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: July 1 – September 30, 2009

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 $100,400.	

WORK COMPLETED:
Research team completed corrections to Task 1 report and submitted the revised report to Mn/DOT. The research team obtained and evaluated Mn/DOT thermocouple sensor data from Cell 6. It was found that more than 97% of the data were reliable – unreliable/low-quality data were flagged and eliminated from consideration. Temperature data from Cell 54 were found to be of insufficient quality and were disregarded from use in the project research. The research team conducted a complete evaluation of the structural models for cracking of AC overlays. This evaluation called into question underlying assumptions made by the MEPDG models, and the validity of these assumptions will be further examined going forward. The research team began work on these structural models and continues that work into the next quarter.

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:
All work is on schedule.

Task 1. Literature review.

A revised literature review was completed according to suggestions from panel reviewers.

Task 3. EICM Validation and Analysis

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.

Background

Cell 106 and Cell 206 are AC over PCC composite pavements located on the mainline section at the MnROAD test facility. Sensors were installed at various depths throughout the pavement.

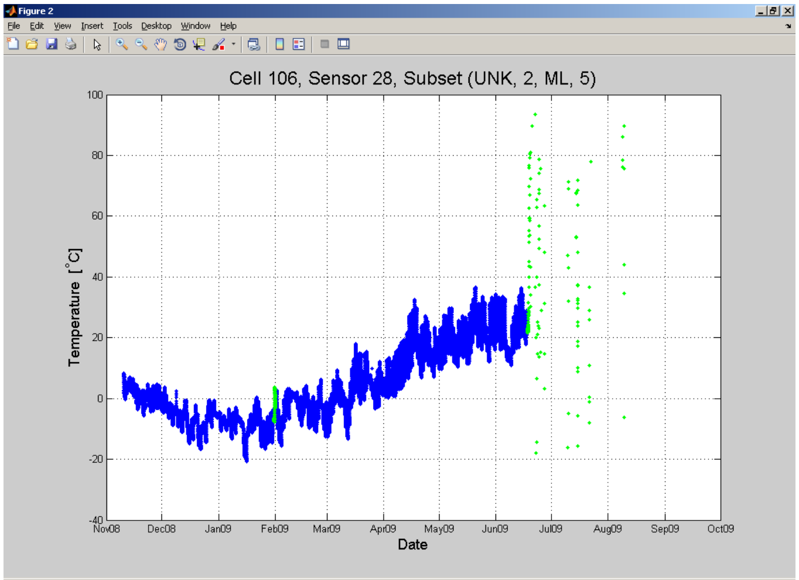
Analysis

Temperature data that appears to be erroneous to the statistical software is flagged. There are fourteen different "flags", each of which represents a different data test failure. The flags are defined as follows:

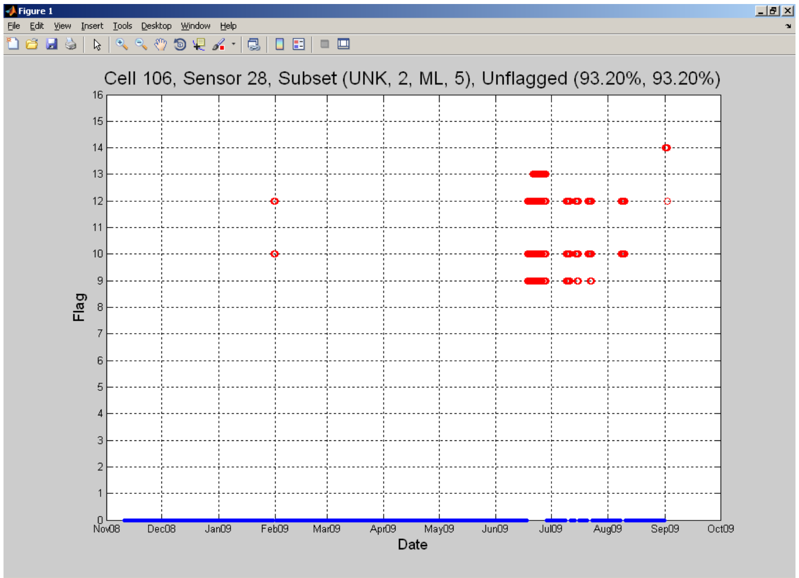
```
In this section we define constants for each of the flags.
%----------------------------------------------------------------------------
--

% Missing data flags
FLAG_MISSING_DATA            = 1;    % missing data
FLAG_NOT_YET_OPERATIONAL     = 2;    % missing data at the beginning
FLAG_DEACTIVATED             = 3;    % missing data at the end
FLAG_TOO_SPARSE_DAY          = 4;    % not enough data in any day

% Time-series based
FLAG_OUT_OF_RANGE            = 5;    % sensor outliers with annual &
diurnal fit
FLAG_NEIGHBORHOOD_OUTLIERS   = 6;    % sensor outliers with local
neighborhood fit
FLAG_LAG_ONE_OUTLIERS        = 7;    % sensor outliers in lag one

% Subset-based flags
FLAG_POINT_EXTREMES          = 8;    % subset outliers, record-by-record
FLAG_DAILY_RANGE             = 9;    % subset daily range outliers, day-
by-day
FLAG_DAILY_EXTREMES          = 10;   % subset daily extreme outliers, day-
by-day

% Sensor-by-sensor consistency
FLAG_INTERMITTENT_DATA       = 11;   % too many flagged data points around
FLAG_INCONSISTENT_DAY        = 12;   % too small of a fraction of good
data, day-by-day
FLAG_INCONSISTENT_WEEK       = 13;   % too small of a fraction of good
data, week-by-week
FLAG_INCONSISTENT_MONTH      = 14;   % too small of a fraction of good
data, month-by-month
```

