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EFFECTS OF THERMAL PROPERTIES ON TEMPERATURE AND MOISTURE PROFILES, AND THE PERFORMANCE OF PCC PAVEMENTS

Upender Kodide and Alex Hak-Chul Shin
Department of Civil and Environmental Engineering, Louisiana State University, Patrick F. Taylor Hall, Baton Rouge, LA, USA
E-Mail: shin@lsu.edu

ABSTRACT

To understand the effects of thermal properties on temperature and the moisture profile in Portland cement concrete (PCC) pavements, an Enhanced Integrated Climatic Model (EICM) analysis was performed for a typical PCC pavement section in Louisiana. The EICM analysis showed that the temperature in the middle layer of PCC pavement decreased as thermal conductivity increased, and the temperature remained constant for higher thermal conductivity values. Temperature was measured at several depths of a concrete block embedded in soil and was compared to the temperature profile predicted by the EICM. Measured temperatures inside the concrete block were higher than the temperatures predicted by the EICM. The measured temperatures reached a peak hour temperature gradient on the hottest time of day, but the EICM model did not predict the peak hour temperature gradient. MEPDG analysis was performed to estimate the effect of thermal properties on the distress of PCC pavements. From the analysis it was found that thermal cracking increased with the decrease of thermal conductivity. It was also noticed that an Integrated Climatic Model (ICM) stability failure occurred for a specific set of thermal conductivity and heat capacity readings in the MEPDG analysis. A line is proposed to differentiate the ICM stability check error passing zone and failure zone.

Keywords: Portland cement concrete pavements, thermal properties, EICM, MEPDG, temperature gradient, ICM stability check.

1. INTRODUCTION

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is new pavement design guide developed to overcome the limitations of the current AASHTO design guide. MEPDG was developed based on the National Cooperative Highway Research Program (NCHRP) project 1-37A [1, 2]. MEPDG is the first design guide to consider thermal properties as the major input parameters and their effects on the serviceability of the Portland cement concrete (PCC) pavements. Thermal properties incorporated in MEPDG exhibit the heat flow based on the construction materials used in pavements. Heat flow mechanism describes the temperature gradients and moisture profiles to analyze the thermal stresses and strains in PCC pavements in MEPDG. Enhanced Integrated Climatic Model (EICM) included in the MEPDG predicts the temperature and moisture profiles. EICM requires input data such as hourly sunshine, hourly temperature, humidity, and rainfall data at the site of the pavement.

1.1 Thermal properties and moisture in PCC pavements

Climatic conditions are related to pavement performance by the heat flow mechanisms and moisture models. The amount of heat flow and moisture is determined by the thermal properties of the material. Three thermal properties incorporated in MEPDG are coefficient of thermal expansion (CTE), thermal conductivity, and heat capacity. The CTE measures strains that occur due to a change in temperature. Thermal conductivity indicates temperature flow, and heat capacity represents the amount of heat energy stored in a material. Among these thermal properties, thermal conductivity is one of the most important input parameters in heat transfer modeling. MEPDG recommends ASTM 1952 to test concrete thermal conductivity for the Levels 1 and 2 analysis and recommends a range of 1.0 - 1.5 Btu/ft·hr·°F, with a typical value of 1.25 Btu/ft·hr·°F for the Level 3 [3, 4].

According to Donald J. Jansen [5], moisture distribution in concrete is non-linear from top to bottom surface in PCC pavements. The moisture increases rapidly in the top two inches and then gradually increases from that point to the bottom surface. The usual moisture content in concrete is 70-80%. From the top two inches of pavement surface the moisture content remains around 80 - 90% and is even 100% at times.

1.2 Enhanced integrated climatic model (EICM)

EICM, software embedded in MEPDG, analyzes the temperature and moisture profiles of pavements. EICM was designed to simulate one-dimensional coupled heat and moisture profiles based on climatic behavioral change. The prediction process is carried in four stages by inputting several parameters at different stages. The non-linear temperature variation is converted into linear temperature gradient. The linear temperature gradient is used to estimate the pavement heat transferring ability and average moisture present per month using thermal properties as one of the input parameters. Levels 1 and 2 are detailed hierarchical material input data which is used to estimate accurate moisture levels. Default thermal conductivity and heat capacity values are taken for prediction of temperature and moisture, but thermal properties are unique values for every concrete mixture [6, 7].

To run an EICM model, several input parameters are required including pavement properties, material properties, local environment data, optimum moisture content, material properties of unbound layers and gradation, GWT (ground water table), and hourly climatic data such as temperature, precipitation, sunshine, and wind speed. This data is collected from the databases of weather stations [2, 3].

