Minnesota Road Research Data for Evaluation and Local Calibration of the *Mechanistic–Empirical Pavement Design Guide*'s Enhanced Integrated Climatic Model

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This paper describes research to evaluate modeling of the thermal behavior of concrete and composite pavements by the Enhanced Integrated Climatic Model (EICM), the climate-modeling package used in the *Mechanistic–Empirical Pavement Design Guide* (MEPDG). First, the study uses temperature data collected at the Minnesota Road Research Project (MnROAD) facility from portland cement concrete (PCC) and asphalt concrete (AC)–PCC pavements to investigate benefits of AC overlays on the thermal characteristics of PCC slabs. Furthermore, the study validates EICM predictions of thermal gradients through the slabs and investigates the effect of MEPDG-user inputs for thermal conductivity of PCC. Overall, the paper examines measured data from MnROAD for AC-PCC pavements and their single-layer PCC counterparts and attempts to explain how similar pavement systems and their thermal characteristics are taken into account in the MEPDG. The paper concludes that evaluation of the material thermal inputs should be part of a process of local calibration and adaptation of the MEPDG.

Pavement temperature is not constant in time or through depth. Temperatures throughout a pavement structure are dominated by the atmospheric conditions at the surface. The surface of the pavement is subject to more environmental effects, and its temperature will fluctuate more than the temperature at the bottom of the structure.

Factors affecting the top surface temperature of a pavement are incoming short-wave radiation, reflected short-wave radiation, incoming long-wave radiation, outgoing long-wave radiation, convective heat transfer, condensation, evaporation, sublimation, precipitation, and the temperature of the one or more layers immediately beneath the one or more bound layers (*1*). The bottom of a portland cement concrete (PCC) slab is affected by the temperature of the layers directly beneath the slab and from energy transferred by conduction from the surface. Although the temperature at the bottom of the slab is ultimately influenced by the conditions at the top surface, it is not directly subjected to the factors that affect the surface temperature. Consequently, pavement temperature is not constant in time and through depth. In particular, temperature variations are especially high at the surface. These variations affect the behavior of rigid pavement structures.

Like almost all other materials, concrete expands when it is heated. If the temperature at the top of a concrete slab is not equal to the temperature at the bottom, different layers of the slab want to expand to varying degrees. The warmer layer attempts to expand more than the cooler layer, but if the shape of the slab is restrained due to foundation support, dowels, tie bars, and self-weight, stresses are induced (*2*). These stresses are known as thermal, or curling, stresses. Tensile stresses at the bottom of the PCC layer occur when the top of the slab is warmer than the bottom, and this temperature difference occurs most commonly during diurnal periods; these stresses are known as daytime curling stresses. Tensile stresses at the bottom of the PCC layer are the main cause of transverse cracking in PCC pavements. Thermal stresses can contribute significantly to cracking and failure of a PCC layer. Therefore, with all other factors equal, a reduction in the temperature difference in the PCC layer would result in lower thermal stresses and less transverse cracking. Thermal stresses can also contribute to other types of distress in rigid pavements. If the bottom of the slab is warmer than the top, the edges of the slab attempt to curl upward. This nighttime curling stress (so named because when it generally occurs) contributes to joint faulting. Thus, thermal gradients in a PCC pavement are undesirable. Limiting the environmental effects at the top of a PCC slab would reduce the temperature fluctuations at the surface. Because the bottom of the slab does not respond as quickly as the surface does to temperature changes, limiting these effects would reduce thermal gradients.

An asphalt concrete (AC) overlay is a common rehabilitation technique for concrete pavements. Thick AC overlays are used to rehabilitate degrading PCC pavements and improve structural capacity of the existing pavements. Thin AC overlays are used for rehabilitation of structurally sound PCC pavements to cover surface defects, reduce noise attributed to traffic, and improve ride quality. It has been suggested that the placing of a thin asphalt layer on top of a PCC layer provides an insulating effect (*3*). Other researchers have observed that an asphalt layer placed on top of an existing PCC pavement can improve pavement performance. While there is a stiffness contribution to the pavement structure from a thin asphalt layer, the improve-

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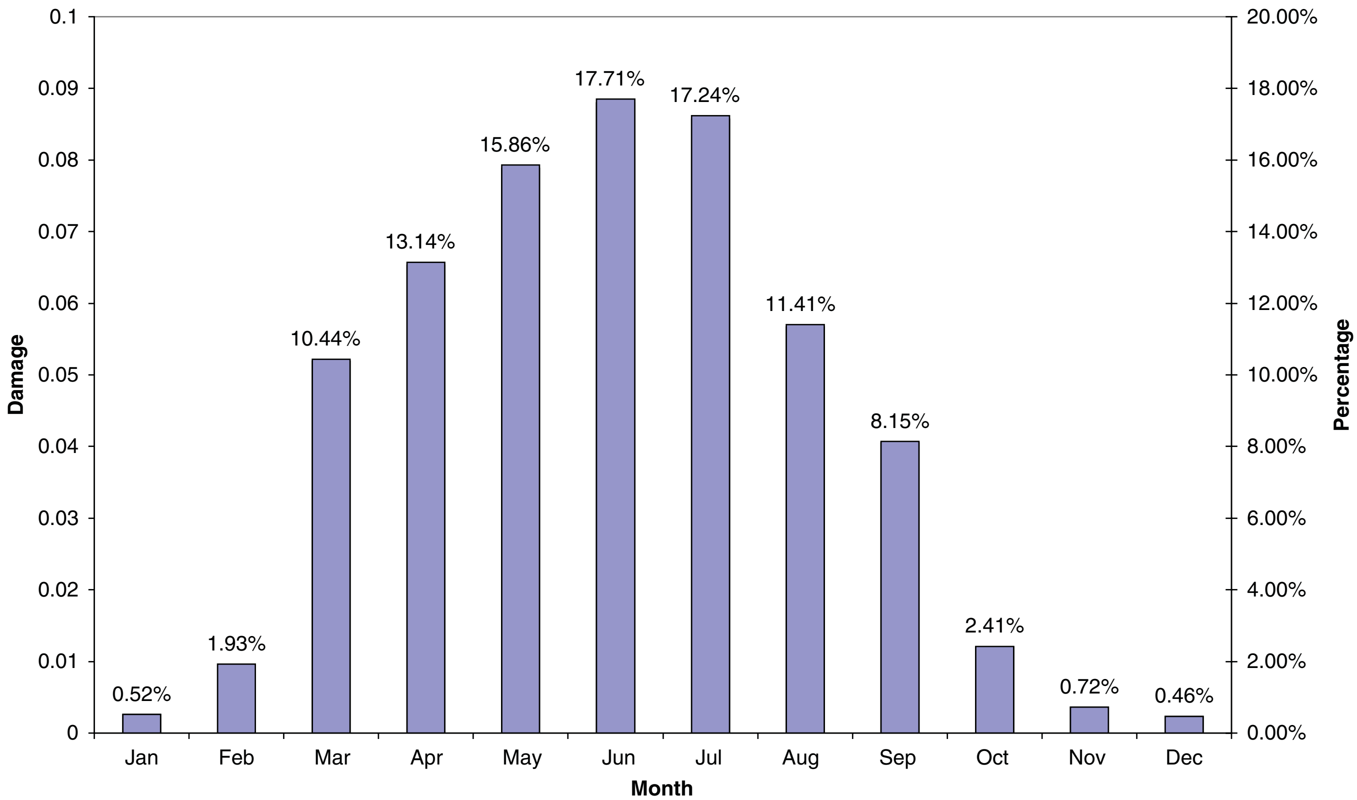


