

**PCC Slab Temperature Gradients as a Function
of Structure and Environment**
Experience from the SHRP II R21 Composite Pavement Test Track
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Abstract

The Strategic Highway Research Program (SHRP) II R21 Composite Pavement Research Project test track constructed at University of California Pavement Research Center (UCPRC) ATIRC facility has yielded significant Portland cement concrete (PCC) temperature data over the nearly past two years of testing. The nine different test sections consisted of combinations of plain and hot mix asphalt (HMA) overlaid jointed plain concrete (JPCP) pavement sections of varying thicknesses. Over 135 thermo couples were placed at five depths and three locations within each slab and have been continuously monitored since test track construction. This paper will identify the changes in PCC slab temperature gradients as a function of PCC slab thickness (178mm and 127mm), HMA overlay thickness (114mm, 64mm, and 0mm) and type (Polymer modified and rubber). Results provide important information about the thermal insulation effect of HMA layer to reduce temperature gradients in PCC layers and provide experimental data for continued evaluation of the effects of reduced temperature gradients on PCC layer cracking performance.

Introduction

The effect of temperature and moisture gradients can lead to significant tensile stresses at the top and bottom of concrete slab. If a pavement slab is subjected to a temperature gradient through its depth, the slab will tend to curl. The edges of the slab will curl upward if the temperature at the bottom of the slab is higher than the temperature at the top (night time condition). During day time, when the process is reversed and the slab is subjected to a positive temperature gradient (temperature at the top higher than the temperature at the bottom), the slab will either curl downward or it will compensate the upward curl to a certain degree. Change in volume due to non-uniform shrinkage through the slab thickness also impacts slab deformation. A higher shrinkage at the top of the slab causes the corners to warp upwards relative to the mid panel. The tendency to curl or warp will be restrained by the weight of the slab itself. Stresses induced by temperature and moisture gradients are independent of applied loads (Yoder and Witzack 1975). Stresses can also result from uniform temperature changes which cause the slab to contract or expand. Daily temperature

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gradient reversals and the more seasonal moisture gradients, in the presence of restraining effects from the slab weight, friction with the underlying base layer, and joint load transfer mechanisms, can sometime induce stresses that are equal or exceed load-induced stresses.

Westergaard pioneered the theory for analyses of stresses in concrete caused by variations of temperature and moisture (Westergaard 1927). His closed form solutions for corner, edge, and interior loading conditions based on the slab-on-elastic foundation assumption were later extended (Bradbury 1938) to account for positive and negative temperature gradients in the analysis. The temperature gradients were considered to be linear through the thickness of the slab. Superposition of stresses induced by load and temperature was recommended for positive temperature gradients but stresses due to a negative temperature gradient were not subtracted from load-induced stresses. This approach resulted in more conservative solutions. Thomlinson (1940) reviewed the curling stress assumptions and focused on the elimination of the limitation of a linear temperature distribution. Compared to a linear temperature gradient, a nonlinear gradient causes higher tensile stresses at the top of the slab during night time curled up conditions. Field measurements also confirmed that the actual distribution of temperature gradients through the thickness of the slab is nonlinear (Richardson and Armaghani 1987). Numerically based solution methods have been developed for calculating the effect of nonlinear gradients on internal stresses in concrete pavements. One study (Mohamed and Hansen 1997) indicates that linear gradient analysis cannot accurately capture the curling stresses in a concrete pavement, especially during the evening and early morning hours when tensile stresses are present in both the top and the bottom surfaces. Predicted stresses due to the temperature variations significantly increase the level of stresses the pavement is subjected to, and can contribute to considerable reduction of the fatigue life of the pavement. According to this study, the shape of the temperature profile rather than the temperature difference is important in controlling internal stresses.

Other studies focused their attention on the effects of built-in stresses. Analysis based on temperature and profile measurements from two new built concrete sites in Mankato, Minnesota and Phoenix, Arizona (Rao et al. 2001) showed that concrete pavements develop built-in curling and that its magnitude depends on the climatic conditions at the time of paving. In addition to built-in temperature gradients, moisture and creep effects have to be considered while modeling. By controlling the time of paving (e.g. night time paving), the slab built-in curl can be significantly reduced, hence contributing to improved fatigue performance.

In an attempt to reduce the temperature gradient in concrete slabs, avenues such as new construction composite pavements (asphalt concrete over concrete) were explored. Although more expensive to build, the longer life performance and reduced maintenance costs may offset the initial cost. A pavement structure with an asphalt concrete surface course and concrete slab as a base course was shown to reduce the temperature gradient in the underlaid concrete slab, resulting in the reduction of thermal stress in the concrete slab. A more detailed study on the impact of the type and thickness of the asphalt surface on the thermal gradient in the concrete slab underneath was done by Nishizawa et al. (2000). Results of this study were based on the temperature gradients from test pavements consisting of five composite pavements with different surface types (a porous asphalt concrete with 20% void ratio, and a dense graded asphalt concrete), different asphalt surface thicknesses (50 mm and 100 mm) on top of concrete slabs of different thicknesses (150mm and 200 mm), one conventional asphalt concrete pavement and two conventional concrete

pavements of 150 mm and 200 mm. Comparison of thermal gradient data showed that for same thickness of the asphalt concrete surface, the temperature at the slab's surface underneath the asphalt was almost the same regardless of the surface type. Numerical simulations results revealed that the thickness of the asphalt surface course considerably influences the temperature gradient in a concrete slab. An asphalt surface less than 40 mm thick may increase the temperature gradient. Comparison of day and night temperature variation within the slab for a conventional concrete pavement versus a similar concrete pavement overlaid with a thin friction course (Belshe et al. 2010) showed a reduction in temperature fluctuation especially at the surface of the slab in the presence of a thin open graded friction overlay. Consequently, adding a thin open graded friction course reduces the temperature differentials between the top and the bottom of the slab. In addition to the buffering effect the overlay has on the concrete slab, the traffic is also considered to increase the aeration effect on the open-graded friction course which helps reduce the temperature differential between the top and bottom of the slab. Finite element analysis showed that the friction course reduces curling stresses in the summer and that curling stresses are controlled by the temperature profile within the slab rather than by the temperature differences between the top and bottom of the slab.

Research Significance

In this study, temperature data collected from over 135 thermocouples placed at five depths and three locations within each slab were analyzed to identify the thermal insulation effect of HMA layer to reduce temperature gradients in PCC layers. Changes in PCC slab temperature gradients as a function of PCC slab thickness (178mm and 127mm), HMA overlay thickness (114mm, 64mm, and 0mm) and type (Polymer modified and rubber) were determined to provide experimental data for continued evaluation of the effects of reduced temperature gradients on PCC layer cracking performance. In this study, only the thermal insulation effects of HMA layers are investigated. The effects of the reduced temperature gradients on PCC cracking performance should also be determined by finite element modeling. The contributions of HMA layers to the structural performance should also be investigated by incorporating the results of this study into the finite element model.

