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Effects of recycled asphalt pavements on the fatigue life of asphalt under different strain levels and loading frequencies

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A B S T R A C T

Fatigue lives of Hot Mix Asphalt (HMA) and binder have been studied separately for a long time. However, fatigue lives of HMA containing Recycled Asphalt Pavement (RAP) and the binder extracted from the same HMA containing RAP have not been studied yet. This study examines the effects of RAP, loading frequency and strain level on the fatigue lives of asphalt mixtures and binders. In addition, the relationship between the fatigue lives of asphalt mixture and binder is determined. Beam fatigue tests were conducted to determine the fatigue behaviors of two asphalt mixtures: one with 35% RAP and the other without RAP. To evaluate binder's fatigue behavior, binders were extracted and recovered from these two mixtures. Then, fatigue lives of these two binders were determined using time sweep and Linear Amplitude Sweep (LAS) tests. Results show that presence of RAP in mixture causes a decrease in the mixture's fatigue life, whereas it causes an increase in the fatigue life of binder. As expected, an increase in loading frequency results in an increase in the fatigue lives of asphalt mixture as well as binder. In addition, increase in strain level causes a decrease in the fatigue lives of both mixtures and binders. Fatigue lives of binders from time sweep and LAS tests show a good correlation with the mixture's fatigue life by the beam fatigue test.

1. Introduction

Fatigue cracking occurs due to repeated traffic loading on flexible or asphalt pavements. Fatigue life of a flexible pavement is affected by two major factors: one is load related and other is material related [1,2]. Load related factors include the loading frequency which relates the vehicle speed and load-induced strain at the bottom of the asphalt layer. Material related factors include Hot Mix Asphalt (HMA) properties and asphalt binder properties. Of course, temperature affects all of these material properties. Effects of these factors such as loading frequency and strain level on fatigue life of HMA have been studied for a long time. However, effects of these factors on fatigue life of HMA and binder containing Recycled Asphalt Pavement (RAP) have not been studied yet.

Various laboratory methods have been used to measure fatigue behavior of asphalt mixtures for several years. However, the majority of researchers [2–5] have used the four-point beam fatigue test to determine fatigue life of asphalt mixtures. In this test, some localized damages occur in the material at the micro-scale under each cycle of loading, which results in decrease in material's stiffness. This reduction in stiffness is used to monitor the damage. Regarding the failure criteria, there are broadly two approaches; one considers reduction in initial stiffness and another considers the dissipated energy. In this study, 50% reduction in initial stiffness approach is used to determine the fatigue life of mixes and binder. The stiffness reduction approach is considered instead of the dissipated energy approach because according to study conducted by Tarefder et al. [6] shows that the dissipated energy approach fails to describe the viscoelastic nature of asphalt mixes.

During Strategic Highway Research Program (SHRP) [7], researchers found that asphalt binder in the mixes has significant impact on the fatigue behavior. However, in the current binder specification, complex shear modulus (G^*) and phase angle (δ) related parameter $G^*sin\delta$ does not adequately determine binder fatigue behavior [8–11]. Therefore, an extensive amount of research has been done to develop a test procedure which can accurately determine the binders fatigue behavior. Among them four major developments are: Time Sweep test [9], Linear Amplitude Sweep (LAS) test [12], Multiple Stress Creep Recovery (MSCR) test [13] and Double Edged Notched Tension (DENT) test [11]. The time sweep test applies repeated cyclic loading at any frequency to binder sample using the Dynamic Shear Rheometer (DSR) to mimic the mixture testing. Different loading frequencies

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can be considered while conducting this test according to the loading pattern in the pavement. In this test, the fatigue life is calculated using the degradation of modulus (G^*) under repeated loading. However, time sweep tests at low strain levels are time consuming. On the other hand, LAS test is a newly developed accelerated asphalt binder fatigue test to replace the time sweep. In this test, linearly increasing strain is applied under cyclic loading at a constant frequency. However, all these binder tests are fairly new and require further investigation to relate the contribution of binder fatigue behavior to pavement performance, which has been done in this study.

