Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 6(1):31-36

Fatigue Characteristics of Hydrated Lime Modified HMA

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Abstract: Characterizing the fatigue cracking damage of asphalt concrete pavements is considered one of the valuable methods for improving the design of asphalt concrete pavements. Hydrated lime (HL) is widely used in asphalt mixtures as a multifunctional additive (filler). In spite of wide use of HL in asphalt pavements, the fatigue characteristics of HL modified asphalt mixtures are not well understood. This paper studied the effect of the addition of HL on phenomenological fatigue model parameters. Moreover, researchers investigated the response of the phenomenological fatigue model parameters of HL modified asphalt mixtures under frequency and temperature variation. A controlled stress split tension fatigue test was conducted to study fatigue characteristics of HL modified asphalt mixtures. A large fatigue database of laboratory testing was developed to achieve this goal. Based on the fatigue test results, it was observed that, the intercept (a) of the S-N fatigue curve increased with the addition of HL. The slope (b) of the S-N fatigue curve seemed to be independent of mixture type. Fatigue model parameters (a and b) could be considered constants at low loading frequencies, but could not be considered constants for different testing temperatures.

***Key words**: Fatigue characteristics; Hydrated lime; Loading frequency; Temperature.*

Background

Fatigue cracking due to repeated traffic loading is one of the major distresses in asphalt concrete pavements. Fatigue is a phenomenon in which a pavement is subjected to repeated loads that are less than the ultimate failure load. Hveem [1] was one of the first researchers who reported fatigue failure caused by repeated loading on asphalt pavement over highly resilient soils. Fatigue life is commonly defined as the number of load cycles causing asphalt concrete to fail at stress (strain) occurring at the bottom of the asphalt layer.

Transport vehicles are increasing in number as well as magnitude, which leads to increased pavement deterioration, including fatigue, resulting in higher costs to maintain road networks at an adequate level. The limited properties of asphalt concrete mixtures have led to numerous research activities to improve the properties of the mixtures to overcome asphalt pavement distresses. Extensive experimental studies have revealed that, the use of hydrated lime (HL) in asphalt mixtures is a cost effective way to reduce pavement distresses. HL plays an important role in preventing fatigue damage of Hot Mix Asphalt (HMA) pavements. Since crack phenomena are governed substantially by properties of the mastic, mixture performance can be improved if the mastic is engineered to resist fracture and fatigue. HL can reduce asphalt fatigue cracking to some extent because the initial microcracks can be intercepted and deflected by tiny, active HL particles [2]. The improvement in fatigue performance of asphalt mixtures by the addition of HL is a result of the reaction between HL and the polar molecules in the asphalt cement, which increases the effective volume of the lime particles by surrounding them with large organic chains [3]. Consequently, the HL particles are better able to intercept and deflect microcracks, preventing them from coalescing into large cracks that can cause pavement failure [4]. Kabir [5] reported that HL particles toughen the mastic, making it more resistant to fracture and crack propagation. Unlike typical mineral fillers, HL chemically reacts with the carboxylic acids and 2-quinolone types that are concentrated in the highly associated viscosity building components of asphalt. That increases the ability of asphalt to dissipate stress in the asphalt, which in turn increases the fatigue damage resistance of mixtures. In spite of HL's wide use in asphalt pavements, fatigue characteristics of HL modified asphalt mixtures have not been studied. Before studying the fatigue characteristics of asphalt mixtures it is worthwhile to first review fatigue models. Generally speaking, these models can be classified into three categories; the phenomenological model, the energy-based model, and the fracture mechanics model. In the phenomenological model, the fatigue performance is shown as the relationship between the stress or strain in an asphalt mixture and the number of load cycles to failure [6]. The energy-based model uses the dissipated energy concept to evaluate fatigue performance. The concept behind this approach is that damage will accumulate when a material is subjected to repeated loading. Therefore, this damage can be defined as the deterioration, which occurs in the material before failure [7]. The fracture mechanics model relates the crack growth rate to the stress intensity factor (SIF) in conjunction with Paris' law, where the number of cycles to failure can be related to stress intensity factor [8]. The current research focuses on studying fatigue characteristics of HL modified asphalt mixtures using the phenomenological model.

