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Laboratory evaluation of fatigue life characteristics of polymer modified porous asphalt: A dissipated energy approach

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HIGHLIGHTS

- Porous asphalt specimens with SBS polymer modified binder were made.
- Four-point beam fatigue tests at ambient and freezing temperatures were performed.
- Statistical models of relation between dissipated energy and fatigue life have been derived.
- Porous asphalt can be a good alternative (from fatigue viewpoint) instead of HMA in rainy areas.

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ABSTRACT

Porous asphalt (PA) is considered as one of the efficient solutions to mitigate the dangerous aspects of runoff. Beside, fatigue cracking, as the most important structural failure in asphalt mixtures, plays a key role to keep performance and durability of porous asphalt. In this experimental research, fatigue characteristics of porous asphalt with dissipated energy viewpoint were investigated. SBS polymer modified binder and limestone materials were employed to make PA samples. In order to examine the porous asphalt fatigue life, 4-point beam fatigue test was conducted. A strain control loading with various strain levels at two temperatures was selected as the test conditions. Finally, two models to calibrate dissipated energy and fatigue life of porous asphalt were presented. Dissipated energy models to estimate of dissipated energy in various cycles of load repetitions are applicable. Also, reverse form of these models could be useful to predict fatigue life based on total dissipated energy.

1. Introduction

Researches of the production of pavement through which water can pass, were started in the late 1960s with accompany of The Franklin institute laboratories in the United States and the support of United States Environmental Protection Agency (EPA). The original proposed structure of a porous pavement consisted of an open-graded surface course, placed over a filter course and open-graded base course (or reservoir layer), all built on permeable subgrade. Porous asphalt (PA) has many benefits, for example; it can manage storm water, reduce noise pollution, improve the hydroplaning effect and water spraying, and enhance skid resistance during rainfall [1].

In the past years, pavements were maintained, but not managed. the experts experience tended to dictate the selection of Maintenance & Repair (M&R) methods with little regard given to life cycle costing nor or priority as compared to other pavement in the network. Nowadays, as the pavement structures has aged, a more systematic viewpoint to determining M&R requirements and priorities is necessary. So, pavement networks must be managed, not maintained. Beside, alligator or fatigue cracking, is a major distress that causes decreasing performance and durability of various types of asphalt mixtures. This crack, is a series of sharp and polygonal cracks caused by the fatigue of an asphalt surface under repeated traffic loads. The cracking initiates at the bottom of the asphalt, where the tensile stress or strain is highest. The cracks propagate to the top initially as one or more longitudinal cracks. After repeated traffic loading, these cracks connect and form many-sided, sharp-angled pieces that develop a shape resembling the skin of an alligator. These cracks is considered a major structural distress [2,3]. Thus, the prediction of fatigue life of porous asphalt is very important.

Generally, the models describe the fatigue characteristics of asphalt mixtures, is classified in four major groups. These groups

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are mentioned as Empirical Phenomenological (E-P) models, Fracture Mechanics (FM) models, Damage-based models, and dissipated energy (DE) models. Models falling into E-P models, were developed based on experimental data to connect fatigue life (maximum allowable number of load repetition) to tensile strain and sometimes, dynamic modulus of asphalt. General form of E-P models formulation can be expressed as Eq. (1).

$$N_f = k_1(\varepsilon_t)^{-k_2}|E^*|^{-k_3} \tag{1}$$

in which N_f = fatigue life; ε_t = tensile strain; $|E^*|$ = dynamic modulus value, and k_1, k_2 and k_3 are regression coefficients.

The well-known and advanced E-P models that considered additional important parameters of asphalt, includes Mechanistic-Empirical Pavement Design Guide (MEPDG), Shell Oil Company, Asphalt Institute, and SHRP A-404 model. In porous asphalt category, Liu et al. [4] found that fatigue life of porous asphalt, can be extended by multiple induction heating. They presented fatigue line of beam fatigue test as Eq. (2).

$$N_f = 2 \times 10^{14}(\varepsilon)^{-3.7625} \tag{2}$$

Fracture mechanics models use cracking propagation law for both Linear Elastic Fracture Mechanics (LEFM) and inelastic fracture mechanics. For LEFM, the Paris Law and for inelastic fracture mechanics, the J-integral are usually used.

The damage-based models, rest on the accumulative damage concept. The models developed by Bodin [5], Castro and Sanchez [6], and Lee [7] are the most important models in damage field in asphalt. Some of researchers used dissipated energy approach to model the fatigue behavior of asphalt concrete. Concept of dissipated energy is described as the energy which is dissipated by materials during each loading and unloading cycle [8]. Studying the evaluation of fatigue behavior of porous asphalt based on dissipated energy approach seems to be the missing link in asphalt studies. In this research, the fatigue behavior of porous asphalt is investigated using dissipated energy approach.

