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Abstract

Steric hardening is a time dependent phenomenon thatт can affect the healing properties of bituminous binders. In the experimental investigation reported in this paper, the rheological test method proposed for the evaluation of healing involved the use of a prolonged rest period included between two continuous oscillatory loading phases. A simple model was developed to subtract the contribution of steric hardening to the total stiffness gain attained during rest and thus to evaluate the recovery in mechanical properties due to self healing only. Analysis of the results indicated that cumulated damage of binders is composed by a reversible and a non reversible part. True self healing potential of the materials, as evaluated by means of the relative reversible damage index (RRD) and the relative index of fatigue life increase ($RFI_{HEALING}$), was found to be a function of imposed damage, binder source and polymer modification.

Key words: Bituminous binders, fatigue damage, self healing, steric hardening, dynamic shear rheometer

1. INTRODUCTION

Based on laboratory investigations and field observations, it is well recognized that asphalt paving mixtures have the capability to recover their mechanical properties, such as stiffness and strength, after being damaged under loading [1-6]. Such a property, commonly referred to as self healing, can significantly enhance the fatigue life of asphalt pavements and should be taken into account both in materials selection and pavement design. In particular, in order to fully understand this phenomenon investigations should focus on the healing properties of bituminous binders which are in most part responsible for the abovementioned damage recovery.

Most of the studies on the healing potential of bituminous binders have been performed by means of tests carried out with the Dynamic Shear Rheometer (DSR). However, different approaches have been proposed in terms of testing protocols and modelling in the attempt of capturing specific aspects of the phenomenon.

A recent approach is based on the intrinsic two piece healing test method [7,8]. In this type of test, samples of bitumen are placed on the upper and bottom plates of the DSR and are subsequently pressed against each other to reproduce crack healing mechanisms. Self healing is quantified on the basis of the change of shear modulus measured at a very low stress level. The materials' response in the two piece configuration have been demonstrated to be extremely sensitive to sample geometry (thickness) and compressive normal force applied to the specimen [9]. When employing this test method it is therefore necessary to make use of a suitable gap control and/or normal force control system to achieve reliable experimental results.

Other researchers use cyclic stress or strain controlled loading at a predefined frequency and temperature interrupted by the inclusion of rest periods. In particular, two main approaches have been adopted in defining the number and extension of rest periods, either by including multiple short rest periods between intermittent loading [10-12] or by introducing a single long rest period between two continuous loading phases [13-17]. In the Authors' opinion, the use of a single long rest period as opposed to multiple short rest periods leads to a more straightforward comprehension of healing kinetics and other phenomena which can occur simultaneously in the binder during rest [16]. Furthermore, the inclusion of multiple healing events appears to be a possible source of variability of test results [18].

In fatigue and healing studies it is very important to distinguish true damage and self healing from other spurious effects such as thixotropy and steric hardening [9, 19-20]. In particular, steric hardening may be significant in the case of healing tests in which a prolonged rest time is given to the binder to recover damage between continuous loading phases.

Steric hardening can be defined as a progressive, heat reversible, isothermal increase in mechanical properties of the material due to molecular rearrangements. This effect was first reported by Traxler and Schweiyer [21] who studied the time dependent hardening at ambient temperature of binders, recognizing the phenomenon to be strongly influenced by binder type and source. The proposed interpretation of steric hardening generally relies on the sol gel picture with the build up of a stronger asphaltenes network with time [22,23]. By making use of modulated differential scanning calorimetry, Masson et. al [24] established a link between steric hardening and ordering of asphaltenes. It was also demonstrated that steric hardening effects can be reduced in polymer modified binders due to the reduced capacity of alkanes and alkyl aromatics to order in the presence of styrene butadiene styrene (SBS) [25]. The increment of stiffness exhibited at the end of rest time due to steric hardening can overlap with the stiffness gain due to self recovery of the binder, thus leading to an overestimate of the real healing potential of the binder itself.

The experimental study presented in this paper focuses on investigating the self healing characteristics of different bituminous binders taking into account steric hardening effects. A simple model was developed to subtract the contribution of steric hardening to the total stiffness gain attained during rest time and thus to highlight the recovery in mechanical properties due to self healing only.

In addition, differences in self healing potential between binders of various origin and the effect of polymer modification were also discussed.

2. EXPERIMENTAL

2.1 Materials and equipment

Three different bituminous binders were considered in this study, including two neat bitumens (A and B) and one polymer modified binder (C). The neat bitumens, belonging to the same penetration grade (70/100), were sampled from two different refineries located in North Western Italy, each of which operates on crudes of various origins. The polymer modified binder was originated from base bitumen B by adding a high percentage of SBS according to the undisclosed processing scheme adopted by the plant which provided the material.

All the binders were subjected to a preliminary rheological characterization in order to determine their Performance Grades according to AASHTO M 320 [26]. Obtained results are summarized in Table 1. It can be observed that SBS modification upgraded the base binder only in the high temperature range (the upper grading temperature raised by 18°C), whereas low temperature performance was not significantly affected.

