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Obtaining the fatigue laws of bituminous mixtures from a strain sweep test: Effect of temperature and aging

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ABSTRACT

Fatigue is associated with the deterioration caused by applying repeated loads, and is affected by temperature or aging. Generally, time sweep tests are used to simulate fatigue, in order to obtain the fatigue laws. However, this requires too much time, often preventing its use. A method to estimate the fatigue laws from a strain sweep test is presented. The test was performed on a semi-dense mixture with different types of binder (unconditioned or aged) tested at different temperatures. This test is able to estimate fatigue laws more quickly, allowing the effect of different factors on the mixtures' fatigue life to be studied.

1. Introduction

Fatigue cracking by applying repeated loads due to traffic is one of the major failure modes in asphalt mixtures and contributes to the degradation of pavements [1]. Fatigue failure is one of the main factors considered in the design of asphalt pavements [2]. Furthermore, due to the complex behavior of mixtures, fatigue failure not only will depend on traffic loads, but also on the duration of those loads [3] and on the environmental conditions, temperature being one of the most important factors to take into account [4]. The asphalt mixtures' properties will vary according to the temperature they are subjected to, behaving in a more rigid and elastic way at low temperatures, and in a softer and viscous form at high temperatures [5]. Furthermore, it must be added that because of environmental conditions, mixtures undergo an aging process during their service life. This process produces changes in the physical and/or chemical properties of the binder of asphalt mixtures. These changes are manifested in an increase in stiffness and brittleness [6]. In addition, temperature can play a very important role in the effect of aging on the mechanical response of the bitumen that forms asphalt mixtures [7], it being advisable to study their combined effect on the fatigue of mixtures. It is therefore important to evaluate the effect of phenomena such as aging or temperature variation, as well as the combination of different phenomena that may produce variations in the fatigue behavior of a mixture during its service life.

To analyze the fatigue behavior of the mixture layers, the fatigue laws of the material are used. Their determination is essential for the design of asphalt pavements by analytical methods. These laws are usually obtained experimentally in the laboratory from the results of standardized fatigue tests. These tests are based on subjecting the samples to a series of cyclic loads. The applied stress, strain or displacement remains constant until the failure of the mixture occurs [8]. Such tests are called time sweep tests. In the literature, there are different methods to evaluate the fatigue resistance, which are difficult to perform. According to the European standard, fatigue can be characterized using five methods [9]. They are two-point bending on trapezoidal specimens, two, three and four point bending on prismatic specimens, and an indirect tensile test on cylindrical samples.

The fatigue laws allow the level of strain or stress to which the mixture is subjected to be related to the number of cycles the mixture can withstand before failure. They have the following expression (1):

$$\varepsilon = a \cdot N^{-b} \tag{1}$$

where N is the number of applications to produce the fatigue failure of the material, a and b are the regression parameters which are adjusted by experimental data, and ε is the strain the material is subjected to in each load application. Thus, this law allows the lifespan of the mixture to be determined.

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The prediction and proper assessment of the fatigue process is a difficult task [10]. This is not only because of the complex nature of the phenomenon itself, but also because the time sweep tests to determine the material fatigue law are time consuming and often very expensive. The study of the fatigue behavior of the materials is even more complicated if the evaluation of the effect of different variables such as temperature or moisture, or the state of the mixture (aged or not, different degrees of aging, etc.) is expected, making it an almost impossible task to carry out. For this reason, researchers try to use other procedures simpler than the standard.

In this context, recently strain sweep tests have appeared. Their main advantage is the speed in assessing fatigue compared to other tests. The LAS (Linear Sweep Amplitude) test is an accelerated fatigue test for bitumens, the intention of which is to replace the time sweep tests. It is based on the application of a cyclic loading at a strain which increases linearly [11]. In the case of bituminous mixtures, the UPC Road Research Laboratory has developed the EBADE test (from the Spanish acronym of strain sweep test). This test applies a cyclic tension-compression loading to an asphalt mixture specimen at a constant strain which increases progressively every certain number of cycles [12]. These tests are based on Schapery's viscoelastic theory [13]. This theory states that changes in the dissipated energy are an indicator of cummulated damage. Schapery found that the damage is defined by Paris' law, Eq. (2).

$$dD/dt = (-\partial W/\partial D)^{\alpha} \tag{2}$$

where D is the damage, W is the energy and α is a constant of the material related to the damage growth ratio.

