Investigation of Curling and Warping on US 34 near Greeley, Colorado

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Abstract
Construction of a jointed concrete pavement on US 34 near Greeley, Colorado in 2012 led to an investigation of slab curling and warping that appeared to be contributing to undesirable levels of pavement roughness. The Colorado Department of Transportation (CDOT) initiated an investigation to quantify the effects of slab curling and warping on ride quality for the US 34 project and to identify possible changes in construction practices to mitigate the effects of slab curling on future projects. This paper summarizes the various analyses that were conducted under this research project and the results from this investigation. It also provides recommendations for improvements in construction practices to help minimize jointed concrete pavement slab curling and warping and recommendations for the collection of smoothness acceptance data such that the effects of curling and warping can be captured.

Introduction

Reconstruction of a section of US 34 near Greeley, Colorado in 2012 led to an investigation of jointed concrete pavement slab curling and warping that appeared to be contributing to undesirable levels of pavement roughness. Specifically, the westbound lanes which were constructed in July appeared to exhibit higher roughness than the eastbound lanes which were constructed in September. Furthermore, smoothness testing by the contractor at three different times of the day on one of the westbound lanes revealed significant differences in roughness values depending on the time of day. In response, the Colorado Department of Transportation (CDOT) initiated an investigation to quantify the effects of slab curling and warping on ride quality for the US 34 project and to identify possible changes in construction practices to mitigate the effects of slab curling on future projects.

For this investigation pavement profile data were collected during winter and summer conditions during four different periods of the day to examine the effects of slab curling on roughness. Using the profile data, slab curvature was analyzed using the Second Generation Curvature Index (2GCI), and HIPERPAV was used to evaluate early age pavement behavior using the actual construction conditions. This paper summarizes the various analyses that were conducted under this investigation. It also summarizes the recommendations provided to CDOT to help minimize curling and warping of jointed concrete pavements constructed in hot weather, along with recommendations for the collection of ride quality acceptance data to capture effects of slab curling and warping.

Research Significance. While the effects of jointed concrete pavement slab curling on pavement smoothness have been known for generations, the issue has become more pressing in recent years as agencies continue to tighten pavement smoothness requirements for new construction in

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response to user demand for smooth-riding pavements. Although the solution proposed herein to addressing this issue requires additional profiling for acceptance, the advancement and proliferation of high-speed and lightweight inertial profiling technology has made these additional testing requirements practical to achieve.

Jointed Concrete Pavement Curling and Warping. Curling and warping of jointed concrete pavement slabs is a complex issue, and still not fully understood within the concrete pavement industry to the point where accurate predictions of its effect on pavement smoothness can be made. The two primary factors which affect curling and warping are temperature and moisture gradients, or differentials in temperature and moisture over the depth of the slab. Although terminology is used interchangeably throughout current literature, curling is generally associated with the effects of temperature gradients and warping with moisture gradients. Regardless of the cause, curling and warping deformations of jointed concrete pavement slabs effectively impose a curvature on the slab, as shown in Figure 1, which can significantly affect ride quality of the pavement.

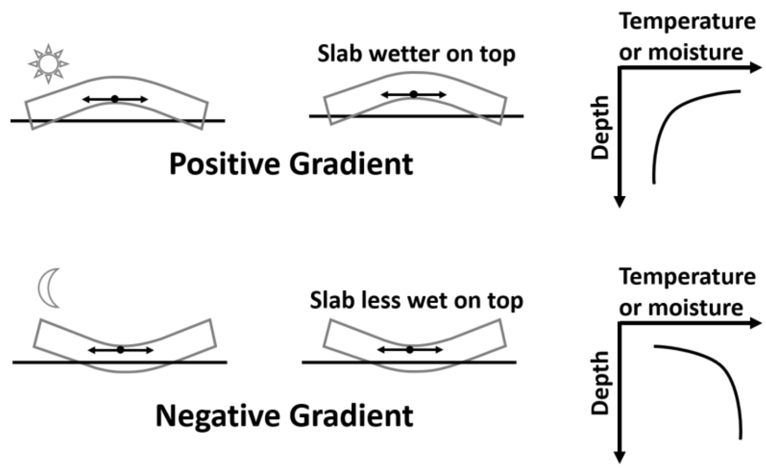

Figure 1. Effects of positive and negative slab temperature and moisture gradients on slab curling and warping. (after Van Dam 2015)

The phenomenon of "built-in" slab curling, while well documented, is still difficult to predict with certainty. Built-in curling is effectively a permanent curling propensity of the concrete slab resulting from temperature and moisture gradients over the depth of the slab when the concrete reaches final set, or transitions from a plastic to hardened (elastic) state. If the top of the slab is warmer than the bottom at final set, a negative built-in temperature gradient will result, meaning that when the temperature gradient is zero the edges of the slab will curl upward as if the top of the slab were cooler than the bottom (i.e., a negative temperature gradient). The converse occurs when the bottom of the slab is warmer than the top at final set, leading to a downward-curled slab shape from a positive built-in temperature gradient. Effects of moisture gradients almost always result in a negative built-in gradient as the bottom of the slab generally stays moist while drying shrinkage occurs at the top of the slab due to evaporation of moisture from the pavement surface, resulting in differential shrinkage strain and a curled-up shape. Moisture-related curling is commonly quantified as an effective (negative) temperature gradient for simplicity.

The built-in effects of temperature and moisture gradients can effectively cancel each other out, but more often are additive, resulting in an overall curled-up slab shape. For pavement design using the AASHTOWare Pavement ME software, the default value for "permanent curl/warp effective temperature difference" which accounts for both temperature and moisture effects, is -5.6°C [-10°F] (Vandenbossche et al. 2011).

Dowelled joints can help restrain curling, and creep effects can reduce curling stresses as movement is restrained, but curling has also been documented to increase over the life of the pavement (Karamihas and Senn 2012) due to creep deformation caused by sustained moisture gradients where the bottom of the slab remains moist while the top goes through continual wetting and drying cycles.

While the slab temperature gradient changes over the course of a day with changes in ambient temperature, moisture gradients generally remain constant (in the absence of precipitation). Therefore diurnal changes in slab curling are generally the result of changes in temperature gradients only. These changes in slab curling can have a significant impact on pavement smoothness, as will be discussed with regard to the US 34 project below. Currently, there are no pavement smoothness specifications in the United States which address this phenomenon.

