

Assessment of JPCP Slab and Joint Movement under Multiple Structural and Environmental Conditions

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Abstract

Jointed plain concrete (JPC) pavement slab curling and joint movement have been shown to play a major role in the cracking performance of conventional JPCP pavements and composite HMA/JPC pavements with a renewable surface. These movements have been assessed as part of the SHRP II R21 Composite Pavement project at the University of California Pavement Research Center ATIRC test track. Environmentally induced slab movement both internal and at slab joints was evaluated under several conditions; two slab thicknesses, doweled and undoweled slabs, and overlaid (two thicknesses) and non-overlaid JPC slabs. The aim of this paper is to summarize findings of slab movement research and how this movement is affected by different variables. With the increasing push toward mechanistic design for concrete pavements, the importance of this information becomes ever greater.

Introduction

Composite pavements consisting of hot mix asphalt (HMA) placed over jointed plain concrete (JPC) pavements are used throughout the United States, whether intentionally constructed or as a result of an HMA overlay placed over JPC. Many large agencies use composite pavement structures as the design choice for major arterial and collector streets (Malella 2008). The most common distress, reflective cracking in the HMA surface results from a combination of shear and bending at the JPC joints. With the HMA overlay bonded to the rigid pavement, any movement in the underlying pavement produces tensile stresses in the overlay and can cause physical tearing in the overlay. This level of induced stress in the HMA is proportional to the joint movement which depends on slab length, temperature variation, and coefficient of thermal expansion (CTE) of the concrete (Dempsey 2002).

Pavement slab and joint movements have been studied by researchers for many years. Movements caused by warping, curling, and expansion and contraction lead to accelerated fatigue and joint failure in JPC pavements. A detailed study of thermal deformations on undoweled JPC pavements was performed in Chile (Poblete, et al., 1988). Transverse joint movement was monitored throughout the year and

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under varying conditions of temperature and sun exposure. It was found that warm sunny days led to higher thermal gradients and greater downward slab curvature. Joints would close at the top of the slab and remain open at the bottom. This difference in joint opening between the top and bottom of the slab was considered insignificant as it constituted only a few percent of total joint movement. On cool and cloudy winter days, with smaller thermal gradients, slabs would stay open with minimal to no rotation of slab edges and faces.

Work was performed looking at the joint movement related to slab temperature and slab length, dowel bars, and base friction for JPC slabs. (Bodosci, et al., 1993). The authors found from that field study that dowel bars and base type have only a small effect on joint movement. Joint movements of 1 mm to 3 mm were commonly measured resulting from midslab temperature changes of 40C to 50C and tended to follow a linear trend with temperature. In further work on this subject, (Lee and Stoffels 2001) quantified slab movement with temperature through an extensive study of thousands of joint movements extracted from LTTP data. The researchers presented the “Effective Ratio” (ER) of the joints, the ratio of the surface measured joint opening and closing to the change in temperature. For many joints, a linear change in joint closing occurred with temperature up to a temperature at which the joint closed; the closure temperature. Above the closure temperature the joints did not close further. Measured ER values ranged from approximately 2 mm/100° C to 25 mm/100° C from the sources cited, though slab length details were not evident.

Studies into joint load transfer, joint lockup, and void detection were performed using the Falling Weight Deflectometer on MnRoad pavements (Vandenbossche 2007). Slab temperature changes were shown to affect load transfer efficiency (LTE). Uniform temperatures result in opening and closing of the joint and subsequent decrease and increase in LTE. Temperature gradients within slabs can cause dowel bar lockup due to pressure on the dowel bar, and subsequently higher LTE.

Slab curling was investigated (Yu et al. 1996) with instrumented slabs and it was found that curling is a function of thermal gradients and slab length. Corner and edge slab movements were measured throughout the day and temperature was recorded. Pavements face the least resistance to curling when curling in the upward direction since only slab corners lift, whereas in downward curling, there is downward slab bearing resistance on the base and more force is required for the same degree of curling.

At the R21 HVS HMA/JPC composite pavement test track at UC Davis, Joint Displacement Measurement Devices (JDMDs) were used to monitor 1) the horizontal opening and closing of the slab joints and 2) the vertical movements of the slab corners caused by daily temperature variation, and without traffic loading, on a number of slab corners. Data were collected both before and after HMA overlay construction. The significance of this research is that the data were used to establish the effects of HMA overlay thickness and overlay material type on JPC pavement joint movements when used in composite pavements. Notably, joint movement rates (JMR), similar to ER are presented to illustrate these effects. This information is crucial for understanding composite pavement performance as well as calibrating mechanistic-empirical models.

