MEPDG Guidelines for Implementation of FORTA Fiber-Reinforced Mixtures

Prepared by

Waleed Zeiada, Ph.D.
Postdoctoral Scholar

B. Shane Underwood, Ph.D.
Assistant Professor

Kamil E. Kaloush, Ph.D., P.E.
Associate Professor

School of Sustainable Engineering and the Built Environment
Department of Civil, Environmental, and Sustainable Engineering
Arizona State University, Tempe, AZ 85287-5306

Submitted to

FORTA Corporation
100 Forta Drive
Grove City, PA 16127-9990

October, 2014

NATIONAL CENTER of EXCELLENCE for SMART INNOVATIONS
ARIZONA STATE UNIVERSITY

Table of Contents

1.1 Introduction 1
1.2 Objective 2
1.3 Material Inputs 2
1.4 Calibration of Bottom-up Fatigue Cracking Model 5
1.5 Calibration of Rutting Model 7

1. INTRODUCTION

The National Cooperative Highway Research Program (NCHRP) has developed a new pavement design and analysis tool, The Mechanistic-Empirical Design Guide (MEPDG) for New and Rehabilitated Pavement Structures, under NCHRP 1-37A. The NCHRP 1-37 product offers procedures for evaluating existing pavements and recommendations for rehabilitation treatments, drainage, and foundation improvements. The MEPDG is designed to update the 1993 AASHTO Guide for Design of Pavement Structures, which is primarily based on empirical observations from the AASHO Road Test that began in the 1950s. In conjunction with the MEPDG research project, software was also developed to assist in organizing and performing these design calculations. The MEPDG software is currently known as AASHTOWare Pavement ME. Under the MEPDG approach, the principles of engineering mechanics are used to compute the internal material behaviors in a pavement structure (i.e., deflections, stresses, and strains) as it is subjected to predicted future traffic loadings and environmental conditions (e.g., moisture and temperature). Those predicted material behaviors are then related to accumulated pavement damage through developed “transfer” functions, and then correlated with actual performance (distress) data.

The MEPDG requires an extensive number of inputs, although there is some flexibility in the level of precision that is used for the required traffic, materials, and environmental variables. Level 1 data offer the highest reliability, but require site-specific data such as laboratory testing on soils or construction materials. Level 2 data provide intermediate accuracy, but require less site-specific testing. At Level 2, inputs may be selected based on previous tests that have been conducted on similar types of materials or other forms of agency experience. At Level 3, agencies select default values that represent typical averages for the geographic region where the design project is located. For a given paving project, all inputs do not have to be at the same input level. That is, an agency may choose input levels depending on the availability of different types of data and the resources available to support the data-collection efforts.

For the initial development of the MEPDG models, the data was calibrated with pavement-performance data from the Federal Highway Administration’s (FHWA’s) Long-Term Pavement Performance (LTPP) program to develop the nationally calibrated performance models used in the MEPDG. Thus to provide a reasonable prediction of actual performance, it is necessary to calibrate these models for local highway agencies implementation taking into account local materials, traffic information, and environmental conditions. There are two different adjustments for the nationally calibrated performance models so it can be implemented by different states and agencies. The first adjustment is the local calibration/validation process which involves three important steps: verification, calibration, and validation. The term verification refers to assessing the accuracy of the nationally (globally) calibrated performance models for local conditions. The term calibration refers to the mathematical process through which the total error or difference between observed and predicted values of distress is minimized. The term validation refers to the process to confirm that the calibrated model can produce robust and accurate predictions for cases other than those used for model calibration. The second adjustment is the material calibration of the performance models by changing the models coefficient to match the performance of specific materials. These coefficients can be obtained for local or new materials through laboratory testing. Most of the LTPP data used on the national calibration of the performance models were collected from sections that include conventional Hot Mix Asphalt (HMA). However, the use of modified HMA is growing tremendously due to their enhanced performance against most of pavement distresses such as cracking and rutting. The currently used modified HMA includes rubber-modified mixture, polymer-modified, poly phosphoric acid-modified, sulfur-modified, and fiber-reinforced mixtures. The laboratory performance of each of these mixtures is unique and quiet different compared to the conventional mixtures. Therefore, the implementation of any of these materials in the MEPDG would requires the use of the laboratory test results to adjust the performance model coefficients according to their performance.

