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Investigating cohesive healing of asphalt binders by means of a dissipated energy approach

Ezio Santagata *, Orazio Baglieri, Davide Dalmazzo, Lucia Tsantilis

Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, 24, corso Duca degli Abruzzi, 10129 Turin, Italy

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Abstract

The paper reports the results of an experimental investigation in which the cohesive healing properties of different types of asphalt binder were evaluated by means of the dissipated energy ratio approach. A specifically designed testing methodology was proposed which involves comparing the response of binders subjected to continuous oscillatory shear loading carried out without rest periods and with single rest periods introduced at predefined levels of damage A rheological parameter (Healing Ratio) was introduced to quantify the magnitude of healing occurring during rest time and to rank the consequent healing potential of binders. Obtained results indicate that the investigated binders did not completely recover their original fatigue resistance after rest time, confirming the existence of some intrinsic irreversible damage, the amount of which depends on the total damage experienced before load removal. Experimental results also indicate that healing performance of binders can be significantly enhanced by polymer modification.

Keywords: Healing; Fatigue; Dissipated energy ratio; Asphalt binder; Polymer modification

1. Introduction

The evaluation of fatigue resistance of asphalt concrete mixtures employed in road pavements is traditionally carried out by subjecting them to continuous cyclic loading until failure in controlled temperature and stress/strain conditions. Such an approach does not reproduce what happens in the field, where, due to the intermittent nature of traffic, rest periods exist between each axle load application. It has been widely demonstrated that asphalt concrete mixtures have the capability to recover stiffness or strength during rest time [1–11]. This capability, commonly referred to as healing, is responsible for the significant difference between fatigue life predicted by means of traditional laboratory tests and actual fatigue life observed in the field, with the first one being considerably shorter than the second one. To overcome such a limitation, laboratory-to-field shift factors, the values of which can range from 3 to about 100, are commonly used in pavement design [12].

Two types of healing exist in asphalt concrete mixtures: adhesive healing at aggregate binder interface and cohesive healing within the asphalt binder at microcrack surfaces [5,7]. The study of adhesive healing is out of the scope of this paper which focused on cohesive healing only.

A number of research works has been carried out to investigate cohesive healing of asphalt binders. The Dynamic Shear Rheometer (DSR) has been generally employed in these works and different methods and criteria have been proposed.

In the majority of cases researchers used cyclic stress or strain at a predefined frequency and temperature,

* Corresponding author. Fax: +39 0110905614.
E-mail addresses: ezio.santagata@polito.it (E. Santagata), orazio.baglieri@polito.it (O. Baglieri), davide.dalmazzo@polito.it (D. Dalmazzo), lucia.tsantilis@polito.it (L. Tsantilis).
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interrupted by the inclusion of a single long rest period [13–20] or of multiple short rest periods [21–25]. In these studies healing behaviour of binders was quantified in terms of complex modulus recovery and/or increase in load repetitions to failure due to rest time.

Other authors used the so called two-piece bitumen healing setup [26–28] in which two specimens of asphalt binder are attached to the upper and bottom plates of a DSR. The surfaces of the two specimens are brought into contact with each other and during the test the change in complex shear modulus is recorded by applying small strain cyclic loading at different time intervals.

Despite the remarkable efforts made by researchers worldwide, more work is needed in order to fully understand cohesive healing mechanisms and to develop scientifically sound procedures to assess and rank performance of materials.

This paper presents the results obtained from an experimental investigation in which the cohesive healing characteristics of three types of asphalt binder were analysed. A novel approach, based on the concept of dissipated energy, was used in the analysis and a healing index was introduced to quantitatively evaluate and compare healing potential of materials. The effectiveness of the proposed method in capturing the effects of polymer modification on binder response was also discussed.

2. Experimental investigation

2.1. Hypothesis

Cohesive healing is believed to be the results of several processes which take place at crack interfaces, such as wetting (which depends on surface energy of the material), interfacial cohesion and interdiffusion and randomization of molecules between wetted surfaces [29–31]. Such processes contribute to cracks to be repaired and original internal structure of the asphalt binder to be restored.