U.S. Highway 34 Project. The US 34 project was a reconstruction of an existing asphalt pavement following the same footprint of the original pavement from approximate mileposts 113.4 to 115.3 near Greeley, CO. The pavement consists of two 3.7 m (12 ft) lanes, 1.2 m (4 ft) inside, and 3 m (10 ft) outside tied concrete shoulders. The pavement structure consists of 23 cm (9 inch) jointed plain concrete pavement over a (full-depth) reclaimed asphalt base. The depth of the asphalt varied from 6-8 inches and the full-depth reclamation process mixed in approximately two inches of the underlying aggregate base into the reclaimed asphalt. No treatment was applied to the reclaimed material except water in order to achieve density requirements.

The design joint spacing was 4.6 m (15 ft) with 46-cm (18-inch)-long, 32 mm (1.25-inch)-diameter epoxy-coated dowels. Dowels were placed in the wheelpaths only, with 5 dowels per wheelpath, spaced 30 cm (12 inches) apart. Tie-bars were No. 5 epoxy-coated bars, 76 cm (30 inches) in length placed at the three longitudinal joints at 76 cm (30 inches) on center. The concrete mix design was typical for CDOT projects but did feature an optimized (three coarse aggregates) aggregate gradation. The eastbound (EB) and westbound (WB) lanes were each placed in a single pass, 11.6 m (38 ft) wide, over five day of paving.

Table 1 shows the paving sequence along with ambient high and low temperatures during each paving day.

Table 1. Paving sequence for the US 34 project.

Date	Paving Day	Distance, m (ft)	Side of Bridge	Paving Window	Ambient High Temp, °C (°F)	Ambient Low Temp, °C (°F)	Difference, High-Low, °C (°F)
WB Lanes							
7/20/2012	1	699 (2,292)	East	7:00-19:15	39 (102.2)	17 (62.6)	22 (39.6)
7/23/2012	2	185 (608)	West	7:30-11:14	31 (87.8)	20 (68)	11 (19.8)
7/24/2012	3	746 (2,447)	West	7:21-19:10	37 (98.6)	19 (66.2)	18 (32.4)
7/25/2012	4	440 (1,445)	West	7:27-14:20	34 (93.2)	23 (73.4)	11 (19.8)
7/26/2012	5	382 (1,254)	West	7:20-13:58	29 (84.2)	16 (60.8)	13 (23.4)

EB Lanes							
9/13/2012	1	508 (1,699.5)	East	7:40-18:00	22 (71.6)	11 (51.8)	11 (19.8)
9/14/2012	2	212 (697)	East	7:20-11:30	21 (69.8)	7 (44.6)	14 (25.2)
9/17/2012	3	721 (2,366)	West	7:15-17:15	20 (68)	9 (48.2)	11 (19.8)
9/18/2012	4	700 (2,295)	West	7:15-18:00	27 (80.6)	6 (42.8)	21 (37.8)
9/19/2012	5	479 (1,571)	West	8:30-17:12	28 (82.4)	10 (50)	18 (32.4)

Initial concerns about the effects of slab curling on ride quality were raised after ride quality values for profile data collected by the contractor and values collected by CDOT on the same section of pavement were substantially different, varying up to 0.63 m/km (40 in/mi). Testing of a calibration site by both profilers at the same time confirmed that both profilers were measuring the same values and functioning properly. The difference was determined to be the result of collection of profile data at different times of the day, with CDOT data collected in the early morning and contractor data collected in the afternoon. This was verified by the contractor who collected additional profile data at three different times during the same day and found variations in excess of 0.47 m/km (30 in/mi) from early morning to afternoon. These results led to the investigation of the causes and effects of curling and warping on pavement ride quality described herein.

Data Collection

In addition to information from construction (paving logs, paving sequence, equipment, etc.), the following data were collected for the purposes of this study.

Profile Data. In order to evaluate the effects of slab curling on ride quality on the US 34 project, profile data were collected for analysis. Profile data were collected by CDOT using their high-speed inertial profiler at two times during the year and at four different times of the day. Profile data were collected in February and August, traditionally two of the coldest and warmest months of the year at this location, in order to examine the two extreme conditions. Diurnal profiling during each of these site visits sought to capture the effects of daily temperature cycles on pavement curling by collecting data at the following times:

- Early AM: just before sunrise when the maximum negative slab temperature gradient is expected.
- Mid-AM: a few hours after sunrise when a near-zero slab temperature gradient is expected.
- Early-PM: near or shortly after noon when the maximum positive slab temperature gradient is expected.
- Late-PM: shortly before sunset when a near-zero slab temperature gradient is expected.

Slab Temperature Data. In addition to profile data, slab temperature data were collected to correlate the top-bottom slab temperature gradient to the measured profile. Self-contained logging temperature sensors were embedded in the slab prior to collection of profile data. Sensors were installed approximately one inch from the top and bottom of the slab and at mid-depth. During each site visit (February and August) profile data were collected when slab temperature gradients were at the approximate maximum negative value (early AM), maximum positive value (early PM), and near zero (late AM and late PM). Figure 2 shows slab temperature gradients during profile data collection in August 2014, with the shaded bard indicating the window in which profile data were collected.

