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**TRB 12-2198**

**DETERMINATION OF CRITICAL BENDING STRESSES IN THE PCC LAYER WITH ASPHALT OVERLAY**

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Paper submitted November 15, 2011 in consideration for the  
Transportation Research Board 91st Annual Meeting,  
22-26 January 2012

Words: 5182  
Figures: 6  
Tables: 3  
Total Word Count: 7432

# DETERMINATION OF CRITICAL BENDING STRESSES IN THE PCC LAYER WITH ASPHALT OVERLAY

## ABSTRACT

An asphalt concrete (AC) overlay of a jointed plain concrete pavement (JPCP) is intended to extend the service life of the existing pavement structure. Also known as composite pavements, these pavements exhibit features of both rigid and flexible pavements. While behavior of rigid pavements is mainly elastic, behavior of an asphalt layer is load-duration dependent. At the same time, temperature curling causes non-linear interaction with the foundation. The available structural models for composite pavements ignore the behavior of the load duration dependent asphalt layer when the composite pavement is subjected to a combination of temperature curling and traffic loads. This research concentrates on the improvement of structural modeling of composite pavements that are subjected to slow developing temperature curling and instantaneous traffic loads. In order to maintain compatibility with the Mechanistic-Empirical Pavement Design Guide (MEPDG) framework, a simplified procedure is developed. This procedure uses a different asphalt modulus for curling than for axle loading; and determines the total stresses in the pavement as a combination of the stresses from solutions of three elastic boundary value problems. The simplified procedure is compared with the existing MEPDG structural model for fatigue cracking in AC overlaid JPCP. A framework for implementing the proposed procedure into the MEPDG is also developed.

## INTRODUCTION

Asphalt concrete (AC) overlays are used routinely to rehabilitate existing jointed plain concrete pavements (JPCP). However, many asphalt overlays fail prematurely due to transverse cracking in the portland cement concrete (PCC) layer reflecting through the asphalt. The Mechanistic Empirical Pavement Design Guide (MEPDG) identifies transverse cracking in the PCC layer as a major distress that is important to control.

The MEPDG assumes that a transverse crack developed in the PCC layer will eventually propagate through the AC layer over time and traffic. Figure 1 shows the propagation of a fatigue crack in the PCC layer to the top of the AC layer. The cracking in the AC layer due to crack propagation is known as reflective cracking. The MEPDG uses a separate distress model to compute reflective cracking. However, analysis of reflective cracking is out of the scope of this paper. The state of the art modeling of reflective cracking can be found elsewhere (*1*).

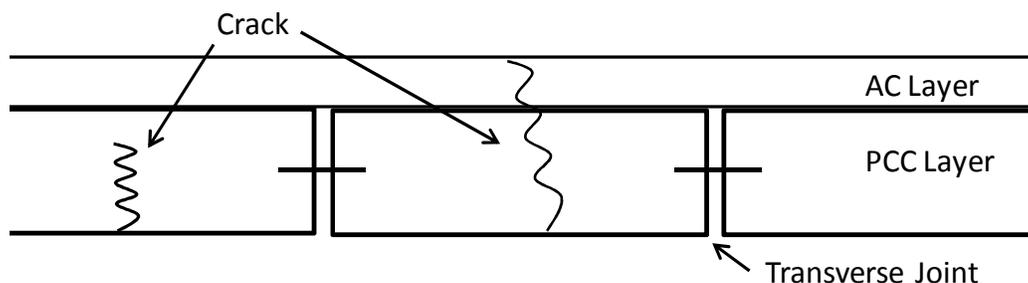


Figure 1. Propagation of fatigue cracking in a composite pavement.

1 The MEPDG distress model for predicting transverse cracking in the PCC layer of an AC  
 2 overlaid JPCP (referred herein as a composite pavement) was adopted directly from the fatigue  
 3 cracking model of a new jointed plain concrete pavement (2). The model has the following  
 4 form:

$$5 \quad TCRACK = (CRK_{Bottom-up} + CRK_{Top-down} - CRK_{Bottom-up} \cdot CRK_{Top-down}) \cdot 100\% \quad (1)$$

$$6 \quad CRK = \frac{100}{1 + FD^{-1.68}} \quad (2)$$

$$7 \quad FD = \sum \frac{n_{t,j,k,l,m,p}}{N_{t,j,k,l,m,p}} \quad (3)$$

$$8 \quad \log(N_{t,j,k,l,m,p}) = C_1 \cdot \left( \frac{MR}{\sigma_{t,j,k,l,m,p}} \right)^{C_2} \quad (4)$$

9

10

11 where

12 *TCRACK* is the total transverse cracking (percent, all severities),13 *CRK* is the percentage of bottom-up or top-down PCC cracking,14 *FD* is the fatigue damage,15 *n* is the applied number of load applications at conditions *t, j, k, l, m, p*,16 *N* is the allowable number of load applications at conditions *t, j, k, l, m, p*,17 *t, j, k, l, m, p* are conditions relating to the age, month, axle type, load level, temperature  
 18 difference, and traffic path, respectively,19 *MR* is the modulus of rupture of PCC,20  $\sigma$  is the applied stress at conditions *t, j, k, l, m, p*, and21 *C*<sub>1</sub>, *C*<sub>2</sub> are calibration constants (*C*<sub>1</sub> = 2.0, *C*<sub>2</sub> = 1.22).

22

23 Equation (4) implies that cracking in the PCC layer is a function of the “applied stress” and thus  
 24 depends on the various factors related to traffic loads and temperature gradients. Accurate  
 25 computation of the stress at the critical location in the PCC layer is an important step in the  
 26 calculation of fatigue cracking.

27 To compute structural responses such as stresses, strains, and displacements, constitutive  
 28 relationships for each layer in the structural model should be provided. Asphalt is a viscoelastic  
 29 material; its structural responses depend not only on the magnitude of the applied load but on the  
 30 load duration as well. However, conducting a viscoelastic analysis for each combination of site  
 31 and loading conditions required by the MEPDG damage computation process would be  
 32 computationally prohibitive. In order to simplify the structural analysis, the MEPDG treats  
 33 asphalt layers as elastic, but to account for the viscoelastic behavior of the asphalt layer, the  
 34 MEPDG assumes that the asphalt modulus of elasticity is equal to the load duration-dependent  
 35 dynamic (complex) modulus.

