

**State Planning and Research Program  
Quarterly Report**

**PROJECT TITLE:** Design and Construction Guidelines for Thermally Insulated Concrete Pavements

**OBJECTIVES:**

The main objective of the proposed research is to develop design and construction guidelines for thermally insulated concrete pavements (TICP), i.e. composite thin HMA overlays of new or structurally sound existing PCC pavements. A secondary objective is to develop recommendations for feasibility analysis of newly constructed TICP or thin overlays of the existing concrete pavements.

**PERIOD COVERED:** April 1 – June 30, 2010

**PARTICIPATING AGENCIES:** Minnesota Department Of Transportation, Caltrans, Federal Highway Administration, Local Road Research Board, Washington State Department of Transportation

**PROJECT MANAGER:**

Tim Clyne

**LEAD AGENCY:**

Minnesota Dept. of Transportation

**PRINCIPAL INVESTIGATOR:**

Lev Khazanovich

**SP&R PROJECT NO:**

TPF 5(149)

**PROJECT IS:**

         Planning

  X   Research & Development

**ANNUAL BUDGET:**

The total project budget is \$455,000. Of that \$16,000 is reserved for pooled fund administrative costs, which leaves \$439,000 available for research.

**PROJECT EXPENDITURES TO DATE:** The estimated expenses are \$205,400.

**WORK COMPLETED:**

See attached.

**SUMMARY OF ACTIVITIES EXPECTED TO BE PERFORMED NEXT QUARTER:**

The research team will finalize validation of the MEPDG EICM model and will continue work on improvements to the MEPDG structural models.

**STATUS AND COMPLETION DATE:** There was a delay ~~bringing~~ in issuing subcontract/consulting agreements with the Dr. John Harvey and other members of the research team. The subcontracts were finalized last quarter, but there will be a need for a no-cost time extension of the project. The request will be submitted next quarter.



### *Task 2. Perform Initial Life-Cycle Analysis*

The subtask was delayed due to problems with consulting agreements with Drs, John Harvey and Jim Signore and Mr. Nick Sentera. This subcontracts were finalized in June 2010. A team meeting had been conducted in Davis, CA. The work on this task has been initiated. The scope of input data required to conduct this analysis has been finalized and contact persons at Minnesota, Washington, and California DOTs have been identified.

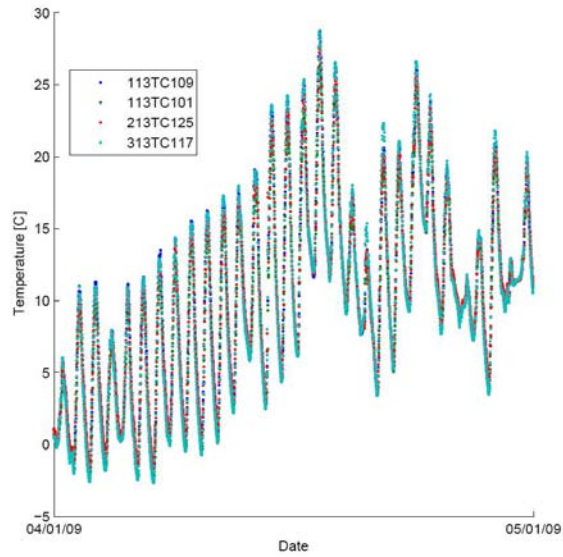
### *Task 3. EICM Validation and Analysis*

Previously, temperature data from cells 106 and 206 at MnROAD were processed in order to determine the quality of the data. The data was processed using statistical analysis tools developed by Dr. Randal J. Barnes at the University of Minnesota. This testing was expanded to include data from cells 113, 213, & 313. This was done not only to assess the quality of the data from the MnROAD test cells, but to use the quality data as a comparison and measure against the predicted values from the M-EPDG.