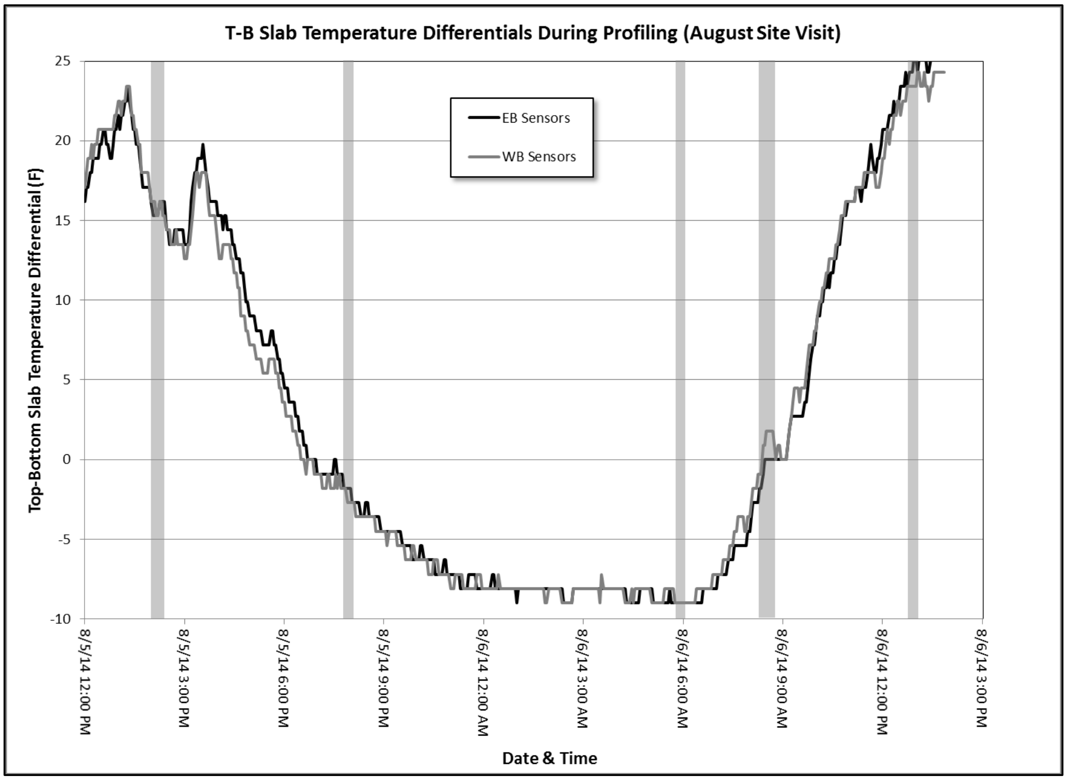

Figure 2. Top-bottom slab temperature differentials during profiling. ***(Note: for Temperature Differential, 5 °F = 2.8 °C)***

Analysis

Several analyses were conducted using the profile data, temperature data, and construction information in order to investigate the slab curling issues on US 34. The various analyses conducted are summarized below.

Roughness. Pavement ride quality (roughness) was analyzed in several different ways, including:

- Overall roughness – diurnal differences in roughness were examined by direction (EB vs. WB), lane (Lane 1 vs. Lane 2), and side of bridge (east vs. west side of South Platte River Bridge in the middle of the project), and season (February vs. August).
- Roughness by wheelpath – differences in wheelpath roughness were examined for all of the profile data collected.
- Roughness by paving day – profile data were separated based on the limits of each day's paving and differences in roughness values were examined.
- Roughness vs. slab temperature gradient – slab temperature gradients during collection of each set of profile data were correlated to roughness values.

Slab Curvature. The slab curvature analysis was the most critical aspect of the project evaluation. For the slab curvature analysis, profile data were used to approximate the curled slab shape which was then quantified in terms of the Second Generation Curvature Index (2GCI) per the procedure developed by Chang et al. (Chang et al. 2008; Chang et al. 2010). This analysis requires isolating individual slabs within profile data, then computing the 2GCI value for each individual slab. The median curvature values from each set of profile data were then correlated to the roughness values (International Roughness Index, IRI and Half-car Roughness Index, HRI) and slab temperature gradients to examine any possible relationships between slab curvature and roughness or temperature gradient. Figure 3 shows an example of the 2GCI curve-fitting to profile data for one individual slab. For this analysis a total of 80 sets of profile data were analyzed, resulting in 2GCI computation for roughly 520-540 slabs for each set of profile data or approximately 21,000 slabs total.

HIPERPAV. HIPERPAV is a tool used to predict early-age concrete pavement behavior based on various design and construction inputs. (Ruiz et al. 2005) The program can be used to evaluate different scenarios based on construction conditions and concrete design parameters in order to prevent early-age cracking and help ensure long-term pavement performance. HIPERPAV was used for the US 34 evaluation to estimate temperature gradients in the pavement slab during construction. Actual concrete design parameters (slab thickness, joint spacing, base type, subgrade support), concrete mixture design, and climatic conditions for the EB and WB lanes were used by HIPERPAV to compute slab temperature gradients during construction. With the structural and concrete mixture design and climate inputs fixed, variables that were examined included the initial concrete mix temperature, the support layer (reclaimed asphalt base) temperature, and the curing method (i.e., single vs. double coat of liquid curing compound). Because actual concrete and base temperatures were not known, assumptions were made within reasonable limits and alternative strategies were also examined.

Mechanistic-Empirical Pavement Design Guide Analysis. A mechanistic-empirical pavement design analysis of the US 34 project was used to predict the long-term performance of the US 34 project to determine if any differences in performance can be expected for the EB and WB lanes. For this analysis, the AASHTOWare Pavement ME Design program was used to predict performance of the US 34 project based on the local climatic data, and based on varying the built-in slab temperature gradients and initial roughness (IRI).

