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Asphalt Pavement Fatigue Cracking Prediction Model with Mode Factor

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Abstract: A sigmoidal transfer function with Mode Factor (MF) was developed to consider the fatigue life transition from constant strain mode to constant stress, or intermediate mode. The transfer function was combined with a laboratory fatigue prediction model which was developed under 618 constant strain four point bending fatigue tests to form a new asphalt pavement fatigue cracking prediction model. Subsequently, the model was calibrated with 26 full-scale accelerated and real pavement test sections. The calibration results indicate that the proposed model has achieved better prediction than the Asphalt Institute (AI) MS-1 fatigue prediction model in the most common region for the real pavement design life. This model can be an option for Mechanistic-Empirical pavement design and further refined upon verification.

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Key words: *Asphalt pavement; Fatigue cracking; Loading mode; Mode factor; Prediction model.*

Introduction

Fatigue cracking is one of the major modes of distress considered in pavement design. Proper design of asphalt concrete pavements requires that the thickness of the structure and its components be sufficient to insure that repeated deflections of a transient nature will not cause fatigue cracking of the asphalt course. Since Hveem's investigation in 1955 [1], the fatigue distress of asphalt pavement has assumed great significance, and many agencies have focused considerable attention on this problem not only through field studies but also through laboratory studies.

Past studies have shown damaging fatigue loading gradually alters the strength and stiffness properties of asphalt layers. This phenomenon requires consideration of the manner in which stress and strain levels are permitted to vary during fatigue loading, that is, the mode of loading. The infinite spectrum of possible modes of loading is bounded by two well-defined test methods, namely, constant stress testing and constant strain testing, which are generally applied for laboratory asphalt mixture fatigue characterization. The constant stress type of loading is generally considered applicable to thick asphalt pavement layers, usually thicker than 200 mm, while the constant strain type of loading is considered more applicable to thin asphalt pavement layers, usually thinner than 50 mm.

In the early 1960s, Monismith et al. [2] and Pell [3] established the relationships between Hot Mixed Asphalt (HMA) fatigue life and horizontal tensile strain or tensile stress at the bottom asphalt layer by using the basic forms shown in Eqs. (1) and (2).

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

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

where N_f is the number of repetitions to failure, ε_t is the magnitude of the tensile strain repeatedly applied, σ_t is the magnitude of the tensile stress repeatedly applied, and k_1, k_2, k_3, and k_4 are the experimentally determined coefficients.

Eq. (1) was expanded in 1969 by Monismith and Epps [4] to include HMA stiffness to account for varying temperature, loading frequency, and mix type. The formulation is shown in Eq. (3) which becomes a basic structure for almost every fatigue model developed and presented in the literature for asphalt mixture fatigue characterization.

$$N_f = k_1\left(\frac{1}{\varepsilon_t}\right)^{k_2}\left(\frac{1}{S_m}\right)^{k_3} \tag{3}$$

where S_m is the stiffness modulus of asphalt mixture, and k_1, k_2, and k_3 are the experimentally determined coefficients.

Because of the known impact between stress states and damage mechanism for different thicknesses of asphalt layers, Bonnaure et al. [5] developed fatigue damage prediction equations for the two major forms of laboratory fatigue testing in 1980. The constant strain and constant stress equations developed are shown in Eqs. (4) and (5), respectively.

$$N_f = A_f\left(0.17PI - 0.0085PI \cdot V_b + 0.0454V_b - 0.112\right)^5 \varepsilon_t^{-5} S_m^{-1.8} \tag{4}$$

$$N_f = A_f\begin{pmatrix} 0.0252PI - 0.00126PI \cdot V_b \\ +0.0067V_b - 0.0167 \end{pmatrix}^5 \varepsilon_t^{-5} S_m^{-1.4} \tag{5}$$

where PI is the penetration index of the binder in the mix, V_b is the volumetric bitumen content of the mix, and A_f is the laboratory to field adjustment factor.