The decision of the failure criterion used in determining the fatigue law is a critical element in the fatigue behavior characterization of asphalt materials. The classical failure criterion defines the failure as the moment at which the relative reduction of 50% of the initial modulus occurs [14]. However, this failure criterion has been refuted by different authors [15,16] based on its arbitrariness. Di Benedetto, et al. [17] divided the fatigue process into three stages depending on the evolution of the complex modulus. They defined the failure criterion as the point at which the transition between the second stage and the third stage occurs. This is the point where damage spreads rapidly until total failure [18]. Other failure criteria are defined from the dissipated energy. Throughout the literature, different failure criteria have been proposed based on the concept of dissipated energy, such as the cumulative dissipated energy (CDE) approach, the dissipated energy ratio (DER) approach, the energy ratio (ER) approach, or the ratio of dissipated energy change (RDEC) approach [19]. The advantage of these criteria based on dissipated energy versus that calculated from the reduction of the initial modulus to 50% resides in that the former are based on mechanical principles and depend on the material [20]. Furthermore, by comparing the energy ratio (ER) approach with the classical one, Tarefder, et al. [21] found that fatigue life using the first approach was longer than that found using the classical failure criterion, indicating its conservative position.

Although the determination of asphalt mixture fatigue laws is not possible from the strain sweep tests, this paper shows a method to estimate them from the EBADE test results. The test was performed on a semi-dense mixture, manufactured with different types of binder, subjected or not to a laboratory aging process, and performed at different temperatures. Results show that it is possible to evaluate the variation of an asphalt mixture fatigue life which depends on its conditioning (unconditioned or aged) and temperature in a simpler and faster way. This study would be impossible by standard time sweep tests due to the cost it would entail.

2. Materials and methods

The aim of this work is to study the effect of temperature and aging on the fatigue behavior of a mixture from an EBADE test. For this reason, a methodology to estimate the classic fatigue laws of the material is proposed.

Tests on aged specimens were performed and then compared with tests carried out on unconditioned samples. Two types of bitumen were used. Tests were performed at different temperatures (−5, 5 and 20 °C). At least 3 replicates of the test were performed for each condition.

2.1. Materials

A semi-dense asphalt mixture manufactured with a maximum limestone aggregate of 16 mm maximum size (AC16S) and aggregate gradation at the center of the grading envelope (Fig. 1) was selected to study the effect of temperature and aging on the fatigue behavior. This mixture was prepared with two types of bitumen, one conventional (50/70) and one polymer modified (PMB 45/80-65), with the characteristics shown in Table 1. The PMB 45/80-65 bitumen was chemically modified with Styrene-Butadiene-Styrene (SBS) polymer. The content of the SBS modifier was 4% by weight of the asphalt binder. The bitumen content was 4.5% by mixture weight.

2.2. Aging protocol

The protocol followed in the laboratory to simulate the effect of aging on asphalt mixtures is based on the one established by the RILEM ATB-TG5 committee [22]. This protocol considers two aging levels: the short- and the long-term. Short-term aging consists of maintaining the loose mixture in a convection oven at 135 °C for 4 h. Long-term aging consists of maintaining the mixture, also loose, in the oven at 85 °C for 9 days.

However, to simulate the long term aging in this study the loose mixture was maintained in the oven at 85 °C for only 7 days. The reduction of the aging period is because, according to the results of De La Roche, et al. [22], 7 days of aging provides similar results to 9 days, and it can reduce the time for the aging effect study [23]. During the period of aging, the mixture was stirred three times. The mixture was compacted, once aged.

2.3. EBADE test

The EBADE test (from the Spanish acronym of Strain Sweep test) is a tension-compression cyclic test, where a number of load cycles is applied with a constant strain amplitude. This amplitude is gradually increased in successive steps until the mixture fails. The number of cycles in each step is 5000, 25 μm/m is the strain amplitude in the first step which is increased by 25 μm/m in each step (Fig. 2). The test frequency in this study, and in the EBADE test, is 10 Hz. The frequency selected in these tests, which is defined as the number of loading cycles applied to the material per unit time, is given by the loading speed. Thus, in an asphalt pavement, higher speeds of load application are related to higher frequencies. Both entail higher values of the mixture's stiffness, which involves minor deformations of the pavement. The work of Barksdale [24] showed that high speeds are related to short load application times. The load application time is related to the frequency, so that short load application times correspond to higher frequencies. According to the NCHRP [25] report, for a speed of 96 km/h on a highway, the estimated load frequency for an asphalt mixture layer with a thickness within the 7.6 and 30.5 cm range is between 10 and 25 Hz. For a speed of 80 km/h, Mollenhauer, et al. [26] found