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Review

A review of fatigue damage in bituminous mixtures: Understanding the phenomenon from a new perspective

F. Moreno-Navarro *, M.C. Rubio-Gámez

Construction Engineering Laboratory of the University of Granada (LabIC.UGR), Granada, Spain

HIGHLIGHTS

- Innovative fatigue phenomenon approach to study bituminous materials.
- Molecular mobility could play a significant role in the appearance of fatigue damage in bituminous materials.
- Various materials under different test conditions were performed through UGR-FACT.

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ABSTRACT

Fatigue cracking constitutes one of the main distresses responsible for the decline in the service life of asphalt pavements. The study of fatigue phenomena is therefore a field of research that has become crucially important for enhancing the durability of these structures. In spite of the advances achieved in the understanding of the fatigue phenomenon in bituminous materials, there remain some questions that are in need of further research. Firstly, the majority of studies do not consider the influence that permanent deformations can exert on the mechanical response of materials. Secondly, reversible phenomena that co-exist with damage during the development of fatigue processes make it difficult to accurately measure the latter. Further, given that the fatigue phenomenon has both global and local effects that cannot be dissociated, the analysis and failure criteria used could lead to non-homogenous results and incorrect fatigue life predictions. This research therefore constitutes a deeper examination of these issues and proposes a new approach that allows for a global analysis of the fatigue phenomenon. This approach has been tested through the study of various types of materials under different test conditions using the UGR-FACT device. Results have shown that using this approach it is possible to distinguish between the different phenomena that appear during cyclic loading and to establish a homogenous failure criterion. In addition, it has been demonstrated that molecular mobility could play a significant role in the appearance of fatigue damage in bituminous materials.

Contents

* Corresponding author.
E-mail addresses: fmoreno@ugr.es (F. Moreno-Navarro), mcrubio@ugr.es (M.C. Rubio-Gámez).

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1. Introduction

Roads and highway pavements are designed to support the traffic loads and climatological events (rain, thermal changes, solar radiation, etc.) that they will be expected to endure during their service life. Traffic loads are cyclical and their magnitudes are considerably inferior to those that cause the breakage of the asphalt mixtures used to build them. Nevertheless, the repeated passage of these loads (combined with the effects caused by environmental agents) induce a fatigue process that leads to the appearance of cracks, which, in the long-term, is one of the main causes that can bring an end to the service life of a road. It is therefore important to develop materials that can offer greater resistance to this distress, and recent years have seen more studies conducted with the aim of offering a better understanding of the fatigue phenomenon that occurs in bituminous materials.

Based on these studies, the fatigue that occurs in bituminous mixtures due to cyclic efforts can be considered as a global process (Fig. 1) which involves three main phenomena [1]: (i) accumulation of permanent deformations; (ii) reversible degradation (thixotropy) and initiation of irreversible damage (micro-cracks); (iii) crack propagation (the coalescence of micro-cracks produces the localization and propagation of macro-cracks).

During the study of the fatigue behavior of asphalt mixtures, the occurrence of these phenomena can be identified by the changes produced in their mechanical properties (traditionally expressed through the changes produced in the phase angle and modulus [2]). Thus, the results obtained in a typical cyclic loading test can be divided into three stages (Fig. 2a, [3]): (1) a rapid decrease of the modulus and increase of the phase angle (which is related to the occurrence of plastic deformations, along with other viscoelastic reversible phenomena such as heating or thixotropy [1]); (2) a quasi-stationary stage where the changes produced in these parameters are small (due to the effect of the reversible phenomena and the initiation of the fatigue damage in the form of micro-cracks); (3) a rapid decrease of modulus and phase angle (due to the occurrence and propagation of the macro-crack). The study of the fatigue behavior of asphalt mixtures should therefore be approached as a global study that takes into account the developments and changes that asphalt materials suffer during the entire process.

Nonetheless, as several authors have pointed out [4–8], this type of analysis is not easy to accomplish, and more research is needed in order to offer a better understanding of this phenomenon.

