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Effect of Short-Term and Long-Term Aging on Fatigue Performance of Superpave Hot-Mix Asphalt (HMA)

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ABSTRACT

This study aims at investigating the influence of laboratory aging on the fatigue performance of asphalt mixtures prepared using the superpave method. In this study, one type of asphalt binder (PG64-10) and one type of aggregate (limestone) were used. Loose mixtures were short-term aged (STA) in a draft oven at 135°C for 2 hours, 3 hours and 4 hours. Half of tested samples were long-term aged (LTA) in a draft oven at 85°C for time periods of 3 days, 5 days and 7 days. Fatigue test was performed on test specimens using the Indirect Tensile Test (IDT) under stress-controlled mode. Four initial strain levels: 100, 200, 300 and 400με, two test temperatures: 40 and 20°C and one loading frequency: 10 Hz, were used and considered in the testing matrix of the study. Data analysis was conducted and fatigue curves were obtained for each case in this study. The effect of STA and LTA on fatigue life was investigated at the two test temperatures. It was found that the STA led to an increase in fatigue life at both test temperatures under stress-controlled mode in the IDT test. Nevertheless, the fatigue life increased as the LTA period increased from 3 to 5 days, but then it was reduced for 7-day LTA. Findings of this study also showed that the fatigue life increased as the temperature increased from 20 to 40°C. Control specimens (short-term aged for 2 hours) tested at 20°C were found to have the shortest fatigue lives. On the other hand, specimens that were long-term aged for 5 days and tested at 40°C had the longest fatigue lives.

KEYWORDS: Fatigue cracking, Fatigue performance, Indirect tensile test, Aging, STA, LTA.

INTRODUCTION

Although asphalt binder composes about 5 percent of the asphalt mixture, its physical and mechanical preoerties play an important role in the performance of the mixture. Asphalt, due to its chemical composition, is susceptible to changes in the environmental impacts and the traffic loading cycles during its servie life. In the USA, asphalt pavements compose approximately 95 percent of the total paved highway network (Al-Khateeb et al., 2005).

Fatigue cracking is considered to be one of the vital distress modes in asphalt pavements associated with repeated traffic loadings. Fatigue failure is known to occur when asphalt pavements undergo repeated loading in the intermediate temperature range from roughly 5 to 40°C (Al-Khateeb and Shenoy, 2004). The most common fatigue cracking occurs in asphalt pavements due to tensile stresses at the bottom of the asphalt layer under repeated traffic loadings. In this case, cracking is initiated at the bottom of the asphalt layer and

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propagates up until it is seen on the pavement surface.

The main factor that leads to fatigue cracking is the damaging effects due to traffic loading, poor quality materials and design and environmental conditions. Furthermore, fatigue cracking is a long-term pavement distress and as the pavement ages, the binder is oxidized and becomes stiffer (Ofori-Abebresse, 2006).

Asphalt pavements age with time during their service life. As a result, pavements become stiffer and susceptible to fatigue cracking. Fatigue performance of hot-mix asphalt (HMA) pavements can be simulated and measured in the laboratory by several experimental fatigue modes and tests performed on asphalt mixtures. The indirect tensile test (IDT) for fatigue under stress-controlled mode is an example of such tests (Al-Khateeb et al., 2007). Stiffness of asphalt binder or HMA is a factor affecting the fatigue behavior of these materials.

Aging of asphalt has been an important subject area that has received extensive research in recent years (Liang and Lee, 1996). Short-Term Aging (STA) is caused primarily by a loss of volatile components and oxidation during mixing and lay down (Liang and Lee, 1996; Harvey and Tsai, 1997). Simulation of STA of asphalt binders is a widely used procedure in asphalt binder characterization for predicting the binder response to plant mixing and paving under controlled laboratory conditions (Shalaby, 2002). On the other hand, Long-Term Aging (LTA) is due to a sequence of progressive oxidation of the in-place mixture in the field (Liang and Lee, 1996). Therefore, LTA occurs during the life of HMA pavements after several years of service. The oxidation process in the LTA can increase the tendency to crack and ravel and loss of durability in terms of wear resistance and moisture susceptibility.