The phenomenological model is based on the endurance concept using Wohler's technique [9]. Typically, fatigue life is shown by

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Note: Submitted March 13, 2012; Revised July 17, 2012; Accepted September 4, 2012.

plotting the stress or strain at the initial load cycles versus number of load cycles to failure. This approach of studying fatigue is known as the phenomenological, or the S-N, approach [6, 10]. Typically, a traditional fatigue curve is shown by plotting a relation between the stress or strain at the bottom of the asphalt concrete layer against number of number of load cycles to failure (Fig. 1). Because of its simplicity, the S-N approach was widely used in conjunction with Miner's linear law of cumulative damage [11]. There are several phenomenological fatigue models developed to predict fatigue cracking. Phenomenological fatigue models are divided into two main types, the strain-controlled and the stress-controlled mode based models. In the strain-controlled based model, the strain level or deflection is maintained constant during the fracture life. The strain-controlled relation can be expressed mathematically in the following form:

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

where:
N_f = fatigue life (no. of cycles),
ε_t = tensile strain at the critical location (in. /in.), and
(k_1, k_2)= experimentally determined parameters.

Another strain based model was introduced by Monismith et al. [12]. As shown in Eq. (2), the strain at critical location is a function of the number of load cycles and mixture stiffness (modulus).

$$\varepsilon_t = k_3 \left(\frac{1}{N_f} \right)^{k_4} \left(\frac{1}{E} \right)^{k_5} \tag{2}$$

where:
N_f = fatigue life (no. of cycles),
ε_t = tensile strain at the critical location (in./in.),
E = asphalt concrete initial modulus (psi), and
(k_3, k_4, k_5) = experimentally determined parameters.

In case of stress-controlled mode, the nominal stress level or load is maintained constant during the fracture life. The stress-controlled fatigue test was performed in this research. The stress-controlled relation can be expressed mathematically in the following form:

$$\sigma_t = a \left(\frac{1}{N_f} \right)^{b} \tag{3}$$

where:
N_f = fatigue life (no. of cycles),
σ_t = applied tensile stress (psi), and
(*a*, *b*) = experimentally determined parameters.

The parameters *a* and *b* are determined by fitting a power law regression function with the testing data on a log scale (Fig. 1). These parameters represent the material properties of the mixture. There are many factors that contribute the wide range of fatigue parameters values. In a study performed by Ghuzlan and Carpenter [13], it was concluded that these parameters (*a*, *b*) are affected by mixture variables (asphalt type, air voids level, asphalt content, aggregate gradation) as well as affected by mode of loading and

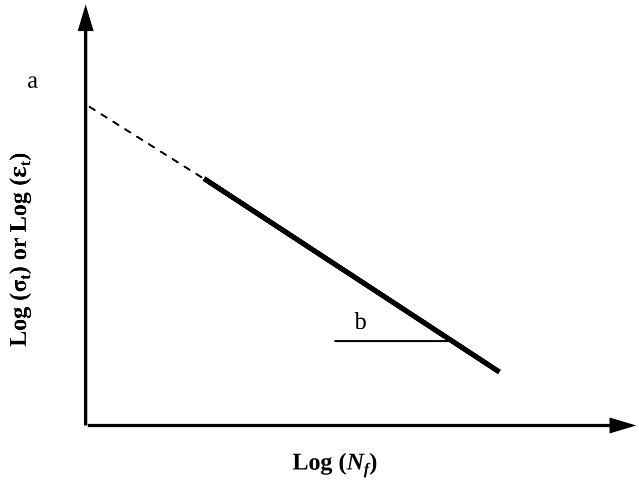

Fig. 1. Relation between Fatigue Life (N_f) and Applied Stress (σ_t) or Strain (ε_t) (or (S-N) Curve).

testing temperature. Also, the study concluded that there is a consistent uniform relationship between them that does not change and may be useful in pavement design. Mode of loading, testing temperature, and asphalt content have a significant effect on the a-b relation. On the other hand, asphalt type, air voids levels, and aggregate gradations have no significant effect on the a-b relation. The current research investigates the effect of loading frequency and testing temperature on fatigue parameters response.