Monitoring Program

Site Layout and Slab Labeling Figure 1 shows a plan view of the test sections and Figure 2 shows the labeling system for each individual PCC slab. The experiment design allows evaluation of the following factors in pavement response and performance:

- Existence of dowel at joints: Lane A is doweled while all other lanes are undoweled;
- HMA overlay thickness: thickness of the overlay varies from 114mm for column 1, 64mm for column 2 to 0mm for column 3;
- HMA overlay mix type: Lane A and B use dense graded HMA with PG 64-28 polymer modified binder (PM mix) while Lane C and D use rubberized HMA with gap graded aggregates (RHMA-G mix);
- PCC slab thickness: PCC slab thickness is 178mm for Lane A, B and C, and 127mm for Lane D

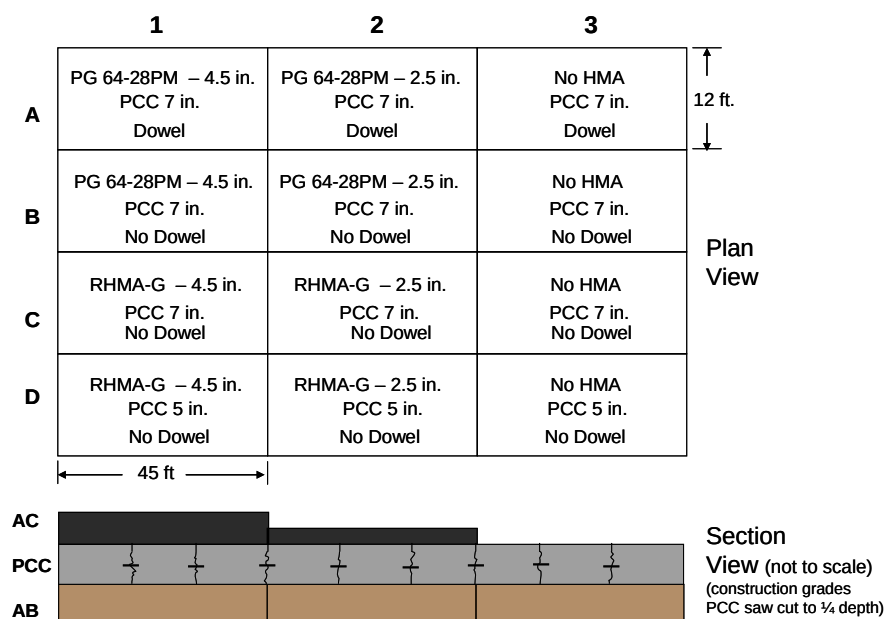


Figure 1: Plan (top) and section view (bottom) of test section layout with approximate construction elevations (1 in. = 25.4 mm, 1 ft. = 304.8 mm).

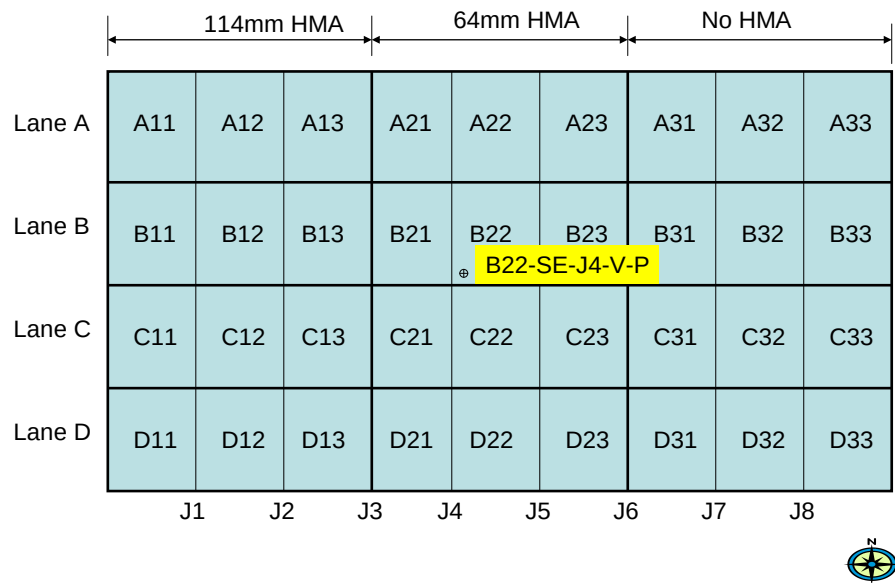


Figure 2: Section layout and slab labeling system: Each slab is named with one letter indicating the lane and two digits indicating the location within each lane. The first digit indicates the structure type, while the second digit indicates the slab sequence from south to north within each structure.

JDMD Locations and Labeling When monitoring joint movements, JDMDs are deployed at the corners of the slabs. A vertical JDMD monitors the upward and downward curling of one PCC slab corner, while a horizontal JDMD monitors relative horizontal displacements between two adjacent corners. A JDMD is identified by its location, orientation, nearby joint, and the surface type (HMA or PCC) it is measuring. More specifics of the naming scheme include:

- A slab has four corners: NW (northwest), NE (northeast), SW (southwest), and SE (southeast);
- There are two orientations: H (horizontal) and V (vertical)
- There are eight joints: J1 to J8 as shown in Figure 2.
- There are two surface types: A (HMA) and P (PCC)

For example, JDMD-B22-SE-J4-V-P, shown in Figure 2, indicates that the JDMD is located at the southeast (SE) corner of slab B22, near Joint J4, that it is measuring vertical movements, and is installed on the PCC surface (P).

