On the contrary, in the case of the SBS-modified binder, as a result of the abovementioned phenomena the phase angle increases from very beginning, following an asymptotic trend without abrupt variations associated to failure.

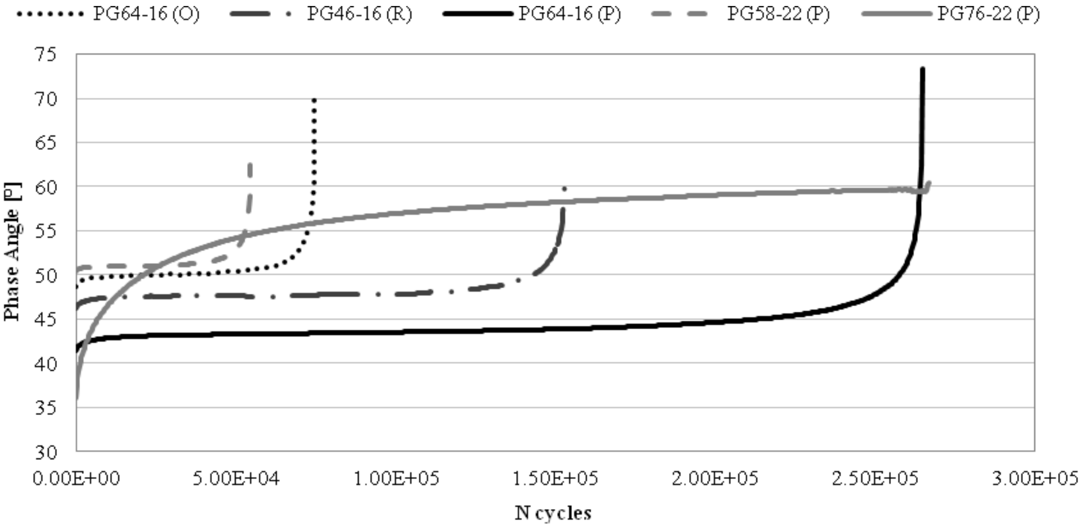

Figure 2 : Plots of phase angle as a function of loading cycles

Figures 1 and 2 provide further information about the impact of ageing on the damage properties of binders. Results obtained from PG64-16 tested at different state of ageing (Original, RTFOT and PAV) indicate that fatigue resistance of the material is progressively extended when it is subjected to short-term and successively to long term treatments in the laboratory. In particular, the number of cycles at failure (determined by means of both the 50% loss criterion and the DER approach, as reported in Table 3) raises of about one order of magnitude after PAV with respect to the unaged binder, whereas the phase angle (plateau value) decreases of about 6-7°.

A significant gap is finally observed between neat materials when compared to each to other, with the PG64-16 (P) binder exhibiting a number of cycles at failure considerably higher than those of the PG58-22 (P) binder.

Table 3 : N_{50} and N_{max} values obtained from fatigue tests

Binder code	N_{50}	N_{max}
PG64-16 (O)	69,991	60,750
PG64-16 (R)	132,902	115,050
PG64-16 (P)	245,873	216,150
PG58-22 (P)	57,750	49,650
PG76-22 (P)	13,087	234,900

The response of the different binders to repeated loading expressed in terms of stiffness and phase angle variations with loading cycles reflects on its representation in terms of DER. In particular, the variation of the peak value of the DER-N function (DER_{max}) with the number of loading cycles corresponding to the peak value of DER (N_{max}) can be associated to the variation of the energy that each binder dissipates during the so-called crack propagation phase, which spans from the crack propagation point (N_p) to failure (6,9). From the data represented in Figure 3, the slopes of the regression lines obtained for the unmodified binders appear to be very similar each to other, thus indicating that neither binder origin nor ageing treatment have a significant influence on the relative extent of crack propagation. On the contrary, the lower gradient of the PG76-22 line once again highlights the peculiar characteristics of the SBS-modified binder, which shows a pronounced aptitude in expanding the energy dissipation process before reaching failure conditions.