In order to reduce the confusion of using different prediction models, a few previous efforts tried to establish a compatible prediction model that can combine the two loading modes and provide a reasonable transfer to represent the intermediate loading

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(a) James Cox & Sons (b) Cooper (c) IPC

Fig. 1. Four-point Bending Fatigue Test Apparatuses.

conditions. Witczak and Mirza [6] utilized a sigmoid function accounting for the layer thickness and stiffness to combine Eqs. (4) and (5) into a generalized fatigue cracking prediction model as shown in Eq. (6).

$$N_f = A_f\left(1+\frac{13909S_m^{-0.4}-1}{1+e^{(1.354h_{ac}-5.408)}}\right)\begin{pmatrix}0.0252PI-\\0.00126PI\cdot V_b\\+0.0067V_b-0.0167\end{pmatrix}^5 \varepsilon_t^{-5}S_m^{-1.4} \quad (6)$$

where h_{ac} is the thickness of the HMA layer.

The Asphalt Institute (AI) MS-1 fatigue prediction model shown in Eqs. (7) to (9) was re-calibrated by Witczack and El-Basyouny [7, 8] for the American Mechanistic-Empirical Pavement Design Guide (M-E PDG). Another sigmoid function was used to account for the effect of asphalt layer thickness to fatigue life. The modified fatigue cracking model is shown in Eqs. (10) and (11).

$$N_f = 18.4\times 0.00432\times C\left(\frac{1}{\varepsilon_t}\right)^{3.291}\left(\frac{1}{E}\right)^{0.854} \quad (7)$$

$$C = 10^M \quad (8)$$

$$M = 4.84\left(\frac{v_{be}}{v_{be}+v_a}-0.69\right) \quad (9)$$

where v_{be} is the effective binder content (%), v_a is the air void (%).

$$N_f = 0.00432\times K\times C\left(\frac{1}{\varepsilon_t}\right)^{3.9492}\left(\frac{1}{E}\right)^{1.281} \quad (10)$$

$$K = \frac{1}{0.000398+\dfrac{0.003602}{1+e^{(11.02-3.49h_{ac})}}} \quad (11)$$

In order to identify and describe modes of loading between constant strain and constant stress loading, Monismith and Deacon [9] developed an index named mode factor which is described in Eq. (12).

$$MF = \frac{|A|-|B|}{|A|+|B|} \quad (12)$$

where MF is mode factor, A is percentage change in stress due to a stiffness decrease of C, B is percentage change in strain due to a stiffness decrease of C, and C is an arbitrary but fixed percentage reduction in mixture stiffness. The mode factor of Eq. (12) assumes values of -1 for constant stress testing and +1 for constant strain testing. For intermediate modes, it lies between the limits of -1 and +1.

In this study, MF in Eq. (12) was used as an adjuster to develop a sigmoidal transfer function, considering the transition of the laboratory constant strain testing mode to the actual load mode of field pavement. Incorporated with a laboratory prediction model based on the constant strain four point bending tests, a new general field fatigue cracking prediction model was then provided. Subsequently, 17 full-scale accelerated pavement test sections (ALF, HVS, NCAT, WesTrack) and 9 in-service pavement test sections (MnROAD) were selected to calibrate the field fatigue cracking prediction model.

Development of Fatigue Cracking Prediction Model

Laboratory Fatigue Test Method

A reliable laboratory fatigue test method for asphalt mixture is the foundation for establishing a field fatigue cracking model for asphalt pavement. In 1993, the American Strategic Highway Research Program (SHRP) recommended the four-point bending beam fatigue test to estimate the fatigue cracking of asphalt mixture [10]; since then, it has become a standard test adopted into the specification of the American Association of State Highway and Transportation Officials (AASHTO) [11]. It has advantages such as high sensitivity to mixture variables, a larger portion of the specimen is subjected to a uniform maximum stress level, and similar bending behavior to real pavement deformation, etc. Four-point bending beam fatigue has been used by various researchers to evaluate the fatigue performance of pavements and has become a popular world-wide fatigue test for asphalt mixtures. Due to reasons discussed above, a new laboratory fatigue prediction

