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Effect of ageing and temperature on the fatigue behaviour of bitumens

Rodrigo Miró [a], Adriana H. Martínez [a,*], Fernando Moreno-Navarro [b], María del Carmen Rubio-Gámez [b]

[a] UPC-BarcelonaTech, Jordi Girona 1–3, Módulo B1, 08034 Barcelona, Spain
[b] Laboratorio de Ingeniería de la Construcción de la Universidad de Granada, C/Severo Ochoa s/n, 18071 Granada, Spain

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ABSTRACT

Bitumen ageing plays a significant role in determining the resistance of asphalt mixes to fatigue cracking. Regardless of the type of ageing (oxidation during manufacture or during the service life), hardening effects increase the risk of cracking. The objective of this work is to examine the combined effect of the loss of volatiles and oxidation produced during ageing on the fatigue behaviour of the bitumen. To this end, different types of bitumen were subjected to accelerated ageing in the laboratory, simulating long-term ageing (RTFOT + PAV). They were then subjected to traditional tests (penetration, softening point, Fraass fragility point, dynamic viscosity, etc.), Dynamic Shear Rheometer tests (frequency and temperature sweep), and the EBADE test (a fatigue strain sweep test at different temperatures). Different temperatures have been used to evaluate the effect of viscoelastic phenomena on aged binder fatigue. The results showed that, in terms of their response to ageing, modified binders show a higher rate of variation in their general properties than conventional binders. In addition, it was shown that temperature plays an important role in the impact of ageing on the fatigue response of bituminous binders, and in the same way, in the mechanical response of these materials.

1. Introduction

The ageing of bitumen plays a critical role in determining how asphalt mixtures are able to resist fatigue cracking [1]. Bitumen hardening due to ageing is primarily linked to two factors; one is the loss of volatile components and bitumen oxidation that occurs during the manufacture of asphalt mixtures and the other is the progressive oxidation of the material during the service life of the mixture. Both factors cause an increase in bitumen viscosity and a consequent stiffness of the mixture.

From a mechanical viewpoint, it is universally accepted that ageing takes place in two stages [2]. The first stage, known as short-term ageing (STA), occurs during asphalt mixing and laying. The second stage, referred to as long-term ageing (LTA), results from the environmental conditions that prevail during the service life of the mixture, although its effect is greater at the pavement surface, and decreases with depth.

Hardening due to ageing is the result of several processes that occur during the life of asphalt mixtures [3] and can be attributed to chemical ageing and physical ageing or steric hardening [4,5].

Physical ageing is a reversible process that consists of a re-orientation of the molecules in the bitumen structure, combined with the slow crystallization of waxes at room temperature [6]. This process results in increased viscosity (without chemical modification) of the bitumen components. This phenomenon can be reversed through heat or mechanical work [7].

Chemical ageing is the most important and complex process, and includes loss of volatiles, exudative hardening, and oxidation process. Together, these three chemical processes lead to a hardening of the mixture [8] caused by the ageing of the bitumen, which becomes hard and brittle [9]. The oxidation and volatilization processes, slow at room temperature, are accelerated when the bitumen is exposed to high temperatures, such as during the manufacturing, transportation, and laying of the mixture. Unlike physical hardening, this process is irreversible.

Volatilization only plays an important role during the manufacturing of asphalt concrete (at high temperatures), i.e., this process is linked to short-term ageing of the bituminous mixture. Temperatures reach and exceed 150 °C, causing lighter fractions of the bitumen to evaporate. An additional temperature of 10–12 °C could double the emissions of volatiles [8].

With respect to the oxidation process, it is known that oxygen diffuses rapidly through interconnected air voids following compaction of the mixture. Gradual chemical reactions between oxygen and the aggregate-binder interface then appear. This phenomenon, known as "oxidative ageing" [10–12], is one of the most important factors that substantially contributes to the hardening and embrittlement of the mixtures. This process leads to an increase in stiffness and a decrease in ductility that most probably affects the resistance of the mixture to cracking [13], thereby reducing the fatigue life of the pavement [14]. In addition, recent studies have demonstrated that UV photo-radiation could considerably increase the rate of oxidation of bituminous binders,

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* Corresponding author.
E-mail addresses: r.miro@upc.edu (R. Miró), adriana.martinez@upc.edu (A.H. Martínez), fmoreno@ugr.es (F. Moreno-Navarro), mcrubio@ugr.es (M. del Carmen Rubio-Gámez).

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and compared with thermal ageing, it could be dominant in the increase of binder's hardening [15].

Regardless of the type of ageing, hardening effects increase the risk of cracking. Bitumen loses its ability to relax the stresses suffered under repeated traffic loads and during the cooling process [16]. This is the reason why durability problems are closely linked to the ability of the bitumen to resist oxidation and/or physical hardening.

Among the most influential variables involved in ageing is the composition of the bitumen. Bitumens derived from various crude oils have differing compositions and therefore do not have the same sensitivity to ageing. This is particularly important in the case of polymer-modified bitumens, where polymer degradation must also be considered [17], since it could reduce the effectiveness of the modification [18]. In this sense, it must be remarked that the oxidation produced after ageing may lead to more or less important modification of the mechanical response of bituminous binders according to their original composition [19].

Temperature appears to be the extrinsic variable which plays the most important role in bitumen ageing, since during the manufacturing of the asphalt mixture the bitumen is heated to high temperatures, promoting the volatilization of some bitumen components and polymerization of some molecules. Depending on the temperature, there are considerable variations in the degree of ageing [20].