EICM consists of three major components: the Climatic-Material-Structural (CMS) model, the Cold Regions Research and Engineering Laboratories (CRREL) model for frost and thaw penetration, and the Infiltration and Drainage (ID) model. The CMS model is a finite heat transferred model to predict temperature profiles in pavement using convection, radiation, conduction, and latent heat processes. This model requires the following input parameters: heat capacity of pavement materials, thermal conductivity of pavement materials, air temperature, pavement surface absorptivity and emissivity, wind speed, and incoming solar radiation. The CRREL model predicts the moisture flow in the subgrade soil as well as the frost and thaw penetration of layers. Using the output of the CMS model, the CRREL model also predicts the soil temperature profile and frost and thaw penetration.

2. OBJECTIVES

The objective of this research is to verify the EICM predicted temperature profile by comparing with the measured temperature profile. The measured thermal conductivity and heat capacity values were used as input data in the EICM analysis to estimate the temperature profiles and moisture profiles in a pavement. MEPDG analysis was performed with measured thermal properties to study the effects of thermal properties on the performance of a PCC pavement.

3. METHODOLOGY AND MODELING OF EICM

3.1 Temperature measurement

A concrete block with the depth of twelve inches was fabricated to monitor temperature gradients and humidity inside the concrete as shown in Figure-1. The concrete block was made of 60% coarse aggregate (Kentucky limestone), 40% fine aggregate (siliceous sand), and Type-1 Portland cement with a water-cement ratio of 0.45. The concrete block has five perforations located at certain depths (1, 3.5, 6, 8.5, 11-inches) along the breadth and five I-buttons were placed in all perforations. I-button is a wireless sensor that measures and records the temperature and humidity in concrete. The diameter of the sensor is 0.79 inches. This sensor was placed in a void created during casting and sealed off with a rubber stopper in order to prevent any air or water from traveling through it. The concrete block was then covered with aluminum foil to prevent temperature and humidity penetration from the sides. This kept the block intact for one-dimensional heat transfer model, i.e., heat only moves from the top to the bottom, thus preventing heat loss from the sides. This specimen was then placed into the soil, exposing its top surface clearly to the sunlight. Readings of temperature and humidity were taken for 53 days, using the I-buttons.

Thermal conductivity and heat capacity were measured using Quickline-30 equipment; the top surface of the concrete cylinder was finely grounded for better contact to the Quickline-30 probe. The details of the measured thermal properties are presented in another publication [8]. The measured thermal properties were used as input data in EICM.

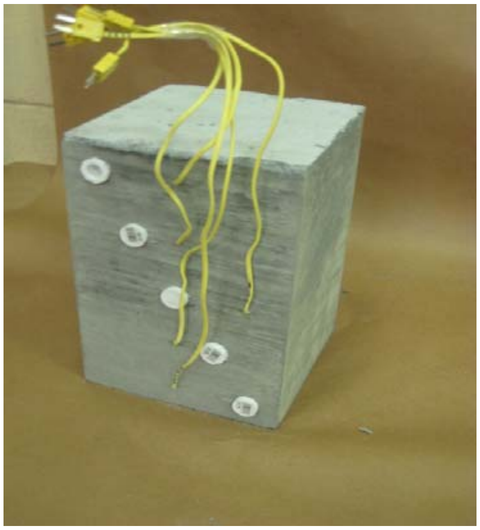

Figure-1. Concrete block with five I-buttons.

3.2 EICM analysis

The major input parameters required for the EICM analysis are (a) hourly air temperature, (b) hourly wind speed, (c) hourly sunshine percentage, (d) hourly precipitation, (e) hourly humidity, and (f) water table of the site where pavement is to be modeled. Pavement properties such as (g) thermal conductivity, (h) heat capacity, (i) unit weight, (j) thickness of the pavement, (k) base layers properties, and (l) soil layers properties are essential for modeling pavement in EICM. The EICM 3.4 version also requires sieve analysis details of the base layer and sub-base layers. Using the pavement properties and climatic conditions data collected from the site, a model was developed for analysis. Two different models were designed for understanding the reliability of EICM software and thermal conductivity effects on pavement performance. First, the EICM model was run to verify the accuracy of EICM model by comparing the predicted temperature profile with measured profile at a site in Louisiana Transportation Research Center (LTRC). Secondly, EICM model was used to calculate the temperature and moisture profiles in concrete specimens for predicting pavement performance for different thermal conductivity and heat capacity values.

3.2.1 Comparison of temperature profiles (EICM prediction vs. measured)

A concrete block was casted and installed with sensors to record the temperature and moisture as stated earlier. An EICM model was developed with the site conditions where concrete specimens were placed. Climatic data of the pavement was collected from the weather site.
(http://www.wunderground.com/history/airport/KBTR/2010/7/13/DailyHistory.html)

The pavement model consists of the following input data:

- 12 inches thick PCC pavement with a typical concrete mixture using in Louisiana. The mixture has dry thermal conductivity (1.262 Btu/ft·h·˚F), heat capacity (0.198 Btu/lb·˚F), and a unit weight (147.4 lbs/yd^3).
- Two 120 inches A-6 type soil layers.
- The pavement model was made without base layer to simulate the practical experiment.
- Temperatures at specific depths of concrete specimen were measured using I-buttons. Hourly climatic data measured for fifty three days was as input in the model.