Objectives

The primary purpose of this study is:

1. To compare PCC temperature gradients for sections with thick, thin, and no HMA layers to identify the effect of an HMA layer as a thermal insulator;
2. To identify the effect of HMA type (PG 64-28 PM, RHMA-G) on the variation of PCC temperature gradients;
3. To determine the effect of PCC layer thickness on the variation of PCC temperature gradients.
4. To provide experimental data for continued evaluation of the effects of reduced temperature gradients on PCC layer cracking performance.

Instrumentation and Test Section

As part of the SHRP II R21 project, nine HVS composite (asphalt over PCC) and three PCC pavement test sections were constructed at the Advanced Transportation Infrastructure Research Center (ATIRC) facility at UC Davis (Signore et al. 2012) located in Davis, California. Highest air temperatures are observed to be 34°C (93°F) (daily average) on July and August while lowest air temperatures are measured to be

12°C (54°F) (daily average) on December and January. The design plans were developed to support the Heavy Vehicle Simulator (HVS) experimental design and testing plan to evaluate rutting and cracking performance and provide data for validation of performance models.

Materials and Experimental Design Figure 1 shows the pavement plan and cross section designs. The composite HMA/PCC pavement consists of four lanes (A-D), comprised of two HMA mixtures, with two HMA thicknesses, two PCC thicknesses, and PCC with and without dowels for load transfer. Two asphalt concrete (AC) mixture types were used in this study, a dense-graded mixture with PG 64-28 polymer modified (PM) binder and a gap-graded mixture with asphalt rubber binder (PG 64-16), RHMA-G. Both mixes were specified based on California Department of Transportation (Caltrans) specifications for both mix and binder. Nominal maximum aggregate sizes (NMAS) for PG 64-28 PM and RHMA-G mixtures were 19 mm (0.75 inches) and 12.5 mm (0.5 inches), respectively. The underlying concrete slabs were jointed plain concrete pavement placed on 150 mm (6 inches) of granular base, with slabs that were 3.7 m (12 ft) wide and 4.6 m (15 ft) long. Each of the three sections (1, 2, 3) in each lane consists of three slabs, each 4.6 m length, totaling 13.8 m length, to ensure that the HVS is properly supported and that the pavement trafficked by the HVS includes one complete slab and two PCC joints. Figure 2 shows the construction and sensor installation steps. An anionic emulsion tack coat was applied over the PCC layers to create bonding between PCC and HMA layers. Proper creation of this bond is expected to minimize the cracking on the PCC layers and hence the reflection of cracks to the HMA layers.

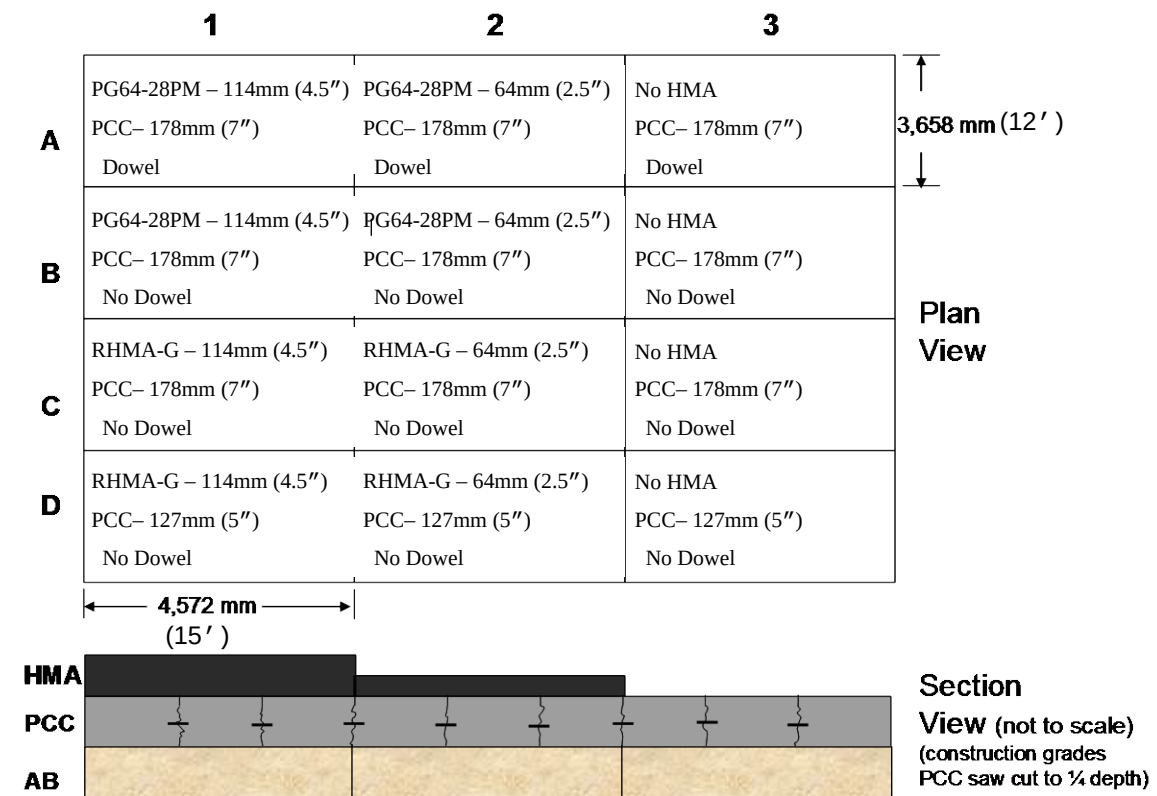


Figure 1 Plan (top) and section view (bottom) of test section layout with approximate construction elevations.

Note: HMA=Hot mix asphalt; PCC=Portland cement concrete; AB=Aggregate base.

