



VERIFICATION OF TESTING PARAMETERS OF SEMI-CIRCLE NOTCHED BEAM FATIGUE TEST

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Received: 10 November 2012; **Accepted:** 25 February 2013

ABSTRACT

Fatigue testing is commonly conducted using the single-edge notched beam (SENB) test, which is not simple to prepare. With the widely use of Superpave gyratory compactor with its consistent circular compacted samples, the industry is keen to find ways to utilize these samples in testing. Therefore, the semi-circle notched beam (SCNB) fatigue test setup was introduced. However, there are no justified design criteria and/or standard test procedure to evaluate fatigue life of asphalt mixes using SCNB. Thus, there is a critical need for understanding the effect of the significance of each controlling testing parameters to evaluate Superpave mixes resistance to fatigue cracking using SCNB. In this study, common testing parameters were investigated and the failure point due to fatigue was clearly defined. In addition, when comparing test results to the Asphalt Institute (AI) model, it was found that the cyclic load range of 30% to 60% of the ultimate strength could be utilized as an appropriate range with a loading frequency of 1 Hz, at which test results illustrated that strain rate and loading range lay within reasonable range of AI design guidelines.

Keywords: Asphalt mixes; super pave; fatigue; fatigue parameters; semi-circle notched beam testing procedures.

1. INTRODUCTION

Fatigue failure (cracking) in pavements is contributed to cyclic loading of moving traffic, which may be characterized as a progressive failure phenomenon. Failure begins by the initiation and subsequent propagation of cracks causing fatigue failure. However, there is no

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reasonable explanation on the mechanism of the initiation and propagation of fatigue cracks and testing procedures including testing parameters.

Evaluation procedures for fatigue testing are cumbersome due to the fact that these procedures were developed to simulate cyclic loadings until the sample failure, and controlling test variables for testing are not well-explained and understood, especially the definition of fatigue failure point. Thus, researchers [1,2] have used alternate methods (i.e., prediction models) to estimate the total number of loading cycles to failure based on tensile strength and strain, binder/air contents, elastic modulus of asphalt mixes, strain energy, and other factors that are related to material properties. When studying/testing fatigue cracking, some basic concepts should be understood, especially the effect of material strength and characteristics, maximum and minimum stresses, loading frequency, etc.

In this study, the controlling fatigue testing parameters were studied to enhance the understanding of their effects on testing procedures. Therefore, the main objective of this study was to verify and improve evaluation procedure of fatigue life for asphalt mixes using the semi-circle notched beam (SCNB) test.

2. SCNB TESTING PROCEDURE

Early work in the 1960's and 1970's guided researchers to the use of notched beam specimens, statically loaded in a 3-point loading configuration, to assess fatigue and fracture properties of asphalt mixes. This test is well known as the single-edge notched beam (SENB) test ASTM E399 [3]. Lee and Hesp [4] and Lee et al. [5] used the same test setup to evaluate the fracture toughness of modified asphalt binders at low temperatures. All studies concluded that a three-point bending beam test was repeatable, and test results illustrated their sensitivities to material variations. In fatigue testing, beam specimens were convenient to perform experiments. However, it was neither easy nor simple to produce homogenous beam samples that represent the mix conditions in the field, due to adopted compaction methods.

When Superpave mix design method was introduced in the 1990's, the pavement industry was and still in favor of the use of compacted samples that are produced by the Superpave Gyratory Compactor (SGC). Gyratory compacted samples are more consistent and the compaction method was developed to mimic actual field conditions. In addition, extracting field cores is much easier than cutting beams from pavement slabs, when testing field samples are needed for evaluation. However, there is still a concerning issue on the orientation of aggregates in the compacted mix, since the direction of fracturing process (crack propagation) may be differed by the orientation of aggregates in the mix because of the way of samples preparation.