A flow chart of the work plan is presented in Figure-2. The EICM predicted temperature and moisture profiles will be compared to the measured ones to verify the EICM model.

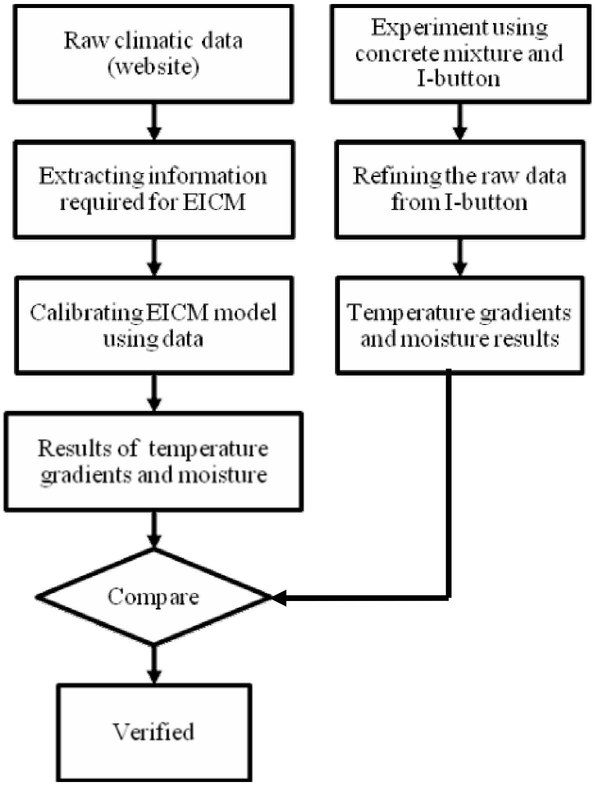

Figure-2. Flow chart for the first model of EICM.

3.2.2 Effect of thermal conductivity on thermal gradients and moisture content

Based on the pavement structure in West Feliciana of East Baton Rouge parish, an EICM model was developed. MEPDG climatic file on the specific location was generated and imported into the EICM model for the analysis. Measured thermal conductivity and heat capacity of several casted concrete specimens were inputted into the model to analyze thermal gradient and moisture profiles closely.

A flow chart of the work plan is presented in Figure-3. Details used to develop the model are provided below:

- The model was simulated for five years starting from September 1, 2000.
- Hourly temperature, wind speed, sunshine, and precipitation are collected from an ICM file, available in MEPDG website. Data for five years were generated.
- A 16 inches thick PCC pavement layer is modeled for various mixture designs, i.e., for different thermal conductivity and heat capacity values.
- A 12 inches thick soil cement base layer and sieve analysis details are used. A 6 inches soil treated sub-base layer and sieve analysis details of the layer are inputted. A 240 inches A-6 type soil layer was also added.

3.3 MEPDG analysis

MEPDG analysis was performed to predict the impact of thermal properties on the performance of concrete pavement. Results of MEPDG analysis were expressed as pavement distresses such as mean joint faulting, transverse cracking, and terminal international roughness index (IRI). The thermal properties (CTE, thermal conductivity, and heat capacity) and concrete mechanical properties were collected from laboratory testing of each mixture. The range of CTE and thermal conductivity were between 5 and 8με/°F, and between 1.2 and 2 Btu/ft·h·˚F, respectively. The heat capacity was kept constant on 0.26 Btu/lb·˚F to prevent ICM stability error. The joint spacing in the jointed plain concrete pavement (JPCP) was selected to be 20 feet to represent a typical value for pavement design in Louisiana. The MEPDG requires many inputs to perform a successful JPCP design. Subsequently, input data was determined for a JPCP project on US 61, West Feliciana Parish, Louisiana. The design life of the pavement was 20 years with a pavement thickness of 16" and the average annual daily truck traffic (AADTT) to be 1379 vehicles. CTE was maintained constant (7.14 με/°F) for investigating the effects of heat capacity and thermal conductivity. The heat capacity and thermal conductivity values were varied at 0.21-0.30 Btu/lb·˚F and 0.998-1.601 Btu/ft·h·˚F. Other layers considered under pavements were crushed stone (4 inches), soil cement (6 inches), and cement treated layer at 6% (8 inches).

