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Self-heating and other reversible phenomena in cyclic testing of bituminous materials

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HIGHLIGHTS

- The temperature inside asphalt binder specimen during cyclic testing was measured.
- Cyclic testing caused an important increase in the inside temperature of the binder.
- At least 88% of the modulus loss was explained by temperature change.
- Mixture resistance to cyclic testing showed strong dependency on rest periods.
- Heating has to be taken into account on fatigue life prediction.

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ABSTRACT

This paper's objective is to evaluate the reversible phenomena that take place when asphalt materials are subjected to cyclic loads, i.e., self-heating and thixotropy. A strain sweep test was adapted to capture the stiffness variation of binders with the change in strain amplitude. The evolution of the internal temperature of the binder during the test was measured. Results show that the temperature can increase very significantly during cyclic testing and can account for a great part of all stiffness reduction captured during the test at different strain amplitudes. These results led to the conclusion that internal heating should be very important in asphalt mixtures as well. For that reason two types of time sweep tests were performed on the same mixture, with the introduction of rest periods in one of them long enough to let the inside temperature of the material lower after cycling. The results showed that the specimen that was allowed to cool down did not experience any loss of stiffness, while the specimen submitted to the conventional time sweep test failed in a few cycles. These results show the importance of the sequencing of loading and discourage the application of the Miner's law to estimate pavement life.

1. Introduction

Fatigue behavior of asphalt mixtures is a matter of great importance to pavement engineers all around the world. It depends on several properties of the mixture, one of the most important being the properties of the asphalt binder that is used in its manufacture [1–6]. For that reason, several researchers have developed different methods to characterize the fatigue behavior of asphalt binders [7–12], the majority of them based on cyclic testing. However, bituminous materials exhibit a complex behavior when exposed to cyclic loading, which leads to different interpretations of the results of these kinds of tests.

It is well known that asphalt materials exhibit a non-linear behavior during the initial stage of any kind of cyclic test. For that reason, several authors divide the stiffness evolution of bituminous materials during cyclic tests into three phases. Phase I corresponds to that initial stage in which a fast and non-linear loss of stiffness is observed. The explanation for this phenomenon is normally attributed to non-linear viscoelastic effects, thixotropy and/or self-heating [13–19]. Phase II corresponds to a change in the stiffness reduction pattern. After the initial non-linear phase, phase I, the material exhibits a linear loss of stiffness with the number of cycles. Typically this loss is associated with irreversible damage produced by the repetition of loads. The higher the strain/stress applied the steeper is the slope of this linear phase, leading to

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failure in fewer cycles. Finally phase III is associated with a final deviation from the linear behavior observed during phase II, resulting in a rapid loss of stiffness. This stage is considered the failure stage of the specimen, and the cause of this behavior is normally attributed to the coalescence of the micro-cracks formed during phase II to form macro-cracks that cause the complete failure of the material.

These kinds of cyclic tests are very time consuming, and normally several of them are required in order to portray the fatigue behavior of the mixture, i.e., obtain the fatigue law of the material. For that reason, recently, different alternatives have been developed to accelerate this process. Such is the case of the procedures in which a variable strain/stress amplitude is applied, i.e., strain/stress sweep tests [9–20]. Combining this method with the viscoelastic continuum damage theory, a fatigue law can be estimated. This procedure is much faster than the classical approach based on computing the fatigue law of the material from several time sweep tests.

The EBADE test [20,21] is based on this strain sweep test concept. Its name stands for the Spanish words for strain sweep test. This procedure provides information on the variation of the dissipated energy density, DED, the complex modulus, $|E^*|$, and the phase angle, δ, of the material at different strain amplitudes. It provides the maximum strain amplitude the material can sustain without permanent change to its properties, and the maximum strain amplitude it can endure under cyclic conditions before failing completely. These two strain values may be used to sketch an approximation of the fatigue law of the material [22]. The fatigue laws obtained through this procedure were compared with those obtained by applying the classical method based on time sweep tests, showing a good agreement between them [23,24]. These time sweep test results were also used to found a linear correlation between the complex modulus and the dissipated energy density that propagated through phases I and II. It was also found that the slope of these linear correlations depended on the strain amplitude applied, leading to the same slopes for the same strain amplitudes in time and strain sweep tests [25]. In addition, the superposition of results from the time and strain sweep test showed that the complex modulus and dissipated energy density values were the same after 5000 cycles at the same strain amplitude in time and strain sweep tests, regardless of the previous loading history. This result led to the hypothesis that the complex modulus loss was related only to the strain amplitude, independently of the previous loading history, and that it could be recovered if the strain amplitude was decreased or the test stopped. A strain sweep test performed with increasing and decreasing strain amplitudes alternatively proved this hypothesis [17]. This kind of reversible behavior could be explained by the thixotropic nature of the material or its capacity to convert the dissipated energy into a temperature increase, or both.