Several studies have investigated the use of gyratory compacted samples to determine tensile strength and fracture toughness by creating semi-circular specimens. Van de Ven et al. [6], Molennar et al. [7], and Li and Marasteanu [8] adopted the semi-circular bending (SCB) test setup. Using samples compacted by SGC, models were developed to determine the tensile strength of asphalt mixes in an effort to replace the indirect tension (IDT) test. However, un-notched samples were used and their studies were not focused on fracture

resistance parameters. Lim et al. [9] used a semi-circular notched specimen in a bending test to evaluate fracture properties of natural rocks by determining the stress intensity factor (K_{IC}). Huang et al. [10] used semi circle notched bending (SCNB) test to study fracture properties of various reclaimed asphalt pavement (RAP) mixes. Further, Mohammad et al. [11] extended the concept of SCNB test to study fatigue crack propagation of asphalt mixes. Their results showed that the geometry of SCNB test was suitable for fatigue crack propagation analysis of asphalt mixes, thus making SCNB a more convenient test setup than SENB.

3. SCNB FATIGUE TESTING

When studying fatigue cracking, some basic concepts should be understood including testing parameters, especially the frequency of loading and its range. Stress spectra are required to assess fatigue life. The simplest fatigue stress spectrum is a zero-mean sinusoidal stress-time pattern of constant amplitude and fixed frequency, applied for a specified number of cycles. Such a stress-time pattern is illustrated in Figure 1, and several useful terms and symbols can be defined:

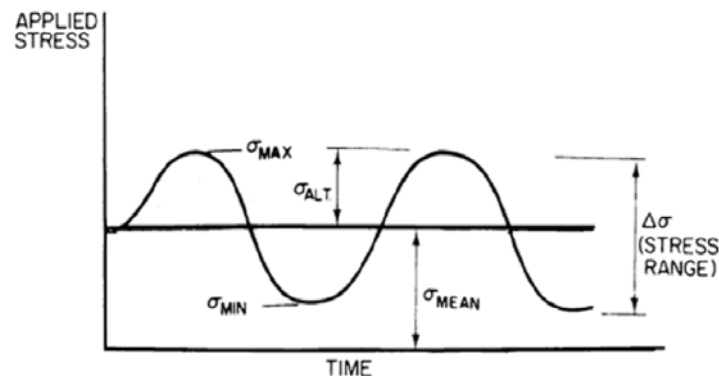


Figure 1. Constant-amplitude stress time pattern

where,

σ_{MAX} : Maximum stress in the cycle,

σ_{MEAN} : Mean stress = $(\sigma_{max} + \sigma_{min}) / 2$,

σ_{MIN} : Minimum stress in the cycle,

σ_{ALT} : Alternating stress amplitude = $(\sigma_{max} - \sigma_{min}) / 2$, and

$\Delta\sigma$: Range of stress (loading) = $\sigma_{max} - \sigma_{min}$.

Fatigue cracking occurs in asphalt pavement mainly due to the concentration of tensile stresses in the bottom of the asphalt mix layer resulting from cyclic traffic loads. Although, there is no well-established fatigue testing procedure of the semi circle notched bending (SCNB) test for asphalt mixes, a review of published fatigue test parameters was conducted, especially of the single-edge notched beam (SENB) test; a summary of parameters review is shown in Table 1. Based on this summary, a testing procedure could be adopted for SCNB fatigue testing by investigating the strain rates, loading frequencies, and loading ranges. Preliminary evaluation of SCNB fatigue tests was conducted using a combination of the

recommended parameters (Table 1) to obtain reasonable justification for using these parameters in fatigue testing.

Table 1: Review of fatigue test parameters

Study	Strain rate (10^{-6} units/s)	Frequency (Hz)
Daniel [12]	10, 30, 500, 1500	1 and 10
Lundstrom & Isacson [13]	100, 200, 400, 800	10
Medani & Molenaar [14]		10 – 50

4. EXPERIMENTAL DESIGN

Materials and Testing Configuration

Two different Superpave mixes (Mix 1 and Mix 2) from ongoing projects in the State of Idaho, USA were modified to create a wide range of mixes to investigate the effects of different mix properties (i.e. binder content and grade) on the fatigue life of asphalt mixes. Three binder contents (optimum binder content and $\pm 0.5\%$ from optimum content) and eight binder grades were used for a total of fourteen mixes, as shown in Table 2. Further, seven field mixes were obtained for additional testing and evaluation (Table 3). Aggregates gradations for tested mixes are shown in Figure 2.

