MEASUREMENT AND ANALYSIS OF SLAB CURVATURE IN JPC PAVEMENTS USING PROFILING TECHNOLOGY

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ABSTRACT

The feasibility of measuring slab-curvature using a non-contact, high-speed profiler system was assessed by the Pavement Surface Analysis Laboratory (PSAL) of Turner-Fairbank Highway Research Center of the Federal Highway Administration (FHWA). The primary objectives of the pilot study were to (1) measure the curvature of the concrete slabs using existing profiling technology, (2) establish a standard procedure to identify warp and curl from profiler data, (3) quantify the change in curvature due to temperature changes, (4) determine the sampling interval required to measure curvature, (5) determine the relationship between curvature and roughness measurements, and (6) relate curvature data to premature transverse pavement cracking and construction conditions. The PSAL research profiler was used in the survey of 104 lane-km of interstate highway in a period of 24 hours. A single pass of 26 km in each lane was collected during four windows of two hours. The time windows were 4-6am, 6-8am, 11am-1pm, and 6-8pm.

The authors will present the results of the analysis of the data, including curvature and roughness, with the effect of temperature on these parameters and relationship of curvature to transverse cracking performance.

INTRODUCTION

To assist a State Department of Transportation (DOT) determine the cause of a premature cracking failure on a 104 lane-km of jointed plain concrete pavement (JPCP) the Federal Highway Administration, Pavement Surface Analysis (PSA) Lab performed a pavement profile survey. The survey was conducted to support a hypothesis that slab deformation relating to temperature curling, moisture warping and built-in curvature may have contributed to the premature transverse cracking experienced on this project.

Determining the magnitude of slab curvature for a isolated slab is a simple but labor intensive task through use of precision manual surveying techniques. To determine the slab deformation of approximately 16,000 slabs of an in-service pavement over a short time period is quite another. A high-speed inertial profiler was selected to collect the profile data.

The phenomena of slab warping, curling, and built-in curvature is related to moisture gradient, temperature gradient while in-service, and temperature gradient at time of construction, respectively. The mechanism of built-in curvature and its relationship to pavement performance is not well understood within the pavement community, however, it can contribute significantly to environmental loading in jointed concrete pavement performance.

To determine the gross slab deformation resulting from all sources, at a given time, a slab deformation can be measured. However, to determine the portion of slab deformation resulting from temperature gradients, time-history profile data over a range of temperatures is required.

SCOPE

To determine deformation of individual concrete pavement slabs with a high degree of precision a complex set of pattern recognition algorithms were developed to identify joints, faulting, cracks, and other feature that may interfere with the computation of slab curvature.

The task of identifying features in the pavement was separated from the analysis of slab deformation. The interpretation of the results for adjacent slabs, different treatments, construction types and repairs depends on the robustness of the approach to quantify curvature. Once the process of measuring slab deformation was established, the primary objective of the project was to study the following hypotheses:

Hypothesis 1:	Change in deformation of slabs is proportional to change in temperature
Hypothesis 2:	Pairs of adjacent left-lane right-lane slabs have similar behavior of deformation.
Hypothesis 3:	Roughness (IRI) is related to deformation of slabs
Hypothesis 4:	Cracked slabs in the right lane correspond to slabs in the left lane with high deformation differences
Hypothesis 5:	Sign of deformation is related to temperature at construction

METHOD

Using the Federal Highway Administrations (FHWA) PRORUT II road profiler, data was collected on 104 lane-km of interstate highway at 80 km/h. Data was recorded every 5 mm from 3 lasers, 2 accelerometers, a distance pulsar and a temperature sensor, from which the following analysis steps were undertaken:

Step 1: Locate joints, cracks, and other surface features with 5 mm data. A sampling interval of 1 mm would provide a crisp level of detail to classify patterns of laser depth for joints and cracks. Conversely, a sampling interval of 150 mm would not provide sufficient data to identify needed features

Step 2: Identify start and end of slabs for each time period.

Step 3: Pre-process data set keeping 5-mm interval.

Step 4: For each slab, use 5-mm data from accelerometer and laser to compute the slope of the profile. From the slope-profile, compute an estimate of the curvature of the profile.

Step 5: Compute the profile to visualize the shape of the surface of the slab and estimate the maximum deformation of the slab.

Step 6: For each slab; identify regions of curvature of constant sign. Classify pattern of curvature. For each pattern of curvature, define parameters that describe this pattern.

Step 7: With the same basic data used above, compute IRI, number of cracks for each slab.

Step 8: Within each type of curvature, study the trends between computed IRI, construction schedule, alignment (stationing).

Figure 1 illustrates the method of quantification of curvature using a profile. The plot labeled "initial estimate" shows four curves: the raw profile of the slab, a linear, quadratic and cubic fits of the profile. In order to compute the maximum deformation of the slab, the profile is normalized to remove grade. The cubic fit of the profile is used to determine the point of maximum deformation, as shown in the plot labeled "normalized".

Figure 2 is an example of data extracted from four survey of the same lane of traffic at different time windows. The left plots are the normalized raw profiles, and the right plots are the curve-fit profiles. The effect of temperature on the shape of the slab is captured by the profile. The sign of the maximum deformation indicates the direction of curling and its magnitude, the severity of curling.

