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Extended summary

Fatigue phenomenon in bituminous binders: a rheological approach for the evaluation of damage and healing mechanisms

Curriculum: structure and infrastructure engeneering

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Abstract. One of the most common distresses occurring in asphalt pavements is fatigue cracking, which is taken into account both in pavement design and in the selection of base materials and mixtures. In particular, care must be taken in evaluating the fatigue resistance of bituminous binders, in which cracks actually form and propagate. 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. 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 the present work the results of an extensive laboratory investigation, carried out in order to understand the behaviour of a wide range of bituminous binders employed for paving applications, is presented. Specific test protocols were adopted in order to show the effects of several factors on fatigue and healing response such as binder type, ageing, and modification.

Keywords. Bituminous binders, damage, healing, rheology.

1 Problem statement and objectives

The performance of a flexible pavement is dictated by its resistance to specific distresses; mainly cracking caused by repeated loadings or low temperatures, and rutting [1].

Fatigue, in particular, is a phenomenon that is influenced by the intrinsic peculiarity of the constituent materials, structural characteristics and environmental and loading conditions [2]. Although microcracks initiation and propagation have frequently been thought of as an irreversible process, in the last decade bituminous materials ability to partially reverse damage has been widely proven. While traffic induces to progressive degradation, in the time elapsing between consecutive loads, a recover of mechanical properties can be observed, partly due to the self-healing potential of the material [3].

The fatigue response of a bituminous mixture is governed by a strict interaction between aggregates and binder, that entails a non-homogeneous stress and strain distribution in the material. Due to the pronounced viscoelastic property, the binder phase leads the energy dissipation process, covering a role of paramount importance in the damage accumulation mechanism. On the other hand, the peculiar physico-chemical nature of bitumen determines the capability to heal. The study of the binder phase alone, isolated from the lithic component, can yield to a simplification of the problem and, at the same time, lead to a clear comprehension of the phenomena involved [4, 5].

According to the above stated concepts, an extensive laboratory investigation was conducted with the aim of analysing the rheological response of a wide range of bituminous binders to fatigue, taking into account the effects ascribable to both modification and ageing.

2 Research planning and activities

In the present work the assessment of the fatigue behaviour of several bitumen for paving applications was carried out by means of a Dynamic Shear Rheometer (DSR).

The developed experimental plan can be divided into two different phases. The former focused on the study of the damaging process, without considering the phenomena that occur during rest periods. The latter envisaged the introduction of a span of time between traditional fatigue tests. This further examination allowed a better comprehension of the fatigue behaviour that binders exhibit in the field, which is widely influenced by the variation in mechanical properties that takes place when materials are maintained idle.

The analysis of damage accumulation was carried out by comparing traditional and innovative energy-based approaches. The materials involved were, beyond a broad range of neat bitumen diversified in physical properties, bitumen modified using styrene-butadiene-styrene, crumb tyre rubber, industrial paint sludge and carbon nanotubes. The effect induced in the binder by short and long-term ageing treatments in accordance with Rolling Thin Film Oven (RTFO) and Pressure Ageing Vessel (PAV) tests [6, 7], were studied on both neat and polymer modified materials.

Healing capability was explored by considering the influence of several factors such as the length of rest period, the level of damage withstood by the sample, the presence of a modifying agent, and the degree of ageing experienced.

The effect of rest periods on the rheological behaviour of the binders was analysed in terms of recovery of the mechanical properties and in terms of extension of fatigue life. In an attempt to isolate steric hardening effects in the mechanical improvement, rest periods were applied when negligible damage occurred on the sample.

3 Analysis and discussion of main results

In this section the assessment of the self-healing capability for three of the binders tested is extrapolated from the complete work. The materials include two neat bitumen (A and B) and one polymer modified binder (C). The polymer-modified binder was originated from the base bitumen coded as B, by adding a high percentage of styrene-butadiene-styrene (SBS) according to the undisclosed processing scheme adopted by the plant which provided the material.

