Effect of Loading Frequency and Temperature on the Fatigue Parameters of Asphalt Concrete

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Abstract. Investigating the behavior of asphalt concrete at low loading frequency is essential to understand the thermal fatigue damage due to cyclic day-night temperature cycles, where the loading frequency is usually very low. This study determines some properties (e.g., fatigue damage, dissipated energy, and stiffness) of asphalt concrete beam samples at a low frequency of loading using four-point bending test apparatus. Results show that fatigue damage is more significant at a lower frequency of cyclic loading and the number of cycles at failure becomes stable at a frequency equal to or lower than 0.01 Hz. The concept of initial stiffness at the 50th cycle of loading is inappropriate at a low frequency of loading as the stiffness reduction with a number of loadings is so considerable at a frequency of loading. In addition, the dissipated energy per loading cycle decreases with a decrease in loading frequency.

Keywords: asphalt concrete, fatigue life, initial stiffness, frequency, temperature.

1 Introduction

Fatigue cracking is one the most common forms of distress in flexible pavement. It happens due to the repeated tensile strain at the bottom of asphalt concrete (AC) caused by the traffic loading. The integrity of the asphalt concrete material starts losing with the initiation of microcracks upon applying repeated traffic loading. These microcracks coalesce to form macrocracks under further traffic loading, leading to pavement failure. The fatigue behavior of hot-mix asphalt (HMA) has been characterized by four-point bending (4PB) fatigue test in the laboratory by many researchers in the past [1, 2]. In this test, an AC beam is subjected to repeated bending in strain-controlled mode until the stiffness is decreased by 50 % of its initial stiffness, which is the traditional failure criteria. Several factors might affect the test results in the fatigue test. The effect of loading pattern (haversine and sinusoidal) and rest period between loading of the fatigue test have been widely explored in the literature [3–6].

American Association of State Highway Transportation Officials defines fatigue failure as the number of cycles at which material stiffness decreases by 50 % [7, 8]. The initial stiffness of a beam is measured at the 50th cycle of loading to account for the initial setting of the beam. However, one might expect stiffness reduction from the first cycle, especially at higher strain amplitude. Other researchers have used dissipated energy to model fatigue behavior [9–11]. Dissipated energy is defined as energy lost to the system during each loading cycle. Energy loss is due to damping, viscoelastic effects, and damage growth. On the other hand, the Viscoelastic Continuum Damage approach has shown promising results in terms of robustness and efficient utilization of available resources [12, 13]. In addition, the test is typically performed at several temperatures to evaluate the effect of stiffness on the fatigue life since the stiffness of AC is affected mainly by temperature.

The above discussion clarifies that the researchers have widely explored the fatigue damage of AC. The loading pattern, failure criteria, and the effect of temperature are well known. However, the effect of the loading frequency, mainly the low frequency, is still an unknown issue. The behavior of AC at a low frequency of loading is essential to understanding the thermal fatigue behavior. The reason is that the thermal fatigue damage occurs mainly due to the day-night temperature fluctuations whose loading frequency is $1/(24 \cdot 60 \cdot 60) = 1.16 \cdot 10^{-5}$ (Hz). It may mislead or produce wrong results if the behavior of AC at a high frequency (usually 10 Hz) is used to analyze the thermal fatigue damage. Another form of thermal damage, single cycle

low-temperature cracking, also occurs at slow loading (cooling) rate.

The main objective of this study is to investigate the AC's fatigue parameters (flexural modulus, initial stiffness, dissipated energy, and fatigue damage) at a low loading frequency using flexural beam fatigue tests at different temperatures, strain levels, and low frequencies.

2 Research Methodology

Plant-produced asphalt mixture was used to prepare the samples, and the mix was collected from a construction site in cooperation with New Mexico Department of Transportation. This is a widely used dense-graded Superpave (SP) mix, type SP-III, with a maximum aggregate size of 25 mm. The mixture contained 35 % reclaimed asphalt pavement materials. Performance Grade (PG) binder, PG 76-22, was used for an amount of 4.4 % by the weight of the mixture. About 5 % of materials passed through the No. 200 sieve size (0.075 mm).