36 The loading duration for traffic loads depends on the vehicle speed. If vehicle speed is  
 37 approximately 60 mph, then the loading duration ranges between 0.01 sec and 0.05 seconds.  
 38 However, the duration of temperature loading is significantly longer. The MEPDG analysis of  
 39 flexible pavements ignores temperature-induced asphalt stresses and strains for all the distress  
 40 models except the low-temperature cracking model. In the low-temperature cracking model, the

1 temperature-induced stresses are accounted for but asphalt material is characterized differently  
 2 and the axle load-induced stresses are ignored. Therefore, the MEPDG framework used to  
 3 account for the viscoelastic behavior of asphalt layers in the design of flexible pavements can be  
 4 considered reasonable.

5 The situation is quite different in the case of asphalt overlays of concrete pavements  
 6 because the MEPDG implicitly accounts for both traffic and temperature induced stresses and  
 7 strains in the asphalt layer. The MEPDG recognizes that there is an interaction between  
 8 temperature curling and deformations due to traffic loading for the JPCP and AC overlays of  
 9 JPCP. Temperature gradients and traffic loads both cause bending stresses in the concrete layer  
 10 that cannot be simply added when asphalt overlaid concrete pavements are subjected to a  
 11 combination of temperature gradients and instantaneous traffic loads. This is because  
 12 temperature curling causes a separation of the slab from the subgrade, causing the system to  
 13 behave non-linearly. Moreover, the loading durations of temperature gradients and fast moving  
 14 traffic loads are significantly different. Therefore, for the case of asphalt overlays of JPCP in the  
 15 MEPDG framework, the characterization of the AC layer using a single dynamic modulus may  
 16 be an over-simplification.

17 The objective of this study is to verify whether the use of a single dynamic modulus to  
 18 characterize the AC layer (in the case of composite pavements only) is a valid assumption in the  
 19 adoption of the JPCP fatigue cracking structural model when the composite pavement is  
 20 subjected to a combination of temperature gradients and traffic loads. Secondly, a procedure  
 21 named *2-moduli approach* is developed such that two different AC moduli, corresponding to the  
 22 different loading durations of temperature loads and traffic loads, are used to represent the AC  
 23 layer. The combined stress in the composite pavement, subjected to temperature gradients and  
 24 traffic loads, is computed and a framework is developed to allow for the implementation of this  
 25 procedure in the existing framework of the MEPDG methodology.

## 26 27 **AC MODULUS UNDER TRAFFIC LOADS AND TEMPERATURE GRADIENTS**

28  
29 The MEPDG characterizes the viscoelastic behavior of the AC layer using a load duration-  
 30 dependent dynamic modulus. The dynamic modulus of asphalt is computed using a master curve  
 31 of sigmoidal shape (3), at a reference temperature of 70°F, as shown by the following equations:  
 32

$$33 \quad \log(E_{AC}) = \delta + \frac{\alpha}{1 + \exp(\beta + \gamma \log(t_r))} \quad (5)$$

34  
35 where

36  $E_{AC}$  is the dynamic modulus of asphalt,  
 37  $\delta$ ,  $\alpha$ ,  $\beta$ , and  $\gamma$  are parameters based on the volumetric property of the asphalt mix, and  
 38  $t_r$  is the reduced time.

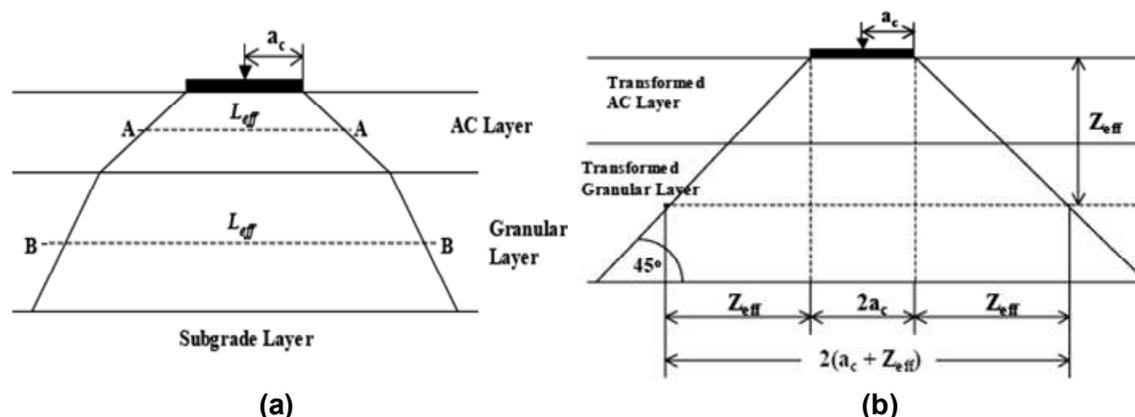
39  
40 The reduced time accounts for the effects of temperature and the rate of loading. It is given as:

$$41 \quad \log(t_r) = \log(t) - c * (\log(\eta) - \log(\eta_{TR})) \quad (6)$$

42  
43  
44 where

1  $t$  is the actual loading time,  
 2  $c = 1.255882$ , and  
 3  $\eta, \eta_{TR}$  are viscosities at temperature  $T$  and reference temperature  $T_R$ , respectively.  
 4

5 Equations (5) and (6) demonstrate that the asphalt behavior is dependent on the duration of the  
 6 loads. For the case of axle loading, the MEPDG utilizes Odemark's method of equivalent  
 7 thickness (MET) to calculate the actual loading time  $t$ . Using the MET, all layers above the  
 8 subgrade are transformed into equivalent subgrade layers, i.e., the moduli of the transformed  
 9 layers are equal to the subgrade modulus (figure 2) (2). The axle loading duration is then  
 10 calculated in terms of effective depth ( $Z_{eff}$ ), effective length ( $L_{eff}$ ), and the speed of the vehicle.  
 11



