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Evaluation of healing potential of bituminous binders using a viscoelastic continuum damage approach

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HIGHLIGHTS

- The proposed experimental procedure clearly highlights healing effects.
- VECD modelling is effective for the quantitative assessment of binder healing.
- Results reveal the existence of irreversible damage after continuous shear loading.
- Polymer modification enhances healing properties of base bitumen.
- Neat binders may outperform polymer-modified binders.

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ABSTRACT

A simplified viscoelastic continuum damage model was adopted to analyze experimental data obtained from healing tests consisting of continuous shear loading interrupted by single rest periods. Tests were conducted on various bituminous binders with the purpose of highlighting the aptitude of the proposed methodology in discriminating and ranking their healing potential. Healing was quantitatively assessed by introducing two indicators (HR_C and HR_S) derived from damage characteristic functions. Results revealed the existence of some irreversible damage after continuous shear loading. In addition, even though polymer modification enhances healing properties of base bitumen, in some cases neat binders may outperform polymer-modified binders.

1. Introduction

The capability to recover stiffness and strength after being damaged under loading represents a peculiar property of bituminous mixtures used in road paving applications, commonly referred to as healing. Healing is generally associated to phenomena of micro-crack repair that take place within the material when external loading is removed and sufficient rest time is given [1–5]. Since pavement structures are subjected to non-continuous vehicle loading due to the intermittent nature of traffic, microdamage healing occurring during non-loading phases contributes in extending their actual fatigue life. Experimental evidence of such an occurrence has been provided in several research studies, based both on laboratory testing [6–11] and field data [12,13].

Mechanisms driving microdamage healing are not yet fully understood. By referring to the model originally proposed for polymers [14], microdamage healing is depicted as a two-stage process consisting in the closure of micro-cracks due to wetting and in the subsequent gain of mechanical properties due to interdiffusion of molecules across crack surfaces. In their recent study, Sun et al. [15] were able to identify wetting and molecular diffusion stages by means of fluorescence microscope observations. They also found that healing rate at the wetting stage is lower than at the diffusion stage. Healing rates have been proven to increase as rest periods are extended [16–18]. In addition to time, temperature is the other external factor which significantly affects healing rates. An increase in temperature leads to the softening of the material which flows more quickly towards the crack surfaces. Moreover, at higher temperatures overall mobility of molecules is greater, thus promoting interdiffusion and consequent homogenization of interfaces in contact. Based on complex viscosity measurements, Tang et al. [19] identified the softening point as the optimal healing temperature of penetration-graded bitumen.

When focusing on intrinsic material-related factors, the key role played by chemical composition and molecular morphology needs to be considered. Sun et al. [20] showed that the healing rate of bituminous binders is highly sensitive to the content of aromatics.

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Kim et al. [6] linked healing capability to the length of molecules and to their degree of branching. In particular, the presence of molecules characterized by long chains and limited branching promotes interdiffusion, with the consequent improvement of healing properties. Correlation between self-diffusivity and molecular morphology was confirmed by molecular dynamics simulations conducted by Bhasin et al. [21]. Further confirmation, based on the results of laboratory testing, was provided by Santagata et al. [22] that found the healing ratio of neat binders to be positively influenced by the relative amount of long molecules within the oil phase. In addition to chemical composition and morphology of the base bitumen, the use of polymer modifiers may have a great impact on healing response. In fact, studies conducted on polymer-modified binders indicated enhanced performance for this type of materials in terms of stiffness recovery and fatigue life extension [23,24].

A number of methods and indexes have been proposed by researchers in order to evaluate healing properties of bituminous binders and mixtures. In the case of binders, test procedures are mostly based on the use of the dynamic shear rheometer. Shen et al. [25,26] characterized bituminous binders by subjecting them to intermittent loading sequences in which short rest periods (varying from 0 to 6 s) were inserted. Healing effects were then analyzed by adopting an approach that relies on the ratio of dissipated energy change concept. Tan et al. [17] used a healing test consisting of an initial fatigue test with continuous loading followed by a rest period (varying from 1 to 48 h) and by another fatigue test. Two healing indicators were introduced: the first one was calculated as the ratio of the initial modulus values after and before rest, while the second one was calculated as the ratio between the number of loading cycles applied in the two fatigue tests until failure. Results reported in the paper showed that both indicators well reflect healing potential. A similar protocol was employed by Shan et al. [27] that established three different indexes based on the curves of normalized modulus, elastic modulus and viscous modulus versus loading cycles. These indexes were found to lead to the same ranking of the studied materials. Santagata et al. [22,23,28–30] used test procedures based on cyclic loading interrupted by the inclusion of either a single long rest period or multiple shorter rest periods at predefined levels of damage. In both cases, healing response was assessed on the basis of stiffness recovery exhibited by the binders during the unloading phases. Stimilli et al. [31] and Canestrari et al. [24] performed multiple rest tests and referred to the recovered number of cycles after a given number of rest periods as a criterion for the evaluation of healing properties.

