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New methodology to estimate the fatigue behavior of bituminous mixtures using a strain sweep test

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HIGHLIGHTS

- New methodology to estimate the fatigue law of bituminous mixtures using strain sweep test.
- Analysis of the effect of temperature and aging in bituminous mixtures.
- Estimation of the predicted cycles to failure of mixtures aged and at different temperatures.
- The same study performed using time sweep tests would take 10 times more testing time.

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ABSTRACT

Fatigue cracking of bituminous mixtures is closely related to the loss of ductility produced by the stiffening of the bituminous binder. The main two factors that cause the asphalt binder to lose its ductility are aging and exposure to low temperatures. However, most of the tests designed to evaluate the fatigue behavior of bituminous mixtures are very time consuming, and make unpractical those studies that try to evaluate the influence of many variables. In this research project a strain sweep test was used to analyze the influence of aging, test temperature and bituminous binder type on the fatigue behavior of a continuously graded mixture. As expected, the mixture with SBS polymer modified binder retained more ductility at low temperatures, while the mixture with crumb rubber modified binder had the highest stiffness modulus. All mixtures exhibited the worst fatigue behavior at low temperatures and aging was equivalent to testing an unaged mixture at a lower temperature. The main result of this paper was the implementation of a new methodology to estimate the fatigue law of the material using a strain sweep test, which allowed this fatigue analysis to be carried out in nearly 10 times less testing time than that required by the procedure described in the EN 12697-24 standard.

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1. Introduction

Cracking of asphalt pavements due to cyclic loading is a matter of utmost importance in the pavement engineering field. This phenomenon is closely related to the embrittlement the mixture suffers due to exposure to low temperatures and/or aging caused by weather agents. Oxidation produces a chemical change of the asphalt binder that increases its stiffness and makes the mixture more brittle and susceptible to fatigue and thermal cracking [7,25,4,1,16]. Another factor that increases the asphalt binder stiffness is a reduction in temperature. There is some disagreement about the mechanism responsible for this phenomenon [31]. A commonly accepted explanation of this phenomenon combines the effect of the reduction of the free volume between molecules [30] and the formation of crystalline fractions, especially the wax contained in the asphalt binder [26,5,2,12].

Despite the importance of the in-service temperature and aging in the cracking resistance of the mixture under cyclic loading, these variables are rarely studied when designing a bituminous pavement. This is due to the amount of time required to evaluate this property. The European standard UNE-EN 12697-24 establishes a minimum of six cyclic tests at three different loading levels to estimate the fatigue law of the mixture, i.e. an exponential relationship between the strain or stress and the cycles to failure. The duration of each of these tests can range between 10 min and 3 days. One third of the specimens have to last over 10^6 cycles, which implies at least 6 tests over 9 h duration at 30 Hz. A common laboratory

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can spend more than a week obtaining a fatigue law of a bituminous mixture. Therefore, studying the influence of different variables in just one type of mixture can involve months of testing, making the process very unpractical.

As a consequence, several research teams have been looking for a way to reduce the time needed to characterize the fatigue behavior of bituminous materials either by developing new test procedures [14,8] or implementing computer simulation programs [13,10], that would make it possible to study the influence of different variables in the fatigue cracking process. Special attention should be paid to the work carried out to develop the Viscoelastic Continuum Damage Model (VECD) [19], since most of the publications in this field follow this line of research. This theory is based on defining three key relationships. First the relationship between stresses and strains, then the law that governs the evolution of damage in the material and finally the dependency of the damage on the measurable variables that can be extracted from testing. Over the last 20 years this model has been developed to predict the behavior of mixtures under cyclic loading, and still today several authors are researching how to use and improve this methodology [27,18,28].

Following the VECD approach, in 2010 Johnson developed [11,9] a test method based on the Dynamic Shear Rehometer (DSR) that provided the number of cycles to failure at a given strain amplitude for bituminous binders using a strain sweep test that accelerated the accumulation of damage in the specimen, and applying the damage evolution law provided by the VECD theory.