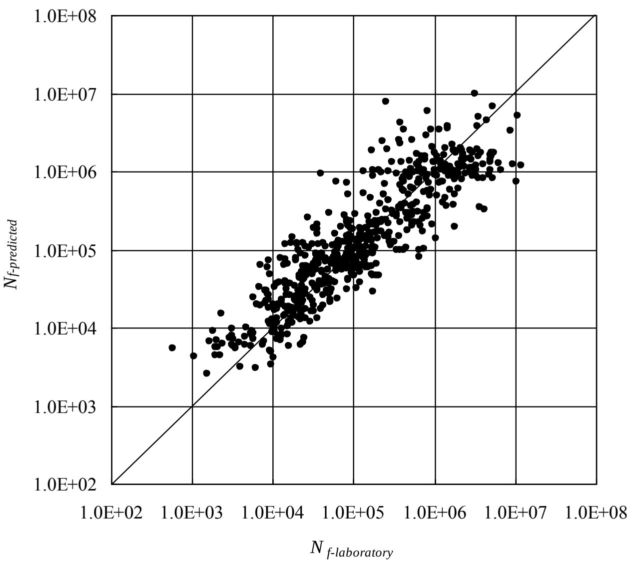

Fig. 2. Predicted Fatigue Lives by Eq. (14) vs. Laboratory Fatigue Lives.

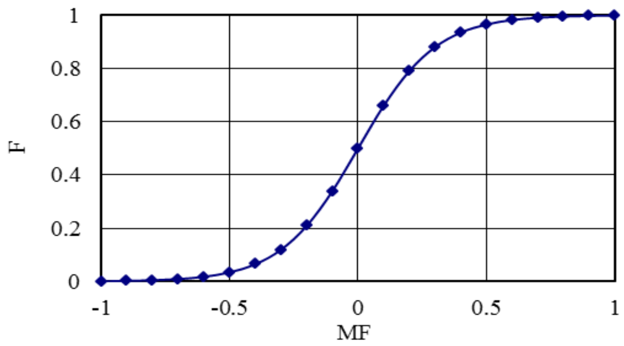

Fig. 3. Sigmoidal Relationship between *F* and *MF*.

model under constant strain loading mode was developed by analyzing four-point bending fatigue test results.

Fig. 1 shows the main four-point bending fatigue test devices provided by James Cox & Sons, Cooper Research Technology, and Industrial Process Controls (IPC), respectively. Yu [12] evaluated the compatibility of these three types of bending devices under constant strain test mode and found no apparent difference of the fatigue test results. Way et al. [13] compared the different four-point bending equipment models (made by IPC and James Cox & Sons), and found that, although the equipment is made by different manufacturers and samples were transported over the ocean, the test results appear reasonably close.

Laboratory Fatigue Prediction Model

The fatigue test data used to develop the laboratory model were collected from two different types of four-point bending beam fatigue test apparatuses among the above mentioned. One was Cooper used by South China University of Technology (SCUT), and the other was James Cox & Sons used by the University of California Pavement Research Center (UCPRC). There were 188 fatigue tests from SCUT [14] and 430 tests from UCPRC [10, 15-16], with a total of 618 tests collected to develop the laboratory constant strain fatigue prediction model.

Volumetric properties of mixture were found to be essential for fatigue performance of asphalt mixture [10, 14-15, 17]. Hence, the index of voids filled with asphalt (VFA) was considered to be added in Eq. (3) as an independent variable to create a new structure which is shown in Eq. (13).

$$N_f = k_1 \left(\frac{1}{\varepsilon_t}\right)^{k_2} \left(\frac{1}{S_m}\right)^{k_3} (VFA)^{k_4} \tag{13}$$

where *VFA* is voids filled with asphalt, k_1, k_2, k_3, and k_4 are the experimentally determined coefficients.