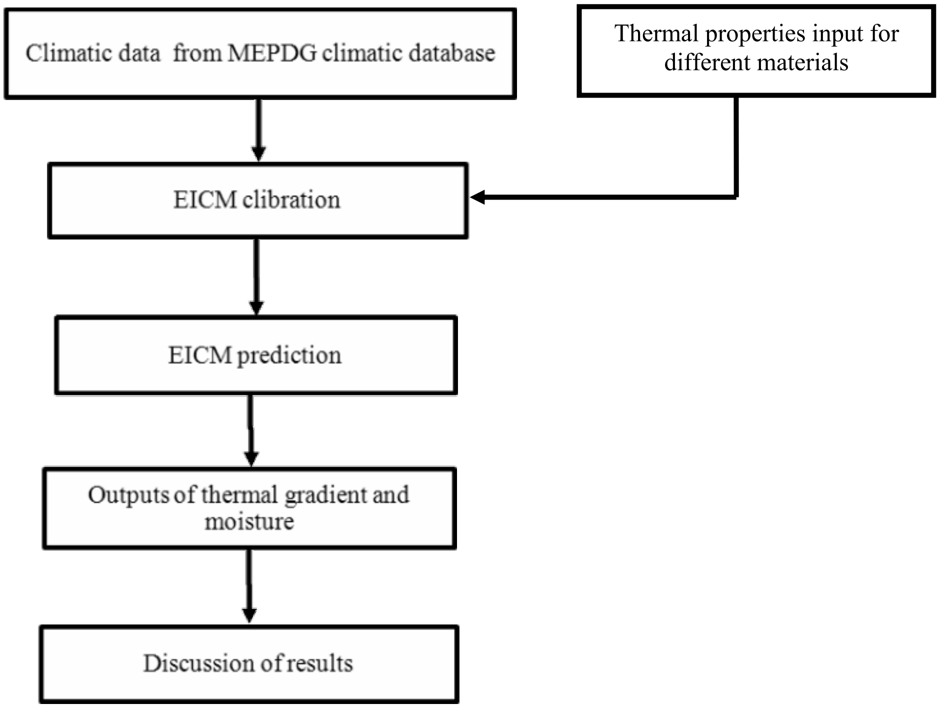

Figure-3. Flow chart for the second EICM model.

4. RESULTS AND DISCUSSIONS

4.1 EICM modeling results

4.1.1 Analysis of EICM model results and test results

An experiment was conducted to compare the EICM predicted temperature profiles to real-time temperature measurement in a pavement for 53 days. Using an I-button, temperature and humidity values were recorded for every hour.

A. Temperature gradients

Figure-4 shows temperature profiles calculated using the EICM model as well as measured readings from I-buttons. Temperature profiles were collected on August 2nd, 2010 and labeled by hour of the day accordingly. From the Figure-4, EICM predicted (calculated) temperatures were lower compared to experimental readings recorded (measured) by the I-buttons. Temperature profiles from the EICM and experimental results followed the same trends of hourly temperature profiles. Experiment readings had higher temperature differences from the top to the bottom of the pavement compared to the model results.

Weather data was collected from a weather station located at the Baton Rouge airport, and the location of the experiment was about 8 miles away. This could have the cause for the difference in temperatures calculated from EICM and the measured values of the I-button. Rezqallah *et al*., noted that temperatures in concrete pavement at a depth of 0.79 inches are higher compared to air temperature and these temperature differences were from 2°C to 7°C, (i.e., about 4°F-13°F) depending on the hour of the day [9, 10]. This may be a reason for the higher temperature recorded by the I-button in the experiment. Another possible reason may be found due to errors in temperature measurement. Concrete specimen was wrapped with aluminum foil in order to arrest any lateral heat transfer in the specimen. This was done to imitate the one-dimensional heat transfer model of EICM. Due to the aluminum wrap, dissipation of heat through the sides was not possible, which would have resulted in more heat storage in the concrete block.

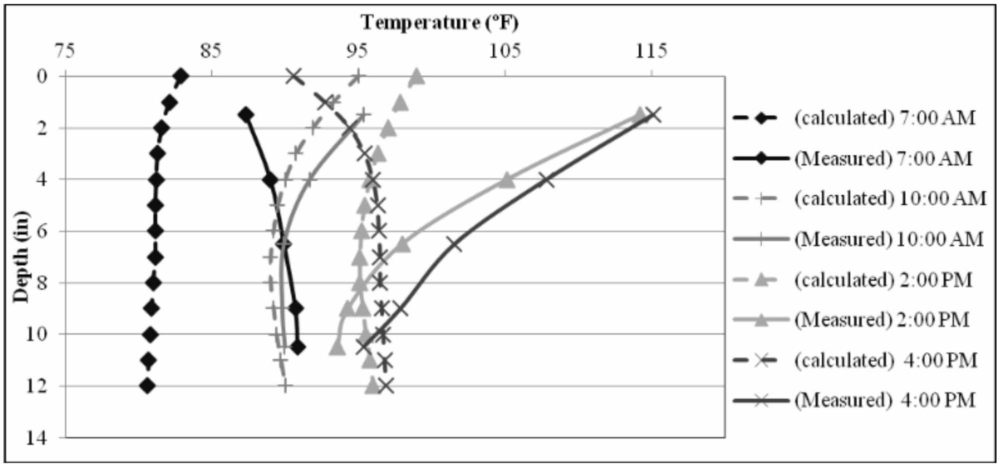

Figure-4. Temperature profiles from EICM and I-button.