3.1 Healing tests

The healing test procedure employed in the research consisted in a continuous sinusoidal load applied to binder specimen in stress controlled mode, in which an intermediate rest period was introduced between a first (loading) and a second (re-loading) phase. Both in loading and re-loading phases, the oscillatory shear stress amplitude was set at 250 kPa with a frequency of 10 Hz.

The specimens were conditioned at the test temperature for one hour before running healing measurements. During conditioning time a low oscillatory shear strain of 0.01% at a frequency of 10 Hz was applied to the specimen and the evolution of the complex modulus over time was then recorded.

With the purpose of preventing possible drawbacks related to stiffness-dependence of the material damage process, the tests were carried out in iso-stiffness conditions. An initial complex modulus of 15 MPa was selected for measurements both to assure the occurrence of true fatigue within the sample and to limit machine compliance [8, 9].

The first loading phase of healing tests was interrupted when a predefined level of damage was reached by the material, expressed in terms of relative loss of the initial complex modulus; on the contrary, the re-loading phase was prolonged up to 100% shear strain.

Two different values of modulus loss were used for each material, selected to reproduce potential 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 and corresponds to the loss of complex modulus at the peak of the *DER* function [10].

The duration of rest periods was set equal to the time requested by each binder to reach the peak *DER*. During the rest period, the same low oscillatory shear strain applied in the conditioning phase was used to monitor the evolution of complex modulus over time.

Figure 1 shows a typical result gathered from the test procedure conceived to study the healing properties of the bituminous binders. The curve was obtained by plotting the measured values of complex modulus G^* as a function of load repetitions N. As can be observed, the different stages of the tests can be clearly identified from the different portions of the curve.

The magnitude of stiffness recovery occurred during rest time can be quantified on the ratio between the increment of complex modulus registered after rest time and the complex modulus loss registered before loading removal. Such a parameter was computed by taking into account the data acquired both in strain controlled mode (ΔG^*_R) and stress controlled mode (ΔG^*_L) by means of the following formulas (1, 2):

$$\Delta G^*_R = \frac{G^*_{fR} - G^*_{iR}}{G^*_{fC} - G^*_{iR}} \cdot 100 \tag{1}$$

$$\Delta G^*_L = \frac{G^*_{iRL} - G^*_{fL}}{G^*_{iL} - G^*_{fL}} \cdot 100 \tag{2}$$

From the results reported in Figure 2, it is evident that the relative recovery of stiffness is strongly affected by the amount of damage experienced by the binder during the first loading phase with ΔG^*_R and ΔG^*_L decreasing as the loss in the initial complex modulus increases.