FIGURE 1 MEPDG-predicted monthly damage for 2-in. AC over 7-in. PCC pavement at Minneapolis–Saint Paul International Airport.

ments in pavement performance suggest that stiffness alone cannot be fully responsible.

This paper examines the thermal insulating effects of AC over PCC overlays and evaluates the accuracy of predictions (of pavement temperature) from the MEPDG by means of Minnesota Road Research Project (MnROAD) data. Although thermal stresses can contribute to several types of pavement distresses, transverse cracking is the primary measure of pavement performance used in this paper.

ENHANCED INTEGRATED CLIMATIC MODEL

The *Mechanistic–Empirical Pavement Design Guide* (MEPDG) incorporates the Enhanced Integrated Climatic Model (EICM) to account for the environmental effects that influence pavement performance (*1*). Previous studies have tested the sensitivity of MEPDG predictions of pavement performance to many variables, including traffic, layer thickness, material strength, and material stiffness (*4–6*). Recent research has examined sensitivity to climatic inputs. A study at the University of Minnesota simulated a single AC overlay of PCC design for over 600 locations across the United States. The percentage of cracked slabs varied from 0.0% in Cold Bay, Alaska, to 79.1% in Nogales, Arizona. The study concluded that environment has a significant effect on predicted pavement performance in the MEPDG and that climatic data files defining location may have a larger influence on predicted pavement responses than is currently understood (*7*).

To illustrate further the effect of climate on the MEPDG performance predictions, one may consider the example of a 7-in. PCC jointed plain concrete pavement (JPCP) with a 2-in. AC overlay. In this example, which used all default values, annual average daily truck traffic (AADTT) was set to 7,420 to reach a target of 20% transverse cracking over a 20-year design life. The location selected was the Minneapolis–Saint Paul International Airport; all other MEPDG default values, including the traffic monthly adjustment factors, were used. Therefore, the amount of traffic did not vary from month to month within a year.

Figure 1 shows a portion of the cracking damage in the PCC layer accumulated for each month over a 20-year design life. The figure shows that almost no damage was accumulated between November and February. During this period, the air temperature in Minneapolis is low. It can be expected that the asphalt layer temperature is low, and the base and the top of the subgrade may be frozen. This makes the asphalt and the unbound layers very stiff and decreases stresses in the PCC layer. Figure 1 also shows that most of the damage occurred from March to September. Incoming daytime solar radiation and ambient air temperature and its daily fluctuations are at maximums during the summer months. These maximums lead to an increase in the mean AC temperature, which reduces AC stiffness, and to high temperature gradients in the PCC layer. All design parameters, except climate variables, remained constant from month to month, providing another example of the importance that climate has on pavement performance prediction in the MEPDG.

CHARACTERIZATION OF THERMAL PROPERTIES IN EICM

In addition to climatic inputs, several EICM material properties may affect EICM temperature predictions and subsequently MEPDG performance predictions. The thermal property inputs are heat capacity and thermal conductivity. Heat capacity is the amount of heat energy required to change the temperature of a material a specified amount.

Although the heat capacity of a pavement material is an important attribute to consider and may influence the predictions of pavement performance, the focus of this study is on the effects of thermal conductivity.

Thermal conductivity is a material characteristic that indicates the ability of a material to transfer heat. Heat energy is transferred to or from the pavement surface by convection, radiation, or conduction. Materials with a lower rate of thermal conductivity resist the transfer of heat energy. The conduction of heat energy from the surface and from below is what directly influences the temperature in the PCC layer. The MEPDG recommends the following default values of thermal conductivity: 0.67 Btu/h-ft-°F for AC and 1.25 Btu/h-ft-°F for PCC.

The sensitivity of the thermal conductivity input on predicted transverse cracking was tested for a 2-in. AC over 7-in. PCC composite pavement. AADTT was set to 7,420 to reach a target of 20% transverse cracking over a 20-year design life, and all default values were used. The location selected was the Minneapolis–Saint Paul International Airport; all other MEPDG default values were used. The AC layer thermal conductivity was held constant at the MEPDG default value for the model runs in which the PCC thermal conductivity was adjusted, and vice versa. Following are the results from the MEPDG model runs:

- Effect of PCC thermal conductivity on transverse cracking in the PCC layer:
  - 1.38 Btu/h-ft-°F: 15.8% cracking,
  - 1.25 Btu/h-ft-°F (default): 20% cracking,
  - 1.13 Btu/h-ft-°F: 25.6% cracking,
  - 1.00 Btu/h-ft-°F: 32% cracking,
  - 0.94 Btu/h-ft-°F: 35.6% cracking, and
  - 0.85 Btu/h-ft-°F: 41% and
- Effect of AC thermal conductivity on transverse cracking in the PCC layer:
  - 0.80 Btu/h-ft-°F: 30.1% cracking,
  - 0.67 Btu/h-ft-°F (default): 20.0% cracking, and
  - 0.54 Btu/h-ft-°F: 10.3% cracking.

These results show that the thermal conductivity values can substantially influence the amount of predicted transverse cracking. The differences in the amount of predicted transverse cracking are a result of variations in temperature distributions in the PCC layer. The EICM predicts that the thermal conductivity of the AC and PCC layers is capable of significantly altering the temperature distributions in the PCC layer; consequently, these temperature distributions have a noteworthy effect on predicted pavement performance.