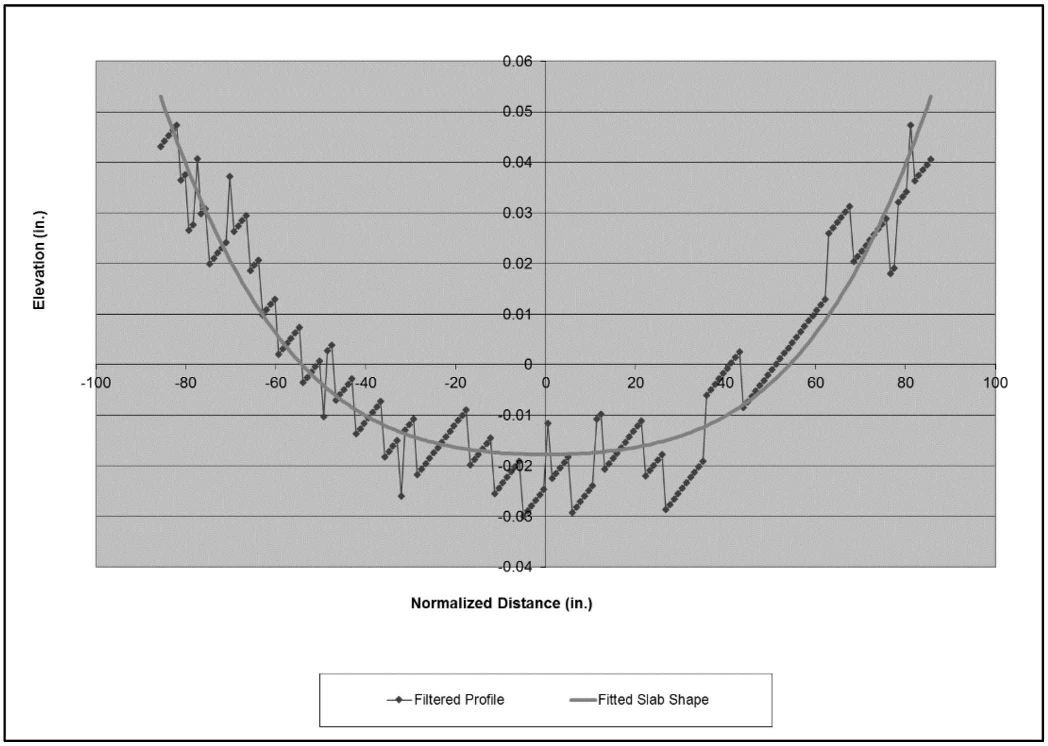

Figure 3. Example of 2GCI curve-fitting for US 34 profile data. ***(Note: 1 in. = 25.4 mm)***

Summary of Results

Summarized below are some of the key findings from the various analyses performed during this investigation.

Overall Roughness Evaluation. Roughness of the WB lanes was consistently (but not always) higher than EB lanes for both profiling periods and all diurnal measurements. The HRI for the WB lanes was up to 0.25 m/km (16.5 in/mi) higher than EB lane roughness, depending on the time of day of profiling, with an overall average of 0.09 m/km (6 in/mi) higher. Figure 4 shows the diurnal variation in roughness for the August profile data, separated by lane and the side of the South Platte River Bridge.

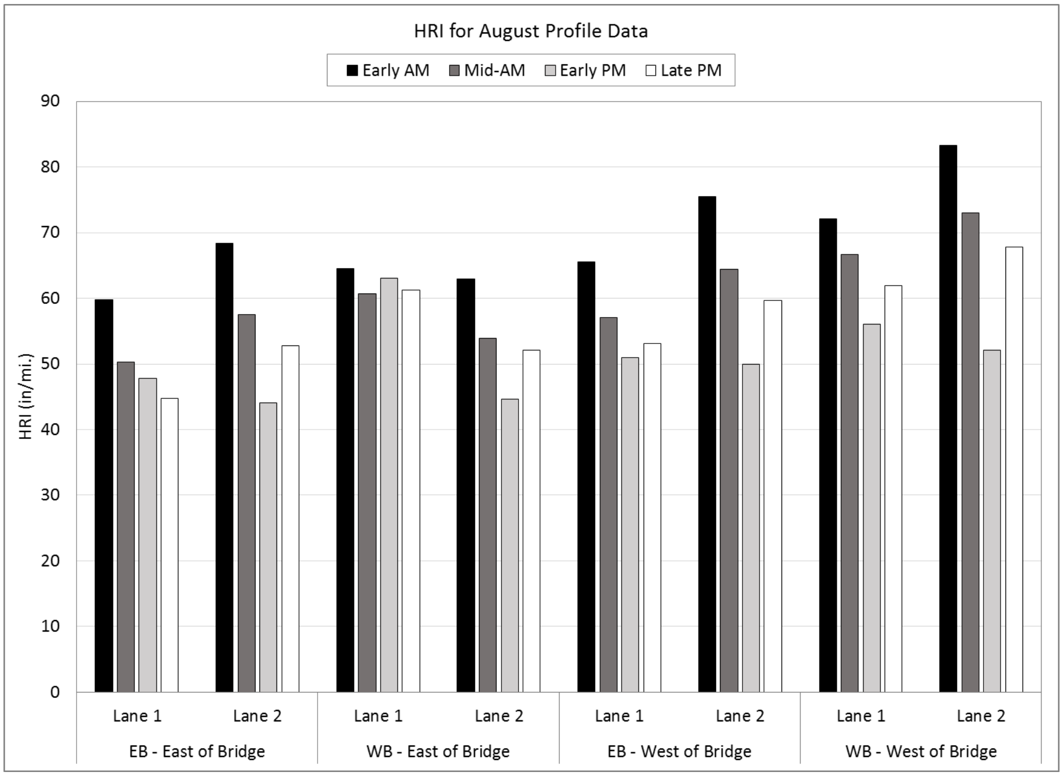

Figure 4. Overall roughness values from August profile data. ***(Note: 10 in/mi = 0.16 m/km)***

Roughness was consistently higher for the August profile data than February. This may be due to differences in slab temperature gradient during profiling (-5°C to +13°C [-9°F to +24°F] in August vs. -2.8°C to +10.6°C [-5°F to +19°F] in February), but may also be due to a larger moisture gradient in the slab which would be more likely in August (rainy/wet subbase) than February (frozen subbase). Diurnal changes in roughness are also greater for August than February. This again could be due to differences in slab temperature gradient, but could also be due to greater solar warming of the pavement surface in August.

With one exception (WB Lane 1, east of the bridge), early AM roughness was significantly higher than subsequent times of the day. Diurnal differences in roughness (HRI) range from 0.01 m/km [0.9 in/mi] (EB Lane 1) up to 0.49 m/km [31.1 in/mi] (WB Lane 2), with an overall average of 0.22 m/km (14.1 in/mi). The largest difference was generally between the Early AM profiles and Early PM profiles.

Overall, the diurnal variation in roughness, as well as between seasons (February to August) clearly indicate that temperature gradients in the slab are causing the slabs to curl, significantly impacting pavement smoothness.

Roughness by Wheelpath. Further examining roughness trends by wheelpath, Figure 5 shows an example of the roughness data by wheelpath for one set of profile data (August, early AM). With one exception (WB Lane 2) left wheelpath (LWP) roughness was consistently higher than right wheelpath (RWP) roughness in both directions. In some cases LWP roughness was as much as 0.28 m/km (18 in/mi) higher, with an overall average of 0.12 m/km (7.7 in/mi) higher. This is not believed to be caused by measurement/profiler error as the trend was the same for both the February and August profiles, and was also observed with the contractor's profile data. While the reason for this is not obvious from the data, it is speculated that it could be related to whether or not the longitudinal joint between the lanes and the longitudinal joint between the lanes and shoulders have formed (cracked) through the slab. For joints that have formed, the slabs on either side of that joint may be curling independently, whereas for joints that have not formed, the slabs would be curling monolithically with each other or with the shoulder. Again, this is speculation and none of these scenarios have been confirmed for US 34 through further investigation (e.g., coring of longitudinal joints).