Binder Code	Description	Pen Grade	PG
A	Neat	70/100	64-16
B	Neat	70/100	58-22
C	Modified with SBS	50/70	76-22

Table 1: Bituminous binders used in the investigation.

Measurements were performed by means of 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). An 8 mm parallel plate sensor system was used with a 2 mm gap between the plates.

All bituminous binders were tested after laboratory simulated long term ageing, carried out with the Pressure Ageing Vessel (PAV). As known, long term ageing is considered the most significant condition for fatigue and healing analysis, because of the intrinsic long term nature of damage phenomena.

Tests were performed in triplicate runs and average results were used for analysis.

2.2 Test method

The healing test procedure employed in the investigation required the application in the stress controlled mode of a continuous sinusoidal torque, with an intermediate rest period introduced between the first (loading) and the second (reloading) oscillation phase.

Premoulded specimens were used for testing. In order to improve the bond between the binder and steel plates, specimens were preheated at 50°C for three minutes and thereafter conditioned at test temperature for one hour before loading. During conditioning a low oscillatory shear strain of 0.01% was applied to the specimen at a frequency of 10 Hz and the evolution of complex modulus with time was consequently monitored.

With the purpose of preventing possible drawbacks related to the stiffness dependency of the damage process, tests were carried out in isostiffness conditions. When operating at low initial stiffness, several studies have indicated the possible occurrence of edge effects and instability flow rather than internal microdamage during oscillatory loading performed with parallel plates [27]. Thus, as suggested by Planche et al [28], an initial complex modulus of 15 MPa was selected for measurements both to ensure the occurrence of true fatigue within the sample and to limit machine compliance. Isostiffness temperatures, reported in Table 2, were determined by subjecting each material to a preliminary temperature ramp performed 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.

Both in the loading and in the reloading phase, oscillatory shear stress amplitude was set for all binders at 250 kPa with a frequency of 10 Hz. Such a choice may lead to tests carried out in different conditions with respect to the linear visco-elastic limit [28], but allows testing time to be adequately shortened as pointed out by Tan et al [17].

The first loading phase of the healing tests was interrupted at a predefined level of damage, expressed in terms of percentage reduction of the initial complex modulus ($\%\Delta G_0^*$). After the rest period, reloading was continued until 100% shear strain.

By referring to the different approaches adopted to identify fatigue failure conditions, two values of $\%\Delta G_0^*$ were used for each material. The first value refers to the classical 50% stiffness loss criterion [29]. The second one was established according to the Dissipated Energy Ratio (DER) concept [30] and corresponds to the complex modulus loss at the peak of the DER function [31]. The values of $\%\Delta G_0^*$ corresponding to peak DER were obtained from traditional fatigue tests carried out without intermediate rest at the same temperatures, frequency and stress amplitude of healing tests. Obtained results are reported in Table 2.

It can be observed that in the case of binders A and B the loss of stiffness at peak DER is lower than 50% whereas an opposite response is exhibited by binder C, for which $\%\Delta G_0^*$ at peak DER is significantly higher. This type of behaviour is typical of highly modified binders and reveals their aptitude in dissipating a great amount of energy before failure [31].

Duration of rest periods was set equal to the time required by each binder to reach the peak DER, determined on the basis of the fatigue tests mentioned above. During each rest period, the same low oscillatory shear strain applied in the conditioning phase (equal to 0.01%) was used to monitor the evolution of complex modulus with time.

Binder Code	Isostiffness temperature [°C]	$\%\Delta G_0^*$		Rest time [min]
		½ G^*_0	Peak DER	
A	20.3	50%	27%	360
B	23.0	50%	23%	80
C	18.0	50%	92%	390

Table 2: Measurement conditions adopted in healing tests.

A no damage condition was also considered in binder testing. In this case, the materials were subjected to "steric hardening" tests, in which a prolonged rest period was imposed (with 0.01% shear strain at 10 Hz) following the initial thermal conditioning phase in order to evaluate isothermal growth of complex modulus due to molecular rearrangement. At the end of the initial conditioning phase and before the rest period few loading cycles at 250 kPa amplitude were applied to the specimens in order to induce a structural reorganization of molecules and reproduce testing conditions similar to those occurring at the beginning of the loading phase of healing tests. After the rest period, specimens were subjected to stress controlled cyclic loading at 250 kPa amplitude until failure.

3. RESULTS AND DISCUSSION

3.1 Results of healing and steric hardening tests

Figure 1 shows typical results obtained from the above described test procedure conceived to study the healing properties of bituminous binders. By plotting measured values of complex modulus G* as a function of loading cycles N, the different stages of the test sequence can be clearly identified. Characteristic values of the complex modulus are identified by two pedexes: the first one refers, for each phase, either to initial (i) or final (f) conditions; the second one to the conditioning (C), loading (L), rest (R) and reloading (RL) phases. During the first stage of conditioning G* raises from a very low initial value to the value G^*_{fC} as a consequence of the combined effects of thermal conditioning and steric hardening. In the following stage, the material is progressively damaged by oscillatory loading, with the complex modulus decreasing from G^*_{iL} (nominally equal to the isostiffness value of 15 MPa) to G^*_{fL} which corresponds to the predefined modulus loss reached before interrupting loading (50% or peak DER). The initial sudden drop of complex modulus occurring in the loading phase is explained by some researchers by referring to thixotropy effects and to temperature increase due to energy release [32-33]. A significant gain in stiffness is exhibited by the binder during the third stage of the test (rest period), as indicated by the growth of complex modulus from G^*_{iR} to G^*_{fR}. Finally, after reloading the complex modulus decreases from the value G_{iRL} until complete failure of the material is reached (100% shear strain).