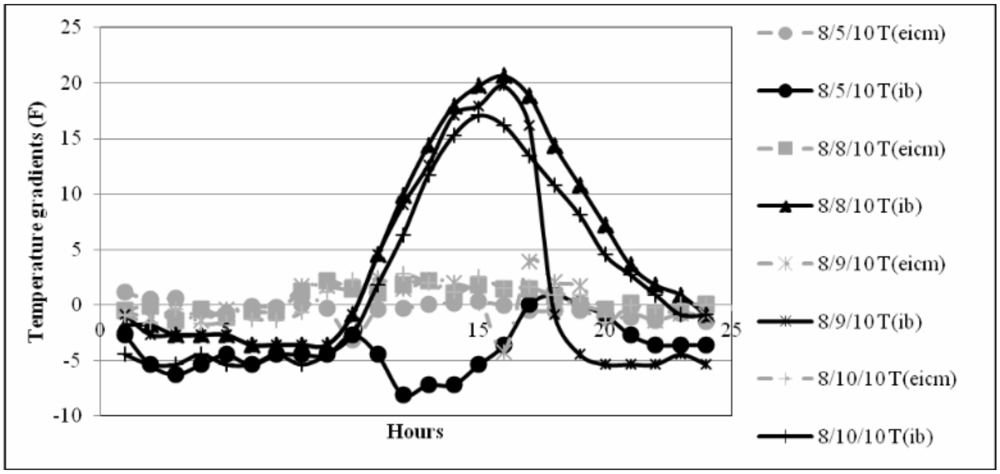

Figure-5. Peak hour temperature gradient.

Temperature gradients are known as the rate of change in temperature for a given depth (in this study depth of pavement). Differences in temperatures from the bottom 1.5 inches to top 1.5 inches were calculated at every hour for an interval of 24 hours; these differences are defined as temperature gradients in this study. These temperature gradients were calculated to understand maximum temperature differences in top and bottom of pavement on a particular hour of a day. The maximum temperature difference was usually at the hottest hour of the day, named the "peak hour temperature gradient". These temperature gradients were calculated from the output results of EICM and the I-button. Figure-5 shows the hourly temperature gradients for temperatures measured by an I-button and the EICM model for randomly selected days. A peak value was observed during the hottest hour of the day for I-button readings, but EICM had no significant peak value. The peak hour temperature gradient was in the range of 15-20°F for I-button measured readings and the gradient was around 3-5°F for EICM predicted readings. The difference in the peak hour temperature gradient was 15°F for EICM predicted readings and the I-button measured value. This difference in gradients causes large differences in calculation of thermal stresses that would have impact on pavement performance prediction of MEPDG.

In Figure-5, the temperature gradients on August 5th, 2010 had slight variations; this was due to a five hour precipitation noted from 10:00 am in the morning to 2:00 pm in the afternoon. EICM fails to consider the water content and temperature profiles with regard to precipitation recorded. In days other than precipitation, there are notable temperature differences between the top and bottom of the pavement.

According to Heydinger *et al*., [11], it was observed that EICM temperature profiles showed a significant difference compared to observed field results in pavement as shown in Figure-6. Ahmad *et al*. worked on predicting EICM and LTPP site temperature and moisture content profiles. Their study concluded that a strong and consistent correlation did not exist between predicted and observed values [12].

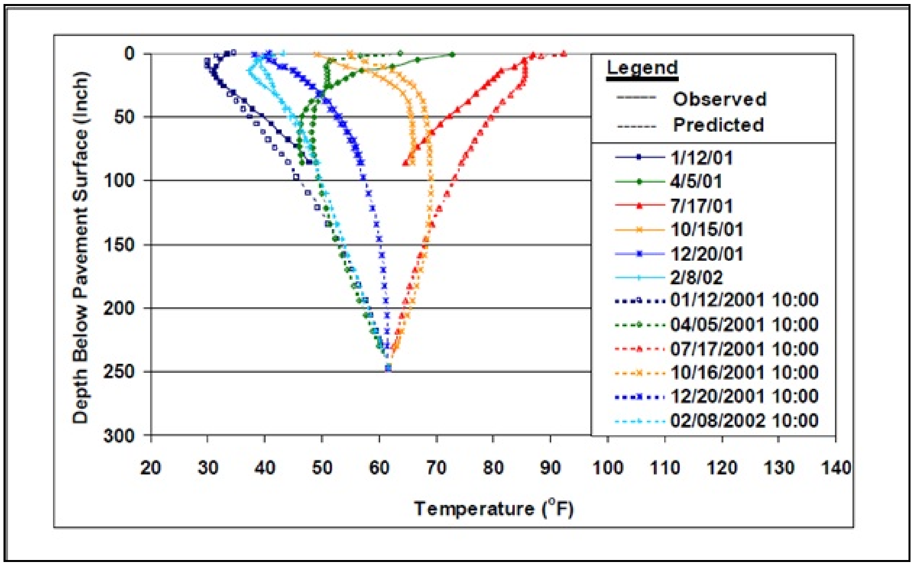

Figure-6. Temperature profiles from Andrew [11].