Instrumentation and Monitoring Methods For this study, two types of data were collected: ambient air temperature and joint movements. Ambient air temperature is recorded continuously by an automatic weather station at the project site that recorded hourly temperature, wind speed, sun radiation, and precipitation. Joint movements were recorded with JDMDs, which are essentially LVDTs. Figure 3 shows the configuration for measuring vertical and horizontal joint movements. The anchoring rods are each five feet (1.5 m) long.

Albedo values were also measured for the three kinds of surface at the R21 track: overlay with PM mix, overlay with RHMA-G mix, and plain PCC.

Measurement was done on 4/8/2011 using NovaLynx 240-8104 Albedometer (Dual Pyranometer).

The HVS data acquisition (DAQ) system recorded joint movements at one minute intervals. Due to the channel number limit of the HVS DAQ system, a maximum of 15 JDMDs could be deployed at a time. Joint movements were monitored in batches with each batch consisting of about one week of data.

Monitoring Schedule Ten batches of testing were conducted in total. Batch numbers one to five were conducted before HMA overlay while batches six to ten were conducted after HMA overlay. The longitudinal joints between adjacent lanes were sawn to remove the interference between lanes. As an example, the JDMD layout for Batch No. 10 is shown in Figure 4, with the JDMD label indicating which HVS DAQ channel it was attached to. Each batch was given a unique code to indicate its objective and location. A circle or arrow on each figure shows the location of each vertical JDMD, and an arrow indicates each horizontal JDMD. Note that the northwest corner of Slab C32 was monitored as part of every batch to provide reference joint movements. This is important because average ambient temperature changed among different batches, and as a result the shape of PCC slabs changed and caused joint movement characteristics to change. Also, some of the JDMDs did not function properly and their labels are enclosed in parentheses.



Figure 3: A photo showing the JDMD configuration for monitoring both horizontal and vertical movements at a joint. The horizontal JDMD shown is model DSD800SE5 made by Daytronic, and the vertical JDMDs are model GHSD/GHSDR 750 made by Macro Sensors.

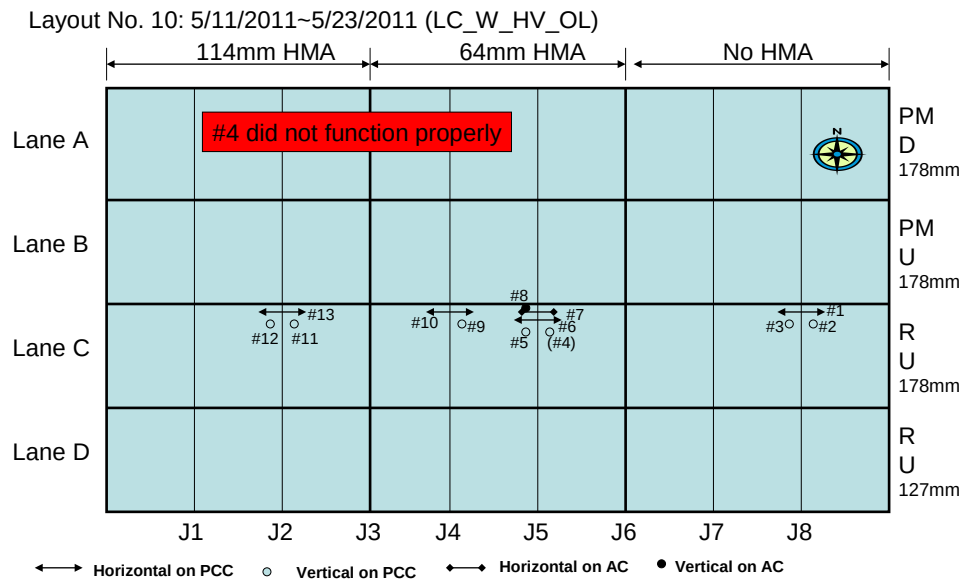


Figure 4: JDMD monitoring layout for Batch No. 10, coded LC_HV_OL, monitored the movements of joints on west edge of Lane C after HMA overlay, with Slab C32 as a reference.

Results Summary

Examples of the variations of deflection and ambient temperature with time are shown in Figure 5 for horizontal movements and Figure 6 for vertical movements during Batch No.10 respectively. Note that an increase in deflection reading corresponds to downward movement for vertical JDMDs and opening movement for horizontal JDMDs. In the figures, the legends include the JDMD number as well as its label, and these numbers correspond to those shown in Figure 4.

The reference JDMDs shown in each figure are always the ones located at the northwest corner of Slab C32, i.e., C32-NW-J8-V-P for vertical movements and C32-NW-J8-H-P for horizontal movements. As pointed out earlier, these two JDMDs are part of every batch and therefore provide a consistent reference for all the other measurements.

Also note that the starting value for JDMD measurements is arbitrary. The starting values were set to be exactly the same for each type of JDMD (i.e., horizontal or vertical) within each batch to show clearer trends.