Temperature data from 48 sensors in cell 106 and 16 sensors in 206 were tested. In some cases, such as cell 106 sensor 28, it is obvious there is a problem with the temperature data when looking at the temperature versus time plots, as is observed below starting in mid-June 2009.

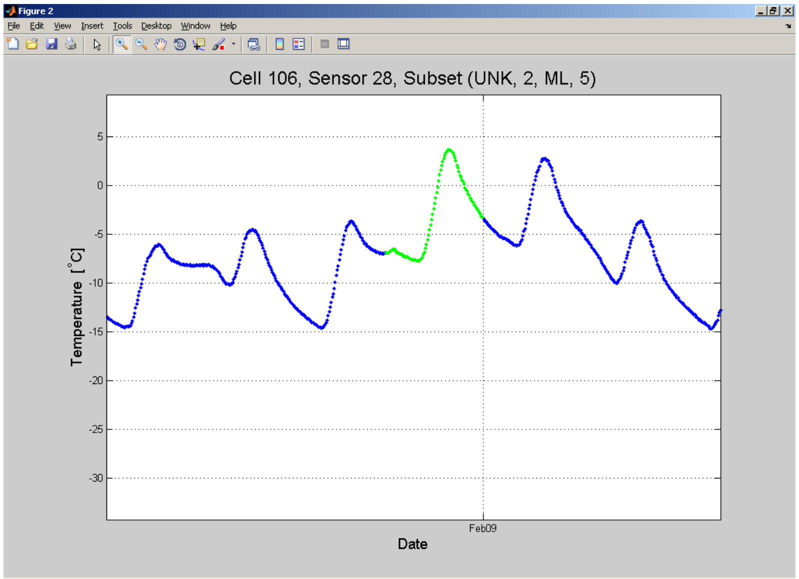
Flagged data is green-colored, un-flagged is blue.



Not all temperature plots are as revealing at first glance. Even within one temperature plot, some data may be overlooked. Note that there is also a period at the end of January 2009 that is flagged. To account for this, another output consists of a plot of flags versus time. The Y – axis consists of the flag present, the X – axis represents time.

