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Investigation of effectiveness of prediction of fatigue life for hot mix asphalt blended with recycled concrete aggregate using monotonic fracture testing

Shenghua Wu [a,*], Balasingam Muhunthan [b], Haifang Wen [c]

[a] Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N Mathews Ave., Urbana, IL 61801, USA
[b] Department of Civil and Environmental Engineering, Washington State University, PO Box 642910, Spokane Street, Sloan Hall 101, Pullman, WA 99164-2910, USA
[c] Department of Civil and Environmental Engineering, Washington State University, PO Box 642910, Spokane Street, Sloan Hall, Pullman, WA 99164-2910, USA

HIGHLIGHTS

- A dissipated energy based fatigue life prediction was developed for HMA.
- The predicted fatigue life from monotonic test is lower than the cyclic test.
- The difference between two tests is due to loading mode and healing effect.
- Fatigue resistance of HMA is adversely affected by recycled concrete aggregate.

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ABSTRACT

The fatigue property of asphalt mixtures is important for the purpose of pavement engineering design; however, assessing fatigue life using cyclic tests in the laboratory is time-consuming and tedious. This study investigates the potential of using monotonic fracture testing to predict the fatigue life of asphalt mixtures. Both monotonic tests and cyclic tests were conducted using hot mix asphalt (HMA) blended with recycled concrete aggregate (RCA) at different ratios (0%, 20%, 40%, 60%, 80% and 100%). The predicted fatigue life obtained from monotonic testing are found to be much lower than the fatigue life obtained from cyclic testing, which could be due to the hysteresis loss and healing effect in the cyclic testing. It is also found that the fatigue resistance of HMA is adversely affected by the use of RCA.

1. Introduction

"Fatigue" is a very common mode of failure and deterioration for various materials and structures [1]. For asphalt pavements that undergo cumulative damage when subjected to repeated vehicle loads, fatigue deterioration results in either top-down cracking or bottom-up cracking. The fatigue property of asphalt mixtures is complicated, due to the fact that asphalt material is sensitive to temperature and loading mode and there exists a combined effect of asphalt binder and aggregate. Thus, the accurate quantification of the fatigue behavior of an asphalt mixture is difficult; moreover, it is always tedious and time-consuming to assess the fatigue life in the laboratory.

Fatigue life is an intuitional indicator of the fatigue resistance in that the longer the material resists load repetitions, the better it resists fatigue and subsequent damage. Generally, fatigue life can be determined by cyclic load tests in the laboratory, such as four-point or two-point bending beam fatigue tests [2–4] and the semi-circle notched beam fatigue test [5]. Fatigue life can be also predicted based on known mechanical parameters using, for example, a fracture mechanics approach [6] or the continuum micromechanics surface energy (CMSE) approach [7]. The widely used method to determine fatigue life is based on empirical observation [8,9]. It relates fatigue life to the applied tensile strain (ε_t) through the laboratory determined material constants (k_1, k_2), as:

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[*] Corresponding author.
E-mail addresses: wusheng@illinois.edu (S. Wu), muhuntha@wsu.edu (B. Muhunthan), haifang_wen@wsu.edu (H. Wen).

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$$N_f = k_1 \left(\frac{1}{\varepsilon_t}\right)^{k_2} \quad (1)$$

Eq. (1) has been modified by incorporating additional factors, such as modulus, binder content, thickness, etc. [10,11], in order to establish the fatigue model as in the Mechanical-Empirical Pavement Design Guide (MEPDG) to predict the fatigue crack performance of asphalt pavements [12].

The dissipated energy during fatigue fracture testing is useful to quantify fatigue behavior. The dissipated energy-based method for predicting the fatigue life of metal and polymer materials can be found in the literature [13–16]. Roque et al. [17] developed an approach based on dissipated creep strain energy (DCSE) that is the fracture energy subtracted by the elastic energy from the indirect tensile (IDT) test. The fracture energy and fracture work density obtained IDT test at room temperature has also been proven to be a promising material indicator of the resistance to fatigue cracking [18–21]. The fracture work density is the fracture work divided by the volume of specimen, where the fracture work is the entire area beneath the load-displacement curve [22].

The monotonic IDT test applies a constant load or displacement rate that crushes the sample quickly, and thus, it is convenient and efficient. As such several researchers have used the results of monotonic IDT testing as measures for predicting the fatigue life of asphalt mixtures. Different failure criteria have been proposed for determining fatigue life in the laboratory using IDT tests [4,5,8,17–19]. The deterioration of the stiffness modulus value up to 50% is widely accepted as a failure threshold for fatigue cyclic loading test. Some researchers have used the occurrence of micro-crack length of 7.5 mm as the failure threshold value for crack initiation, based on four-point bending beam fatigue test [7]. The validity of fatigue life predictions using monotonic testing is based on the assumption that the accumulative dissipated energy during cyclic testing is equivalent to the strain energy that is dissipated during monotonic testing, and thus, a fatigue life prediction equation can be derived.