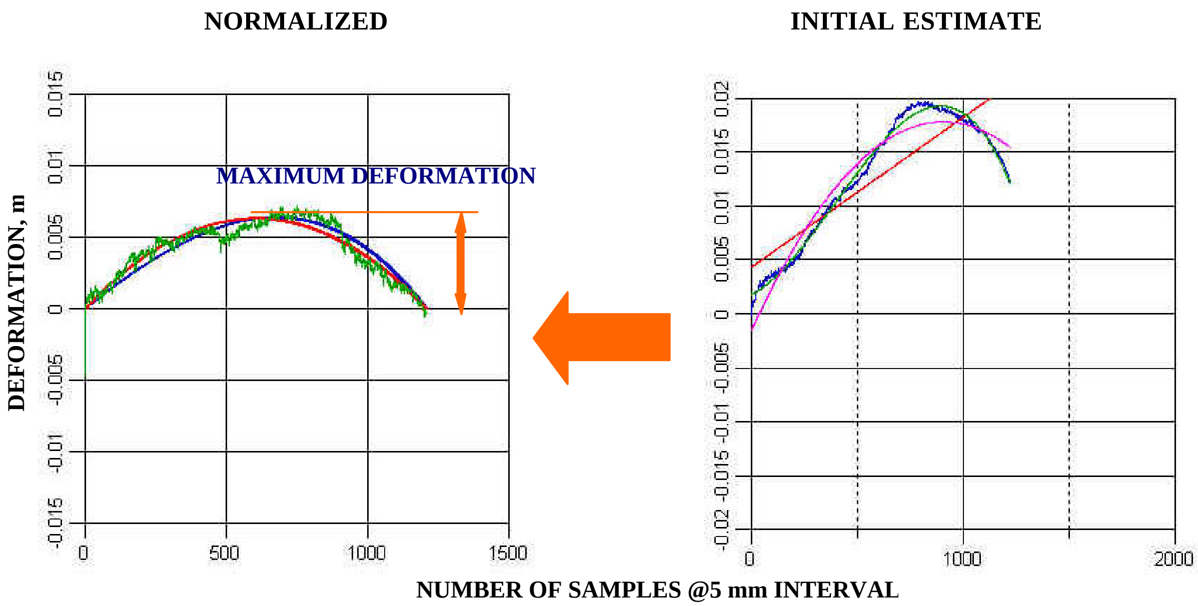

Figure 1: Illustration of Method of Computation and Definition of Maximum Deformation for any Isolated Slab

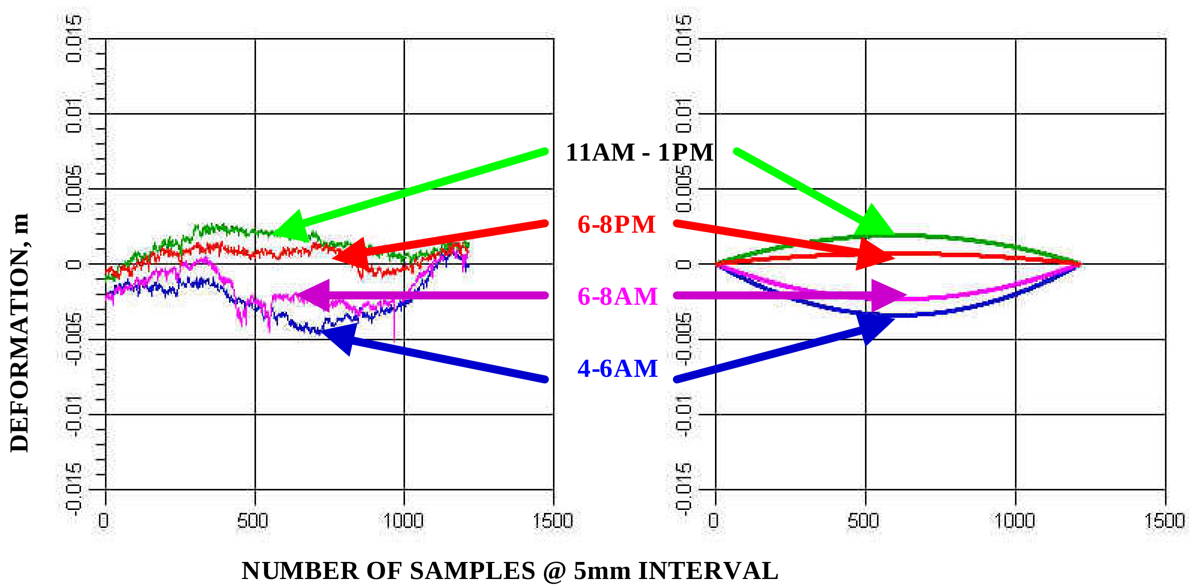

Figure 2: Maximun Deformations of a 6.1-meter Slab at 11AM-1PM, 6-8PM, 6-8AM, and 4-6 AM Time Windows

DATA COLLECTION

Four separate surveys were conducted on 26 km of a four-lane interstate highway within a 24-hour time period. Each survey consisted of collecting data on each of the four lanes (totaling 104.lane-km for each survey) within a specific two-hour window. The time windows for the surveys were: (1) 6:00 PM to 8:00 PM, (2) 4:00 AM to 6:00 AM, (3) 6:00 AM to 8:00 AM, and (4) 11:00 AM to 1:00 PM.

Prior to the initial survey 8 foam rubber "markers" were secured to the shoulders of the road just off the lanes of travel to mark the beginning and end of each lane to be surveyed. The markers were deliberately run over by the profiler to allow the lasers to "see" them. Doing so establishes precise locations for the beginning and ending of data collection thus allowing for accurate stationing, feature location, and identifying any one of the approximately 16,000 slabs surveyed.