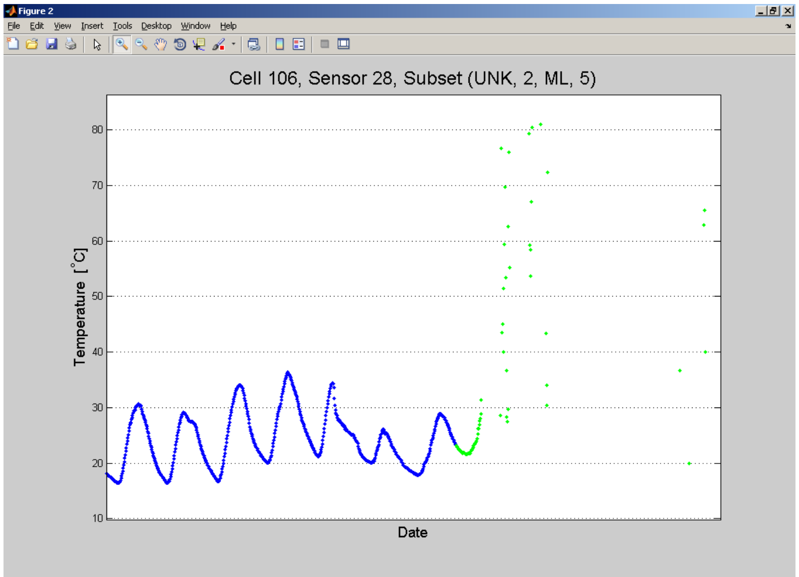


The flags present in late January 2009, 10 and 12, indicate that the data has daily extreme outliers, and is inconsistent from day to day, respectively. This means the daily maximum and minimum values are too extreme, and there is too small a fraction of good data day by day. The data flagged in mid-June has the following flags present: 9 (daily range), 10 (daily extremes), 12 (inconsistent day to day), 13 (inconsistent week to week), 14 (inconsistent month to month). Closer examination of the data flagged in January reveals what is likely the problem, which can be seen below.



The minimum value was "expected" to be lower than what was recorded. This is determined by other observations in the same subset. Sensors in the same subset are of similar depth and material. This is visible where the data first is flagged "green". Even though the data looks reasonable, the software indicates there is a problem.

The following image is shows a close-up of the data in mid-June. It is clearly visible from the following image that something went completely wrong with the sensor.



Below is a table indicating the percentage of un-flagged data for each temperature sensor in cell

106 and cell 206. This information is calculated during the data analysis, and is visible on the flag versus time plots.

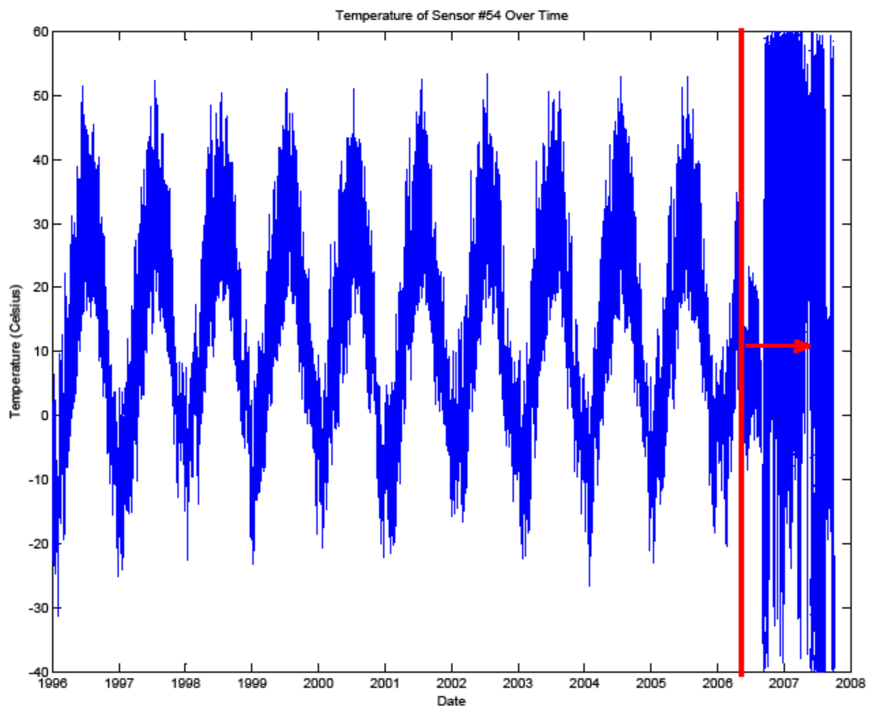
Cell	Sensor	Unflagged
106	1	98.95%
106	2	99.29%
106	3	99.29%
106	4	99.29%
106	5	99.29%
106	6	99.29%
106	7	99.63%
106	8	98.28%
106	9	98.61%
106	10	98.95%
106	11	98.95%
106	12	99.29%
106	13	99.29%
106	14	99.29%
106	15	99.63%
106	16	99.29%
106	17	98.28%
106	18	91.51%
106	19	88.80%
106	20	98.28%
106	21	94.22%
106	22	85.42%
106	23	93.54%
106	24	96.92%
106	25	98.28%
106	26	98.28%
106	27	98.28%
106	28	93.20%
106	29	99.29%
106	30	99.63%
106	31	99.63%
106	32	99.63%
106	33	99.63%
106	34	99.63%
106	35	99.63%
106	36	99.63%
106	37	99.63%
106	38	99.63%
106	39	98.28%
106	40	98.61%
106	41	98.61%
106	42	98.61%
106	43	98.61%
106	44	99.29%
106	45	99.63%
106	46	88.13%
106	47	98.95%
106	48	98.61%

