Fatigue Evaluation of Asphalt Pavement using Beam Fatigue Apparatus

by

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Abstract: *The fatigue resistance of asphalt mixtures is predicted based on material properties and load responses. In this study, four-point bending beam fatigue testing has been used for a typical Michigan Asphalt mixture under various loading frequencies (10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz) and test temperatures (21.3°C, 13°, and 4°C). This study includes evaluation of different fatigue prediction models (Asphalt Institute Model and Shell Model) over wide ranges of laboratory testing conditions. In addition, this paper also provides a linkage between compression modulus and flexural stiffness, this study helps substantiate the concept that compression modulus can be used for evaluating both rutting due to vertical compression and fatigue due to flexural bending. The results in this study showed that there is a strong linear correlation between the flexural stiffness and compression modulus, with the flexural stiffness about 30% lower than the compression modulus.*

Keywords- Multiconductor transmission lines, capacitance, inductance, finite element method, modeling

I. Introduction

The distress of asphalt concrete like fatigue crack, rutting (permanent deformation), low temperature crack, surface wearing etc are related to vehicle loads, temperature, speed of load, material properties, soil condition etc. Fatigue cracking is recognized as the load/structural related distress. Rutting and low temperature cracking are temperature related distress. The Mechanistic Empirical Pavement Design Guide requires fatigue related laboratory test to determine pavement performance of the asphalt concrete.

The prediction of fatigue cracking is generally challenging while considering strain level, temperature, loading frequency, and modulus on the asphalt concrete. Fatigue cracking prediction is normally based on the cumulative damage concept which was given by Miller [1]. The allowable number of load repetitions is related to the tensile strain at the bottom of the asphalt layer. Fatigue models are developed to predict the number of repetitions at failure of asphalt layer. Most of the fatigue models are related to the horizontal tensile strain and stiffness (modulus) of the asphalt mixture.

The fatigue resistance of asphalt mixture is commonly determined by the flexural bending beam test [2]. A constant haversine loading was applied in an asphalt concrete beam with a number of load repetitions to get the failure status of the beam. In this paper, fatigue failure is defined as 50% reduction of initial stiffness. The reduction of stiffness can be related to the micro crack that appeared in asphalt concrete. Beam fatigue test is used to evaluate the different fatigue models. The four-point beam fatigue test was used at a constant strain level of 400, 300, and 200 micro strains and frequency level of 10Hz, 5Hz, and 1Hz. The test temperature of the beam was 21.3°C, 13°, and 4°C. The numbers of cycles measured from laboratory tests are compared with the Shell model and the Asphalt Institute model.

II. Background on fatigue model

There are many fatigue models to determine the fatigue life of an asphalt specimen. The simplest fatigue models considered the fatigue prediction based on either controlled strain mode or controlled stress mode. Equation 1 shows the simplest fatigue models of controlled strain mode and equation 2 shows the simplest fatigue models of controlled stress mode. The simplest fatigue model does not consider the temperature, modulus, and loading frequency of the asphalt pavement.

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

$$N_f = k_1 \left(\frac{1}{\sigma_t}\right)^{k_2} \tag{2}$$

Where:

N_f = cycle of load to failure
ε_t = tensile strain at bottom of specimen
σ_t = applied tensile stress
k_1, k_2 = experimental determined coefficient

The coefficient k1 and k2 are determined by fitting a linear regression function to the testing data. The models require field calibration to provide the in-service fatigue life of an asphalt pavement. The calibrated models, which are also called transfer functions, relate to the mechanistically determined responses under repeated loading.

There are different fatigue transfer functions that are used by different agencies or based on different considerations, for example, the Finn model [3], the Asphalt Institute Model [4], and the Shell Model [5]. The major role of these models is to provide a relation between mixture properties, pavement response (strain), and load repetitions to failure. The parameters of these models are mainly based on a continuous loading sequence and the coefficients are determined from empirical data regression. Equations 3 and 4 show the Asphalt Institute Model, and the Shell Model respectively.

$$N_f = 0.0796(\varepsilon_t)^{-3.291}(E_1)^{-0.854} \quad (3)$$
$$N_f = 0.0685(\varepsilon_t)^{-5.671}(E_1)^{-2.363} \quad (4)$$

Where:

N_f = cycle of load to failure
ε_t = tensile strain at bottom of specimen (in/in)
E_1 = asphalt concrete initial flexural modulus (psi)

Monismith et al. [6] introduced the fatigue life prediction from initial modulus and tensile strain of the asphalt mixture. Prior to Monismith's contribution, Pell and Cooper [7] introduced the fatigue model, which was based on the effect of the volumetric asphalt content and air void content of the asphalt mixture.

