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A study on fatigue modeling of hot mix asphalt mixtures based on the viscoelastic continuum damage properties of asphalt binder

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HIGHLIGHTS

- Asphalt binders' integrity is well correlated to fatigue of asphalt mixture.
- The contribution of damage rate of binder to mixture fatigue is investigated.
- A fatigue model for mixture is suggested in terms of VECD analysis of binder.

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ABSTRACT

Asphalt mixtures are time, temperature and stress dependent and categorized as viscoelastic materials. A wide range of models have been proposed to characterize the fatigue behavior of asphalt mixtures. In this study continuum damage theory is used to characterize fatigue properties of asphalt binders and their effects on mixture's fatigue resistance. Neat, polymer modified and nanoclay modified bitumens were tested using linear amplitude sweep test. Four point bending beam fatigue tests were conducted on mixtures made with these binders at different loading rates namely 400, 600, 800 and 1000 micro-strain. Results showed that a strong correlation exists between the viscoelastic parameter of binder's integrity and the fatigue resistance of asphalt mixtures. Furthermore, a phenomenological fatigue relationship was introduced which is a function of the strain loading of the mixture as well as the viscoelastic continuum damage properties of the binder phase in the mixture. The proposed model can be used as a surrogate to time consuming beam fatigue tests.

1. Introduction

Fatigue damage in asphalt pavements generally results from repeated traffic loads. It usually occurs when asphalt pavements undergo repeated loadings at intermediate temperature range from approximately 10 °C to 30 °C [1,2]. In asphalt pavements the vehicular cyclic loads create areas of tensile stresses at the bottom of wearing course which contribute to forming microcracks. These microcracks coalesce and propagate upward to the surface of the pavement under repeated traffic loads [3].

Asphalt mixtures are stress and time dependent materials and exhibit viscoelastic effects when subjected to various kinds of loadings. Asphalt binder has a major contribution to the viscoelasticity of asphalt mixture. Therefore, many researchers have attempted to enhance the pavement performance characteristics by modifying the bituminous mixtures [4–12]. During the last decades many kinds of modifiers and additives have been used in asphalt binder and hot mix asphalt (HMA) mixture. They include polymers (both elastomers and plastomers), fibers, Sulfur and mineral fillers [13] of which polymers have the most application in the asphalt technology and pavement industry.

There are different approaches to quantify the fatigue process in asphalt concrete mixtures. Among different approaches, the strain approach firstly introduced by Monismith and the energy approaches have more application by the practitioners due to their simplicity and experimentally oriented procedures [14–18]. The most common fatigue model adopted by the Mechanistic Empirical Pavement Design Guide (MEPDG) is a strain approach considering the material's properties by the value of dynamic modulus in the following form [19]:

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$$N_f = k_1\left(\frac{1}{\varepsilon_t}\right)^{k_2}\left(\frac{1}{E}\right)^{k_3} \qquad (1)$$

In which N_f is the fatigue life of asphalt mixtures, ε_t is the tensile strain at the bottom of asphalt layer, E is the dynamic modulus and the other parameters are experimentally determined.

Most fatigue tests proposed to characterize fatigue properties of asphalt mixtures are time consuming and costly. Evaluation of the binder properties influencing associated mixture fatigue resistance and its field performance can be a good criterion. Therefore beside other factors influencing asphalt mixture performance (pavement structure, construction quality, etc.) characterization of binder fatigue properties is a good indicator or predictor of the fatigue resistance properties of the associated asphalt mixture. During the Strategic Highway Research Program (SHRP) project, researchers proposed to use binder's shear modulus (G^*) and its phase angle (δ) as the mixture fatigue index to evaluate asphalt pavement performance [20,21].

The proposed testing procedures by the Strategic Highway Research Program (SHRP) project were based on some simplified assumptions including wide linear viscoelastic (LVE) range, similar loading rate dependency and time temperature equivalency. These are valid for most neat asphalt binders. However, other researches showed that the PG based criteria (i.e. the "$G^*\cdot\sin\delta$") cannot be the only parameter to characterize the fatigue behavior of polymer modified bitumens (PMBs). Therefore other test protocols such as the Time Sweep (TS) test were introduced to characterize the fatigue behavior of asphalt binders [13]. However this kind of testing procedure is time consuming and hence other test methods were investigated as surrogate to time sweep test [22,23]. The Linear Amplitude Sweep (LAS) test which is recently introduced to assess the fatigue properties of neat and polymer modified asphalt binders has been used in order to characterize the fatigue properties of asphalt binder [22–26].