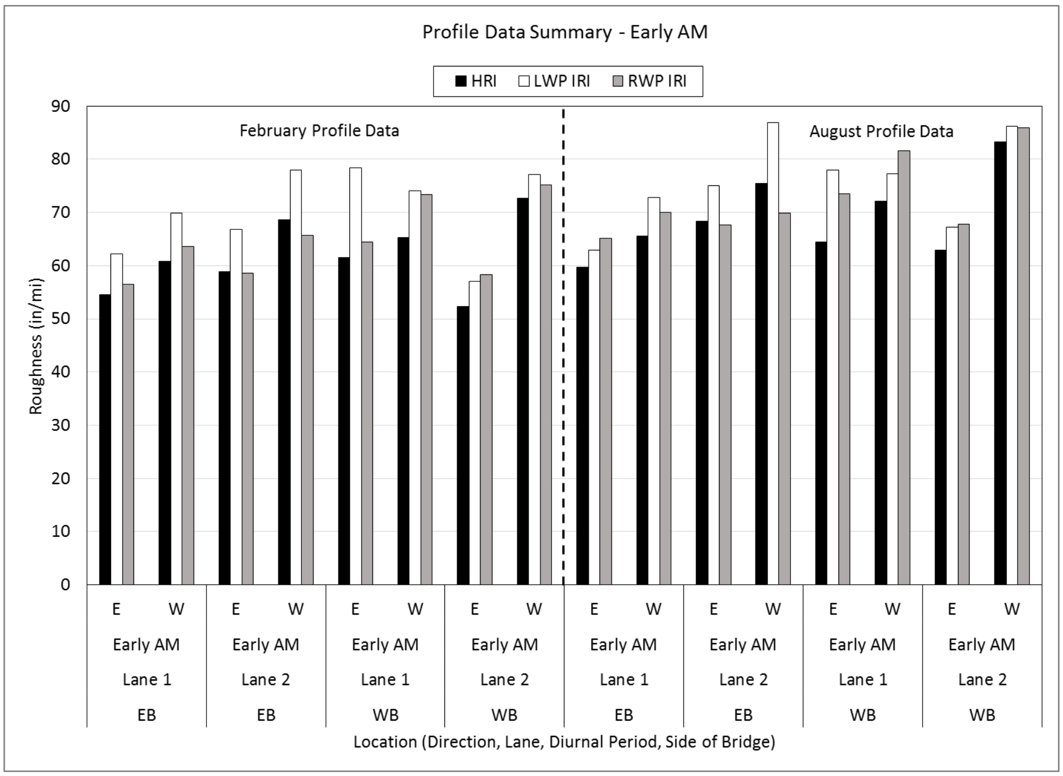

Figure 5. Wheelpath roughness data from Early AM profile data. ***(Note: 10 in/mi = 0.16 m/km)***

Roughness and Slab Temperature Gradient. In order to examine the effect of the slab temperature gradient (during profiling) on roughness, Figure 6 shows a plot of HRI values versus top-bottom slab temperature differentials by lane (excluding WB Lane 1, east of the bridge which showed little change in roughness with temperature). The trend for each lane shows increasing roughness with increasingly negative temperature gradient and decreasing roughness with increasingly positive temperature gradient, but not necessarily linearly across negative and positive temperature gradients. This trend confirms the effect of slab temperature differentials on roughness and also confirms a built-in upward slab curl which becomes more severe, increasing roughness, as the negative temperature differential increases, and becomes less severe, decreasing roughness, as a positive temperature differential increases. While the trend is clear, a definitive correlation between roughness (HRI) and temperature gradient is not very strong, even separated by lane.

When examining temperature gradient versus roughness by wheelpath IRI (since LWP and RWP were generally quite different), a reasonable – but still not very strong for all lanes – correlation was observed for the RWP profiles but not for the LWP profiles.

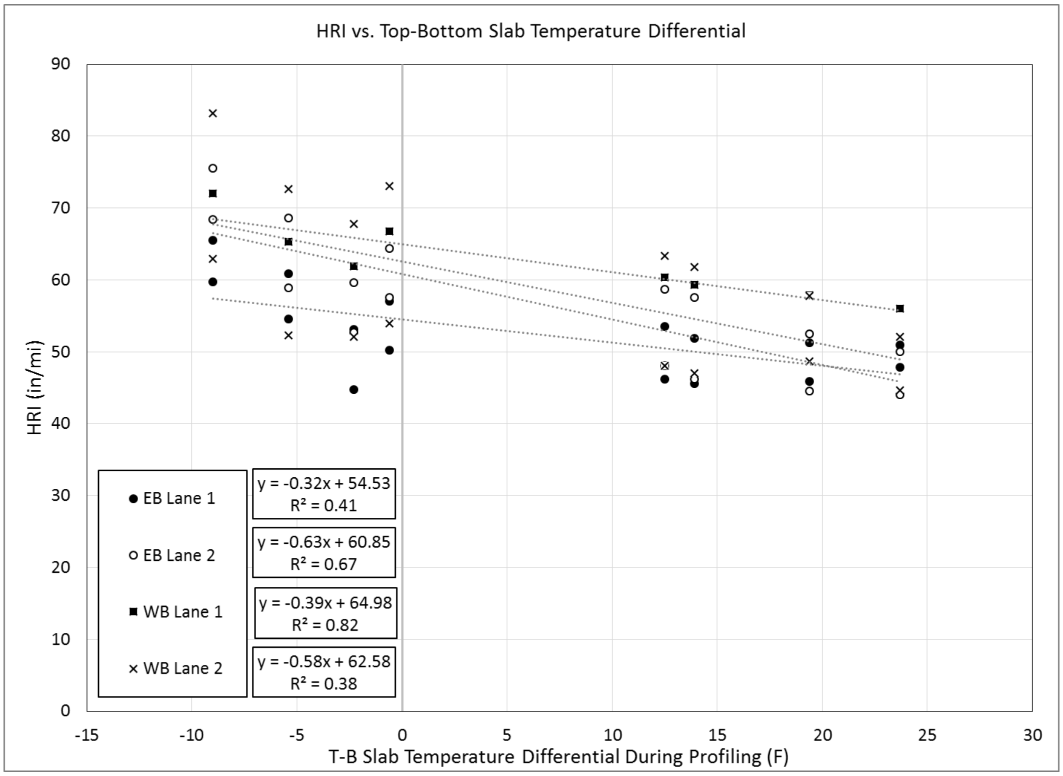

Figure 6. Correlation between roughness and slab temperature gradient. ***(Note: for IRI, 10 in/mi = 0.16 m/km; for Temperature Differential, 5 °F = 2.8 °C)***

Roughness by Paving Day. One of the key questions surrounding this evaluation was related to the effect of climatic conditions during construction on roughness. As discussed previously, the WB lanes were constructed primarily during warm to abnormally hot days, whereas the EB lanes were constructed under much cooler temperatures. To examine roughness by paving day, profile data were segmented based on the limits provided in the paving log, and analyzed separately.