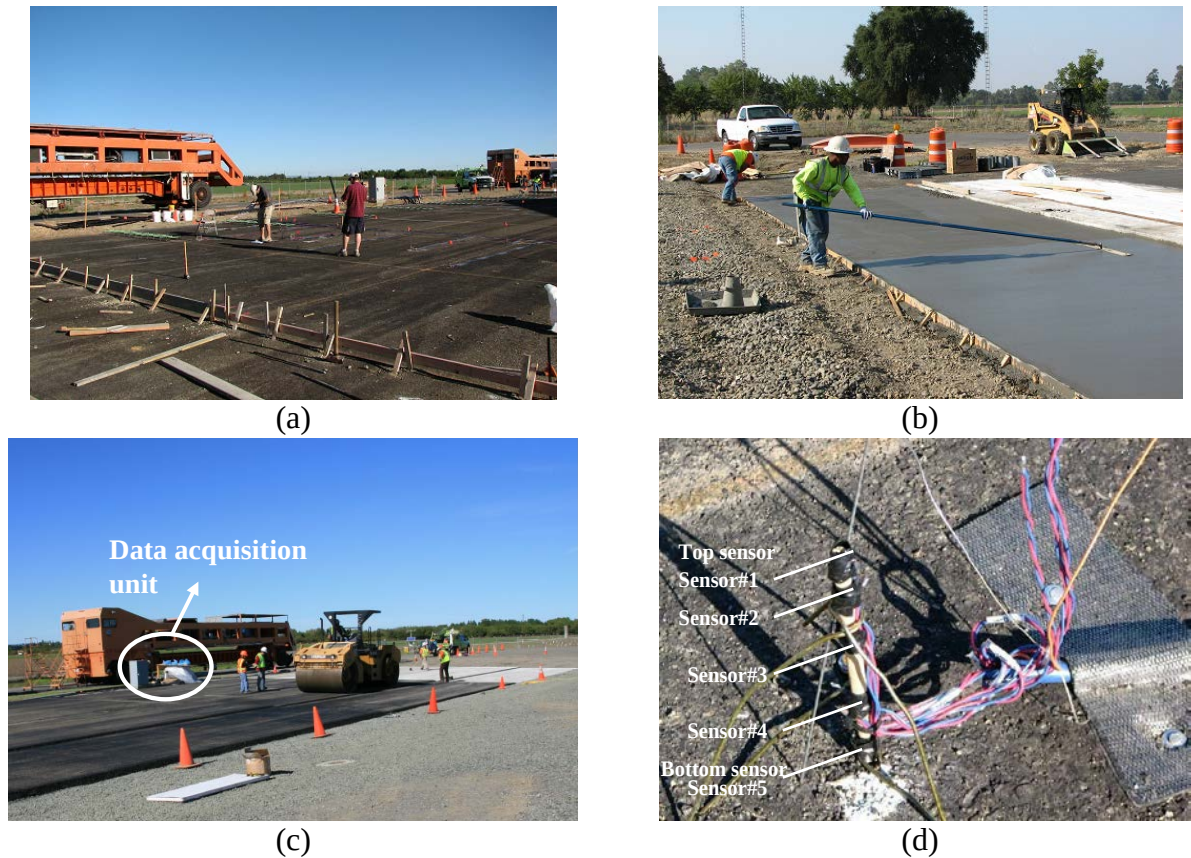


Figure 2 Construction and sensor installation steps (a) Installation of thermocouples (b) Construction of PCC layer (c) Construction of HMA layer (d) Thermocouple setup in PCC layer.

Portland cement concrete was supplied meeting Caltrans Standard Specification Section 90: Portland Cement Concrete Mix Design. The concrete was classified as a Type 3 concrete, having a cementitious material content of 335 kg/m^3 , which includes 39 kg of Fly Ash. No chemical admixtures were used in the concrete. Concrete was batched at the ready mix plant and hauled approximately 32 km to the test track site. Table 1 presents the concrete mix design.

Table 1 Portland Cement Content Mix Design

Material	Abs. Volume (m ³)	Weight (kg)	Percent of Mix
Coarse Aggregate	0.31	862	47
Fine Aggregate	0.23	603	33
Portland Cement Type II/V	0.07	217	12
Class F Fly Ash	0.02	39	2
Water	0.12	125	7
Air	0.01	-	0
TOTAL	0.76	1,845	100
Slump:	75 to 125 mm		
Design Air:	1.5 percent		
Design Unit Weight:	2,414 kg/m ³		
Design W/C Ratio:	0.49		

In order to identify the effects of HMA and PCC layer thickness and HMA type on the variation of the PCC temperature gradients, one year of hourly temperature data (1/1/2010 to 12/31/2010) was analyzed from the thermocouples located on every section. Lane A has the PG 64-28 PM HMA layer with the thick PCC layer (7 in./178 mm). Temperature data for Lane B is assumed to be similar to the data for Lane A and was not considered for the temperature analysis because the only difference between Lane A and Lane B is the use of dowel bars on Lane A transverse joints. Lane C has the RHMA-G layer with thick PCC layer (7 in./178 mm) underneath while Lane D has the same mix with thin concrete (5 in./127 mm) underneath (Figure 1).

Thermocouple Preparation and Installation Thermocouples for measuring PCC temperature were placed in three locations in the PCC slabs; two slab corners and center slab. At each of these three locations, the sensors were placed at five depths within the PCC slabs. The thermocouples used were T-type, model number # 8TX20PP from Omega Engineering.

To prepare the thermocouples for installation, the wires were cut to appropriate length and the ends of each thermocouple wire were stripped and soldered together at the tip. Each of the five sensor wires was attached to a pre-cut thin wooden dowel at the appropriate height with electrical tape (Figure 2d). Thermocouple distances below PCC surface were 26, 45, 89, 134 and 165 mm for the sections with 178 mm thick PCC layer while the distances for the 127 mm thick slabs were 23, 36, 62, 93 and 112 mm.

Measurement and Analysis of PCC Slab Temperature Profiles

As an initial look at the effect of HMA thickness on temperature gradients and the reversal of slab curling, Figure 3 shows plots of temperature gradients for test sections on Lanes A and D. All these plots were made from data taken on October 27, 2009. Figure 4 shows the air temperature for October 27, 2009, the day for which these gradients are plotted.

It can be seen that the temperature gradients increase with decreasing PCC and HMA thickness. In addition, the effect of the HMA overlays was to increase the overall temperature of the PCC compared to the PCC without an HMA overlay by reflecting less solar radiation (lower albedo) as a result of its darker color.

