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The combined effect of loading frequency, temperature, and stress level on the fatigue life of asphalt paving mixtures using the IDT test configuration

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ABSTRACT

The main objective of this study was to investigate the combined effect of the loading frequency, temperature, and stress level on the fatigue life of asphalt paving mixtures. Asphalt mixtures were designed using the Superpave design procedure using a 60/70-penetration grade asphalt binder having a Superpave performance grade of PG 64-10 and crushed limestone aggregate. The indirect tension (IDT) fatigue test was used to determine the fatigue behavior of asphalt mixtures. The IDT fatigue test was conducted in the stress-controlled mode of loading using five stress levels: 288, 360, 432, 504, and 576 kPa (approximately in the range of 42–84 psi loading) representing truck or heavy traffic loadings in real-life conditions, two intermediate temperatures: 20 and 30 °C, and four loading frequencies: 3, 5, 8, and 10 Hz representing truck speeds of about 12.5–45 km/h. Three replicates were used for each IDT fatigue test. A total of 120 IDT fatigue tests were conducted in this study. Findings of the study showed that the increase in loading frequency resulted in an increase in the fatigue life at the two test temperatures 20 and 30 °C. In addition, the rate of increase in the fatigue life with the loading frequency was exponential, and the difference in the fatigue life (N_f) between the different loading frequencies was found to be higher at lower stress levels than that at higher strain levels at the two temperatures. It was also found that the difference in the fatigue lives between the different stress levels was much higher at higher loading frequencies than that at lower loading frequencies for both temperatures. For the stress-controlled mode of loading, which was used in this study, an increase in temperature provided shorter fatigue lives for asphalt mixtures.

1. Background

Fatigue is a phenomenon in which an asphalt pavement is subjected to repeated stress levels less than the ultimate failure stress. Fatigue behavior of asphalt mixtures is studied using two approaches, the traditional approach using the strain (or stress)-based models [19], and the dissipated energy approach were the dissipated energy is used and defined as a damage indictor of the material [14,5]. In addition, fatigue failure is defined using the stress–strain hysteresis loop in each loading cycle of the fatigue test [6,7]. Fatigue behavior is also affected by asphalt mixture variables and testing variables (such as temperature and loading frequency).

In asphalt pavements, higher speeds correspond to higher frequencies and higher dynamic stiffness and this will produce lower strains in the asphalt pavement [18].

Frequency of loading in asphalt concrete is defined as number of load cycles subjected to the material per unit of time. Studying the effect of loading frequency on fatigue life of asphalt concrete mixtures is difficult because it is interconnected with the load duration and rest period. Changing any of these variables will change the other variables [23].

Barksdale [9] correlated vehicle speed with vertical stress pulse time at different depths beneath pavement surface. He found that higher speeds are related to shorter loading times, which correspond to higher frequencies. Load duration time for a vehicle speed of 72 km/h at a depth a round 30.5 cm. is about 0.044 ss (22.7 Hz).

According to [15], for operating speed of 96 km/h on an interstate highway, the estimated loading frequency at the med asphalt layer depth (depth varies from 7.6 to 30.5 cm) is between 10 and 25 Hz.

Furthermore, Mollenhauer et al. [18] developed a relation between vehicle speed and frequency of traffic loading. This relation was based on an in situ testing of real vehicle speed reached up to

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31.4 km/h, and then the curve was extrapolated up to 90 km/h. The relation between frequency (f) and vehicle speed (v) was represented by a power equation ($f = 0.277\ v^{0.944}$). For instance, a speed of 31.4 km/h corresponds to 7.1 Hz while 60 km/h and 90 km/h corresponds to 13.2 and 19.4 Hz, respectively.

According to Mollenhauer et al. [18], loading speeds in pavement structure depend on asphalt layer thickness. Loading speed at the bottom of thin asphalt layer is higher than the loading speed at thick asphalt layer. For 80 km/h traveling speed, the loading frequency varies between 8 Hz and 22 Hz based on the asphalt layer thickness.

Deacon [11] studied the effect of load duration on fatigue life with keeping load frequency constant (the rest period changed simultaneously). It was found that longer load durations produced shorter fatigue lives.

Epps and Monismith (1972) studied the effect of loading frequency on fatigue life. They used different loading frequencies, with keeping the load duration constant and changed the corresponding length of rest periods. The results showed that increasing the frequency (by decreasing the rest period) from 3 to 30 loads per minute had no effect on fatigue life. However, later research indicated that increasing loading frequency from 30 to 100 loads per minute decreased the fatigue life in the strain-controlled mode of loading.

Jiang-Maio et al. [16]and Mollenhauer et al. [18] performed four-point bending beam fatigue tests using strain-controlled mode of loading and found that increasing loading frequency resulted in shorter fatigue lives.