In the stress-controlled mode, mixtures with stiffer asphalt binders have been shown to have longer fatigue lives and flatter slopes in the stress-fatigue relationship irrespective of whether the repeated flexural testing was conducted using two- or four-point bending (Pell and Cooper, 1975).

In this study, the influence of test temperature and laboratory aging on the fatigue performance of asphalt mixtures is investigated. Specifically, the effect of short-term aging and long-term aging on fatigue performance of laboratory-produced HMA samples prepared using the Superpave Gyratory Compactor (SGC) and in accordance with the superpave specifications and design method, is investigated.

OBJECTIVES

The main objectives of this study are:

1. To utilize the superpave system in mixture design and performance for asphalt paving mixtures.
2. To assess the impact of temperature on fatigue performance of superpave asphalt paving mixtures.
3. To investigate the effect of short-term and long-term aging on fatigue performance of superpave asphalt paving mixtures.

RESEARCH APPROACH

To achieve the objectives of this study, HMA specimens were prepared at design asphalt content using superpave mixture design. Superpave Gyratory Compactor (SGC) was used in preparing the HMA specimens at target air voids of 7% ±1%.

Materials Used

Aggregate

The aggregate used in this study was crushed limestone aggregate. Dry sieve analysis was conducted in laboratory on both coarse and fine aggregates using mechanical sieve. Aggregate gradation was selected to meet superpave aggregate gradation requirements. One aggregate gradation with 12.5 mm nominal maximum aggregate size (NMAS) that is located above restricted zone (ARZ) was used. This gradation was selected to be the design aggregate structure. Table 1 shows the selected aggregate gradation used in this study.

Asphalt Binder

PG64-10 graded asphalt was used in this study to prepare the asphalt mixtures. The asphalt binder was obtained from the Jordan Petroleum Refinery in Zarqa city of Jordan.

Table 1. Design aggregate structure

Sieve size	3/4"	1/2"	3/8"	No.4	No.8	No.16	No.30	No.50	No.100	No.200
% Passing	100	100	99	89	71	57	45	32	22	7

Determination of Design Asphalt Content

The design asphalt content (DAC) of the asphalt mixture was determined using superpave mix. The loose mixture sample was placed for 2 hours in an oven at 135°C for short-term aging immediately after mixing according to AASHTO PP2-00 (1994). To achieve the objectives of this study, 108 test specimens were prepared. Three levels of short-term aging (STA) of loose mixtures: 2 hours (control), 3 hours and 4 hours were used. The SGC shown in Figure 1 was used in preparing the compacted HMA specimens. At the end of SGC compaction, specimens were tested for bulk specific gravity and absorption. The percent maximum theoretical specific gravity values: (%G_{mm}) at N_{des}, %G_{mm} at N_{ini} and %G_{mm} at N_{max} were also determined. The volumetric properties of the mixtures including air voids (Va), Voids in Mineral Aggregates (VMA), Voids Filled with Asphalt (VFA) and Dust Proportion (DP) were calculated at four asphalt binder contents. The design asphalt content was obtained from the air void *versus* asphalt binder content curve at 4% air voids. DAC was obtained to be 5.4% by weight of the mixture.

Indirect Tensile Fatigue Test

The constant stress indirect tensile (IDT) fatigue test was conducted to evaluate the fatigue life based on the reduction in the stiffness modulus of the HMA specimens. The fatigue test was performed using the Universal Testing Machine (UTM) shown in Figure 2; an electro-hydraulic test system in the highway and transportation laboratory at Jordan University of Science and Technology (JUST). The indirect tensile fatigue test was performed according to the inputs shown in Table 2. The deformations of the specimen in the UTM machine were measured using Linear Variable Differential Transducers (LVDTs) and recorded using the data acquisition system of the machine. These LVDTs were clamped vertically on the diametrical side of the specimen. Different repeated dynamic pulse loads were applied to the specimens across the diameter of the specimen using two loading strips of 12.5 mm width. The resulting total deformation was measured along with the applied load.