One of these aspects is the effect caused by the permanent deformations that appear during the cyclic loading process, which in turn leads to fatigue. Whilst these deformations cannot be considered as fatigue damage, their appearance changes the viscoelastic properties of the material (making it more elastic and rigid, due to the strain hardening phenomenon [9,10]), and therefore they can exert a significant influence on its mechanical response. Thus, when a controlled stress fatigue test is used, the initial decrease of the modulus can be largely due to the effect of permanent deformations, which can conceal the real damage produced by the fatigue process (Fig. 2b) [11]. Given this possibility, the majority of fatigue tests are conducted under controlled strain conditions (with the aim of avoiding the effects caused by permanent deformations when studying fatigue damage) [12–15]. However, this type of test does not reproduce the same load conditions that affect bituminous materials during their service life (a stress relaxation and fatigue process under constant strain occurs in the laboratory tests, whilst creep, strain hardening, and fatigue process occurs in the roads due to the presence of constant loads). Therefore, significant differences can be obtained between laboratory fatigue-life predictions and real fatigue lives [16,17], and between laboratory tests carried out at controlled stress or strain conditions [18]. Thus, despite the fact that permanent deformations do not cause damage, their effect on the mechanical properties of the bituminous mixture cannot be neglected when analysing fatigue processes. For this reason, it is necessary to use tests that take into account the influence of this phenomenon and its relationship with fatigue behavior.

Another aspect that limits the analysis of fatigue in bituminous mixtures is the presence of other phenomena that co-exist with damage during cyclic loading (heating, thixotropy, etc.) [1,19,20]. Indeed, many studies have demonstrated that in the stages where these phenomena co-exist (stages 1 and 2, Fig. 2a), it is very difficult to distinguish which of them causes the changes in the mechanical properties of the material, and similarly, it is difficult to quantify the changes that are due only to real damage [21]. Other authors have stated that, due to the large and relatively sudden recoveries produced in the modulus during a short rest period [22–24], the observed recoveries cannot only be related to the healing of the damage (as it is not possible to produce such an amount of healing in such a short time period) [25,26]. These studies have shown that a considerable part of the loss in modulus that occurs during the first stages of a cyclic loading test is due to these reversible phenomena. During the loading process, thixotropy causes the bitumen to change progressively from a gel to a sol structure (ascribed to the dissociation and deformation of inter- and intra-molecular bonds), which reduces the viscosity and the modulus of the material (on the cessation of the loads, viscosity and modulus increase again) [27,28]. Heating is caused by molecular friction during the loading process; it produces chain separation due to thermal expansion and a consequent reduction of the secondary intermolecular forces (this reduces the modulus of the material, which is recovered when the loads disappear and the molecular temperature is restored) [29–31]. Therefore, the fatigue life calculated in traditional tests (where damage is measured

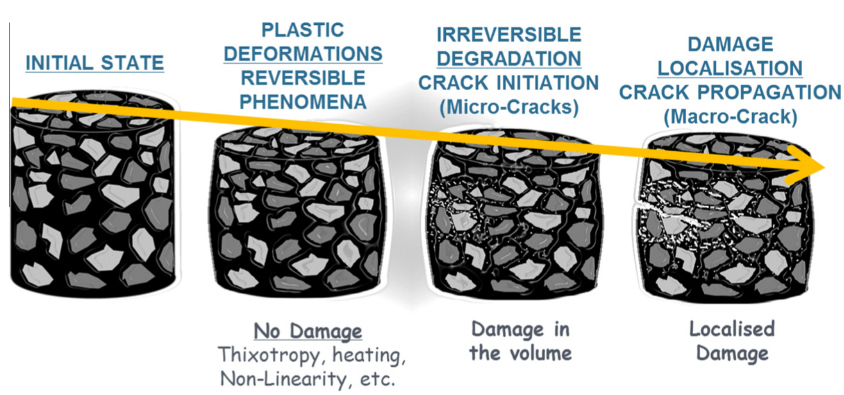

Fig. 1. Sketch of the global process due to the action of cyclic loading.