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Analysis of the thixotropic behavior and the deterioration process of bitumen in fatigue tests

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HIGHLIGHTS

- We applied time and strain sweep tests to 7 different bitumens.
- A relation was found between the modulus and energy curves obtained in both tests.
- A new interpretation for the work potential theory was found.
- A new procedure to estimate the fatigue law of the bitumen was developed.

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ABSTRACT

The characterization of fatigue damage on bituminous materials under cyclic loading has been classically studied using tests and procedures previously developed for the characterization of metallic materials. However, these materials present important differences in their behavior in cyclic testing. For instance, the significant loss of modulus the bitumen exhibits at early stages of the test or its total recovery when loading is removed.

Comparison between two types of cyclic testing applied to bitumens, time and strain sweep tests has proven that this phenomenon is related with the nonlinear behavior of the bitumen, thixotropy and viscoelasticity, and that the amount of modulus loss during the initial part of cyclic testing is directly related to the strain applied.

Using the framework of the work potential theory, a new expression has been found for the damage law that describes the loss of modulus of bitumens during the linear phase of the fatigue tests. Additionally, a procedure is proposed to estimate the fatigue relation between the strain applied and the number of cycles to failure using only the data obtained in strain sweep tests. These relations fit reasonably well the experimental data obtained in more time consuming time sweep tests.

Applying this estimation procedure implies a great time savings in the characterization of the fatigue behavior of asphalt binders and the determination of their fatigue laws.

1. Introduction

Fatigue in mechanics is associated with material damage caused by repeated loading. This property first became important in the design of metallic components used in the manufacture of early railway axles [19,23]. It has subsequently been applied to other materials which, like bitumen, undergo property deterioration under cyclic loading. However, significant differences are observed between metal and bitumen.

Loss in stiffness of metallic materials during repeated loading is mainly caused by the appearance of microcracks that grow into a macrocrack with the number of cycles, ultimately leading to material fracture in an irreversible process. In the case of bitumen, stiffness decreases without the appearance of macroscopic cracking or structural change. Moreover, if the material is allowed to rest, it can recover some, if not all, of its initial stiffness. Despite these differences, asphalt damage due to cyclic loading has typically been characterized using theory and concepts developed for the study of metallic materials.

However, to account for the ductile behavior of the bituminous materials, many researchers have studied fatigue in these materials through the analysis of the dissipated energy during cyclic testing [18,25,9].

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The work potential theory has also been used to model asphalt materials behavior during fatigue failure [22,6,14,29,31]. This theory establishes a relationship of equality between available thermodynamic energy and energy required for damage to increase. This relationship is called the damage evolution law (1):

$$\frac{\partial W}{\partial S_m} = -\frac{\partial W_S}{\partial S_m} \tag{1}$$

where $W = W(\varepsilon_{ij}, S_m)$ = strain energy density function, ε_{ij} = strain tensor, S_m = internal state variable (or damage parameter), and $W_S = W_S(S_m)$ = dissipated energy due to damage growth.

Eq. (1)is only valid for elastic materials. For application to visco-elastic materials, such as bitumen, several authors have suggested the following modification [16]:

$$\dot{S}_m = \left(-\frac{\partial W^R}{\partial S_m}\right)^{\alpha_m} \tag{2}$$

where $W^R = W^R(\varepsilon^R, S_m)$ = pseudo-strain energy density function, $\dot{S}_m$ = damage evolution rate with time or number of cycles, α_m = material-dependent constant related to viscoelasticity, and $\varepsilon^R = \frac{1}{E_R}\int_0^{\xi} E(\xi-\tau)\frac{\partial\varepsilon}{\partial\tau}d\tau$ = pseudo-strain.

Eq. (2) was adapted from the Paris law [15] for crack propagation calculation in quasi-elastic bodies by replacing strain with pseudo-strain using the elastic-viscoelastic correspondence principle [21].

Traditionally, it is stated that the evolution of complex modulus during strain-controlled fatigue tests undergoes three different stages or phases. In phase I, a sudden drop in complex modulus is observed, which is often explained by an increase in the temperature of the material due to the energy released during the test, an initial adaptation and a time-dependent change in viscosity, also known as thixotropy. These factors can partially account for stiffness loss and subsequent recovery after a rest period during fatigue tests [7,24,17,5]. In phase II, the modulus remains constant or decreases linearly with the number of cycles. In phase III, the complex modulus drops suddenly, leading to complete failure of the specimen [8].