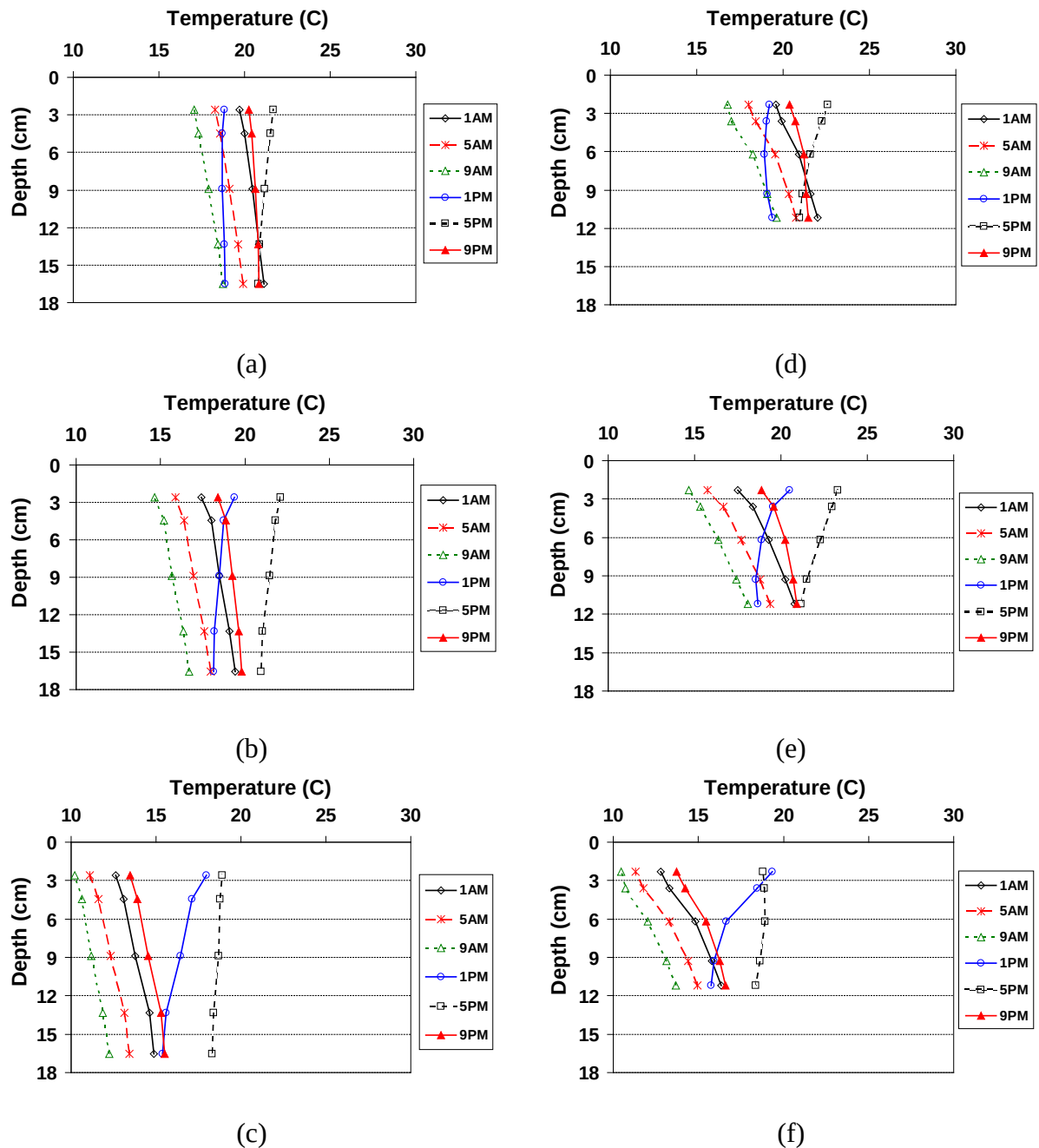


Figure 3. PCC temperature gradients for test sections (a) Section A1: $H_{ac}=114\text{mm}$, $H_{PCC} = 178\text{mm}$ (b) Section A2: $H_{ac}=64\text{mm}$, $H_{PCC} = 178\text{mm}$ (c) Section A3: $H_{ac}=0\text{ mm}$, $H_{PCC} = 178\text{mm}$ (d) Section D1: $H_{ac}=114\text{mm}$, $H_{PCC} = 127\text{mm}$ (e) Section D2: $H_{ac}=64\text{mm}$, $H_{PCC} = 127\text{mm}$ (f) Section D3: $H_{ac}=0\text{ mm}$, $H_{PCC} = 127\text{mm}$.

Note: H_{AC} is HMA layer thickness, H_{PCC} is PCC layer thickness.

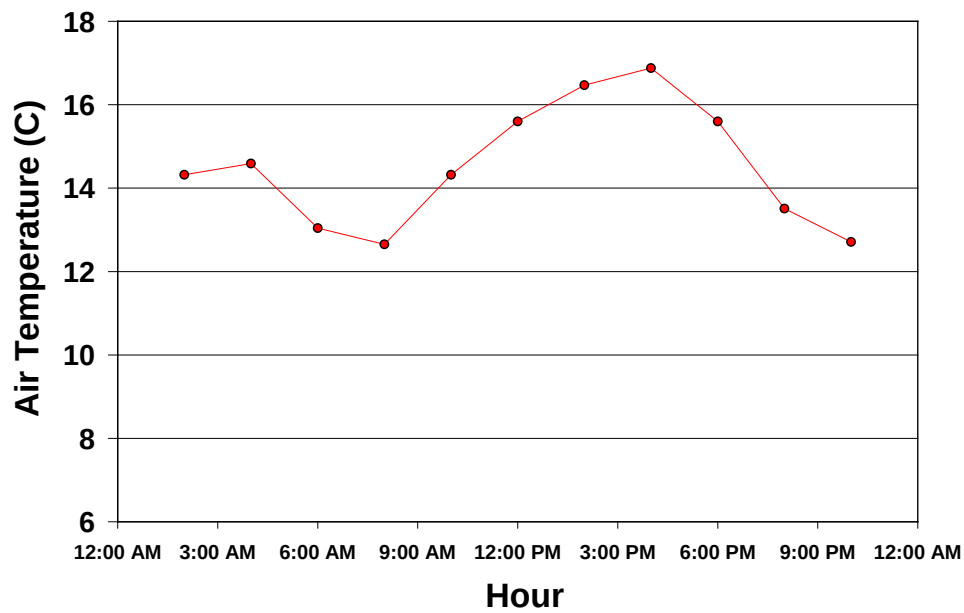


Figure 4. Air temperature corresponding to PCC temperature gradient charts (10/27/2009).

Figure 5 illustrates the temperature changes within the PCC layer for a five-day period. It can be observed that temperature measured by the thermocouple at the top of the PCC layer is immediately affected by the changes in air temperatures. On the other hand, the measurements show a time-lag between the air temperature peak and peak temperature at the bottom of PCC layer. This time-lag creates the PCC temperature gradients between the top and bottom of the PCC layer which cause stresses at the top and bottom of PCC. PCC temperature gradients are also given in Figure 5, calculated by using the following equation:

$$\nabla T = \frac{(T_{\text{top}} - T_{\text{bottom}})}{(D_{\text{top}} - D_{\text{bottom}})} \quad (1)$$

Where,

∇T : PCC temperature gradient ($^{\circ}\text{C}/\text{m}$);

T_{top} : Temperature measured by the top thermocouple ($^{\circ}\text{C}$);

T_{bottom} : Temperature measured by the bottom thermocouple ($^{\circ}\text{C}$);

D_{top} : Depth for top thermocouple (m);

D_{bottom} : Depth for bottom thermocouple (m).