Through the general regression process for the 618 laboratory constant strain four-point bending fatigue tests, the value of k_1, k_2, and k_3 were determined, which are shown in Eq. (14) (R^2 = 0.71). The relationship between the predicted fatigue lives using the Eq. (14) versus laboratory measured fatigue lives is shown in Fig. 2.

$$N_{f\varepsilon} = 1.509 \times 10^{16} \left(\frac{1}{\varepsilon_t}\right)^{3.973} \left(\frac{1}{S_0}\right)^{1.589} (VFA)^{2.720} \tag{14}$$

where $N_{f\varepsilon}$ is the laboratory fatigue life under constant strain mode, ε_t is the magnitude of the tensile strain repeatedly applied (10^{-6} mm/mm), S_0 is the initial flexural stiffness (MPa), and *VFA* is voids filled with asphalt (%).

Development of transfer function

In order to have a continuous transition between constant strain and stress conditions, it was assumed that a sigmoidal relationship would be applicable [6, 18]. A sigmoidal transfer factor *F* with *MF* shown in Eq. (15) was created. In Eq. (15), when *MF* equals to +1, the value of *F* is close to 1, which means there should be no reduction when the pavement is under constant strain loading mode; when *MF* does not equal to +1 ($-1 \leq MF < 1$), the value of *F* is less than 1, which means there has been reduction when the pavement is under intermediate loading mode and constant stress. An approximate relationship between *F* and *MF* is illustrated in Fig. 3.

$$F = \frac{1}{1 + e^{k \cdot MF}} \tag{15}$$

where *F* is transfer factor based on constant strain mode, *k* is a coefficient under calibration.

Subsequently, a field fatigue cracking prediction model can be structured by combining Eq. (14) and Eq. (15), which is shown in Eq. (16).

$$N_f = k_1 k_2 \left(\frac{1}{1 + e^{k_3 \cdot MF}}\right) \left[1.509 \times 10^{16} \left(\frac{1}{\varepsilon_t}\right)^{3.973} \left(\frac{1}{S_0}\right)^{1.589} (VFA)^{2.720}\right] \tag{16}$$

where, N_f is field fatigue life, k_1 is laboratory to field adjustment factor, k_2 is coefficient of wheel tracking transverse distribution (if no traffic wander is applied), k_3 is adjustment factor for MF.

Field Fatigue Data Collection

In Eq. (16), the value of 2.03 was determined for k_2 by Chen in the earlier study [19], but conducted Accelerated Loading Facility (ALF) test sections did not apply the traffic wander, therefore, the fatigue lives of ALF sections were multiplied by 2.03. Factors k_1 and k_3 are the ones needed to be calibrated by the field fatigue data. There were 26 test sections from 5 different projects that were selected for model calibration. The projects selected include: University of California Pavement Research Center (UCPRC) Heavy Vehicle Simulator (HVS) test sections; Bejing National Highway Test Center Accelerated Loading Facility (ALF) test sections, WesTrack [20-21], Minnesota Road Research Project (MnROAD), and National Center for Asphalt Technology (NCAT) test track [22-24]. Table 1 shows the features and properties of the different projects.

The following rules and standards were determined or assumed during the data processing:

1) Fatigue failure criteria for HVS and ALF is cracking density of 1.0 m/m^2; for WesTrack, MnROAD, and the NCAT test track, it is 10 percent of the wheelpath cracking. According UCPRC's study, the two criteria were assumed to have good consistency; both criteria are at a relatively lower, but measureable, fatigue distress level.
2) In order to keep the traffic loads consistent, the axle loads of 120 kN and 160 kN were selected for counting the fatigue life of HVS and ALF test sections, respectively. The track loads on WesTrack, NCAT, and MnRoad test sections were converted into ESALs of 80 kN for counting the fatigue life.
3) The Falling Weight Deflector (FWD) backcalculated asphalt layer moduli were corrected to the moduli at the reference

Table 1. Features and Properties of the Projects Used for Model Calibration.