Pavement engineers require a comprehensive knowledge of the performance characteristics of the asphalt mixtures in designing both new pavements and overlays. Asphalt pavements are subjected to a variety of loads with different amplitudes. By incorporating Viscoelastic Continuum Damage Mechanics (VECD) concepts of asphalt binders, one can estimate the fatigue resistance of binder in terms of the applied shear strain as an indicator of the traffic [22,24–26].

2. Objectives

The goal of this study was to investigate any quantitative correlation between the fatigue life of different kinds of asphalt binders based on the VECD and fatigue failure criteria of the associated asphalt mixtures. To achieve this, the following objectives were considered in the present research study:

- Comparing fatigue performance of different kinds of binders in terms of their VECD parameters.
- Conducting bending beam fatigue tests at different loading amplitudes to investigate effects of binder modification on the fatigue lives of the corresponding mixtures.
- Investigating the role of binder's integrity upon fatigue resistance of asphalt mixtures at different loading rates.
- to develop a phenomenological fatigue model for asphalt mixtures in terms of the VECD parameters of asphalt binder

3. Continuum damage mechanics approach

The Viscoelastic Continuum Damage (VECD) theory is based on Schapery's elastic–viscoelastic correspondence principle and the work potential theory. According to this theory, the time dependent viscoelastic behavior of a material can be changed to linear elastic case. Based on the Schapery's work potential theory, the relation of work to damage is [27]:

$$\frac{dD}{dt} = \left(\frac{\partial W}{\partial D}\right)^{\alpha} \qquad (2)$$

In which W is the work done, D is damage intensity and α is a material constant.

The application of VECD in the characterization of bituminous mixtures dates back to the work done by Park et al. and evolved through the years [28–30]. Recently, the feasibility of VECD concepts in bitumen fatigue properties was investigated and proposed as the AASHTO standard [31].

Based on the VECD theory the damage accumulation in the bitumen subjected to fatigue loading is calculated by [31]:

$$D(t) = \sum_{i=1}^{N}\left[\pi I_D \gamma_0^2 (|G^*|\sin\delta_{i-1} - |G^*\sin\delta_i|)\right]^{\frac{\alpha}{1+\alpha}} (t_i - t_{i-1})^{\frac{1}{1+\alpha}} \qquad (3)$$

In which $D(t)$ is the damage accumulation at time t, I_D is the initial undamaged value of $|G^*|$, G^* and δ are complex modulus and phase angle respectively, γ_0 is the shear strain and α is a material's constant.

By converting the classical index properties (i.e. softening point, penetration, etc.) to performance characteristics of asphalt binders, the parameter $G^*\cdot\sin\delta$ has been used as the material performance characteristics against the fatigue loads. However, this parameter is only valid at the range of linear viscoelastic behavior of the bitumen and by increasing the applied loads. It cannot be used in the nonlinear region of the bitumen's response to loads [13]. On the other hand, research showed that the $G^*\cdot\sin\delta$ does not correlate well with the fatigue properties of polymer modified asphalt mixtures [13]. During the NCHRP 9-10 project, the Time Sweep (TS) test was introduced to investigate the fatigue characteristics of different kind of asphalt binders [13]. Recently, the Linear Amplitude Sweep (LAS) test was introduced as a surrogate to time sweep test, since the time sweep is a very time consuming test [23,24].

In the VECD analysis of fatigue properties of asphalt binders, a power law similar to the traditional fatigue relationship of asphalt concrete mixtures is proposed by the following relationship [31]:

$$N_f = A(\gamma_{\max})^{-B} \qquad (4)$$

In which N_f is the number of cycles to failure, $\gamma_{\max}$ is the maximum expected binder strain for a given pavement structure and A and B are parameters derived from the LAS test.

The fatigue characteristics of bitumens in the LAS test is described by the parameter "A_{35}" which is a function of loading amplitude, material's undamaged properties, accumulated damage at failure, etc. The fatigue criteria in this test is a 35% reduction in initial value of $G^*\cdot\sin\delta$ [23,24,31]. The "B" parameter represents the damage rate of the binder with the changes in the level of strain [23].

4. Materials and testing

Materials in this research study included one base binder and one polymer modified binder (PMB) and the Nanoclay additives with three different percentages as well as one specific gradation of crushed limestone which altogether constitute eight binder blends and eight different hot mix asphalt (HMA) mixtures.

4.1. Asphalt binders

Four different kinds of asphalt binders have been used in this study. The base binder was a 60/70 penetration grade bitumen obtained from Tehran's oil refinery. Properties of the base bitumen are presented in Table 1. The second one is polymer modified bitumen (PMB). This binder is a 60/70 binder blended with six percent of