Jordan Journal of Civil Engineering, Volume **5**, No. **4**, **2011**

Framework for Level-I Alligator Cracking Methodology for Use in the Mechanistic-Empirical (M-E) Pavement Design Guide

Mohammad Abojaradeh [1], Michael Mamlouk [2], Basim Jrew [3] and Ghazi Al-Khateeb [4]

[1] Ph.D., P.E., Assistant Professor, Department of Civil Engineering, Zarqa University, Zarqa, Jordan. Email: abojaradeh@yahoo.com
[2] Ph.D., P.E., Professor, Department of Civil and Environmental Engineering, Arizona State University, Tempe, AZ 85287-5306. Email: mamlouk@asu.edu
[3] Ph.D., Professor, Department of Civil Engineering, Al-Isra University, Amman, Jordan.
[4] Ph.D., Assistant Professor, Department of Civil Engineering, Jordan University of Science and Technology, Irbid 22110, Jordan. Email: ggalkhateeb@just.edu.jo
Homepage: www.just.edu.jo/~ggalkhateeb

ABSTRACT

The recently published Mechanistic-Empirical Pavement Design Guide (MEPDG) includes a global flexure fatigue model that can be used for Level 3 material input. This paper develops a typical framework for highway agencies to follow to calibrate their laboratory results and determine Level 1 flexure fatigue input for use in the design guide. An extensive flexure fatigue testing program was carried out on six hot-mix asphalt (HMA) materials typically used by the Arizona Department of Transportation. General fatigue models are developed using both constant strain and constant stress modes of loading. The general fatigue lab models were then calibrated to the global fatigue model in the MEPDG to be used as an input to Level 1 design. Shift factors were developed for each mix used and for different thicknesses of asphalt layers. The shift factor decreased from 20 at a 1-in. layer to 9 at a 4-in. layer, after which it remained constant. The procedure used in this paper serves as a guide for other agencies to follow to obtain Level 1 fatigue data input for the M-E Pavement Design Guide.

KEYWORDS: Alligator cracking, Fatigue, Mechanistic, Empirical, Pavement design, HMA, Asphalt.

INTRODUCTION

The new Mechanistic-Empirical Pavement Design Guide (MEPDG) (formerly known as the 2002 Pavement Design Guide) has been recently completed and is expected to be adopted by AASHTO in the near future (2002 Design Guide, 2003). The guide employs three hierarchical levels of inputs for material, traffic and environment. Level 1 inputs provide the highest level of accuracy and require laboratory or field testing. Level 2 inputs provide an intermediate level of accuracy and typically would be user-selected from an agency database, derived from a limited testing program or estimated through correlations. Level 3 inputs provide the lowest level of accuracy and typically would be user-selected values or typical averages for the region.

The Level 1 fatigue cracking laboratory test input recommended by the design guide is the flexural beam

Accepted for Publication on 15/10/2011.

fatigue test of asphalt mixtures. The test is intended to simulate field traffic loading and is summarized in subjecting an HMA beam specimen to repeated third-point bending (AASHTO TP8 (2)). Laboratory-determined fatigue results must be adjusted or "shifted" to account for the inaccuracies in simulating field fatigue (bottom-up) cracking in the HMA layer.

The MEPDG includes a global flexure fatigue model that can be used for Level 3 material input. The model has been calibrated with national field data from the General Pavement Sites (GPS) and Special Pavement Sites (SPS) in the LTPP database having different environmental, material and traffic conditions (FHWA DataPave, 2000; 2002 Design Guide, 2003; El-Basyouny and Witczak, 2005). A total of 82 pavement sections from 24 states were used in the calibration with 1897 data points.

The global fatigue model can be used as is by highway agencies that choose not to perform laboratory flexure fatigue tests. In this case, the design is not expected to be very accurate since fatigue properties vary from one asphalt mixture to another. For agencies that choose to use Level 1 material input, they must perform laboratory flexure fatigue tests on their mixtures and calibrate their laboratory-developed model either to field data or to the global fatigue model in the M-E Pavement Design Guide. At present, the guide does not have examples for various highway agencies to follow to calibrate laboratory fatigue models to the global fatigue model. Currently, there is a need for a typical framework for highway agencies to follow to calibrate their laboratory results and determine Level 1 flexure fatigue input.

LITERATURE REVIEW

Fatigue cracking is one of the major distresses that occur in flexible pavements and considered in mechanistic-empirical pavement design procedures. Fatigue cracking occurs in asphalt pavements due to repeated traffic loading at intermediate temperatures ranging normally between 5°C and 40°C. Extensive research has been conducted to study the phenomenon of fatigue cracking in asphalt pavements. Some of this research intended to develop theoretical models for fatigue performance (Zhang and Raad, 1999, 2001; Lee et al., 2000; Rodrigues, 2000; Lundstrom and Isacsson, 2003). Other researchers used experimental laboratory testing techniques and data analysis methods to predict fatigue performance of asphalt mixtures (Van Dijk, 1975; Pronk and Hopman, 1990; Tayebali et al., 1992, 1993; Rowe, 1993; Kim et al., 1997; Rowe and Bouldin, 2000; Ghuzlan and Carpenter, 2000; Al-Khateeb and Shenoy, 2004).

To evaluate fatigue performance of asphalt mixtures, it is necessary to understand fatigue failure and how it is defined. Fatigue failure has been defined in the literature using different ways. The most common and widely used fatigue failure criterion in the constant strain mode is the 50-percent reduction in the initial stiffness or modulus (Van Dijk and Vesser, 1977; Pronk and Hopman, 1990; Tayebali et al., 1992, 1993). Later on, this failure criterion, which is based on the 50-percent reduction in stiffness, was adopted to define the fatigue failure point by the AASHTO as a provisional standard TP8-94 (2002).

Besides the fatigue failure definition of 50-percent stiffness reduction, some researchers used energy-based failure criteria and definitions. The "Energy Ratio" was proposed in some cases (Hopman et al., 1989; Rowe, 1993; Rowe and Bouldin, 2000). The "Pseudo Stiffness Reduction" was also used in other cases (Kim et al., 1997), and the concept of "Dissipated Energy" was proposed to define fatigue failure as well (SHRP-A-404 Report, 1994; Ghuzlan and Carpenter, 2000). On the other hand, Al-Khateeb and Shenoy (2004, 2011) presented a new distinctive fatigue failure criterion for asphalt paving mixtures that was based on observing the load-deformation (or stress-strain) hysteresis loop or tracking the stress and strain waveforms during fatigue testing to define the point of fatigue failure.

Fatigue testing can be conducted in the constant strain mode or the constant stress mode of testing. The previous fatigue failure definitions or criteria are related to the constant strain mode of testing. However, in the constant stress mode of testing, fatigue failure was defined differently. Some researchers defined fatigue failure as the complete fracture at the end of the fatigue test when the specimen fails due to tensile strains (Pell and Cooper, 1975; Tayebali et al., 1992). Other researchers, such as Rowe (1993), defined fatigue failure as occurring when the initial complex modulus has been reduced by 90 percent. On the other hand, Van Dijk (1975) defined fatigue failure as occurring when the initial strain doubled.

