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Application of the partial healing model on laboratory fatigue results of asphalt mixture

Ning Li [a,b,*], A.A.A. Molenaar [b], A.C. Pronk [c], M.F.C. van de Ven [b], Shaopeng Wu [d]

[a] Division of Materials & Pavements, National Engineering Laboratory for Advanced Road Materials, JSTI Group, Nanjing, PR China
[b] Road and Railway Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands
[c] AP Consultancy, Vlaardingen, The Netherlands
[d] State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan, PR China

HIGHLIGHTS

- Specimen size significantly influence the inhomogeneous fatigue test results.
- The PH model is able to describe the fatigue process for a unit volume.
- Based on the model parameters $\delta\gamma_1$ and $\delta\gamma_2$, the endurance limit can be predicted.
- By the weighing procedure, the 4PB results are predicted by the UT/C results.

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ABSTRACT

Fatigue characterization of an asphalt mixture is commonly estimated by laboratory fatigue tests. Based on the classical fatigue analysis, fatigue lives obtained from different test methods are not comparable even though the test conditions are the same. One of the main reasons causing the difference in fatigue results is the difference in stress–strain distribution of the different specimens. The stiffness measured from the inhomogeneous test is not a material property but a specimen property, which depends on the geometry and dimension of the specimen. With regard to the homogenous tests, the stress–strain field within the specimen is uniform in theory. The measured stiffness corresponds to a material property and is not influenced by the specimen dimension. The objective of this research is to find a correlation between the different fatigue test results by means of the partial healing (PH) model.

In this paper, a homogenous test, the uniaxial tension and compression (UT/C) fatigue test, and a inhomogeneous test, the four-point bending (4PB) fatigue test were conducted. For each type of test, specimens with different sizes were tested to explore the size effect on the fatigue results. It is found that for the standard specimen size, the model parameters deduced from the UT/C and 4PB are comparable. It indicates that the PH model is able to describe the fatigue process in the 4PB test based on the UT/C fatigue results.

1. Introduction

With the increase of traffic volume and weight, fatigue cracking of the bituminous layer has become one of the major distress modes in flexible road pavements associated with repeated traffic loads. The fatigue properties of asphalt mixtures are important parameters in pavement structure design. In order to determine the fatigue resistance of asphalt mixtures, the fatigue tests under cyclic loading are conducted in the laboratory to simulate the repeated traffic loading. A number of laboratory fatigue test methods are currently used as the standard tests for the asphalt pavement design [1]. According to the mode of loading the most commonly used tests are classified as simple flexural test (2-, 3- and 4-point bending test), direct axial loading test and diametral loading test [2,3]. The two-point bending (2PB) test with trapezoidal specimen was adopted by the researchers from Shell [4] and LCPC [5]. The Shell Laboratory at Amsterdam has used the three-point bending loading equipment to estimate the fatigue life [4]. In the US [6] and the Netherlands [7], the four-point bending (4PB) test is specified. In the UK and Sweden, the standard fatigue

* Corresponding author at: 2200 Chengxin Road, Jiangning Science Park, Nanjing, PR China.
E-mail addresses: lining0618@hotmail.com, ln243@jsti.com (N. Li).

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test is the indirect tensile fatigue test (ITFT). The Nottingham Asphalt Tester (NAT) was specially designed for this test [8]. The previous researches indicates that the fatigue test results obtained from different test methods are different and difficult to be compared to each other. Normally it was found that the fatigue life obtained from the bending fatigue tests is longer than that from the other test methods and the diametral loading test has the shortest fatigue life [9–11].

The difference in the fatigue results is mainly caused by the stress–strain distribution throughout the specimen, which depends on the loading configuration, specimen geometry and specimen dimension. For the beam bending tests and the indirect tensile test, the stress and strain distribution inside the specimen is not uniform. The decrease in local stiffness depends on the local stress and strain situations. During the fatigue test, the stiffness calculated by the measured deflection and force is related to the geometry and dimension of specimen, which means that the backcalculated stiffness does not represent a material property but a specimen property. This is the reason why the fatigue life based on the stiffness reduction is highly dependent on the test type and specimen size for the so-called non-homogeneous fatigue tests [12]. In a homogenous fatigue test, like the uniaxial loading fatigue test, the stress–strain field is in theory uniform over the length and the cross area. In that case, the back calculated stiffness is a material property in principle and not influenced by the specimen size [13].

Some advanced fatigue models were proposed to describe the fatigue behavior of the asphalt mixtures. A mechanical damage model was proposed by Bodin [14] based on the non-local damage theory. This damage model has been used to describe the local complex modulus decrease induced by microcrack development. Kim [15] and Lundstrom [16] applied the work potential theory to simulate the damage evolution under cyclic tests. Castro and Sanchez used a continuum damage mechanics approach to estimate fatigue curves for the three point bending test [17]. However, most of these fatigue damage models do not take into account the test type and the specimen size. The partial healing (PH) model proposed by Pronk [18] has been proven to be a good material model, making it possible to simulate the evolution of a material property for a unit of volume. It provides the possibility to correlate the fatigue results measured from the different fatigue test methods.