Another approach has been proposed by some authors. The hypothesis is that the resistance to cracking exhibited by the material in monotonic tests should be related to the cracking behavior under cyclic loading. Such is the case of the approach proposed by Pérez-Jiménez et al. [20,22]. Using the direct tension fracture test Fenix, it was proven that a reasonably good correlation exists between the results obtained in flexural fatigue tests and those obtained from the fracture test. In this case, authors related the coefficients from the fatigue law obtained using the three-point bending beam test (UNE EN 12697-24) with two parameters obtained in the Fenix test.

Recently, following the same line of research, Na Chiangmai [15], showed that a fairly good correlation exists between the released energy during cyclic testing and the fracture energy, both obtained using the Disk-shaped Compact Tension tests (DC(T)).

This paper presents a method to estimate the fatigue law of bituminous mixtures using a strain sweep test that reduces the testing time required from weeks to hours. The originality of this method lies in estimating the fatigue law of the material using two key strain amplitude values obtained in this test. The procedure is called EBADE (standing for the Spanish words for strain sweep test) [21] and it is based on a uniaxial cyclic test performed on a double-notched prismatic specimen. This quick procedure was employed to analyze the influence of binder type, aging and test temperature on the fatigue behavior of a semi-dense graded mixture.

The UNE EN 12697-24 standard requires 6 replicates to be tested at three strain amplitudes, a total of 18 replicates. These strain amplitudes should be chosen so the number of cycles to failure is around 10^4 and $2{\cdot}10^6$ cycles. The results of each group of 6 replicates are averaged and 3 data points (strain, cycles) are obtained. These 3 points are then fitted to an expression described by Eq. (1):

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

where ε is the strain amplitude, N is the number of cycles to failure and a and b are the fitting coefficients.

Assuming three groups of tests of 50,000, 300,000 and 1,000,000 cycles of duration are conducted, at 30 Hz as described by the standard, 75 h of testing time are required to obtain the fatigue law of one mixture. Multiply that by three mixtures, three temperatures and two aging conditions, the result is 1350 h of testing time. However, an EBADE test takes less than 3 h, which resulted in less than 162 h of testing to conduct the same study, nearly a tenth of the testing time required by the four point bending beam fatigue test, as described in the UNE EN 12697-24 standard.

2. Materials and test methods

2.1. Materials

Three different mixtures were manufactured, with three different asphalt binders and the same gradation. The binders were a conventional binder with a penetration grading at 25 °C of 50–70 0.1 mm, from now on 50/70, a crumb rubber modified binder, BC 35/50 and an SBS polymer modified binder PMB 45/80-65. The characteristics of these three binders are summarized in Table 1.

The gradation employed to fabricate the mixtures was a semi-dense AC mixture with an upper sieve size of 16 mm (AC16 Semi-dense), a 5.0% of binder content by mass of the aggregates and the target void content was 4.0% (Table 2 and Fig. 1). The specimens were prepared using the Marshall compactor with 75 blows per side, and then sawn to get the prismatic specimens required for the test. The mixtures manufactured using the conventional and polymer modified binder presented very similar densities, 0.12% difference in the average densities, while the mixture manufactured using the crumb-rubber modified binder showed an average density 1% lower.

To simulate aging, the procedure designed by the RILEM ATB-TG5 group was employed [6]. After mixing the aggregates with the binder, the mixtures were spread out in trays with a maximum height of 6 cm and placed in a forced air oven at 85 °C for 7 days.

Table 1
Characteristics of asphalt binders

Property	Unit	Standard	50/70	BC 35/50	PMB 45/80-65
Penetration	*0,1* mm	EN 1426	57	46	48
Softening point	°C	EN 1427	50.2	66	62
Pen. Index		Annex A	−0.85	1.94	1.31
Elastic recovery @ 25 °C	%	EN 13398	No data	61	86
Fraass breaking point	°C	EN 12593	No data	−11	−17
Residue after RTFOT					
Mass change	%	EN 12607-1	0.02	0.01	0.01
Penetration after RTFOT	*0,1* mm	EN 1426	35	36	40
Retained pen. @ 25 °C	%	EN 12607-1	61.4	78.3	83.3
Softening point after RTFOT	°C	EN 1427	56.4	72	68.8
Increasing of softening point R&B	°C	EN 12607-1	6.4	6	6.8

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