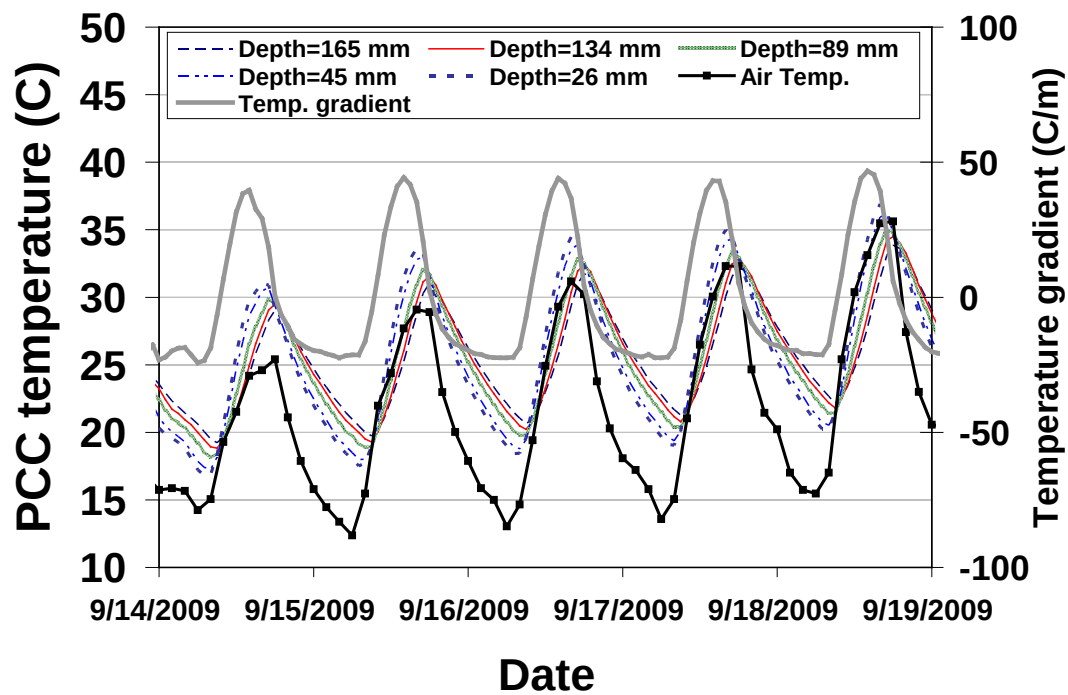
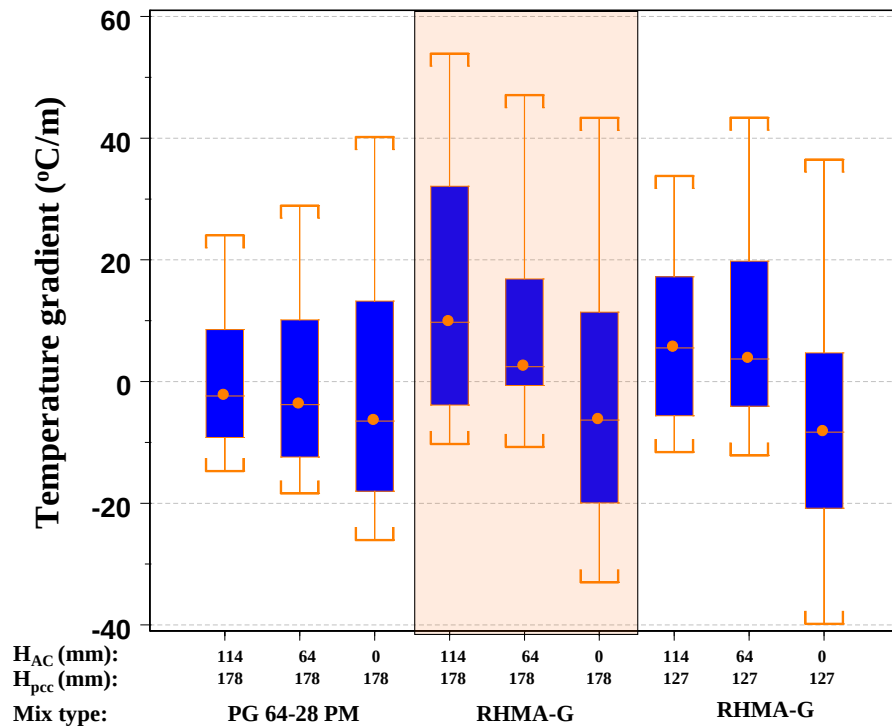


Figure 5. Changes in temperature within the PCC layer for a 5-day period.

In order to identify the effects of HMA and PCC layer thickness and HMA type on the variation of the PCC temperature gradients, one year of hourly temperature data (1/1/2010 to 12/31/2010) were analyzed from the thermocouples located on every section. One complete year was selected to be able to evaluate the effects of all seasons on temperature gradient variability without repeating the effects from the same months from different years. Figure 6 shows the PCC temperature gradients for Lanes A, C, and D by truncated (a few outliers were excluded) box plots. In the box plots, the middle line is the median value. The top and bottom of the box are the 25th and 75th percentile values and the bracketed lines above and below the boxes are the minimum and maximum values. It can be observed that the inclusion of the HMA layers causes a significant decrease in the PCC temperature gradients while no significant effect of PCC layer thickness on the variation of PCC temperature gradients is observed. However, it should be noted that thickest PCC layer in this study had a thickness of 178mm which is lower than most PCC pavements. Temperature gradients for thicker PCC layers should also be measured to identify the effects of larger thicknesses on temperature gradients.



Note: 1) H_{AC} is HMA thickness, H_{PCC} is PCC thickness.

2) In the box plot, the middle line is the median value. The top and bottom of the box are the 25th and 75th percentile values and the bracketed lines above and below the boxes are the minimum and maximum values.

Figure 6. Distribution of PCC temperature gradients for all sections.

In order to evaluate the effect of HMA thickness on the variation of PCC temperature gradients, exact distributions of PCC temperature gradients are given in Figure 7. Figure 7(a) shows that the section with the 114-mm thick PG 64-28 PM HMA layer has the lowest level of positive and negative PCC temperature gradients, and that the range of gradients increases when the HMA layer thickness is decreased to 64 mm. The corresponding section with no HMA layer has the largest variability in PCC temperature gradients, ranging from -44 to +75 °C/m. This result indicates that the HMA layer acts as a thermal insulator that decreases the temperature gradient within the PCC layer, reducing the overall probability of negative temperature gradients and most of the extreme negative temperature gradients, which cause tensile stresses on the top of the slab, and generally increasing the probability of small temperature gradients.