Objective

The main objective of this paper is to develop a framework methodology that can be used by various highway agencies for Level 1 alligator cracking input for use in the M-E Pavement Design Guide. Flexure fatigue tests are performed on six HMA materials typically used in Arizona and general fatigue models are developed. The lab models are then calibrated to the global fatigue model in the guide to be used as an input to Level 1 design. The procedure used in this paper serves as a guide for other agencies to follow to obtain Level 1 fatigue data input for the M-E pavement design.

Flexural Fatigue Test

Flexural beam fatigue testing of asphalt mixtures in the laboratory (Figure 1) has been used for several decades by many researchers to simulate field conditions. It is anticipated that the test will gain wider acceptance since it is recommended by the M-E Pavement Design Guide. In this test, either the strain or stress is fixed throughout the test until the specimen fails. Normally 6 to 8 specimens are tested at different strain or stress levels to establish the fatigue relationship for a specific temperature. Since the stiffness of HMA is largely affected by temperature, the test is typically performed at several temperatures to evaluate the effect of stiffness on the fatigue life. The test equipment is controlled by software that allows for an automatic calculation of stress, strain and stiffness throughout the test. According to the AASHTO TP8 (2002) procedure, the specimen fails when the material stiffness is reduced to 50 percent of its initial stiffness.

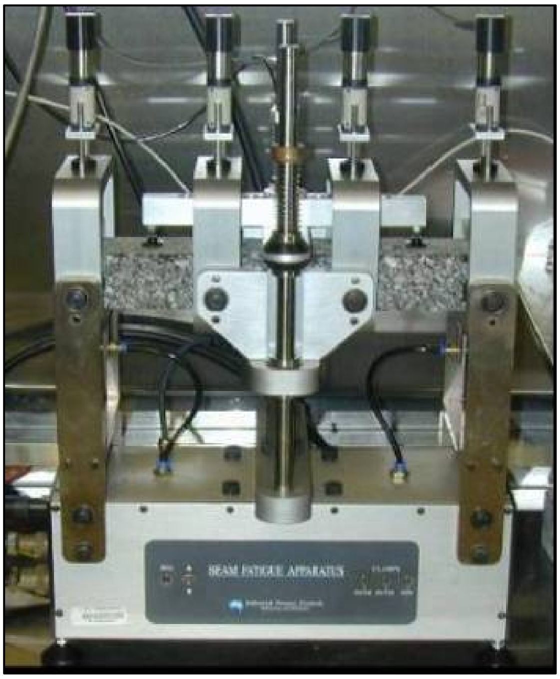


Figure 1: Flexural Fatigue Test Device

General Fatigue Model

In the flexure fatigue test, results at different strain or stress levels and different temperatures are compiled and a linear regression line is fitted on a log-log scale between the initial tensile strain and the number of load repetitions to failure. A regression model is developed to correlate the number of load repetitions at failure to the initial tensile strain in the beam in the following form:

$$N_f = k_1 * \left(\frac{1}{\varepsilon_t}\right)^{k_2} \left(\frac{1}{E}\right)^{k_3} \qquad (1)$$

where:

N_f = Number of load application to failure.

ε_t = Initial tensile strain.

E = Initial stiffness (modulus) of the material.

k_1, k_2 and k_3 = Regression constants.

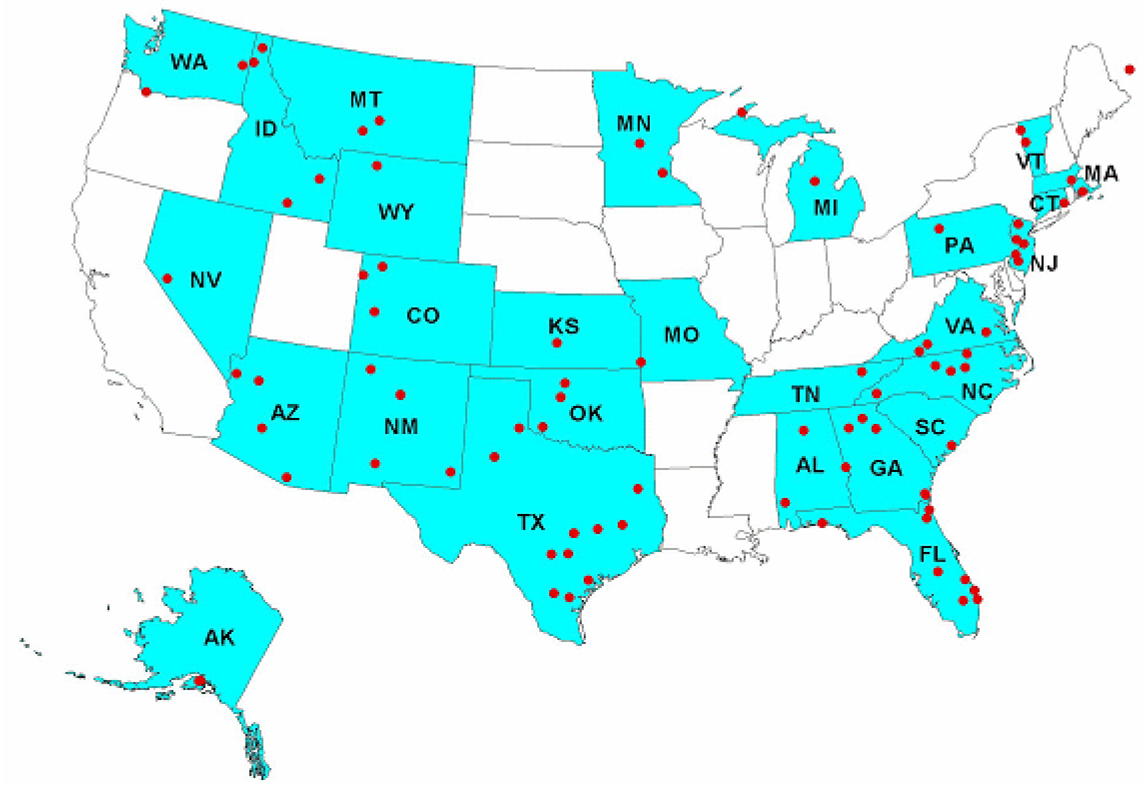


Figure 2: Location of the Sections Used in Pavement Calibration in the M-E Pavement Design Guide (4)

Table 1. Design Properties of Mixtures Used in the Study

Property	**Mixture No.**					
	1	2	3	4	5	6
Binder Type	PG 76-16	PG 64-22	PG 70-10	PG 58-28	PG 64-22	Rubberized PG 58-22
Binder Content (%)	4.2	4.6	4.3	5.0	5.3	7.5
Type of Aggregate	Salt River Base	Salt River Base	Salt River Base	Bidahochi Base	Bidahochi Base	Salt River Base
Bulk Specific Gravity	2.270	2.280	2.269	2.483	2.484	2.200
Max. Theoretical Specific Gravity	2.441	2.456	2.440	2.671	2.672	2.389
Air Void (%)	7.0	7.0	7.0	7.0	7.0	8.0