Table 2: Properties of lab mixes

Mix ID	1	1-2	1-3	1-4	1-5	1-6	1-7	2	2-2	2-3	2-4	2-5	2-6	2-7
PG	70-28	70-28	70-28	70-22	70-34	64-28	58-28	64-34	64-34	64-34	64-22	64-28	70-34	58-34
G_{mm}	2.449	2.431	2.467	2.449	2.449	2.449	2.449	2.424	2.393	2.427	2.424	2.424	2.424	2.424
$P_b\%$	4.9	5.4	4.4	4.9	4.9	4.9	4.9	4.35	4.85	3.95	4.35	4.35	4.35	4.35
G_{se}				2.639							2.568			

where:

PG: Binder Grade,

G_{mm} : Maximum Theoretical Specific Gravity of Mix,

P_b : Binder Content, and

G_{se} : Effective Specific Gravity of Aggregates

Table 3: Properties of field mixes

Mix ID	F1	F2	F3	F4	F5	F6	F7
PG	70-28	64-34	70-28	58-34	70-28	70-28	70-28
G_{mm}	2.449	2.424	2.568	2.480	2.448	2.581	2.460
$P_b\%$	4.9	4.35	5.4	6.2	5.12	5.9	5.1
G_{se}	2.639	2.568	2.808	2.744	2.648	-	-

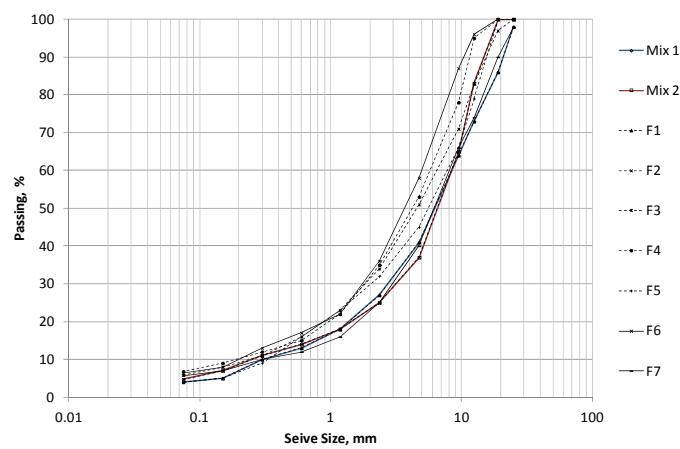


Figure 2. Aggregate gradations of tested mixes

All specimens were mixed and compacted under controlled lab conditions. Specimens were prepared using the Servopac SGC to a number of gyrations to produce specimens with $4\pm 1\%$ air voids. Compacted cylindrical specimens were sliced into 4 semi-circle specimens with a thickness of approximately 53mm each. One specimen was left un-notched to determine the ultimate (fracture) strength (monotonic test), and the remaining three specimens were notched with 12.7, 25.4 and 31.8mm depths, respectively.

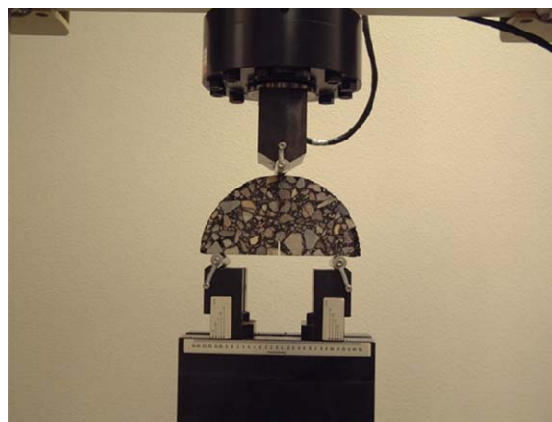


Figure 3. Three point load testing set-up on the MTS machine

All specimens had the standard gyratory compacted sample diameter of 152mm. For both monotonic and fatigue tests, an MTS 810 machine with Flex Test SE Version 5.0 C 2299 system was used for testing. Specimens were tested in a three point configuration, and the spacing between the two roller supports was 120mm (Figure 3). In this study, most of the experiments were conducted at room temperature (21°C) to minimize the effect of test variation and as per Superpave requirements, fatigue resistance of asphalt binders is always evaluated in the mid-range temperatures of the binder grade (PG), which is around room temperature in this case