Project Name	Section Type	Section Length, m	Traffic Type	Axle Load, kN	Traffic Wander Applied	Reference Temperature,℃
HVS	Full Scale	8	Dual-wheel Tire	120	Yes	20
ALF	Full Scale	8	Dual-wheel Tire	160	No	21.8
WesTrack	Full Scale	70	3-trailer Truck	80	Yes	15.4
MnRoad	Real Pavement	150	Real Traffic	80	Yes	11.0
NCAT	Full Scale	61	3-trailer Truck and Box Trailer	80	Yes	20.0

Table 2. Summarized Data for Fatigue Prediction Model Calibration.

No.	Section	ε_t ($\times 10^{-6}$)	S_0 (MPa)	VFA (%)	h_{ac} (cm)	MF	$N_{f\text{-}field}$ (10^6)	$N_{f\text{-}predicted}$ (10^6) Equation 18	Original AI MS-1	Calibrated AI MS-1
1	A1	265	5111	57.6	10.0	-0.014	0.81	0.43	0.12	0.09
2	A2	202	4933	56.3	15.0	-0.235	0.85	0.87	0.25	0.19
3	H 567	192	7239	55.2	8.0	-0.733	0.05	0.17	0.21	0.15
4	H 568	192	7239	59.2	8.1	-0.660	0.20	0.25	0.32	0.24
5	H 571	199	7239	52.2	7.8	-0.995	0.06	0.06	0.13	0.10
6	H 573	212	7239	60.3	8.0	-0.868	0.54	0.10	0.27	0.20
7	WT 2	120	6215	60.0	16.4	-0.307	3.57	4.90	2.73	2.04
8	WT 3	146	4637	56.6	16.8	-0.292	3.15	3.15	1.21	0.90
9	WT 5	112	5918	62.7	16.9	-0.275	1.76	8.26	4.53	3.39
10	WT 6	141	5319	58.7	17.4	-0.435	1.67	2.34	1.65	1.24
11	WT 8	155	4811	62.5	17.1	-0.414	1.52	2.36	1.99	1.49
12	WT 10	164	3889	69.4	16.0	-0.176	1.77	5.68	3.68	2.76
13	WT 16	138	5470	59.6	16.4	-0.382	4.15	2.88	1.86	1.39
14	WT 26	139	5076	61.8	18.2	-0.458	1.46	2.92	2.58	1.93
15	MR 1	199	4380	71.7	15.0	-0.523	6.83	1.16	2.82	2.11
16	MR 2	190	4369	73.3	15.5	-0.535	7.82	1.44	3.95	2.96
17	MR 3	184	4174	72.1	16.0	-0.499	6.85	1.83	3.91	2.93
18	MR 4	98	4608	69.5	23.1	-0.757	9.07	9.07	23.40	17.52
19	MR 14	79	4284	75.0	27.7	-0.666	11.10	37.25	96.30	72.11
20	MR 16	97	5843	70.5	20.3	-0.597	10.90	9.93	21.40	16.01
21	MR 17	103	5682	74.8	20.1	-0.616	10.80	9.35	29.70	22.25
22	MR 18	107	5888	77.4	20.1	-0.666	10.90	7.23	34.60	25.93
23	MR 19	101	5907	78.4	19.8	-0.614	11.00	10.85	45.90	34.39
24	N 1	180	5348	61.8	12.8	-0.338	1.60	1.26	0.99	0.74
25	N 2	149	7150	65.1	12.7	-0.398	2.50	1.71	2.18	1.63
26	N 8	116	5517	62.8	18.2	-0.491	3.40	5.09	4.97	3.73
				$\bar{\delta}$				0.194	0.255	0.248

NOTE. – A = ALF, H = HVS, WT = WesTrack, MR = MnRoad, and N = NCAT.

temperature (Table 1). These asphalt layer moduli were then used as input factors for strain calculation and fatigue life prediction. Moreover, in order to keep the consistency of moduli for each layer, the average values of FWD backcalculated dynamic moduli for the base and subgrade of the test sections were also used for strain calculation.