MnROAD DATA AND DATA ANALYSIS

MnROAD Data

The temperature data used in this report were retrieved from the "mainline" test sections along I-94 at the MnROAD facility. MnROAD is a full-scale cold-region pavement testing facility constructed in 1994 and administered by the Minnesota Department of Transportation (Minnesota DOT). MnROAD is located near Albertville, Minnesota, along I-94. The full-scale testing facilities at MnROAD consist of over 35 sections (or cells) distributed over a westbound stretch of I-94, a low-volume road loop, and a farm loop. Each of the test cells represents experiments in road research, from pavement materials and design to emerging construction technologies. The test cells are continuously monitored by thousands of live sensors, including more than 1,000 thermocouples located at various depths of pavement sections (*8*). Data from these sensors are catalogued and maintained in Minnesota DOT's database (*9*).

This study used a full year of hourly pavement temperature data, extracted from five test cells along the MnROAD mainline sections, a 3.5-mi stretch of I-94 that carries an average of 26,400 vehicles daily. Those five test cells are three thin-concrete cells (113, 213, and 313) and two composite AC-over-PCC cells (106 and 206). The design for each of these cells is illustrated in Figure 2.

As Figure 2 shows, the designs of the two sets of test cells are quite similar, the main difference being the presence of an AC overlay. This overlay is at the core of the comparison that uses the data, which is to investigate the differences in thermal readings through overlaid and exposed PCC.

The temperature data from MnROAD were filtered by using a program for mining of various pavement data under development by the University of Minnesota, Minnesota DOT, and the Minnesota Local Road Research Board (*11*). This program subjected the temperature data to different tests to identify missing data, insufficient data for a given day, sensor outliers, and data subset outliers, and in so doing, flagged suspect data. Results varied between sensors, but for the vast majority of them, only 1% to 2% of the temperature data were flagged as potentially problematic. No flagged data (i.e., only the highest-quality data) were used in the analysis discussed in this paper. Given the high volume and sometimes suspect nature of temperature data, screening the data allowed the researchers to compare temperature data from the sensors on the exposed PCC and the AC-over-PCC with confidence.

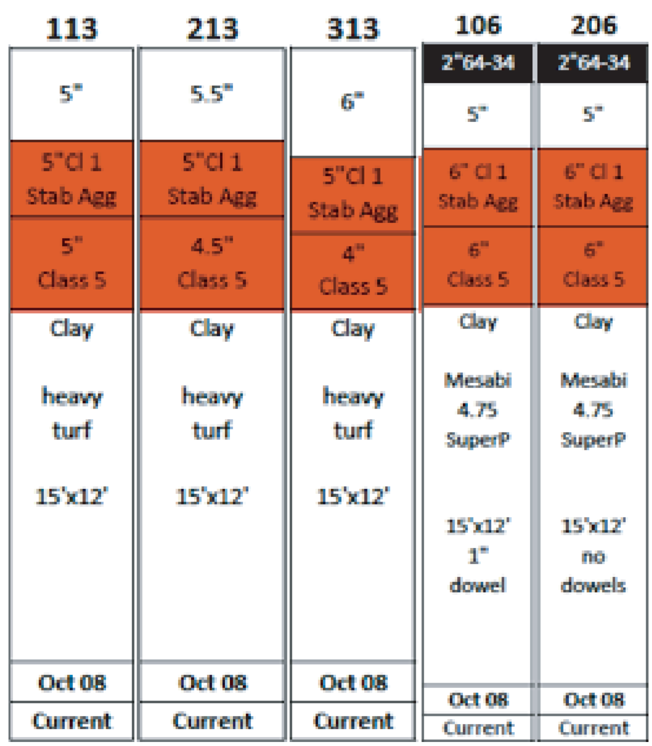


FIGURE 2 Design cross section of MnROAD Cells 113, 213, 313, 106, and 206 (" = inches; ' = feet) (*10*).

Data Analysis

A preliminary analysis of the thermal data meets expectations in many regards. For instance, a natural comparison of an AC-over-PCC pavement with its single-layer counterpart is to investigate the albedo effect. Surface albedo is the effect of color on the degree of absorption of solar radiation and thereby surface temperature. Surfaces with a darker color absorb more incoming solar radiation and thus have a lower albedo; hence, an AC surface typically has a lower albedo than does a PCC surface. To account for the albedo effect, one would expect that the surface of the AC-over-PCC pavement would have higher maximum and daytime temperatures than those of a single-layer PCC pavement. This expectation was confirmed with data from MnROAD Cells 106 (AC overlay) and 213 (JPCP), as illustrated in Figure 3.

In Figure 3, the AC surface temperatures are clearly higher than the PCC surface temperatures. All other factors being equal, these increased surface temperatures attributable to albedo lead to greater positive temperature gradients in the AC-PCC system, if one assumes that the temperature near the base is the same in both systems. (Here a positive thermal gradient is one in which the temperature at the surface exceeds that near the base.)

Larger thermal gradients in the composite system do not necessarily create a larger thermal gradient through the PCC slab itself. The presence of the AC overlay may create an insulating effect, where the gradient in the PCC slab in the composite system is less severe than that in its exposed JPCP counterpart. Figure 4 is a plot of temperature differences between the top and bottom of the PCC slabs in an exposed JPCP pavement (Cell 113) and an AC-over-PCC pavement (Cell 106). For Cell 113, the PCC-only slab, temperature data are recorded at 0.5 and 4 in. from the pavement surface; for Cell 106, the data are taken from thermocouples 2.5 and 6 in. from the surface. In both cases, the gradient through the PCC slab is described for a vertical distance of 3.5 in.

Figure 4 clearly shows that the thermal gradient for the PCC slab is lower in magnitude in the AC-PCC composite structure than in the exposed JPCP. This effect appears in closer detail in Figure 5, which illustrates hourly detail on the thermal gradient in the same PCC slabs (in Cells 113 and 106) over a 2-week span (July 24 to August 7, 2009).

As implied through the use of various periods for the hourly data of Figures 3, 4, and 5, the insulating phenomenon of AC overlays will be observed for all seasons. While the effect is more pronounced in the summer months, when solar radiation and daytime heating are at maximums, the effect remains observable even in the winter months (which are depicted, in part, in Figure 4).