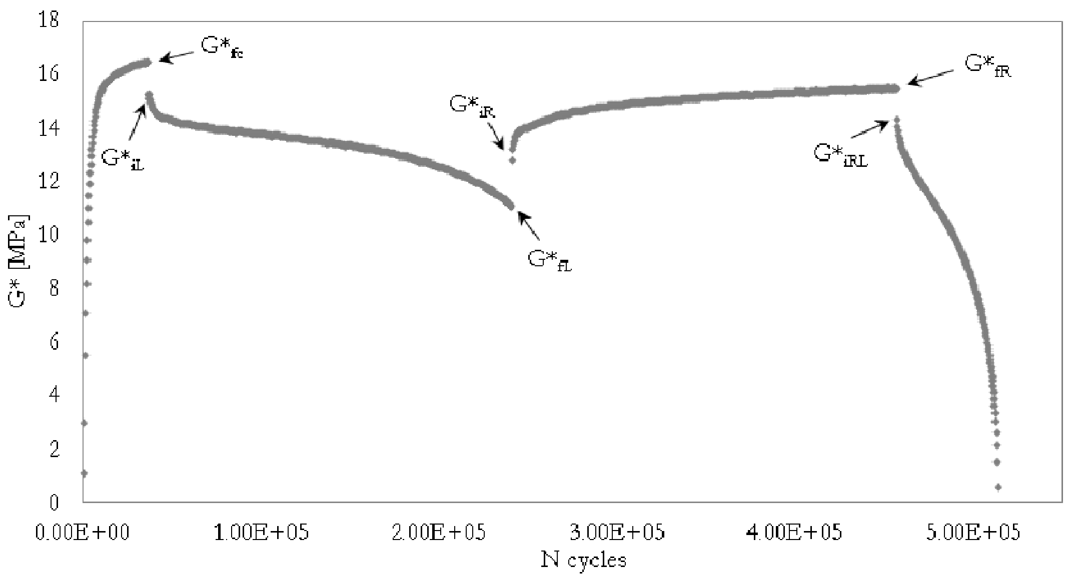

Figure 1. Typical result obtained from healing tests

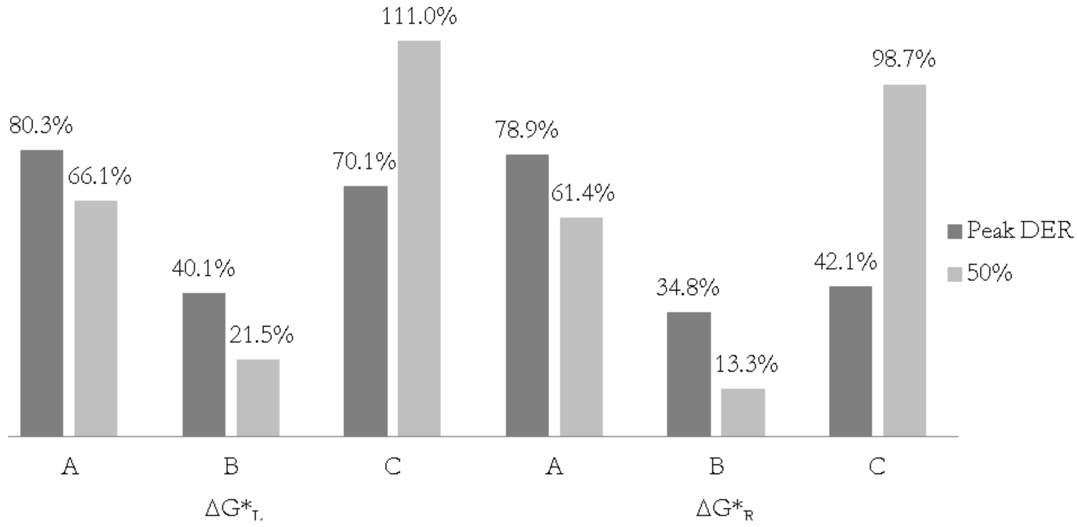

Figure 2. Relative recovery of complex modulus exhibited by the materials during rest time

3.2 Subtraction of steric hardening effects

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 time was applied (with 0.01% shear strain at 10 Hz) following the initial thermal conditioning phase in order to evaluate the isothermal growth of the complex modulus due to molecular rearrangement (steric hardening). At the end of the initial conditioning phase and before the rest time, a minimum number of 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 rest time, the specimens were subjected to cyclic loadings at 250 kPa amplitude up to failure.

In Figure 3 an example of the results obtained from "steric hardening" tests is reported. The presence of stiffness increase registered under no damage conditions reveals the occurrence of stiffening effects during rest time that are not directly involved in the healing mechanism. Such effects are postulated to be related to steric hardening and need to be isolated from true healing for a reliable characterization of real potential of the materials.

In the diagram reported in Figure 4 the increment of complex modulus $\Delta G^*(t)$ typically obtained from the binders during rest time at different levels of damage imposed before loading removal are compared. $\Delta G^*(t)$ is given by the difference between the complex modulus at rest time t and the complex modulus recorded at the beginning of rest phase ($G^*(t) - G_{iR}$). In all cases similar qualitative trends are observed, each one is characterized by an initial abrupt increase of $\Delta G^*(t)$ followed by a stage in which the increment of stiffness takes place at a much lower rate. Similar trends were also observed for the other materials.