FORTA fibers are a performance enhancing technology that has been used to improve the resistance of asphalt concrete materials to permanent deformation and cracking not by only modifying the material strength but also by modifying the material behavior in resisting pavement distresses. The technological capabilities of these fibers have been demonstrated in multiple laboratory and field studies over the years. For a proper design and analysis of fiber-reinforced pavements using the MEPDG analysis, it is essential for agencies to input the fiber-reinforced asphalt concrete properties and to modify the performance models to fit its laboratory performance.

2. Objective

The main objective of this report is to provide guidelines on how to calibrate the MEPDG for the implementation of FORTA fiber-reinforced asphalt mixture. The guidelines include a description to help preparing the material inputs and calibrating the performance models for mainly bottom-up fatigue cracking and rutting.

3. Material Inputs

The most important input material properties of asphalt concrete mixture required in the MEPDG software is the dynamic modulus |*E**|, which determines to a great level the material response to traffic loading and environmental effects. **The available |E*| test results of FORTA fiber-reinforced asphalt mixtures from four different national and international projects showed that the 1 lb/ton fiber reinforced asphalt mixture has 30% higher |E*| values than the control asphalt mixtures**. Depending on the availability of |*E**| data, one of the following three option are followed to input |*E**| for fiber-reinforced asphalt mixture. For the three options, level 1 input is used.

- Option 1: if |*E**| test was performed on fiber-reinforced asphalt mixture, input |*E**| values directly in the MEPDG.
- Option 2: if |*E**| test was performed on conventional asphalt mixture and no results are available for the fiber-reinforced mixture, determine the fiber-reinforced |*E**| values by increasing those of the conventional asphalt mixture by 30% at all test temperatures and frequencies.
- Option 3: if the |*E**| test was not performed on neither conventional nor fiber-reinforced asphalt mixtures, predict the |*E**| values for the conventional asphalt mixture using Witczak's predictive model as shown in Equation (1) and then determine the fiber-reinforced |*E**| values by increasing those of the conventional asphalt mixture by 30% at all test temperatures and frequencies.

$$\log|E^*| = -1.249937 + 0.02923\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 - 0.058097V_a$$
$$-0.82208\frac{V_{beff}}{V_{beff}+V_a} + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{3/8} - 0.000017(\rho_{3/8})^2 + 0.00547\rho_{3/4}}{1+e^{(-0.603313-0.313351\log(f)-0.393532\log(\eta))}} \quad (1)$$

where:

$\lvert E^*\rvert$	= dynamic modulus in 10^5 psi,
η	= binder viscosity at the age and temperature of interest in 10^6 Poise,
f	= loading frequency in Hz,
V_a	= air void content in %,
V_{beff}	= effective binder content in % by volume,
$\rho_{3/4}$	= cumulative % retained on 19 mm sieve,
$\rho_{3/8}$	= cumulative % retained on 9.5 mm sieve,
ρ_4	= cumulative % retained on 4.76 mm sieve, and
ρ_{200}	= % passing 0.075 mm sieve.

The viscosity of the asphalt at |*E**| temperatures can be determined using conventional consistency tests (penetration, softening point, and rotational viscosity tests) across a wide range of temperatures. Most refined asphalt cements, with the exception of heavily air blown or high wax content crudes, exhibit a linear relationship when plotted on a log-log viscosity (centipoises, cP) versus log temperature (in degree Rankine: ºR = ºF + 459.7) scale. In order to make use of all consistency tests variables over a wide range of temperatures, it is necessary to convert all penetration (*pen* in 1/10 mm) and softening point measurements into viscosity units. Penetration data can be converted to viscosity units by the model shoed in Equation (2) developed at the University of Maryland as a part of a Strategic Highway Research Program (SHRP) study. Equation (2) is applicable over a very wide range of penetration from 3 to 300.

$$\log\eta = 10.5012 - 2.2601\times\log(pen) + 0.00389\times(\log(pen))^2 \quad (2)$$

The viscosity obtained from Equation (2) is in poise. The second consistency variable point defined by the softening point is converted to viscosity units by the approach suggested by Shell Oil researchers. It states that all asphalts at their softening point will yield a penetration of approximately 800 and a viscosity of 13,000 poises. The third group of viscosity values at high temperature was obtained by use of the Brookfield Viscometer. Using the above three methods, all penetration and softening point results can be shown or converted to viscosity units, which along with the Brookfield test results can then be used as direct viscosity measurements to obtain a viscosity (η) - temperature (T_R) relationship Equation (3):

$$\log\log\eta(centipoise) = A_i + VTS_i \times \log T_R \quad (3)$$

A_i and VTS_i represents regression coefficients or the intercept and the slope of the viscosity-temperature relationship. Once the regression coefficients are known, the asphalt viscosity can be determined at any specific temperature. If there are no viscosity test results and the asphalt performance grade is known, typical values of A_i and VTS_i can be used as shown in Table 1. Use the developed spread sheet to predict the |*E**| values for both conventional and fiber-reinforced asphalt mixtures using Witczak's predictive model. The |*E**| values were tabulated in the spreadsheet so that they can be copied and then directly pasted in the MEPDG software.