III. Objectives

The objectives of this study are: 1) to evaluate the existing traditional fatigue prediction model which relies on laboratory testing; 2) to develop a relationship between the flexural stiffness and compression modulus of asphalt concrete

IV. Sample Preparation and Testing

The asphalt mixture was mixed with PG 64-28 binder and had an asphalt content of 5.50%. The asphalt mixture studied in this research is a 9.5mm Nominal Maximum Aggregate Size (NMAS) mixture used in Michigan. For the beam fatigue sample, the mixture was first compacted using a slab kneading compactor to a target air void of 4%, and then cut into a dimension of 63mm by 50mm by 380mm. The beam dimensions were 50mm high, 63mm wide by 385mm long. The illustration of compacted and cut samples is shown in Figure 1. For the compression modulus sample, the mixture was compacted with a target air void of 4%.

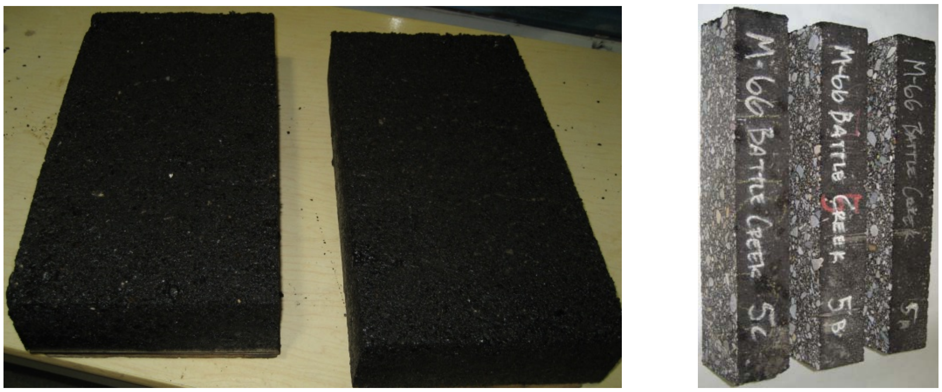

Figure 1. Illustration of compacted and cut samples of slab and beam

The asphalt specimen was tested in the beam fatigue apparatus at different strain levels, different frequencies, and different temperatures. The range of strain levels was 400, 300 and 200 micro strains. The range of frequencies was 10Hz, 5Hz and 1Hz. The temperature was 13°C and 21.3°C. The flexural bending machine was made by Industrial Process Controls (IPC) in Melbourne, Australia. The beam fatigue apparatus is shown in Figure 2. The beam fatigue apparatus is based on four-point loading. All tests were run in the constant strain mode of successive haversine strain cycles. The constant maximum strain level was monitored by measuring deflection at the middle of the beam. The termination cycle was defined as the cycle at which 50% of the initial stiffness was achieved.