Figure 7 (top) shows roughness by paving day for the August profile data (which showed the most variation during the day) and only the Early AM profile data (which was consistently the highest for each lane) is shown. Although there are differences in roughness between paving days for both EB and WB lanes, roughness does not appear to be correlated to either the ambient high/low temperatures or the difference between high and low temperatures on the days of paving. For example, Day 1 had the lowest roughness for both EB and WB lanes, yet was very different in terms of ambient conditions. WB Day 1 was the hottest day (high of 39°C [102.2°F]) with the largest temperature change throughout the day (22°C [39.6°F]), while EB Day 1 was one of the cooler days (high of 22°C [71.6°F]) with the lowest temperature change throughout the day (11°C [19.8°F]).

Figure 7 (bottom) shows the maximum diurnal change in HRI for each lane by paving day, again for only the August profile data. As this plot shows, the diurnal changes in roughness, likewise, do not appear to be correlated to either the ambient high/low temperatures or the change in ambient temperature during the day.

Slab Curvature Evaluation. The slab curvature evaluation revealed that with only a few exceptions, the curvature indices were essentially all negative, indicating a curled-up slab shape at all times of the day in both summer and winter seasons and in both EB and WB directions. This built-in curled up shape is typical for jointed concrete pavements constructed during the daytime in a dry, sunny climate. The severity of this curled-up slab shape varies by time of day, as reflected in the 2GCI, affecting roughness as discussed below.

In order to evaluate the effect of slab curvature on roughness, the 2GCI values (median value from all of the slabs in a given lane) from each set of profile data were correlated to ride quality values for the same profile data. Figure 8 shows the roughness-curvature relationship by direction (EB lanes vs. WB lanes). A clear trend is seen in these plots – that of increasing roughness with an increasingly negative curvature value. Looking at the HRI for the EB and WB lanes overall, the change in roughness with curvature (slope of the trendline) is very similar for both, indicating that despite differences in ambient conditions during construction, changes in slab curvature with temperature are very similar.

As implied by these plots, the "zero curvature" roughness, or y-axis intercept, is the estimated non-curvature-related roughness. The zero-curvature roughness for the overall EB and WB lanes is also very similar (within 0.05 m/km [3 in/mi]), again indicating that the difference in WB and EB is not substantial when looking at the data as a whole. Although the relationship by lane is reasonable, the relationship by wheelpath (not shown) is more erratic. The left wheelpath data for both EB and WB, for example, showed a poor correlation between curvature and roughness (wheelpath IRI), which is not surprising considering what was observed previously, when looking just at roughness data by wheelpath.