Figure 1 shows the preparation of the beam sample in the laboratory.
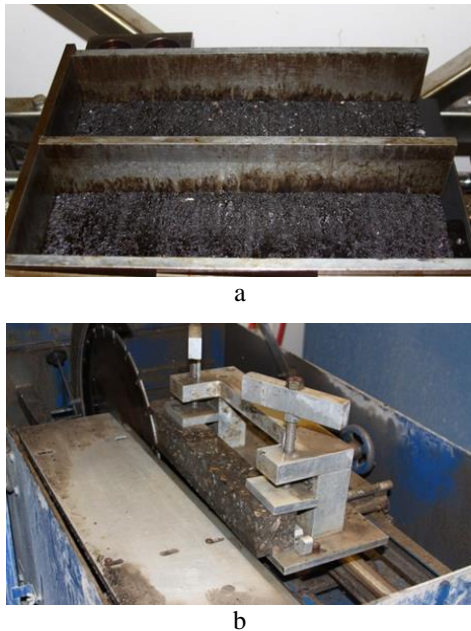

a

b

Figure 1 – Sample's preparation: a – compacted mixture;
b – cutting the slab to prepare the beam sample

As a first step, beam slabs of 450×150×75 mm were prepared using a kneading compactor, as shown in Figure 1 a. Before the compaction, the mixture was oven heated for less than an hour. Then, each slab was cut into two beams of 380×63×50 mm using a laboratory saw, as shown in Figure 1 b. The air voids of the samples ranged from 5.1 % to 5.6 %, with an average value of 5.3 %.

Beam fatigue tests were conducted using a sinusoidal waveform with no rest period at different strain levels, temperatures, and frequencies. The support conditions and the geometry of the sample followed the requirements of the AASHTO T 321-07 test protocol [7]. The test program is shown in Figure 2 a, where a sample has been clamped for testing. The middle two clamps are

loading frames that apply downward and upward force to attain the predefined strain in the sample. Using the deflection history, the maximum strain and stress in a specimen can be calculated using the following equations, respectively [2]:

$$\varepsilon = 12h\delta/(3L^2 - 4a^2); \qquad (1)$$

$$\sigma = PL/(bh^2), \qquad (1)$$

where ε – maximum strain; σ – maximum stress, Pa; $P(t)$ – load applied by actuator, N; t – time, s; b – average specimen width, m; h – average specimen height, m; $\delta(t)$ – deflection at the beam center, m; a – distance between inside clamps, m; L – the distance between outside clamps, m.

Sample flexural stiffness is then calculated using σ and ε data recorded from each cycle:

$$E = \sigma_t/\varepsilon_t, \qquad (3)$$

where E – flexural stiffness.

Figure 2 b shows a typical test result where the stiffness ratio (SR) (current cycle's stiffness divided by the initial stiffness) decreases with the loading cycle due to microcrack formation. According to the AASHTO T 321-07 test protocol, the stiffness at the 50th cycle of loading was considered the initial stiffness, and the number of cycles at a 50 % reduction in stiffness was considered the failure of the beam AASHTO T 321-07 test protocol [7].
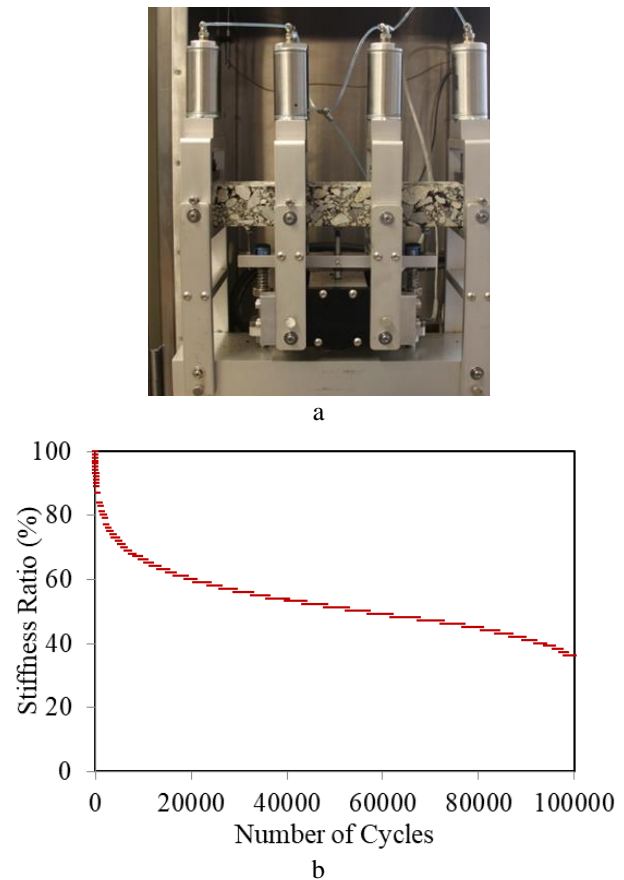