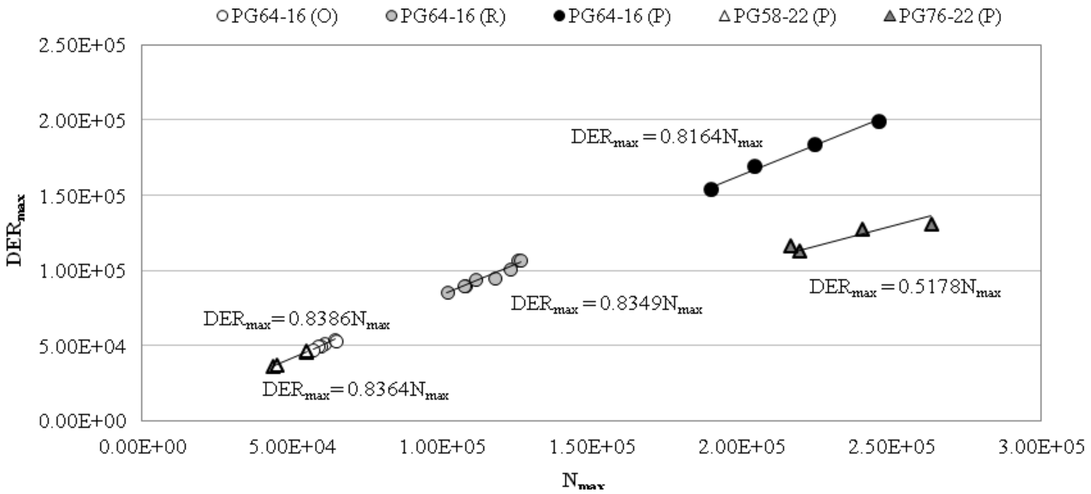

Figure 3 : Peak value of DER as a function of corresponding number of loading cycles

The Relative Crack Propagation Amplitude (RCPA) parameter, introduced in a previous work (9), provides a quantitative measure of the relative extent of the crack propagation phase under repeated loading. It is calculated by dividing the difference between the number of cycles at peak DER and the number of cycles at the onset of propagation by the number of cycles at peak DER ($(N_{max}-N_p)/N_{max}$). In the analysis of the damage properties of binders, such a parameter can be interpreted as a fatigue ductility indicator of the materials. In Figure 4, RCPA values are plotted as a function of N_p. Depending on the position of data points in the N_p-RCPA fatigue mapping plot, the behavior of the different binders can be discriminated. The enhancement in fatigue performance due to polymer modification is clearly identified by comparing PG76-22 and PG58-22 data points. The SBS polymer-modified binder proves to be the material exhibiting the highest anti-cracking potential with respect to the other binders, in terms of both fatigue resistance and ductility. Coherently with the results shown in Figure 3, the increase of N_p due to ageing results in a negligible increase of RCPA for binder PG64-16; moreover a common linear relationship (in the semi-log scale) seems to exist for all data derived from neat binders.