Laboratory-determined fatigue curves must be adjusted or "shifted" to account for the inaccuracies in simulating field conditions and crack propagation through the HMA layer. Unlike laboratory conditions, field conditions have random rest periods, variable loading, wandering effect and different residual stress history. These field conditions allow for recovery and relaxation of the material, which do not exist in the laboratory. Thus, some micro-cracks initiated in the AC pavements may heal partly because of the viscoelastic recovery of the asphalt binder and partly because of the reformation of the bond forces in the material after the removal of the applied load. These two reasons lead to a larger fatigue life of AC pavement in the field as compared to laboratory results (Tseng and Lytton, 1990; Balbissi and Little, 1990; Mahoney and Pierce, 1996). The shift factors that have been reported in the literature vary widely from 3 to over 100 depending upon the thickness of the asphalt layer, the mix properties, traffic volume and vehicle composition, environmental conditions and mode of loading of the fatigue test. Mahoney and Pierce (1996) reported that shift factors appear to fall most commonly into a range between 4 and 10.

MEPDG Fatigue Model

The global fatigue model in the MEPDG has been calibrated with national field data points as shown in Figure 2. The calibrated global fatigue model in the M-E Pavement Design Guide is as shown in Equation 2.

$$N_f = 0.00432 * k_1 * C\left(\frac{1}{\varepsilon_t}\right)^{3.9492}\left(\frac{1}{E}\right)^{1.281} \qquad (2)$$

where:

$$k_1 = \frac{1}{0.000398+\frac{0.003602}{1+e^{11.02-3.49*h_{ac}}}}$$

$$C = 10^M$$

$$M = 4.84\left(\frac{V_b}{V_a+V_b}-0.69\right)$$

h_{ac} = Thickness of the asphalt concrete layer (inches).

V_b = Effective binder content (%).

V_a = Air voids (%).

Note that the number of load applications to failure according to the MEPDG is a function of asphalt layer thickness. During the development of the model, the mode of loading (constant strain or constant stress) was incorporated in the model (2003).

An agency that chooses to perform Level 1 design has to conduct laboratory flexure fatigue tests on its specific materials and calibrate their laboratory-developed model either to field data or to the global fatigue model in the MEPDG. This paper presents a framework methodology for calibrating an agency's laboratory-developed model to the global model in the guide to produce Level 1 fatigue cracking design input.

Materials and Specimen Preparation

In this study, six Arizona Department of Transportation (ADOT) mixtures were tested, five of which were conventional hot mix asphalt and one modified gap-graded asphalt rubber mixture. The volumetric mixture design properties for the six mixtures are shown in Table 1. Further details of various mixtures can be found in Abojaradeh (2003).

Beams were prepared using vibratory loading applied by a servo-hydraulic loading machine. A mold was used with inside dimensions larger than the required dimensions of the beam to allow for sawing to achieve standardized geometric dimensions. The material was compacted using a stress-controlled sinusoidal load until the pre-determined density was reached. The specimens were brought to the required dimensions for fatigue testing by sawing 1/4 inch (6 mm) from each side. Air voids were measured using the saturated surface-dry procedure (AASHTO T166, Method A). Any specimen with an air void larger than 1 percent deviation from the target value of 7 percent was rejected. The details of beam preparation and verification of air void uniformity within the specimen are presented elsewhere (Witczak et al., 2001; Abojaradeh, 2003).

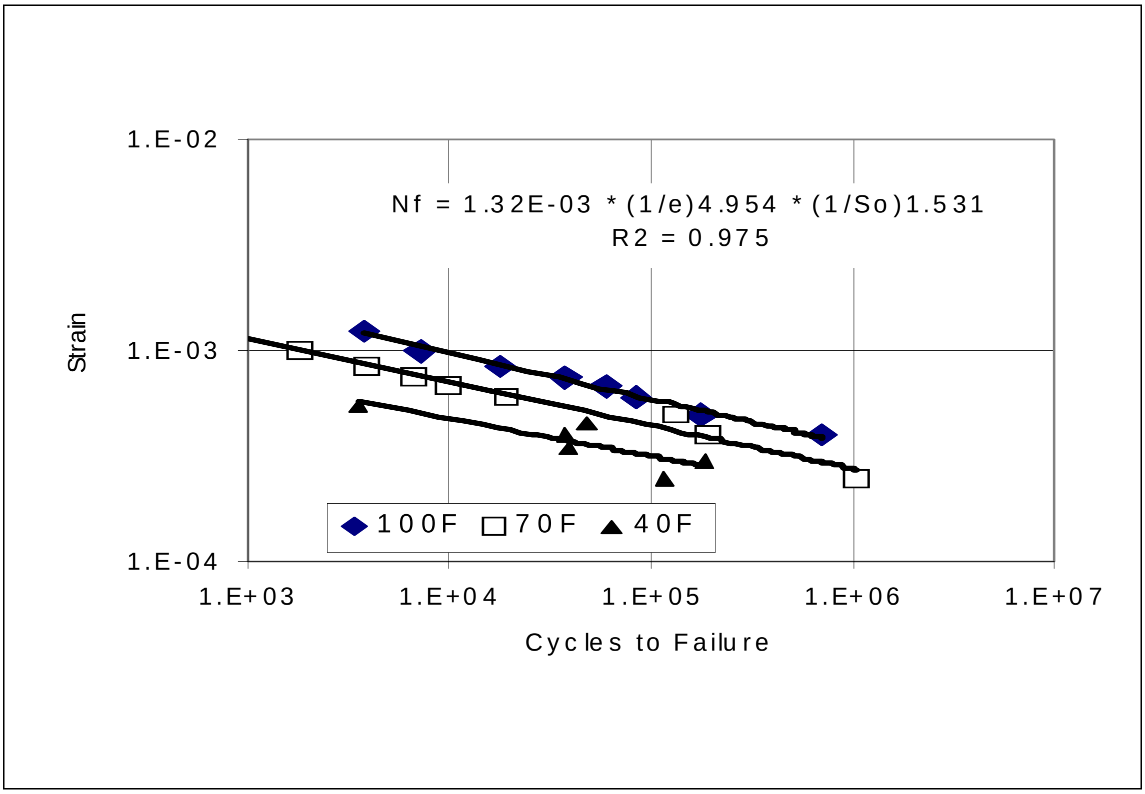


Figure 3: Strain *vs.* Fatigue Life for Mixture No. 1 under Constant Strain Mode

Table 2. Number of Specimens per Mix Tested at Constant Strain and Constant Stress Modes

Mixture No.	Constant Strain	Constant Stress
1	23	14
2	22	26
3	23	25
4	20	20
5	18	19
6	23	20
Total	129	124

Test Conditions

Flexural fatigue tests were performed according to the AASHTO TP8 procedures (2002). The following factors were used in the beam fatigue study:

- Mix type: 6 different mixes as defined earlier.
- Mode of loading: Constant strain and constant stress.
- Wave shape: Haversine for constant strain and sinusoidal with a 10-Hz frequency for constant stress.
- Test temperature: 40, 70 and 100^{o}F (4.4, 21.1 and 37.8^{o}C).