To estimate and verify the range of appropriate strain rates and loading frequencies for this study, the research team examined and conducted a comparison with the Asphalt Institute (AI), CALTRANS, and AASHTO methods for estimating the fatigue life of asphalt pavements based on specimen thickness (76.2mm). AI model [2] was adopted due to its consistency and precision. In addition, AI model is widely used by pavement designers to determine the fatigue life of asphalt pavements. To utilize the AI fatigue model, the elastic modulus should be determined for the tested mixes, therefore the dynamic modulus ($|E^*|$) under the same testing conditions, was used.

Two duplicate specimens per mix were used to determine $|E^*|$ for the tested mixes. Specimens were compacted using Servopac SGC to achieve 175mm high specimens. Specimens were cored and sawed to obtain 100mm diameter and 150mm high specimens with an inner 7% air voids. The dynamic modulus test (AASHTO TP 62-03 [15]) consists of applying a uniaxial sinusoidal compressive stress to an unconfined HMA (Hot Mix Asphalt) cylindrical test specimen while measuring the corresponding strain using three Linear Variable Differential Transformers (LVDTs) mounted on the middle of the specimen. The dynamic modulus test was conducted at 21°C and loading frequencies of 0.1, 1, and 5 Hz.

5. DATA ANALYSIS AND DISCUSSION

Definition of Fatigue Failure

The definition of a failure in pavement is not easy to pinpoint, especially under fatigue loading because of material characteristics. Failure of sample would be very difficult to detect without a clear definition of failure. Thus, it was necessary to define a failure point under cyclic loading of SCNB test. Based on preliminary fatigue testing results, the fatigue failure could be defined by determining the transition point between the elastic and plastic region when a specimen is loaded at 1 Hz (Figure 4-a), at which an uneven peak interval between max and min loading wave could be observed (Figure 4-b). In other words, when the displacement curve starts to deviate from the linear state, it can be identified that the sample has failed (Figure 4-a).