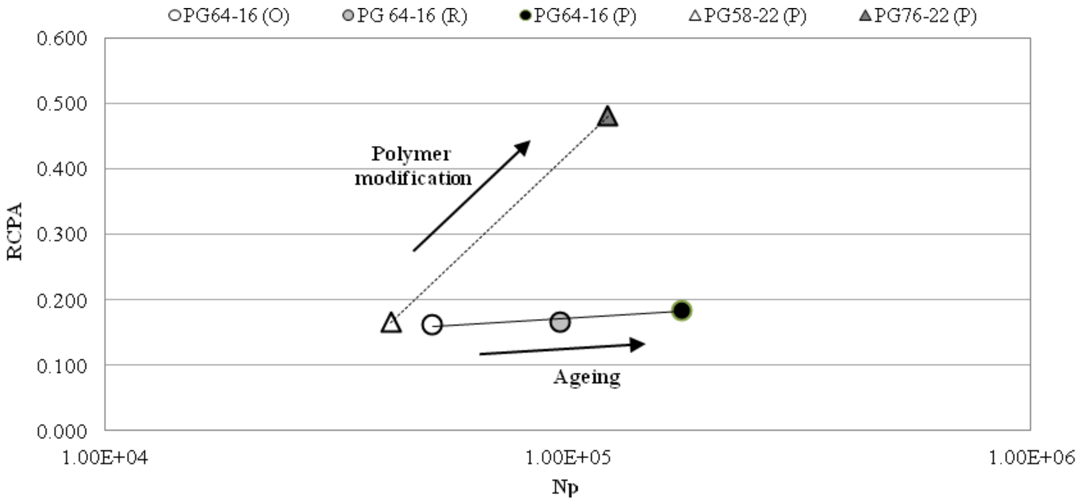

Figure 4 : N_p-RCPA fatigue mapping plot

3.2 Healing properties

Figure 5 displays a typical result obtained from healing tests. During the first loading phase, the complex modulus of the material decreases from the initial value G_0* to the final value G_F*= G_0*(1- ΔG_0*), where ΔG_0* is the predefined loss of modulus as reported in Table 2. The complex modulus G_R* recorded at the beginning of the re-loading phase is greater than G_F*, indicating the occurrence of healing during rest time. In some cases G_R* exceeds the “true” initial modulus G_0*, too. Since healing may involve only the recovery of damage experienced by the material in the first loading phase, the additional stiffness gain is evidently related to other phenomena, such as steric hardening (10). During the re-loading phase, a rapid stiffness decrease is observed with the complex modulus reaching the value obtained before loading removal (G_F) as a result of the loss of both healing and steric hardening effects. Once such a value is attained, the modulus curve exhibits a shape which appears to be coherent with the evolution of stiffness recorded in the first phase of loading, thus revealing that the material has memory of its past damage path.

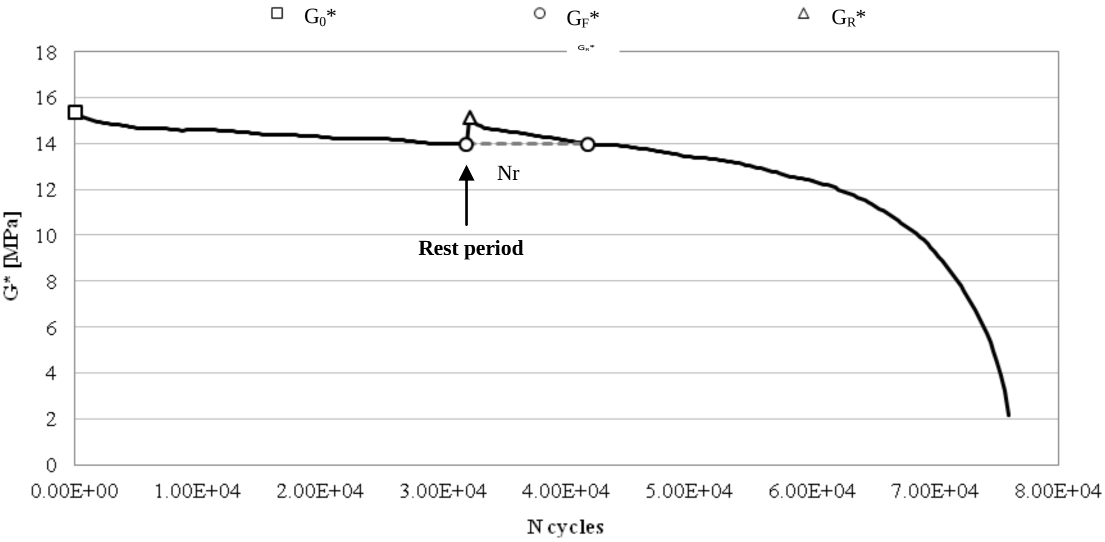

Figure 5 : Complex modulus as a function of loading cycles obtained from a healing test

The number of loading cycles N_R corresponding to the drop of complex modulus from G_R* to G_F* in the second phase gives a quantitative measure of the increment of fatigue life of the material due to the intermediate rest period. Such a parameter is strongly affected by the length of the rest period. This can be observed by considering the data plotted in Figure 6, which indicate, for all considered binders and test results, an overall increase of N_R with rest time.