a

b

Figure 2 – Flexural stiffness test [14]:
a – test setup; b – test result

3 Results and Discussion

3.1 Fatigue damage

Fatigue damage occurs due to a repeated loading cycle for developing micro-cracks inside the material, and the material's stiffness decreases with the loading cycle. Figure 3 presents the number of cycles at failure with a frequency of loading at three different strain levels (500 με, 1000 με, and 1500 με).
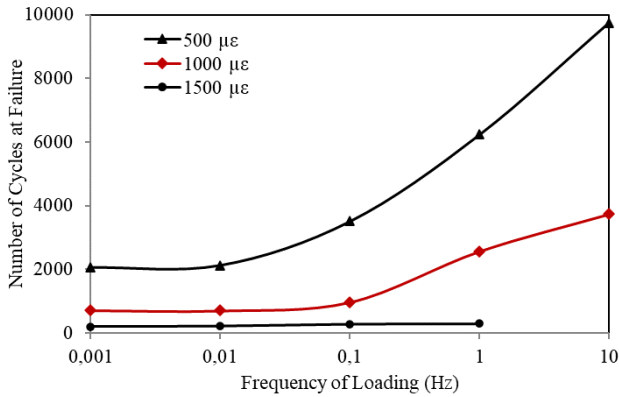

Figure 3 – Allowable load repetitions
at different frequencies at 20 °C

The damage is usually more significant if the load sustains a longer time on a material. A similar observation has been made in AC fatigue damage based on the 4PB fatigue test.

Figure 3 shows that the stiffness decreases upon a decrease in loading frequency. For example, the stiffness decreases from 9751 MPa to 2131 MPa for the frequency decrease from 10 Hz to 0.001 Hz at 500 με.

A similar observation has been found for samples tested at 1000 με. Due to the large vertical scale, it is not well depicted for 1500 με.

The test could not be completed at 1500 με and 10 Hz, as it is too difficult to apply this large strain at this very fast rate.

To examine the temperature effect on the fatigue parameters, tests were also conducted at three different temperatures (–10 °C, 20 °C, and 40 °C). The results are presented in Fig. 4. It shows that the temperature has a very good effect on the fatigue damage of AC.

The fatigue damage is less (a more significant number of cycles at failure) at a higher temperature. For example, the numbers of cycles at failure are 17561, 9751, and 3755 at temperatures of 40 °C, 20 °C, and –10 °C, respectively.

In addition, the frequency dependency in the fatigue damage of AC is very low, as occurred at –10 °C in Figure 4. This is because the asphalt material's behavior is elastic at low temperatures.

Another finding from Figures 3, 4 is that the number of cycles at failure becomes stable at a frequency equal to or lower than 0.01 Hz. It is due to the healing behavior of AC. The material gets more time to heal up at a slower loading rate.

The behavior of AC at $1.16 \cdot 10^{-5}$ Hz can be well understood if the test is conducted at 0.01 Hz or, more conservatively, at 0.001 Hz.

More specifically, thermal fatigue damage occurs due to the day-night temperature fluctuations whose loading frequency is $1.16 \cdot 10^{-5}$ Hz.

It is good enough to study the behavior of AC at 0.001 Hz, to understand the fatigue behavior of AC due to day-night temperature fluctuations.
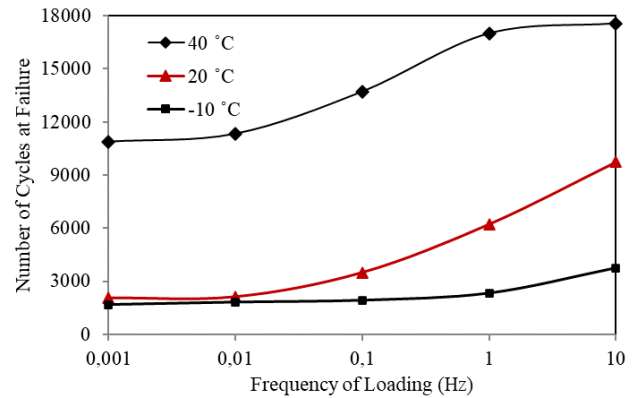

Figure 4 – Allowable load repetitions
at different frequencies at 500 με

3.2 Dissipated energy

Dissipated energy (DE) is the area under the stress-strain curve. This part of energy does not recover upon unloading. It accumulates within the material upon applying repeated load. Due to its simplistic nature, dissipated energy approaches are popular among the pavement engineering community to determine the failure point of asphalt samples [15, 16].