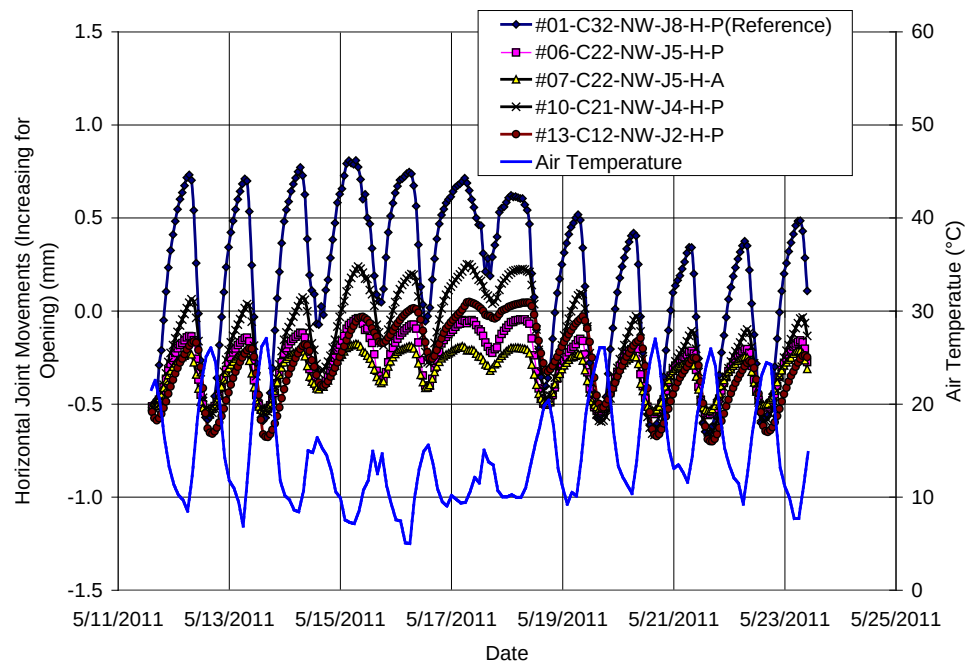


Figure 5: Batch No. 10, horizontal joint movements along Lane C after overlay; see Figure 4 for JDMD layout.

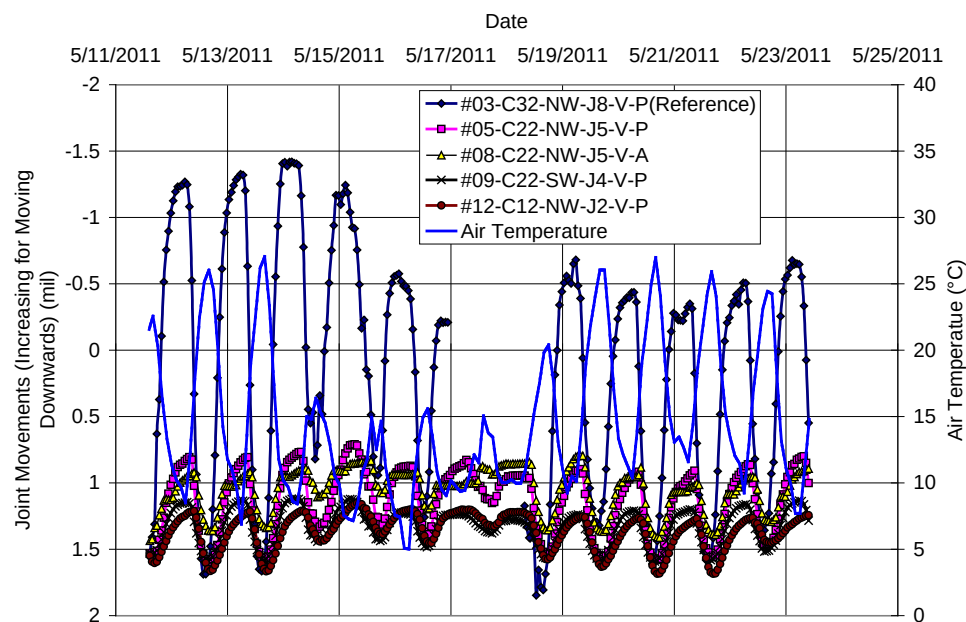


Figure 6: Batch No. 10, vertical joint movements along Lane C after overlay; see Figure 4 for JDMD layout.

Albedo values were measured for the different materials at the R21 test track. These albedo values ranged from PCC (32.3% average, 2.8 St. Dev), Polymer Modified HMA (12.2% average, 0.6 St. Dev, RHMA-G (8.5% average, 0.1 St. Dev) and Aggregate (11.4% average). For reference, the measured albedo of grass is 18.2%. Both HMA overlay materials have significantly lower albedo values than PCC, indicating that more solar radiation is absorbed by the pavement as a result of the overlay. Furthermore, the RHMA-G mix has a smaller albedo value than the PM

mix used in the R21 project. It is believed that this is due to the higher binder content in the RHMA-G (~8.3%) versus PM (~5.0%) and that the RHMA-G binder contains rubber from recycled tires, making it darker and more light absorbent than the PM binder.