B. Moisture profiles

Moisture is always projected at the bottom 1 inches of pavement by EICM, irrespective of their thickness and climatic conditions such as GWT and on precipitation days. According to EICM concepts, moisture and temperature profile are inter-dependent that undergo a sequence of steps to balance temperature profiles as per moisture present in pavements. However, from EICM output results, it may be inferred that only the bottom one-inch of pavement contains moisture. This amount of moisture has minimal effect on temperatures predicted in the EICM model. The moisture prediction of EICM in pavements was not accurate when compared to experimental results. Thus, moisture profiles predicted by EICM should be further verified for accurate prediction of temperature profiles.

4.2 Effect of thermal conductivity on temperature profile

Dry thermal conductivities of concrete for different mix proportions vary [8]. As a result, few random values of thermal conductivity were selected and analyzed in EICM for a specific day. Figure-7 and Figure-8 are EICM analysis results of a temperature profile for different thermal conductivity obtained on August 15th, 2005, at 4:00 pm. From Figure-7, it was observed that the change in concrete composition had no effect on the lower and upper temperatures of PCC pavements. Temperature profiles show that the low thermal conductivity concrete had a high variation of temperatures, due to slow heat propagation. As thermal conductivity increased from 0.998 to 1.202 Btu/ft·h·˚F, temperature variations are decreased. The lowest temperature variation within the pavement was found at thermal conductivity of 1.341Btu/ft·h·˚F, which increased after 1.341Btu/ft·h·˚F to an extent, remaining almost constant till 1.922 Btu/ft·h·˚F. The least temperature stresses were produced by thermal conductivity with 1.341Btu/ft·h·˚F, and the highest temperature stresses by low thermal conductivity. Heat capacity had a negligible effect on the temperature profile in pavements.

In EICM, moisture content starts at one inch bottom in PCC pavements for any chosen day, with the same profile for all seasons. According to Jansen *et al.*, humidity of pavement varies from the top two inches of the pavement and increases rapidly to reach 100% humidity at the bottom of pavement, but this phenomenon was not observed in the EICM results [5]. Altoubat *et al.*, exposed concrete specimens to a relative humidity of 50% for 14 hours: the relative humidity increased for all 7 days with depth [13]. It was also observed that concrete had a drying period of about 150 hours for the top few inches. The results indicate that the bottom of the concrete has a higher relative humidity, compared to the top few inches. In the measurement of thermal conductivity, a concrete specimen was stabilized in a 50% humidity room. Compared to oven dry condition, the specimens had a 1.0-1.5% of gravimetric water content and thermal conductivity of the specimens was 9-15% higher than that in oven dry condition. The amount of moisture absorption is unique for all concrete compositions and the variation of thermal conductivity through the depth of PCC pavement should be considered in the EICM and MEPDG analysis for better prediction of moisture and temperature variations in pavements.

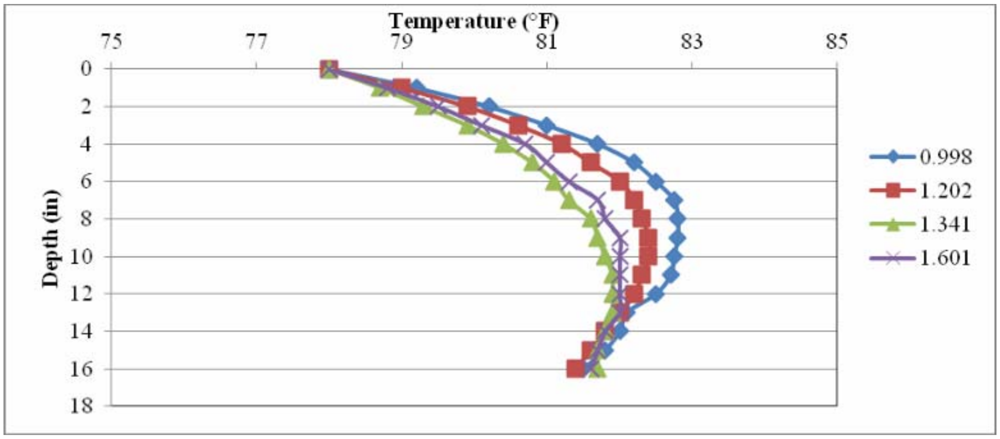

Figure-7. Temperature profiles for different thermal conductivity.