A personal computer was used to record the load and deformation during the fatigue test. A computer program was used to calculate the initial micro-strain level applied on the test specimen just after applying the dynamic load. The horizontal deformation and strain in the specimen were calculated using Equation (1):

$$\mu = \frac{H}{V} - 0.27 \quad (1)$$

where:

μ = Poisson's ratio (0.35),
H = horizontal deformation and
V = vertical deformation.

The horizontal strain in the specimen was then calculated by dividing horizontal deformation by diameter of the specimen. Two specimens were tested for the same initial strain level and temperature. The number of cycles to failure was computed as the average of the two specimens tested under the same conditions. Figure 3 shows the fatigue testing setup that was prepared before testing specimens. The LVDTs measure the vertical deformation of the specimen during the test.

In the stress-controlled mode of loading, the stress is kept constant by maintaining the amplitude at the same level. The end of the fatigue test in this mode of loading is defined by fracture of the sample.

Table 2. IDT fatigue test ınputs

Mode of loading	Wave shape	Load pulse width	Temperature
Constant stress	Haversine	100 ms (10 Hz)	20 and 40°C

Figure (1): Troxler model 4140 superpave gyratory compactor

Figure (2): Universal testing machine

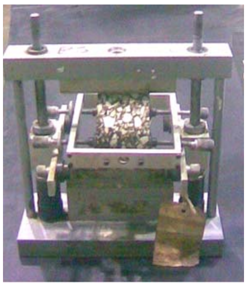

Figure (3): Fatigue test setup

TEST RESULTS AND DISCUSSION

The results of this study are presented and discussed in the next section.

SGC Test Results and Volumetric Properties

The volumetric properties of the asphalt mixture including Va, VMA, VFA, $\%G_{mm}$ @ N_{ini}, $\%G_{mm}$ @ N_{des}, $\%G_{mm}$ @ N_{max} and DP were calculated. It is very important to have a good understanding of the volumetric properties, since they are believed to have an impact on asphalt binder age-hardening and thus on the durability of the asphalt mixture.

The volumetric properties were determined at the four asphalt binder contents used in the design stage. Each property was plotted *versus* asphalt binder content. A polynomial function of the second degree was found to best fit these relationships. The design asphalt content was obtained from the air void *versus* asphalt binder content curve at 4% air voids. Afterwards, the volumetric properties of the asphalt mixture were obtained at the design asphalt content. Table 3 shows mixture volumetric properties obtained at the DAC which was obtained to be 5.4% by weight of the total mixture. All mixture properties met the superpave criteria.

Table 3. Mixture volumetric properties

Property	Value	Superpave Criteria
%G_{mm} @ N_{ini}	88.6	<89
%G_{mm} @ N_{des}	96	=96
%G_{mm} @ N_{max}	96.6	<98
%Va	4.0	4.0
%VMA	14.0	14 min.
%VFA	69.7	65-75
%DP	1.0	0.6-1.2

IDT Fatigue Test Results

Effect of Short-Term Aging

In order to evaluate the effect of short-term aging (STA) of loose HMA samples, fatigue tests were conducted on compacted HMA specimens prepared using three levels of aging: 2, 3 and 4 hours. The 2-hour aged specimens were considered as the control specimens for comaprison. Two replicate specimens were taken per test. Results in Figures 4 and 5 show that fatigue lives of HMA specimens that were short-term aged more than 2 hours are larger under the stress-controlled mode test at 40 and 20°C, respectively. According to the results of Al-Qudah (2009), the increase in mixture stiffness due to the increase in aging time resulted in an increase in the number of load cycles to fatigue failure (N_f). This means that the STA of loose mixture has a clear effect on increasing N_f of tested specimens at the two temperatures. In other words, stiffer specimens due to longer aging time had higher fatigue resistance under the stress-controlled mode used in this study.

Table 4 demonstrates the models and the coefficient of determination (r^2) values for the number of cycles to fatigue failure of short-term aged samples. The data obtained from IDT test and plotted in Figures 4 and 5 was fitted using a power function with high r^2 values (ranging from 0.8643 to 0.9889) as shown in Table 4.