It could be suggested that, because the sensors used in Figure 4 were 0.5 in. from the top of the PCC slab—0.5 in. from the pavement surface for JPCP Cell 113 and 2.5 in. from the pavement surface for AC-PCC Cell 106—and not at similar absolute depths, the

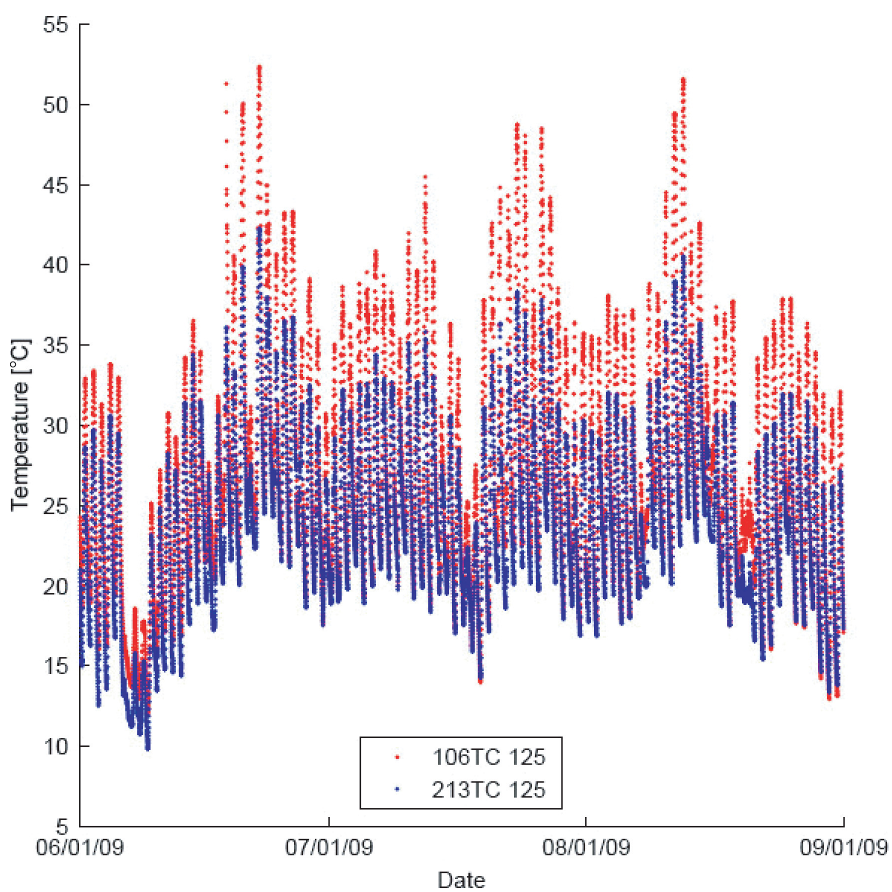


FIGURE 3 Hourly AC surface temperatures from Cell 106 (in red) and hourly JPCP surface temperatures from Cell 213 (in blue) illustration of albedo effect.

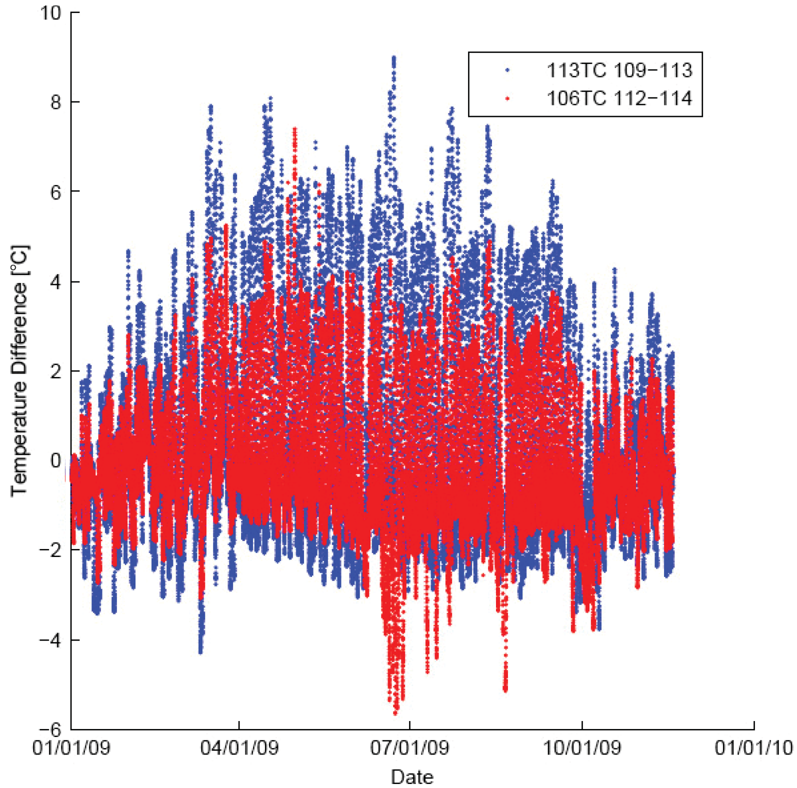


FIGURE 4 Hourly PCC temperature differences throughout AC-over-PCC (Cell 106 in red) and JPCP (Cell 113 in blue) thicknesses as illustration of insulating effect of AC overlay.

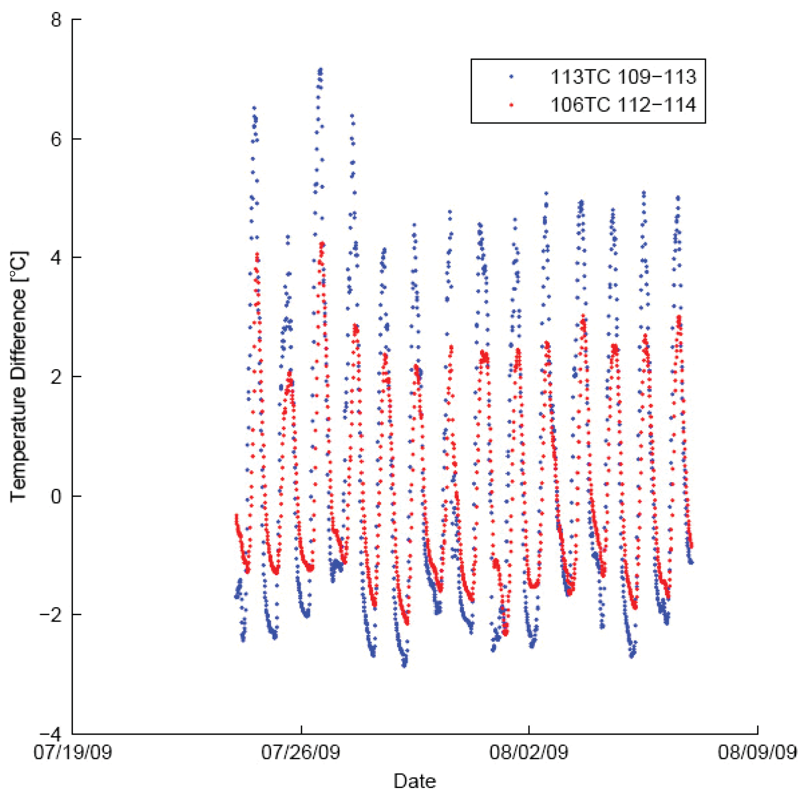


FIGURE 5 Close detail of hourly temperature differences throughout PCC slab thickness for AC-over-PCC (Cell 106 in red) and JPCP (Cell 113 in blue).