Similar results were also observed for Lanes C and D. However, Figure 7(b) and Figure 7(c) show that thickness of the HMA layer did not significantly affect the variability of PCC temperature gradients with the RHMA-G overlay.

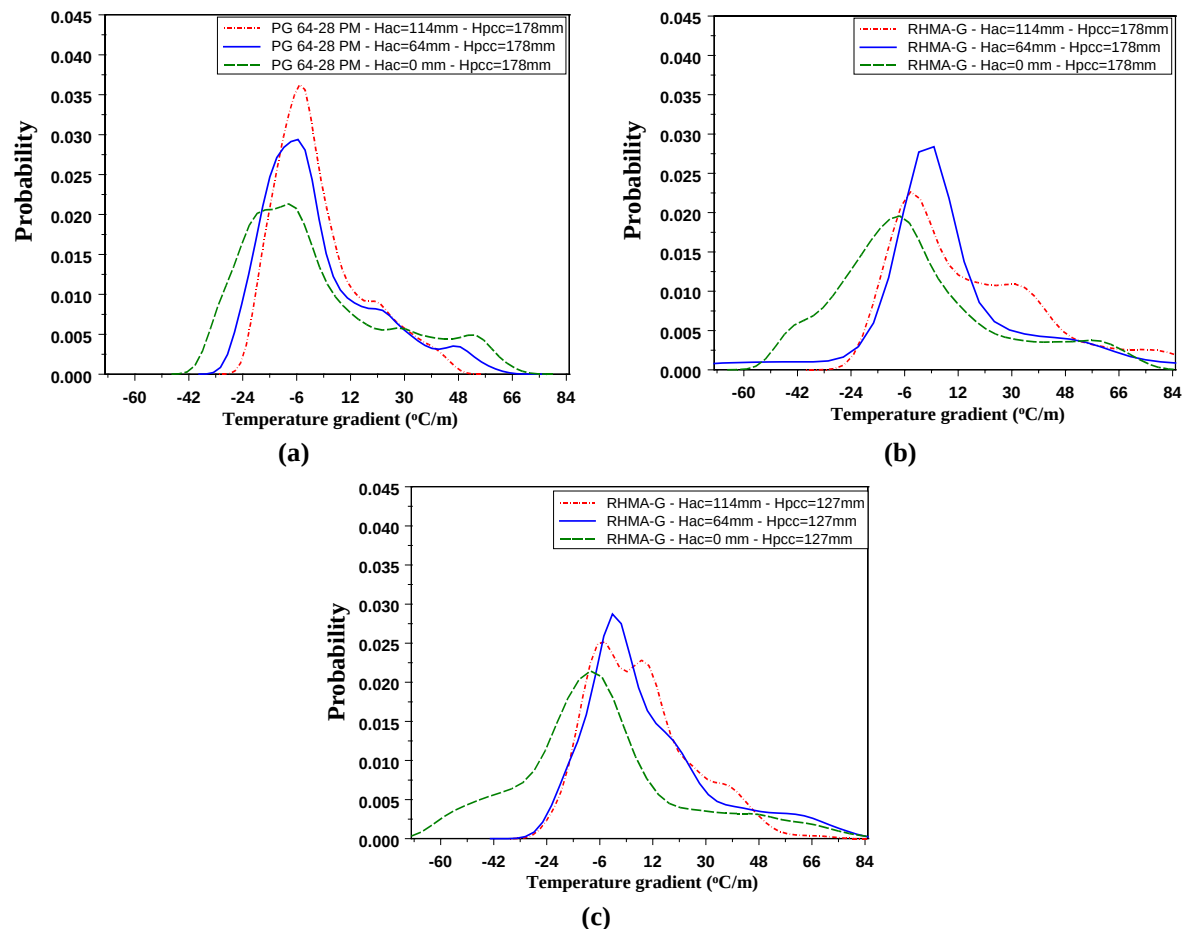


Figure 7. Probability distributions of PCC temperature gradients for year 2010:
(a) Lane A (b) Lane C (c) Lane D.

In order to determine the effect of HMA layer mix type on the variation of PCC temperature gradients, distributions for the gradients for sections with thick HMA layers (Lane A and Lane C) were compared. HMA layers on Lane A and Lane C were constructed from PG 64-28 PM and RHMA-G mixes, respectively, as shown in Figure 8. It can be observed that significantly higher positive PCC temperature gradients occurred on the section with the RHMA-G overlay. This result also agrees with the albedo measurements performed on sections with RHMA-G overlay, PG 64-28 PM overlay, and no HMA overlay (PCC). Albedo is the ratio of reflected solar radiation to the total solar radiation that falls on the surface. A perfect absorber will have an albedo of 0 while a perfect reflector will have an albedo equal to 1. Five albedo measurements were made on five different dates and results were shown in Figure 9. PG 64-28 PM overlay is reflecting more solar radiation (higher albedo) than the RHMA-G overlay which is causing lower positive PCC temperature gradients for the sections with PG 64-28 PM overlay. It should be noted that RHMA-G mix is visible to the human eye "more black" than the PG64-28PM mix. It can be concluded that the section with the RHMA-G overlay will experience larger thermal stresses at the bottom of the PCC layer than the section with the PG 64-28 PM overlay as a result of the larger positive PCC temperature gradients, while the maximum values of negative temperature gradients causing stresses at the top of the PCC slabs are similar for both materials.

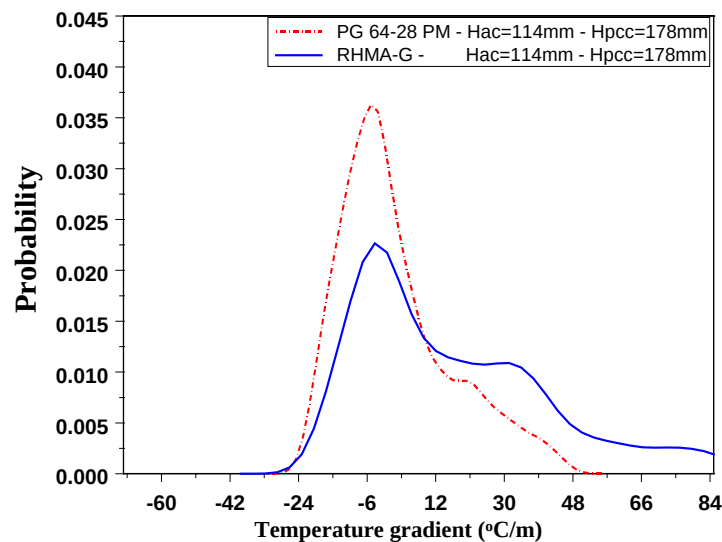


Figure 8. Probability distribution of PCC temperature gradients for sections constructed from PG 64-28 PM and RHMA-G mixes.