Research Objectives and Scope

The main objective of this research was to study fatigue characteristics of HL modified HMA mixtures, which will help present a reliable modeling of the fatigue of HL modified mixtures. In order to achieve this objective, split tension fatigue test under controlled stress mode was performed to study the characteristics of phenomenological approach fatigue model for HL modified asphalt mixtures. A wide variety of specimens was tested to examine the fatigue behavior of asphalt concrete under different testing conditions (frequency and temperature). More than 105 specimen split tension fatigue tests were performed in this research. Fifteen specimens were tested to establish a representative fatigue curve (or S-N curve). Testing was conducted at varying stress levels to generate a fatigue S-N curve for the material.

Design of Mixture and Specimen Fabrication

Coarse and fine basalt aggregates with bulk specific gravities of 2.80 and 2.71, respectively, were used to prepare the asphalt concrete mixtures. Limestone was used as mineral filler. Sieve analysis was performed for aggregates, and the gradation of aggregates is presented in Fig. 2. Bulk and apparent specific gravities (G_{sb} and G_{sa}) of used HL are 2.54 and 2.62 respectively. Table 1 shows the gradation of the HL used in this study. Asphalt binder penetration 60/70 was used within this research. The properties of the asphalt binder, including penetration, softening point, flash point, kinematics viscosity, and specific gravity, are given in Table 2. Asphalt binder content of 5% by total mass of the mixture was used based on Marshall mix design method. The

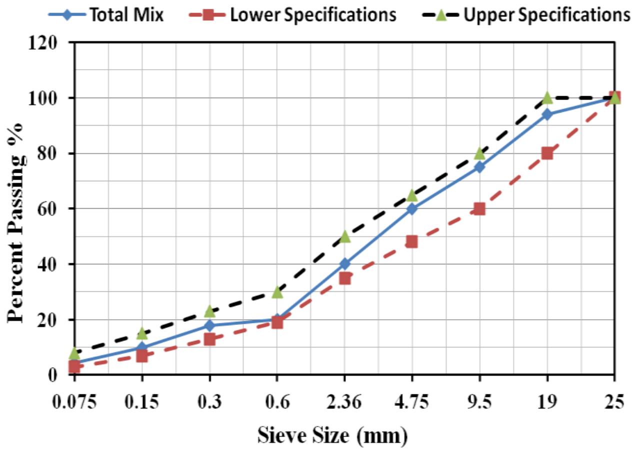

Fig. 2. Total Aggregates Gradation and Specifications.

Table 1. Gradation of Used Hydrated Lime.

Sieve Size (mm)	Percent Passing %
0.3	100
0.15	95
0.075	85

Table 2. Properties of Used Asphalt Binder.

Property	Specification	Measured Value
Penetration, 1/10 mm, 25℃	60-70	67
Flash Point, ℃ (Cleveland open cup)	250+	275
R&B Softening point, ℃	45-55	51
Kinematics Viscosity (Centistokes at 135℃)	320+	430
Specific Gravity	1-1.1	1.02

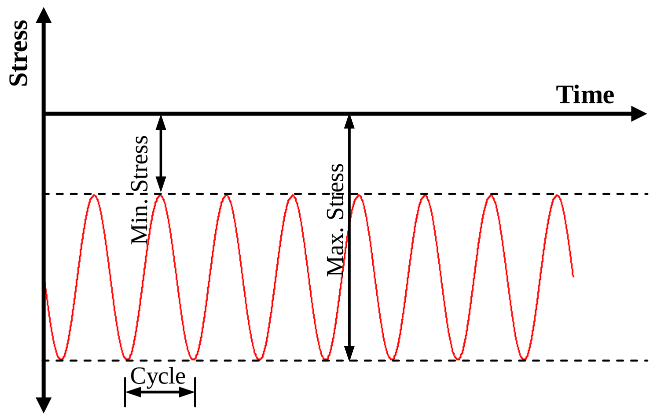

Fig. 3. Schematic Illustrating Cyclic Loading Test.

aggregate batch and asphalt binder container were placed in the oven at 170℃. The heated aggregate was placed into the mixer; immediately after that, the heated asphalt binder was added to the aggregate blend. The mixing process was completed as quickly (to avoid the temperature loss) and as thoroughly as possible to ensure a uniform distribution of the binder and the aggregate particles. Specimens of 2.5" in height and 4" in diameter were prepared from the mixtures in accordance with the standard Marshall design method. To provide adequate data, three samples were prepared from each mixture for each test. If errors were made during either fabrication or testing, then the specimen was discarded and an additional specimen was manufactured and tested. Modified specimens were prepared by mixing the combined aggregate with HL. HL was applied to the aggregate batch with content of 5.5% by dry aggregate weight using slurry method [14]. The treated aggregates received a 48 hour marination time before drying and mixing with asphalt binder.