It is interesting to note that as a result of material non linearity, when passing from strain controlled to stress controlled conditions and vice versa, a significant variation of the complex modulus can be observed (from G^*_{fC} to G^*_{iL}, from G^*_{fL} to G^*_{iR} and from G^*_{fR} to G^*_{iRL}).

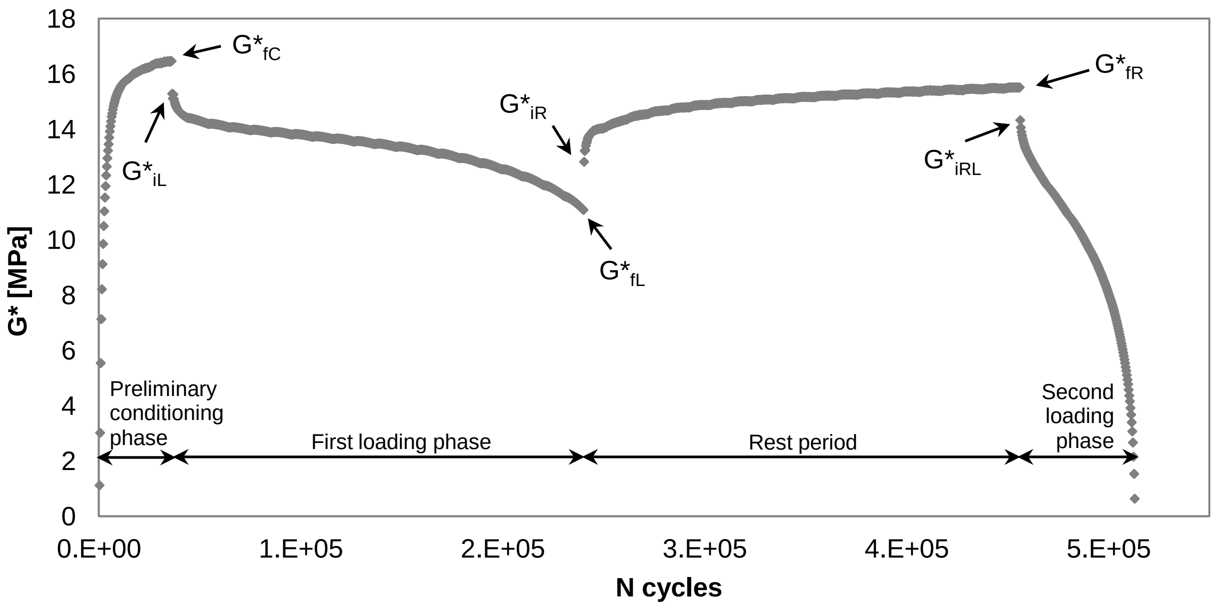

Figure 1: Typical results obtained from healing tests (Binder A).

The magnitude of stiffness recovery occurred during the rest period can be quantified by means of the ratio between the complex modulus increase after rest and the complex modulus loss recorded in the first phase of loading. Such a parameter was computed taking into account the data acquired both in the strain controlled (ΔG^*_γ) and stress controlled mode (ΔG^*_τ) by means of the following formulae:

$$\Delta G^*_\gamma = \frac{G^*_{fR} - G^*_{iR}}{G^*_{fC} - G^*_{iR}} \cdot 100$$

$$\Delta G^*_\tau = \frac{G^*_{iRL} - G^*_{fL}}{G^*_{iL} - G^*_{fL}} \cdot 100$$

Results obtained by following such an approach are shown in Figure 2. ΔG^*_γ and ΔG^*_τ values clearly decrease as a consequence of increasing $\%\Delta G_0^*$, thus revealing that relative recovery of stiffness is significantly affected by the amount of damage experienced by the binders during the first loading phase. Moreover, loading mode also produces non negligible effects, with a higher recovery associated to strain controlled data (ΔG^*_γ) for all the materials considered in this study.