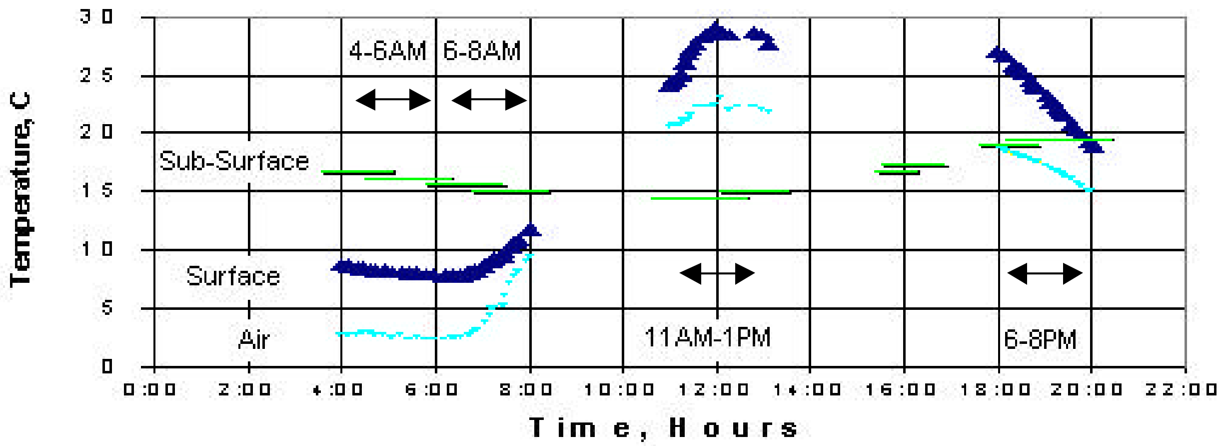

Figure 3: Air, Surface, and Sub-Surface Temperatures vs. Time of Day from Weather Station at milepost 11, for 4-6 AM, 6-8 AM, 11 AM-1 PM, and 6-8 PM Time Windows

In figure 3, the range of temperatures were 3 to 23 °C for air, 8 to 30 °C for ground surface, and 14 to 19 °C for subsurface from a weather station at milepost 11. The coolest surface temperatures were recorded in the 4-6 AM time window and the hottest surface temperatures were recorded in the 11AM-1PM time window. As curling is related to temperature gradients it should be noted that a 22 °C ground surface temperature differential was recorded within a 24-hour period.

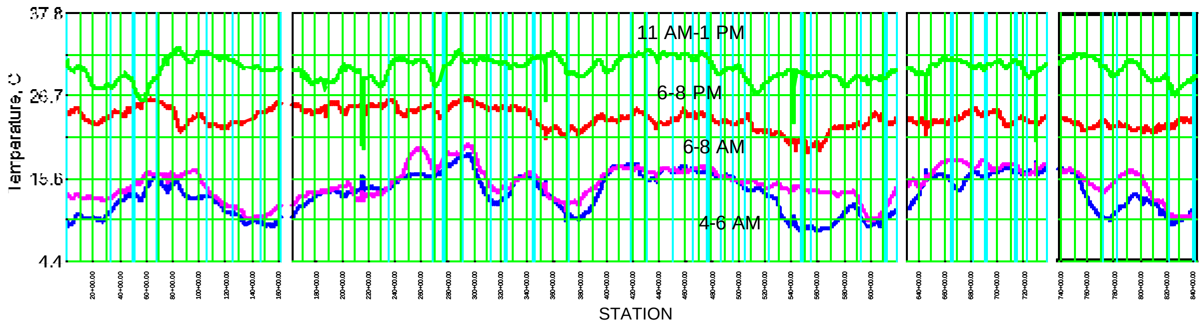

Figure 4: Pavement SurfaceTemperature vs. Station for 11AM-1PM, 6-8PM, 6-8AM, and 4-6 AM Time Windows, Left Lane

Surface temperatures on eastbound lanes were recorded with an infrared sensor during each of the four time windows. Figure 4 shows that the surface temperatures measured in the left lane were very similar in 4-6 AM and 6-8 AM time windows. In the case of the data shown for the left lane, the 11AM-1PM and 6-8 PM time windows are distinct from each other. As shown in figure 3, the ground temperature in the 6-8 PM time window is rapidly decreasing. The pavement surface temperature slowly decreased as the four lanes were being surveyed.

Similar to the weather station data the coolest pavement surface temperatures were recorded in 4-6 AM time window and the hottest surface temperatures were recorded in 11AM-1PM time-window. The range of the surface temperatures was 9 to 33 °C. Again, as curling is related to temperature gradients it should be noted that a 24 °C pavement-surface temperature differential was achieved within the 24-hour period. This temperature data was used in the analysis of slab deformation.

RESULTS

Table 1 lists the data used in the analysis by hypothesis. The results are organized and presented by hypothesis.

Table 1

Hypothesis	Deformations		IRI	Cracks		Construction Data
	Right lane	Left lane	Right lane	Right lane	Left lane	Temperature/ Station
H1	xx					
H2	xx	Xx				
H3	xx		xx			
H4	xx	Xx		xx	xx	
H5		Xx				xx

Hypothesis 1

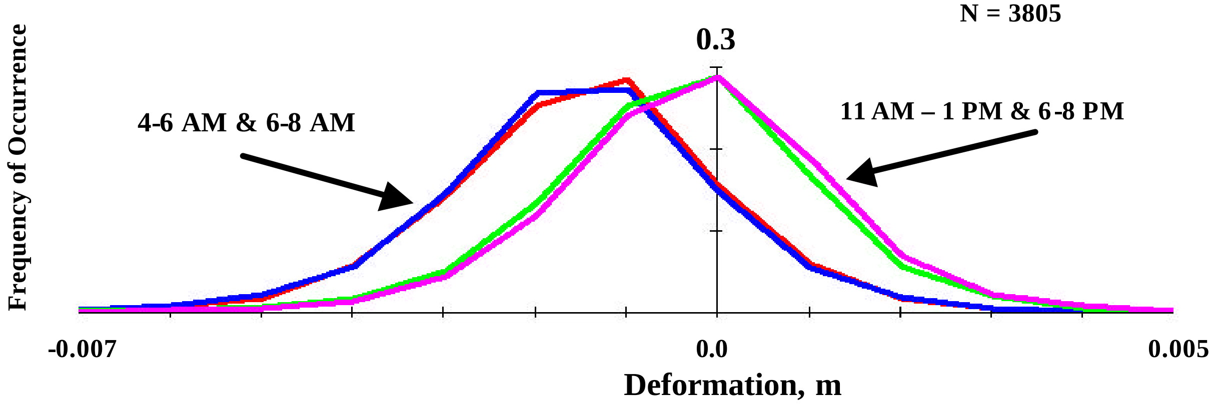

Figure 5: Distribution of Deformations of 3805 Slabs at 11AM-1PM, 6-8PM, 6-8AM, and 4-6 AM Time Windows, Right Lane

Figure 5 shows a clear migration of the distribution of maximum deformations from left to right on the horizontal axis (negative to positive), proportional to the temperature. The 4-6 AM and 6-8 AM time windows have the lowest temperatures and the 11 AM-1 PM and 6-8 PM time windows the highest.