Table 1 Relationship between asphalt binder grade and viscosity parameters

Asphalt Binder Grade	*A*	*VTS*	Asphalt Binder Grade	*A*	*VTS*
PG 46-34	11.504	−3.9010	PG 70-28	9.715	−3.2170
PG 46-40	10.101	−3.3930	PG 70-34	8.965	−2.9480
PG 46-46	8.755	−2.9050	PG 70-40	8.129	−2.6480
PG 52-10	13.386	−4.5700	PG 76-10	10.059	−3.3310
PG 52-16	13.305	−4.5410	PG 76-16	10.015	−3.3150
PG 52-22	12.755	−4.3420	PG 76-22	9.715	−3.2080
PG 52-28	11.84	−4.0120	PG 76-28	9.2	−3.0240
PG 52-34	10.707	−3.6020	PG 76-34	8.532	−2.7850
PG 52-40	9.496	−3.1640	PG 82-10	9.514	−3.1280
PG 52-46	8.31	−2.7360	PG 82-16	9.475	−3.1140
PG 58-10	12.316	−4.1720	PG 82-22	9.209	−3.0190
PG 58-16	12.248	−4.1470	PG 82-28	8.75	−2.8560
PG 58-22	11.787	−3.9810	PG 82-34	8.151	−2.6420
PG 58-28	11.01	−3.7010	AC-2.5	11.5167	−3.8900
PG 58-34	10.035	−3.3500	AC-5	11.2614	−3.7914
PG 58-40	8.976	−2.9680	AC-10	11.0134	−3.6954
PG 64-10	11.432	−3.8420	AC-20	10.7709	−3.6017
PG 64-16	11.375	−3.8220	AC-3	10.6316	−3.5480
PG 64-22	10.98	−3.6800	AC-40	10.5338	−3.5104
PG 64-28	10.312	−3.4400	PEN 40-50	10.5254	−3.5047
PG 64-34	9.461	−3.1340	PEN 60-70	10.6508	−3.5537
PG 64-40	8.524	−2.7980	PEN 85-100	11.8232	−3.6210
PG 70-10	10.69	−3.5660	PEN 120-150	11.0897	-3.7252
PG 70-16	10.641	−3.5480	PEN 200-300	11.8107	−4.0068
PG 70-22	10.299	-3.426	—	—	—

4. Calibration of Bottom-up Fatigue Cracking Model

The prediction of bottom-up fatigue cracking of flexible pavement in the MEPGG is based on the cumulative damage concept which uses Miner's law as shown in Equation (4). The damage is calculated as the ratio of cumulative predicted wheel load repetitions to the allowable number of wheel load repetitions. The equation to calculate the total fatigue damage is:

$$D = \sum_{i=1}^{T} \left(\frac{n}{N_f} \right)_{j,m,I,p,T} \tag{4}$$

where:

D	= damage,
n	= actual number of axle-load applications within a specific time period,
$N_{f,}$	= allowable repetitions under conditions prevailing within a specific time period,
j	= axle-load interval,
m	= axle-load type (single, tandem, tridem, quad, or special axle configuration,
I	= truck type using the truck classification groups included in the MEPDG,
p	= month, and
T	= median temperature for the five temperature intervals or quintiles used to subdivide each month.

The number of allowable repetitions to failure, N_f, is a function of the tensile strain developed at the bottom of the asphalt layer and the stiffness of the asphalt layer. The calculations of N_f of asphalt concrete are shown in Equation (5):

$$N_f = 0.00432 \times C \times \beta_{f1} \times k_{f1} \left(\frac{1}{\varepsilon_t} \right)^{\beta_{f2} \times k_{f2}} \left(\frac{1}{E} \right)^{\beta_{f3} \times k_{f3}} \tag{5}$$

where:

$C = 10^M$,

$M = 4.84 \left[\dfrac{V_{beff}}{V_a + V_{beff}} - 0.69 \right]$,

N_f	= number of load applications to failure,
ε_t	= tensile strain at critical location (in/in),
E	= stiffness of the asphalt layer (psi),
C	= correction factor
$k_{f1,2,3}$	= laboratory fatigue coefficients,
$\beta_{1,2,3}$	= local calibration coefficients,
V_{beff}	= percentage of bitumen volume in the mix, and
V_a	= percentage of air voids.