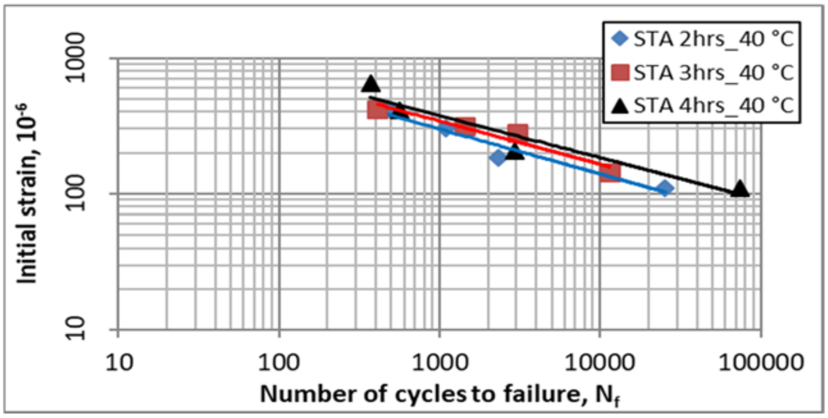

Figure (4): Effect of short-term aging at 40°C

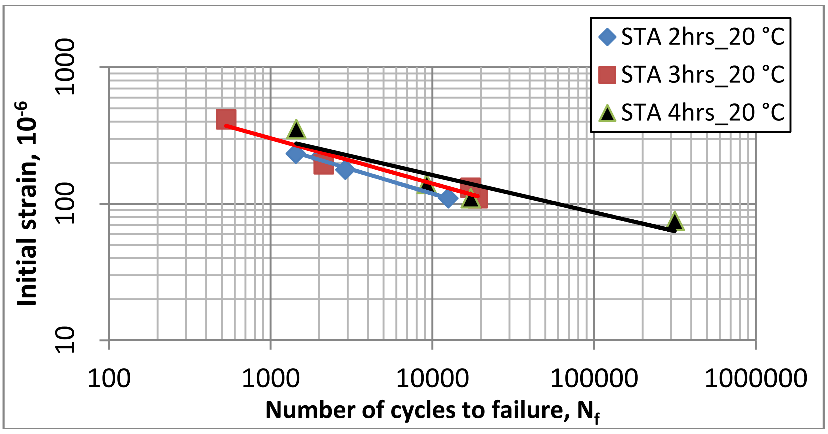

Figure (5): Effect of short-term aging at 20°C

Table 4. Experimental models for short-term aged IDT samples

Sample	Test Temperature (C)	Model*	r^2 Value
STA 4 hrs	20	$y = 2030.7x^{-0.274}$	0.8643
STA 3 hrs		$y = 2972.3x^{-0.331}$	0.9429
STA 2 hrs		$y = 3122.8x^{-0.355}$	0.9889
STA 4 hrs	40	$y = 3225x^{-0.311}$	0.9183
STA 3 hrs		$y = 3114.1x^{-0.319}$	0.9340
STA 2 hrs		$y = 2976.2x^{-0.332}$	0.9463

* The variables x and y in the models represent number of cycles to failure (N_f) and initial strain (με), respectively.

Effect of Long-Term Aging

In order to study the effect of long-term aging (LTA) of compacted HMA specimens, three levels of long-term aging were conducted (3, 5 and 7) days at 85°C.

In this stage of laboratory aging, results revealed that at the same initial strain level and the same temperature, specimens that were long-term aged for 5 days have fatigue lives longer than those specimens that were long-term aged for 3 days. Specimens that were long-term aged for 7 days showed a significant reduction in fatigue life compared to those aged for 5 days. This is due to the very high stiffness of mixtures as a result of the long aging period, which resulted in high susceptibility to fatigue cracking.