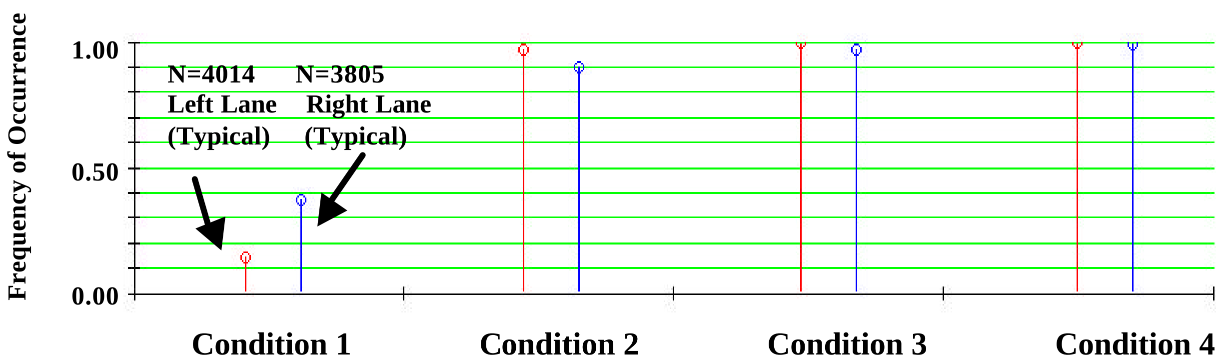

Figure 6: Slabs Passing Conditions of Proportionality between Surface Temperature and Maximum Deformation for Time Windows at 11AM-1PM, 6-8PM, 6-8AM, and 4-6 AM, Left Lane (4014 Slabs) and Right Lane (3805 Slabs) (see below for definition of four conditions)

No.	Condition*
1	D@T1<D@T2<D@T3<D@T4
2	D@T1<D@T3 & D@T1<D@T4 & D@T2<D@T3 & D@T2<D@T4
3	{D@T1<D@T3 or D@T1<D@T4 }& {D@T2<D@T3 or D@T2<D@T4}
4	D@T1<D@T3 or D@T1<D@T4 or D@T2<D@T3 or D@T2<D@T4

*Note: D = Maximum Deformation and T1, T2, T3, T4 = Surface Temperatures for all four time windows for each slab in ascending order of magnitude. T1 and T2 are always the 4-6 AM and 6-8 AM morning time windows.

Figure 6 shows the frequency of occurrence of each condition. Condition 1 requires a strict proportionality of temperature and maximum deformation. Conditions 2 and 3 relax the requirement to the point that the time windows are lumped into two sets, in order to consider the temperature variations within any time window: cold (4-6 AM and 6-8 AM) and hot (11 AM – 1 PM and 6-8 PM). More than 90% of all slabs show that from cold to hot, the maximum deformation increases.

Hypothesis 2

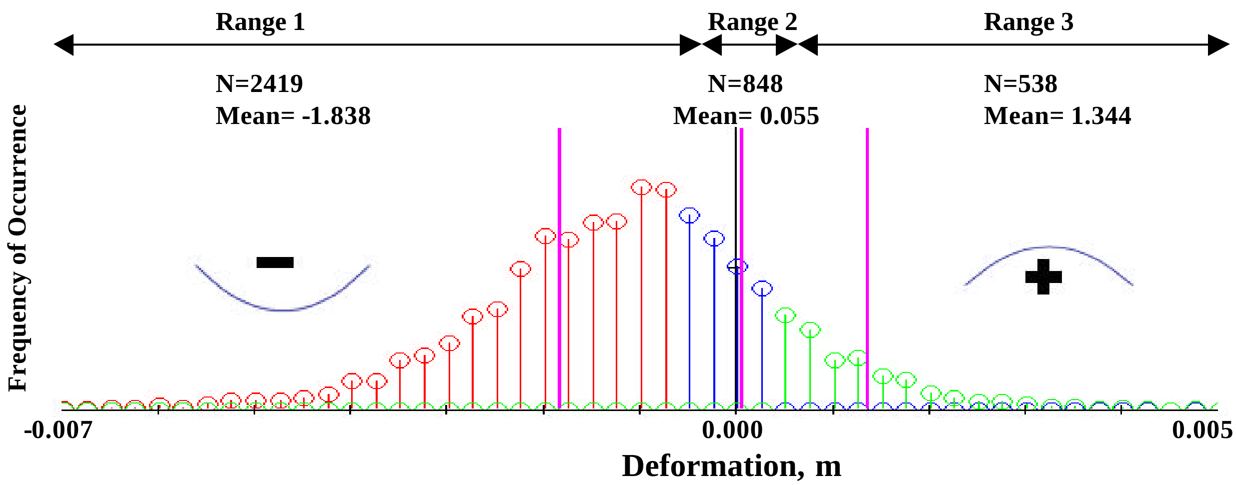

Figure 7: Definition of Ranges of Deformation and Distribution of Deformations by Range of 3805 Slabs at 4-6 AM Time Window, Right Lane

Figure 7 shows the three ranges of maximum deformation. Range 1 includes all values below -0.5 mm. A negative deformation corresponds to a slab shape with edges up. Range 2 is defined between –0.5 mm and 0.5 mm. The slabs in this range are approximately flat. Range 3 includes all values above 0.5 mm. The slabs in range 3 are curled down. Slabs are grouped by change in range of maximum deformation. All slabs belong to one of the six groups that describe the different migrations from one group to another.