It can be stated that any change occurring in the internal structure of materials due to damage reflects in a change in their energy dissipation processes. Moving from this basic assumption, the study described in this paper introduces a methodology based on the comparison of dissipated energy measured under continuous oscillatory shear loading without rest periods (fatigue tests) and after single long rest periods introduced at fixed values of complex modulus loss (healing tests). In such a context, the Dissipated Energy Ratio (DER) concept originally proposed by Pronk and Hopman [32] is used to analyse fatigue and healing test data.

The DER parameter after N loading cycles is calculated by means of the following expression:

$$\mathrm{DER} = \frac{\sum_1^N W_i}{W_N} \quad (1)$$

where W_i and W_N are the energy dissipated per unit volume in the generic i-th and in the N-th cycle which are calculated by means of the following general expression:

$$W_i = \pi \cdot \tau_{0,i} \cdot \gamma_{0,i} \cdot \sin(\delta_i) \quad (2)$$

in which $\tau_{0,i}$ and $\gamma_{0,i}$ are respectively the stress and strain amplitudes, while δ_i is the phase angle value.

In the case of stress-controlled tests, the plot of DER as a function of the number of loading cycles N is of the type shown in Fig. 1. It can be observed that after an initial phase of testing with no damage accumulation, the experimental data points gradually deviate from the equality line (with 45° horizontal slope). A peak value is reached, after which DER values decrease until complete failure of the specimen.

Several fatigue life indicators can be derived from the DER function obtained from continuous oscillatory loading test data [33,34]: N_p, which identifies the onset of crack propagation and corresponds to the intersection between the equality line and the horizontal line passing through the maximum DER value; N_{p20}, which is associated with 20% deviation of DER from the equality line; N_{max}, which corresponds to peak DER.

For the purpose of healing evaluation, the DER function obtained from fatigue tests is considered as a reference point, since it is representative of the response of the material in its original state. Its comparison with the DER function obtained after a certain amount of damage has been induced in the binder may provide information on the healing capability of the material.

2.2. Materials and methods

The materials employed in the experimental investigation included one unmodified bitumen (50/70 penetration grade), indicated as "Neat", and two commercially available polymer modified binders containing styrene-butadienestyrene (SBS), indicated as "Soft" (45/65 penetration grade) and "Hard" (50/70 penetration grade). The terms "Soft" and "Hard", commonly used in Italy, refer to products prepared with a low and high polymer dosage,

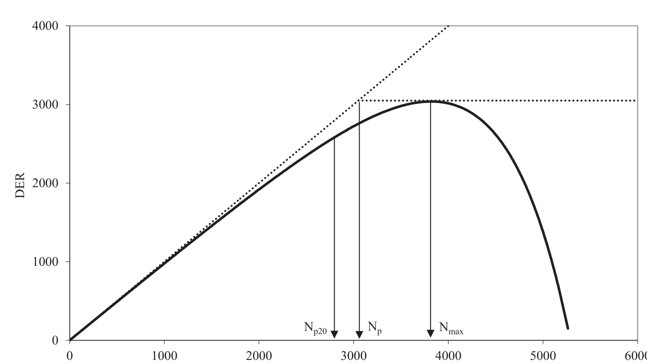

Fig. 1. Example of a typical DER function obtained from a stress-controlled fatigue test.

respectively (of the order of 2–3% and 4–6% by weight of base bitumen). With the purpose of investigating their fundamental cohesive healing properties, asphalt binders were tested in their original state thereby excluding ageing effects.

The instrument used for measurements was a Physica MCR 301 DSR from Anton Paar Inc. operated with 8 mm parallel plates and 2 mm gap between the plates. In order to avoid slippage or interface failure phenomena at binder-plate interfaces, bitumen specimens were prepared and conditioned following a previously developed procedure [14]. In particular, after being placed between the parallel plates, pre-moulded binder specimens were trimmed at 20 °C and thereafter heated up to a temperature of 50 °C at which they were maintained for 3 min. Specimens were then brought to test temperature, where they were conditioned for 45 min before starting rheological measurements.