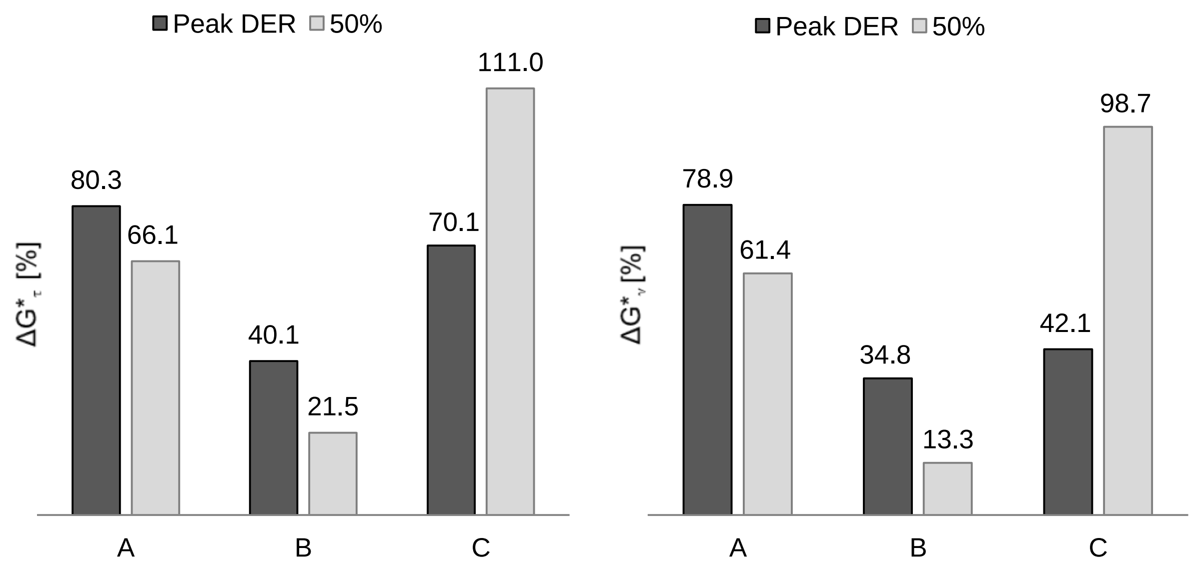

Figure 2: Relative recovery of complex modulus exhibited by the binders during rest period.

In Figure 3 an example of the results obtained from "steric hardening" tests is reported. During the rest period G* values increase by following a trend which appears to be coherent with the evolution of the complex modulus recorded in the preliminary conditioning phase. Since only a negligible damage may have been induced in the material immediately before the rest period by means of the few loading cycles, the observed increase in stiffness cannot be related to self healing effects. Thus, such effects are postulated to be related to steric hardening and need to be subtracted from apparent healing assessed by means of the previously described test procedure for a reliable characterization of the true healing potential of the bituminous binders.

Once again, non linearity effects were highlighted in the transition from one mode of loading to the other (from strain controlled to stress controlled and vice versa). Moreover, trends observed in the rest and reloading phase are of the same type recorded in healing tests.

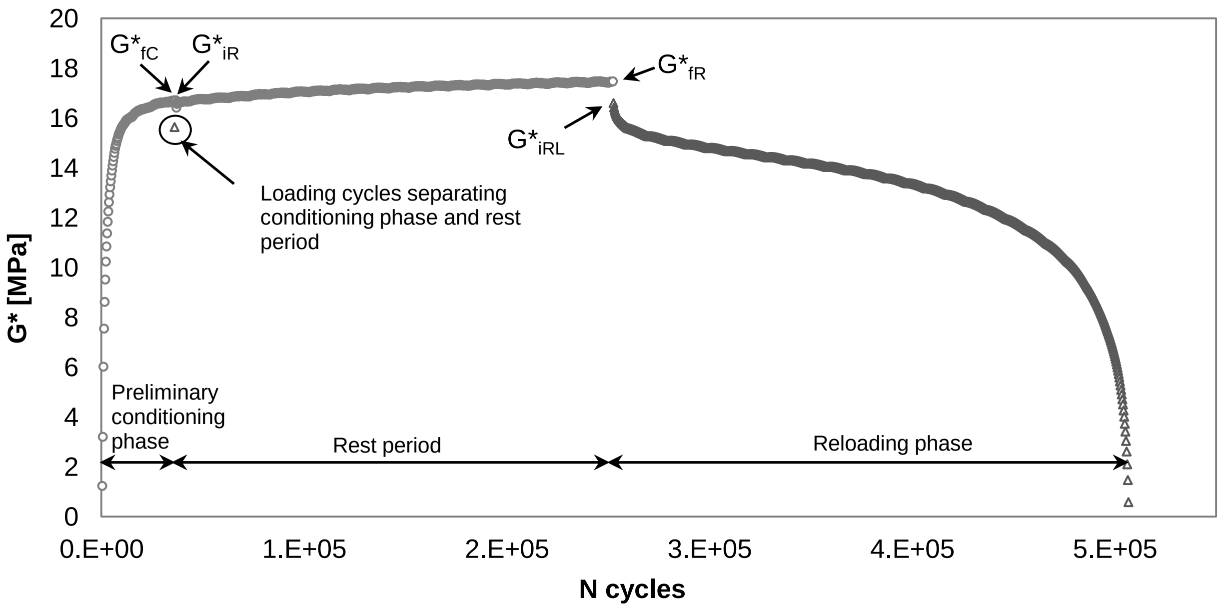

Figure 3: Typical results obtained from steric hardening tests (Binder A).

3.2 Evaluation of true self healing

Evaluation of true self healing potential of the binders stems from the comparative analysis of the time dependent complex modulus increase ΔG*(t) observed during rest periods starting from different levels of damage. This is shown in Figure 4, where ΔG*(t) values derived from healing and steric hardening tests are plotted for all considered binders. ΔG*(t) is given by the difference between the complex modulus measured at rest time t and the complex modulus recorded at the beginning of rest period ($G^*(t) – G^*_{iR}$).