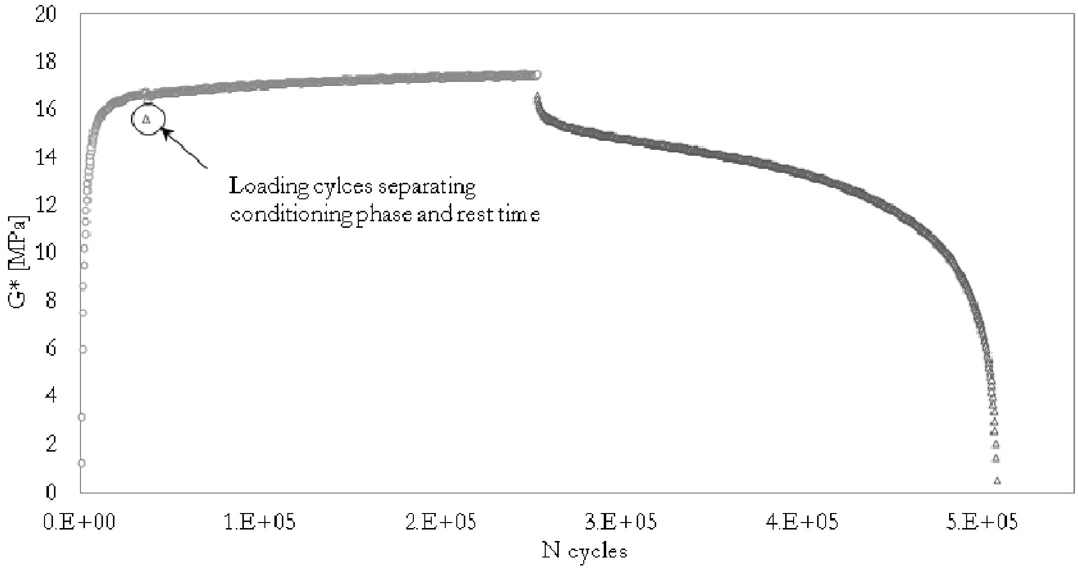

Figure 3. Evolution of complex modulus under prolonged iso-thermal conditions

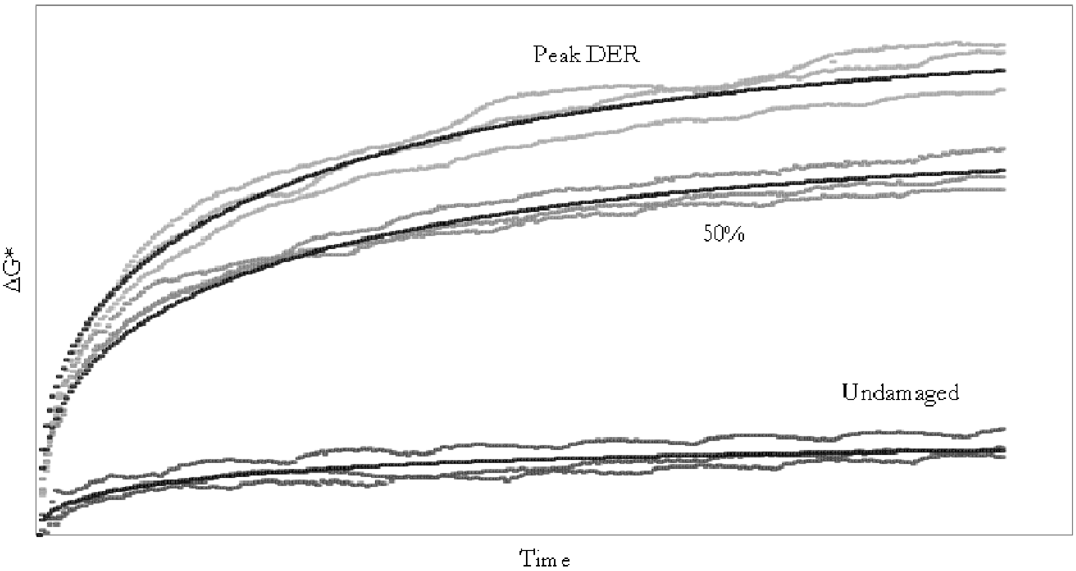

Figure 4. Evolution of complex modulus during rest time at different levels of damage

The following expression (3) was used to interpolate the experimental data:

$$\Delta G^{*}(t) = \Delta G_{\infty} \cdot \left(1 - \frac{1}{\exp(\alpha t)}\right)^{\beta} \tag{3}$$

where 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 infinite rest time.

The regression analysis revealed that α and β values are marginally influenced by the level of damage imposed by the loading phase, hence both parameters were assumed to be the same for each binder, independently of the loss in initial complex modulus. On the contrary, the values of the asymptote ΔG_∞ varied significantly with the level of damage imposed; in particular the higher the loss of stiffness the lower the values of ΔG_∞.

The asymptotic increments of complex modulus estimated from steric hardening tests were subtracted from those derived from healing tests. The differences $\Delta G'_\infty$ provide the theoretical maximum stiffness gains attainable by the binders due to the contribution of self-healing only.

3.3 Self-healing potential of binders

In figure 5 the values of the theoretical maximum increase of the complex modulus at infinite time $\Delta G'_\infty$ obtained for the different binders are plotted against the actual values of the complex modulus loss ($G^*_{fC} - G^*_{iR}$) registered 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 sufficient long rest time is given to such a material, it is able to recover all the amount of damage imposed before loading removal.

As can be observed, all the data points reported in the graph are located under the equality line indicating the maximum stiffness gain achievable at infinite time to be lower than the actual stiffness loss for each binder and test conditions considered in this study. This result reveals that the total damage experienced by the material is the sum of two distinct components: a reversible damage which is restored during rest time and a non-reversible damage, due to the formation of internal fractures that cannot be healed.

The magnitude of reversible damage was expressed in relative terms by the ratio between $\Delta G'_\infty$ and ($G^*_{fC} - G^*_{iR}$) which provides a quantitative measure of self-healing potential of the binders. The results obtained are reported in Figure 6. In general, it is observed that the relative amount of recoverable damage decreases as the level of damage imposed increases since the un-healable damage grows more and more.