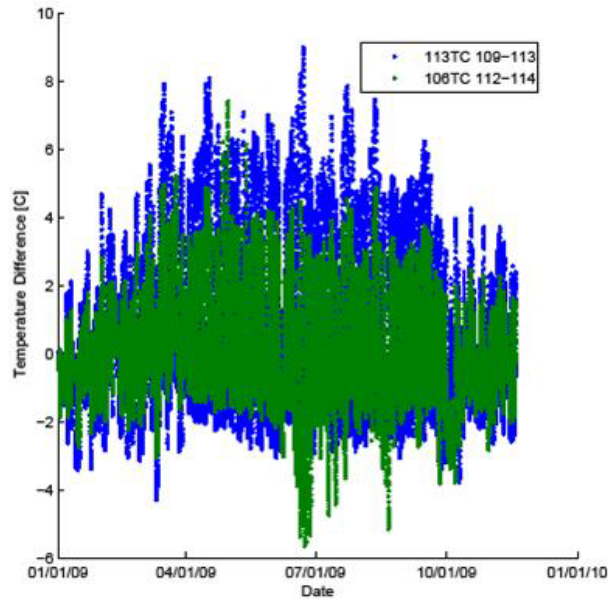
Several tests of pavement temperature data were conducted to determine the quality of the measured data. Data that was “flagged” was not used in the comparisons of temperature measurements. The following is a list of some of sensor comparisons that have been completed

- Comparison of PCC surface temperatures in PCC cells (113, 213, 313)
- Comparison of AC surface temperatures in composite cells (106, 206)
- Comparison of AC and PCC surface temperatures between composite and PCC cells
- Comparisons of temperature at the bottom of the PCC slab in PCC cells
- Comparisons of temperature at the bottom of the PCC slab in composite cells
- Comparisons of temperature from the PCC and composite cells at the bottom of the PCC slab
- Comparisons of temperature from the PCC and composite cells at the top of the PCC layer
- Comparisons of temperature between composite and PCC cells at a depth of 2.5” below pavement surface – 2.5” below top of slab for PCC cell, 0.5” below top of slab for composite cell
- Difference between top & bottom of slab for PCC pavements
- Comparison of temperature differences between composite and PCC cell slabs

Below are two figures that show some of the plots made. The first is a plot of surface temperature from sensors in the PCC cells.