4) The multi-layer linear elastic program BISAR 3.0 was used for the mechanistic analysis and strain stress calculations. During the MF calculation, a 50% reduction in stiffness of asphalt layer and no reduction in stiffness of aggregate layer were assumed at the fatigue failure point. The strains and stresses of original and failure point situations were calculated; subsequently, the MF values were obtained by Eq. (12).

The summarized factors and values used for the fatigue prediction model calibration are shown in Table 2.

Calibration and Optimization of Model Factors

The optimization method was used for model calibration. In order to get the minimum value of $\bar{\delta}$, which was an error index defined to evaluate the accuracy of the predicted result. Eq. (17) shows the structure of $\bar{\delta}$; the smaller value of $\bar{\delta}$ represents the higher accuracy of the prediction model.

$$\bar{\delta} = \sum_{i=1}^{n} \delta_i = \frac{\sum_{i=1}^{n} \left| \log\left(N_{f-predicted}\right)_i - \log\left(N_{f-field}\right)_i \right|}{\sqrt{2}n} \quad (17)$$

where $\bar{\delta}$ is the error index; $N_{f\text{-}predicted}$ is the predicted fatigue life; $N_{f\text{-}field}$ is the real field fatigue life; n is the number of test sections (default n =26).

A minimum $\bar{\delta}$ value of 0.194 was obtained with the corresponding calibrated values of k_1 = 3.165 and k_3 = -2.911. The final form of the calibrated fatigue cracking prediction model is shown in Eq. (18).

The value of the calibrated laboratory to field adjustment factor k_1 is 3.165, which implies that if a constant strain deterioration mode is followed, the field fatigue life is about 3 times of the laboratory four-point bending fatigue life under constant strain test mode. A k_3 value of -2.911 determined for transfer factor F implies that the field fatigue life under constant strain deterioration mode will be approximately 18 times of the fatigue life under constant stress deterioration mode if the other parameters keep the same.

$$N_f = 4.775 \times 10^{16} \left(\frac{1}{1+e^{-2.911MF}} \right) \left(\frac{1}{\varepsilon_t} \right)^{3.973} \left(\frac{1}{s_0} \right)^{1.589} (VFA)^{2.720} \quad (18)$$

The fatigue lives predicted for each section by Eq. (18) are listed in Table 2. The AI MS-1 model was selected as a comparison. The fatigue prediction model of American MEPDG under evaluation considers failure at 50 percent cracking of the total lane area, which might lead to a much longer field fatigue life than Eq. (18), which uses 10 percent wheelpath cracking. Since there is no relationship established between these two failure criteria, Eqs. (10) to (11) were not selected due to the different fatigue failure criteria. An additional supporting point for using cracking initiation failure

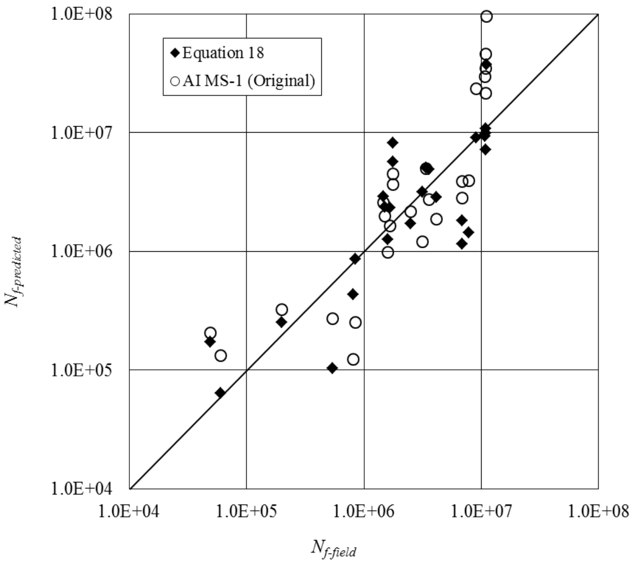

Fig. 4. Predicted Fatigue Lives by Eq. (18) and AI MS-1 (Original) vs. Field Fatigue Lives.