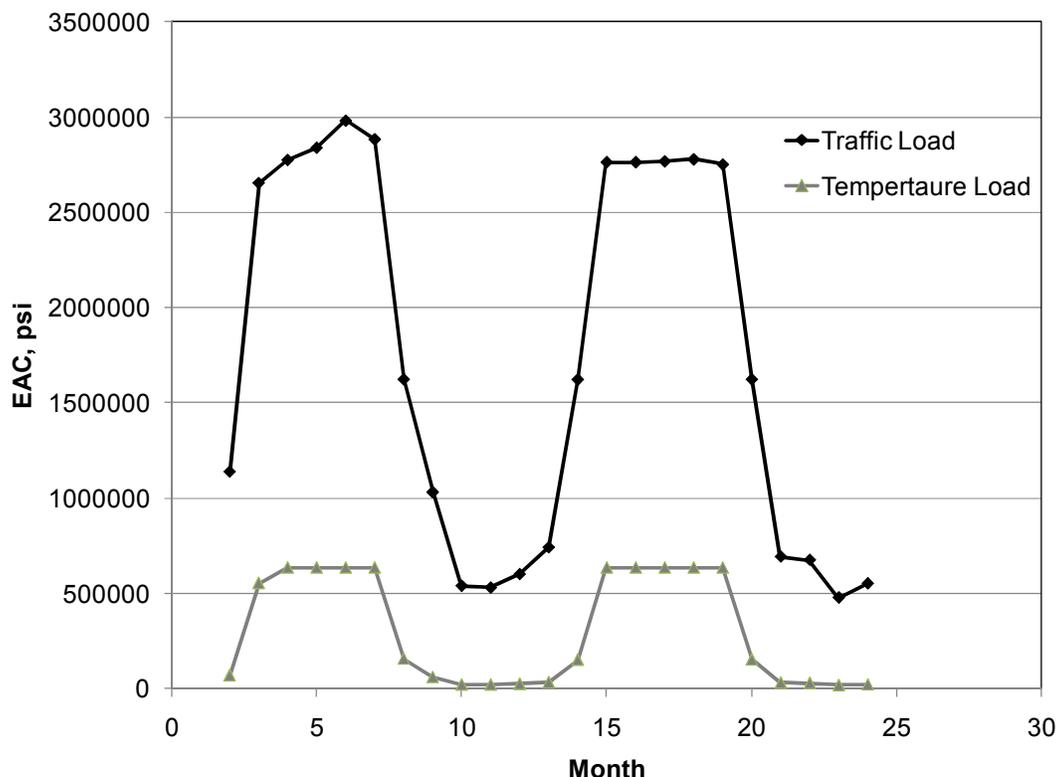
12  
 13 Figure 2. (a) Effective length and (b) effective depth for single axle in a conventional flexible  
 14 pavement (2).  
 15

16 Furthermore, for the case of temperature curling, the MEPDG assumes that the pavement is  
 17 subjected to hourly temperature gradients, i.e. the temperature distribution throughout the asphalt  
 18 layers does not change for at least an hour. This means that the duration of an axle loading and a  
 19 temperature gradient may differ by five orders of magnitude. Equations (5) and (6) suggest that  
 20 the AC moduli for axle load durations may be significantly different than for the temperature  
 21 gradient durations.

22 To investigate this effect, an analysis of the AC dynamic modulus, based on the MEPDG  
 23 guidelines, was conducted and the results are presented herein. To maintain consistency with the  
 24 MEPDG, the duration of temperature loads is selected to be one hour. The MEPDG assumes  
 25 that the temperature distribution in the base layer is constant through its thickness and is equal to  
 26 the temperature at the bottom of the PCC layer. The same assumption is applied herein to the  
 27 temperature distribution in the base layer.

28 A composite pavement located in Minneapolis, MN is analyzed. The pavement structure  
 29 consists of a 4 in AC layer placed on a 6 in PCC, 8 in A-1-a base, and semi-infinite A-6  
 30 subgrade. All other inputs are taken as the MEPDG defaults. The AC dynamic modulus is  
 31 calculated for the 3<sup>rd</sup> quintile monthly AC temperatures at the mid-depth of the AC layer  
 32 obtained from the Enhanced Integrated Climatic Model (EICM) outputs for the MEPDG. The  
 33 dynamic modulus was calculated using equations (5) and (6) for the loading time  $t$  corresponding  
 34 to (a) the MEPDG default traffic speed of 60 mph, and (b) 3600 seconds (i.e., one hour of  
 35 temperature loading). Figure 3 illustrates the dynamic modulus of AC layer versus pavement

1 age corresponding to the traffic duration and the temperature duration for the first two years of  
 2 the design life of the composite pavement.  
 3



4 Figure 3. Asphalt dynamic modulus using the MEPDG versus pavement age.  
 5  
 6

7 It can be established from figure 3 that the AC dynamic modulus is significantly different under  
 8 typical traffic load durations and one hour of temperature loading. Therefore, for composite  
 9 pavements under combined traffic and temperature loading, the use of a single dynamic modulus  
 10 to characterize the stress-strain relationship in the viscoelastic AC layer may be insufficient.

11 A rigorous viscoelastic extension of ISLAB2000 was developed to analyze the behavior  
 12 of rigid pavements incorporating viscoelastic AC layers, but the discussion of the viscoelastic  
 13 analysis is out of the scope of this paper. The details of the viscoelastic extension of ISLAB2000  
 14 analysis can be found elsewhere (4). It should be noted that the viscoelastic analysis is  
 15 computationally expensive and is not expected to be implemented into the MEPDG in the near  
 16 future.

17 In order to address these limitations, a procedure is developed such that two different  
 18 moduli are used to represent the AC layer for different loading durations determined using the  
 19 MEPDG process. The *2-moduli approach* employs a combination of three elastic solutions such  
 20 that the total stresses in the pavement are computed using a combination of the stresses from  
 21 these three solutions. The details of this procedure are presented below.  
 22

### 23 THE 2-MODULI APPROACH

24 Consider a composite pavement subjected to an arbitrary temperature distribution throughout the  
 25 slab thickness acting on time interval  $0 < t < t_T$ . The pavement is also subjected to an axle  
 26

1 loading that acts at the end of the same time interval. As demonstrated by figure 3, the AC  
2 dynamic modulus is significantly different under typical traffic loads and temperature gradients.  
3 It is proposed that two separate AC dynamic moduli should be considered as follows:

- 4
- 5 1. Traffic-duration-dependent dynamic modulus,  $EACL$  – to characterize the pavement  
6 response under typical traffic loads, and
- 7 2. Temperature-duration-dependent dynamic modulus,  $EACT$  – to characterize the  
8 pavement response for the duration of temperature loads,  $t_T$ .
- 9

10 The stresses obtained by executing separately the curling analysis and the traffic load analysis  
11 cannot simply be added to obtain the stress under a combination of traffic loads and temperature  
12 curling (2). This is due to the fact that the slab-foundation interaction is non-linear. Under  
13 compression, the deformation of the foundation increases linearly with an increase in surface  
14 pressure, but the foundation cannot resist vertical upward movement. The curling of the slab due  
15 to the daytime temperature gradient may cause a void under the center of slab as a result of  
16 separation from the foundation. The night-time temperature gradient may cause a void under the  
17 edges of the slab. Hence, due to non-linear interaction of slab with the foundation, the two  
18 different loading cases (and resulting stresses) cannot be linearly superimposed to mimic the  
19 combined loading.