Benedetto et al. [16] measured the increase of the inner temperature of asphalt mixtures during cyclic testing and determined the amount of complex modulus they can recover. Afterwards they separated this recovery into three phenomena: self-heating, thixotropy and non-linear effects, assigning different quantities of complex modulus to each one. In addition, they proposed that the thixotropy effect could be modeled as an increase in the inner temperature of the material.

Thixotropy is a very complex phenomenon, so much so that there is not full agreement in the scientific community as to what its exact definition should be [26,27]. The most general definition that it is accepted nowadays is as follows: "the continuous decrease of viscosity with time when flow is applied to a sample that has been previously at rest and the subsequent recovery of viscosity in time when the flow is discontinued" [27]. Viscoelasticity is not referenced in the definition, but it is not excluded either. The implications of this can lead to some ambiguous interpretation of the results, because self-heating, if it happens, has to be related to the energy the material dissipates during cyclic testing, which is a consequence of the viscoelastic response of the material (a pure elastic material would not dissipate energy and therefore it could not increase its temperature by itself). Benedetto et al. [16] showed that the increase in temperature at the beginning of the test was proportional to the dissipated energy. However, a definition of thixotropy from Bauer and Collins [28] clearly states that this phenomenon should take place under isothermal conditions. Therefore, depending on the definition that is adopted, thixotropy and self-heating could be independent phenomena or the second could be the cause of the first.

Measuring thixotropy during cyclic testing presents several technical complications. To fulfill the definition, it is necessary to change bi-directionally the flow applied to the material, i.e., increase and decrease the strain/stress amplitude several times keeping constant flow after each change for enough time to reach stabilization. However, when testing materials whose stiffness is highly dependent on temperature, heating and cooling down may give the same response as that expected from a thixotropic fluid. In that case, the only way to tell one from the other is to measure the temperature inside the material continuously during the test.

Recent research suggests that the increase of internal temperature is fully explained by viscous dissipation [29]. By considering the viscoelastic dissipated energy, obtained in a finite element simulation of a cyclic mechanical loading, as an internal heating source, a temperature increase was obtained close to experimental values from literature.

This paper presents the results obtained in a cyclic test designed specifically to analyze the effect of thixotropy and self-heating in asphalt binders. The procedure is based on the EBADE test, but adapted to capture the stiffness variation of binders with the change in strain amplitude. By embedding a thermocouple probe inside the specimen during its manufacture, it was possible to measure the evolution of the internal temperature of the asphalt binder during the test. Results show that the increase in temperature during cyclic testing can account for an average of 88% of all stiffness reduction captured during the test at different strain amplitudes, before failing. This result was consistent with the work carried out by Mangiafico et al. [18] that found that 90% of the stiffness variation during cyclic testing of asphalt mixtures was completely reversible. For that reason two time sweep tests were performed on the same mixture, introducing rest periods in one of them long enough to let the inside temperature of the material lower after cycling. The results showed that the specimen that was allowed to cool down did not experience any loss of stiffness in more than 180,000 cycles, while the specimen submitted to the conventional time sweep test failed completely after fewer than 100,000 cycles. These results show the importance of the sequencing of loading and discourage the application of the Miner's law to estimate pavement life.

2. Methods and test plan

2.1. EBADE test

The EBADE test takes its name from the Spanish words for the strain sweep test. It consists of a cyclic uniaxial tension-compression test in which the strain amplitude increases at a constant value every certain number of cycles. In its common configuration, each strain amplitude is applied for 5000 cycles at a frequency of 10 Hz. This test can be performed on asphalt binders, asphalt mastics and asphalt mixtures, Fig. 1.