Six to eight beam specimens were tested for each mix type, mode of loading and test temperature, with a total of 253 specimens. Table 2 shows the number of specimens tested for different mixes at constant strain and constant stress mode of loading.

Development of Fatigue Models

The first step in developing fatigue models for ADOT mixes was to use the laboratory data to generate general fatigue models according to Equation 1 for both constant stain and constant strain modes of loading. The second step was to adjust these fatigue models to match the MEPDG model using shift factors.

Data from each fatigue test (ε_t , E and N_f) were obtained from the software. Data from each mix and each mode of loading (6-8 specimens and 3 test temperatures) were then compiled. Regression equations were fitted using the STATISTICA software to develop fatigue models for each mix and each mode of loading according to Equation 1. Figure 3 shows an example of linear regression lines fitted between the initial tensile strain and the number of load repetitions to failure for mix number 1 under constant strain. Table 3 shows the fatigue regression parameters k_1, k_2 and k_3 and the values of R^2 for all mixes. The regression equations for different mixes were used to determine the number of load applications to failure ($N_{f\text{-General}}$) for each specimen.

Table 3. Regression Coefficients for ADOT Mixes Using the General Fatigue Model

Mixture No.	Mode of Loading	k_1	k_2	k_3	R^2
1	Constant Strain	1.32E-03	4.9536	1.5306	0.975
	Constant Stress	7.77E-07	4.3611	0.8578	0.999
2	Constant Strain	4.99E-07	5.1193	1.0271	0.700
	Constant Stress	4.92E-09	4.4502	0.4735	0.988
3	Constant Strain	4.02E-15	6.4674	0.6409	0.878
	Constant Stress	1.41E-07	2.9598	-0.1434	0.820
4	Constant Strain	4.80E-13	5.5656	0.3194	0.795
	Constant Stress	8.48E-05	3.7209	0.7248	0.916
5	Constant Strain	2.60E-17	6.0596	-0.1635	0.993
	Constant Stress	5.78E-10	3.8443	-0.1286	0.959
6	Constant Strain	1.98E-01	3.7100	1.0273	0.834
	Constant Stress	3.19E-14	10.1531	3.0044	0.988

The number of load applications to failure according to the MEPDG fatigue model (Equation 2) is a function of ε_t, E, h_a and the constants k_1, k_2, k_3, V_b and V_a. The data obtained from each specimen of ADOT mixes (ε_t, E, V_b and V_a) were used in Equation 2 to predict the number of load applications to failure ($N_{f\text{-MEPDG}}$) for different asphalt layer thicknesses 1, 2, 4, 6 and 8 inches.

Data were plotted to compare the number of load applications to failure using both the general fatigue model and the MEPDG fatigue model. Figure 4 (a) shows an example of number of load applications to failure predicted using both the general fatigue and the MEPDG fatigue models for mixture number 1 and asphalt layer thickness of 1 inch. The figure shows that the number of load applications to failure predicted from the general fatigue model is less that that predicted by the MEPDG model. Therefore, an adjustment is needed to shift the general fatigue model prediction to match the MEPDG model prediction.

A shift factor for all ADOT mixes was developed by determining the ratio of the number of load applications to failure using the MEPDG model to the number of load applications to failure using the general fatigue model for each specimen. The ratios for all mixtures were averaged to determine the shift factor for all mixtures as shown in Equation 3.

$$SF = \frac{\sum_{1}^{n} (N_{f-MEPDG} / N_{f-General})}{n} \quad (3)$$

where:

SF = Shift factor for all ADOT mixtures.

Since the $N_{f-MEPDG}$ is a function of asphalt layer thickness, a shift factor was developed for each layer thickness used. Also, since the lab tests were performed using either the constant strain or constant stress mode of loading, different shift factors were developed for different modes of loading. Table 4 shows various shift factors for different layer thicknesses and modes of loading.

From the data in Table 4, it is clear that the shift factors decrease with increasing the layer thickness for both modes of loading. Since the constant strain loading is associated with thin layers and the constant stress loading is associated with thick layers, the controlling shift factors were selected accordingly as shown in Table 4. The controlling shift factors were then multiplied by $NB_{f\text{-GeneralB}}$ for each test to determine the adjusted number of load application to failure as shown in Equation 4.

$$N_{f-Adjusted} = SF * N_{f-General} \quad (4)$$

Figure 4 (b) shows the number of load applications to failure predicted using the MEPDG fatigue model *versus* the number of load applications using general fatigue for mixture number 1 after multiplying it by the corresponding shift factor (SF = 20) for an asphalt layer thickness of 1 inch. As expected, the results after adjustment (Figure 4 (b)) show closer match between $NB_{f\text{-AdjustedB}}$ and $NB_{f\text{-MEPDGB}}$ predictions as compared to the case before adjustment (Figure 4 (a)). Table 5 shows a numerical example of the results of mixture number 1.

Figure 5 shows a similar example for mixture number 1 for an 8-inch layer thickness (constant stress loading).

Figure 6 shows the predicted fatigue lives using the general fatigue model *versus* predicted fatigue life using the MEPDG model for 1-in. asphalt layer for all mixtures before and after adjustment (constant strain). Figure 7 is similar to Figure 6, except for 8-inch layer (constant stress).

Figure 8 shows the shift factors for different asphalt layer thicknesses using the constant strain mode for thin layers and the constant strain mode for thick layers. The figure shows that the shift factor decreases from 20 at a 1-in. layer to 9 at a 4-in. layer. The shift factor remains the same when the layer thickness is increased afterwards.

SUMMARY AND CONCLUSIONS

The recently published Mechanistic-Empirical Pavement Design Guide (MEPDG) includes a global flexure fatigue model that can be used for Level 3 material input. This paper develops a typical framework for highway agencies to follow to calibrate their laboratory results and determine Level 1 flexure fatigue input. An extensive flexure fatigue testing program was carried out on six HMA materials typically used in Arizona and general fatigue models were developed. Both constant strain and constant stress modes of loading were used. The lab models are then calibrated to the global fatigue model in the guide to be used as an input to Level 1 design. Shift factors were developed for each mix used and for different thicknesses of asphalt layers. The shift factor decreased from 20 at a 1-in. layer to 9 at a 4-in. layer. The shift factor remains the same when the layer thickness is increased afterwards. The procedure used in this paper serves as a guide for other agencies to follow to obtain Level 1 fatigue data input for the M-E Pavement Design Guide.

Acknowledgement

The authors of this study would like to thank the Arizona Department of Transportation (ADOT) for the financial support of this project and the continuous guidance and advice throughout the study.