20 To account for the effect of load duration dependency of the AC layer and non-linear slab  
21 foundation interaction, the following section presents a procedure that involves a combination of  
22 solutions of three elastic boundary value problems (BVP).

## 23

## 24 **STRESS COMPUTATION PROCEDURE USING THE 2-MODULI APPROACH**

## 25

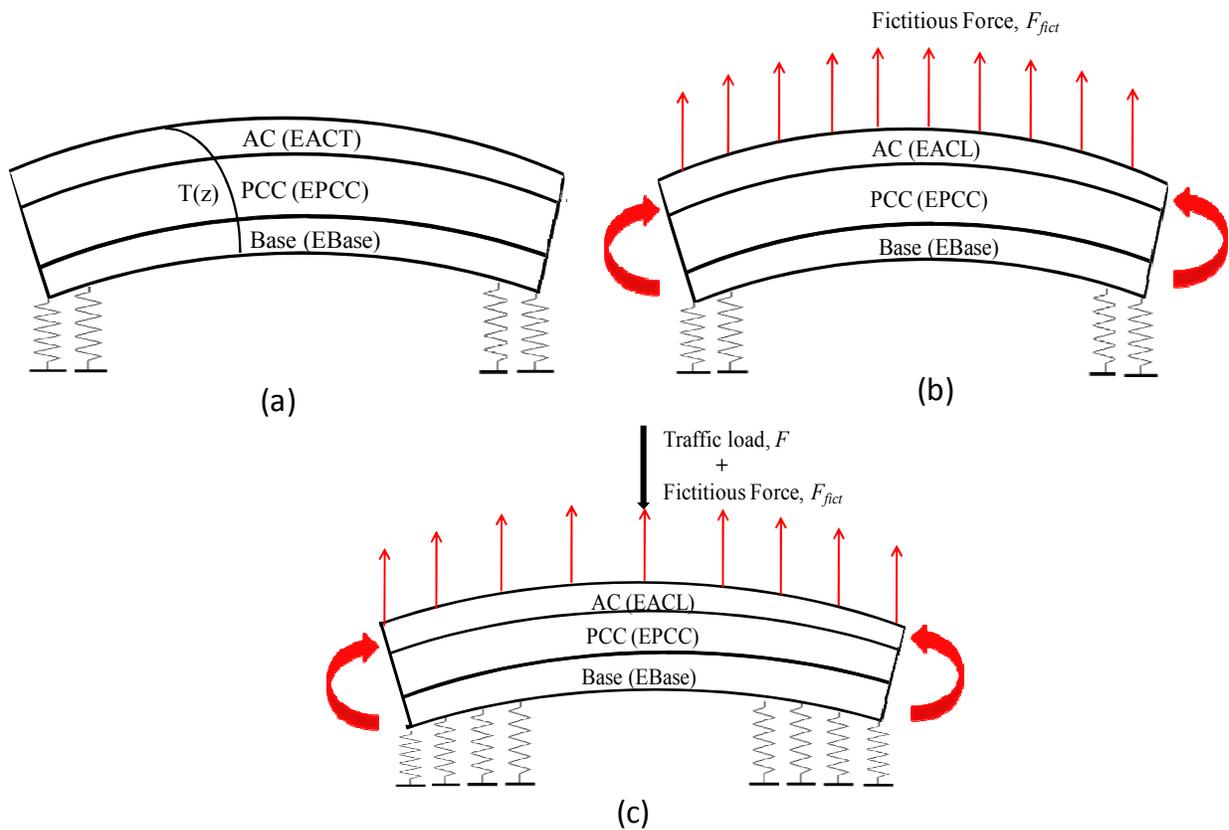
26 The first elastic BVP considers slab curling only and uses the temperature-duration-dependent  
27 AC modulus,  $EACT$  to characterize the AC stiffness. The second elastic BVP involves  
28 determination of the stress field in the composite pavement with the AC layer characterized by  
29 the traffic-duration-dependent AC modulus  $EACL$  subjected to curling and having the same  
30 deflection profile as it was determined in the first elastic solution. In the third elastic BVP, the  
31 traffic-duration-dependent AC modulus  $EACL$  is used to determine the stress field from the  
32 combined effect of curling and axle loading. The total stresses in the pavement are computed as  
33 a combination of the stresses from these three solutions. The solution of the BVPs is obtained  
34 using the finite element (FE) formulation of the medium-thick plate theory (5, 6) which is  
35 traditionally adopted for modeling of concrete layers.

### 36

### 37 ***The First Boundary Value Problem***

38 Consider problem 1 – a three-layered system of AC-PCC-base layers. The system rests on the  
39 spring idealization of an elastic Winkler foundation. The AC layer is modeled as an elastic  
40 material with an elastic modulus corresponding to the temperature-duration-dependent modulus,  
41  $EACT$ . The PCC and base layers are elastic with moduli of elasticity equal to  $E_{PCC}$  and  $E_{Base}$ ,  
42 respectively. The thicknesses of the AC, PCC, and base layers are  $h_{AC}$ ,  $h_{PCC}$ , and  $h_{Base}$ ,  
43 respectively. The unit weights of the AC, PCC, and base layers are  $\gamma_{AC}$ ,  $\gamma_{PCC}$ , and  $\gamma_{Base}$ ,  
44 respectively. All the layers have Poisson's ratio equal to  $\mu$ . The coefficient of thermal expansion  
45 for the AC layer is  $\alpha_{AC}$  while that for the PCC and base layers is selected as  $\alpha_{PCC}$  to maintain  
46 compatibility with the MEPDG. The interface conditions between the layers could be either

1 fully bonded or unbonded. The pavement system of problem 1 is subjected to a positive  
 2 temperature gradient  $T(z)$  as shown in figure 4(a).  
 3



4  
 5 Figure 4. (a) System 1 under positive temperature gradient  $T(z)$  only, (b) system 2 under  
 6 fictitious force  $F_{fict}$ , (c) System 2 under mid-slab traffic load  $F$  and fictitious force  $F_{fict}$ .  
 7