Based on all these considerations, it can be said that one of the main aspects affected by ageing would be the long term mechanical behaviour of bituminous materials, and therefore their resistance to fatigue (as the effect of oxidation is produced progressively and affects the visco-elastic response of the bitumen). Nonetheless, the evaluation of this phenomenon on asphalt binders through the variation of stiffness modulus is not an easy task due to the co-existence of fatigue damage with other visco-elastic phenomena (plastic flow, thixotropy, heating, etc.) that also produce changes on this property, but they are not related to fatigue damage [21]. In this respect, several authors have shown that to evaluate “true” fatigue in asphalt binders it is necessary to conduct the tests under certain temperature conditions [22,23], to ensure that the stiffness provided by the material is enough to avoid the appearance of such visco-elastic phenomena that could hide real damage. Thus, temperature conditions would also play an interesting role in the effect caused by ageing on the fatigue resistance of bituminous binders.

The objective of this work is to analyse precisely the combined effect of both the loss of volatiles, and oxidation produced during ageing, on the fatigue behaviour of bitumen. In addition, the influence of temperature conditions and the presence of biased visco-elastic phenomena have been also assessed. In order to achieve this, different types of bitumen were subjected to accelerated ageing in the laboratory by RTFOT and PAV, simulating LTA and then tested with Dynamic Shear Rheometer (DSR) and a specific fatigue strain sweep test (EBADE).

2. Methodology

In order to analyse the effect of ageing on the fatigue behaviour of asphalt bitumens, three different types of bitumen were considered: a conventional bitumen (B), a crumb rubber modified bitumen (CRMB), and an SBS polymer modified bitumen (PMB).

These bitumens were aged in the laboratory by means of the standardized combined procedures of the RTFOT (Rolling Thin Film Oven Test) and PAV (Pressure Ageing Vessel) to simulate long-term ageing. Although some researchers suggest that these procedures could underestimate the real evolution of ageing in bituminous binders (as they do not apply UV radiation [15]), this type of thermal ageing was selected as it is the reference in the Spanish Specifications [24].

First, standard tests (penetration, softening point, brittle point, elastic recovery, force-ductility and dynamic viscosity) were conducted in order to establish the physical characteristics of the bitumen. After that, the visco-elastic characteristics of the unaged and aged binders were then established using the Dynamic Shear Rheometer (DSR) in order to define the reference temperatures to conduct the fatigue tests. Finally, the fatigue behaviour of the bitumens both before and after ageing was evaluated by using a new cyclic tension-compression test at controlled strain (strain sweep test) and at the temperatures defined in the previous step.

2.1. DSR Test

The rheological response of the various binders was analysed using the frequency sweep test at various temperatures (10, 20, 30, 40, 45, 52, 58, 64, 70, and 80 °C). This test was carried out using the Dynamic Shear Rheometer (DSR) and oscillatory shear loading was applied at constant amplitude (0.1% strain) over a range of loading frequencies (from 0.1 Hz to 20 Hz). During the tests, complex shear modulus (G^*) and phase angle (δ) were recorded at each frequency (EN 14770). The results are shown using the Black diagrams, which display the values of complex shear modulus and phase angle at different temperatures for each binder. Further, in order to analyse the influence of this parameter on the viscoelastic response of the mixture, the results for a fixed frequency (5 Hz) at different temperatures are displayed. Based on the results, the reference temperatures to conduct the fatigue tests were selected to assess the influence of this parameter on the effect of ageing in bituminous binders and the impact of biased visco-elastic phenomena.

2.2. EBADE test

The resistance of these binders to repeated loads was assessed using a new cyclic tension–compression test at controlled strain – the EBADE test – see Fig. 1 [25]. This test has been developed at the Road Research Laboratory of the Technical University of Catalonia and is described below. EBADE is the Spanish acronym for strain sweep test.

All the specimens were fabricated with the aforementioned bitumen. The specimens were cylinders of 20 mm of diameter and around 40 mm in height (see Fig. 1a). The asphalt binder was heated to 165 °C in the oven. Specimens were left to cool at room temperature, after which they were removed from the mould and glued to a servo-hydraulic press in order to conduct the tests (see Fig. 1b).

The EBADE test is a cyclic tension–compression test at controlled strain. Several strain amplitudes were applied, in ascending order, in stages of 5000 loading cycles at a frequency of 10 Hz.

The strain amplitude applied in the first step was $7.6\text{E}-4$, and every 5000 cycles the strain was increased by $7.6\text{E}-4$. Thus, the number of cycles and the strain amplitude were directly correlated. The test finished upon total failure of the specimen.

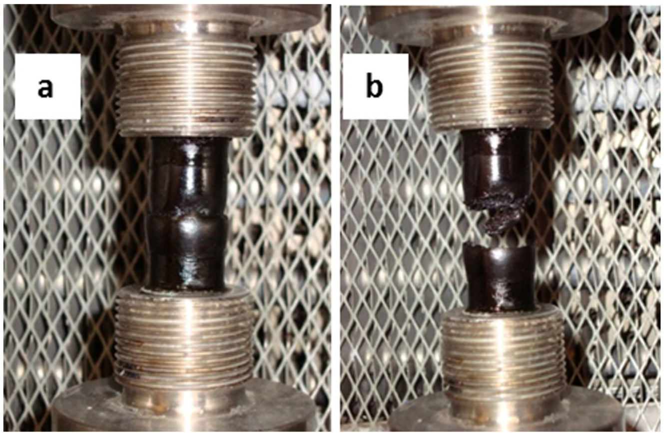

Fig. 1. EBADE test in bitumens: (a) initial strain, and (b) specimen failure.