Figure 5 shows the DE loop for two tests conducted at frequencies of 0.01 Hz and 10 Hz at 500 με (250 με to –250 με) strain level.
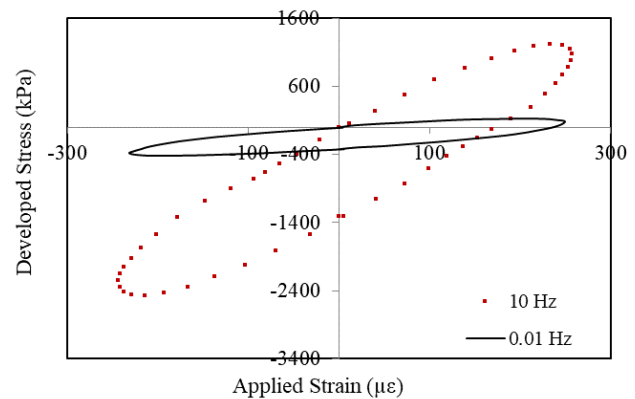

Figure 5 – Hysteresis loop of dissipated energy
at 0.01 Hz and 10 Hz

The area of the DE loop of 0.01 Hz is much smaller than the 10 Hz curve. That means the material dissipates less energy at a low frequency of loading. This is because the stiffness of AC decreases with a decrease in stiffness. The DE loop area decreases as the stiffness decreases (under controlled strain test). However, the total DE of any material is independent of the loading mode. Therefore, at a low loading frequency, the material undergoes a more significant number of cycles to reach the DE capacity of AC. More specifically, the number of

cycles at failure is more significant than the traditional criteria of a 50 % reduction in stiffness.

Figure 6 shows the ASU energy ratios (stiffness ratio multiplied by the number of loading cycles) of two samples tested at 10 Hz and 0.01 Hz at 1000 µε strain level.
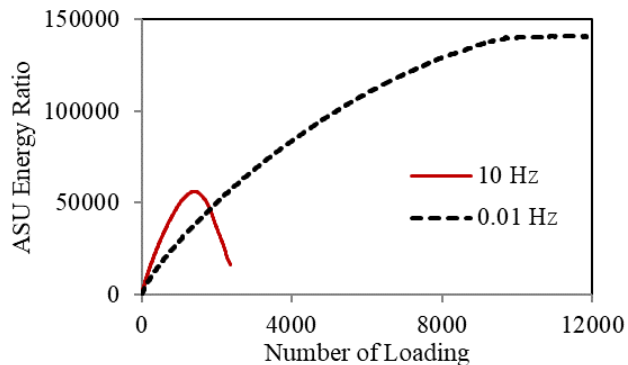

Figure 6 – ASU energy ratio with the number of loading at 1000 µε

According to the energy dissipation approach, a material is considered to fail when the ASU energy reaches its peak. The ASU energy ratios of the samples tested at 10 Hz and 0.01 Hz are 56,200 and 140,500 (2.5 times of 56,200), respectively. The corresponding numbers of cycles at failure are 1260 and 9880 for the samples tested at 10 Hz and 0.01 Hz, respectively. This also implies that sample tested at lower loading frequency always has greater fatigue life if the DE approach is adopted, which is the opposite of the traditional criteria of 50 % reduction in stiffness as presented in Figures 3, 4.

Therefore, it can be said that the DE approach cannot predict the failure cycle considering the viscoelastic property of AC.