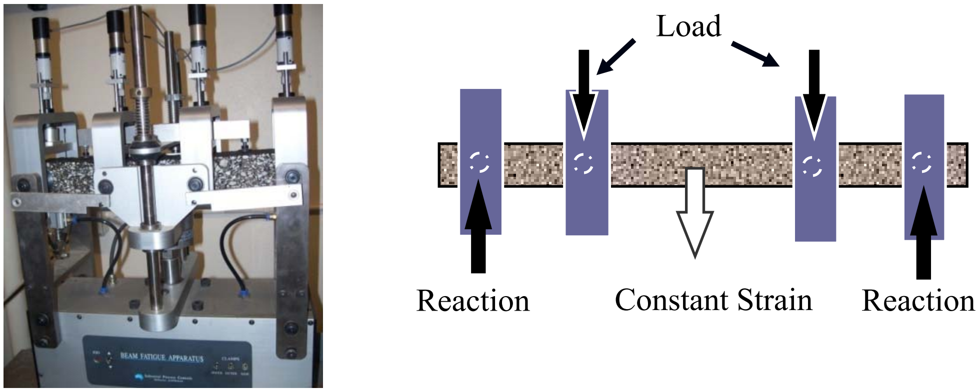

Figure 2. Beam fatigue apparatus showing four-point loading

V. Experiment results

a) Comparison between compression modulus and flexural stiffness

The compressive modulus was measured from Uniaxial compressive set up and flexural stiffness was measured from flexural test. The cylindrical specimen of 100mm diameter and 100mm height was used for a uniaxial test and beam specimen of 50mm high, 63mm wide and 385mm long was used for a flexural test. The aggregate size and properties, binder content, and air void level was same for the cylindrical specimen and beam specimen. The compressive modulus and flexural stiffness was captured at 50 cycles. The modulus was measured at temperature of 4°C, 13°C, and 21.3°C and loading frequency of 10Hz, 5Hz, and 1Hz. Figure 3 shows the relationship between compressive modulus and flexural stiffness of asphalt concrete. When comparing compressive modulus and flexural stiffness, the compressive modulus was 30% higher than flexural stiffness along the temperatures and loading frequencies. In general, the flexural stiffness is lower than the corresponding compressive modulus at the same loading conditions due to that the asphalt concrete materials are relative weaker in tension than compression.

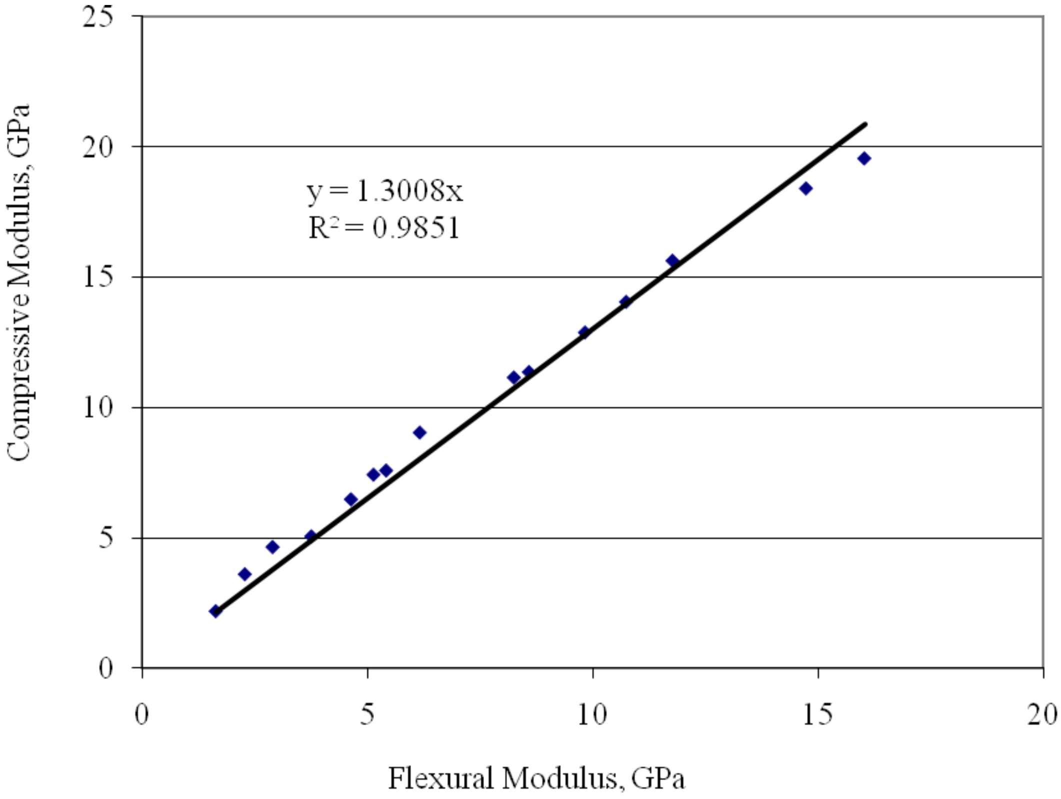

Figure 3. Relationship between compressive modulus and flexural stiffness

b) Comparison of Beam fatigue using fatigue model

The lab measurement fatigue life data were compared with different fatigue models in this section. Fatigue life was measured at the strain level of 400με, 300με, and 200με and frequency level of 10Hz, 5Hz, and 1Hz. Figure 4 shows the flexural stiffness along the strain level and loading frequencies at 21.3°C. At 10 Hz loading frequency, fatigue life is low at 400με level and fatigue life is exponentially high at 400με. When comparing fatigue life at different loading frequency, 10Hz has low fatigue life compare to 1Hz loading frequency. Figure 5 shows comparison of fatigue life along the range of strain level, loading frequency, and test temperature. Stain level is 200με, 300με, and 400με.