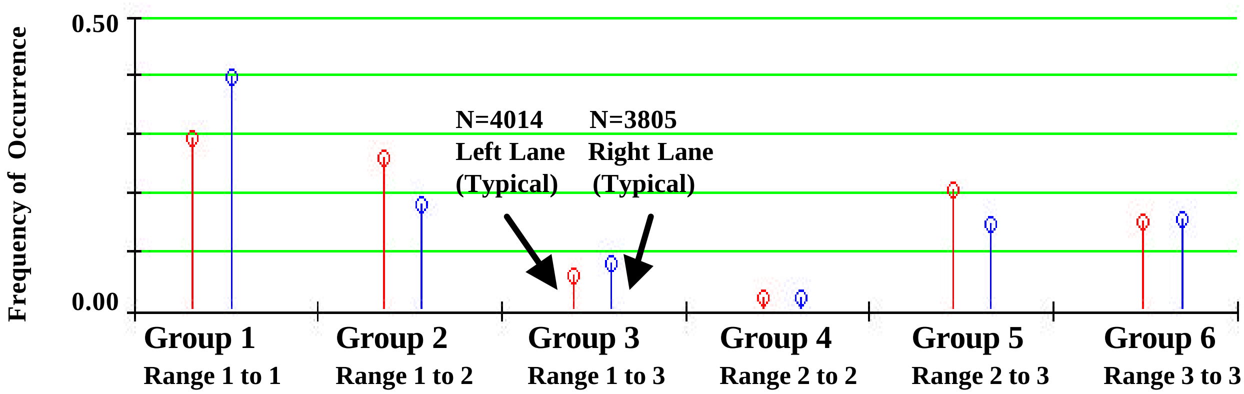

Figure 8: Definition of and Distribution by Groups of Transition between Deformation Ranges from Colder to Hotter Temperatures for Both Lanes

In the eastbound direction of the project, 4014 and 3805 slabs were mapped in the left and right lanes, respectively. Of those, 3510 slabs are pairs of adjacent slabs. Of those, 1655 pairs of slabs have compatible temperature profiles. Of those, 1397 pairs of slabs have variations in maximum deformations due to temperature in the same ranges, and therefore, belong to the same group. Figure 9 shows the distribution of pairs of left-lane right-lane slabs in the six groups, using N=3510.

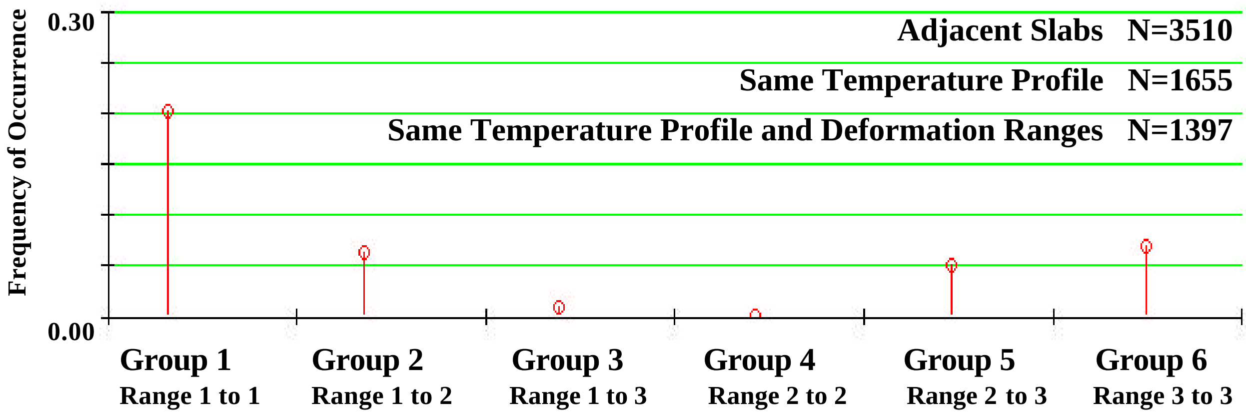

Figure 9: Distribution by Groups of Transition between Deformation Ranges from Colder to Hotter Temperatures Similar for Adjacent Slabs in Both Lanes

<u>Hypothesis 3</u>

Profiles were generated from laser and accelerometer data acquired at the 5 mm sample interval. Before computing the International Roughness Index (IRI) and Ride Number (RN), a 250 mm wide moving median filter was applied to the computed profile to simulate a tire footprint. A 100 m moving average filter applied to remove long waves. This filter has little effect on the magnitude of IRI. The roughness algorithms were applied to the filtered data. No post-process filtering was applied to the data. Cumulative IRI was computed for each slab between two its two joints..