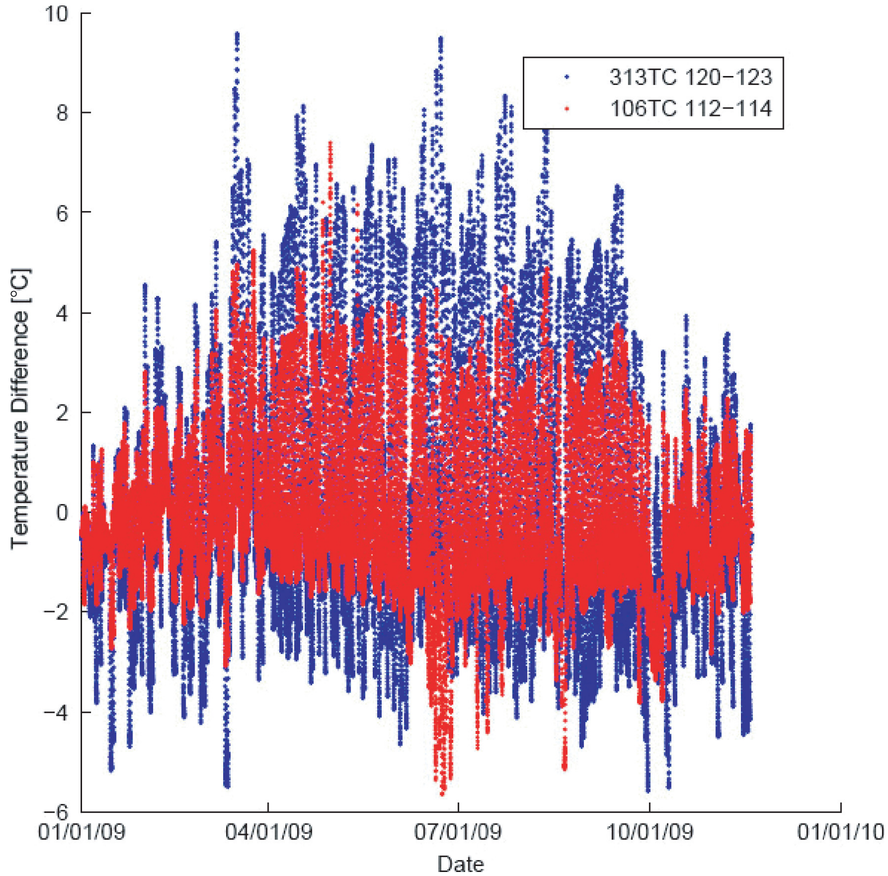


FIGURE 6 Thermal gradients at similar locations in AC-over-PCC (Cell 106 in red) and JPCP (Cell 313 in blue).

reduction in temperature differences could be attributed to the effect of the sensor location. To disprove this explanation, Figure 6 examines thermal gradients for similar overall depths in the composite and JPCP structures. This comparison differs from the comparison visible in Figure 4, as both upper locations are at an absolute depth of 2.5 in. below the pavement surface. The bottom locations for this analysis are 5.5 in. for the JPCP Cell 113 and 6 in. for the AC-PCC Cell 106. The vertical distance assumed for each thermal gradient, then, is 3 in. for Cell 113 and 3.5 in. for Cell 106.

Figure 6 confirms the insulating effect of the asphalt layer. The plot shows that, even over a slightly greater vertical distance of 0.5 in., whose additional thickness would increase the magnitude of the thermal gradient, AC-PCC Cell 106 has markedly lower temperature differences. If temperature distributions were not affected by the asphalt layer, this comparison would yield similar results for each system at the indicated depths. Hence, the insulating effect is not an artifact of selective data analysis.

The EICM simulations also predict that an AC overlay reduces temperature gradients in the PCC layer directly beneath it. Figure 7 compares July cumulative frequency distribution of simulated data from MEPDG with that of measured data from MnROAD. The figure reveals that the data analysis of both temperature data and climatic modeling support the hypothesis that the AC overlay significantly alters the temperature distributions in an underlying PCC slab. Moreover, Figure 7 shows good qualitative agreements between the EICM predictions and the measured data. In the next section, a quantitative comparison of measured and predicted temperature differences is conducted.

MEPDG AND EICM SENSITIVITY TO THERMAL CONDUCTIVITY

Although numerous studies have demonstrated the importance of climatic effects on MEPDG performance predictions, few large-scale studies have compared EICM predictions for thermal gradients through pavement slabs with measured data. Therefore, readers should be aware that the EICM uses historical climatic data and neither uses or produces climatic forecasts. The climatic data used to produce the modeled data were recorded from a 9-year, 8-month period from 1996 to 2006, ending nearly three full years before the temperature measurements recorded at MnROAD in 2009. Thus, it is not expected that the modeled data from any single year or an average of years of modeled data will match with the 1 year of measured data used in this report.

The aim in this discussion of EICM, then, is to understand better the model and the key parameters that drive its predictions for climate—and, consequently, predictions of pavement performance for the MEPDG. One parameter that has received little notice given its relative obscurity in pavement research is thermal conductivity. This parameter is often left untouched by pavement engineers; however, as was illustrated earlier for predictions of transverse cracking,