Although some authors have questioned the use of parallel plates in fatigue analysis due to possible edge effects and instability flow [35], many other findings support the validity of such a technique. By comparing parallel plate and torsion cylinder geometries, Martono et al. [36] demonstrated that in the first case edge effects are not significant and that errors resulting from the heterogeneous flow field can be considered as part of experimental data variability. Other authors [21,23] observed the formation of hairline cracks within DSR test specimens, thus revealing the presence of internal micro-damage associated to fatigue.

Other criticisms to the use of DSR testing protocols in the evaluation of fatigue and healing properties of asphalt binders have been made with respect to the possible occurrence of biasing effects due to bitumen thixotropy, which causes time-dependent changes in the response under loading that are due to molecular rearrangement [37–39]. Nevertheless, specific methods of data analysis have been proposed to identify and separately quantify the effects due to true fatigue, true healing and thixotropy [38,40].

The methodology adopted in this study to investigate cohesive healing properties of the asphalt binders included two types of test:

- Fatigue tests, in which binders were subjected to continuous oscillatory loading (with no rest periods) until failure;
- Healing tests, in which binders were subjected to continuous oscillatory loading with an intermediate single long rest period introduced between the first (loading) and the second (reloading) oscillation phase at fixed levels of damage.

Both in fatigue and healing tests, oscillatory shear loads were applied in stress controlled conditions, at a frequency of 10 rad/s and at a temperature of 20 °C. Selected values of imposed shear stress were equal to 100 kPa and 140 kPa.

Table 1
Average initial values of complex modulus recorded during fatigue and healing tests.

Binder	τ (kPa)	G^*_{in} (kPa)
Neat	100	3164
	140	3152
Soft	100	2959
	140	2977
Hard	100	3138
	140	2956

As shown in Table 1, at the selected testing temperature, which is commonly used in fatigue analysis [13,27,28,40], the three binders exhibited a similar stiffness, with an average value of the initial complex modulus (G^*_{in}) at both stress levels of approximately 3 MPa. Thus, considered materials were compared in conditions very close to iso-stiffness.

For the selection of stress levels to be used in testing, preliminary strain amplitude sweep tests were carried out at the abovementioned temperature and frequency to establish the linear viscoelastic limits of materials. Raw data obtained from measurements were smoothed with natural cubic spline interpolation (5% smoothing range) and the non-linear domain was defined as the region where the complex modulus was 95% or less of the initial value. Strain amplitude sweep tests were performed in three replicates and the results, expressed in terms of limiting values of shear stress (τ_{lim}) and shear strain (γ_{lim}), are reported in Table 2. In order to ensure all the materials to be tested in their non-linear domain, thus simulating the conditions experienced in weak pavements structures [41], two stress values (τ_{test}) were chosen for testing, equal to 100 and 140 kPa, which are approximately twice the linear limits of binder Soft and Neat respectively.

Values of complex modulus loss (ΔG^*) adopted in healing tests as thresholds for the interruption of the first loading phase were selected in order to evaluate the response of binders after being subjected to different levels of damage. In this respect, it was postulated that level of imposed damage is related to reduction of the DER function and not to stiffness reduction (i.e. materials exhibiting same DER reduction experience same level of damage). This is coherent with the assumption that energy dissipation is the mechanism driving damage evolution of materials. In particular, the modulus loss corresponding to the peak value of DER (ΔG^*_{MAX}) and one half of it ($\Delta G^*_{0.5MAX}$) were used

Table 2
Stress and strain limiting values of linear viscoelastic regions determined from amplitude sweep tests.

Binder	τ_{lim} (kPa)	γ_{lim} (%)
Neat	70.2	2.4
Soft	54.6	1.9
Hard	36.8	1.2

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for testing. For reasons that are explained further on in the paper, in the case of binder Hard an additional condition was considered, corresponding to 75% of modulus loss at peak DER ($\Delta G^*_{0.75MAX}$).

Duration of rest periods was set equal to three times the duration of loading phases and varied depending upon binder type and selected modulus loss. The choice of using a single long rest time rather than multiple rest periods was dictated by the need of providing sufficient time to the materials to recover the stiffness lost before loading interruption, thereby allowing their healing potential to be clearly highlighted. It was also considered that according to existing studies the ratio of length of rest period to number of loading cycles is statistically more significant than the length of rest period alone with respect to the evaluation of healing potential [42]. Table 3 provides a synthesis of the average duration of rest periods employed for each binder at the two considered stress levels.