8 The deflection profile of the slab under the temperature gradient  $T(z)$  is recorded. The stress at  
 9 the bottom of the PCC layer at the mid-slab location under temperature gradient  $T(z)$  is denoted  
 10 as  $\sigma_1$ . The equilibrium equation for system 1 can be expressed as follows (6):  
 11

$$12 \quad [K_1]\{\delta_1\} = \{F_{therm}\} \quad (7)$$

13 where

15  $[K_1]$  is the global stiffness matrix for system 1 with temperature-duration-dependent AC  
 16 modulus  $EACT$ ,

17  $\{F_{therm}\}$  is the global force vector due to temperature distribution  $T(z)$ , and

18  $\{\delta\}$  is the global displacement vector of system 1.  
 19

20 The displacements of the slab,  $\delta_1$  can be written as:  
 21

$$22 \quad \{\delta_1\} = [K_1]^{-1}\{F_{therm}\} \quad (8)$$

1 Since system 1 is subjected to temperature distribution  $T(z)$ , elastic stress in an element of system  
 2 1 can be calculated as:

$$3 \quad \{\sigma_1\}_e = [\bar{D}_T] (\{\varepsilon_1\} - \{\varepsilon_{therm}\})_e \quad (9)$$

5 where

6 subscript  $e$  denotes an individual element in the plate,  
 7  $\{\sigma_1\}$  is the elastic stress from the first elastic solution,  
 8  $[\bar{D}_T]$  is the material property matrix corresponding to modulus  $EACT$ ,  
 9  $\{\varepsilon_1\}$  is the total strain corresponding to the global displacements  $\delta_1$ , and  
 10  $\{\varepsilon_{therm}\}$  is the thermal strain due to temperature distribution  $T(z)$  .  
 11  
 12

### 13 ***The Second Boundary Value Problem***

14 Consider problem 2 that has the same three-layered structure and material properties as problem  
 15 1, except that the AC layer is modeled as an elastic material with an elastic modulus  
 16 corresponding to the traffic-duration-dependent modulus,  $EACL$ . The layer interface condition is  
 17 exactly the same as that for problem 1.

18 Assume that a fictitious force  $F_{fict}$  acts on the pavement system such that its deflection  
 19 profile is exactly the same as that from problem 1, i.e. the deflection at each node of system 2 is  
 20 exactly equal to the deflection at the corresponding node in system 1. Since the deflection  
 21 profile does not change between BVPs 1 and 2, it ensures that the subgrade below system 2 is  
 22 under the same stress distribution as the subgrade below system 1 and the contact area between  
 23 the slab and foundation does not change. This ensures that the non-linear behavior of the slab-  
 24 foundation interaction is properly accounted for. Figure 4(b) presents system 2 under fictitious  
 25 force  $F_{fict}$ . The stress resulting from the fictitious force  $F_{fict}$  at the bottom of the PCC layer at the  
 26 mid-slab location is denoted as  $\sigma_2$ . Solutions detailing the computation of this stress are  
 27 discussed next.

28 Since the global displacements of problem 2 are assumed to be exactly the same as those  
 29 from problem 1, the fictitious force  $F_{fict}$  can be computed as follows (6):

$$30 \quad \{F_{fict}\} = [K_2] \{\delta_1\} \quad (10)$$

31 where

32  $K_2$  is the global stiffness matrix for system 2 with traffic-duration-dependent AC modulus  
 33  $EACL$ .  
 34  
 35  
 36

37 Since no initial strains act on system 2 and the global displacements of system 2 are exactly the  
 38 same as those of system 1, the elastic stress in an element of system 2 can be calculated as  
 39 follows:

$$40 \quad \{\sigma_2\}_e = [\bar{D}_L] \{\varepsilon_1\}_e \quad (11)$$

41 where

1  $\{\sigma_2\}$  is the elastic stress from the second elastic solution, and  
 2  $[\bar{D}_L]$  is the material property matrix corresponding to modulus  $EACL$ .  
 3

#### 4 ***The Third Boundary Value Problem***

5 Since system 2 characterizes the AC layer with an elastic modulus corresponding to the traffic-  
 6 duration-dependent modulus,  $EACL$ , the traffic load  $F$  can be superimposed on top of the  
 7 fictitious loading  $F_{fict}$ . Therefore, in the third elastic problem, system 2 is loaded by a total load  
 8 consisting of traffic load  $F$  and fictitious load  $F_{fict}$  as shown in figure 4(c). The stress at the  
 9 bottom of the PCC layer at the mid-slab location due to the total load is denoted as  $\sigma_3$ . The  
 10 global displacements  $\delta$  under a combination of loads can be computed as follows:  
 11

$$12 \quad \{\delta\} = [K_2]^{-1} (\{F\} + \{F_{fict}\}) \quad (12)$$

13 where

14  $\{F\}$  is the global force vector due to traffic loads, and  
 15  $\{F_{fict}\}$  is the global fictitious force vector from the second elastic solution.  
 16  
 17

18 The elastic stress from the third elastic problem can be calculated as follows:  
 19

$$20 \quad \{\sigma_3\}_e = [\bar{D}_L] \{\varepsilon_T\}_e \quad (13)$$

21 where

22  $\{\sigma_3\}$  is the elastic stress from the third elastic solution, and  
 23  $\{\varepsilon_T\}$  is the total strain corresponding to the global displacements  $\delta$ .  
 24  
 25

#### 26 ***Combined Stress***

27 Finally, to obtain the stress distribution in the pavement due to the combined effects of  
 28 temperature and traffic loading, solutions of the three elastic problems are combined as follows:  
 29

$$30 \quad \sigma_{2M} = \sigma_1 + (\sigma_3 - \sigma_2) \quad (14)$$

31 where

32  $\sigma_{2M}$  is the combined stress at a given location,  
 33  $\sigma_1$  is the stress at the given location from the first elastic solution,  
 34  $\sigma_2$  is the stress at the given location from the second elastic solution, and  
 35  $\sigma_3$  is the stress at the given location from the third elastic solution.  
 36  
 37

38 The stress solution obtained using the *2-moduli approach* is compared with simple examples  
 39 presented below. In order to maintain compatibility with the MEPDG, the AC moduli are  
 40 computed using the existing MEPDG procedure for calculating the dynamic modulus of the AC  
 41 layer. However, any other existing procedure for characterizing the viscoelastic constitutive law  
 42 for the AC layer could also be used.  
 43

**COMPARISON OF THE STRESS SOLUTION USING THE 2-MODULI APPROACH WITH SIMPLE ADDITION OF THE STRESSES**

To confirm that the stress in a pavement subjected to the combination of traffic loads and temperature gradients is not the direct addition of stresses computed separately under such loads, a three-layered pavement slab placed on an elastic Winkler foundation is considered. A 15 ft long by 12 ft wide pavement slab is loaded with single-axle dual-wheel (SADW) loads at the edge of the slab as shown in figure 5 (a). The SADW loads have a tire footprint of 7 in x 7 in and tire pressure of 100 psi. A uniform mesh consisting of 6 in x 6 in elements is generated. The modulus of subgrade reaction for the Winkler foundation is equal to 100 psi/in.