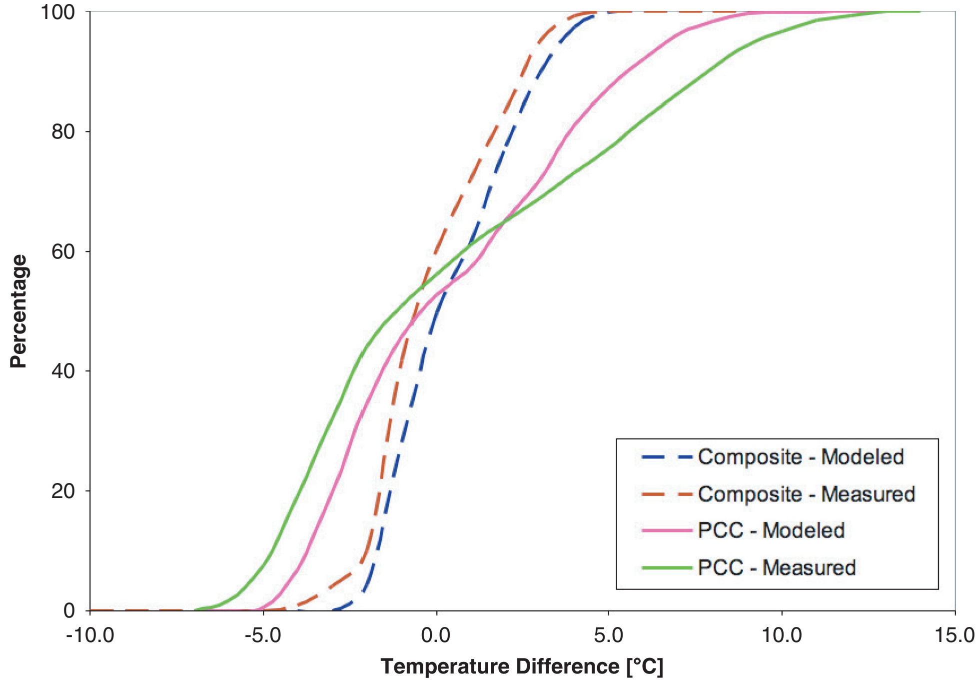


FIGURE 7 Simulated thermal gradients for AC-over-PCC (Cell 106) and JPCP (Cell 113) structures and their measured analogues from MnROAD.

its influence can be far reaching for MEPDG performance predictions. The following discussion attempts to characterize the influence of this parameter on EICM predictions.

Measured temperature differences through a JPCP pavement (MnROAD Cell 113) and modeled temperature differences for a JPCP pavement (from MEPDG and EICM) were plotted in a cumulative frequency distribution. For this initial comparison, the MEPDG default thermal conductivity value of 1.25 Btu/h-ft-°F was used for the PCC in the JPCP. The plot represents the temperature distributions for 1 month (July) of measured data from MnROAD and the minimum and maximum predicted values of seven simulated instances of the same month from 7 years of modeled climate data from EICM-MEPDG.

As Figure 8 shows, the MEPDG underestimates frequencies of positive and negative temperature gradients that were measured in the PCC cells at MnROAD. For example, the EICM predicts that the temperature differences between the top and the bottom surfaces of the PCC should be less than +7°C more than 95% of the time. The MnROAD measurements show that temperature differences less than +7°C occurred only 86.3% of the time; therefore, 13.7% of the temperature differences recorded were greater than +7°C. Similarly, the EICM predicts that the temperature difference between the top and the bottom surfaces of the PCC should be less than −3°C 22.4% of the time. The MnROAD measurements show that the temperature differences less (more negative) than −3°C occurred 32.3% of time.

One explanation for this difference is that the reduced temperature differences in the modeled data are, in part, a result of the MEPDG forcing an unnecessarily high value for thermal conductivity on EICM; that is, the thermal conductivity does not match that of Cell 113 at MnROAD (the actual value of which is unknown, as it would be for most as-designed or in-field pavements). The thermal conductivity input was adjusted to a lower value of k = 0.94 Btu/h-ft-°F. Figure 9 illustrates a similar comparison to the one in Figure 8 but with the new value for the thermal conductivity.

Here it is evident that the lower value of k = 0.94 Btu/h-ft-°F for the thermal conductivity input brings the simulated minimum and maximum thermal gradients closer to the measured cumulative frequency distribution from MnROAD. To confirm that the adjusted thermal conductivity value improved on the model that used the MEPDG default value, other months were examined. Figure 10*a* compares modeled and measured data from March for the MEPDG default value for thermal conductivity, while Figure 10*b* compares the measured data with MEPDG predictions by using the adjusted thermal conductivity value of k = 0.94 Btu/h-ft-°F.

The analyses for March and July are indicative of similar analyses performed for other months, all of which suggested that a reduction of the MEPDG default thermal conductivity input value resulted in better agreement between the measured data and the modeled thermal gradients.

Further analyses found, however, that the relationship between measured data and modeled data began to deteriorate for values of thermal conductivity that were less than k = 0.94 Btu/h-ft-°F. Figure 11 is representative of modeled data that use a thermal conductivity input less than 0.94 Btu/h-ft-°F; for this figure, k = 0.85 Btu/h-ft-°F for the simulated data, which is illustrated against the measured MnROAD data from July once again.

As Figure 11 shows, the thermal conductivity input value of 0.85 Btu/h-ft-°F results in modeled data that is in poor agreement with the measured data collected at MnROAD. This is especially evident by noting the range of values along the abscissa.

Hence, by adjusting the thermal conductivity input to a value lower than the MEPDG default of 1.25 Btu/h-ft-°F, the predictions of temperature gradients were found to agree better with measured

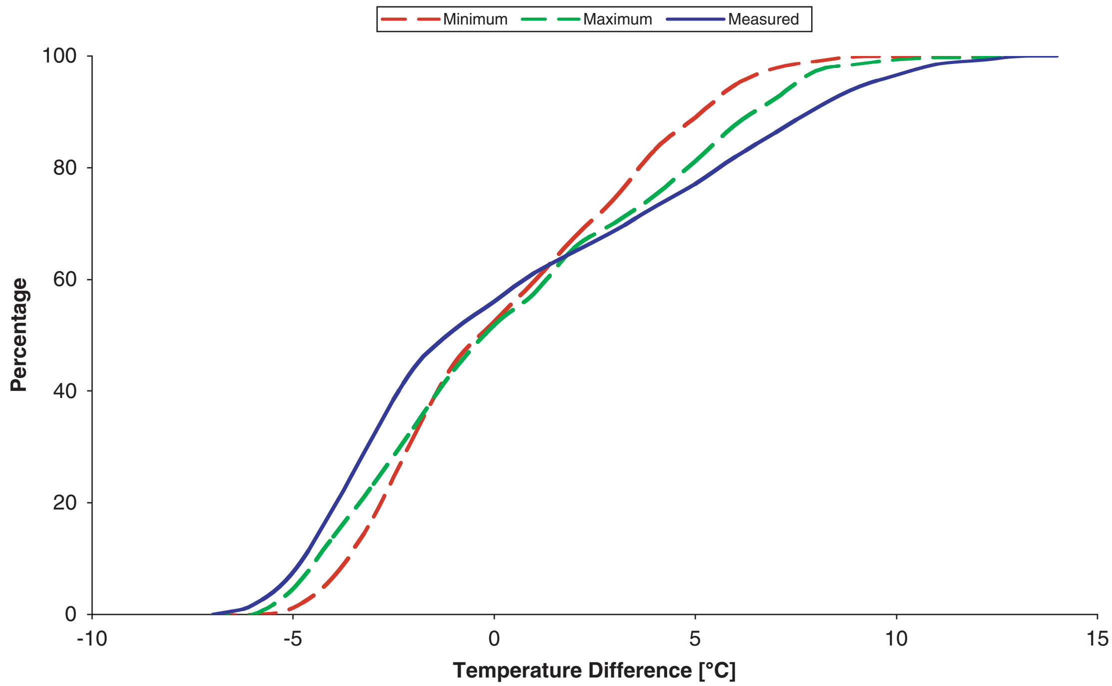


FIGURE 8 Measured versus modeled cumulative frequency distribution for thermal gradient through JPCP pavement in July (k = 1.25 Btu/h-ft-°F).