All measurements were performed at least in duplicate runs and average results were used in data analysis. In order to check the reliability of obtained results, additional repetitions were carried out in all those cases in which considered fatigue indicators showed a relative difference higher than 15%.

3. Results and discussion

3.1. Fatigue test results

Results of fatigue tests carried out on the considered binders are synthesised in Table 4, where they are expressed in terms of the previously described fatigue life indicators N_p, N_{p20} and N_{max}. Table 4 also lists the values of two further parameters: $N_{50\%}$ which is the number of loading cycles associated with 50% modulus reduction [43], and RCPA, the so-called Relative Crack Propagation Amplitude, calculated by means of the following expression [34]:

$$\mathrm{RCPA} = \frac{N_{\max} - N_p}{N_{max}} \quad (3)$$

While the former parameter is coherent with one of the classical pavement design criteria, the latter provides a quantitative measure of the extent of the crack propagation phase under repeated loading and deals with the concept of binder fatigue ductility.

Table 4
Fatigue parameters of the asphalt binders determined from fatigue test data.

Binder	τ_{test} (kPa)	$N_{50\%}$	N_{p20}	N_p	N_{max}	RCPA
Neat	100	4175	4032	3235	4140	0.22
Soft		6549	5097	4254	6004	0.29
Hard		3048	2845	5665	10,513	0.46
Neat	140	1797	1501	1209	1574	0.23
Soft		2251	1801	1508	2118	0.29
Hard		723	552	1484	2722	0.45

From the data provided in Table 4 it can be observed that the asphalt binders are ranked differently depending on the adopted fatigue criterion. In the case of binders Neat and Soft, values of the considered fatigue life indicators at a given shear stress are quite similar to each other while for binder Hard one parameter (N_{max}) is considerably higher than the other two ($N_{50\%}$ and N_{p20}). As a consequence, binder Hard would be ranked better with respect to binders Neat and Soft when referring to N_{max}; on the contrary, it would show inferior fatigue properties if compared to the other binders on the basis of parameters $N_{50\%}$ and N_{p20}. Since it is recognised that the performance of asphalt pavements are greatly improved when a high amount of SBS polymer is used for binder modification, it follows that the use of N_{max} to evaluate binder properties appears to be more reasonable and consistent with the inherent characteristics of the materials.

RCPA values range from 0.22 (binder Neat) to 0.46 (binder Hard) and, unlike fatigue life indicators, do not seem to be influenced by shear stress variations. The very high RCPA values are typical of highly modified binders and indicate the capability of such materials to extend the energy dissipation process after crack initiation as a result of the presence of a diffused rubber-like network within the asphalt matrix [15,34].

The different aptitudes in dissipating energy of the considered binders highlighted above are also reflected by the magnitude of complex modulus loss before reaching peak DER. As demonstrated by the data reported in Table 5, the decrease in the initial complex modulus at peak DER spans from 35% to 38% in the case of binder Neat to 80% in the case of binder Hard.

Table 3
Average duration of rest periods adopted in healing tests.

Binder	τ_{test} (kPa)	Rest period (minutes)		
		$\Delta G^*_{0.5MAX}$	$\Delta G^*_{0.75MAX}$	ΔG^*_{MAX}
Neat	100	100	–	140
Soft		50	–	180
Hard		100	300	330
Neat	140	30	–	50
Soft		40	–	70
Hard		15	35	125

Table 5
Values of complex modulus loss at peak DER obtained from fatigue tests.

Binder	τ_{test} (kPa)	ΔG^*_{MAX} (%)
Neat	100	35
Soft		45
Hard		80
Neat	140	38
Soft		47
Hard		80

3.2. Healing test results

Values of complex modulus loss ΔG^*_{MAX} and $\Delta G^*_{0.5MAX}$ to be adopted in healing tests (Table 6) were determined from average results obtained in fatigue tests at peak DER (Table 5). Due to the large amount of initial modulus reduction, in the case of binder Hard an additional intermediate condition was considered, indicated as $\Delta G^*_{0.75MAX}$.