A comparative plot of mixture results of LTA test is shown in Figures 6 and 7. Specimens aged for 7 days were observed to have better indirect tensile strength characteristics than those aged for 5 days and 3 days, respectively. The control mixture (2-hour short-term aged mixture) has less tensile strength compared to short-term aged and long-term aged mixtures at the same temperature. From the results, the higher indirect tensile strength (ITS) of the aged specimens would further imply that aged mixture appears to be capable of withstanding higher tensile strains prior to cracking, at least from the point of view of the testing conditions of this study. Additionally, results indicated an increase in mixture stiffness associated with aging. Table 5 shows the models and r^2 values for the number of cycles to fatigue failure of long-term aged samples. The data obtained from IDT test and plotted in Figures 6 and 7 was fitted using a power function with high r^2 values (ranging from 0.8676 to 0.9837) as shown in Table 5.

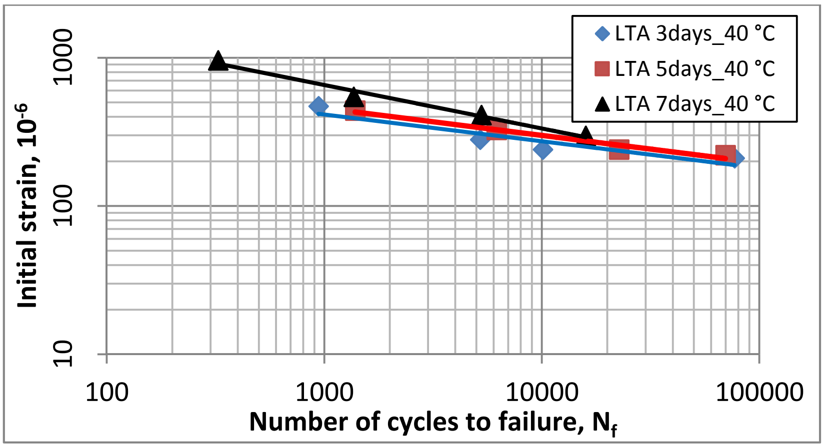

Figure (6): Effect of long-term aging at 40°C

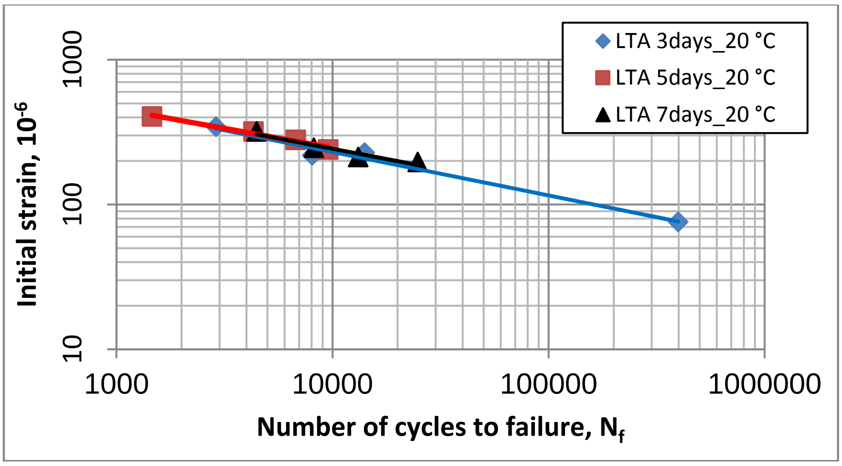

Figure (7): Effect of long-term aging at 20°C

Table 5. Experimental models for long-term aged IDT samples

Sample	Test Temperature (°C)	Model*	r^2 Value
LTA 7days	20	$y = 3326.4x^{-0.284}$	0.9351
LTA 5days		$y = 2949.7x^{-0.27}$	0.9778
LTA 3days		$y = 3650.5x^{-0.3}$	0.9817
LTA 7days	40	$y = 4964.6x^{-0.293}$	0.9837
LTA 5days		$y = 1633x^{-0.184}$	0.9735
LTA 3days		$y = 1439.5x^{-0.18}$	0.8676

* The variables x and y in the models represent number of cycles to failure (N_f) and initial strain (με), respectively.