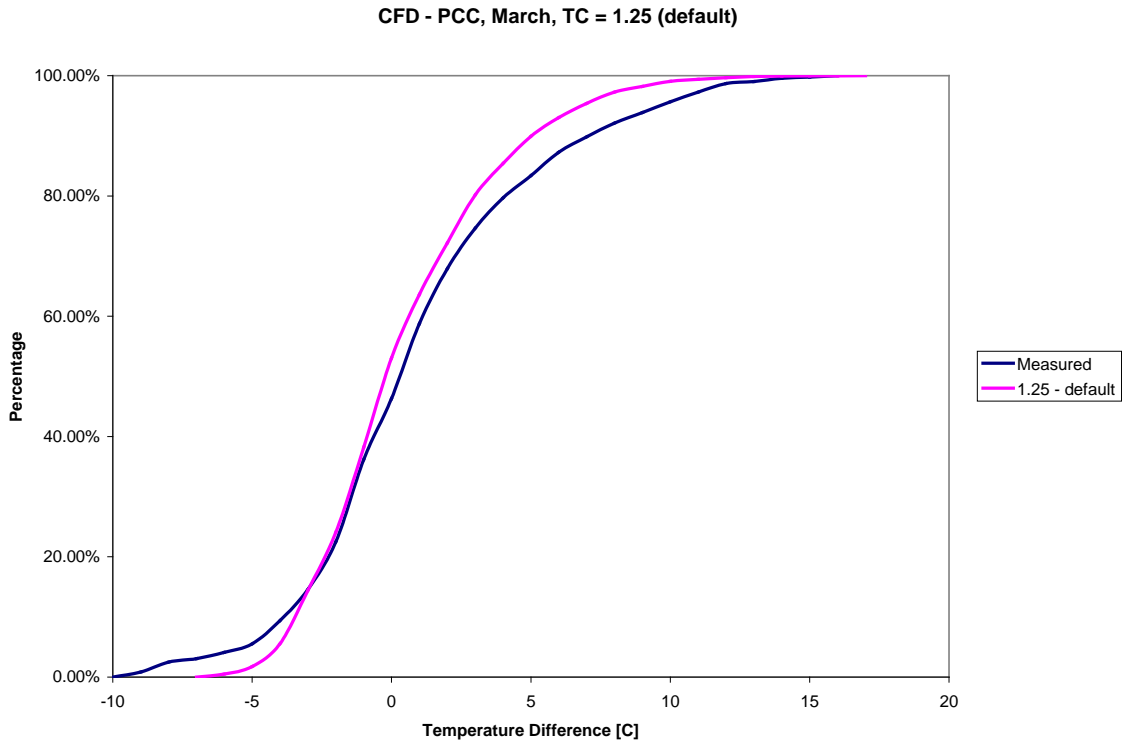


The following is a plot of the temperature differences in from the top to the bottom of the slab in the PCC and composite cells. This image shows the composite cell has less temperature difference from the top to the bottom of the slab.



The measured data was compared with modeled data produced by the MEPDG. The temperature

differences were plotted in a cumulative frequency distribution. The default thermal conductivity value of 1.25 BTU / hr-ft-°F was used in the following example for the PCC structure.



As can be seen from the plot, the MEPDG underestimates the temperature distributions that were measured in the PCC cells at MnROAD. The measured data reports greater values at both extremes.

The above plots are examples of some of the work completed. The rest of the images are prepared and will be included in the written report which is in preparation.

#### *Task 4. Evaluation of Pavement Response Models*

This section reports the following:

- Two-moduli approach for computing the dynamic modulus of asphalt in MEPDG,
- Modification of MEPDG rapid solutions for predicting critical PCC bottom surface stresses using the two-moduli approach, and
- Initial assessment of CALME Rutting model.

This document presents a revision to the MEPDG stress computation procedure presented in the 1<sup>st</sup> quarterly report for 2010. The procedure builds on the MEPDG methodology but is modified to incorporate the two-moduli approach that shall represent the dynamic modulus of AC layer.

## 1. Dynamic modulus of asphalt using two-moduli approach

Asphalt concrete is a viscoelastic material whose load-deflection response is dependent on the elastic and the viscous components of the material. MEPDG simplifies the representation of the stiffness of asphalt through the use of a time-temperature dependent dynamic modulus. The dynamic modulus is computed using a master curve of sigmoidal shape, at a reference temperature of 70°F, as shown by the following equations:

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

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

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

$$\log(t_r) = \log(t) - c * (\log(\eta) - \log(\eta_{TR})) \quad (2)$$

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

For computing the AC dynamic modulus, the MEPDG uses vehicle speed to determine the rate of loading. However, axle loading and temperature curling have quite different loading durations. The traffic loads usually have a duration ranging between 0.01 sec. to 0.05 sec. depending on factors such as vehicle speed, radius of tire contact area, thickness of AC layer, modulus of subgrade etc. On the other hand, the temperature gradient that causes curling in the slab is a continuous function of time. However, as the stresses are computed for each hour of the pavement design life, the temperature gradient can be assumed to be a step function of time with duration of 1 hour (3600 sec).

An analysis was conducted to compare the dynamic modulus of the AC layer under such a state of traffic loads and temperature curling. Figure 1 illustrates the dynamic modulus of AC layer versus pavement age for a composite pavement located in Minneapolis, MN. The pavement consists of 4 in. AC over 6 in. PCC layer placed on an 8 in. A-1-a base and A-6 subgrade. All other inputs are MEPDG defaults. The AC dynamic modulus is calculated for the 3<sup>rd</sup> quintile monthly AC temperatures at the mid-depth of the AC layer. It was calculated using equations (1) and (2) for the loading time  $t$  corresponding to a) the MEPDG default traffic speed of 60 mph, and b) 3600 seconds (i.e., 1 hour of temperature loading).