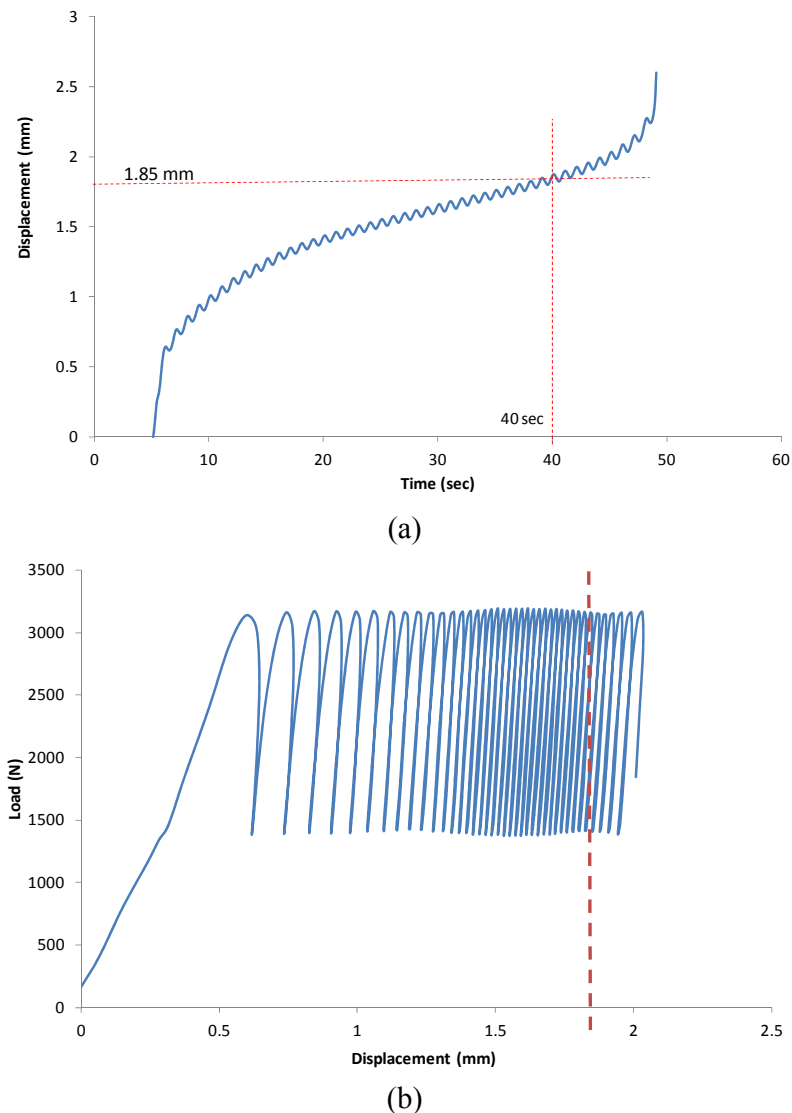


Figure 4. Transition point from elastic to plastic behavior during fatigue test

Fatigue Loading Range

Fatigue research has been progressing slowly due to very complicated combinations of its testing parameters and due to time consuming experimental procedures. The loading frequencies and strain ranges, used by other researchers (Table 1), were investigated to determine experimental parameters. However, there is no clear justification of the reason for adopting these parameters. To estimate the reasonable range of stress during SCNB fatigue testing, preliminary experiments were conducted to determine an equivalent range of parameters to simulate field conditions; loading range for a fatigue test should be within the elastic range of fracture strength, determined by monotonic three point bending test, to prevent sudden failure due to stress effect.

AI model was used to compare different testing parameters effects. AI model was

developed using laboratory testing and later applied a widely used factor of 18.417 to shift the laboratory test results to actual field testing results. The shifted model can be described as,

$$N_f = 0.0796(\varepsilon_t)^{-3.291}(E)^{-0.854} \quad (1)$$

where,

N_f : number of load application to failure,

ε_t : tensile strain at the bottom of the asphalt mix layer, and

E : asphalt mixture elastic modulus, psi.

E and ε_t should be determined to calculate N_f in Eq. 1; the dynamic elastic modulus (E^*), at the same testing temperature and frequency of the fatigue tests, was used instead of E . ε_t was determined using Hook's Law since all fatigue tests were conducted within the elastic region of mixes. Thus, it was required to determine the tensile stress (σ_t) at the tip of the notch for SCNB test setup. A finite element method [16] was used to determine σ_t ; 3-D models were constructed, to study the sensitivity of σ_t to different notch depths: 12.5, 25.4, 38.1, and 50.8mm and different sample thicknesses, as well. The simulation results of these models showed, as expected, that the highest σ_t values were located at the tip of the notch (Figure 5), and for the same load the bigger the notch, the higher σ_t at the tip would be. Utilizing the output of these simulations, a simple statistical analysis was conducted to develop a numerical solution to determine σ_t at the tip of the notch as shown in Eq. 2.

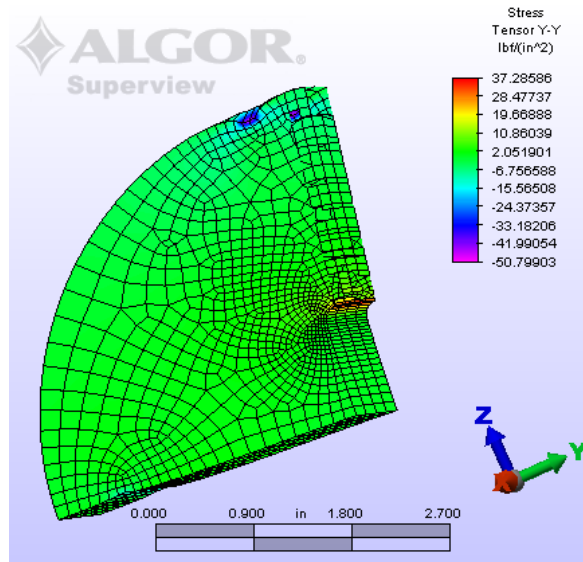


Figure 5. Resulting stresses in FEA for SCNB model with 12.7mm notch after loading