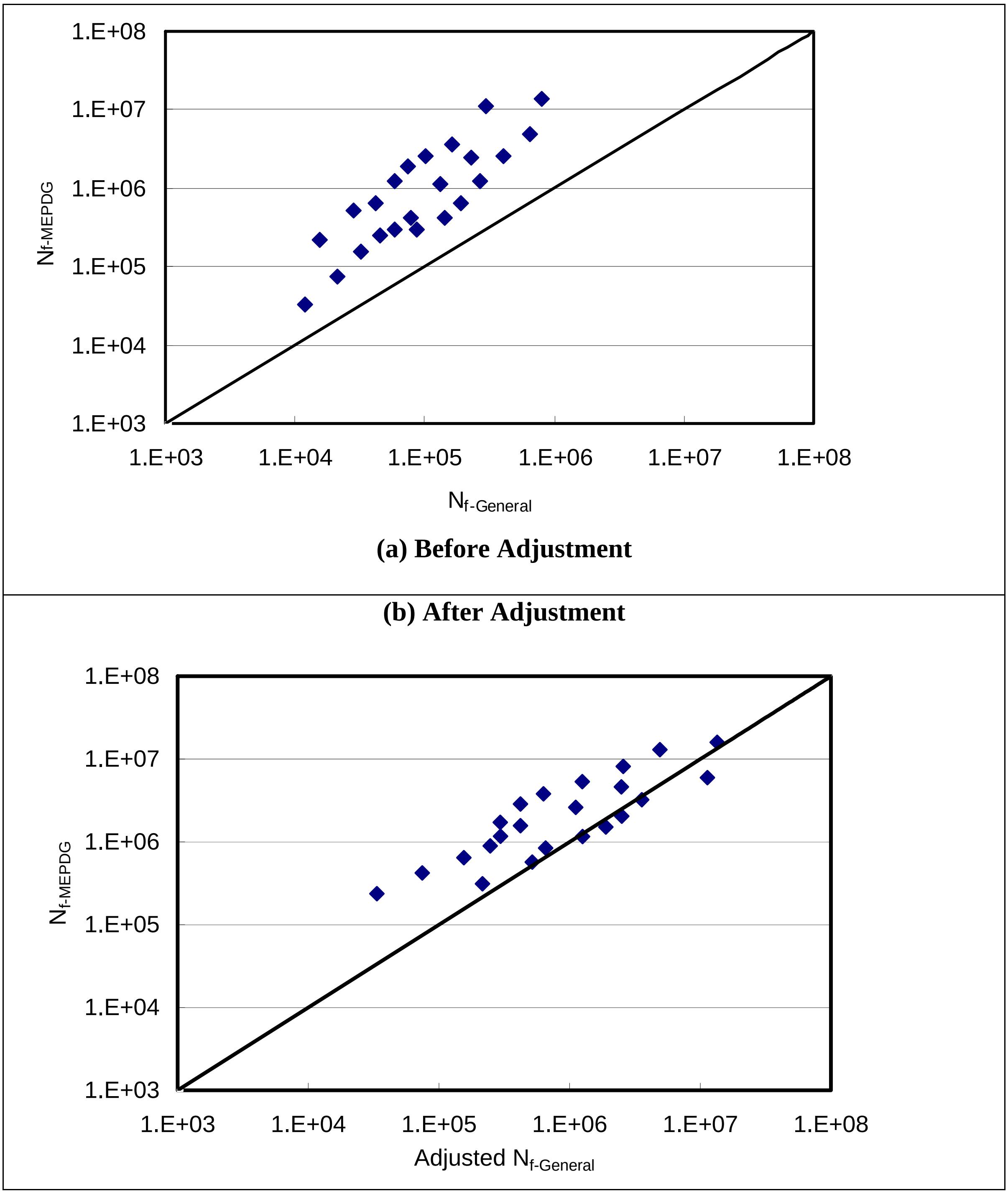


Figure 4: General Fatigue Model *vs.* MEPDG Model: Predicted Fatigue Life for 1-inch Asphalt Layer for Mixture No. 1 (Constant Strain Mode)

$N_{f\text{-MEPDG}}$ = Number of load applications predicted using the MEPDG fatigue model (Equation 2).
$N_{f\text{-General}}$ = Number of load applications to failure using the general fatigue model (Equation 1).

Table 4. Shift Factors between the General and the MEPDG Models for Different Thicknesses of Asphalt Layers

Asphalt Layer Thickness (in.)	Shift Factor		
	Constant Strain	Constant Stress	Controlling Shift Factor
1	20.1	88.2	20.1
2	17.4	76.6	17.4
3	4.7	20.6	4.7
4	2.1	9.2	9.2
5	2.0	8.8	8.8
6	2.0	8.8	8.8
8	2.0	8.8	8.8

Table 5. Example of Data of Mixture No. 1 and 1-inch Layer Thickness (Strain Control)

Beam No.	$N_{f\text{-General}}$ (Equation 1)	$N_{f\text{-MEPDG}}$ (Equation 2)	Shift Factor for Each Specimen	Adjusted $N_{f\text{-General}}$* (20.1* $N_{f\text{-General}}$)
B04	15,580	215,530	14	312665
B07	28,376	518,244	18	569464
B14	42,135	655,922	16	845568
B08	58,109	1,253,954	22	1166140
B16	75,145	1,894,143	25	1508019
B09	101,861	2,510,949	25	2044176
B23	160,867	3,561,609	22	3228312
B11	297,324	11,328,759	38	5966780
B25	11,848	33,549	3	237772
B30	21,063	74,539	4	422688
B27	32,206	154,868	5	646310
B28	44,727	246,525	6	897595
B32	58,363	296,145	5	1171249
B29	78,057	420,948	5	1566474
B31	130,451	1,113,799	9	2617915
B33	230,553	2,483,296	11	4626789
B34	791,585	13,475,777	17	15885710
B48	85,901	294,997	3	1723875
B49	142,408	421,253	3	2857871
B38	189,486	630,625	3	3802643
B47	265,938	1,251,759	5	5336907
B45	407,072	2,567,319	6	8169224
B41	645,277	4,901,476	8	12949572

* Note: The shift factor for all mixes and 1-inch layer is 20.1, which is the average of the shift factors of all 6 mixes.