2. Dissipated energy approach

Initial dissipated energy (IDE) is measured in initial cycle of loading. Usually, first 50 cycles of loading as coordination cycles are considered and DE at 50th cycle is introduced as initial dissipated energy [9]. Ghuzlan [10] found that IDE is one of most important factors which affect behavior of asphalt mixtures. Eq. (3) was used by SHRP-A-404 to relate the IDE and fatigue life of asphalt mixtures.

$$N_f = 6.72 \times \mathrm{Exp}(0.049VFB) \times (w_0)^{-2.047} \tag{3}$$

in which N_f = fatigue life; w_0 = initial dissipated energy, and VFB = voids filled with bitumen.

Baburamani and Porter [11] showed there was a good correlation between IDE and fatigue life. Nevertheless this approach is inappropriate for all loading range and this point is one of the blind spot of it. Carpenter and Shen in 2006 found there wasn't appropriate correlation between IDE and fatigue life of asphalt concrete [12].

Based on the relationship between dissipated energy and the number of cycles up to fatigue or fracture, the following energy model was developed by van Dijk [13]:

$$N = \left(\frac{\pi.S_{fat}.\sin\varphi}{A_\varphi}\right)^{\frac{1}{z-1}}.\varepsilon_0^{\frac{2}{z-1}} \tag{4}$$

where N = load cycles, S_{fat} = initial stiffness modulus, = strain, φ = phase angle between stress and strain, and A, z are material constants.

Ghuzlan and Carpenter [14] suggested another equation to model the asphalt concrete. This equation depended on stress amplitude, strain amplitude, and phase angle between stress and strain. Eq. (5) derived the value of dissipated energy at cycle *i*.

$$W_i = \pi.\sigma_i.\varepsilon_i.\sin\varphi_i \tag{5}$$

where W_i = dissipated energy, σ_i = stress amplitude, ε_i = strain amplitude, and φ_i = phase angle between stress and strain.

Also, sum of dissipated energy in each cycle known as cumulative dissipated energy (CDE). CDE is described as Eq. (6).

$$W_{tot} = \sum_{i=1}^{n} W_i \tag{6}$$

where W_i = dissipated energy, W_{tot} = cumulative dissipated energy.

Conventionally, fatigue life was related to the total dissipated energy in the fatigue test as Eq. (7) [8]:

$$W_{tot} = A.(N)^z \tag{7}$$

where W_{tot} = cumulative dissipated energy, N = number of cycles to failure, and A, z = experimental coefficients.

The common criterion to asphalt failure is 50% loss of initial stiffness, but new failure criterion has been presented. This criterion is defined as the change in dissipated energy at cycle "i" and "i + 1" (ΔDE) divided by cumulative dissipated energy (DE) to load cycle "i". This failure criterion is shown below [8]:

$$\frac{\Delta DE}{DE} = A.(N)^z \tag{8}$$

In various frequencies, temperatures, stress amplitudes, and strain amplitudes, values of *A* and *z* were reported between 0.6 and 0.7 for hot mix asphalts [15,16].

Some of researchers have worked on dissipated energy approach of asphalt. Shen and Carpenter (2005) used 4-point beam fatigue Test to evaluate fatigue characteristics of Hot Mix Asphalt (HMA) by Plateau Value (PV) concept. PV is the constant-state zone of DER vs. Cycles curve .They found very good correlation between PV and fatigue lives (N_f50). They suggested PV = $0.4471(N_f)^{-1.1028}$ with $R^2 = 0.9988$ [17].

Maggiore et al. (2012) focused on dissipated energy concept of HMA with Tension- Compression Test. They found that rate of dissipated energy change is a suitable value to describe the fatigue in asphalt mixtures [18].

Boudabbous et al. (2012) performed Double Shear Test to characterize the fatigue specification of HMA. Both Cumulative Dissipated Energy (CDE) and Dissipated Energy Ratio (DER) method were employed. They suggested $W_N = 1065.5\ N_f^{0.5807}$ ($R^2 = 0.98$) for controlled forced and controlled displacement at 10 and 20 $^{\circ C}$ temperatures [19].

3. Laboratory program

3.1. Aggregates

Aggregates used for this research, were crashed limestone materials. The gradation of these materials was according to National Asphalt Pavement Association (NAPA) standard [20] for porous asphalt and the median limit was chosen for final gradation design.

The source of aggregates is the Asbcheran Mine in Damavand Town in Tehran Province. Properties of these aggregate materials are reflected in Table 1.

Upper, used aggregates gradation and lower limits of NAPA gradation for PA are shown in Fig. 1.