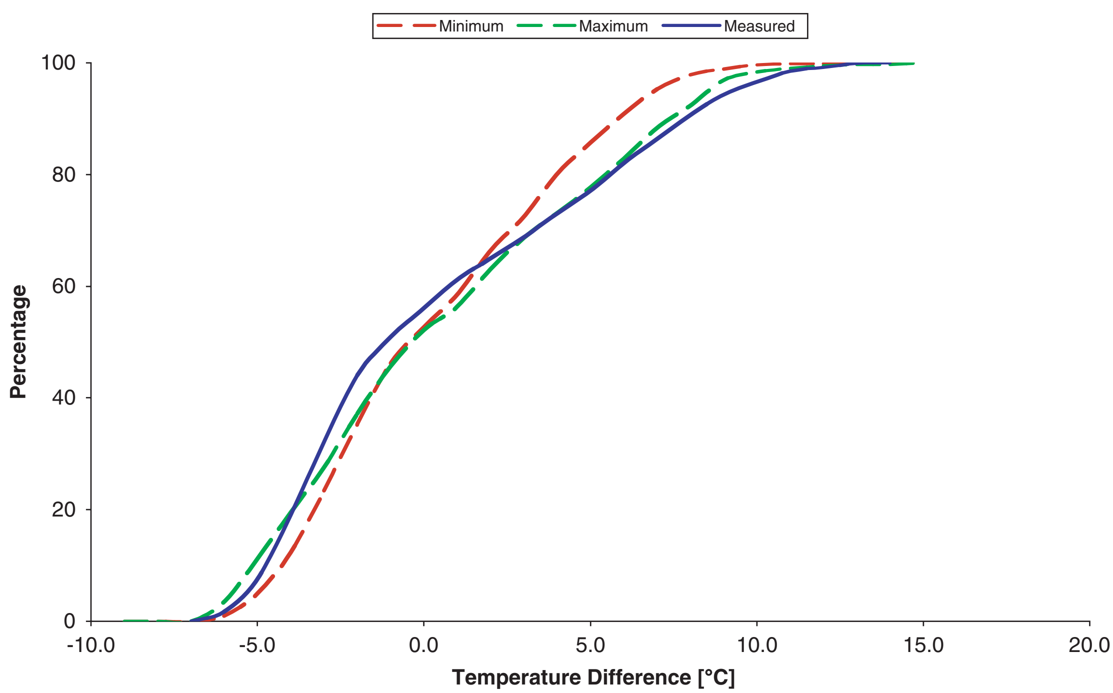
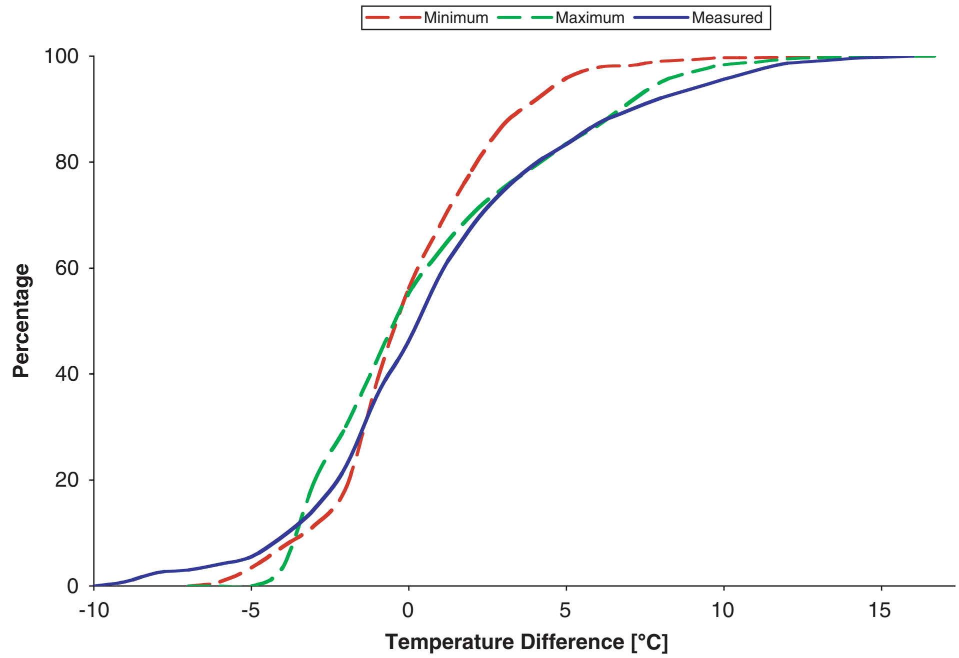
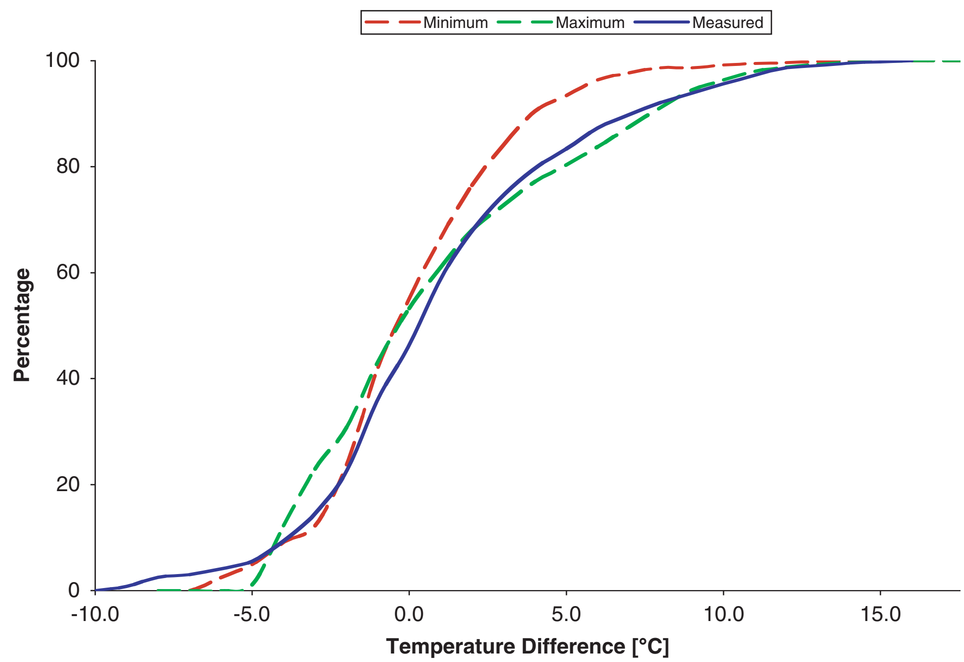


FIGURE 9 Measured versus modeled cumulative frequency distribution for thermal gradient through JPCP pavement in July (k = 0.94 Btu/h-ft-°F).