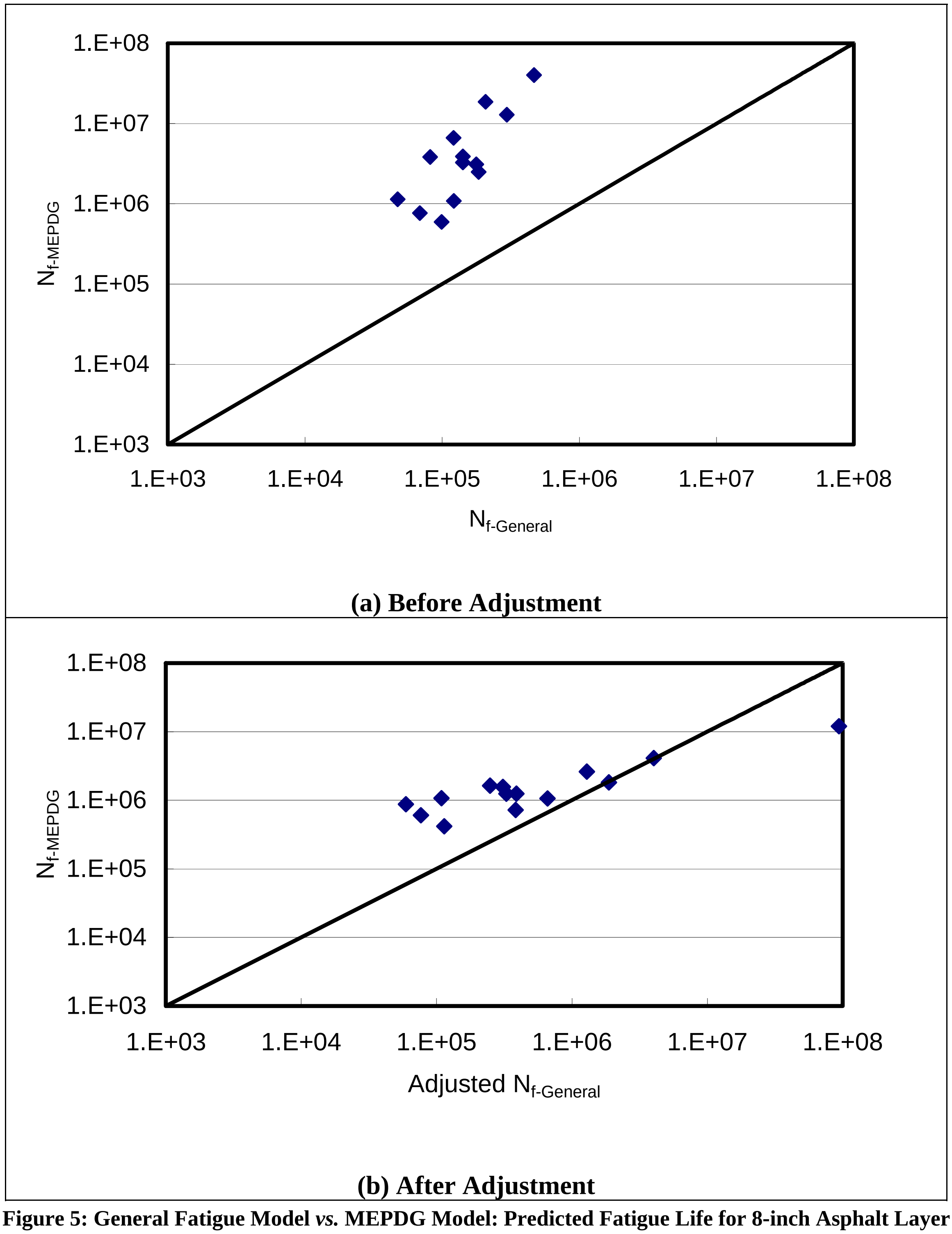
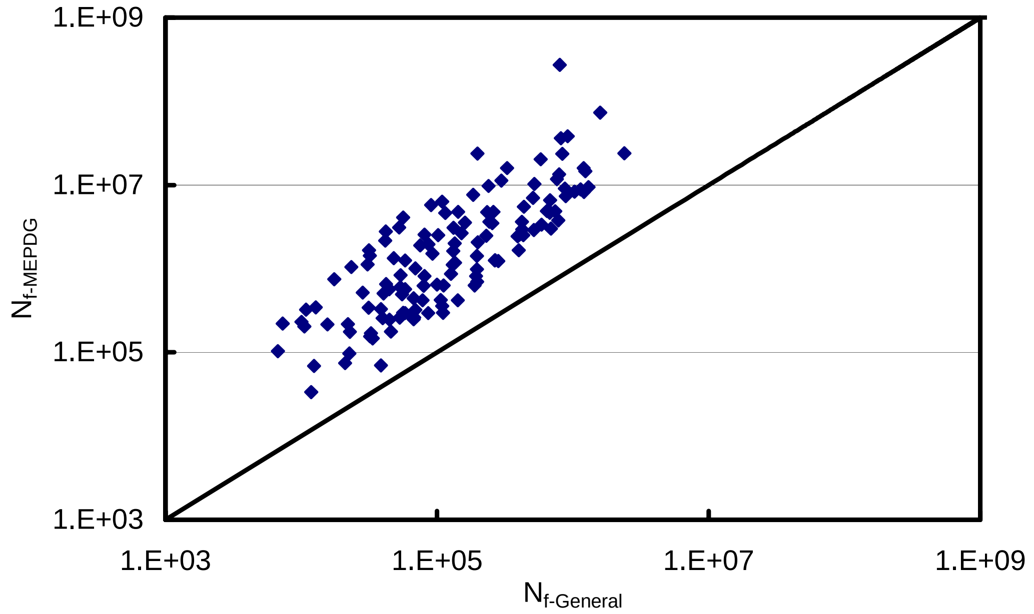
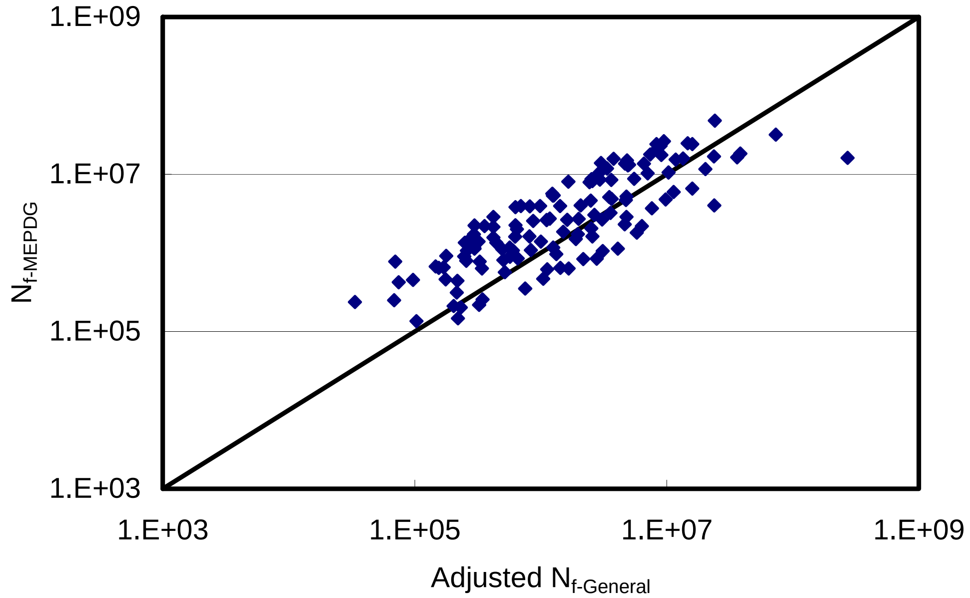


Figure 5: General Fatigue Model *vs.* MEPDG Model: Predicted Fatigue Life for 8-inch Asphalt Layer for Mixture No. 1 (Constant Stress Mode)