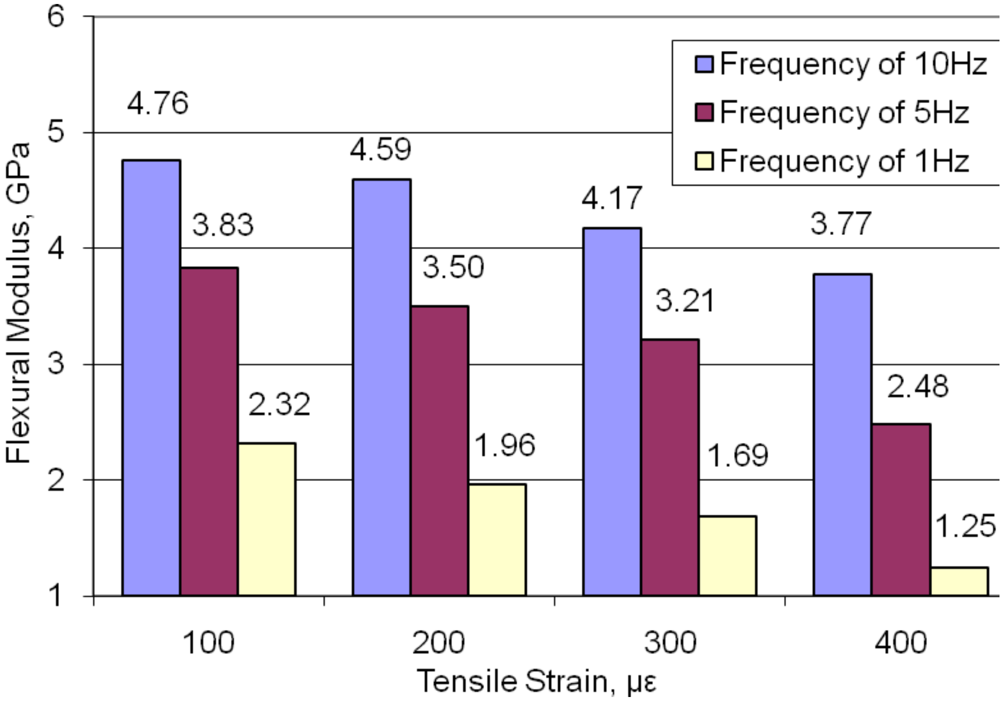

Figure 4. Flexural stiffness of asphalt concrete at different strain levels and loading frequencies

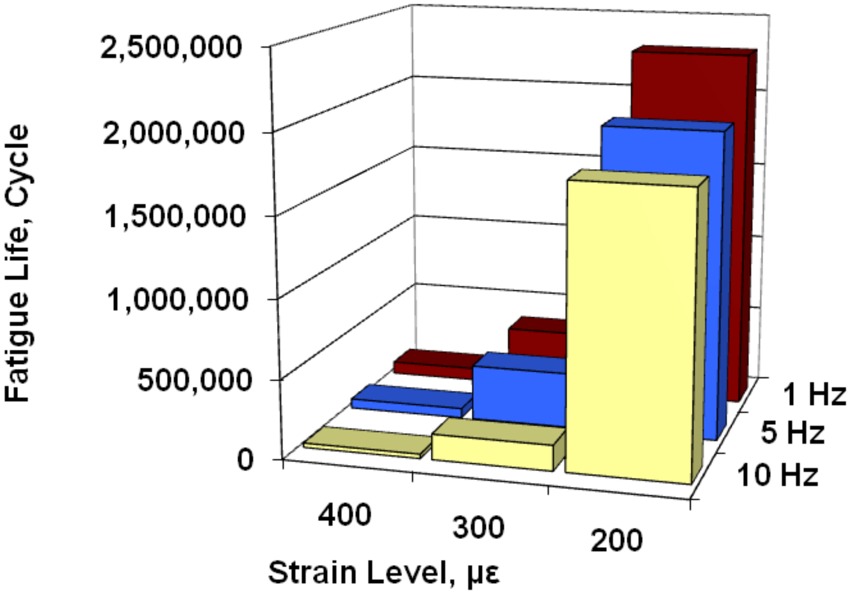

Figure 5. Comparison of Fatigue life at different strain level, loading frequency and temperature at 21.3˚C