This study examines the feasibility of predicting the fatigue life of asphalt mixtures using monotonic testing. It assumes the equivalence of dissipated energy in the cyclic load testing and monotonic testing. Hot mix asphalt (HMA) is typically composed of asphalt and aggregate, but more recently, recycled materials have been widely used to replace virgin aggregate. Recycled concrete aggregate (RCA) is one of the sustainable materials that could be potentially used as an alternative to natural aggregate in HMA. As such the fatigue property of HMA with recycled materials needs to be investigated. This study investigates the fatigue properties of HMA blended with RCA at different ratios (0%, 20%, 40%, 60%, 80% and 100%) using monotonic fracture testing and cyclic testing. The fatigue life predicted from the monotonic fracture tests is compared with the measured fatigue life obtained from the cyclic tests.

2. Theory

2.1. IDT test

Fig. 1 depicts IDT test with a cylinder specimen of a given diameter (D) and thickness (t). The linear variable differential transducers (LVDTs) are mounted on the surface of specimen to measure vertical and horizontal deformation when the specimen is subjected to pressure (P).

The horizontal stress acting on the specimen can be calculated by Hondros [23]:

$$\sigma = \frac{2P}{\pi D t} \quad (2)$$

The IDT modulus can be calculated by dividing the horizontal stress (σ) by the center strain (ε), as:

$$|E^*| = \frac{\sigma}{\varepsilon} \quad (3)$$

where σ = horizontal stress (Pa); P = applied load (N); D = specimen diameter (m); t = specimen thickness (m); ε = horizontal tensile strain at the center of specimen; $|E^*|$ = IDT modulus (Pa).

Assuming the material to be viscoelastic the expressions for the Poisson's ratio and center strain were developed by Wen and Kim [18] as:

$$\nu = -\frac{\alpha_1 H(t) + V(t)}{\alpha_2 H(t) + \alpha_3 V(t)} \quad (4)$$

$$\varepsilon = H(t)\frac{\gamma_1 + \gamma_2 \nu}{\gamma_3 + \gamma_4 \nu} \quad (5)$$

ν = Poisson's ratio; ε = horizontal tensile strain at the center of specimen; H(t) = horizontal displacement (m); V(t) = vertical displacement (m);

α_1, α_2, α_3, α_4, γ_1, γ_2, γ_3, γ_4 = coefficients can be found in Wen and Kim [18], depending on the size of specimen and LVDT gauge length.

2.2. Monotonic IDT test

If the applied load is monotonic in IDT test, a typical test result of stress-strain curve obtained is shown in Fig. 2.

The damage to the material is seen to increase with increasing in dissipated energy. The cumulative dissipated strain energy per unit volume, W_{mon}, is the area of the stress-strain curve that stretches to the area where the stress almost reaches zero, which can be calculated approximately as the sum of each tiny trapezoidal areas, as shown in Eq. (6). For monotonic strain-controlled tests, the dissipated energy can be expressed in terms of strain rate, as shown in Eq. (7):

$$W_{mon} = \sum_{i=0}^{n} \frac{1}{2}(\sigma_{i+1} + \sigma_i)|\varepsilon_{i+1} - \varepsilon_i| \quad (6)$$

$$W_{mon} = \sum_{i=0}^{n} \frac{1}{2}(\sigma_{i+1} + \sigma_i)\frac{|\varepsilon_{i+1} - \varepsilon_i|}{t_i} t_i = \frac{1}{2}\sum_{i=0}^{n}(\sigma_{i+1} + \sigma_i)\dot{\varepsilon} t_i \quad (7)$$

where, W_{mon} = dissipated energy during monotonic test; $\dot{\varepsilon}$, t_i = strain rate, time; σ_{i+1}, σ_i = stress at the (i + 1)th time and ith time; ε_{i+1}, ε_i = stress at the (i + 1)th time and ith time; n = time when the stress is close to zero; i = the integer, depending on the data sampling rate.

The cumulative dissipated energy during the monotonic test is positively related to the strain rate, time, and stress development during the test. Usually, a monotonic fracture test is stopped before all the energy is dissipated, to protect the measuring device as the stress-strain curve is asymptotic towards zero stress.

2.3. Dissipated energy in cyclic test

Fatigue testing is an accumulative deterioration process during which energy dissipates, as shown in the form of a hysteresis loop. Fig. 3 shows an exaggerated hysteresis loop to highlight the similarity to observations made from general cyclic testing.

The dissipated energy can be calculated as the total area of the stress-strain curve up to the peak strain during loading subtracted by the area of the stress-strain curve during unloading as shown in Eqs. (8) or (9). The stiffness value decreases during the entire test procedure, whereas the way the dissipated energy develops can