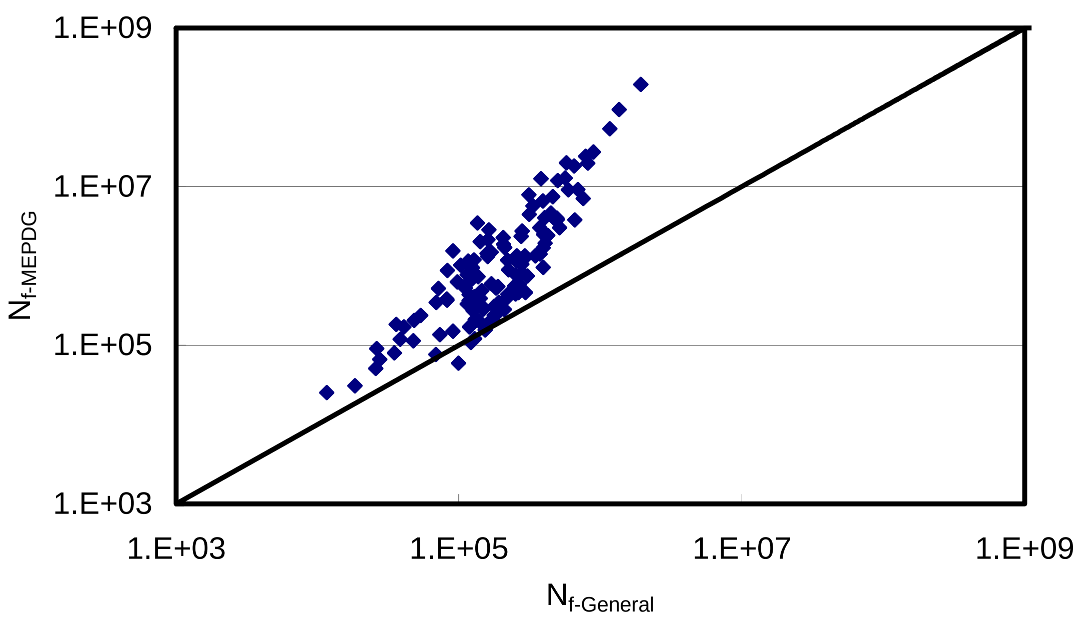


(a) Before Adjustment

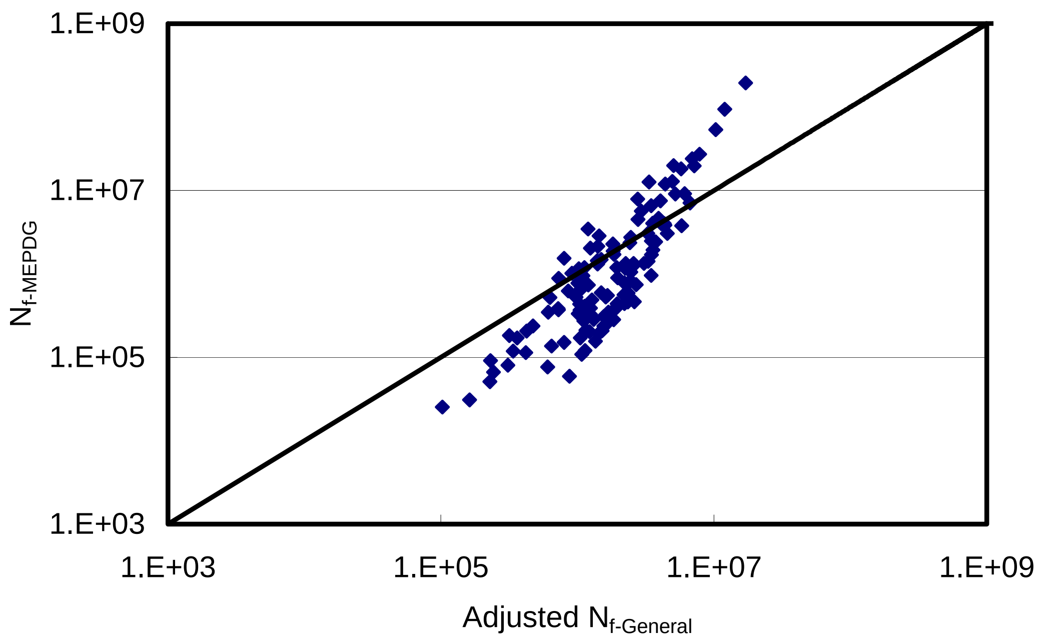


(b) After Adjustment

Figure 6: General Fatigue Model *vs.* MEPDG Model: Predicted Fatigue Life for 1-inch Asphalt Layer for all Mixtures (Constant Strain Mode)



(a) Before Adjustment



(b) After Adjustment

Figure 7: General Fatigue Model *vs.* MEPDG Model: Predicted Fatigue Life for 8-inch Asphalt Layer for all Mixtures (Constant Stress Mode)