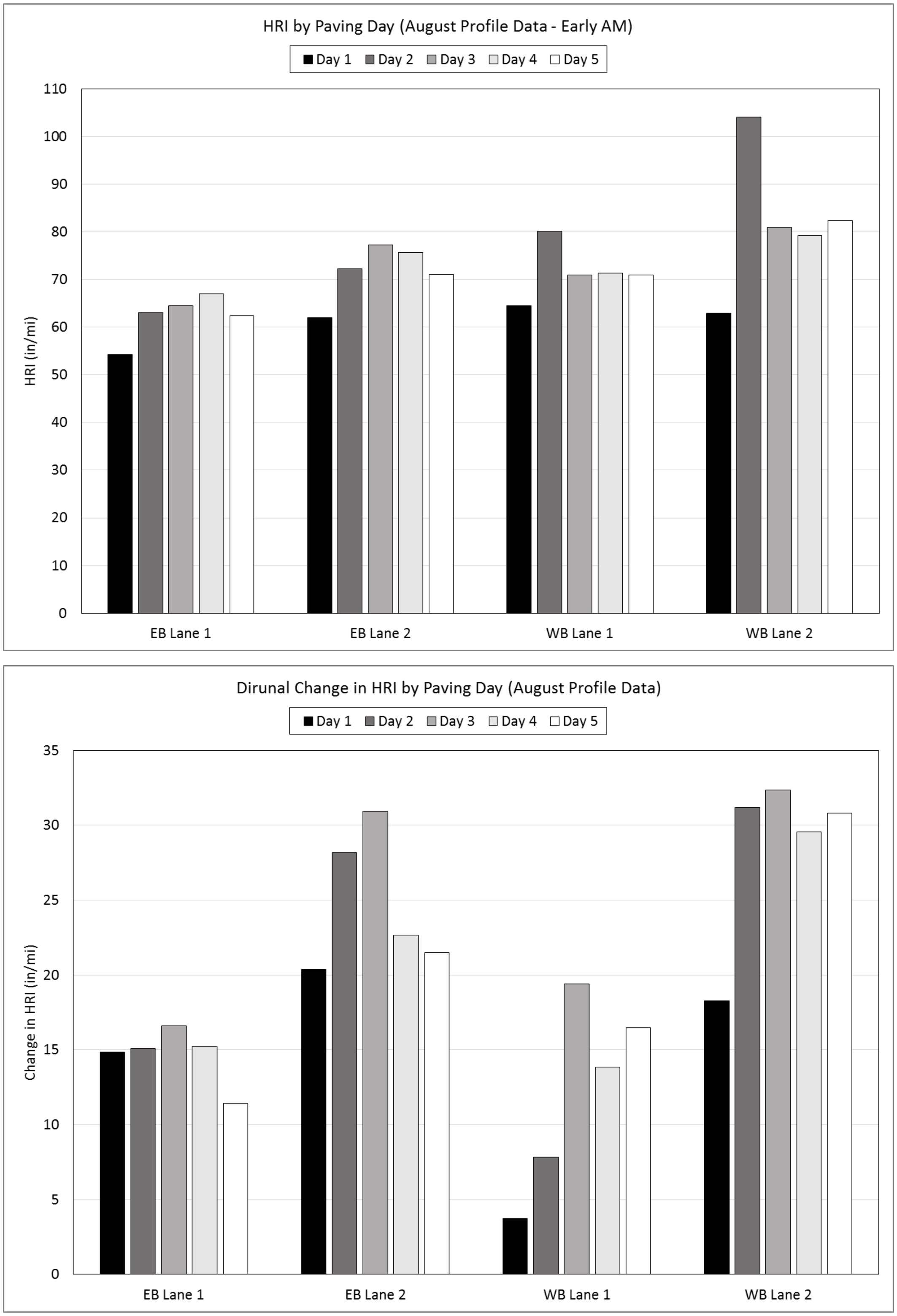

Figure 7. Roughness (top) and diurnal change in roughness (bottom) by paving day. ***(Note: 5 in/mi = 0.08 m/km)***

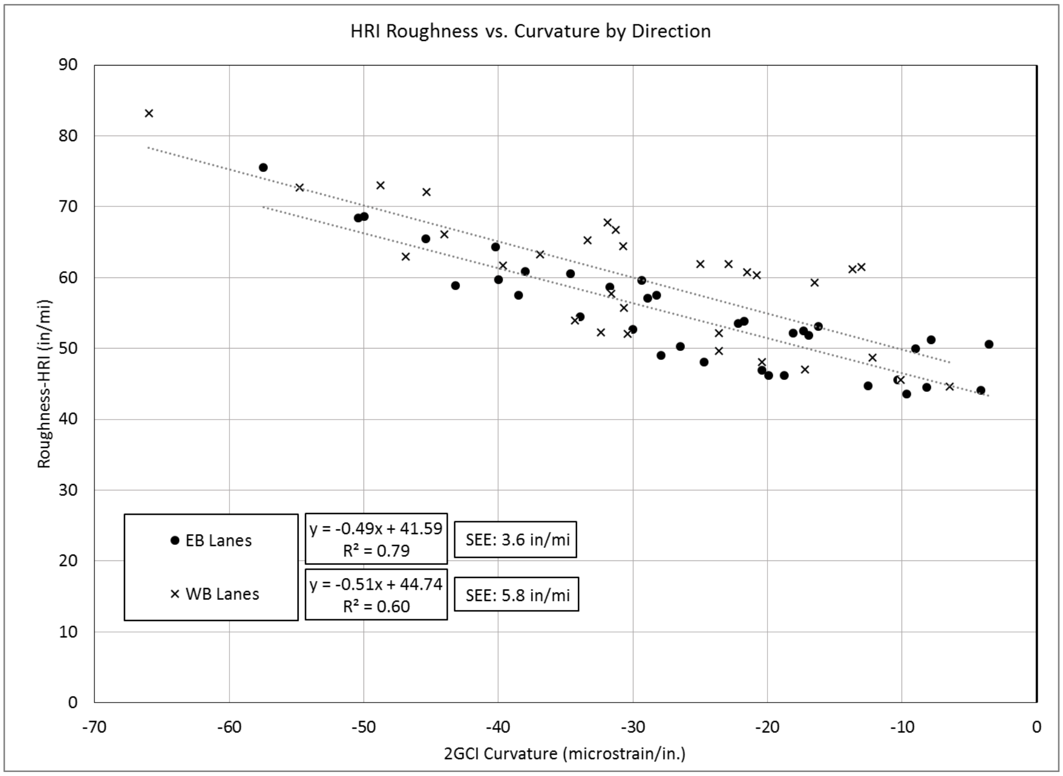

Figure 8. Correlation between roughness and slab curvature. **(*Note: 10 in/mi = 0.16 m/km; 1 in = 25.4 mm*)**

Curvature and Non-Curvature Related Roughness. Using the relationships between curvature and roughness shown above, curvature-related roughness and non-curvature-related roughness can be separated. Figure 9 (top) shows curvature-related roughness in terms of HRI, and Figure 9 (bottom) shows non-curvature-related roughness by lane (as HRI) and by wheelpath (IRI). Non-curvature-related roughness was computed by subtracting curvature-related roughness from overall roughness.

As Figure 9 (top) shows, the effect of curvature on roughness over the course of a given day can be substantial. For WB Lane 2, nearly 0.63 m/km (40 in/mi) of roughness can be attributed to slab curling when profile data is collected in the early morning but only 0.27 m/km (17 in/mi) when profile data is collected in the early afternoon. The reason for the significant difference between lanes for a given direction and side of the bridge is not readily evident, but may be related to formation of longitudinal and transverse joints, as discussed previously, or it may be related to the width of the tied shoulder. In each case, curling-related roughness was higher for Lane 2 than Lane 1 for all periods of the day. It was noted, however, that curvature-related roughness was not higher for the WB lanes than the EB lanes in all cases.

Figure 9 (bottom) shows the non-curvature roughness for each lane on either side of the bridge in both directions. Note that non-curvature roughness is not affected by changes in slab curling, and is therefore a constant for each lane. As noted previously, there is a significant difference between the LWP and RWP for most, but not all, of the lanes. When examining HRI, the WB lanes generally show higher roughness, with the exception of Lane 2 west of the bridge. All of the non-curvature HRI data, however, fell well below the CDOT smoothness specification upper limit for full pay.