Data Analysis and Observations

The *joint movement rate* (JMR), defined as the amount of horizontal or vertical displacement caused by a unit increase in ambient air temperature, was calculated as the slope of the straight line fitted through the joint displacement-versus-air temperature data for each individual JDMD. Figure 7 shows example variations of horizontal joint displacements with ambient air temperature. JMR for horizontal JDMDs are negative, indicating that joints close as air temperature increases. JMR for vertical JDMDs are positive, which indicates slab corners curling downward as air temperature increases.

Figure 8 shows the variation of JMR with average ambient air temperature for the two reference JDMDs. It is apparent that JMR is not a constant, but rather that it varies with ambient air temperature when the joint movements are measured. This is reasonable because ambient air temperature affects the shape of a PCC slab which in turn affects the amount it would deform with a unit temperature change.

Figure 8 also indicates that JMR for both vertical and horizontal movements peak at around 60°F, which may indicate that the shape of that particular slab allows maximum freedom of movement at around that temperature. It may also indicate that when the temperature is very low, upward curling can lead adjacent slabs to lock up and hence limit further slab movement, and that when temperature is very high, expansion of the slabs causes the joint to close, which also locks up the slabs and provides additional constraints on their movement.

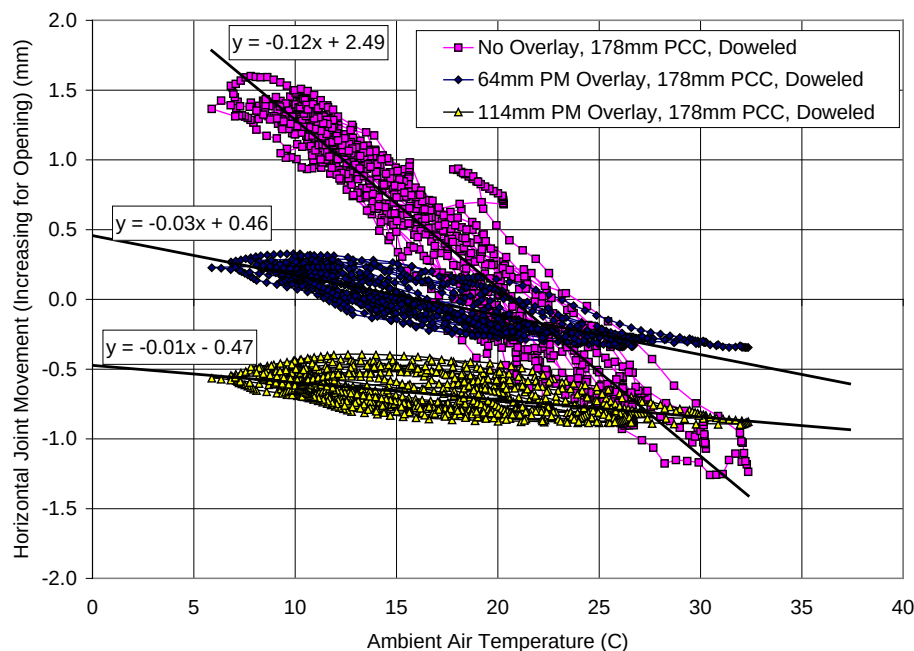


Figure 7: Horizontal joint movement versus air temperature plots for Lane A after overlay construction.

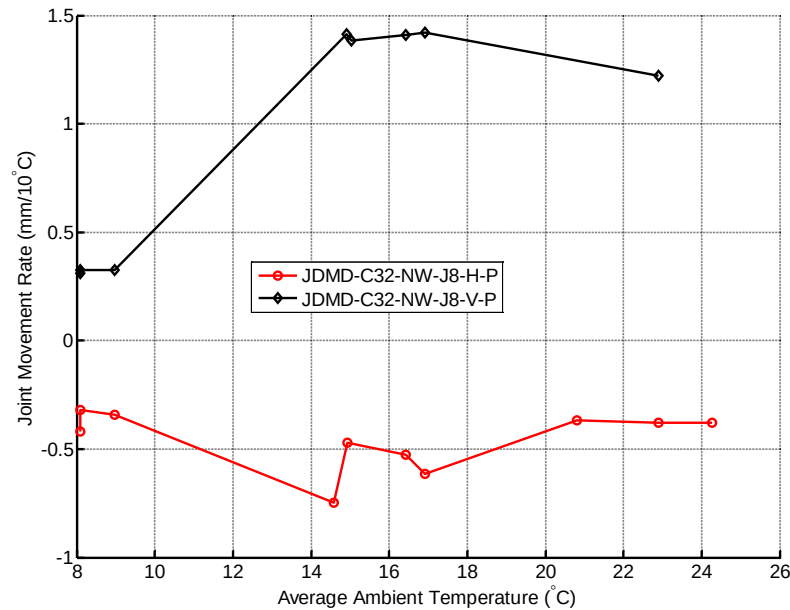


Figure 8: Variation of joint movement rate (JMR) versus average ambient temperature for the reference JDMDs.

Since joint movement is affected by ambient temperature, it is important to only compare results measured within the same batch or among batches with similar ambient temperature. In the following two sections, the joint movements before and after overlay will be examined. The data collected before overlay provide information about effects of dowels and PCC thickness on joint movements in plain PCC pavement pavements as well as variability in JMR. The data collected after overlay provide information on effects of dowels, overlay thickness, and overlay mix type on joint movements in composite pavements.