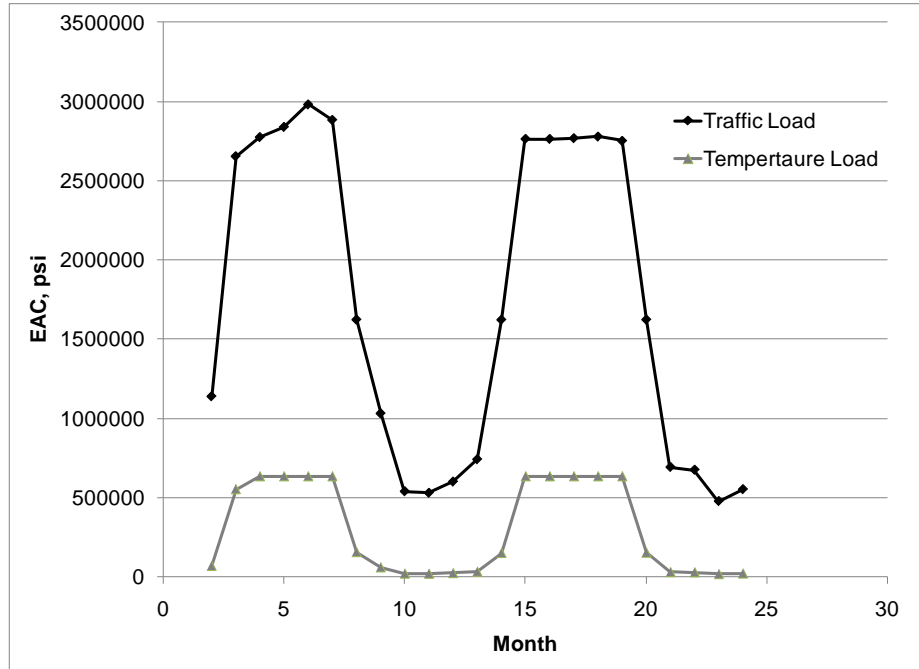


Figure 1. Asphalt stiffness versus pavement age.

It can be deduced from Figure 1 that the AC dynamic modulus is significantly different under typical traffic load durations and 1 hour of temperature loading. This implies that there are limitations in the characterization of the AC layer for composite pavements and it needs to be re-evaluated for stress computation under a combination of traffic loads and temperature curling.

As identified previously, the use of a single value of the AC dynamic modulus over-simplifies the stress computation process due to a combination of traffic loads and temperature curling. The over-simplification is attributed to the viscoelastic behavior of asphalt. Therefore, rather than attempting to solve the viscoelastic problem directly, a method is developed for approximating the viscoelastic process as multiple “equivalent-elastic” processes. It involves the use of the two separate moduli that represent the asphalt stiffness under traffic loading and temperature curling separately. The total PCC stress in the composite system is obtained as a combination of load stress computed using the instantaneous modulus, and temperature stress computed using long-term modulus. The following section describes the stress computation procedure using the two-moduli approach.

## 2. Modification of MEPDG algorithm for predicting critical PCC bottom surface stresses.

As stated before, the MEPDG algorithm for computing critical PCC stresses is modified to account for two-moduli of asphalt; 1) EACT based on temperature loading, and 2) EACL based on traffic loading. The stresses were determined for a wide range of site conditions, design parameters, and axle loading. Finally, the trained neural networks (NN), as implemented in the MEPDG, along with the concept of slab similarity were used to compute PCC stresses for each hour of the pavement design life.

### Step 1. Calculate the Effective Slab Thicknesses

Based on the interface conditions between AC-PCC layers and PCC-Base layers, the effective single-slab thickness for slabs 1 and 2 were calculated. The following equations are written for fully bonded interfaces. Similar equations were developed for other interface conditions.

$$h_{eff} = \sqrt[3]{\frac{E_{AC}}{E_{PCC}} h_{AC}^3 + h_{PCC}^3 + \frac{E_{Base}}{E_{PCC}} h_{Base}^3 + 12 \left[ \frac{E_{AC}}{E_{PCC}} h_{AC} \left( x - \frac{h_{AC}}{2} \right)^2 + h_{PCC} \left( h_{AC} + \frac{h_{PCC}}{2} - x \right)^2 + \frac{E_{Base}}{E_{PCC}} h_{Base} \left( h_{AC} + h_{PCC} + \frac{h_{Base}}{2} - x \right)^2 \right]} \quad (3)$$

where:  $h_{eff}$  is the thickness of the effective single layer slab.

