Construction and Building Materials 98 (2015) 703–712

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Fatigue resistance of asphalt binders: Assessment of the analysis methods in strain-controlled tests

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HIGHLIGHTS

- The DE and S_C^R variation rate have an excellent relation with $N_{f,50}$ results.
- Different *C*–*D* curves (VECD–DE method) are obtained for the TST and LAS tests.
- A single *C*–*D* curve can be fitted to all TST data of a single binder.
- The variation of DPSE is similar in TST and LAS tests.
- It is recommend further studies of defining test failure at the DPSE peak.

ARTICLE INFO

Article history:
Received 23 May 2015
Received in revised form 4 August 2015
Accepted 9 August 2015
Available online 2 September 2015

Keywords:
Asphalt binder
Fatigue
Dynamic shear rheometer
Viscoelastic damage mechanics

ABSTRACT

Fatigue testing of binders is an important subject in asphalt research and in recent decades several test procedures and analysis methods have been proposed. This paper discusses the application of several analysis methods to two different strain-controlled tests, implemented with the DSR.

The fatigue laws obtained from the time sweep (TST) and the linear amplitude sweep (LAS) tests with the traditional failure limits, based on a fixed stiffness reduction value, are quite different. Using LAS, with maximum shear stress as failure criterion, gives rise to better results that can be further improved when changing the failure criterion to one based on the dissipated pseudo strain energy evolution.

1. Introduction

Asphalt fatigue cracking due to repeated traffic loading strongly contributes to road pavement degradation. For this reason, the (mechanistic-empirical) pavement design guides use asphalt fatigue laws to define the time, or the number of traffic loading cycles, that the pavement structure can hold before failure. These fatigue laws can be obtained from lab tests and then calibrated to field conditions based on the local road network pavements performance data. Several test protocols may be adopted for lab evaluation, with different testing apparatus being used as listed in EN 12697-24 [1]. These tests are time consuming and relatively expensive.

The fatigue properties of asphalt mixtures are strongly related with those of binders, which are controlled by the rheology, cohesion, adhesion and durability properties. In this context, fatigue testing of bituminous binders is an important task with considerable research potential [2,3].

The microstructure of asphalt mixtures is rather complex and comprises randomly oriented aggregate particles, with a significant range size variation, binder and small air voids. Furthermore, nonlinear-inelastic behaviour of the mixture is a result of the viscoelastic behaviour of the binder and the micro stress–strain state variations in bulk volume, which induce a complex damage distribution pattern [4]. Lytton [5] states that asphalt distresses like fatigue cracking and rutting are related to the occurrence of adhesive fracture in thin mastic films and of cohesive fracture in thick mastic films.

In recent decades many authors have investigated the cohesive cracking properties of asphalt mixtures based on binder or mastic testing. In the Strategic Highways Research Program (SHRP) a maximum value for the binder's shear loss modulus ($|G^*|\cdot\sin\delta$) was proposed, considering that lower dissipated energy per loading cycle corresponds to lower damage accumulation [2,6,7]. The complex shear modulus (G^*) and phase angle (δ) are used to characterize the rheological properties of binders in the linear viscoelastic

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http://dx.doi.org/10.1016/j.conbuildmat.2015.08.070
0950-0618/

domain, with measurements performed using the Dynamic Shear Rheometer (DSR). However, several research studies concluded that there is not a strong relation between $|G^*|\cdot\sin\delta$ of the binder and the fatigue life of the asphalt mixtures [6,8,9]. In the NCHRP 9–10 research project [10] the application of repeated cycling (time sweep) with the DSR, in strain- and in stress-controlled mode, to evaluate the fatigue resistance of the binder was tested for the first time with promising results. The research team also recommended using the rate of change in dissipated energy to analyse the test results considering that this approach is independent of the test loading mode. Shen et al. [11–13] also based the evaluation of the fatigue performance and the effect of healing of asphalt mixtures and binders on the dissipated energy concept.

Bahia et al. [14] recently proposed a new binder fatigue test in which the loading amplitude (strain) is rapidly increased during the test to accelerate damage progression in the binder sample. The test results are analyzed and a fatigue law derived, based on the Viscoelastic Continuum Damage Mechanics (VECD) theory principles.

Also, Chailleux et al. [15] and Botella et al. [2] proposed tension–compression tests run on diabolo-shaped and cylindrical binder specimens, respectively. Both argued that this test mode could evaluate the resistance to cracking opening in mode I, which is the most important in asphalt mixture damage. In a different way, Qiu et al. [16] described double samples (two layers) tested in DSR to investigate the self-healing behaviour of asphalt binder.

On the other hand, several researchers [17–20] state that some reversible phenomena (heating, thixotropy, steric hardening, non-linearity) also affect asphalt material behaviour under cyclic loading other than fatigue damage, which brings extra complexity to the analysis.