3.3 Initial stiffness

According to AASHTO T 321-07 (2007), the stiffness at the 50th cycle of loading is considered the initial stiffness. The first 50 cycles are neglected to accommodate the initial setup and stabilization of the test. However, one might expect significant damage in the first 50 cycles of loading, especially at high temperatures and low loading frequency. The effect of a low loading frequency at 20 °C and 500 µε is presented in Figure 7.
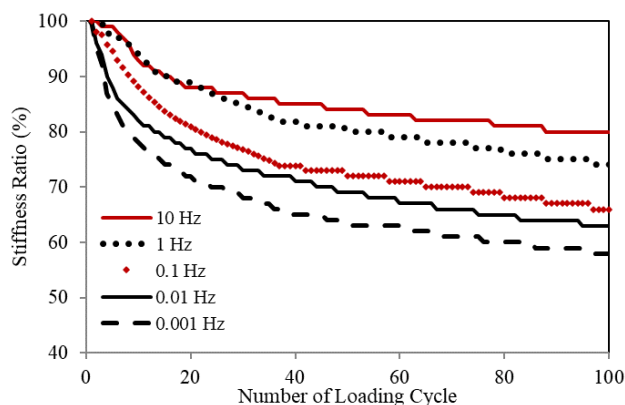

Figure 7 – A decrease in stiffness with a number of loading at 500 µε

The decrease in stiffness ratio has been plotted due to loading between 0.0001 Hz and 10 Hz. The vertical dash line cuts the stiffness ratio at the 50th cycle of loading. It can be observed that the stiffnesses decrease to about 84 %, 80 %, 72 %, 69 %, and 63 % for the frequencies of 10 Hz, 1 Hz, 0.1 Hz, 0.01 Hz, and 0.001 Hz, respectively.

The stiffness decrease, especially at 0.1 Hz, 0.01 Hz, and 0.001 Hz, is significant and should not be neglected. In addition, the test stabilizes within 5 cycles of loading at a slow frequency, as shown in Figure 7.

Therefore, it is recommended that the initial stiffness should be considered at the 5th cycle of loading for the testing at 0.1 Hz, 0.01 Hz, and 0.001 Hz of loading.

3.4 Modulus of AC

The flexural modulus of AC is frequency-dependent in addition to the temperature effect. Figure 8 plots the moduli of AC tested at different temperatures at $1.16 \cdot 10^{-5}$ Hz, the frequency of the day-night temperature cycle, using the 4PB test at 200 µε.
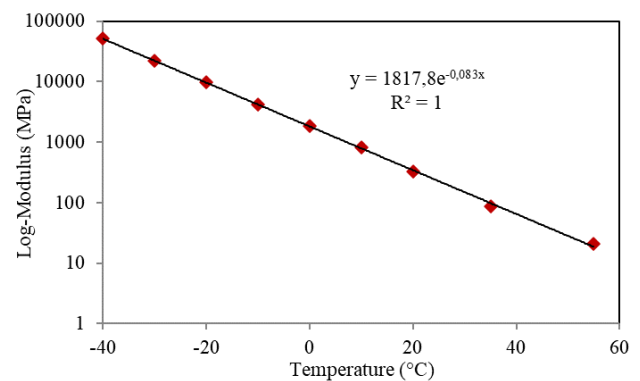

Figure 8 – Modulus of AC at the day-night temperature frequency of $1.16 \cdot 10^{-5}$ Hz

It shows that the stiffness of AC decreases with the expected decrease in frequency. It can also be observed that the modulus is very low compared to the typical values tested at 10 Hz of loading. For example, at 20 °C, the modulus of AC at $1.16 \cdot 10^{-5}$ Hz is 324 MPa, whereas the dynamic modulus of the same material at 10 Hz is 9970 MPa [17].

Therefore, while analyzing thermal fatigue damage, the stiffness should be considered at the frequency of $1.16 \cdot 10^{-5}$ Hz of loading.

4 Conclusions

This study determines AC's fatigue properties such as fatigue damage, dissipated energy, stiffness, and threshold stress-strain at a low loading frequency using 4PB test apparatus. Based on the study's findings, it can be said that fatigue damage increases at a low frequency of cyclic loading using AASHTO failure criteria, and the number of cycles at failure becomes stable at the frequency of equal to or lower than 0.01 Hz. The dissipated energy per cycle of loading decreases with a decrease in loading frequency, and the damage decreases at a low frequency of cyclic loading using the dissipated energy criteria. Considering initial stiffness at the 50th

cycle is not appropriate at a low loading frequency as the stiffness reduction is so considerable at slow loading.

The findings of this study can be used to simulate the behavior of AC better, and research can use the results of this study to develop a new testing program. The above conclusions are because the initial stiffness was considered at the 50th cycle of loading for testing at 10 Hz. For testing at a frequency lower than 10 Hz, the initial stiffness was taken at the 5th cycle of loading. In addition, the current study used a single SP mixture.

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