For slab 1, the effective thickness  $h_{eff}$  was determined using  $EAC = EACT$ ; and for slab 2, the effective thickness  $h_{effL}$  was determined using  $EAC = EACL$ .

### Step 2. Calculate Unit Weight of the Effective Slabs

Based on the interface conditions between PCC and base layers, the effective single-slab unit weight was calculated. The weight of the AC layer is always accounted for as it is over the PCC layer.

$$\gamma_{eff} = \frac{h_{AC}\gamma_{AC} + h_{PCC}\gamma_{PCC} + h_{Base}\gamma_{Base}}{h_{eff}} \quad (4)$$

where:  $\gamma$  is the unit weight.

For slab 1, the effective unit weight  $\gamma_{eff}$  was determined using  $EAC = EACT$ ; and for slab 2, the effective unit weight  $\gamma_{effL}$  was determined using  $EAC = EACL$ .

### Step 3. Calculate Radius of Relative Stiffness

The radius of relative stiffness of effective slabs 1 and 2 are:

$$l_{eff} = \sqrt[4]{\frac{E_{PCC} h_{eff}^3}{12 * (1 - \mu_{eff}^2) * k}} \quad (5)$$

$$l_{effL} = \sqrt[4]{\frac{E_{PCC} h_{effL}^3}{12 * (1 - \mu_{eff}^2) * k}} \quad (6)$$

where:  $k$  is the coefficient of subgrade reaction.



#### Step 4. Calculate Effective Temperature Differential for Slab 1

Based on the interface conditions between AC-PCC layers and PCC-Base layers for slab 1, the equivalent temperature difference is determined.

$$\Delta T_{eff} = \frac{-12}{h_{eff}^2} \left( \begin{array}{l} \frac{\alpha_{AC} E_{AC}}{\alpha_{PCC} E_{PCC}} \frac{h_{AC}}{24} \sum_{i=1}^4 \left( T_i * \left( (3i-2) * \frac{h_{AC}}{4} - 3x \right) + T_{i+1} * \left( (3i-1) * \frac{h_{AC}}{4} - 3x \right) \right) \\ - \frac{\alpha_{AC} E_{AC}}{\alpha_{PCC} E_{PCC}} \frac{T_{11}}{2} h_{AC} (h_{AC} - 2x) \\ + \frac{h_{PCC}}{60} \sum_{i=1}^{10} \left( T_i * \left( (3i-2) * \frac{h_{PCC}}{10} - 3(x - h_{AC}) \right) + T_{i+1} * \left( (3i-1) * \frac{h_{PCC}}{10} - 3(x - h_{AC}) \right) \right) \\ - \frac{T_{11}}{2} h_{PCC} (h_{PCC} + 2h_{AC} - 2x) \end{array} \right) \quad (7)$$

#### Step 5. Compute Korenev's Non-dimensional Temperature Gradient

The Korenev's non-dimensional temperature gradient for effective slab 1 is given as:

$$\phi = \frac{2\alpha_{PCC}(1 + \mu_{PCC})l_{eff}^2}{h_{eff}^2} \frac{k}{\gamma_{eff}} \Delta T_{eff} \quad (8)$$

Since slabs 1 and 2 are similar, it implies that their Korenev's non-dimensional temperature gradients must be equal. Therefore for slab 2, the equivalent temperature difference can be defined as:

$$\Delta T_{effL} = \frac{l_{eff}^2}{h_{eff}^2 \gamma_{eff}} \frac{h_{effL}^2 \gamma_{effL}}{l_{effL}^2} \Delta T_{eff} \quad (9)$$

#### Step 6. Compute Adjusted Load/Pavement Weigh Ratio (Normalized Load)

$$q^* = \frac{P}{LW\gamma_{effL}h_{effL}} \quad (10)$$

where:  $q^*$  is the adjusted load/pavement weigh ratio,  
 $P$  is the axle weight,  
 $L$  is the slab length, and  
 $W$  is the slab width.