This paper presents a discussion of the analysis methods used to evaluate and quantify fatigue performance of asphalt binders. A neat bitumen and a SBS polymer modified bitumen were tested using two different strain-controlled fatigue testing protocols (time-sweep tests with and without resting periods; linear amplitude sweep tests) and the experimental results were analysed using different methods, based on complex modulus reduction, on dissipated energy and on continuous damage mechanics. An alternative analysis method is also presented and the results discussed.

2. Review of fatigue damage analysis

Asphalt binders and mixtures show a strong power law relationship between load stress or strain amplitude (X) and fatigue life (N_f):

$$N_f = A \cdot X^B \tag{1}$$

where N_f is the number of cycles to failure and A and B are constants (material dependent). To obtain the material dependent constants, several tests are required at various load amplitudes, in strain- or stress-controlled conditions. Various testing apparatus and protocols are used for this purpose, the DSR being commonly used for binder testing.

For strain-controlled fatigue tests, failure is usually defined as the point at which the material's complex modulus value falls to 50% of its initial value, with the corresponding number of cycles denoted as $N_{f,50}$. Although arbitrary and controversial, this failure criterion has been used extensively [12,19,21–23]. Differently, Reese [24] proposed using another test variable, the phase angle, setting failure at the point when the upper limit of the phase angle is reached. During testing the phase angle increases gradually till there is a sudden decrease, which is considered to have a closer relation to the material's accumulated damage than a certain decrease in the complex modulus.

An alternative approach to quantify fatigue resistance of asphalt materials is based on dissipated energy (DE) during cyclic loading [12]. Because asphalt materials have viscoelastic behaviour, in each loading cycle, loading and unloading follow different paths and a hysteresis loop is created. The area inside the loop is DE density. The area can be computed using a numerical integration method (e.g. Gauss method) from the stress–strain test data or, alternatively, considering ideal behaviour, an expression can be derived from the work potential theory:

$$\mathrm{DE}_i = \pi \cdot \sigma_i \cdot \varepsilon_i \cdot \sin\delta_i \tag{2}$$

where DE_i, σ_i, ε_i and δ_i are, respectively, the dissipated energy density, the stress amplitude, the strain amplitude and the phase angle at loading cycle i. In the SHRP program, the researchers hypothesized that damage accumulation is lower when the dissipated energy per loading cycle is lower, based on the assumption that fatigue is a strain-controlled phenomenon [6,10]. Hence, a maximum value for $|G^*|\cdot\sin\delta$ is defined in the performance-grade (PG) binder specifications [25] with the objective of preventing the use of binders prone to fatigue damage.

Shen et al. [13] stated that only the relative amount of dissipated energy coming from each additional cycle is related to damage propagation. Hence, the rate of dissipated energy change (RDEC) was proposed as:

$$\mathrm{RDEC} = \frac{\mathrm{DE}_p - \mathrm{DE}_q}{\mathrm{DE}_p(q-p)} \tag{3}$$

where p and q are the initial and final number of cycles of the interval used for the calculation of RDEC.

In a strain-controlled fatigue test, three different phases of RDEC variation can usually be found. First, there is a fast increase of the RDEC value, then a phase with an almost constant value and finally a sharp decrease before the test is terminated. The RDEC value in the second stage is called the Plateau Value (PV). Several authors [11,26] have concluded that the lower the PV value, the longer the fatigue life is. They have also concluded that there is a unique relation between PV and $N_{f,50}$ for different materials and testing conditions.

Although the dissipated energy concept relates well to damage propagation, a fatigue law is not obtained and the fatigue failure analysis of bituminous layers in pavement design relies on fatigue laws.

A more robust approach to describe and model asphalt materials is the Viscoelastic Continuum Damage Mechanics (VECD) that has been developed based on Schapery's work [27–29]. Park et al. [30] proposed the following model for the damage growth in viscoelastic materials:

$$\frac{dD}{dt} = \left(-\frac{\partial W^R}{\partial D}\right)^{\alpha} \tag{4}$$

where D is the damage intensity; W^R is the pseudo strain energy density function; t is the time; α is a material constant. Schapery [28] defined the pseudo-strain (ε^R) as:

$$\varepsilon^R = \frac{1}{E^R}\int_0^t E(t-\tau)\cdot\frac{d\varepsilon}{d\tau}\cdot d\tau \tag{5}$$

where E^R is the reference modulus; $E(t)$ is the relaxation modulus; τ is the time variable of integration. In a strain-controlled cyclic test, the physical strain (ε) is:

$$\varepsilon = \varepsilon_i \cdot \sin(w\cdot t) \tag{6}$$

and, the corresponding pseudo-strain (ε^R) is:

$$\varepsilon^R = E^* \cdot \varepsilon_i \cdot \sin(w\cdot t + \delta) \tag{7}$$

where ε_i is the strain amplitude in cycle i; E^* and δ are the complex modulus and the phase angle, respectively, of the undamaged material.