Pell [20] and Pell and Taylor [22] investigated the effect of increasing the load frequency on fatigue life by maintaining the ratio of rest period to load duration constant. Rotating bending cantilever was tested using sinusoidal load pulse under stress-controlled mode of loading. Load frequency varied from 80 to 2500 load cycles per minute. It was found that increasing load frequency increased fatigue life. The significant effect of load frequency was at low frequency levels (below 200 load cycles).

Raithby and Sterling [24] performed two sets of tests using stress-controlled mode of loading; one with 40 ms loading period and rest periods of 0 and 80 ms and the other with 400 ms loading period with rest periods 0 and 800 ms. The specimens with 400 ms loading periods had much shorter fatigue lives. In other words increasing the frequency (by decreasing load duration) increased fatigue life.

Based on stress-controlled mode of loading, Pell and Taylor [22] found that low temperatures produced longer fatigue lives for asphalt concrete mixtures.

Epps and Monismith [13] found that under stress-controlled mode of loading, decreasing the test temperature increased the fatigue lives of asphalt concrete mixtures.

Jiang-Maio et al. [16] conducted four-point bending beam fatigue tests using strain-controlled mode of loading and found that increasing the temperature resulted in an increase in the fatigue life. Minhoto et al. [17]also used the four-point bending test in the strain-controlled mode of loading. The tests were performed at four test temperatures of −5, 5, 15, and 25 °C. The fatigue test results showed that the fatigue life decreased when the test temperature decreased up to a certain value. After that value, the fatigue life increased when the test temperature decreased.

In this study, the combined effect of the loading frequency, test temperature, and stress level was investigated on the fatigue life of Superpave asphalt paving mixtures using the indirect tension (IDT) fatigue test in the stress-controlled mode of loading. The laboratory conditions including load, test temperature, and loading frequency were selected such that they represent to a certain extent the field conditions (truck loading, pavement intermediate temperature for fatigue, and truck speeds). The IDT fatigue test was used to study the effect of all these conditions on the fatigue life of Superpave asphalt mixtures tested in the stress-controlled mode of loading.

2. Materials and designing asphalt mixtures

2.1. Aggregate

2.1.1. Aggregate gradation

The aggregate used in this study was crushed limestone from Al-Huson quarry in the northern part of Jordan. Limestone is the most common aggregate type used for asphalt pavement construction in Jordan. For surface asphalt mixtures, Superpave typically recommends five types of asphalt mixtures with nominal maximum aggregate sizes (NMAS) of 37.5, 25.0, 19.0, 12.5, and 9.5 mm. In this study, the aggregate gradation was selected based on the Superpave specifications with a NMAS of 12.5 mm. The aggregate gradation is shown on the 0.45 power chart (Fig. 1).

2.1.2. Aggregate properties

The limestone aggregate was tested and evaluated for Superpave consensus properties and source properties as well. The tests for consensus properties included: Coarse Aggregate Angularity (CAA), Fine Aggregate Angularity (FAA), Flat and Elongated (F&E) Particles, Sand Equivalent (SE), whereas, the tests for source properties included: specific gravity and absorption of coarse aggregate, specific gravity and absorption of fine aggregate, Los Angeles (LA) Abrasion, and deleterious materials. Table 1 below shows the consensus properties and LA abrasion for the limestone aggregate.

2.2. Asphalt binder

The asphalt binder used in this study was a 60/70-penetration grade asphalt binder obtained from Jordan Petroleum Refinery (JPR) having a Superpave performance grade of PG 64-10. The conventional (traditional) asphalt binder tests and the needed Superpave asphalt binder tests were conducted on the asphalt binder. The conventional tests included: specific gravity, penetration, ductility, softening point, and flash and fire points. On the other hand, the Superpave tests included: Rotational Viscosity (RV) test, Dynamic Shear Rheometer (DSR) test, Rolling Thin-Film Oven (RTFO) test, Pressure Aging Vessel (PAV) test, and Bending Beam Rheometer (BBR) test required to grade the asphalt binder. The Superpave test results for the asphalt binder are summarized in Table 2.

2.3. Superpave asphalt mixtures

2.3.1. Mixing and compaction temperatures

Using the ASTM viscosity-temperature relationship, and based on the rotational viscosity test results of the asphalt binder at

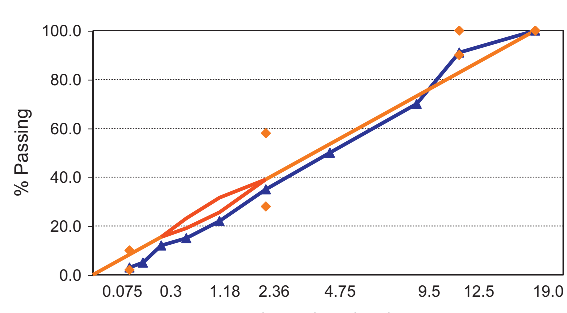

Fig. 1. 0.45 Power chart for aggregate gradation used in this study.