Fig. 2 displays a comparison between the DER functions obtained from fatigue tests and those derived from the reloading phases in healing tests carried out on the three binders at the two considered stress levels. The curves corresponding to different values of complex modulus loss are clearly discriminated with the gap between reloading curves and the base fatigue curve increasing as the modulus loss increases. According to the basic hypothesis assumed in this study, variations in dissipated energy as measured by the DER parameter indicate the occurrence of changes in the internal structure of the materials during the first phase of healing tests that persist after the rest period. Such changes seem to confirm the existence of some intrinsic and irreversible load-induced damage, the magnitude of which depends on the level of total damage undertaken before load removal.

Table 6
Values of complex modulus loss adopted in healing tests.

Binder	$\Delta G^*_{0.5MAX}$ (%)	$\Delta G^*_{0.75MAX}$ (%)	ΔG^*_{MAX} (%)
Neat	18	–	36
Soft	23	–	46
Hard	40	60	80

The formation of cracks and the development of a fracture process zone at crack tips can be described in terms of disentanglement of molecular chains as proposed for thermoplastic polymers [44]. The previously described healing processes occurring at crack surfaces allow molecules to re-bond with each other and crack lips to be closed. The bond between molecules appears to be less strong and more precarious than the original one, since the previous entanglement of chains cannot be fully restored. As a consequence, cracks cannot close durably and reopen sooner

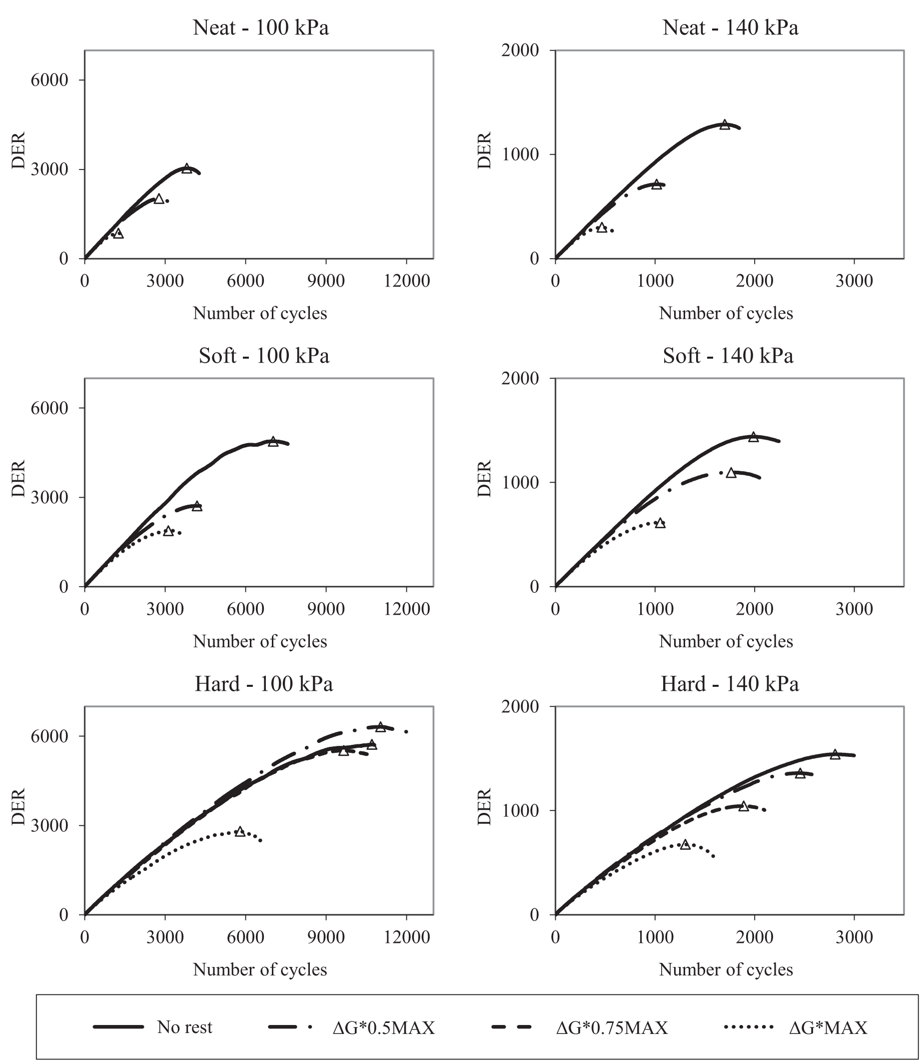

Fig. 2. Comparison of DER functions obtained from fatigue and healing tests.