The bottom-up fatigue damage, *D*, as percentage damage is then used to bottom-up fatigue cracking, *F.C.* as a percentage of lane area by using the transfer function shown in Equation (6).

$$F.C. = \left(\frac{6000}{1+e^{(C_1 \times C_1^{'} + C_2 \times C_2^{'} \times \log(\% D))}} \right) \times \left(\frac{1}{60} \right) \tag{5}$$

where:

$C_1^{'} = -C_2^{'}$,

$C_2^{'} = -2.40874 - 39.748 \times (1 + h_{ac})^{-2.856}$, and

h_{ac} = total thickness of asphalt layer (in).

Based on the overall average results from nine national and international projects, the cyclic fatigue tests results showed that the 1 lb/ton fiber-reinforced mixture exhibits 3 times more fatigue life compared to the control mixture. This significant improvement in fatigue life, N_f, due to the use of FORTA fiber requires the calibration model shown in Equation (5) to reflect this enhancement. It was found also that the three times improvement was constant at different tensile strain values which means fiber-reinforced mixtures have the same k_{f2} values. According to the available fatigue results, the fatigue model calibration can be done using either of the following three options:

- Option 1: if full fatigue characterization was performed on the fiber-reinforced mixture which means running cyclic fatigue tests at different strain levels and at least two temperatures, input the actual laboratory k_{f1}, k_{f2}, and k_{f3} coefficients into the MEPDG software instead of the default or the nationally calibrated coefficients.
- Option 2: if full fatigue characterization was performed on the control and not the fiber-reinforced mixture, determine the k_{f1} for the fiber-reinforced mixture by as three times the k_{f1} coefficient of the control mixture and keep the k_{f2}, and k_{f3} coefficients as the same for the control mixture.
- Option 3: if there is no fatigue characterization of both control and fiber-reinforced mixtures, use the national calibrated coefficients of k_{f1}, k_{f2}, and k_{f3} for the control mixture. For the fiber-reinforced mixture, the k_{f2}, and k_{f3} coefficients the same and multiply the national calibrated coefficient k_{f1} by three for the fiber-reinforced mixture. The national calibrated k_{f1}, k_{f2}, and k_{f3} coefficients are 0.007566, 3.9492, and 1.281 respectively.

5. Calibration of Rutting Model

Rutting is caused by the accumulation of rutting in all layers in the pavement structure. Rutting appears as longitudinal depressions along the wheel paths causing roughness, hydroplaning, and other safety concerns. The rutting model of Asphalt Concrete (AC) layer in the MEPDG depends on the laboratory test data for permanent strain as shown below in Equation (6) before national calibrations.

$$\frac{\varepsilon_p}{\varepsilon_r} = 10^{K_1} \times T^{K_2} \times N^{K_3} \tag{6}$$

where:

εp = accumulated plastic strain at N repetitions of load (in/in),
εr = resilient strain of the asphalt material as a function of mix properties, temperature and time rate of loading (in/in),
K_1, K_2, K_3 = non-linear regression coefficients,
T = temperature (°F), and
N = number of load repetitions.

The nationally calibrated AC rutting model used in the MEPDG is shown in Equation (7).

$$\frac{\varepsilon_p}{\varepsilon_r} = kz \times 10^{k_1 \times \beta_{r1}} \times T^{k_2 \times \beta_{r2}} \times N^{k_3 \times \beta_{r3}} \tag{7}$$

where:

$\beta_{r1}, \beta_{r2}, \beta_{r3}$ = are local calibration coefficients,
k_1, k_2, k_3 = National calibrated coefficients (-3.4488, 1.5606, 0.479244 respectively),
k_z = Function of total asphalt layers thickness (h_{ac}) in inches and depth (d) in inches to computational point, to correct for the confining pressure at different depths,
$kz = (C_1 + C_2 \times d) \times 0.328196^d$,
$C_1 = -0.1039 h_{ac}^2 + 2.4868 h_{ac} - 17.342$, and
$C_2 = 0.0172 h_{ac}^2 - 1.7331 h_{ac} + 27.428$.

The calibration of the rutting model for the fiber-reinforced asphalt mixture requires the performing of the repeated load permanent deformation test where both accumulated plastic and resilient strains are tracked during the entire test. These specific types of data are not comprehensively available for the fiber-reinforced mixtures. Therefore the calibration of rutting model for the fiber-reinforced case is not recommended at this stage unless reasonable amount of test results are available.