#### Step 7. Calculate Equivalent Slab Thickness

The equivalent slab thickness is a thickness of a slab with the modulus of elasticity and Possion's

ratio equal to 4,000,000 psi and 0.15, respectively, resting on the Winkler foundation with the coefficient of subgrade reaction equal to 100 psi/in, and having the same radius of relative stiffness as the effective slab. The equivalent slab thickness is determined using the following equation:

$$h_{eq} = \sqrt[3]{\frac{l_{eff}^4}{3410}} \quad (11)$$

where:  $h_{eq}$  is the equivalent slab thickness

Steps 8 to 13 (as explained in 1<sup>st</sup> quarterly report for 2010) were employed but with the modified Korenev's non-dimensional temperature gradient,  $\phi$ , and normalized load ratio  $q^*$ . Details of these steps are not provided to avoid repetition (refer to 1<sup>st</sup> quarterly report 2010 for further information).

Step 8. Compute Curling-Related Stresses in the Equivalent Slab

Step 9. Compute Curling-Related Stresses in the Effective Slab

Step 10. Using NNB1, Compute Load-only Caused Stresses in the Equivalent Structure from the Wheels Located at the Mid-slab

Step 11 (only if tandem or tridem). Compute Stresses from the Remaining Wheels in the Axle using NNB2

Step 12. Determine Load-only Caused Stresses in the Equivalent Structure from the Entire Axle

Step 13. Determine Load-only Caused Stresses in the Effective Slab

Step 14. Find Stress Load Transfer Efficiency for the Given Axle Load Configuration and the Axle Load Position

$$LTE_{stress} = \frac{\sigma_{eff}^B(LTE_{sh})}{\sigma_{eff}^B(0)} \quad (12)$$

Step 15. Find Axle Loading Induced Component of Bending Stresses in the Effective Slab if the Shoulder Provides no Edge Support to the Traffic Lane Slab

The axle loading induced component of bending stress is the stress in the slab caused by the action of axle loading along with temperature curling and is given as:

$$\sigma_{load,noshoulder} = \sigma_{eff}^A(P, \Delta T) - \sigma_{eff}^A(0, \Delta T) - \sigma_{eff}^A(P, 0) + \sigma_{eff}^B(0) \quad (13)$$

Step 16. Find Axle Loading Induced Component of Bending Stresses Accounting for the

### Shoulder Edge Support to the Traffic Lane Slab

$$\sigma_{load,shoulder} = \sigma_{load,noshoulder} * LTE_{stress} \quad (14)$$

### Step 17. Find Curling Stress using Similarity of Slabs

$$\sigma_{eff}^A (curling) = \frac{E_{PCC} * h_{eff} * \gamma_{eff} * k * (h_{eff} / 2) * l_{effL}^2}{E_{PCC} * h_{effL} * \gamma_{effL} * k * (h_{effL} / 2) * l_{eff}^2} \sigma_{eff}^A (0, \Delta T) \quad (15)$$

### Step 18. Find Bending PCC Stresses

Bending stresses (i.e., stresses caused by an axle load and a linear component of the temperature distribution) at the bottom and top of the PCC slab can be found using the following relationship:

1. Fully bonded AC/PCC and fully bonded PCC/base interfaces

$$\sigma_{PCC,bend} = \frac{2 * (h_{PCC} + h_{AC} - x)}{h_{effL}} \sigma_{load,shoulder} + \frac{2 * (h_{PCC} + h_{AC} - x)}{h_{eff}} \sigma_{eff}^A (curling) \quad (16)$$

2. Unbonded AC/PCC and unbonded PCC/base interfaces

$$\sigma_{PCC,bend} = \frac{h_{PCC}}{h_{effL}} \sigma_{load,shoulder} + \frac{h_{PCC}}{h_{eff}} \sigma_{eff}^A (curling) \quad (17)$$

3. Unbonded AC/PCC and fully bonded PCC/base interfaces

$$\sigma_{PCC,bend} = \frac{2 * (h_{PCC} - x)}{h_{eff}} \sigma_{load,shoulder} + \sigma_{eff}^A (curling) \quad (18)$$

4. Fully bonded AC/PCC and unbonded PCC/base interfaces

$$\sigma_{PCC,bend} = \frac{2 * (h_{PCC} + h_{AC} - x)}{h_{effL}} \sigma_{load,shoulder} + \frac{2 * (h_{PCC} + h_{AC} - x)}{h_{eff}} \sigma_{eff}^A (curling) \quad (19)$$

where:  $x$  is the depth of the N.A. from the top of the AC layer.