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when the specimen is reloaded, resulting in a more rapid damage evolution of the material. This interpretation is supported by the findings of other research works [8,45].

3.3. Healing ratio

In order to quantitatively evaluate the magnitude of healing occurring during rest time, a Healing Ratio (HR) was defined as follows:

$$HR = \frac{N_{\text{max-RP}}}{N_{\max}} \tag{4}$$

where $N_{\text{max-RP}}$ is the number of loading cycles at peak DER determined from the reloading phase of healing tests and $N_{\max}$ is the number of loading cycles at peak DER determined from corresponding fatigue tests.

By definition, HR can vary in the interval comprised between 0 and 1. The lower limit is obtained when $N_{\text{max-RP}} \ll N_{\max}$ and refers to an ideal material which exhibits a negligible fatigue resistance after being subjected to a former loading phase. The upper limit is obtained when $N_{\text{max-RP}} = N_{\max}$ and refers to a material which attains a full recovery of its original fatigue resistance after rest time. It should be underlined that the choice of $N_{\max}$ in the calculation of HR was dictated by the results obtained in fatigue tests which showed that such a fatigue life indicator is the one that better reflects field performance ranking of polymer modified binders.

Obtained results are reported in Table 7. As expected, for each binder HR decreases as the loss of stiffness occurring in the initial loading phase increases, thus indicating that the amount of irreversible damage imposed during the first phase of testing is related to the reduction of residual fatigue life. Moreover, HR values are higher in the case of polymer modified binders with respect to the unmodified one when compared at the same level of imposed damage. This can be explained by considering that the presence of the SBS polymer in the base asphalt matrix enhances the recovery of fatigue strength as a result of the self-healing capability of the polymer and of the local bridging of microcracks induced by the polymer network [46]. It should finally be noticed that due to the higher polymer dosage, binder Hard shows a superior healing performance than binder Soft.

Table 7
Healing Ratio values obtained at different complex modulus losses.

Binder	τ_{test} (kPa)	HR		
		$\Delta G^*_{0.5MAX}$	$\Delta G^*_{0.75MAX}$	ΔG^*_{MAX}
Neat	100	0.71	–	0.30
Soft		0.69	–	0.47
Hard		1.06	0.92	0.56
Neat	140	0.69	–	0.29
Soft		0.86	–	0.45
Hard		0.91	0.76	0.58

4. Conclusions

In the experimental study described in this paper the cohesive healing properties of three different asphalt binders were evaluated by means of a novel approach based on the dissipated energy ratio (DER) concept. A specifically designed testing methodology was proposed which involves analysing the response of binders under continuous oscillatory shear loading with no rest periods (fatigue tests) and with single rest periods introduced at desired levels of modulus loss (healing tests).

It was shown that the healing capability of asphalt binders can be assessed by comparing the DER functions obtained from fatigue and healing tests. In particular, a synthetic parameter, the so-called Healing Ratio (HR), can be successfully employed for the analysis of test results.

Results obtained from fatigue and healing tests seem to confirm the existence of some intrinsic damage that for all binders cannot be entirely recovered during rest time. Such an occurrence is consistent with the formation of weak bonds at crack surfaces due to the physical impossibility of restoring the original entanglement of molecular chains.

With respect to the newly-introduced Healing Ratio, it was observed that, as expected, for each binder considered in the study it decreases as the level of total damage induced by previous loading increases. Moreover, such a parameter highlights the superior healing potential of polymer modified binders containing styrene-butadienestyrene (SBS) which are coherent with the inherent healing properties of the polymer and with its crack-bridging capability.

Further studies are certainly needed to validate the proposed approach by considering a wider array of binders. Moreover, extensions to the case of bituminous mixtures are recommended in order to link the process of material selection to the prediction of actual field performance.

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