In all cases similar qualitative trends are observed, with an initial abrupt increase of ΔG*(t) followed by a phase in which the increment of stiffness takes place at a much lower rate. Such an evolution is coherent with the kinetics of healing phenomena as described by the intrinsic healing function [7,8]. According to this approach, a short term instantaneous healing effect occurs as a result of the work of cohesion between the fracture faces of the bituminous binder. Consequently, long term healing occurs more gradually and is governed by the molecular diffusion properties of the material.

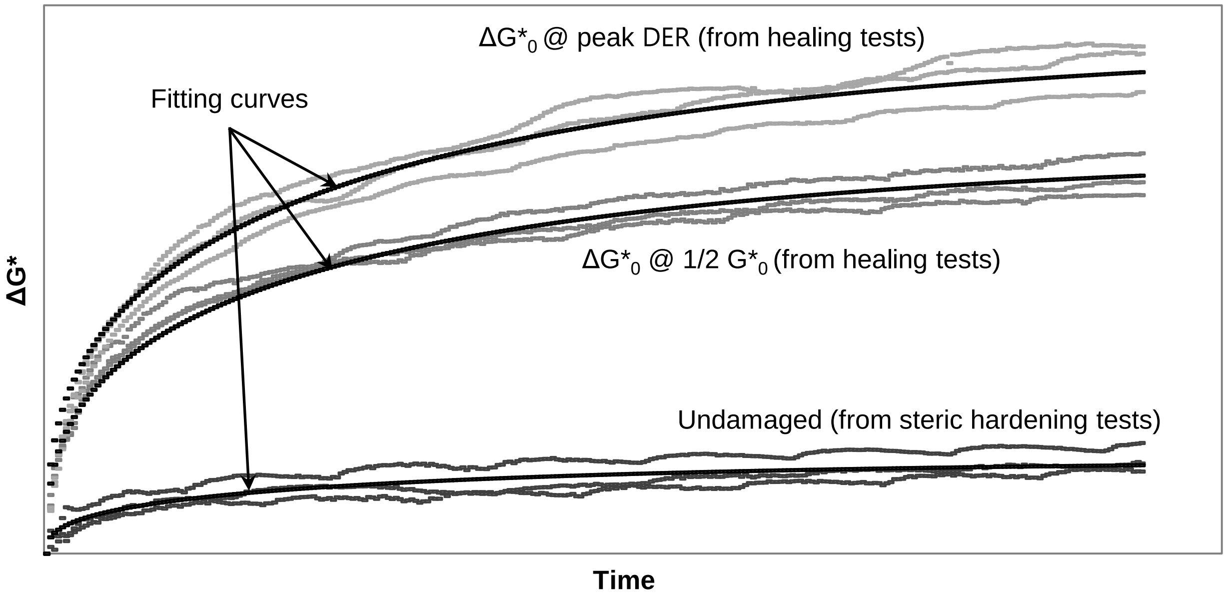

Figure 4: Evolution of complex modulus during the rest period after different levels of damage.

The following expression was used to fit the experimental data:

$$\Delta G^*(t) = \Delta G_\infty \cdot \left(1 - \frac{1}{exp(\alpha t)}\right)^\beta$$

were α and β are non linear regression parameters and ΔG_∞ is the asymptotic value of $\Delta G^*(t)$, representing the maximum gain in stiffness that can be theoretically attained by the material at an infinite rest time. Regression analysis revealed that ΔG_∞ values varied significantly as a function of $\%\Delta G_0^*$, while α and β values were only marginally affected by the level of damage reached in the loading phase. Therefore, in the subsequent data processing both α and β were assumed to be constant for each binder.

Following such a preliminary analysis, the asymptotic increments of complex modulus estimated from steric hardening tests were subtracted from those derived from healing tests. The consequent differences $\Delta G'_\infty$ thus provide the theoretical maximum stiffness gains which can be attained by the binders due to the contribution of self healing only.

The summary of the results obtained from the above described analysis is reported in Table 3.

Binder Code	α	β	%ΔG_0*	ΔG_∞ [MPa]	$\Delta G'_\infty$ [MPa]
A	3.64E-05	0.272	0 %	1.231	-
			27%	4.914	3.683
			50%	3.348	2.117
B	3.00E-05	0.372	0%	0.829	-
			23%	3.088	2.259
			50%	2.595	1.766
C	7.04E-05	0.288	0%	2.763	-
			50%	9.933	7.170
			92%	8.240	5.477

Table 3: Results obtained from the analysis of complex modulus data recorded in rest periods.

As shown by the $\Delta G'_\infty$ values listed in Table 3, the theoretical asymptote in stiffness recovery which can be reached by each binder as a consequence of self healing only is reduced when higher levels of damage are imposed before rest. This observation is coherent with physical expectations and can be related to the reduced capacity of a binder to promote molecular diffusion phenomena across microcracks of increasing opening.