The viscoelastic continuum damage (VECD) model represents a powerful tool in characterizing damage behaviour of viscoelastic materials under loading. Based on the work potential theory developed by Schapery [32,33], VECD theory relates the variation of pseudostiffness (C) to an internal state variable (S) resulting in a damage evolution law (C(S)) which has been demonstrated to be unique for each material and independent from testing conditions (mode of loading, frequency and amplitude) [34–36]. VECD modeling has been widely and successfully used to predict damage evolution of bituminous mixtures subjected to uniaxial cyclic fatigue tests [37–40]. More recently, it has been extended to bituminous binders and mastics tested under cyclic torsion [41,42]. Continuum damage mechanics also represents the theoretical framework used to determine fatigue laws from linear amplitude sweep (LAS) tests. LAS tests, along with a simplified version of the VECD model, have been adopted by Xie et al. [43] to characterize healing in bituminous binders.

This paper presents the results of an experimental study in which the VECD approach was used to analyze test data obtained from healing tests consisting of continuous shear loading interrupted by single rest periods. Two different indicators derived from damage evolution curves before and after rest were introduced to quantify healing. Experiments were conducted on a set bituminous binders of various origins and types with the purpose of highlighting the aptitude of the proposed methodology in discriminating and ranking the healing potential of materials with very different characteristics.

2. Materials and methods

Materials selected for the experimental investigation included two neat bitumens (NA and NB) which were sampled from refineries operating on crudes of different source, and two polymer-modified binders (PMBL and PMBH) which were originated from base bitumen NB by adding a low and high percentage of styrene-butadiene styrene (SBS) elastomer, respectively (of the order of 2–3% and 4–6% by weight of base bitumen, according to the undisclosed processing scheme adopted by the manufacturer). Description of binders, along with their penetration grades and performance grades (PGs), is given in Table 1. All materials were evaluated after being treated with the Pressure Aging Vessel (PAV) in order to simulate long-term ageing, which is considered the most representative condition for the analysis of damage phenomena.

The experimental procedure followed in the study involved the use of fatigue and healing tests.

Fatigue tests consisted in continuous oscillatory shear loading applied in the stress-controlled mode and prolonged until complete specimen failure. They were conducted with the primary purpose of determining the characteristic damage behaviour of the materials to be assumed as a reference for healing analysis. Temperature was set at 20 °C, which represents a typical intermediate temperature used in fatigue studies. Frequency and stress amplitude were fixed at 10 Hz and 250 kPa, respectively. These testing conditions ensure a sufficiently high initial stiffness of materials which has been indicated as a crucial factor in preventing the occurrence of phenomena like instability flow and edge effects, thus highlighting true internal microdamage [44].

Healing tests consisted in two continuous oscillatory shear loading phases with an intermediate rest period. Temperature, frequency and stress level were set equal to those of fatigue tests. A single rest period of 6 h was adopted. Such a choice was suggested by the need of providing sufficient time to the materials to recover mechanical properties lost before loading removal, thereby allowing their healing potential to be highlighted [28]. The rest period was inserted in healing tests at predefined levels of material integrity loss expressed in terms of pseudostiffness reduction. This was practically done by interrupting the first oscillatory loading phase when shear strain amplitude exhibited by the specimen reached a specific threshold corresponding to the C value associated to the target integrity loss level as determined from reference fatigue test curves. The selected values of C before loading removal, C_{BR}, were 0.75 (25% integrity loss) and 0.5 (50% integrity loss) for all binders. Due to its peculiar behavior, in the case of heavily modified binder PMBH an additional C_{BR} value equal to 0.1 (90% integrity loss) was

Table 1
Bituminous binders used in the experimental study.

Binder code	Description	Penetration grade	PG
NA	Neat	70/100	64–16
NB	Neat	70/100	58–22
PMBL	Modified with SBS (low polymer content)	45/65	70–22
PMBH	Modified with SBS (high polymer content)	50/70	76–22