As beam fatigue test takes a long time to finish, introducing a short-length binder fatigue test may be helpful for the quick determination of fatigue life of any mixture. Therefore, an attempt is made in this study to correlate the binder fatigue testing results with the mixture test results at different loading frequencies. In the past, several researchers attempted to predict the binder contribution in fatigue life of asphalt concrete. However, most of these studies focus only on the linear viscoelastic range of binders [7,14,15]. These studies find very poor relationship between the binder and mixture to laboratory fatigue testing. They considered only the $G^* sin\,\delta$, under small strain which does not consider the nonlinear viscoelastic behavior. Therefore, some new approaches are proposed to introduce non-linear viscoelastic properties in measuring the binder fatigue. Many research groups use the time sweep test by DSR to evaluate the non-linearity effect in the binders' fatigue properties [16,17]. For several years, researchers attempted to anticipate binder testing as an indicator of fatigue performance to reduce the need for costly mixture fatigue testing. A study conducted by Johnson et al. [17] investigates the effect of temperature and strain on fatigue life of binder and mixture. They compared the current specification parameter $G^* sin\,\delta$ and stress controlled time sweep test results with mixture fatigue test results. They conclude that $G^* sin\,\delta$ does not correlate with the mix fatigue life and the time sweep test shows a good correlation with the mix fatigue life. However, they did not investigate the effects of loading frequency and mixture type. Another study by Hintz et al. [12] introduces a new fatigue binder test LAS, which shows good correlation with the fatigue performance recorded by the Long-Term Pavement Performance (LTPP) program. However, this study does not correlate the fatigue life of asphalt concrete in the laboratory. Also, the effect of loading frequency and mix type cannot be analyzed using their finding. Few other drawbacks of the previous studies described above are the conventional HMA and virgin binders. If there is a correlation between LAS test on binder and beam fatigue test on mixture, the mixture's fatigue life can be easily characterized with LAS test. In addition, the effects of different test parameters such as frequency of loading; mix type etc. can be addressed. From the discussion above, it reveals that, there is little to no work done to evaluate the effect of loading frequencies in asphalt mixes' and binders' fatigue life containing RAP. In addition, no correlation between the binder's and mixture's fatigue lives is available yet. To this end, the current study addresses all of these issues based on laboratory fatigue testing on HMA mixture and binder.

2. Objectives

The main objective of this study is to evaluate the fatigue lives of HMA and extracted binder from RAP mixtures. Specific objectives of this study are:

(a) To evaluate the effect of RAP on fatigue life of HMA mixture and binder.
(b) To examine the effect of loading frequency on fatigue lives of RAP mixture and binder.
(c) To investigate the effect of strain level on fatigue lives of RAP mixture and binder.
(d) To develop a relationship between the fatigue lives of asphalt mixture and binder.

To fulfill these objectives, time sweep and LAS tests results for the two extracted binders are compared with the four-point beam fatigue test results for those two mixes at different loading frequencies and strain levels. In addition, this study correlate the fatigue lives determined by time sweep and LAS tests on binder with the beam fatigue test on mix. All tests are conducted at a constant temperature (20 °C) to eliminate the temperature effect on fatigue life.

3. Laboratory testing

3.1. Materials

Two plant produced SuperPave (SP) mixtures, type SP-III mixes were used. The mixes were collected from two construction sites in cooperation with the New Mexico Department of Transportation (NMDOT).The first mixture contained 35% RAP and the second mixture had no RAP. Aggregates were collected from a Basalt pit. The Nominal Maximum Aggregate Size (NMAS) of the mixes is 19 mm. Asphalt content was maintained 4.4% by the weight of both mixtures. Performance Grade (PG) 70–22 was used as the virgin binder.

For the binder, asphalt binder was extracted from these mixes using the ASTM D2172 [18] and recovered using ASTM D5404 [19]. After this extraction and recovery two types of binders were recovered one with RAP binder and another without RAP binder.

3.2. Test matrix

Fig. 1 presents the test matrix. Different loading frequencies (10 Hz, 5 Hz and 1 Hz) were tested for the 35% RAP mixes and the extracted binders. However, the no-RAP mix and extracted binder were only tested at 10 Hz due to the time constrain. Therefore, while comparing the fatigue behavior of RAP and no-RAP mixes only the test results at 10 Hz have been used. Beam fatigue test for AC takes a long time to finish. Therefore only two replicate sample were tested at each strain level. And three replicate for binders tests were performed at each strain level. A total of 32 samples for beam fatigue, 48 samples for time sweep and 48 samples for LAS were tested. It took more than 2 years to finish all these tests.

3.2.1. Mixture testing

Four-point beam fatigue test was conducted following the AASHTO T 321 protocol to evaluate the fatigue behavior of the mix [20]. Fig. 2 shows the setup for four-point beam fatigue test. Beam samples were prepared using a kneading compactor. The final dimensions of the beam samples were 380 mm length, 63 mm width and 50 mm height. The air voids of the samples range from 5.1% to 5.8% with an average value of 5.4%.Then, the samples were loaded under strain-controlled conditions using sinusoidal loading at different frequencies at 20 °C. A simplified failure criteria was considered, since at low strain level the beam fatigue test takes a long time to complete. In this study, the failure criteria were a 50% reduction of the initial stiffness value. According to the standard, the sample stiffness at 50th cycle is defined as the initial stiffness. Samples were tested at four strain levels: 1000 $\mu\varepsilon$, 800 $\mu\varepsilon$, 600 $\mu\varepsilon$ and 400 $\mu\varepsilon$ at three different loading frequencies of 1 Hz, 5 Hz and 10 Hz. Ideally, a strain input is specified. Then the test subroutine determines the required deflection using the Eq. (1) [20] to achieve the specified strain levels. This