Cell	Sensor	Unflagged
206	1	98.07%
206	2	98.83%
206	3	98.83%
206	4	98.07%
206	5	98.07%
206	6	98.07%
206	7	98.07%
206	8	98.07%
206	9	99.21%
206	10	99.21%
206	11	99.21%
206	12	99.21%
206	13	98.83%
206	14	98.83%
206	15	99.21%
206	16	99.21%

It should be noted that the percentage of un-flagged data may be misleading, if that is the only parameter considered. For cell 28, which was examined above, 93.20% of the data is un-flagged. Depending upon the use of the data, the user may think that the entire time period should be discarded because of the high percentage of flags. Closer inspection to the temperature and flag graphs indicate that the data is reliable and of high quality until about the middle of June 2009.

Cell 54

Additionally, Cell 54 was also examined. The analysis indicated that temperature sensor in Cell 54 experienced some problems beginning in 2006. All data more recent than early 2006 are considered unreliable.



Task 4. Evaluation of Pavement Response Models

<u>Cracking of the PCC layer in composite pavements –</u>

This section describes the current model adopted in the MEPDG for the cracking of the PCC layer in composite pavements. The Mechanistic Empirical Pavement Design Guide (MEPDG) contains prediction models corresponding to various distresses in a pavement which are used further to predict the design life. One such distress model for predicting the PCC cracking in a composite pavement was adopted directly from the fatigue cracking model of a new rigid pavement. This model and its limitations are discussed in the following sections.

1 Modeling of Cracking in MEPDG

The MEPDG considers the cracking in the PCC layer of a composite pavement to initiate at the bottom of the layer away from the transverse joints (NCHRP 1-40B 2007). It then propagates upwards toward the AC layer as shown in figure 1. Cracking is caused by tensile stresses in the bottom of the PCC layer due to repeated traffic loading, temperature gradient, or their combination that exceeds the structural capacity of the PCC slab. The crack in the PCC layer typically occurs as a hairline crack in the center of the bottom portion of the PCC slab and eventually propagates to the top and across the slab over time and traffic.

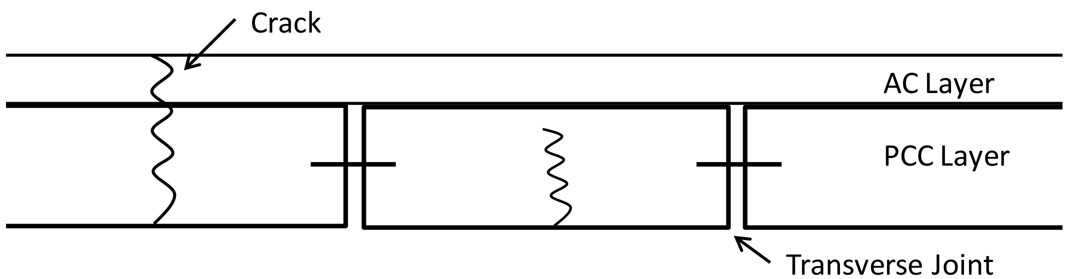


Figure 1. Fatigue cracking in the PCC layer of composite pavement.

The distress model for cracking of the PCC layer in a composite pavement is adopted from the fatigue cracking model of a new jointed plain concrete pavement (JPCP or rigid pavement). The cracking in the PCC layer is given as follows:

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

where: CRK is the percentage of bottom up PCC cracking, and
FD is the fatigue damage defined as follows:

$$FD = \sum \frac{n_{t,j,k,l,m,p}}{N_{t,j,k,l,m,p}} \qquad (2)$$

where: n is the applied number of load applications at conditions t, j, k, l, m, p.
N is the allowable number of load applications at conditions t, j, k, l, m, p.
t, j, k, l, m, p are conditions relating to the age, month, axle type, load level, temperature difference, and traffic path, respectively.