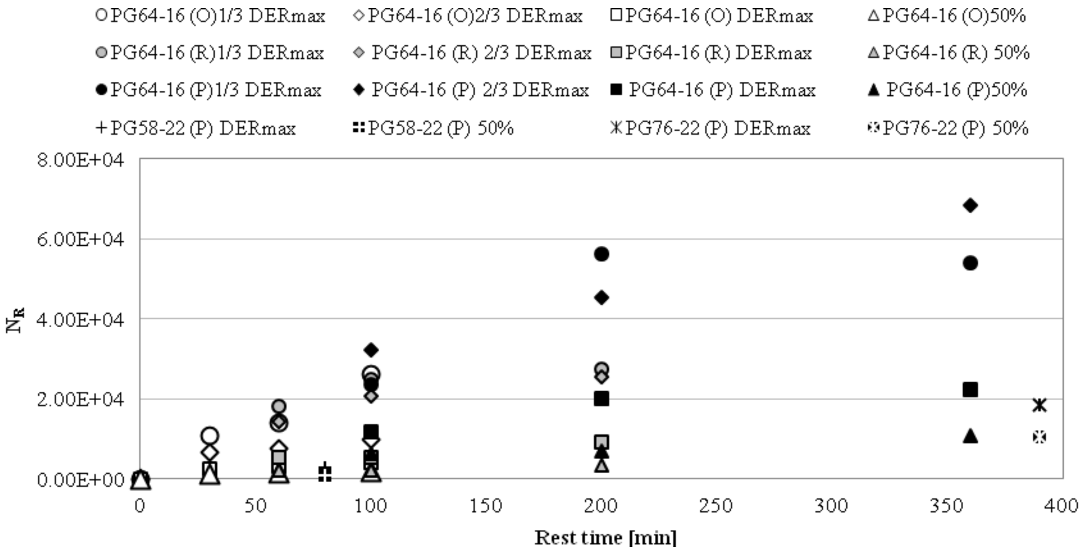

Figure 6 : Variation of N_R with rest time

On the basis of these observations, the Relative Healing Index (RHI) was proposed to be used as a synthetic indicator of healing potential of binders, calculated as the ratio between N_R and the product of rest time t_R and loading frequency f (10). It can be noted that $t_R \cdot f$ represents the duration of the rest period converted in terms of equivalent number of oscillatory repetitions (which are physically not applied).
RHI values determined for all binders are summarized in Table 4. From the survey of the reported data, it is evident how healing response of the materials depends on rest time and the level of damage imposed before load removal. Referring to the PG64-16 binder, in spite of the fact that N_R increases with rest time, the relative improvement of fatigue life is progressively lower, as demonstrated by the decrease of RHI. This result reflects the kinetics of the phenomenon, indicating that the great majority of healing occurs during the first portion of the rest period.
When considering the imposed level of damage, it can be noticed that RHI diminishes as the loss of stiffness before load removal increases. This is true for the neat binders only, whereas an opposite behavior is exhibited by polymer-modified PG76-22. Such a result can be attributed to the characteristics of the SBS polymer network; in this case, the loss of stiffness at peak DER is significantly higher than 50%, reflecting on a higher amount of recovered damage. As a consequence, the number of cycles in the reloading phase necessary to reach the complex modulus attained at the end of the first loading phase is increased, thus resulting in the increase of RHI. The comparison between PG76-22 and PG58-22 indicates that even the healing properties of the material are improved by polymer modification.
Finally, a progressive increment of RHI is observed after short-term and long-term ageing, except in the case of the lowest level of damage imposed in the first phase (1/3 peak DER). A possible explanation of this evidence can be linked to the fact that when a low damage is imposed and a sufficient rest time is given, steric hardening effects are prevalent with respect to true healing, with steric hardening, in turn, becoming less pronounced with ageing.

Table 4 : Relative Healing Index values determined for all binders

Binder Code	Rest Time	Level of damage before load removal			
		1/3 Peak DER	2/3 Peak DER	Peak DER	50% G*
PG64-16 (O)	30 min.	0.609	0.362	0.144	0.059
	60 min.	0.393	0.220	0.090	0.041
	100 min.	0.438	0.166	0.069	0.029
PG64-16 (R)	60 min.	0.502	0.395	0.152	0.059
	100 min.	0.413	0.347	0.091	0.038
	200 min.	0.228	0.213	0.078	0.028
PG64-16 (P)	100 min.	0.393	0.537	0.196	0.106
	200 min.	0.470	0.377	0.167	0.059
	360 min.	0.250	0.317	0.104	0.051
PG58-22 (P)	80 min.	-	-	0.056	0.018
PG76-22 (P)	390 min.	-	-	0.079	0.045

4. CONCLUSIONS

The experimental investigation described in this paper showed the validity of the proposed methods for the evaluation of the fatigue and healing potential of bituminous binders. Analysis of the experimental data derived from time sweep tests was carried out by referring to the Relative Crack Propagation Amplitude (RCPA) parameter, the use of which, in conjunction with a fatigue life indicator expressed in term of number of cycles to failure, was expected to be especially relevant in the case of complex materials, such as polymer-modified binders.