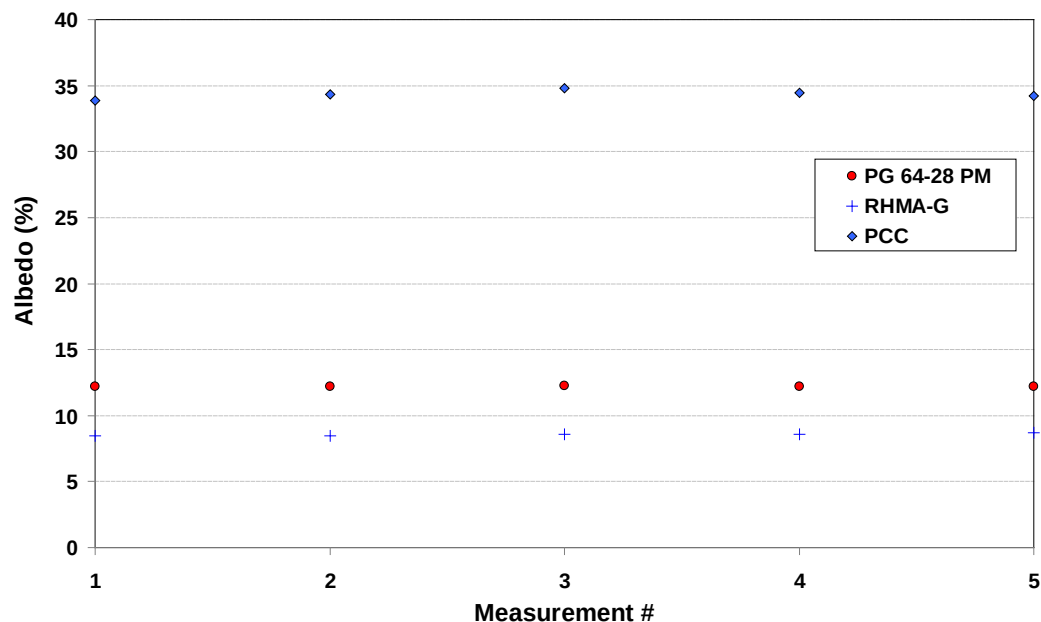


Figure 9. Measured albedo for the HVS test sections.

The effect of PCC layer thickness on the variation of PCC temperature gradients is also determined by comparing the gradient distributions of sections without an HMA layer for Lane C and Lane D. Distributions are given in Figure 10. It can be observed that there are no significant differences between the distributions. This result suggests that thickness of PCC layer does not have any considerable effect on the variation of the PCC temperature gradients for these slab thicknesses.

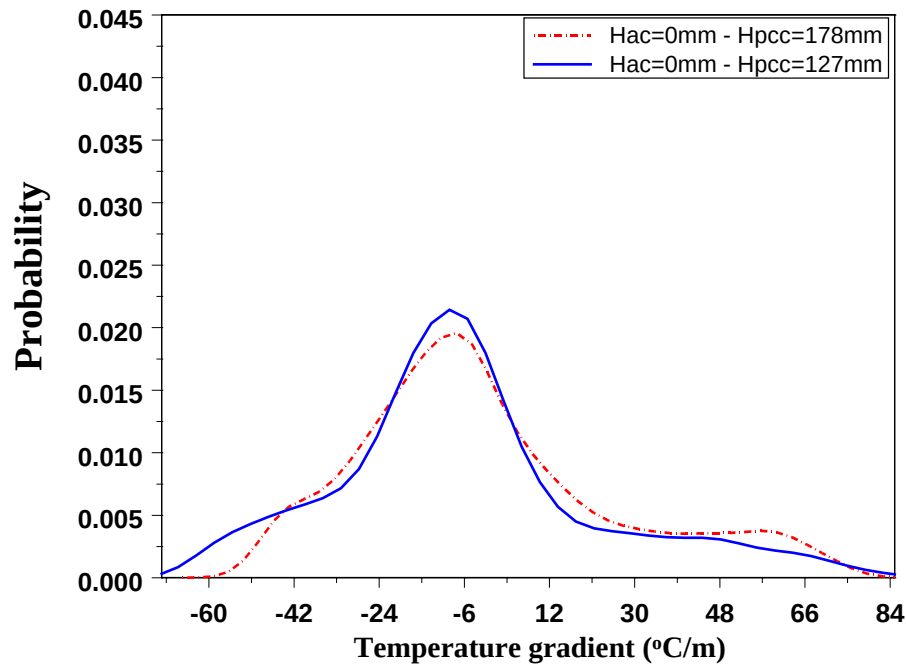


Figure 10. Probability distribution of PCC temperature gradients for thick and thin PCC layer sections without HMA layer.

PCC temperature gradient distributions were further analyzed by using statistical design and interaction plots. Design and interaction plots are generally used to compare the influence of a factor on the variation of the dependent variable with respect to other factors. Absolute values of the PCC temperature gradients were used as dependent variables for the analysis since both negative and positive PCC temperature gradients will cause tensile stresses. PCC and HMA thickness and HMA mix type were used as the independent variables for the design and interaction plots. Figure 11 shows the design plot, with each plot showing the mean for the factor levels for each variable as a short horizontal line, compared with the overall mean of the data shown as a long horizontal line across all variables. It can be observed that PCC thickness does not have any significant effect on the variability of PCC temperature gradients. On the other hand, the HMA layer appears to significantly decrease the PCC temperature gradients within the PCC layer. In addition, the calculated average for thickness of the HMA layer does not have much effect on the PCC temperature gradient. The PG 64-28 PM mix causes considerably lower PCC temperature gradients in the PCC layer than does the RHMA-G mix.