Fatigue Test

Several test methods are available for evaluating the fatigue response of asphalt mixtures, such as uniaxial tension test, diametral test, flexural beam test, and cantilever beam test [15]. The split tension fatigue test (diametral fatigue test) was used in this research. The unique feature about this test is that it can be used to characterize a variety of asphalt concrete mixture properties, especially properties related to resilient elastic, thermal cracking, fatigue cracking, and permanent deformation [16]. The split tension fatigue test is an indirect tensile test conducted by repeatedly loading a cylindrical specimen with a compressive load, which acts parallel to and along the vertical diametral plane. This loading configuration develops a reasonably uniform tensile stress in the specimen perpendicular to the direction of the applied load and along the vertical diametral plane. The test is simple to conduct and is considered by some to be an effective method for characterizing materials in terms of "fundamental" properties. A number of investigators have utilized this test for materials evaluations and pavement analyses [17]. Yun et al. [18] stated that the split tension fatigue test has the advantage of possibly being more similar to the behavior of a real pavement. In addition, the test method is convenient, the amount of materials for the specimen is minimized, and the specimen can be made from field asphalt concrete core.

The Computer Control Electro-hydraulic Servo Universal Testing Machine (UTM) was employed to conduct the split tension fatigue test. Due to this machine's inability to perform the strain-controlled fatigue test, only the split tension fatigue test under constant amplitude stress was performed on Marshall-sized specimens. This research was performed using the method of constant stress ratio between the minimum and maximum stress level. Sinusoidal constant fatigue loading was controlled by the machine, as seen in Fig. 3, where the stress ratio (SR) can be expressed as follows:

$$\text{Stress Ratio (SR)} = \frac{Min.\ \ Stress}{Max.\ \ Stress} \tag{4}$$

The stress ratio cannot be changed from the machine, and it was 0.25 for all fatigue tests. Multiple values of frequencies of 5Hz, 7.5Hz, 10Hz and 15 Hz, at 25°C were selected for all stress levels. Also, the fatigue test was performed under the variation of testing temperature. Additional testing temperatures of 35°C and 45°C were selected for all stress levels to study fatigue characteristics of the HL modified mixture under temperature variation. During this study there was a concern regarding the fracture of specimens or the excessive accumulation of permanent vertical deformation under the loading strip at higher testing temperatures. Therefore, it should be

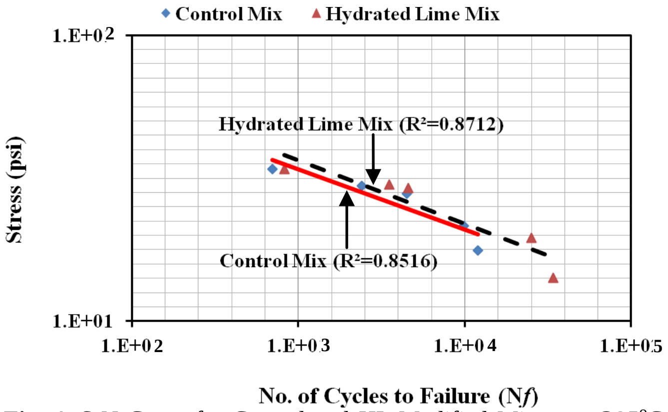

Fig. 4. S-N Curve for Control and HL Modified Mixtures @25°C and 10 Hz.

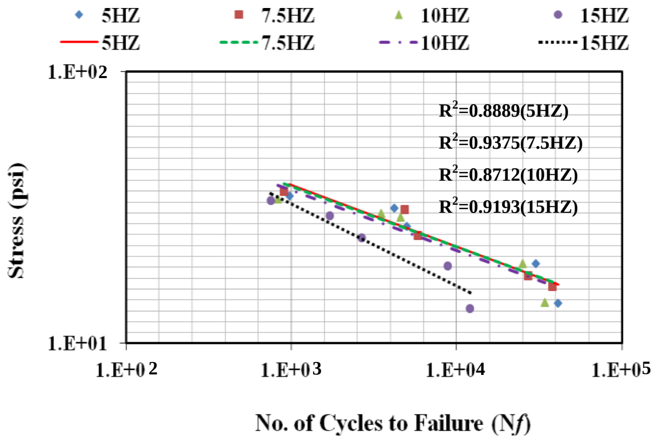

Fig. 5. Effect of Loading Frequency on the S-N Curve of HL Modified Mixtures @25°C.