### Step 19. Find Total PCC Stresses

$$\sigma_{PCC} = \sigma_{PCC,bend} + \sigma_{NL,PCC,bot} \quad (20)$$

where:  $\sigma_{PCC}$  is the total stress at the bottom of the PCC slab,  
 $\sigma_{PCC,bend}$  is the bending stress at the bottom of the PCC slab, and

$\sigma_{NL,PCC,bot}$  is the stress at the bottom of the PCC layer caused by the nonlinear strain component of the temperature distribution.

The neural networks and the computed critical PCC stresses were implemented into a FORTRAN program on guidelines similar to MEPDG. This program computes the stress for each hour of the pavement design life based on the hourly temperature distributions in the AC and PCC layer and traffic distributions obtained from MEPDG internal files.

### 3. Initial assessment of CALME Rutting model.

The calculation of rut depth using the CALME rutting model was analyzed in-depth. It was found that the rut-depth calculation is a two-step process which involves:

- A. Computation of fatigue damage, and
- B. Calculation of rut depth based on fatigue damage.

The following algorithm was used to compute the fatigue damage:

Step A1 – Calculate E at the current damage level, using a time-temperature dependent master curve of sigmoidal shape.

$$\log(E) = \delta + \frac{\alpha(1 - \omega)}{1 + \exp(\beta + \gamma \log(t_r))} \quad (21)$$

where:  $E$  is the dynamic modulus,  
 $t_r$  is the reduced time which depends on the duration of loading, pavement temperature, and asphalt weight,  
 $\omega$  is the damage in the asphalt layer, and  
 $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\delta$  are constants.

Step A2 – Given the modulus, compute the strain at the bottom of the asphalt layer  $\mu\epsilon$  using layered elastic analysis (LEA).

Step A3 – Calculate MNp, i.e. allowable number of load repetitions using E.

$$MNp = A' * \left( \frac{\mu\epsilon}{\mu\epsilon_{ref}} \right)^{\beta 2} * \left( \frac{E}{E_{ref}} \right)^{\gamma 2} * \left( \frac{E_i}{E_{ref}} \right)^{\delta 2} \quad (22)$$

where:  $E$  is the modulus of damaged material,  
 $E_i$  is the modulus of intact material,  
 $E_{ref}$  is the reference asphalt modulus  
 $\mu\epsilon_{ref}$  is the reference asphalt strain in microstrain  
 $\mu\epsilon$  is the strain at the bottom of the asphalt layer computed on the top of the crack or joint, and  
 $\beta 2$ ,  $\gamma 2$ , and  $\delta 2$  are constants.

Step A4 – Calculate the “effective” number of load applications  $MN_0$  (in millions) that would have been required, with the present parameters, to produce the condition at the beginning of the increment.

Step A5 – Calculate damage for the “effective” number of load applications plus the number of applications during the increment (in millions).

$$\omega = \left( \frac{MN}{MN_p} \right)^{\alpha_2} \quad (23)$$

where:  $MN$  is the number of load repetitions in millions  
 $\alpha_2$  is a constant  
 $MN_p$  is the allowable number of load repetitions in millions

Step A6 - Update the modulus E with respect to the damage of the current increment.

$$\log(E) - \delta = (\log(E_1) - \delta) \times (1 - \omega) \quad (24)$$

Step A7 – Repeat Step A1 to A6 for next increment of loads.

Steps A1 through A7 generate the fatigue damage in AC due to each increment of load repetition. The next step now includes calculation of rut depth corresponding to each increment. The rut depth calculations are performed for each AC sublayer in the top 100 mm of the AC layers. The final rut depth is given as the sum of rut depth of each sublayer. This process also involves calculation of the shear stress at a depth of 50 mm beneath the edge of the tire as shown in Figure 2.