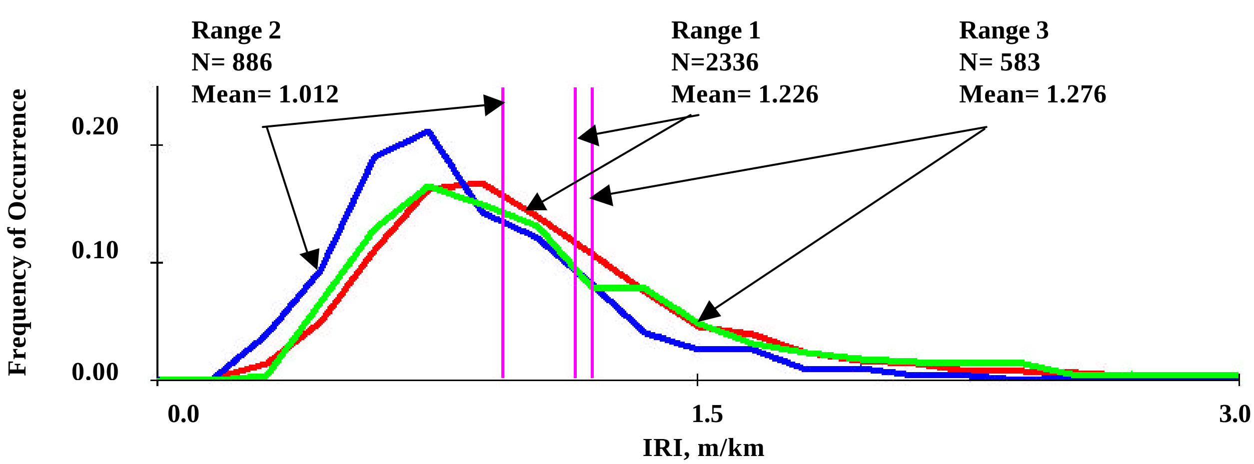

Figure 10: Distribution of IRI values per slab by Deformation Ranges, 4-6 AM Time Window, Right Lane

Figures 7 and 10 show the distribution of maximum deformation and IRI, respectively, by range for the 4-6 AM time window and right lane. The slabs in ranges 1, 2, and 3 have a mean maximum deformation of –1.838, +0.055, and +1.344 mm, respectively, and a mean IRI value per slab of 1.226, 1.012, and 1.276 m/km, respectively. Flatter slabs have smaller IRI values and curled up slabs less rough than those that are curled down.

Hypothesis 4

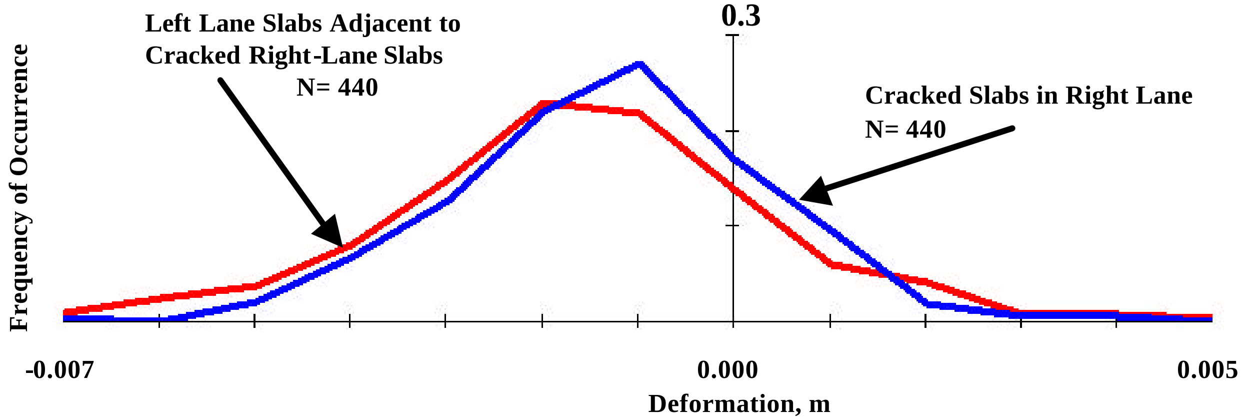

Figure 11: Distribution of Maximum Deformations, 6-8 PM Time Window, Cracked Slabs in Right Lane and Left-Lane Slabs Adjacent to Cracked Right-Lane Slabs

Figure 11 shows the distribution of maximum deformation for each lane for the 440 pairs of adjacent slabs with cracks in the right-lane slab. The right-lane distribution has a narrower width indicating less maximum deformation.

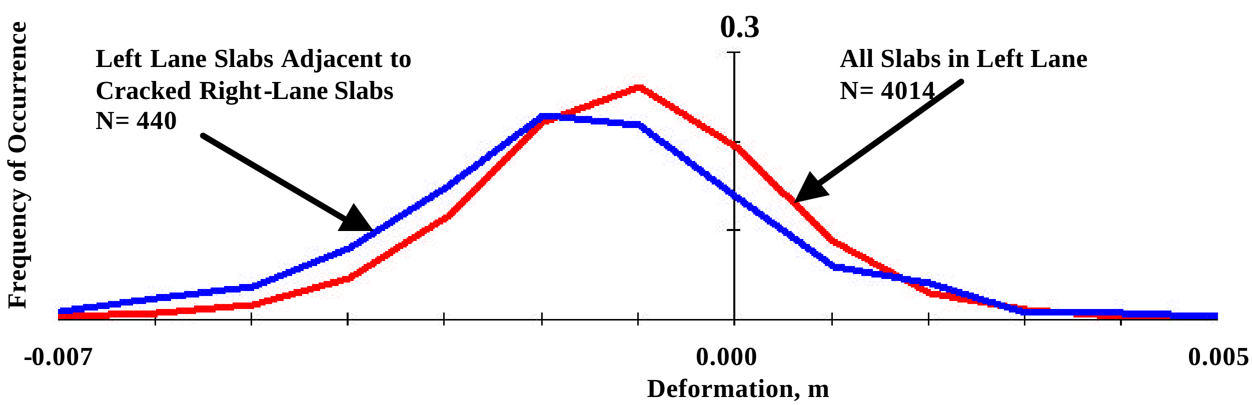

Figure 12: Distribution of Maximum Deformations, 6-8 PM Time Window, All Slabs in Left Lane and Left-Lane Slabs Adjacent to Cracked Right-Lane Slabs

Figure 12 shows the distributions of maximum deformation for all left-lane slabs and for the left-lane slabs adjacent to cracked right-lane slabs only.