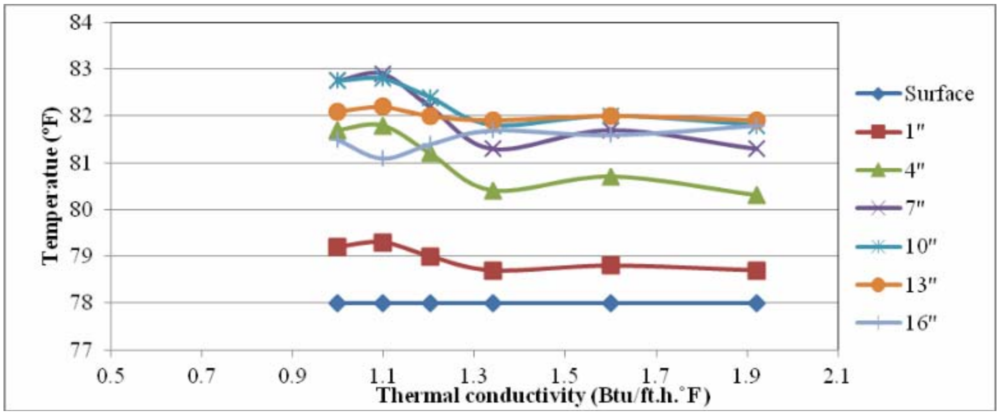

Figure-8. Temperature vs thermal conductivity at several depths of pavement.

4.3 MEPDG analysis results

An MEPDG analysis was performed to understand the effects of thermal properties on the pavement performance. Thermal conductivity, heat capacity, and the unit weight of different specimens were inputted into MEPDG analysis. During the analysis, it was found that MEPDG shows a “stability check error” in climatic data for a thermal conductivity (1.67 Btu/ft·hr·°F) and heat capacity (0.21 Btu/lb·°F) values. MEPDG software developers suggested changing the heat capacity value by (±0.1) when error occurs. By changing the heat capacity value as suggested, the EICM analysis was successful for different thermal conductivity and heat capacity values. For other specimens with different thermal conductivity and heat capacity values, the stability check error was observed. Figure-9 shows all these thermal conductivity and heat capacity values that failed during the ICM stability check. All the ICM stability failure showed a linear variation. From the observation, a passing line separating the ICM stability check passing zone and failure zone is proposed in equation (1). Any values below the passing line failed for the ICM stability check and no MEPDG analysis was performed. All these thermal values showed no failure errors in the EICM climatic model. However, MEPDG cannot start an analysis for specimens with thermal conductivity and heat capacity values in the ICM stability check failure zone.

$$HC = 0.1386 * TC - 0.0219 \quad (1)$$

Where

HC = heat capacity (Btu/lb·°F), and
TC = thermal conductivity (Btu/ft·hr·°F).

MEPDG analysis was conducted for the JPCP on US 61. As thermal conductivity and heat capacity of concrete increased, the mean joint faulting showed a slight decrease, which was not considerable. Although the faulting was within the limit, the trend indicates that higher thermal conductivity and heat capacity values of a concrete specimen would be preferred. This demonstrates that increased thermal conductivity causes a low temperature difference between the top and bottom of the pavement layer, so the curling stress caused by temperature variation can be restrained.

The effects of thermal conductivity and heat capacity on transverse cracking are presented in Figure-10 and Figure-11. The transverse cracking decreases remarkably as thermal conductivity increases. An increase in thermal conductivity decreases temperature differences from the top to the bottom of pavement, thereby decreasing distresses. The transverse cracking reaches 78% at thermal conductivity value of 0.998 Btu/ft·h·˚F, and the heat capacity was constant throughout this analysis. As heat capacity increases, transverse cracking suddenly decreases and then increases slightly after 0.25 Btu/lb·˚F. The transverse cracking was dominantly affected by thermal conductivity rather than by heat capacity. The terminal IRI also shows similar trends in previous results, because smoothness was related to joint faulting and transverse cracking. Therefore, the thermal properties of thermal conductivity were influential on pavement distresses and the transverse cracking was shown to be dominantly controlled by thermal properties.

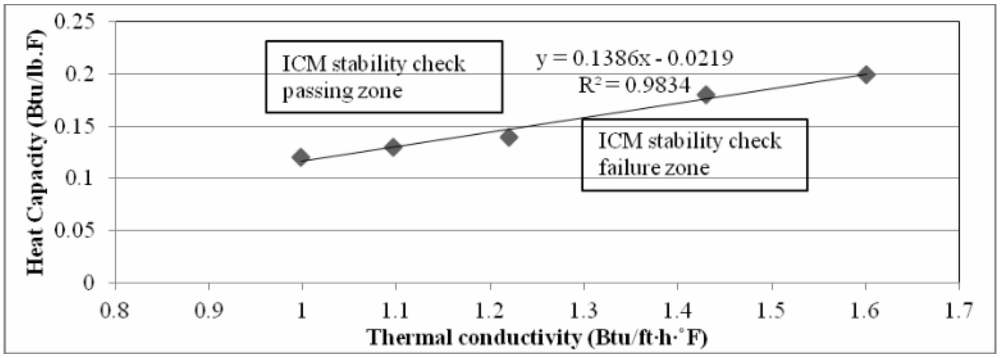

Figure-9. ICM stability check zones.