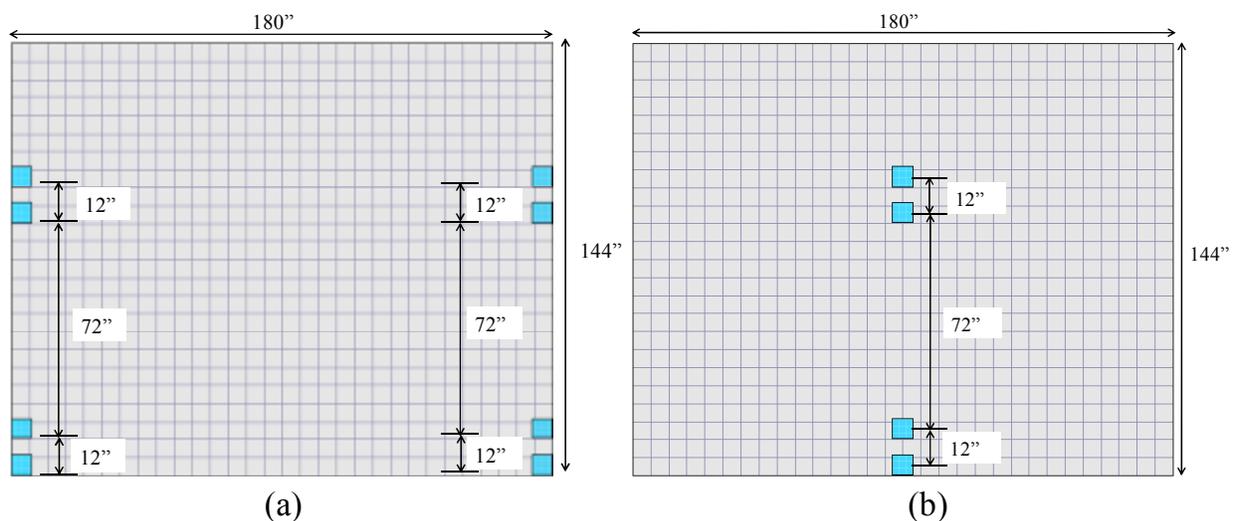


Figure 5. Mesh and load configuration for the composite pavement subjected to SADW load at the (a) edges of the slab and (b) center of the slab.

The material properties for the constituent layers of the composite pavement are presented in table 1. The interface between the AC and PCC layers of the composite pavement is fully bonded while the interface between the PCC and base layers is fully unbonded.

Table 1. Layer properties for the composite pavement.

Layer	Thickness, h (in)	Layer modulus, E (psi)	Poisson's ratio, $\mu$	Unit weight, $\gamma$ (lb/in <sup>3</sup> )	Coefficient of thermal expansion, $\alpha$ (1/°F)
AC	2	$E_{ACT} = 39448.9$	0.15	0.087	1.65E-05
		$E_{ACL} = 2.0E+05$			
PCC	7	4.0E+06	0.15	0.087	5.50E-06
Base	6	4.0E+04	0.15	0.000	5.50E-06

The composite pavement is also subjected to a non-linear night-time temperature distribution given in table 2.

Table 2. Temperature profile for the composite pavement.

Layer		No. of temperature data points										
		1	2	3	4	5	6	7	8	9	10	11
AC	Reference temperature = 55.90 °F											
	Depth, In	0.0	0.5	1.0	1.5	2.0						
	Temp., °F	40.9	46.0	49.0	52.9	57.8						
PCC	Reference temperature = 55.90 °F											
	Depth, in	0.0	0.7	1.4	2.1	2.8	3.5	4.2	4.9	5.6	6.3	7.0
	Temp., °F	57.8	60.2	62.5	64.7	66.9	68.0	70.9	72.8	74.5	76.2	78.8

The stress in the pavement is computed using the *2-moduli approach* presented above. The stress is also computed when the composite pavement is subjected to (a) the temperature load only, and the AC layer has temperature-duration-dependent modulus *EACT* and (b) the traffic load only, and the AC layer has traffic-duration-dependent modulus *EACL*. The combined PCC top stress at the edge of the slab using the *2-moduli approach* is compared against the sum of stresses from case (a) and case (b). The results are presented in table 3 below.

Table 3 also presents the stresses obtained from the finite element model developed based on the viscoelastic extension of ISLAB2000 (4). The viscoelastic constitutive law for the AC layer is defined in terms of the creep compliance using a form of Prony series. The instantaneous modulus of the AC layer is equal to the traffic-duration-dependent modulus *EACL*. The deformations at the end of duration of temperature curling are defined using a modulus in terms of both *EACL* and *EACT*.<sup>1</sup> The Prony series approximation has been used by many researchers to characterize the AC behavior (7, 8, 9).

Table 3. Deflections and stress at the top of the PCC layer at slab edge.

	Location, in		Deflection, in	Rotation		Longitudinal Stress, psi
	X	Y		$\theta_y$	$\theta_x$	
<b>2-Moduli Approach</b>						
# 1	90	0	-0.0077	0.00	0.00	108.74
# 2	90	0	-0.0077	0.00	0.00	-138.36
# 3	90	0	0.0038	0.00	0.00	204.06
Combined stress (equation [14])						451.17
<b>Viscoelastic solution</b>	90	0	0.0038	0.00	0.00	451.12
<b>Simple Addition</b>						

$$^1 \text{ Creep compliance function } J(t) = \frac{1}{E_0} + \frac{1}{E_1} \left( 1 - e^{-\frac{E_1 t}{\eta_1}} \right) \quad \frac{1}{E_0} = \frac{1}{EACL} \quad \frac{1}{E_1} = \frac{1}{EACT} - \frac{1}{EACL}$$

<i>EACT</i> , temperature load only	90	0	-0.0077	0.00	0.00	108.74
<i>EACL</i> , traffic load only	90	0	0.0033	0.00	0.00	284.05
<b>Sum</b>						392.79
<b>% Difference between 2-Moduli Approach and Simple Addition</b>						14.86%

The stress from the viscoelastic solution and the combined stress from the *2-moduli approach* match very well. The difference between the stresses from the *2-moduli approach* and the simple addition clearly demonstrate that the stress from individual traffic and temperature analyses cannot be simply added to obtain the combined stress due to the non-linear behavior of the slab-foundation interaction.