Hypothesis 5

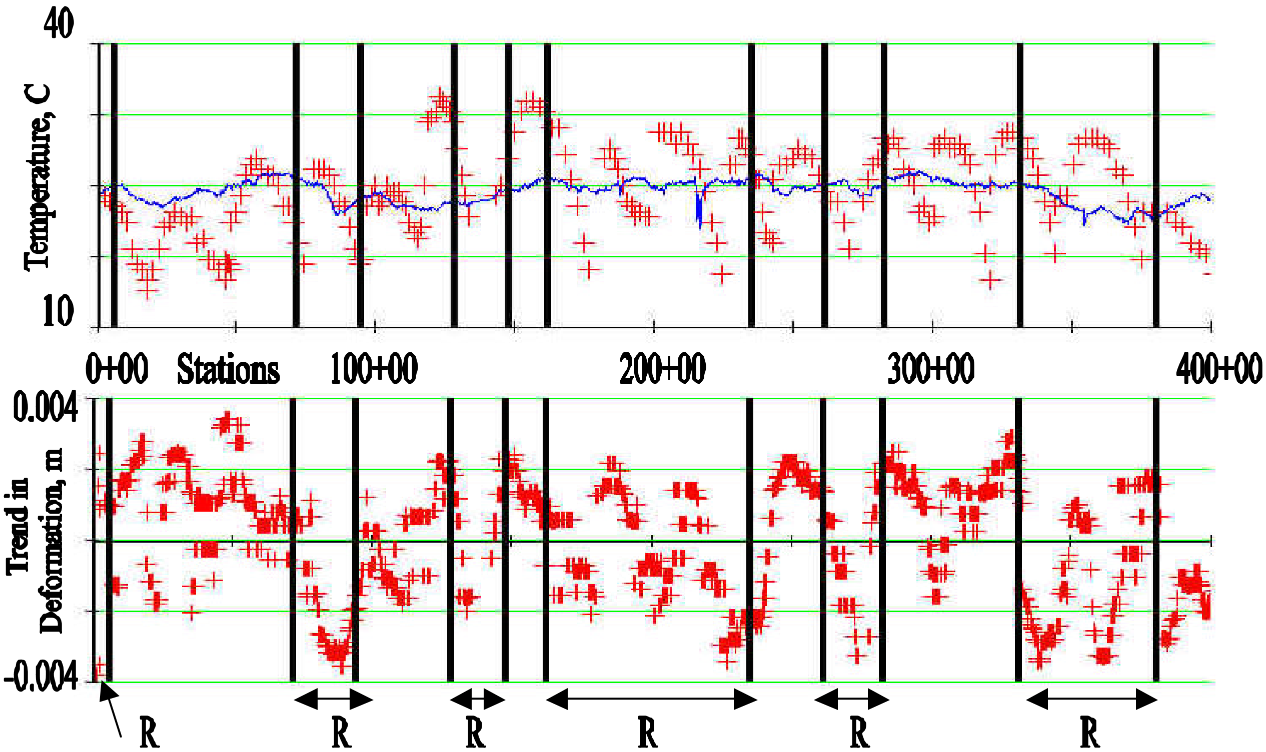

Figure 13: Temperature at Time of Construction and at Data Collection, Trend in Maximum Deformation (Left Lane, 6-8 PM Time Window), and Reconstruct (R) Boundaries vs. Station

Five sources of information were considered for this analysis: 1) measured maximum deformation, 2) measured surface temperature, 3) hourly air temperature at time of construction, 4) stationing from alignment, and 5) station of boundaries of overlay and reconstruct segments. The hourly air-temperature at construction was obtained from the records of the Youngstown weather station (WBAN 14852) located 2 miles away from the site.

Figure 13 shows the five sources of information for the left lane, 6-8 PM time window. The upper portion of the graph shows the hourly air-temperature at time of construction and the surface temperature at time of data collection. The plot of surface temperature at collection is stable around 25 C. The hourly air-temperature at construction fluctuates between 10 and 40 C daily with maximum daily ranges of 20 C.

The lower portion of the graph focuses on the trend in maximum deformation of the approximately two thousand slabs over the distance of 12 km shown on the plot. The trend was obtained by applying a median filter with a 31-point base on the maximum deformation data.

DISCUSSION

All hypotheses were proven to be correct.

Hypothesis 1:
The analysis has shown that the change in deformation of slabs is proportional to change in temperature. However, there is a need to determine the level of sensitivity of the measurement. How stable is the result, and what is the temperature resolution of the method of computation? The objective approach to reduce the data has passed the subjection of a large sample of data. Clear trends have appeared. On an individual case, the result for each slab has also shown to be stable with about 90% of the slabs following the conditions set in the hypothesis.

Figure 5 shows the distribution of slab shape is very similar for both the cold data collection periods and the hot data collection periods. Temperature gradient data previously collected under similar conditions during a forensic investigation on this pavement segment indicates that highly negative temperature gradients can be expected during the 5am to 7am time period and highly positive temperature gradients can be expected during the 1pm to 3pm time period. These temperature gradients were measured April 10, 1999 (Boyle, 2000). Pavement profile measurements were conducted on April 30, 2000.

Figure 6 shows that approximately 97% of the slabs in the left lane and 90% of the slabs in the right lane had the maximum negative deformation in either the 4am to 6am or 6am to 8am data collection period (condition 2).

Hypothesis 2:
Pairs of adjacent left-lane right-lane slabs have similar behavior of deformation. At construction, both lanes are built simultaneously and thus have identical characteristics, except traffic loadings. The right lane typically sees more truck traffic than the left lane. For cracked slabs in the right lanes, the adjacent left-lane slabs may provide insight on the cause of failure if they have not already failed. The reasonable assumption would be that before any failure the right-lane slab behaved like its neighbor to the left. The proof of the second hypothesis is a necessary precursor to any forensic analysis using this data.

Figure 8 shows the number of slabs in the left and right lanes that exhibited similar behavior. Group 1-slabs are slabs that are have negative curvature greater than 2mm at both the coldest and the hottest profile periods. These slabs have negative curvature within the range of temperature gradients observed. Approximately 30% of the left lane slabs and 40% of the right lane slabs are classified as Group1.