Effect of Temperature on Fatigue Performance

It was observed that temperature affected the fatigue performance of aged asphalt mixtures. Fatigue life of short-term aged specimens tested at 40°C is longer than fatigue life of short-term aged specimens tested at 20°C. It was noticed that the lowest N_f values were obtained for the 2-hour short-term aged specimens tested at 20°C and the highest N_f values were obtained for the 4-hour short-term aged specimens tested at 40°C. In the same manner, fatigue curves of the long-term aging conditions (3 days at 40°C, 5 days at 40°C, 7 days at 40°C, 3 days at 20°C, 5 days at 20°C and 7 days at 20°C) showed that temperature affected the relationship between the fatigue performance of asphalt mixtures and aging. This is shown in Figure 8, where N_f values of long-term aged specimens for 5 days tested at 40°C are the highest. Generally, as the temperature increases, the fatigue life increases as well. This is applied for the short-term aged specimens and for the long-term aged specimens. In other words, comparing specimens with the same aging period revealed that specimens tested at 40°C had longer fatigue lives than those tested at 20°C.

Figure 8 shows a typical plot between initial tensile strain and fatigue life N_f of ARZ graded mixture with PG64-10 grade asphalt binder. Figure 8 shows fatigue curves of 12 aging conditions; (3, 5 and 7 days) at 40°C, (3, 5 and 7 days) at 20°C, (2, 3 and 4 hours) at 40°C and (2, 3 and 4 hours) at 20°C. The fatigue performance of HMA is apparent to be sensitive to both temperature and laboratory aging, where control specimens tested at 20°C have the shortest fatigue lives and specimens that are long-term aged for 5 days and tested at 40°C have the longest fatigue lives. However, in comparing the two temperatures, fatigue propagates faster in low-temperature conditions.

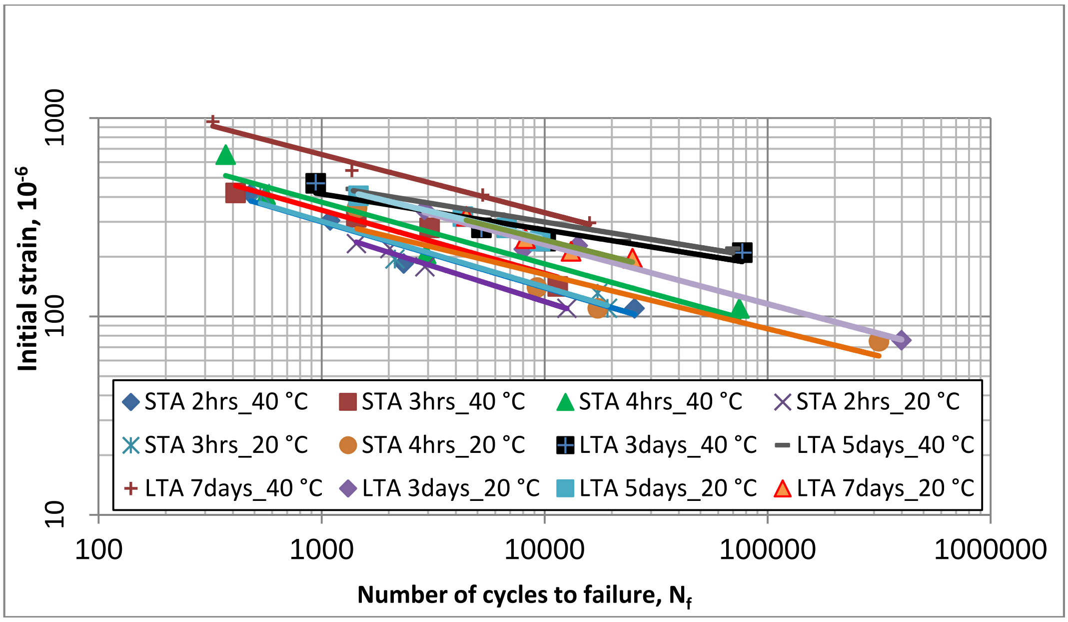

Figure (8): Fatigue performance curves of HMA at low and high test temperatures

In the literature, the effect of temperature on fatigue life is dependent on the fatigue test mode used. Typically, increasing the temperature results in shorter fatigue lives for asphalt mixtures under stress-controlled test mode (Al-Khateeb and Ghuzlan, 2014; Pell and Taylor, 1969; Epps and Monismith, 1971). In the strain-controlled test mode, increasing the temperature results in an increase in fatigue life (Al-Khateeb et al., 2008; Jiang-Maio et al., 2005; Minhoto et al., 2009).