$$\sigma_t = 25.0375 \left(\frac{Pa}{(r-a)tr} \right) \quad (2)$$

where,

σ_t : tensile stress, kPa,

P: load, kN,

a: notch height, m,

r: sample radius, m, and

t: sample thickness, m.

After determining σ_t , corresponding ε_t values were determined and plugged in Eq. 1 to determine N_f for the different tested specimens. Samples with 76.2mm height were tested at various combinations of displacement rates of 1.3×10^{-8} , 25×10^{-8} , 1.3×10^{-9} , and 25×10^{-9} mm/sec (50×10^{-6} , 100×10^{-6} , 500×10^{-6} , and 1000×10^{-6} in/sec) and cyclic loading ranges of 10-30%, 10-50%, 30-50%, 30-70%, 30%-60%, and 20%-60% of ultimate strength with different loading cycles of 0.1, 0.5 and 1 Hz. It was found that when cyclic loading ranges were used, tests yielded better and more consistent results than when displacement rates were used. In addition, when comparing the results of these loading combinations with AI model predictions, the cyclic load range of 30% to 60% of the ultimate strength at 1 Hz loading cycles results (horizontal lines on Figure 6) and samples' thickness range (vertical lines on Figure 6) were closer to AI model predictions (curve on Figure 6). Thus, it was reasonable to select 30% to 60% loading range at 1 Hz for SCNB fatigue testing of asphalt mixes.

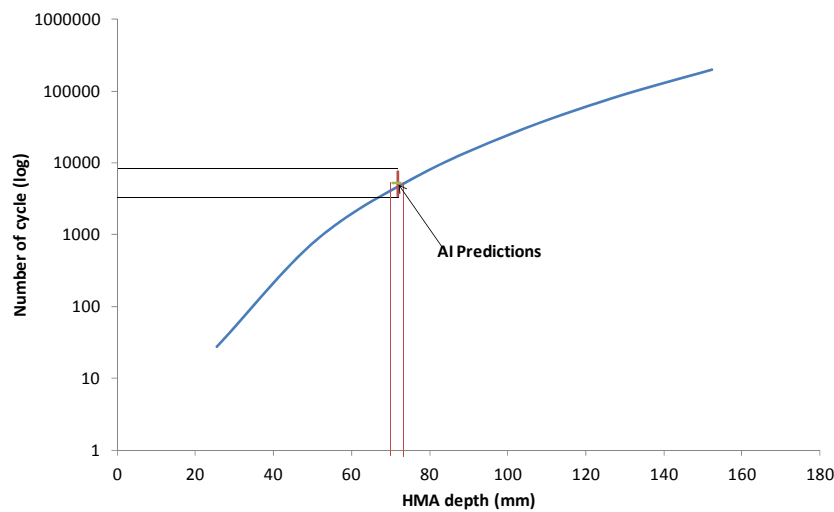


Figure 6. HMA full depth design with range of tested cyclic loading (30-60%)

Validation of Established SCNB Fatigue Testing Parameters

As a final step, the developed SCNB fatigue testing procedure was validated using field mixes, which were not used in the testing procedure determination. N_f values determined by AI model, for these mixes, were compared to actual number of cycles to failure resulting from the developed SCNB test procedure. It was found that a linear correlation existed. Similar to AI model, the resulted number of cycles in the developed fatigue test procedure should be multiplied by a shift factor equal to 132.15 to achieve similar results to AI model with an R-square equal to 0.8778, as shown in Eq. (3) and Figure 7.

$$N_f = 132.15(N_f)_{Test} \quad (3)$$

where,
 N_f : predicted number of load application to failure and
 $(N_f)_{Test}$: actual number of cycles to failure determined by the developed SCNB test procedure.

