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# Modeling and assessment of self-healing and thixotropy properties for modified binders

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ABSTRACT

The fatigue endurance limit of binders is the results of more phenomena (e.g. viscoelasticity, damage, healing, thixotropy, steric hardening) that interact simultaneously making the mechanisms behind the fatigue behavior not properly understood.

Currently, there is no consolidated analytical approach inclusive of such phenomena to characterize fatigue performance.

This research proposes a criterion to determine the fatigue resistance of binders subjected to monotonous cyclic loading with multiple rest periods. The main rheological properties are measured during each stage using a Dynamic Shear Rheometer and the modeling of their evolution is proposed. The experimental program includes different binders in order to investigate the effects of SBS modification levels and aged binder contents on self-healing potential and fatigue behavior.

The proposed criterion enables to identify fundamental contributions leading to a comprehensive fatigue endurance limit. This approach allows different binders to be distinguished taking into account their self-healing capacity and can help to establish a better correlation with in-service performance of mixtures.

Moreover, a comparison with a previous analytical approach based on the same kind of test (time sweep) with only one rest period is proposed in order to evaluate the effectiveness and reliability of the proposed criterion. Results show that multiple rest periods are needed in order to fully understand the self-healing and fatigue behavior of bituminous binders and to quantify the contributions given by thixotropy.



## 1. Introduction

Fatigue cracking is one of the major causes of deterioration of asphalt pavements, caused by continuous application of traffic loads over a period of time. The resistance to this phenomenon can be measured monitoring the variation of the material stiffness and can be quantified as the maximum number of loading cycles that a material is able to endure until failure. Many concerns still exist about fatigue resistance definition and its determination through laboratory tests, often resulting in empirical calibration factors needed to correlate laboratory and in situ measurements. The bituminous phase of a mixture is the component that plays a crucial role in the evaluation of fatigue life [1–5]. The analysis of binder fatigue resistance shall be the results of more mechanisms, time and temperature dependent. In particular, self-healing and thixotropy are two phenomena that can characterize viscoelastic materials, such as bituminous binder, and occur simultaneously when the material is subjected to an external stress.

Self-healing is the ability to recover part of the damage accumulated during the loading phase and occurs when the load is removed (rest period). It has been shown that, for bituminous binders, self-healing is a multi-stage mechanism composed by short term wetting and cohesion at the crack interface and long term interdiffusion, the main responsible for stiffness recovery during time [6]. It is strongly related to the chemical structure of the material, as well as to test conditions (e.g. temperature, strain amplitude, frequency). Self-healing takes place at the interface between the crack edges and contribute to the total fatigue response by enhancing the fatigue life of a material referred as global fatigue endurance limit. It acts as long as the material does not completely fail and there is still contact between the crack surfaces.

Thixotropy is associated to the behavior of a non-newtonian fluid in which the viscosity decreases with time during the application of

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a given shear rate. Once the mechanical disturbing action is removed, the material settles back into its original consistency and recovers its original rheological properties [7]. Thixotropy is an inherent characteristic of materials and represents the capability to recover the microstructure inside the un-cracked part of the sample. It acts when the material is stressed (loading phase), as well as when the stress is removed (rest period). Thus, a certain portion of the stiffness loss during a fatigue test, as well as a part of the stiffness during rest periods, can be considered as a result of the thixotropic phenomenon. Thixotropy depends on time. Since also the fatigue process varies in time, it is believed that thixotropy can be involved in the material properties changes observed during a fatigue test [8,9].

So far, few research activities have been focused on the simultaneous interaction between fatigue, self-healing and thixotropy. Soltani and Anderson [10] performed uniaxial push pull tests on cylindrical specimens to investigate fatigue and self-healing characteristics of mixtures. They concluded that non-fatigue phenomena, in particular thixotropy, play a fundamental role in the drop in modulus during both the loading and the rest phase. Also Shan et al. [11] proposed to interpret healing data using the thixotropy concept. They investigated different binders by correlating the parameters of a thixotropic model with the physically observed asphalt fatigue and healing behavior. Their study is an attempt to interpret a fatigue test considering the influence of thixotropy by focusing on the dynamic viscosity changes recorded during fatigue/healing tests. The authors suggest that these changes can be related to the changes in rheological properties due to thixotropy. They also focused the attention on the Black Space, that depicts the curve of the complex modulus norm ($|G^*|$) and phase angle ($\delta$), trying to identify the dividing point between the thixotropy-influence phase and the second phase in controlled strain model [12]. Di Benedetto et al. [9,13] observed that the initial reduction in modulus during a fatigue test is strongly related to parasitic thixotropic effects developed by bituminous materials during cyclic loading. They considered this effect as an artifact, in the sense that is totally recoverable. They supported this conclusion observing that this stiffness loss is rapidly recoverable when the test is halted, but they recommended further investigation to take into account the self-healing capability of asphalt binder.