Joint Movements Before HMA Overlay Construction Horizontal joint movement rate (JMR) variation for different joints and different lanes on plain PCC pavements are shown in Figure 9. Figure 9(a) shows that dowel joints have slightly lower absolute JMR values than undoweled joints but the difference is comparable to the variation in JMR values within each lane (i.e., construction variability). Figure 9(b) indicates that 178mm PCC slabs generally have the same JMR values as 127mm PCC slabs. Figure 9 shows that the average value of horizontal JMR is around -0.5 mm/10°C. This implies a coefficient of thermal expansion of about $10.9 \mu\epsilon/^\circ\text{C}$ since the slab length is 15 ft, which is reasonable for PCC.

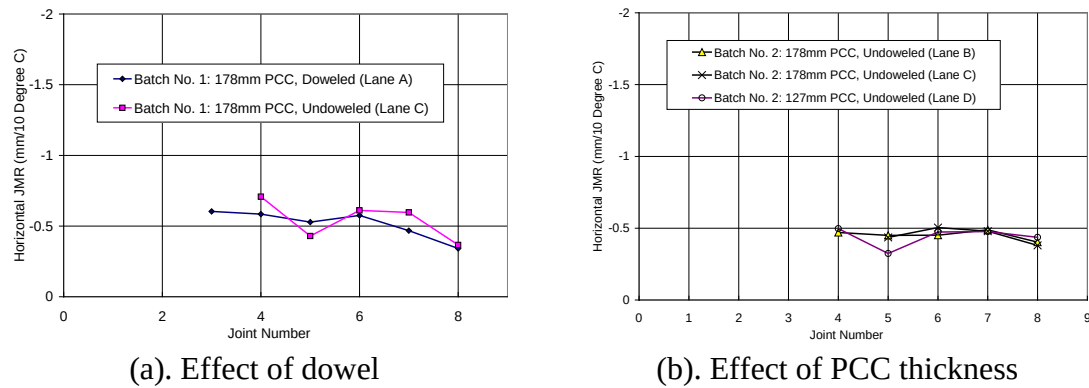


Figure 9: Horizontal joint movement rates (JMR) measured before overlay

The vertical JMR values for different slabs and different lanes are evaluated in Batch Nos. 3, 4, and 5. An example of the result is plotted in Figure 10 for Batch No. 3. Figure 10 indicates that 127mm PCC slabs have higher JMR than 178mm PCC slabs, and that slabs with doweled joints have the lowest JMR values. The difference is however again comparable to construction variability.

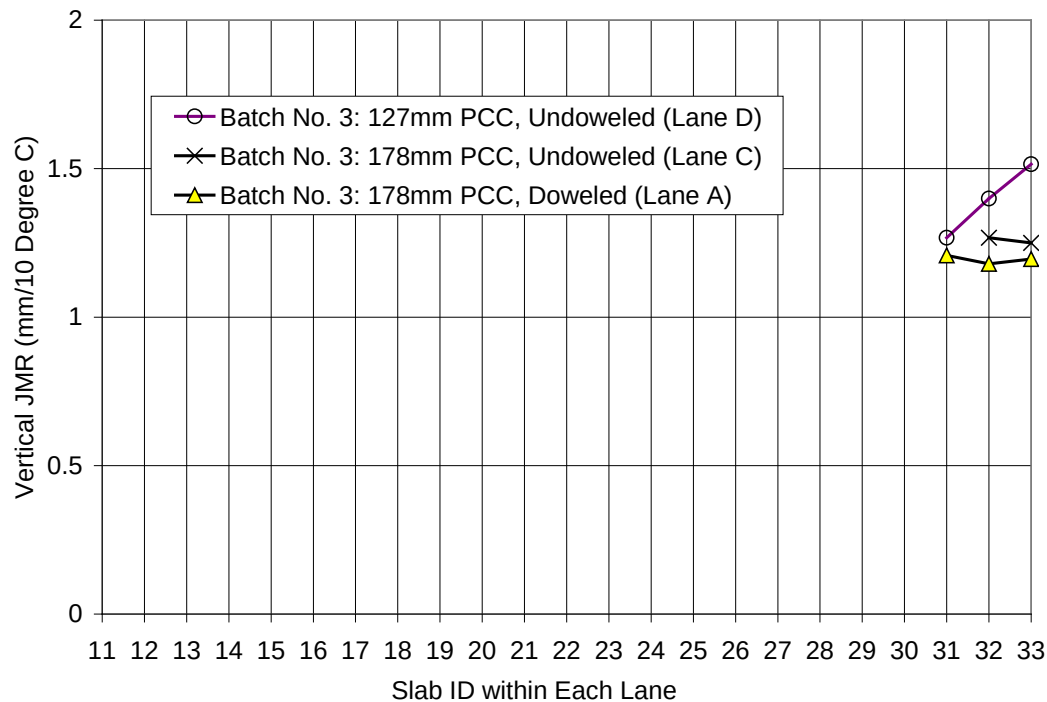
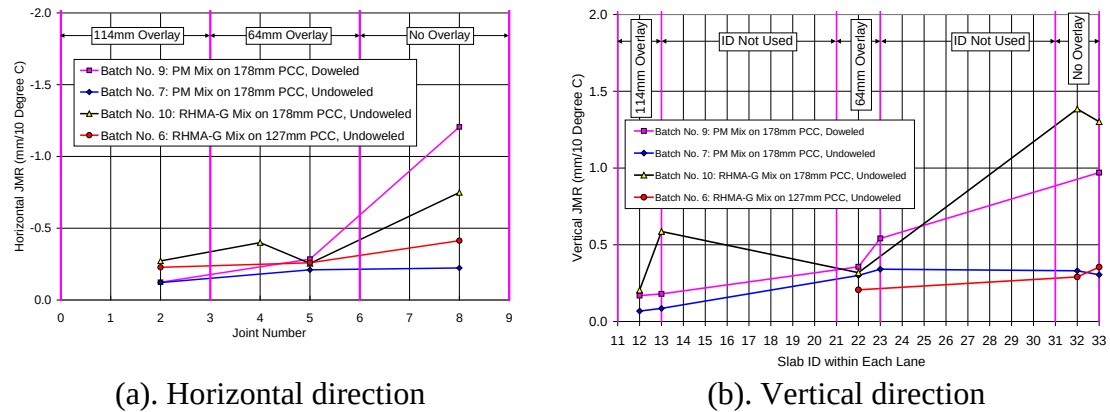