The allowable number of load applications (N) is determined using the following equation:

$$\log(N_{t,j,k,l,m,p}) = C_1 . \left(\frac{MR}{\sigma_{t,j,k,l,m,p}} \right)^{C_2} + 0.4371 \qquad (3)$$

where: MR is the modulus of rupture of PCC,
σ is the applied stress at conditions t, j, k, l, m, p, and
C_1, C_2 are calibration constants (C_1 = 2.0, C_2 = 1.22).

Therefore, cracking in the PCC layer is a function of the "applied stress" and thus depends on the traffic load and the temperature gradient.

The JPCP cracking model was modified to account for the effect of the AC overlay in the composite pavement using an equivalent slab thickness approach (NCHRP 1-40B 2007). According to this approach the composite pavement is converted to an equivalent JPCP structure as shown in figure 2.

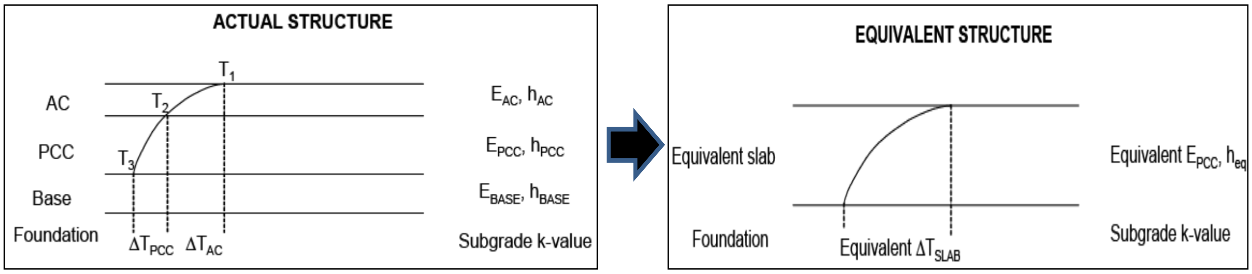


Figure 2. Conversion of a composite pavement structure to an equivalent JPCP structure.

The layer thickness, layer modulus, and the temperature gradient of AC as well as PCC layers were modified to establish the equivalent structure. The following assumptions were made to define the equivalent structure:

- The equivalent temperature gradient must induce the same magnitude of moments in the equivalent structure as in the PCC slab of the original composite structure, and
- The deflection basin of the equivalent structure is same as the original composite structure under the same conditions of traffic and temperature loading.

Establishing the equivalency between a composite structure and an equivalent JPCP structure is a theoretically sound concept, however, the manner in which it modeled the cracking of PCC in composite pavements introduced some limitations. The following are considerable issues:

- It implies from the first assumption that for calculating the moments due to the temperature gradient only PCC layer was considered and the AC layer was neglected.
- The temperature gradient in the AC layer was neglected by setting the coefficient of thermal expansion (CoTE) of asphalt equal to zero. It must be noted that the CoTE of asphalt is reported as approximately 3 times the CoTE of concrete (Jenq et al. 1993).
- The contribution of the flexural stiffness of AC layer was considered but it was based on the dynamic modulus of asphalt which is not representative of the combination of traffic and temperature loads that cause cracking in the PCC layer.
- The dynamic modulus of asphalt was originally developed for rutting predictions in the MEPDG and does not account for the PCC layer placed between the AC layer and the base as in a composite pavement.
- The cracking model is based on the assumption that the AC modulus changes on a monthly basis whereas the stresses at the bottom of the PCC layer are calculated at the end of each hour of the pavement design life. This assumptions needs to be modified as asphalt exhibits high sensitivity to temperature.

Therefore, there is a need to address the limitations of the cracking model for PCC layers and the material model for asphalt modulus utilized for the modeling of cracking behavior in composite pavements in MEPDG. In order to understand the modeling of the AC modulus in MEPDG, section X.2 details the current process. The limitations due to its use for modeling of cracking of PCC layer in composite pavements are also briefly discussed.

Research methodology for addressing both these issues, namely the consideration of AC layer in the equivalent structure and the modulus of asphalt utilized for this analysis, has been developed and the research is under progress in initial stages. The preliminary results are reported in section X.3.