In this paper, the uniaxial tension and compression (UT/C) and four-point bending (4PB) fatigue tests were conducted and the influence of the specimen size on each test method was investigated. The objective of this paper is to find a correlation between the UT/C and the 4PB fatigue results by means of the PH model.

2. Theory of the partial healing (PH) model

The partial healing (PH) model developed by Pronk is a material model that enables to describe the evolution of the stiffness modulus and phase angle for a unit volume during a fatigue test [18,19]. Under cyclic loading, the energy is dissipated into the device (system losses ΔW_{sys}) and the specimen (visco-elastic losses ΔW_{dis}). The area enclosed by the stress–strain loop represents the visco-elastic loss. Most part of this energy is transformed into heat, leading to an increase of the temperature inside the specimen and a small part causes the fatigue damage [19]. In the PH model it is assumed that the fatigue damage can be taken equal to a small part δ ($\ll 1$) of the visco-elastic losses. In a strain controlled fatigue test, the energy causing fatigue damage ΔW_{fat} is expressed by Eq. (1):

$$\Delta W_{fat} = \delta \cdot \Delta W_{dis} = \delta \cdot \pi \cdot \sigma_i \cdot \varepsilon_0 \cdot \sin(\varphi_i) = \delta \cdot \pi \cdot S_i \cdot \varepsilon_0^2 \cdot \sin(\varphi_i) \tag{1}$$

where δ = small parameter ($\ll 1$), S_i = stiffness modulus at cycle i, (MPa); σ_i = stress amplitude at cycle i, (MPa); ε_0 = applied strain amplitude, a constant in the strain controlled mode, (mm/mm); φ_i = phase angle at cycle i, (°).

In the proposed model, a new parameter, stiffness damage Q, is introduced, which directly relates to ΔW_{dis}. The damage Q decreases the stiffness modulus, including both the loss modulus F and storage modulus G. The loss and storage modulus can be expressed by means of Eq. (2).

$$\begin{cases} F(t) = S \cdot \sin\phi = F_0 - \int_0^t \frac{dQ(\tau)}{d\tau}[\alpha_1 e^{-\beta(t-\tau)} + \gamma_1] \cdot d\tau \\ G(t) = S \cdot \cos\phi = G_0 - \int_0^t \frac{dQ(\tau)}{d\tau}[\alpha_2 e^{-\beta(t-\tau)} + \gamma_2] \cdot d\tau \end{cases} \tag{2}$$

where F_0 = initial loss modulus, (MPa); G_0 = initial storage modulus, (MPa); t is the testing time, (s); α_1, α_2, γ_1, γ_2 and β = model parameters.

The terms with α_1, α_2 and β represent the reversible damage which will heal in time. The terms with γ_1 and γ_2 correspond to the irreversible damage which will accumulate during the test. The stiffness damage part Q directly relates to the fatigue damage ΔW_{fat}. In the strain-controlled mode, the fatigue damage rate is given by Eq. (3).

$$\frac{d}{dt}Q = \frac{d}{dt}W_{fat} \approx \frac{\Delta W_{fat}}{\Delta t} = \delta \cdot \frac{\pi \cdot S_i \cdot \varepsilon_0^2 \cdot \sin(\varphi_i)}{\Delta t} = \delta \cdot \pi \cdot f \cdot \varepsilon_0^2 \cdot F_i \tag{3}$$

where Δt = time duration in one cycle, (s); F_i = loss modulus at cycle i, (MPa); f = frequency (Hz).

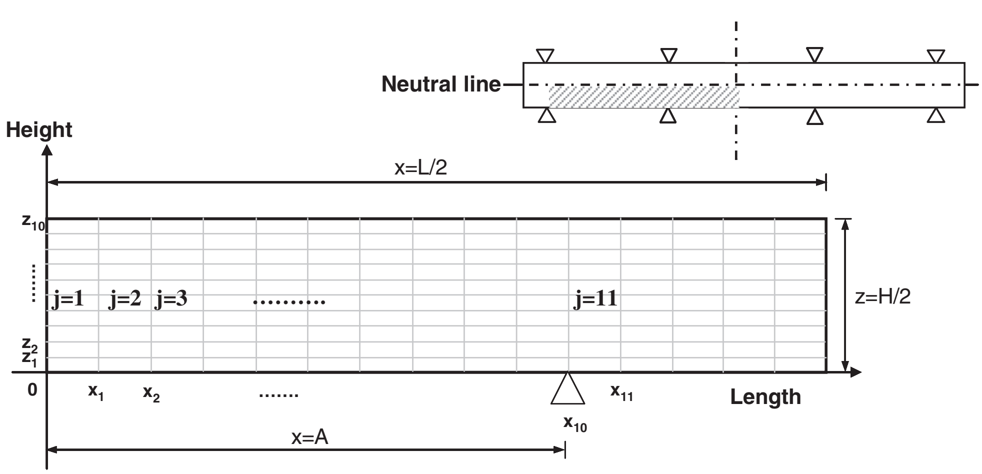

Fig. 1. Schematic diagram of the numerical analysis.