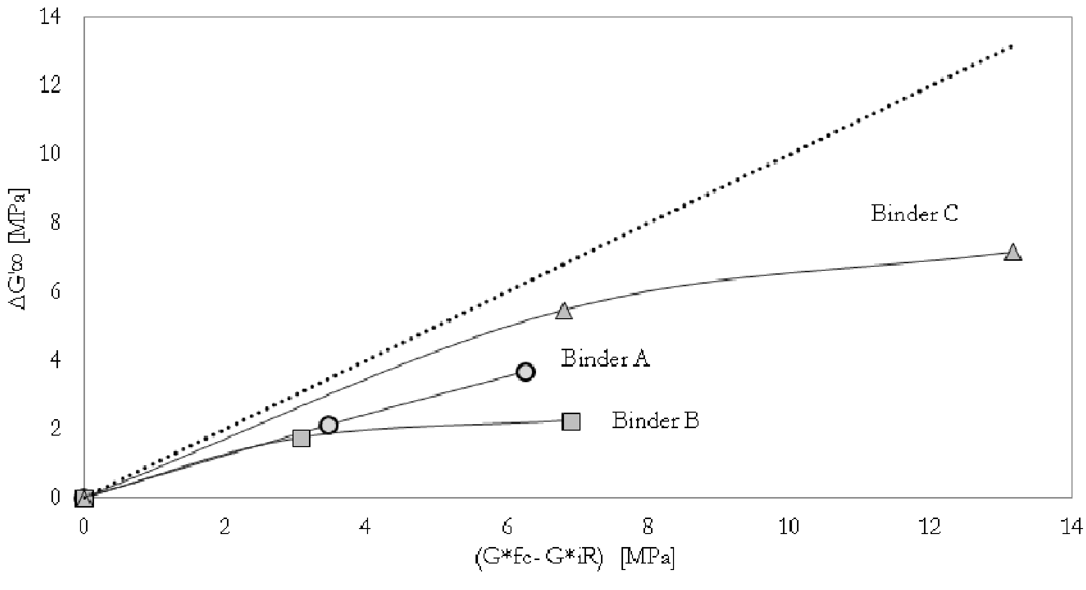

Figure 5. Theoretical maximum stiffness gain plotted against actual stiffness loss

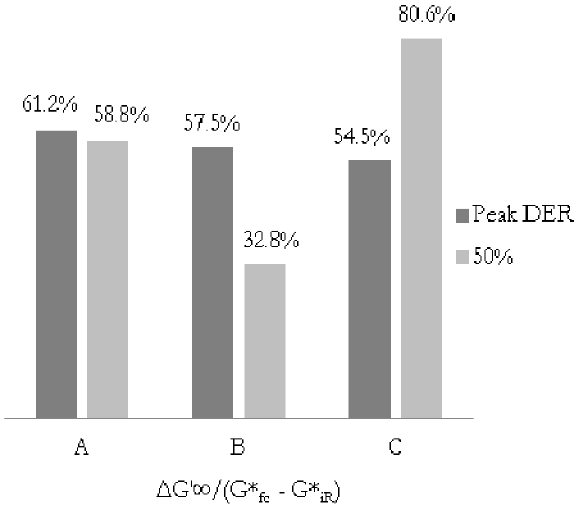

Figure 6. Values of relative reversible damage obtained for the materials

In this case, significant differences are observed among the materials only if compared to each other at the same loss of stiffness (50%), with the modified binder C exhibiting the highest value of relative recoverable damage with respect to the unmodified binders A and B. On the contrary, after a stiffness loss corresponding to peak *DER* the relative unreversible damage is quite similar for all the binders. This confirms the peak *DER* to be a critical fatigue point of the binders and when this point is reached approximately 40-45% of the stiffness loss is not restorable. In interpreting this test result, however, the huge difference in stiffness loss (and consequently in stiffness recovered) at peak *DER* between the polymer modified binder and the unmodified binders should be borne in mind.

4 Conclusions

The experimental investigation highlighted the effects that modifying agents of various nature and dosage induce in the rheological behaviour of base bitumen. Polymer-modified binders 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; while ageing produced an increment of fatigue resistance of the materials without a significant variation of the energy dissipation mechanism.

The assessment of healing capability showed that a test method based on a single long healing event appears to be very useful in capturing the kinetics of stiffening mechanism occurring during rest time, due to both self-healing and steric hardening phenomena. A simple model was developed to separate steric hardening and self healing, that revealed the existence of an asymptotic value of stiffness gain which can be obtained at infinite time. For all the materials considered in this study the maximum stiffness gain was always lower than the actual stiffness loss experienced during the loading phase, indicating that total damage experienced is given by reversible and irreversible damage.

Ageing treatments influenced both the molecular rearrangement of the matrix, that dictate the variation of mechanical properties ascribable to steric hardening, and the molecular inter-diffusion process, responsible for the self-healing of cracks.

Significant differences in healing potential among the materials were detected by means of the relative increment in fatigue life, which is affected by the binder origin and type. The comparison between the base neat binder and the modified binder indicate that the healing properties of the material are greatly improved by the addition of SBS polymer.

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