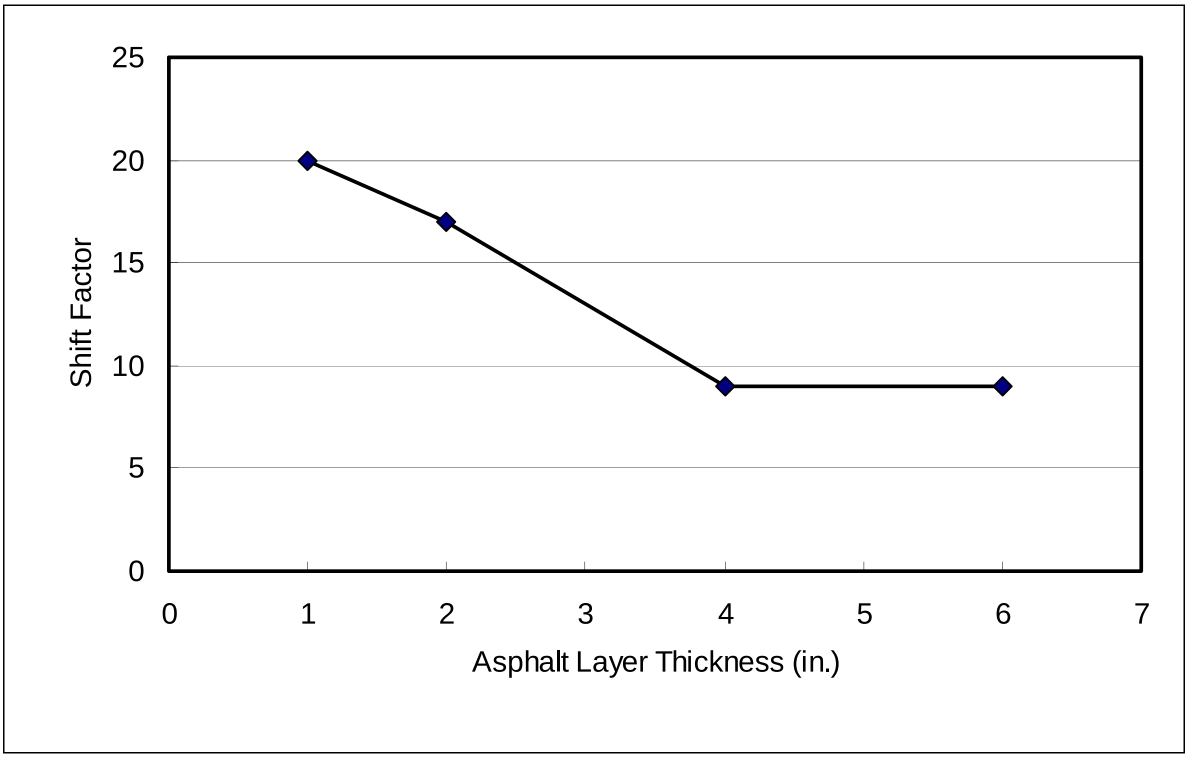


Figure 8: Shift Factors for Different Asphalt Layer Thicknesses

REFERENCES

AASHTO TP8-94. 2002. Method for Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending, AASHTO Provisional Standards.

Abojaradeh, M. 2003. Predictive Fatigue Models for Arizona Asphalt Concrete Mixtures, A Dissertation Presented at Arizona State University, December.

Al-Khateeb, G. and Shenoy, A. 2004. A Distinctive Fatigue Failure Criterion, *Journal of the Association of Asphalt Paving Technologists*, 73: 585-622.

Al-Khateeb, G. and Shenoy, A. 2011. A Simple Quantitative Method for Identification of Failure Due To Fatigue Damage, *International Journal of Damage Mechanics*, 20 (January): 3-21.

Al-Balbissi, A. H. and Little, D. N. 1990. Effect of Fracture Healing on Laboratory to Field Shift Factor, *Journal of the Transportation Research Board (TRB)*, Transportation Research Record No. 1286, National Research Council, Washington, D. C., USA, 173-183.

El-Basyouny, M. and Witczak, M. 2005. Calibration of the Alligator Fatigue Cracking Model for the 2002 Design Guide, Presented in the 84^{th}.*Annual Meeting of the Transportation Research Board*, Washington, DC.

Federal Highway Administration. 2000. LTPP DataPave. Washington D.C.

Ghuzlan, K. A. and Carpenter, S. H. 2000. Energy-Derived, Damage-Based Failure Criterion for Fatigue Testing, *Journal of the Transportation Research Board (TRB)*, Transportation Research Record No. 1723, National Research Council, Washington, D. C., USA, 141-149.

Hopman, P. C., Kunst, P. A. J. C. and Pronk, A. C. 1989. A Renewed Interpretation Method for Fatigue Measurements, Verification of Miner's Rule, 4^{th} *Eurobitume Symposium in Madrid*, 1: 557-561.

Kim, Y. R., Lee, H. J. and Little, D. N. 1997. Fatigue

Characterization of Asphalt Concrete Using Viscoelasticity and Continuum Damage Theory, *Journal of the Association of Asphalt Paving Technologists*, 66: 520-569.

Lee, H. J., Daniel, J. S. and Kim, Y. R. 2000. Continuum Damage Mechanics-Based Fatigue Model of Asphalt Concrete, *Journal of Materials in Civil Engineering*, 12 (2): 105-112.

Lundstrom, R. and Isacsson, U. 2003. Asphalt Fatigue Modeling Using Viscoelastic Continuum Damage Theory, *Road Materials and Pavement Design*, 4 (1): 51-75.

Mahoney, J. P. and Pierce, L.M. 1996. Examination of Washington State Department of Transportation Transfer Functions for Mechanistic-Empirical Asphalt Concrete Overlay Design, *Journal of the Transportation Research Board (TRB),* Transportation Research Record No. 1539, National Research Council, Washington, D. C., USA.

National Cooperative Highway Research Program Project 1-37A. 2003. 2002 Design Guide, Draft Final Report, NCHRP, Washington, DC, August, www.trb.org/ mepdg.

Pell, P. S. and Cooper, K. E. 1975. The Effect of Testing and Mix Variables on the Fatigue Performance of Bituminous Materials, *Journal of the Association of Asphalt Paving Technologists*, 44: 1-37.

Pronk, A. C. and Hopman, P. C. 1990. Energy Dissipation: The Leading Factor of Fatigue. Highway Research: Sharing the Benefits, *Proceedings of the Conference, the United States Strategic Highway Research Program*, London.

Rodrigues, R. M. 2000. A Model for Fatigue Cracking Prediction of Asphalt Pavements Based on Mixture Bonding Energy, *International Journal of Pavement Engineering*, 1 (2): 133-149.

Rowe, G. M. 1993. Performance of Asphalt Mixtures in the Trapezoidal Fatigue Test, *Journal of the Association of Asphalt Paving Technologists*, 62: 344-384.

Rowe, G. M. and Bouldin, M. G. 2000. Improved Techniques to Evaluate the Fatigue Resistance of Asphaltic Mixtures, *Proceedings of* 2nd *Eurasphalt and Eurobitume Congress*, Barcelona, Spain.

SHRP-A-404 Report. 1994. Fatigue Response of Asphalt-Aggregate Mixes, Strategic Highway Research Program, National Research Council, Washington D. C., USA.

Tayebali, A. A., Rowe, G. M. and Sousa, J. B. 1992. Fatigue Response of Asphalt-Aggregate Mixtures, *Journal of the Association of Asphalt Paving Technologists*, 61: 333-360.

Tayebali, A. A., Deacon, J. A., Coplantz, J. S. and Monismith, C. L. 1993. Modeling Fatigue Response of Asphalt-Aggregate Mixes, *Journal of the Association of Asphalt Paving Technologists*, 62: 385-421.

Tseng, K. H. and Lytton, R. L. 1990. Fatigue Damage Properties of Asphaltic Concrete Pavements, *Journal of the Transportation Research Board (TRB),* Transportation Research Record No. 1286, National Research Council, Washington, D. C., USA.

Van Dijk, W. 1975. Practical Fatigue Characterization of Bituminous Mixes, *Journal of the Association of Asphalt Paving Technologists*, 44: 38-72.

Van Dijk, W. and Visser, W. 1977. The Energy Approach to Fatigue for Pavement Design, *Journal of the Association of Asphalt Paving Technologists*, 46: 1-37.

Witczak, M., Mamlouk, M. and Abojaradeh, M. 2001. Flexural Fatigue Tests. Subtask F6 Evaluation Tests, Project NCHRP 9-19, Task F, Advanced Mixture Characterization, NCHRP, July.

Zhang, T. and Raad, L. 1999. Numerical Methodology in Fatigue Analysis: Basic Formulation, *Journal of Transportation Engineering*, 125 (6): 552-559.

Zhang, T. and Raad, L. 2001. Numerical Methodology in Fatigue Analysis: Applications, *Journal of Transportation Engineering*, 127 (1): 59-66.