Figure 10: Vertical joint movement rates (JMR) measured in Batch No. 3 (before overlay).

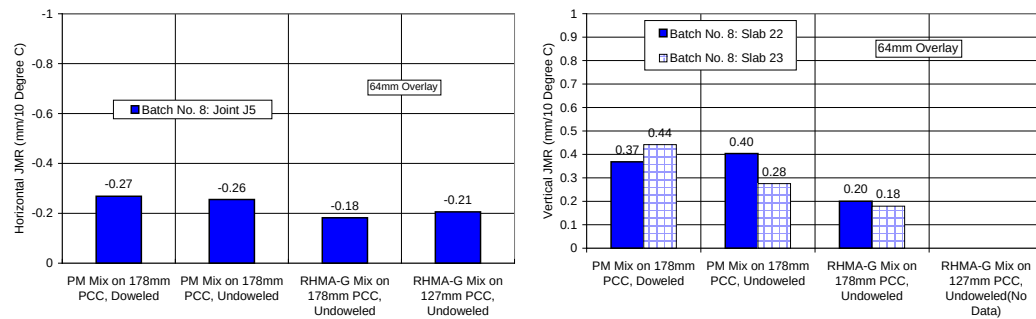
Joint Movements After HMA Overlay Construction Figure 11 show the comparison of JMR for different locations after overlay construction.

Figure 12 shows the variation of JMR for composite pavements that have 64mm overlay. Table 1 summarizes the effect of overlay thickness on horizontal and vertical JMR, respectively.



(a). Horizontal direction (b). Vertical direction

Figure 11: Joint movement rates (JMR) for different lanes and joints after overlay construction.



(a). Horizontal movements along Joint 15 (b). Vertical movements on Slab 22 and 23

Figure 12: Joint movement rates (JMR) for different lanes with 64mm overlay after overlay construction

Table 1: JMR Reduction Effect of Overlay Thickness

Movement Direction	Mix Type	Structure	JMR Values (mm/10°C)			% Reduction	
			0mm	64mm	114mm	64mm	114mm
Horizontal	PM Mix	Doweled, 178mm PCC	-1.21	-0.28	-0.12	76	90
	PM Mix	Undoweled, 178mm PCC	-0.22	-0.21	-0.12	6	46
	RHMA-G	Undoweled, 178mm PCC	-0.75	-0.33	-0.27	56	64
	RHMA-G	Undoweled, 127mm PCC	-0.41	-0.26	-0.23	37	45
Vertical	PM Mix	Doweled, 178mm PCC	2.12	0.98	0.38	54	82
	PM Mix	Undoweled, 178mm PCC	0.69	0.70	0.17	-1	76
	RHMA-G	Undoweled, 178mm PCC	2.94	0.70	0.86	76	71
	RHMA-G	Undoweled, 127mm PCC	0.70	0.45	No Data	36	No Data

Based on these plots and data, the following observations are made with regard to the vertical and horizontal JMR after overlay construction:

- Placement of HMA overlays on PCC pavements lowers the values for both horizontal and vertical JMR compared to plain PCC pavement. The thicker the overlay, the greater the decrease in JMR (see Figure 11).
- On the reduction effect of overlay thickness on horizontal JMR and vertical JMR (Figure 11 and Table 1):
 - All 64mm overlays showed significant reduction in JMR except for PM mix on 178mm undoweled PCC;
 - 114mm PM mix showed a significant further reduction in JMR compared to 64mm overlays;
 - 114mm RHMA-G mix showed only a slight further reduction or even a slight increase in JMR compared to 64mm overlays.
- On JMR for composite pavements with 64mm (see Figure 12):
 - 64mm PM mix overlay on 178mm doweled PCC has roughly the same vertical and horizontal JMR as 64mm PM mix on 178mm undoweled PCC, i.e., the effect of dowel is minimal;
 - Vertical and horizontal JMR for 64mm RHMA-G overlay on 178mm undoweled PCC is 1/2 to 2/3 of the values for 64mm PM mix overlay on 178mm undoweled PCC, i.e., RHMA-G is more efficient than PM mix in reducing JMR when used in 64mm overlay;
 - Horizontal JMR values for 64mm RHMA-G overlay on 178mm and 127mm PCC are roughly the same.
- On the effect of mix type for reducing JMR:
 - The albedo value for RHMA-G mix is lower than the value for PM mix, which is believed to lead to more efficient JMR reduction by

the RHMA-G mix than the PM mix when both are used in 64mm overlay. The lower albedo RHMA-G led to higher overall RHMA-G slab temperatures and generally smaller thermal gradients (Coleri et al. 2012) which results in greater slab expansion and lower curling levels, which is believed to reduce horizontal and vertical joint movement.

Summary of Findings

This paper summarizes a study to monitor horizontal and vertical joint movements for HMA/PCC composite pavements both before and after overlay construction. *Joint movement rate* (JMR), defined as joint deflection per unit ambient temperature increase, was used to describe joint movement characteristics.

JMR was found to change with daily average ambient air temperature. In general, the higher the average daily ambient temperature, the higher the values for JMR.

For joints in plain PCC pavement (i.e., before HMA overlay), doweled joints have lower vertical and horizontal JMR values compared to undoweled joints. It was also found that joints in 127mm PCC slabs have roughly the same horizontal JMR but higher vertical JMR compared to joints in 178mm PCC slabs.

Data collected after overlay construction showed that HMA overlay reduces both horizontal and vertical JMR. The thicker the overlay, the more significant the JMR reduction effect. 64mm overlay can effectively reduce JMR except when PM mix is used and placed on 7 in. undoweled slabs. The benefit of increasing overlay thickness from 64mm to 114mm depends on the mix type: when PM mix is used, the 114mm overlay shows significant improvement over 64mm overlay in reducing JMR; when RHMA-G mix is used, 114mm overlay show only small improvement over 64mm.

Albedo values for both HMA overlay materials were measured and they were found to be significantly lower than the value for plain PCC. This indicates that more solar radiation is absorbed by the composite pavements than plain PCC pavements even though composite pavements still have lower JMR values than plain PCC pavements. The shielding effect of the HMA overlay is the reason for lower JMR in composite pavements compared to plain PCC pavements.

The effect of dowel and overlay mix type were examined for pavements with 64mm overlay. It was found that the effect of dowels is minimal, and RHMA-G is more efficient than the PM mix in reducing JMR. This can be explained by the lower Albedo value for the RHMA-G mix compared to the PM mix.

ACKNOWLEDGEMENT AND DISCLAIMER

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References

Bodوسي, A., I. A. Minkarah, R. S. Arudi (1993), "Analysis of Horizontal Movements of Joints and Cracks in Portland Cement Concrete Pavements", Transportation

Research Record: Journal of the Transportation Research Board, No. 1392, Transportation Research Board of the National Academies, Washington, D.C. pp. 43-52.

Coleri, E., L. Popescu, J. M. Signore, R. Wu, J. T Harvey (2012), "PCC Slab Temperature Gradients as a Function of Structure and Environment - Experience from the SHRP II R21 Composite Pavement Test Track" Submitted for presentation and publication at the 2012 International Conference on Concrete Pavements, Quebec City, Quebec.

Dempsey, B. J., (2002) "Development and Performance of Interlayer Stress-Absorbing Composite in Asphalt Concrete Overlays", Transportation Research Record: Journal of the Transportation Research Board, No. 1809, Transportation Research Board of the National Academies, Washington, D.C., pp. 175-183.

Mallela, J., H. L. Von Quintus, and J. Farina (2008), "Observations, Modeling, and Mitigation Related to Reflective Cracking on Composite Pavements in New York City." Transportation Research Record: Journal of the Transportation Research Board, No. 2084, Transportation Research Board of the National Academies, Washington, D.C., pp. 124-133.

Poblete, M., R. Salsilli, R. Valenzuela, A. Bull, and P. Spratz (1988), "Field Evaluation of Thermal Deformations in Undoweled PCC Pavement Slabs." Transportation Research Record 1207, TRB, National Research Council, Washington, D.C., pp. 217-228.

Vandenbossche, J. (2007), "Effects of Slab Temperature Profiles on Use of Falling Weight Deflectometer Data to Monitor Joint Performance and Detect Voids", Transportation Research Record: Journal of the Transportation Research Board, No. 2005, Transportation Research Board of the National Academies, Washington, D.C., pp. 75-85.

Yu, T. H., L. Khazanovich, M. I. Darter, A. Ardani (2006), "Analysis of Concrete Pavement Responses to Temperature and Wheel Loads Measured from Instrumented Slabs", Transportation Research Record 1639, TRB, National Research Council, Washington, D.C., pp. 217-228