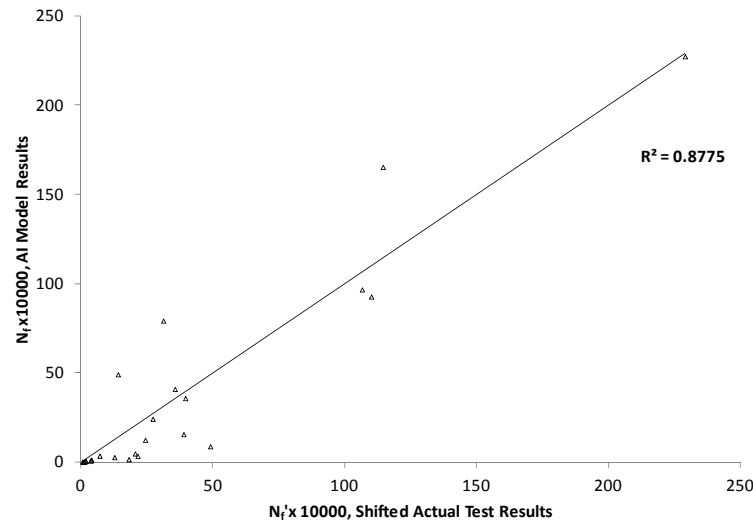


Figure 7. Shifted SCNB Test N_f Results vs. N_f Determined by AI Model

6. SUMMARY AND CONCLUSIONS

Fatigue testing is very critical to evaluate the dynamic strength of asphalt pavements. single-edge notched beam (SENB) test procedure has been widely used to determine fatigue life of asphalt mixes. Unfortunately, this test setup is not easy to conduct, especially by the industry due to the difficulty of obtaining consistent rectangular testing samples. With the wide use of the Superpave gyratory compactor, the industry started looking in favor to the use of the circular compacted samples in different testing setups, since obtaining consistent samples were simpler and easier, and testing of field core samples can be conducted for existing pavements.

When it comes to fatigue testing of semi-circle notched beam (SCNB) testing, there is no standardized or established test procedure. Therefore, it is important to identify and understand the significant testing parameters that may affect fatigue testing of asphalt mixes. Thus, this study was conducted.

Loading frequencies, strain rates, and loading ranges were found to be significant when determining fatigue strength of asphalt mixes, as indicated by earlier studies. Understanding these parameters would be very beneficial to designing pavements and improving the design procedure. Loading frequencies, strain rates, and loading ranges were evaluated and examined. Test results showed that fatigue failure of specimens could be defined by

identifying a transition point between elastic and plastic behavior of tested samples, at which an uneven peak interval between maximum and minimum loading wave could be observed. Further, the Asphalt Institute (AI) design method was used for verification, since it is widely used by designers to estimate fatigue life of asphalt pavements.

To use AI design method, tensile strains should be determined for the tested specimens, since the fatigue test was conducted in the elastic region, thus the tensile strains could be determined using Hook's law. Finite element simulations were used to develop an equation to determine the tensile stress at the tip of the notch in the semi-circular specimen, and then the numbers of cycles to failure were calculated by AI model and then compared to actual test results. It was found that the cyclic load range of 30% to 60% of the ultimate strength could be adopted as an appropriate range for SCNB fatigue testing at frequency of 1 Hz, at which test results illustrated that strain rate and loading range lay within reasonable range of AI design guidelines. In addition, it was found out for better and more consistent results the use of 12.7mm notch height is recommended.

Further, to validate the adopted cyclic load range of 30% to 60% of the ultimate strength at 1 Hz loading cycles, field mixes were tested and compared to AI model predictions. It was found that a linear correlation existed between AI model predictions and the resulted number of cycles in the recommended SCNB fatigue test procedure. Similar to AI guidelines a shift factor equal to 132.15 should be applied to results of the SCNB fatigue test results, to obtain similar results of AI design methods.

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