### COMPARISON OF THE STRESS SOLUTION FROM THE 2-MODULI APPROACH WITH THE STRESS USING THE MEPDG PROCESS

The stresses obtained using the *2-moduli approach* are further compared with the stresses obtained using the MEPDG procedure in order to assess the difference between the two procedures. The MEPDG considers the temperature distribution present in the layers of the pavement to be a step function of time over a duration of one hour. Therefore, the duration of temperature loads,  $t_T$  for computing *EACT* is also taken to be one hour. In this example, the temperature distribution with the maximum temperature difference between the top of the AC layer and the bottom of the PCC layer was selected for each month over two years of data from the EICM data file. The stress in the pavement was then computed using the selected temperature distribution for each month in combination with the traffic loading.

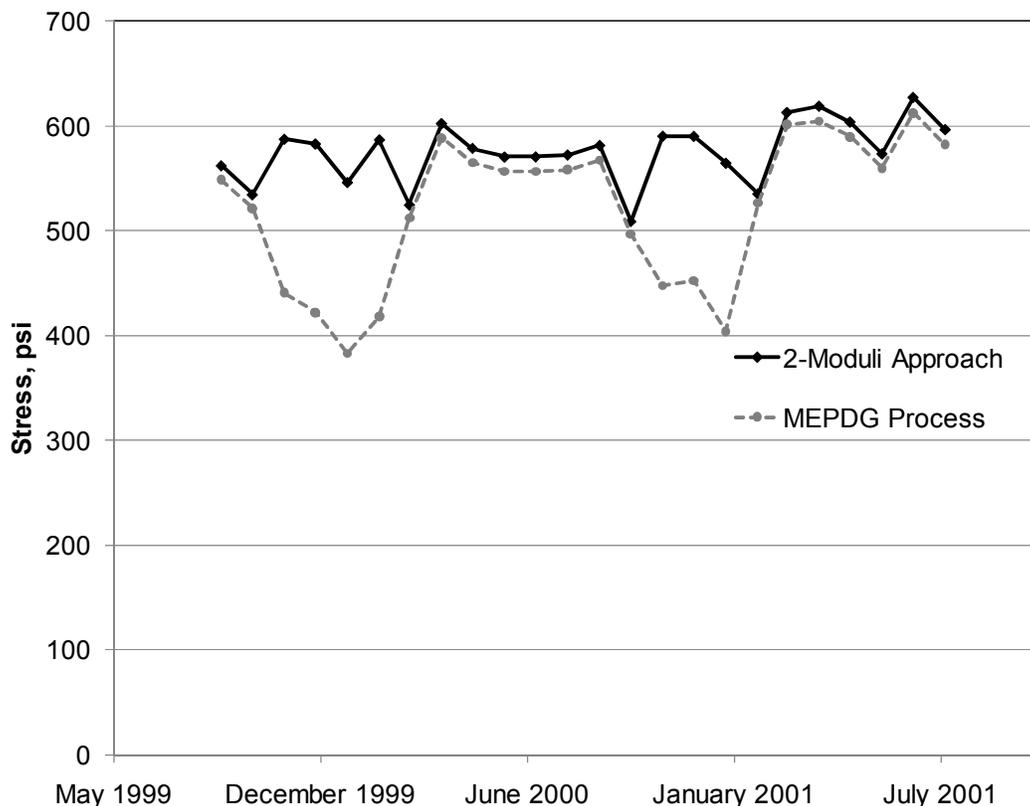
The MEPDG employs neural networks (NNs) to compute the stresses in rigid and composite pavements (2). These NNs are trained using a factorial of ISLAB2000 cases. Therefore, to maintain consistency with the MEPDG, ISLAB2000 cases were executed such that the composite pavement was subjected to a combination of the temperature distribution corresponding to each month of the analysis and traffic loading.

Consider the three-layered composite pavement placed on an elastic Winkler foundation with modulus of subgrade reaction for the Winkler foundation equal to 100 psi/in. Twenty-four cases, corresponding to twenty-four months, are analyzed such that the pavement is subjected to both the SADW load as shown in figure 5(b) and the selected temperature distribution with maximum gradient from each month. The pavement structure consists of a 2 in AC layer placed on a 7 in PCC and 0 in base. The Poisson's ratio for all layers is 0.15. The modulus of elasticity of the PCC and base layer is  $4.0E+06$  psi and  $4.0E+04$  psi, respectively.

The AC layer is represented using the *2-moduli approach* such that (a) the traffic-duration-dependent modulus *EACL* is dependent on the vehicle loading rate and (b) the temperature-duration-dependent modulus *EACT* is dependent on one hour of temperature loading. Also, both *EACL* and *EACT* for each month are calculated using the 3<sup>rd</sup> quintile AC temperatures at the mid-depth of the AC layer for the corresponding month using equations (5) and (6).

ISLAB2000 cannot currently analyze a three-layered system if both the layer interfaces are fully bonded. While this is rarely a limitation for the analysis of rigid pavements, it introduces some limitations when fully bonded composite pavements are analyzed. Therefore, to

1 maintain compatibility with ISLAB2000, the thickness of the base layer of the composite  
 2 pavement is taken to be equal to zero. The stresses obtained using the *2-moduli approach* and by  
 3 executing the ISLAB2000 case for replicating the MEPDG procedure are presented in figure 6.  
 4 The stress is computed at the bottom of the PCC layer at the edge of the slab.  
 5



6  
 7 Figure 6. Comparison of stress using the *2-moduli approach* and the MEPDG procedure.  
 8

9 A difference between the stresses from the *2-moduli approach* and the MEPDG procedure is  
 10 observed. There could be several factors that contribute towards this difference. The MEPDG  
 11 uses a single traffic loading based AC dynamic modulus (*EACL*) whereas the *2-moduli approach*  
 12 employs moduli *EACT* and *EACL*. This may cause a difference between the self equilibrating  
 13 stresses present in a layer due to the non-linear-strain-causing temperature component (10) which  
 14 directly affects the total stress at any point in the pavement.  
 15

### 16 SCOPE OF IMPLEMENTATION OF THE 2-MODULI APPROACH INTO THE 17 EXISTING MEPDG FRAMEWORK

18 The MEPDG uses various techniques for the simplification of stress analysis in the existing  
 19 fatigue cracking distress models for rigid and composite pavements. In order to accommodate a  
 20 large number of design parameters, the following techniques are adopted (2):  
 21

- 22 1. Replacement of the structural system by a combination of two simpler systems, and
- 23 2. Equivalency techniques to reduce the number of independent input parameters.