2 Modulus of Asphalt in MEPDG

The stiffness of asphalt is expressed in terms of a time-temperature dependent dynamic modulus in the framework of MEPDG. It is determined by a master curve of sigmoidal shape, at a reference temperature of 70°F, as shown by the following equation:

$$\log(E_{AC}) = \delta + \frac{\alpha}{1 + \exp(\beta + \gamma \log(t_r))} \tag{4}$$

where: δ, α, β, and γ 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:

$$\log(t_r) = \log(t) - c * \left(\log(\eta) - \log(\eta_{TR})\right) \tag{5}$$

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

MEPDG utilizes the Odemark's method of equivalent thickness (MET) concept for a three-layered system of an AC layer over a granular layer (base) and subgrade as presented by figure 3. According to this concept the stresses and strains below a layer depend on the stiffness of that layer only (AASHTO 2009).

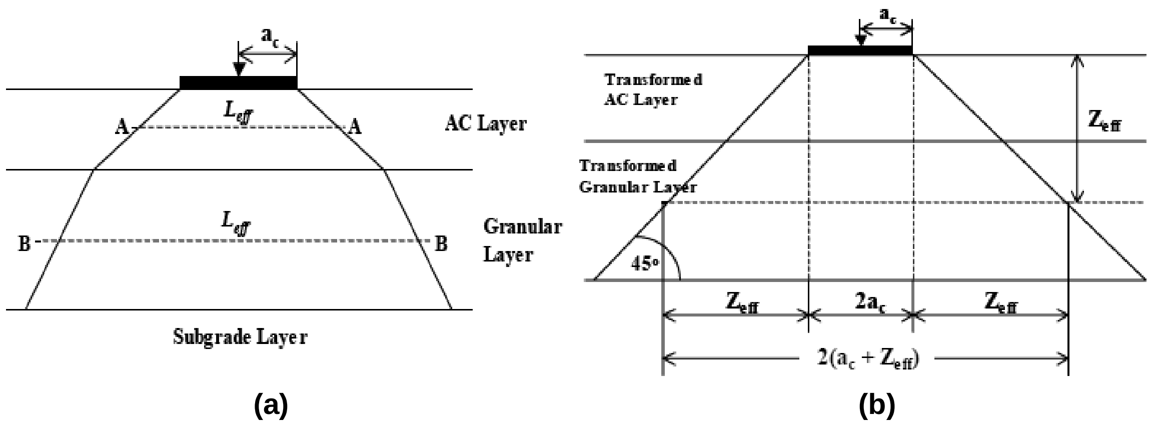


Figure 3. Effective (a) length and (b) depth for single axle in a conventional flexible pavement.

The expression for the actual loading time employs the effective length (L_{eff}) and depth (Z_{eff}) concept based on MET. The loading time (t) is given as:

$$t = \frac{L_{eff}}{17.6 * V_s} \quad (6)$$

where:

$$L_{eff} = 2*(a_c + Z_{eff}) \quad (7)$$

$$Z_{eff} = \sum_{i=1}^{n-1}\left(h_i * \sqrt[3]{\frac{E_i}{E_{SG}}}\right) + \frac{h_n}{2} * \sqrt[3]{\frac{E_n}{E_{SG}}} \quad (8)$$

a_c is the radius of contact area,
n is the layer to be transformed,
h is the thickness of a layer,
E is the modulus of a layer, and
E_{SG} is the modulus of the subgrade layer.

The dynamic modulus of asphalt is the only property that describes the stiffness of asphalt in the MEPDG. The effect of a stiffer PCC layer between the AC layer and the granular base is not considered for the modeling of the dynamic modulus in case of composite pavements. As the distribution of stress depends on the stiffness of the layer, the distribution of stresses in a composite pavement is significantly different than the three-layered system (of AC on base and subgrade) considered by the MEPDG. This limitation needs to be corrected if the dynamic modulus is to represent the asphalt stiffness for composite pavements.

Moreover, on closer inspection it was found that the effect of the base layer is also not considered for the calculation of the effective depth of an asphalt layer placed on a granular base and subgrade. This is a deviation from the theory of Odemark's MET based on which the equivalent thickness model is developed. From equation (8) and figure 3b, the effective depth of the asphalt layer would be expressed as:

$$Z_{effAC} = \frac{h_{AC}}{2} * \sqrt[3]{\frac{E_{AC}}{E_{SG}}} \qquad (9)$$

From equation (9) it can be established that the effective depth for AC layer has no contribution of either the base stiffness or the PCC stiffness. Moreover, it requires the value of unknown parameter – modulus of asphalt (E_{AC}) which is calculated using equation (4). Therefore, the solution to equations (4) to (8) is an iterative process which requires an initial assumption of the dynamic modulus. In this process, the dynamic modulus should converge to a final value at the end of certain number of iterations.