(a)



(b)

FIGURE 10 Measured versus modeled cumulative frequency distribution for thermal gradient through JPCP pavement in March for (*a*) MEPDG default value (*k* = 1.25 Btu/h-ft-°F) and (*b*) adjusted value (*k* = 0.94 Btu/h-ft-°F).

data from MnROAD for a PCC slab in JPCP pavements. Furthermore, a range of values were tested for the thermal conductivity, and the analysis found that a value of 0.94 Btu/h-ft-°F produced the best fit of modeled data to the measured MnROAD data. Although agreement between the measured and the modeled data varied from month to month, the value of 0.94 Btu/h-ft-°F produced the best results for each month. While this value does not produce an exact fit and is not intended to demonstrate the nature of EICM modeling and inherent variability in any data set, the modifications to the thermal conductivity input represent an improvement over the default value.

Only one PCC pavement structure was considered in this analysis. A similar analysis for other MnROAD concrete sections will be conducted in the future.

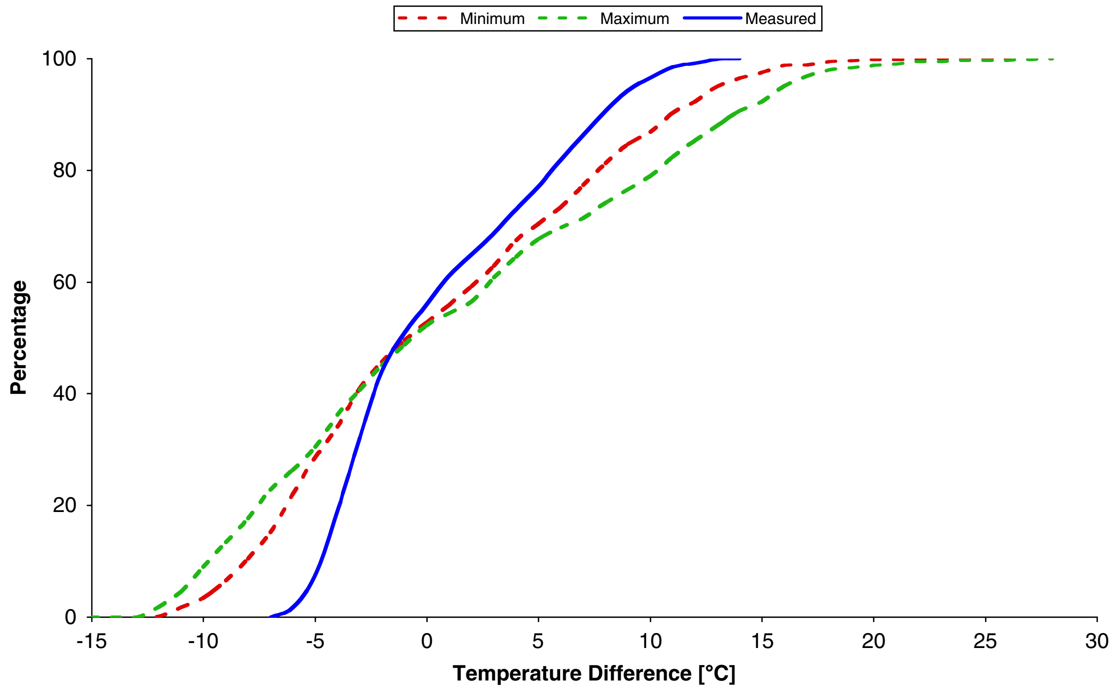


FIGURE 11 Measured versus modeled cumulative frequency distribution for thermal gradient through JPCP pavement in July (*k* = 0.85 Btu/h-ft-°F).

CONCLUSIONS

While many aspects of the MEPDG modeling and design inputs have been the subject of a great deal of research, very little of the MEPDG dealing with climate and its impact on prediction of pavement performance has been a subject of an in-depth analysis. The dual focus of this paper was thermal characteristics of a composite pavement system and the modeling of these characteristics relative to measured environmental conditions. This focus requires an understanding of the EICM, which performs the climate modeling for the MEPDG, and a close examination of reliable temperature data for both a composite AC-PCC pavement system and a single-layer PCC analogue.

This study examined measured and modeled temperature distributions in the PCC layer of JPCP and AC-over-PCC pavement structures. Hourly temperature data recorded from AC-PCC composite and JPCP cells at MnROAD were collected and filtered to remove suspect measurements. These data were then used to investigate the effects of climate on these two pavement systems and to validate expectations as an initial check of data quality. Measured data indicated that diurnal AC surface temperatures were markedly higher than those of a PCC surface because of AC having a lower albedo. Despite the overall greater temperature difference through the full depth of the AC-PCC structure, temperature records showed that the thermal gradient in a PCC layer was significantly less if an AC overlay was present. This effect is thought to contribute to the longevity and improved performance of the underlying PCC structure. EICM simulations were also found to reproduce the insulating effect of an AC overlay observed in the MnROAD data for composite test cells.

Furthermore, the research summarized in this paper examined the sensitivity of the EICM and MEPDG to thermal conductivity input values for the AC and PCC layers. It was found that these parameters significantly influenced predicted pavement performance for MEPDG simulations, and this discovery led to further investigation of the influence of thermal conductivity on EICM predictions for thermal gradients through a simulated pavement system. A quantitative comparison of modeled and measured temperature data was conducted. The EICM simulations produced temperature distributions smaller than the measured distributions when the MEPDG default thermal conductivity value of PCC, *k* = 1.25 Btu/h-ft-°F, was used. Several PCC thermal conductivity values were tested; the highest agreement between the measured and modeled data for a 6-in.-thick MnROAD test section occurred with a PCC thermal conductivity of 0.94 BTU/hr-ft-°F.

Finally, adjustments to the MEPDG thermal property inputs in routine design should be done only with care. Solo improvement in prediction of the temperature distribution in the pavement structure does not necessarily lead to improvement in predictions of pavement performance if the models for predicting performance had been calibrated for the MEPDG default material thermal properties. Therefore, it is important to make evaluation of the MEPDG material thermal properties a part of an MEPDG local calibration process.

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