Another parameter was introduced to evaluate the material response from healing tests, the so-called Relative Healing Index (RHI).

By means of both parameters, the effects related to binder origin, polymer modification and ageing on fatigue and healing potential of the investigated binders were well captured.

The SBS polymer-modified binder proved to be the material exhibiting the highest anti-cracking performance with respect to the other binders, in terms of both fatigue resistance and ductility. Healing properties are also enhanced by the presence of the polymer, as evident from the comparison of the modified binder with the base one.

A clear distinction was made between the two neat binders, indicating the influence of binder source on tests results.

Ageing effects were discussed by comparing the results obtained from a single binder tested in the unaged state with those obtained after RTFOT and PAV treatments. It was observed that ageing produces an increment of fatigue resistance of the material without significant variation of the relative extent of the crack propagation phase. Values of the Relative Healing Index progressively increase with the degree of ageing, except in the case in which a low level of damage is imposed before rest time.

REFERENCES

[1] Distress Identification Manual for the Long-Term Pavement Performance Program, J.S. Miller and W.Y. Bellinger, Publication n. FHWA-RD-03-031, Federal Highway Administration, McLean, 2003

[2] Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, NCHRP 1-37A, National Cooperative Highway Research Program, National Research Council, Washington, D.C., 2004

[3] The SUPERPAVE Mix Design System, Manual of Specifications, Test Method and Practices, E.T. Harrigan, R.B. Leathy and J.S. Youtcheff, SHRP Report A-379, National Research Council, 1994

[4] Fatigue Characteristics of Bitumen and Bituminous Mixes, P.S. Pell Proceedings of the International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, U.S.A., pp. 310-323, 1966

[5] Predict Mix Fatigue Tests Binder Fatigue Properties Measured with a DSR, H. Soenen, C. de La Roche, and P. Redelius, Proceedings of the 3rd Euroasphalt & Eurobitume Congress , Austria, 2004

[6] Characterization of Modified Asphalt Binders in Superpave Mix Design , H.U. Bahia, D.I. Hanson, M. Zeng, H. Zhai, M.A.Khatri, R.M. Anderson, NCHRP Report 459, National Academy Press, Washington, D.C., 2001

[7] Microdamage Healing in Asphalt and Asphalt Concrete. Volume 1: Microdamage and Microdamage Healing, D.N. Little, R.L. Lytton, D. Williams, C.W. Chen, Y.R. Kim, and H.J. Lee, FHWA Research Report 7229, 1998

[8] A Framework to Quantify the Effect of Healing in Bituminous Materials using Material Properties, A. Bhasin, D.N. Little, R. Bommavaram and K. Vasconcelos, Road Materials and Pavement Design, Vol. 9, Special Issue, pp. 219-242, 2008

[9] Experimental Investigation on the Fatigue Damage Behaviour of Modified Bituminous Binders and Mastics, E. Santagata, O. Baglieri, and D. Dalmazzo, Journal of the Association of Asphalt Paving Technologists, Vol. 77, pp. 855-887, 2008

[10] Rheological and Chemical Investigation on the Damage and Healing Properties of Bituminous Binders, E. Santagata, O. Baglieri, D. Dalmazzo, and L. Tsantilis, Journal of the Association of Asphalt Paving Technologists, Vol. 78, pp. 567-595, 2009

[11] Evaluation of Fatigue Criteria for Asphalt Binders, D.A. Anderson, Y.M. Le Hir, M.O. Marasteanu, J.-P. Planche, D. Martin, and G. Gauthier, Transportation Research Record, No. 1766, pp., 2000

[12] Evaluation of Fatigue Properties of Bituminous Binders, J.-P. Planche, D.A. Anderson, G. Gauthier, Y.M. Le Hir and D. Martin, Materials and Structures, Vol. 37, pp. 356-359, 2004

[13] Evaluation of the Dissipated Energy Concept for the Interpretation of Fatigue Measurements in the Crack Initiation Phase, A.C. Pronk, P-DWW-95-001, Road and Hydraulic Engineering Division, Netherlands, 1995

[14] Separation of Thixotropy from Fatigue Process of Asphalt Binder, L. Shan, Y. Tan, B. Underwood, and Y.R. Kim, Transportation research Record, No. 2207, pp. 89-98, 2011