An analysis was performed to obtain the dynamic modulus of AC layer in a composite pavement using Microsoft Excel. The pavement structure designed for the MEPDG analysis is given in table 1. The 4-in AC layer was divided into five sublayers as per the MEPDG methodology. The dynamic modulus was calculated manually for the last sublayer and was compared to the dynamic modulus obtained through MEPDG analysis. The temperature of the AC sublayer required for the analysis was read from the Enhanced Integrated Climatic Model (EICM) files. The result of the analysis for the first two years of the pavement design life is shown in figure x.4.

Table 1 Example of composite pavement designed in MEPDG for analysis.

Design	AC over JPCP		Structure	
Design life	20 years		Surface	AC, 4 inches, PG 58-28
Climate	Minneapolis, MN		JPCP (existing)	PCC, 10 inches, 28-day MR = 690 psi
AADTT	250		Base	A-1-a, 8 inches, Modulus = 40,000 psi
			Subgrade	A-6, semi-infinite, Modulus = 14,000 psi
All else	MEPDG defaults		*All else*	MEPDG defaults

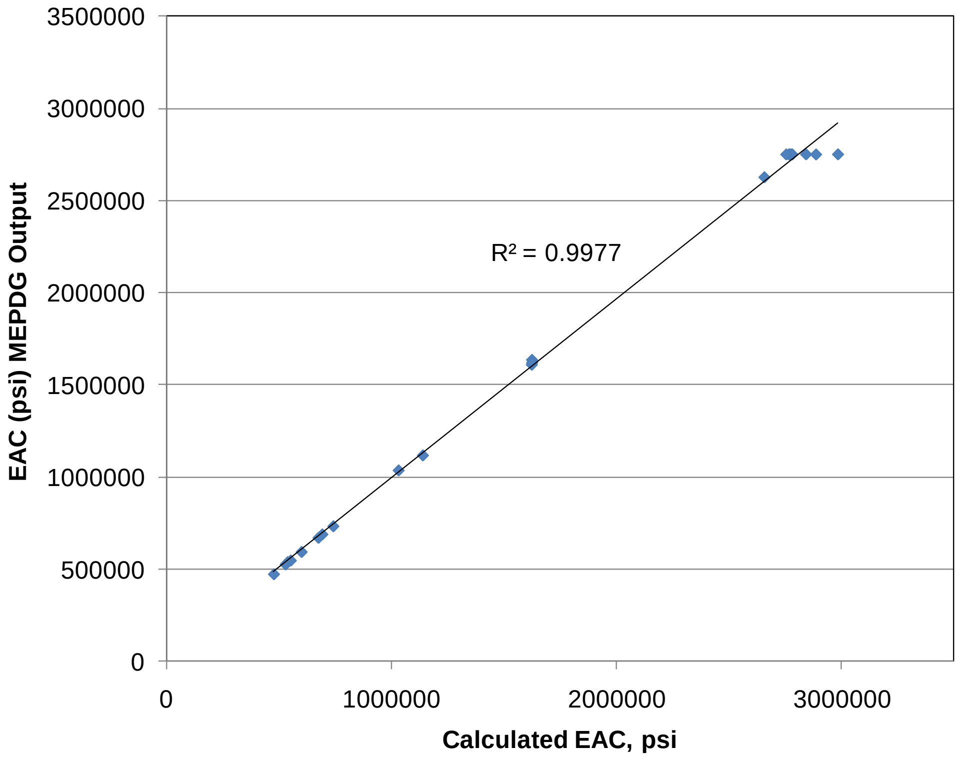


Figure 4. AC modulus – Calculated vs MEPDG output.

Figure 4 confirms the proposition that the base thickness and stiffness are not considered while calculating the dynamic modulus of AC, even though the theory was developed using the transformed base thickness and stiffness.

Since asphalt exhibits viscoelastic properties, it is highly sensitive to temperature and the rate of loading. Therefore, a significant issue relates to the use of only one value of the AC modulus for different rates of loading. This approach over-simplifies the distress computation process due to traffic loads and temperature gradients. The traffic loads have high rate of loading which have extremely small duration (approximately a few milliseconds), whereas the temperature loads are applied for one hour for the sake of stress computation. Since asphalt undergoes creep under constant stress Therefore, there is a need to develop a material model for the behavior of asphalt that can correctly account for the stresses due to traffic and temperature gradient.