The need to find a unique model to quantitatively identify the contribution of every single phenomenon that acts during a fatigue test is still not solved.

In this paper, a new test method and a new model are proposed to analyze and interpret the data collected by running a time sweep test with multiple rest periods. The time sweep test is a fatigue test that consists in subjecting bituminous specimens to repeated cycling of stress or strain loading at a selected temperature and loading frequency [14]. The time sweep allows for the bitumen to go beyond linear viscoelastic behavior and into the damage accumulation rate. In this sense, it is considered a useful tool for characterizing the material in terms of fatigue properties. In this study, the standard time sweep test protocol was modified with the insertion of intermittent multiple rest periods at a specified damage level. By analyzing the results recorded using the proposed interpretative criterion, it is believed to provide an easy and practical tool to identify the true self-healing potential of bituminous binders and its impact on the overall fatigue resistance taking into account also the thixotropic phenomenon that concurrently occurs. Therefore, this criterion should allow to define a more reliable value of the global fatigue endurance limit better correlated with in-service performance of bituminous mixtures.

Based on this approach, self-healing capability of different binders was discussed considering the influence of different levels of polymer modification. In addition, in order to investigate the self-healing potential of mixtures containing Reclaimed Asphalt (RA), long term aged binders were also considered.

Finally, a comparison with a healing analysis previously proposed by other researchers is provided. In particular, Tan et al. [2] performed the same type of test (time sweep) applying one single rest period instead of multiple rest periods. This comparison allows the evaluation of the effectiveness and reliability of the criterion presented in this paper. Analyzing the different results obtained by applying one or multiple rest periods is useful to fully identify and understand the self-healing capability and the fatigue behavior of bituminous binders.

## 2. Materials and test procedure

One base binder (B) and three SBS modified binders have been investigated. The modified binders were obtained from the same base bitumen (B) and three different modification levels, 1.8% (S), 2.8% (M) and 3.8% (H) of SBS radial polymer by bitumen weight (Table 1).

Moreover, binder H was long term aged (R) through Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV), to simulate in laboratory a binder obtainable by a milled highway pavement. Additionally, two fractions (30% and 45% by weight) of so-called "Artificial Reclaimed Binder" R were mixed with each one of the three abovementioned binders S, M, H, in order to investigate the effect caused by Reclaimed Asphalt on the fatigue performance of binder. Therefore, the study included a total of eleven binders as shown in Table 2.

Each bituminous binder was preliminarily characterized in terms of complex shear modulus ($G^*$) performing frequency sweep tests by the application of sinusoidal waves under several frequency and test conditions. The modified CAM model [14] was adopted to analyze the test data and to find the relationship between the complex modulus norm and the reduced frequency at a reference temperature of 30 °C (Fig. 1), following a shift factors variation based on Williams-Landel-Ferry equation [15].

It is possible to note that the binders analyzed are characterized by similar master curve trends: differences in terms of stiffness values between S, M and H do not appear so evident at both high and low frequencies. Moreover, the adding of different percentages of "Artificial Reclaimed Binder" R does not provide different rheological responses in terms of complex shear modulus norm. In particular, it can be noted that no significant differences exist comparing bituminous blends with 30% or 45% of artificial

**Table 1**
Basic characteristics of virgin bituminous binders used in this study.

| Binder type | Code | SBS polymer content by weight (%) | Penetration @ 25 °C 0.1 mm | Ring and ball softening point (°C) | Ductility @ 25 °C (Cm) | Dynamic viscosity @ 135 °C (Pa s) | Residue after RTFOT – Mass loss (%) |
|---|---|---|---|---|---|---|---|
| Base | B | 0 | 68 | 45.4 | 82 | 0.22 | 0.07 |
| Soft | S | 1.8 | 59 | 66.8 | 97 | 0.81 | 0.08 |
| Medium | M | 2.8 | 52 | 68.6 | >100 | 1.02 | 0.13 |
| Hard | H | 3.8 | 54 | 70.8 | >100 | 1.24 | 0.05 |