The fatigue life measured from laboratory test was compared with Asphalt institute and Shell fatigue model. Input parameters of the fatigue model were flexural stiffness at 50 cycles loading and tensile strain level for the Asphalt Institute model and Shell model. Figure 6 shows comparison of fatigue life from lab measurement with different fatigue models at temperature of 21.3°C. When comparing two models from measurement, it was found that Asphalt Institute model was slightly over-predicted the fatigue life and Shell model was slightly under-predicted the fatigue life at a range of temperatures and loading frequencies.

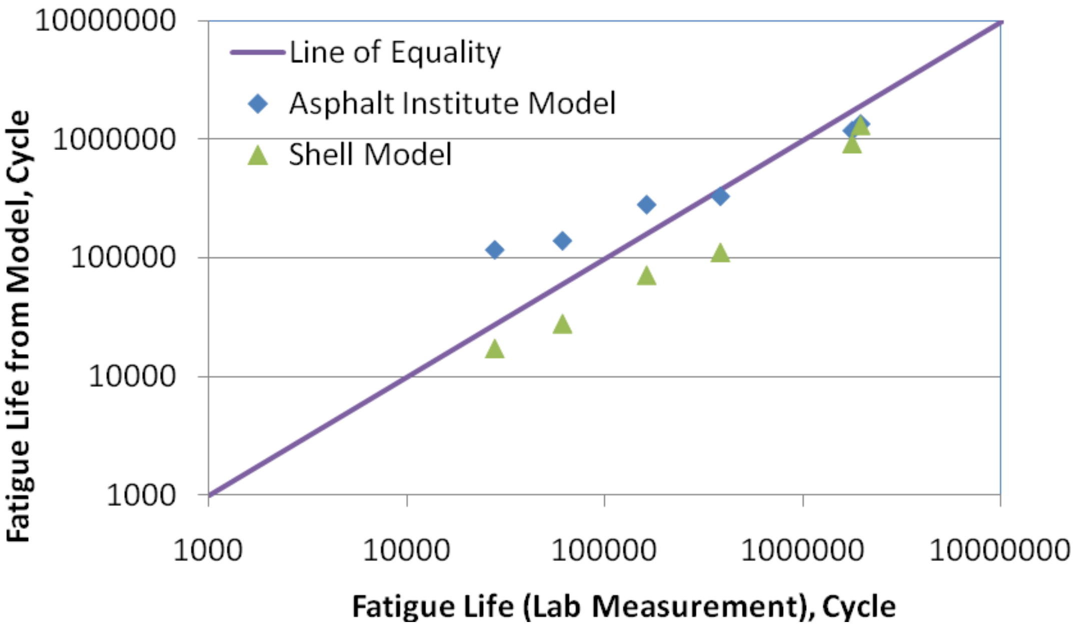

Figure 6. Comparison of Lab measurement with Asphalt Institute model and shell model with different temperature at 21.3˚C

VI. Summary and conclusions

Beam fatigue test was used to evaluate the flexural stiffness and fatigue life of the asphalt beam. The four-point beam fatigue test was used at a constant strain level of 400, 300, and 200 micro strains and frequency level of 10Hz, 5Hz, and 1Hz. When compared the flexural stiffness with compressive modulus, the flexural stiffness was 30% lower than compressive modulus. Beam fatigue test was also used to evaluate the different fatigue models. The number of cycle measured from laboratory tests were compared with different fatigue models. It was revealed that fatigue life was low, when the asphalt beam was tested with high strain level and high loading frequency. Fatigue life was high at low strain level and low loading frequency. Fatigue life is increased with decreasing loading frequency. The laboratory results verify that Asphalt Institute model and Shell model were useful to predict fatigue life at different strain level, loading frequencies and test temperature.

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