Clear differences can be noticed among the considered materials. By comparing the two neat binders, the values of $\Delta G'_\infty$ exhibited by binder A are higher than those exhibited by binder B at both levels of damage. From the comparison of neat binder B with modified binder C, the effect of the SBS polymer network is highlighted as indicated by the considerable increase of $\Delta G'_\infty$ which also exceeds the theoretical maximum stiffness gain at infinite rest time associated to binder A. Such an evidence confirms previous findings documented in literature which reported SBS modified binders to be characterized by superior healing properties [11,34-35].

In Figure 5 the values of $\Delta G'_\infty$ are plotted against the actual values of complex modulus loss ($G^*_{fC} - G^*_{iR}$) recorded during the first loading phase of healing tests. For an ideal material exhibiting a full self healing capability, $\Delta G'_\infty$ and ($G^*_{fC} - G^*_{iR}$) should be equal. In other terms, if a sufficiently long rest time were given to such a material, it would be able to recover the entire damage imposed before load interruption.

It can be observed that all data points contained in Figure 5 are located under the equality line, thus indicating that the maximum stiffness gain achievable at infinite rest time is always lower than the actual stiffness loss exhibited by each binder. This result reveals that the total damage experienced by the material is the sum of two distinct components: a reversible damage which is progressively recovered during rest, and a non reversible damage, due to the formation of internal microfractures that cannot be healed. Similar conclusions were drawn in the past by other Authors which employed the multiple rest period procedure for the quantification of healing effects in bituminous binders and mixtures [36].

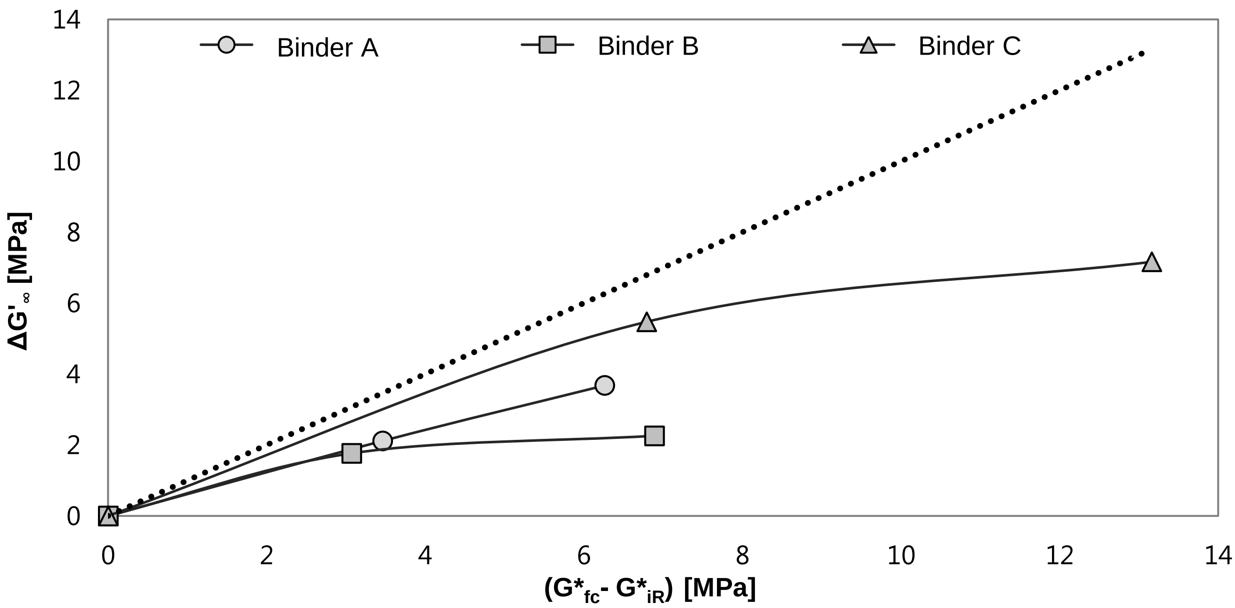

Figure 5: Theoretical maximum stiffness gain plotted against actual stiffness loss caused by loading.

Based on the discussion of the data plotted in Figure 5, the magnitude of reversible damage was expressed in relative terms by introducing in the analysis the following relative reversible damage index (RRD) which provides a quantitative measure of the true self healing potential of the binders:

$RRD = \Delta G'_{\infty} / (G^*_{fC} - G^*_{iR}) \cdot 100$

Corresponding results are reported in Figure 6, which shows that the relative amount of recoverable damage decreases as the level of imposed damage increases. This has been already found and explained when considering $\Delta G'_{\infty}$ values (Table 3); however, as discussed in the following, by expressing the maximum possible stiffness recovery in relative terms (by means of the RRD index) very interesting observations can be made while comparing binders previously damaged to a common level of stiffness loss or to a common condition of energy dissipation (expressed in terms of DER).