Asphalt mixtures soften at higher temperatures and become stiffer at lower temperatures. In other words, as the temperature decreases, the asphalt mixture becomes stiffer and *vice versa*. Using this trend and the analogy of temperature-fatigue life relation in the literature for stress-controlled test mode, stiffer mixtures tend to have longer fatigue lives and softer mixtures should have shorter fatigue lives.

However, in this study, it should be realized that the high stiffness of the asphalt mixture is a result of two factors: temperature and aging (STA or LTA). For this reason, the relationship is complex. The findings of this study show generally that the increase in temperature resulted in an increase in fatigue life and the increase in aging time resulted in an increase in fatigue life as well. For the same aging conditions, the increase in temperature led to an increase in fatigue life and at the same temperature, the increase in the aging time resulted in an increase in fatigue life. Nevertheless, in this study, the temperatures used for fatigue testing were 20 and 40°C; these temperatures are not considered in the low limit of the intermediate temperature range for fatigue cracking. On the contrary, the 40°C temperature is in the high limit of this range, which is the beginning of temperature range for rutting occurrence when the asphalt binder is soft and densification due to the interlock of aggregates starts to take place. For this reason, the resistance of asphalt mixtures to fatigue cracking is higher.

Additionally, the test mode has a significant impact on the fatigue life due to the fatigue failure criteria that are used. Different fatigue failure criteria have been used in the literature to define failure based on the mode of loading whether it is stress-controlled or strain-controlled. Thus, it is found in the literature that the effect of temperature on the fatigue life of asphalt mixtures in stress-controlled test mode is opposite to that in strain-controlled mode. To have opposite trends for the effect of the same factor on the fatigue life based on the mode of loading is somehow awkward. Therefore, Al-Khateeb and Shenoy introduced a distinctive fatigue failure criterion that is independent of the mode of loading (Al-Khateeb and Shenoy, 2004; Al-Khateeb and Shenoy, 2011). In that criterion, the load-deformation hysteresis loop or the response wave form is observed for distortion from the well-defined elliptical shape, which will mark the fatigue failure.

CONCLUSIONS

Based on the analysis and results of this study, the following conclusions are drawn:

1. Keeping the same test temperature, the fatigue life of asphalt mixtures that were short-term aged for 4 hours is longer than the fatique life of those aged for 3 hours more than that of those aged for 2 hours (the control). In other words, the increase in the short-term aging period resulted in an increase in the fatigue life for asphalt mixtures tested at the same temperature.
2. On the other hand, the assessment of the effect of long-term aging on fatigue performance revealed that for the same test temperature, asphalt mixtures that were long-term aged for 5 days experienced the longer fatigue life compared to those aged for 3 days and those aged for 7 days. Indeed, a significant reduction in the fatigue life of mixtures aged for 7 days occurred due to the high stiffness of these mixtures as a result of the long aging period.
3. Power models with high coefficient of determination (r^2) described the relationship between initial strain level and number of cycles to failure (N_f) for short-term aged (STA) and long-term aged (LTA) mixtures at the two test temperatures.
4. Keeping the same aging conditions, the fatigue life of asphalt mixtures tested at 40°C was found to be longer than the fatigue life of those tested at 20°C. This conclusion is at least valid for the testing conditions of this study and was further explained in the discussion part.
5. Based on the results of this study, it was found that asphalt mixtures short-term aged for 4 hours and tested at 40°C had the longest fatigue life compared to the other STA mixtures. In addition, mixtures long-term aged for 5 days and tested at 40°C had the longest fatigue life compared to the LTA mixtures.
6. The longest fatigue life for all mixtures was obtained for those long-term aged for 5 days and tested at 40°C.

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