Recently it has been proven that the strain sweep test (SST) can characterize the fatigue behavior of bituminous binders and provide an estimation for the number of cycles to failure for a given strain amplitude [11,10].

This paper emphasizes the importance of thixotropy in asphalt fatigue characterization by comparing time and strain sweep test results. The comparison between those two procedures provided insight into the damage process in these materials under cyclic loading and the mechanisms leading to the fast initial stiffness loss in phase I. Results in this paper can be used to properly understand the work potential laws describing damage throughout the fatigue process, phase II. Moreover, from similarities between data of both tests, the authors propose an empirical model that provides an approximate relationship between applied strain and the number of cycles to failure using data obtained in a strain sweep test only. This method avoids repeating time sweep test to obtain the fatigue characterization of a material.

2. Test methods

2.1. Time sweep test

Time sweep test is the most common test procedure for asphalt fatigue characterization. It consists in monitoring the stiffness of a material while subjecting it to constant cyclic stress or strain amplitude. Once properties decrease to an arbitrarily established threshold value, the test stops and the number of cycles to failure is recorded. Regarding asphalt binders, complex modulus norm is typically analyzed. Variations of this parameter can be divided into three phases: rapid loss (phase I); slow linear loss with number of cycles (phase II); sharp reduction of property with cycles (phase III) [8]. It is commonly accepted that failure takes place in the third phase. Efforts have been carried out to model this behavior using the three-stage Weibull equation [28]. Nonetheless, since this procedure requires long testing times, an arbitrary relative complex modulus value is fixed to define failure, i.e. half the initial value [2]. This failure criterion works reasonably well for conventional binders (the above percentage is typically reported near the beginning of phase III), but it often leads to errors when testing ductile or modified binders (Fig. 1). Several authors have worked in alternatives to that failure criteria [1,9,30,26,20,32].

Time sweep tests are performed at different strain amplitudes to obtain a fatigue relationship between applied strain and number of cycles to failure. This relationship is assumed logarithmic [4,13,3] and is typically used to fit experimental values:

$$Log\, N_f = k_1 - k_2\, Log\, \varepsilon \tag{3}$$

where N_f = number of cycles to failure, ε = applied strain, and k_1, k_2 = experimental coefficients.

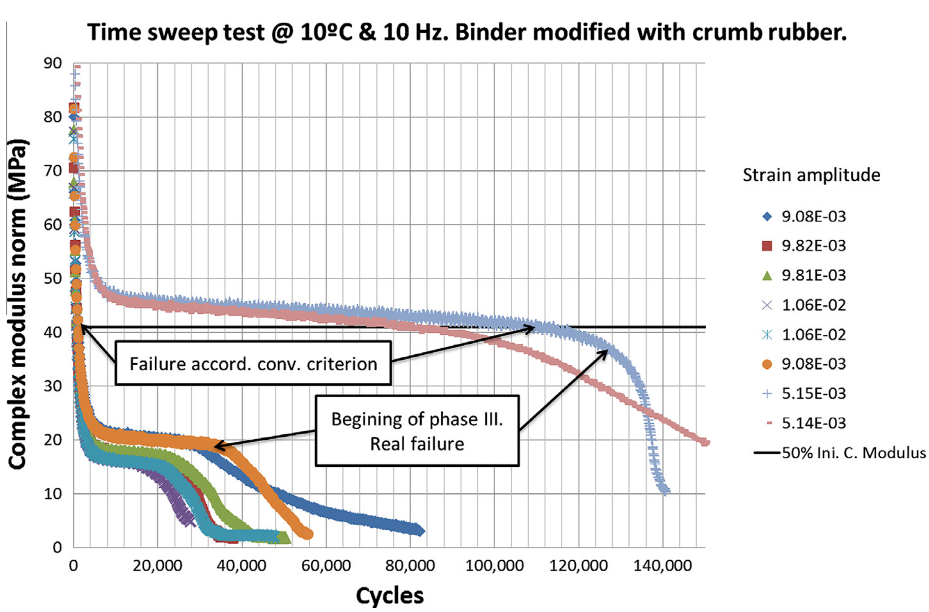

Fig. 1. Time sweep tests performed in uniaxial cyclic tension-compression mode.