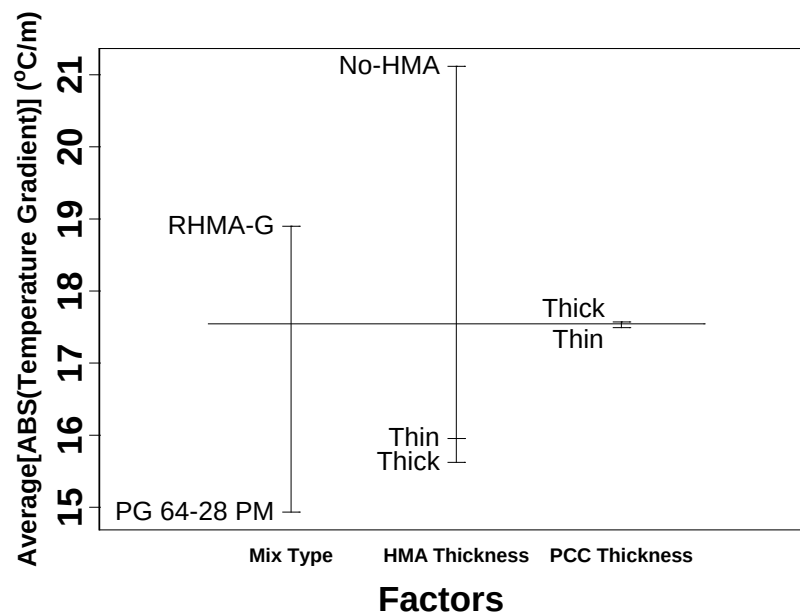
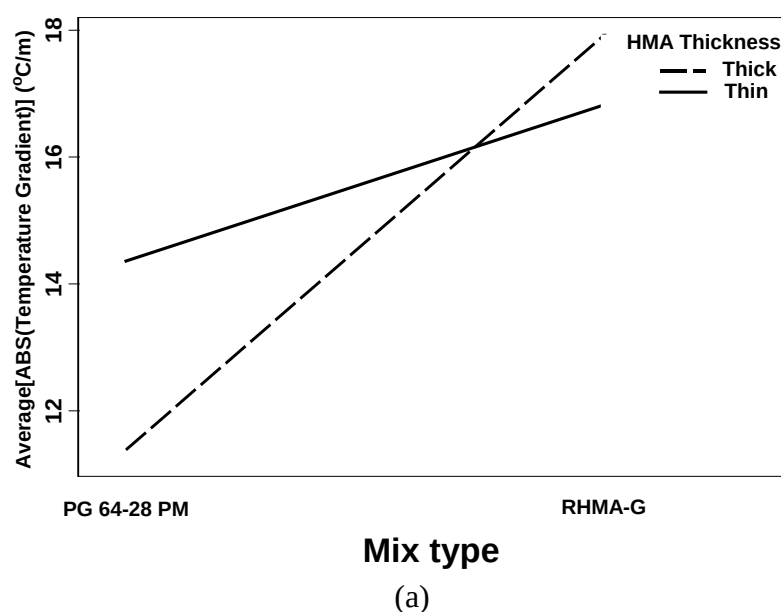
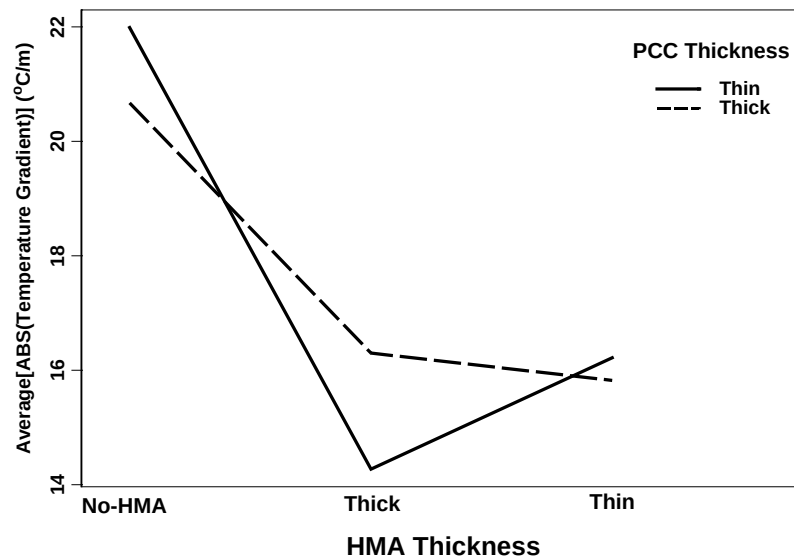


Figure 11. Design plot comparing the influence of variables HMA and PCC thickness and HMA type on the variation of the dependent variable PCC temperature gradient.

To determine the separate effect of each independent variable on the variability of PCC temperature gradients, interaction plots were used (Figure 12). Figure 12(a) shows that RHMA-G overlays cause higher PCC temperature gradients for all thicknesses than do PG 64-28 PM overlays which is a result of the lower albedo of RHMA-G mix. Figure 12(b) shows the extent to which the overlays reduce the PCC temperature gradients. The use of a thick or thin HMA layer does not cause any significant difference between the gradients for the thicker PCC slabs, while HMA layer thickness causes lower PCC temperature gradients for sections with thin PCC slabs (127 mm).





(b)

Figure 12. Interaction plots comparing the influence of variables HMA and PCC thickness and HMA type on the variation of the dependent variable PCC temperature gradient: (a) Mix type evaluation for all PCC thicknesses and (b) HMA thickness evaluation for all mix types.

Conclusions

In this study, temperature data collected from over 135 thermocouples placed at five depths and three locations within each slab were analyzed to identify the thermal insulation effect of HMA layer to reduce temperature gradients in PCC layers. Changes in PCC slab temperature gradients as a function of PCC slab thickness (178mm and 127mm), HMA overlay thickness (114mm, 64mm, and 0mm) and type (Polymer modified and rubber) were determined to provide experimental data for continued evaluation of the effects of reduced temperature gradients on PCC layer cracking performance.

The following are key findings from the PCC thermocouple measurements:

- HMA overlays significantly decreased the PCC temperature gradients.
- The thickness of the HMA overlay (114 mm versus 64 mm) did not have much effect on the PCC temperature gradient. Thus, HMA layer with a thickness of 64mm appeared to be the most cost effective alternative to reduce temperature gradients in the PCC layers.
- The effect of the HMA overlays was to increase the overall temperature of the PCC compared to the PCC without an HMA overlay by reflecting less solar radiation (lower albedo) as a result of its darker color.
- Significantly higher positive PCC temperature gradients can be observed for the section with RHMA-G overlay than for the PG 64-28 PM overlay. This shows that the PG 64-28 PM overlay is reflecting more solar radiation (higher albedo) than the RHMA-G overlay. It can be concluded that the section with the RHMA-G overlay will experience larger thermal stresses at the bottom of the PCC layer than the section with the PG 64-28 PM overlay as a result of the larger positive PCC temperature gradients.

- No significant effect of PCC layer thickness on the variation of PCC temperature gradients was observed. However, it should be noted that thickest PCC layer in this study had a thickness of 178mm which is lower than most PCC pavements. Temperature gradients for thicker PCC layers should also be measured to identify the effects of larger thicknesses on temperature gradients.

Future Study

The effects of the reduced temperature gradients on PCC cracking performance should be determined by finite element modeling. Measured temperature gradients should be entered to a finite element model with the corresponding structural and material properties. Calculated critical stress and strain values should be presented as distributions for each test section to identify the effects of reduced temperature gradients on PCC response. Fatigue life for each section can be calculated by integrating calculated stress and strain values with empirical equations. In this way, life cycle cost analyses can be performed to determine the effectiveness of designing and constructing new composite pavement systems, not those resulting from the rehabilitation of existing pavements, to reduce thermally-induced cracking.

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