Differences between the materials can be clearly identified when comparing results obtained for 50% stiffness loss. In such a case, modified binder C exhibits a RRD value (equal to 80.6%) which is significantly higher than those of the other binders, while differences between the two neat binders are also easily appreciated (with RRD values respectively equal to 58.8 and 32.8% for binder A and B). These results support the conclusions drawn in other experimental studies according to which the source and composition of bituminous binders, either neat or modified, can significantly affect their damage behaviour under the application of repeated loading [11,16].

When considering the data derived from healing tests carried out by cyclically loading the DSR specimens until peak DER, RRD values are quite similar for all binders. This observation validates the assumption according to which peak DER is a critical fatigue point which can be identified by referring to the progression of energy dissipation in the material. According to the experimental data shown in Figure 6, regardless of binder type, in such conditions for the given combination of initial stiffness, loading frequency and applied stress, approximately 40-45% of the stiffness loss cannot be recovered.

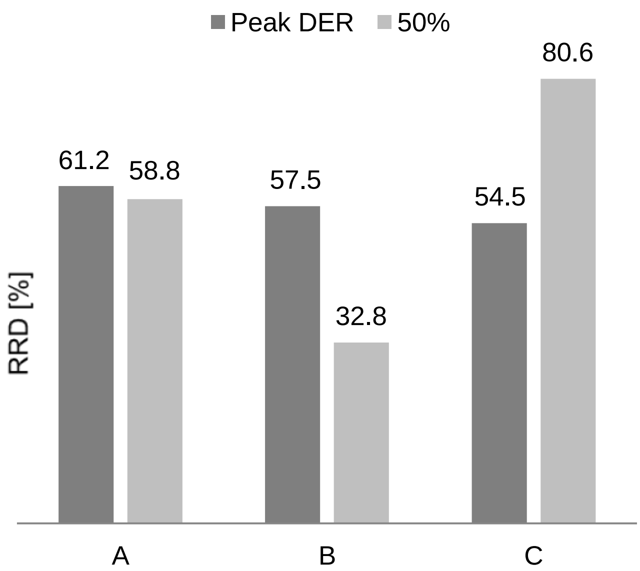

Figure 6: Values of the relative reversible damage index (RRD).

Further observations on the healing potential of the considered binders were made by referring to the relative increase of fatigue life. Such an analysis is based on the scheme displayed in Figure 7, where the results derived from a typical healing test are plotted by omitting the data recorded during the conditioning phase and the rest period. In such a way it can be noticed that after the rest period a certain number of loading cycles (N_R) is necessary to achieve the same value of complex modulus recorded at the end of the first loading phase. Once such a value is attained, the time modulus curve exhibits a shape which appears to be very close to the prolongation of the curve previously interrupted to start the rest period. This finding is coherent with the results of other studies reported in literature [17] and indicates that the binders seem to have memory of their past damage path and continue to follow it until failure.

The number of loading cycles N_R corresponding to the drop of complex modulus from G^*_{iRL} to G^*_{fL} in the reloading phase gives a quantitative measure of the fatigue life increase due to the intermediate rest period. The relative index of fatigue life increase (RFI) can therefore be calculated according to the following formula:

$RFI = N_R / N_f \cdot 100$

where N_f is the fatigue life which the material would exhibit when subjected to continuous oscillatory loading with no rest period, computed by excluding the transient phase comprised between G^*_{iRL} and G^*_{fL} and by operating a horizontal shift of the data points of the second loading phase ($N_f = N_f^* - N_R$).

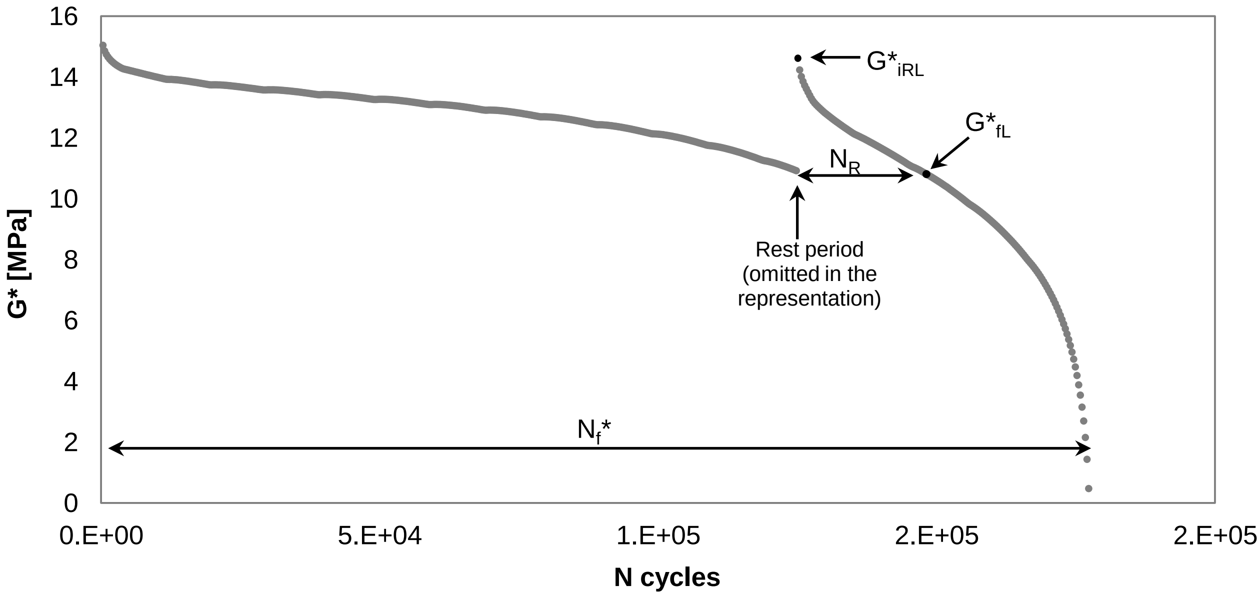

Figure 7: Scheme employed for the determination of the relative increase of fatigue life.