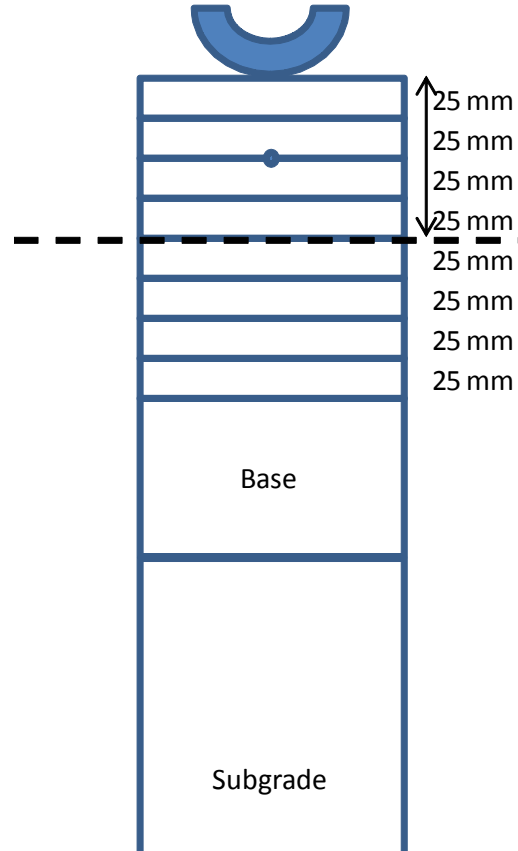


Figure 2. Example of the various sublayers in the top 100 mm of AC layers for rut depth calculations.

Step B1 – With the known fatigue damage and corresponding damaged elastic modulus, the shear stress at a depth of 50 mm beneath the edge of the tire is calculated using LEA.

Step B2 – Calculate elastic shear strain for the given increment.

$$\gamma^e = \frac{\tau}{E_i / (1 + \nu_i)} \quad (25)$$

where:  $E_i$  is the modulus of layer  $i$ , and  $\nu_i$  is Poisson's ratio for layer  $i$ .

Step B3 – Calculate the “effective” number of load applications  $N_0$  that would have been required, with the present parameters, to produce the condition at the beginning of the increment.

Step B4 - Calculate inelastic shear strain for the “effective” number of load applications plus the number of applications during the increment.

$$\gamma^i = \exp\left(A_3 + \alpha_3 * \left[1 - \exp\left(-\frac{\ln(N)}{\gamma_3}\right) * \left(1 + \frac{\ln(N)}{\gamma_3}\right)\right]\right) * \exp\left(\frac{\beta_3 * \tau}{\tau_{ref}}\right) * \gamma^e \quad (26)$$

where:  $\tau$  is the shear stress calculated using the layered elastic analysis program at 50 mm below the tire edge,  
 $N$  is the number of load repetitions,  
 $\tau_{ref}$  is a reference shear stress (0.1 MPa  $\approx$  atmospheric pressure),  
 $A_3$ ,  $\alpha_3$ ,  $\beta_3$ , and  $\gamma_3$  are constants, and  
 $\gamma^e$  is the elastic shear strain.

Step B5 – Calculate permanent deformation.

$$dp_i = K * h_i * \gamma^i \quad (27)$$

where:  $h_i$  is the thickness of layer  $i$  (above a depth of 100 mm), and  
 $K$  is a calibration constant = 1.4  
 $\gamma^i$  is the inelastic shear strain in the asphalt layer.

Step B6 – Repeat steps B1 to B5 for the next increment.

Step B7 – Perform similar calculations for all other AC sublayers and add up the permanent deformations to obtain the total rut depth.

Steps A4 and B3 account for the incremental-recursive process adopted in the CALME models. The algorithms A and B are in the process of development in Excel / Mathematica and would be subsequently written in FORTRAN language for programming purposes.

### *Task 6. Develop Construction Guidelines*

The subtask was delayed due to problems with consulting agreements with Drs. John Harvey and Jim Signore. A team meeting had been conducted in Davis, CA. The work on this task has been initiated.