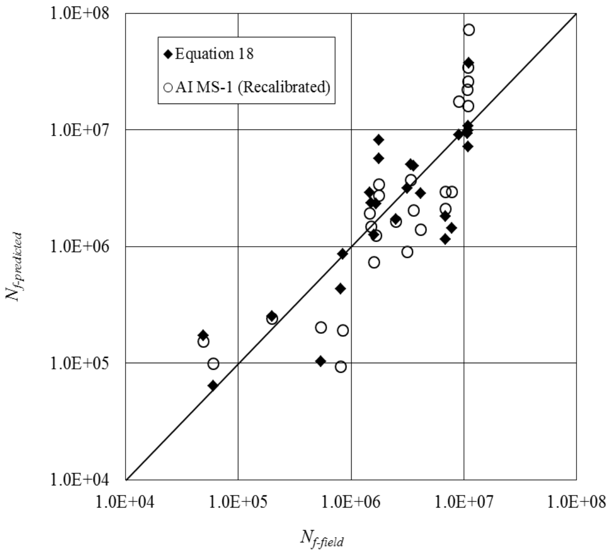

Fig. 5. Predicted Fatigue Lives by Eq. (18) and AI MS-1 (Calibrated) vs. Field Fatigue Lives.

criteria as 10 percent wheelpath cracking is that the fatigue failure can be confirmed earlier in order to keep a higher salvage value for the pavement, resulting in a cost-effective maintenance scheme that can be applied as early as possible.

A new field calibration factor with the value of 10.0 can be obtained if the new test sections were used to recalibrate the AI MS-1 model. The new field calibration factor is slightly smaller than the value of 13.3 corresponding to the failure criteria of 10 percent of wheelpath fatigue cracking. It can be understood that the fatigue life might be slightly over-predicted if the original AI MS-1 model is used. The fatigue lives predicted by the original and recalibrated AI MS-1 are both listed in Table 2. The minimum $\bar{\delta}$ value of 0.255 and 0.248 were obtained for the original and recalibrated AI MS-1 models, respectively. Based on the comparison of $\bar{\delta}$ values, obviously, Eq. (18) has higher accuracy than AI MS-1 models.

The comparison between the Eq. (18), original AI MS-1, and recalibrated AI MS-1 model are shown in Figs. 4 and 5.

From Figs. 4 and 5, the following findings can be concluded: for the field fatigue lives less than 10.0 million, Eq. (18) and the two AI MS-1 models possess a similar accuracy; for the field fatigue lives close to 10.0 million ESALs, which is close to the common region for the real pavement design life, Equation 18 has lower error than the original AI MS-1 model and the recalibrated one, thus showing better prediction accuracy in this region.

Conclusions

The following conclusions can be obtained from this study.

1) For the field fatigue lives less than 10.0 million, Eq. (18) and the two AI MS-1 models reach a consensus on prediction; for the field fatigue lives longer than or close to 10.0 million ESALs, which is the most common region for the real pavement design life, Eq. (18) provides a better prediction than the original and the newly calibrated AI MS-1 models.
2) The recalibration of the field calibration factor for the original AI MS-1 model using the 26 full-scale accelerated and real pavement test results provides a slightly smaller value of 10.0 when compared with the value of 13.3 corresponding to the failure criterion of 10 percent wheelpath fatigue cracking, which can lead to the conclusion of over-predicted fatigue life if the original AI MS-1 model is used.
3) The value of the calibrated laboratory to field adjustment factor k_1 is 3.165, which implies that if a failure criterion of 10 percent wheel path fatigue cracking is defined and a constant strain deterioration mode is followed, the field fatigue life is about three times that of the laboratory four-point bending fatigue life under constant strain test mode.
4) A k_3 value of -2.911 determined for transfer factor F indicates that the field fatigue life under constant strain deterioration mode will be approximately 18 times of the fatigue life under constant stress deterioration mode if the other parameters remain the same.
5) The results of parameter calibration of the proposed model are subject to a sampling error that decreases with increasing sample size. To issue the "exact" results of the proposed model, additional field data may be further collected and evaluated.

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