As in the case of RRD evaluation, even in the case of RFI calculations steric hardening effects need to be appropriately taken into account in order to isolate the contribution due to self healing only. This can be done by subtracting RFI values associated to steric hardening tests from those (RFI_{TOTAL}) directly derived from healing tests carried out on the same binders in identical temperature and stress conditions. Resulting RFI values calculated for the binders considered in this study, indicated as $RFI_{HEALING}$, are listed in Table 4.

It can be observed that the relative increase of fatigue life as quantified by means of the $RFI_{HEALING}$ index decreases as the loss of stiffness imposed before load removal increases. This is true for the neat binders only which exhibit 50% stiffness loss well beyond critical peak DER conditions (that respectively occur at 27 and 23% for binder A and B). However, an opposite behavior is exhibited by polymer modified binder C. This is due to the fact that polymer modified binders characterized by a diffused network structure generally exhibit G* values which rapidly decrease in the early phases of repeated loading, thereafter reaching a condition of constant rate of stiffness abatement which is followed by a final critical phase of rapid stiffness drop. As a result of this peculiar response, the 50% stiffness loss condition is reached very early with respect to the entire fatigue life, thus leading to the argument that such a criterion may not be significant for the characterization of the response of polymer modified binders under the effects of repeated loading [31]. In the specific case of binder C, at 50% stiffness loss the material is quite far from critical conditions and therefore both during loading and reloading it shows a rapid stiffness decrease which leads to a limited value of $RFI_{HEALING}$ (equal to 3.22%). When loading is continued up to critical peak DER conditions, the material follows a non negligible portion of the G* curve which slowly decreases as a function of applied loading cycles. Thus, its recovery properties are adequately highlighted during reloading, with the consequent significant increase of the $RFI_{HEALING}$ value.

When comparing between each other the various materials subjected to testing, it is interesting to note that after reaching damage at peak DER the maximum value of $RFI_{HEALING}$ is exhibited by binder A which as a result of healing phenomena can extend its fatigue life by about 9%. From the comparison of results obtained for binders B and C it can also be concluded that in these conditions polymer modification enhances the healing related gain of fatigue life, approximately bringing it from 4 to 7%.

Binder Code	ΔG_0^*	RFI_{TOTAL} [%]	$RFI_{HEALING}$ [%]
A	0 %	2.42	-
	27%	11.32	8.89
	50%	4.51	2.09
B	0%	1.23	-
	23%	5.17	3.94
	50%	1.78	0.55
C	0%	0.28	-
	50%	3.50	3.22
	92%	7.09	6.81

Table 4: Values of the relative index of fatigue life increase ($RFI_{HEALING}$).

4. CONCLUSIONS

The experimental results presented in this paper highlight the importance of considering steric hardening effects in the assessment of self healing properties of bituminous binders. In particular, employed rheological test methods and proposed analysis procedures seem to be adequate in order to quantify true self healing as a function of imposed damage, binder source and/or polymer modification. Both the relative reversible damage index (RRD) and the relative index of fatigue life increase ($RFI_{HEALING}$) can be easily calculated from test results, provided that healing and steric hardening tests are carried out in the same temperature, stress and rest period conditions.

One of the key aspects which ensures a satisfactory reliability to the proposed approach is the choice of single rest periods. By including them in the testing sequences the time dependent kinetics of healing and steric hardening mechanisms can be captured and clearly separated by simple subtraction. The analytical formulation proposed for the modelling of time dependent stiffening effects revealed the existence of an asymptotic value of stiffness gain ($\Delta G'_{\infty}$) which can be obtained at infinite rest time. For all binders considered in this study the maximum stiffness gain was dependent upon the level of damage experienced during the previous cyclic loading phases and lower than the actual stiffness loss, thus indicating that cumulated damage is composed by a reversible and a non reversible part.

When considering a damage level corresponding to 50% stiffness loss, in the case of both proposed indexes (RRD and $RFI_{HEALING}$) a straightforward ranking of the materials is obtained, with the polymer modified binder showing the highest self healing potential. However, other interesting observations can be made if self healing is evaluated after the binders have reached peak DER, which corresponds to a characteristic failure condition. In this case the relative amount of reversible damage is similar for all materials and the increase of fatigue life deriving from the use of SBS polymers can be appreciated only by comparing the results obtained on the base bitumen and on the corresponding modified binder.

Further studies are certainly needed to validate the proposed approach on the basis of 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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