noted that the selected temperatures did not cause indentation of the loading strip into the specimens for all tests. The indirect tensile strength (ITS) test was conducted to determine the asphalt mixture tensile strength, which is a required input of the stress levels for fatigue analysis. Testing was conducted at varying stress levels to generate a representative fatigue curve for the material. Five stress levels of 30%, 40%, 50%, 60%, and 70% were selected and considered as ratios of fracture static indirect tensile stress (ITS) to plot the S-N curves for mixtures. Fatigue life was recorded automatically by the UTM after the complete failure of the specimen. Regression analysis also was utilized to check the suitability of fitting for all fatigue models.

Results and Discussion

Effect of the Addition of HL on Fatigue Parameters Response

Sinusoidal constant fatigue loading was applied at a frequency of 10 Hz for control and HL modified mixtures at 25°C. The selected frequency simulates in-pavement stress pulses corresponding to vehicle speeds in the 24 to 48 km/h range, and is sufficiently large enough to permit rapid testing while still representing the load pulses generated by rapid moving traffic. The temperature was selected because it is more common in the pavements [19]. The number of cycles at failure was recorded for each stress level, the constant fatigue loading was controlled by the universal testing machine, and testing results are presented in Fig. 4. Each result in Fig. 4 is the average of triplicate specimens result. To find fatigue parameters (*a*, *b*), Excel was used to fit the S-N curve for control and HL modified asphalt mixtures. Regression analysis was also established by the program. The computed values of R^2 showed high correlation of concluded fatigue models. Phenomenological approach fatigue model equations for control and HL modified asphalt mixtures concluded experimentally were as follows:

For control mixtures:

$$\sigma_t = 145\left(\frac{1}{N_f}\right)^{0.2101} \quad (R^2 = 0.85) \tag{5}$$

For HL modified mixtures:

$$\sigma_t = 170\left(\frac{1}{N_f}\right)^{0.22221} \quad (R^2 = 0.87) \tag{6}$$

Fig. 4 shows that, at the same temperature and frequency, the number of cycles to failure for HL modified mixtures is higher than that for the control mixtures. This view was shared by many researchers including Mohammad [20], which indicated that stiffer asphalt mixtures crack more; otherwise, the addition of HL improves fatigue characteristics and reduces cracking. Eqs. (5) and (6) show that the fatigue parameter (*a*) of HL modified mixtures increased 17% higher than that of the control mixtures, while fatigue parameter (*b*) seemed to be independent of mixture type (control mixture and HL modified mixture). The increase of fatigue parameter (*a*) was expected, since the HL modified mixtures lasted longer under fatigue test than the control mixtures.

Effect of Loading Frequency on Fatigue Parameters Response

In an attempt to study the effect of loading frequency on fatigue parameters of HL modified asphalt mixtures, the maximum number of cycles was recorded for each stress level for multiple frequencies of 5 Hz, 7.5 Hz, 10 Hz, and 15 Hz at temperature of 25°C, and results are presented in Fig. 5. The frequencies were selected to include low and high loading frequencies that are expected on the real pavement. Plotting of the S-N curves and regression analysis for all frequencies was established using Excel, as shown in Fig. 5. The computed values of R^2 showed that all models at different frequencies showed high correlation. Fig. 5 also shows that, at low loading frequencies (up to 10 Hz), the values of fatigue parameters have a normal slight trend and maybe considered approximately constant while, fatigue parameters showed dramatic increase at 15 Hz. It seems that (*a* and *b*) are not material parameters (material constants) for all ranges of frequencies. Fatigue parameters can be assumed to be material parameters at low loading frequencies, but are no longer material parameters at high loading frequencies. From these findings, Fig. 5 can be modified to Fig. 6. From Fig. 6, it can be seen that the generalized model at low loading frequencies (up to