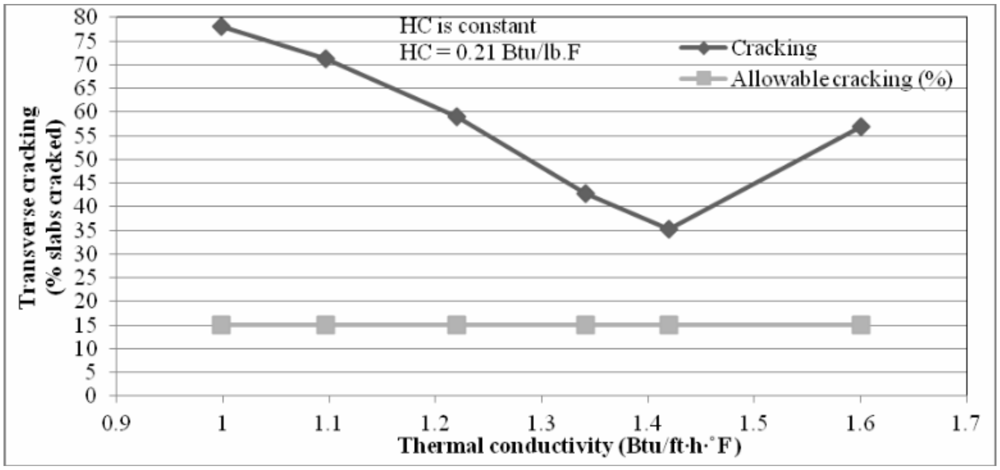

Figure-10. Change in transverse cracking with change in thermal conductivity.

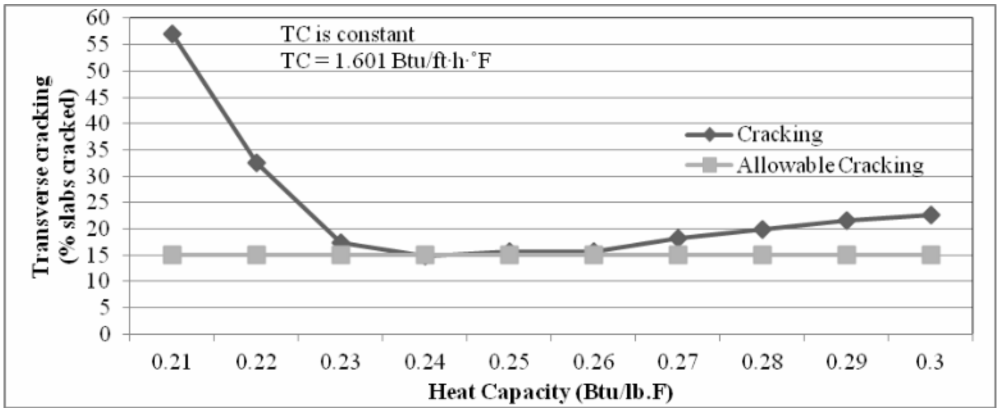

Figure-11. Change in transverse cracking with change in heat capacity.

CONCLUSIONS

Based on the measured temperature, EICM analysis, and MEPDG analysis in a PCC pavement structure in Louisiana, the following conclusions are drawn:

- Thermal conductivity has no effect on the top and bottom temperatures of concrete. Results showed that for different thermal conductivity values temperatures at the top and bottom remained constant, though there was a change in the temperatures of middle layers;
- The water content gradient started at the bottom one-inch of pavement, which indicating that EICM does not consider a moisture profile. Moisture should be considered in pavement analysis since it affects thermal conductivity and temperature gradients in pavement layer;
- The predicted temperature profile of EICM has the same trends as I-button temperature profiles, except on rainy days. The temperature profiles predicted by a model in EICM had lower temperatures than the I-button recorded temperature profiles through experiment;
- Peak hour temperature gradients calculated from EICM and the I-button has no similarity in their patterns when compared. Peak hour temperature gradients measure by I-botton showed a definite peak temperature during the hottest hours of day, whereas EICM predicted temperatures showed no peak hour temperature gradient. EICM do not predict temperature gradients exactly, and the difference was found to be 15 °F;
- As the thermal conductivity increases from 1.2 to 1.8 Btu/ft·h·˚F, the thermal cracking decreases with no significant effect on joint faulting; and
- An ICM stability check failure was observed in MEPDG, while EICM do not show this failure. The ICM stability failure occurred for a set of thermal conductivity and heat capacity values. A passing line is proposed to separate the ICM stability check passing zone and failure zone.

ACKNOWLEDGEMENT

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