When comparing the right lane group classification to the adjacent left lane slab group classification it is noted that 1655 of 3510 slabs identified had similar surface temperatures at through all time windows. Of these slabs with similar surface temperatures, 1397 or 84% had similar deformation characteristics (see Figure 9). This finding is significant in that the left lane will many times have a similar slab shape and behavior as the right lane. Eighty-four percent agreement is considered quite good in this particular case because significant numbers of right lane slabs have been replaced due to premature cracking failure and should not be expected to have similar deformation characteristics.

Hypothesis 3:

Roughness affects the level of dynamic impact of wheel loads, and therefore affects the load histogram. Roughness (IRI) is related to deformation of slabs and varies with temperature. Depending on the time of day, the roughness is affected by the profile of the slabs. The change in roughness is proportional to the difference in the absolute values of the maximum deformations.

Roughness (IRI) is related to deformation of slabs. Figure 10 shows the distribution of IRI with slabs in different deformation ranges. As expected, the Range 2 slabs, the ones that were shown to be generally flat at the cold temperature data collection period had the lowest mean IRI of 1.012 m/km. The negatively curled slabs had significantly higher mean IRI of 1.226 m/km. The positively curled slabs had similar IRI distribution with a slightly higher mean IRI of 1.276 m/km.

Hypothesis 4

Cracked slabs in the right lane correspond to slabs in the left lane with higher deformation differences. To determine the magnitude of deformation of slabs that were determined to have cracked at the time of the profile survey, the left lane slab shape was analyzed. In validating Hypothesis 2, adjacent slab deformation characteristics are a reliable indicator of right lane deformation characteristics.

Figure 11 shows that of 440 slab pairs where the right lane was detected to have cracked and the left lane was not cracked, there is a clear shift in the distribution of slab deformation.
The distribution plot shows a distinct increase in deformation for the left-lane, un-cracked slabs with mean negative deformation around 2.25 mm, adjacent to the right-lane, cracked slabs. The distribution plot of the right lane, cracked slabs shows a frequency peak shifted to the neutral axis by about 1.5 mm. This peak is presumably attributed to the shorter length of the cracked slabs.

Figure 12 shows the distributions of maximum deformation for all left-lane slabs and for the left-lane slabs adjacent to cracked right-lane slabs only. The sub-group of 440 slabs includes more slabs with large deformations than normally distributed. The possible conclusion from these observations is that the slabs with highest negative deformation were more likely to crack than the population of left lane slabs.

Hypothesis 5:

To evaluate the relationship of slab deformations to observed transverse cracking performance a simple analysis was performed. It is known from earlier forensic studies that segments of this pavement which were reconstructed experiences much higher incidence of transverse cracking than those segments that were PCC overlays (ERES, 2000). Figure 14 shows the typical section of the reconstructed sections and the overlay sections.

Figure 13 reveals that the there is no clear trend between temperature at construction and the trend of slab deformation. However, when plotting the reconstruct sections on the deformation trend plot areas of high negative curvature trends are almost exclusively within areas reconstructed. The significance of this difference between the un-cracked, overlay sections and the reconstruct sections with high incidence of cracking is not clear at this time.

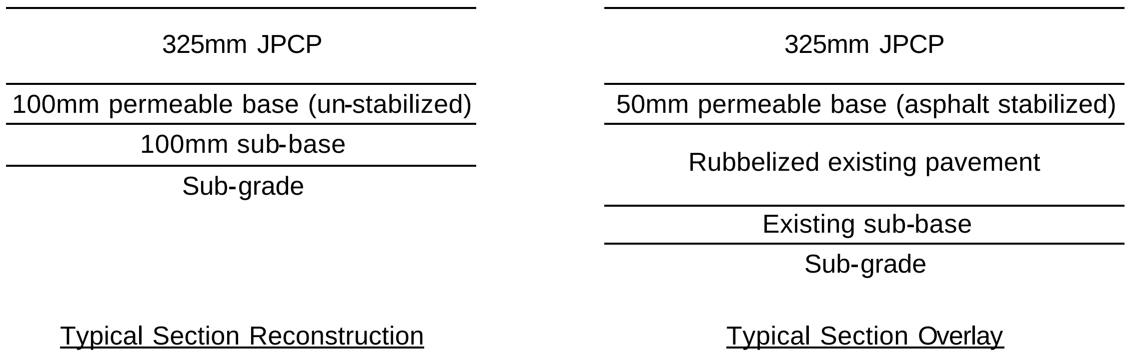

Figure 14 Types of Sections on I-80 Milepost 0 to 15

CONCLUSIONS

It is clear that slab shape analysis can be a powerful tool in engineering analysis of concrete pavement. This study touched the surface of the potential of this technique in solving real-world problems relating to mechanisms behind pavement performance and what separates a long-lived concrete pavement from a premature failure.

More research is needed to develop this technology to its fullest potential. Possible applications include consideration of actual slab shape characteristics in new mechanistic pavement design models, incorporation of slab shape distribution in performance–related specifications, or identification of pavements that require early remedial treatments to avoid a premature failure.

An internal FHWA verification and validation study is currently being conducted at the PSAL. The objective of the study is to compare the shape of a series of slabs measured with the high-speed profiler and static and dynamic high-precision survey equipment.

ACKNOWLEDGEMENTS

The authors would like to thank the staff of PennDOT Districts 1-0 (Terry Nye, Reggie Gianetti), and PennDOT, Bureau of Maintenance (Dan Dawood), Northeast Chapter, ACPA (Bob Long), and FHWA (Charlie Churilla, Roy Trent, Roger Larson), and FHWA Pennsylvania Division (David Cough, Zahur Siddiqui) for their assistance in providing valuable information and support during this project.

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