1 The MEPDG employs a framework of rapid solutions to predict the stress solution for  
 2 rigid and composite pavements under traffic loading, temperature distribution, or their  
 3 combinations (2, 11, 12). The NNs are based on a combination of two simpler systems –  
 4 systems A and B – to compute stresses in the original multi-slab system. System A is a single  
 5 slab with length equal to the transverse joint spacing of the original system, width equal to the  
 6 width of the truck lane in the original system, and thickness equal to the slab thickness of the  
 7 original system. System A is analyzed for three loading conditions, namely: stress due to axle  
 8 loading only, curling stress due to equivalent linear temperature loading only, and stress due to  
 9 combined axle and linear temperature loading. System B is a two-slab system (i.e., single slab  
 10 with shoulder) that has a sufficiently large slab length to ignore slab size effects, slab width equal  
 11 to the width of the truck lane in the original system, and thickness equal to the slab thickness of  
 12 the original system. NNs based on system B accounts for the tire-footprint geometry and the  
 13 effect of shoulder support. System B considers axle loading but does not consider temperature  
 14 curling (2). The total stress in the original system is then expressed as a combination of stresses  
 15 from neural networks NNA and NNB as follows:  
 16

$$17 \quad \sigma_{Tot} = \sigma^A(0, T) + LTE * [\sigma^A(P, T) - \sigma^A(0, T) - \sigma^A(P, 0) + \sigma^B(0)] \quad (15)$$

18 where

19  $\sigma_{Tot}$  is the stress in the original multi-slab composite pavement,

20  $\sigma^A(0, T)$ ,  $\sigma^A(P, 0)$ , and  $\sigma^A(P, T)$  are stresses in system A due to temperature curling  
 21 only, axle loading only, and combined axle loading and temperature curling, respectively,  
 22

23  $\sigma^B(0)$  is the stress in system B when the shoulder provides no edge support, and

24  $LTE$  is the load transfer efficiency between the pavement slab and the shoulder.  
 25

26 A similar approach is adopted for the development of a MEPDG compatible framework that  
 27 shall incorporate the stress solution obtained using the *2-moduli approach*. The AC layer of the  
 28 composite pavement system A is represented using the traffic-duration-dependent modulus  
 29  $EACL$  when the pavement is subjected to the axle load. The AC layer of system A is represented  
 30 by the temperature-duration-dependent modulus  $EACT$  when the pavement is subjected to the  
 31 temperature distribution. Similar to the total stress obtained using the MEPDG procedure  
 32 (equation [15]), the stress in the original multi-slab composite system using the *2-moduli*  
 33 *approach* is related to the stress in systems A and B as follows:  
 34

$$35 \quad \sigma_{Tot} = \sigma_1^A(0, T) + LTE * [(\sigma_3^A(P, T^*) - \sigma_2^A(0, T^*)) - \sigma^A(P, 0) + \sigma^B(0)] \quad (16)$$

36 where

37  $\sigma_1^A(0, T)$  is the stress in system A due to temperature curling only and is equal to the  
 38 stress from the first elastic BVP of the *2-moduli approach*,

39  $\sigma_2^A(0, T^*)$  and  $\sigma_3^A(P, T^*)$  are stresses in system A due to combined axle loading and  
 40 temperature curling; and are equal to the stresses from the second and third elastic BVPs  
 41 of the *2-moduli approach*, respectively,  
 42

43  $\sigma^A(P, 0)$  is the stress in system A due to axle loading only, and

1  $\sigma^B(0)$  is the stress in system B when the shoulder provides no edge support.

2  
3 The similarities between equations (15) and (16) imply that minimum modifications to the  
4 existing MEPDG neural network framework are required in order to implement the stress  
5 solution technique based on the *2-moduli approach*.

## 6 7 **CONCLUSIONS**

8  
9 Composite pavements are complex structures incorporating both asphalt and portland cement  
10 concrete layers. Composite pavement behavior exhibits features of both rigid and flexible  
11 pavements. Because of this, a structural analysis of composite pavements is a challenging  
12 program. This research was concentrated on the improvement of the structural modeling of  
13 stress analysis for predicting the PCC fatigue cracking compatible with the existing MEPDG  
14 framework. The summary of the research findings is presented below.

- 15  
16 • The use of a single load duration-dependent AC dynamic modulus to characterize the  
17 behavior of the AC layer seems insufficient for composite pavements subjected to a  
18 combination of traffic loads and temperature curling, as a significant difference was  
19 found in the load-duration dependent AC dynamic modulus when a composite pavement  
20 is subjected to typical traffic loads and to one hour of temperature loads.
- 21 • A stress computation procedure was developed to calculate stresses in the composite  
22 pavement subjected to a combination of traffic loads and temperature curling using two  
23 load duration-dependent AC moduli. In this research, the AC moduli were computed  
24 using the existing MEPDG procedure for calculating the dynamic modulus of the AC  
25 layer in order to maintain compatibility with the MEPDG. However, any other existing  
26 procedure for characterizing the viscoelastic constitutive law for the AC layer could also  
27 be used.
- 28 • The stresses computed using the *2-moduli approach* and the MEPDG procedure are  
29 found to be significantly different when composite pavements are subjected to a  
30 combination of traffic loading and temperature curling. This issue needs to be  
31 investigated further.
- 32 • A framework for the implementation of the proposed stress procedure into the MEPDG  
33 was developed such that minimum modifications to the existing MEPDG framework are  
34 required. The proposed stress computation procedure can be directly implemented into  
35 the MEPDG for predicting fatigue cracking in composite pavements.

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