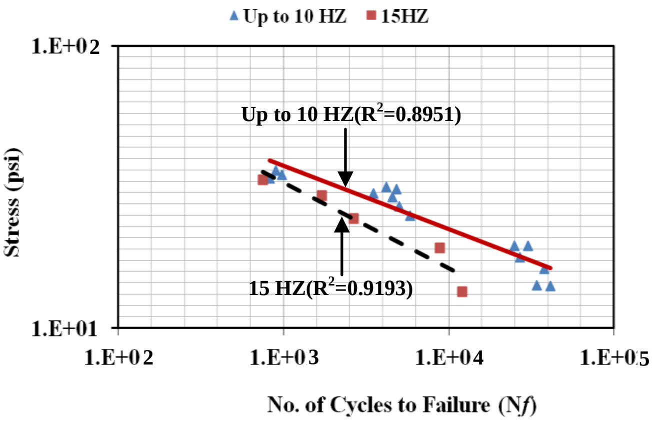

Fig. 6. Modified S-N Curve for Low Loading Frequencies (up to 10 Hz) and S-N Curve for High Loading Frequency (15 Hz) of HL Modified Mixtures @ 25 °C.

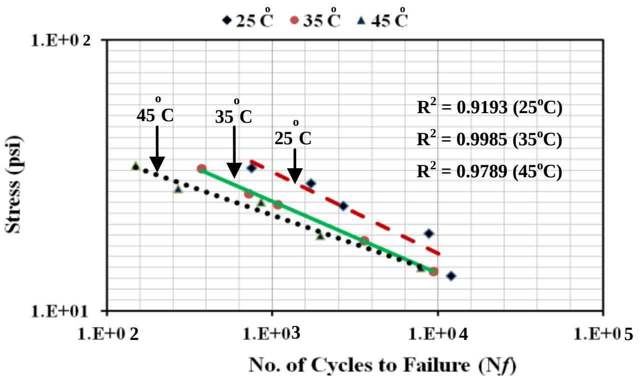

Fig. 7. Effect of Temperature on the S-N Curve of HL Modified Mixtures @ 15 Hz.

10 Hz) showed good correlation (R^2 = 0.90). This correlation study reveals that an exclusive relationship may exist between fatigue life and stress levels at low loading frequencies (up to 10 Hz), as follows.

$$\sigma_t = 176\left(\frac{1}{N_f}\right)^{0.2235} \quad (R^2 = 0.90) \tag{7}$$

Effect of Temperature on Fatigue Parameters Response

The effect of testing temperatures on fatigue parameters was also investigated in this research. Additional testing temperatures of 35°C and 45°C were considered, and the maximum number of cycles for each stress level at frequency of 15 Hz was recorded. The S-N curve for different studied temperatures is plotted in Fig. 7. The computed values of R^2 showed that, all fatigue models at different temperatures showed excellent correlation. From Fig. 7, it can be seen that, fatigue parameters experienced the same behavior and significantly decreased with the increase of temperature. That can be attributed to decrease of stiffness of asphalt concrete mixtures at higher temperatures. However, as temperature increases, fatigue life decreases and consequently fatigue parameters (*a* and *b*) decrease. Fig. 7 shows that, as temperature increases, the intercept (*a*) and the slope (*b*) of the S-N curve decrease. Finally, It can be concluded that, fatigue parameters (*a* and *b*) cannot be considered material parameters at different testing temperatures. From the above findings, it can also be seen that fatigue parameter (*a* and *b*) values from the split tension fatigue test are highly correlated. This emphasizes that, even though different conditions alter (*a* and *b*) values, there is a uniform relationship between them that does not change.

Conclusion

In an attempt to study the effect of the addition of HL on phenomenological approach fatigue model parameters (Intercept (*a*) and slope (*b*) of S-N curve), it was concluded that fatigue parameter (*a*) increased with the addition of HL, while fatigue parameter (*b*) seemed to be insensitive to mixture type (control mixture and HL modified mixture). This means that HL modified mixtures last longer under traffic loading than control mixtures. Additional study of the response of phenomenological fatigue model parameters of HL modified asphalt mixtures under frequency and temperature variation showed that fatigue parameters are highly correlated. This emphasizes that even though different conditions alter (*a* and *b*) values, there is a uniform relationship between them that does not change. Fatigue parameters could be considered material parameters (material constants) at low loading frequencies (up to 10 Hz). Fatigue parameters could not be considered material parameters for different testing temperatures.

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