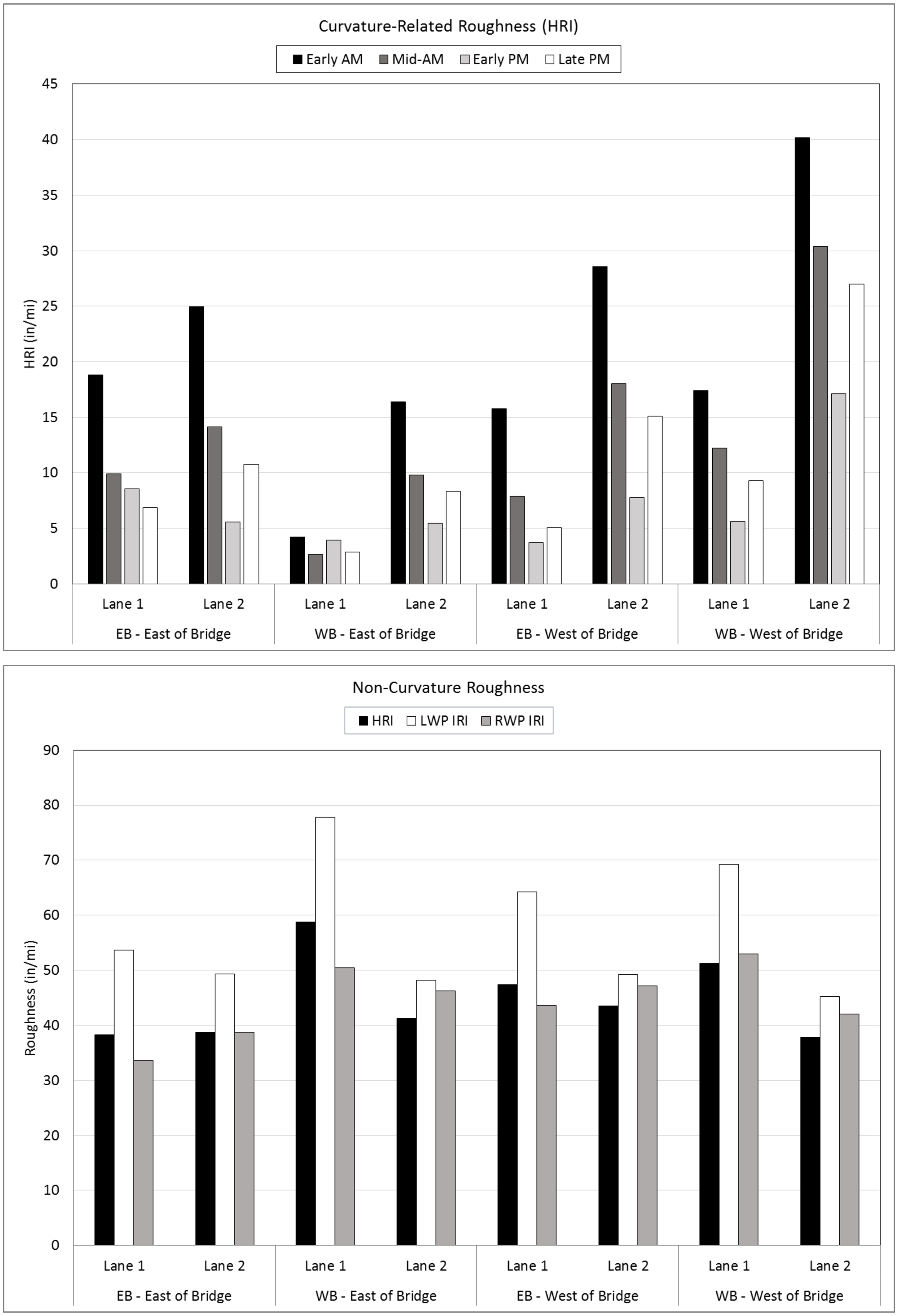

Figure 9. Curvature-related roughness (top) and non-curvature roughness (bottom). ***(Note: 5 in/mi = 0.08 m/km)***

HIPERPAV Analysis. HIPERPAV was used for the US 34 evaluation to estimate temperature gradients in the pavement slab during construction. Actual concrete design parameters (slab thickness, joint spacing, base type, subgrade support), concrete mixture design, and climatic conditions for the EB and WB lanes were used by HIPERPAV to compute slab temperature gradients during construction. With the structural and concrete mixture design and climate inputs fixed, variables that were examined included the initial concrete mix temperature, the support layer (reclaimed asphalt base) temperature, and the curing method (i.e., single vs. double coat of liquid curing compound). Because actual concrete and base temperatures were not known, assumptions were made within reasonable limits.

Table 2 summarizes the results from the HIPERPAV evaluation of slab temperatures for the EB and WB lanes based on actual construction conditions. As these results show, the predicted top-bottom temperature gradients at final set are positive, meaning the top of the slab is warmer than the bottom. After final set, as the top of the slab cools and the gradient returns to zero, a curled-up slab shape results. This is consistent with the curvature observed from profiling, which was essentially always curled upwards, or a negative built-in temperature gradient.

Table 2. HIPERPAV prediction of slab temperature gradients.

	Concrete Temperature*	**EB Lanes**	**WB Lanes**
Estimated top-bottom slab temperature gradient at final set	24°C (75°F)	+1.6°C (+2.8°F)	+10.5°C (+18.9°F)
	32°C (90°F)	+2.2°C (+3.9°F)	+8.7°C (+15.6°F)

***Assumed concrete temperatures (two scenarios).**

The difference in top-bottom slab temperature differentials at final set are significant. This may account for some of the differences in roughness between the EB and WB lanes. However, it must also be recognized that the roughness measured during the site visits nearly two years after construction will inherently be different from that measured during or shortly after construction due to creep effects which may reduce the severity of curling measured at construction over time. It is also important to remember that temperature gradients are not the only cause of slab curling. Curling from moisture gradients in the pavement slab can also have a significant effect, and are not reflected in the HIPERPAV temperature prediction models.

Some additional observations from the HIPERPAV analysis of as-constructed conditions included the fact that concrete temperature at placement (24°C vs. 32°C [75°F vs. 90°F]) had little effect on the top-bottom slab temperature gradients, and the use of a double-coat of curing compound had virtually no effect on slab temperature gradients.

In addition to analyzing actual construction conditions, alternative strategies were also examined in order to identify factors that could help mitigate slab curling. Various combinations of the following variables were examined for these alternative scenarios:

1. Night paving (start time of 7 PM).
2. High base temperature of 49°C (120°F) to simulate a bituminous base temperature in the late afternoon/early evening.
3. Moderate base temperature of 32°C (90°F) to simulate late morning/early afternoon base temperatures.

4. Cooler concrete temperature at placement (18°C [65°F]), achieved by adding ice or cold water to the mix.

The results of these alternative scenarios revealed the following:

- Nighttime paving (start time of 7 PM) resulted in a negative temperature gradient at final set for all cases. This is due to placing concrete over a warm or hot base, which has been heated up during the day, combined with the heat from concrete hydration being trapped in the bottom of the slab while the top of the slab cools at set during the night and early morning hours. A negative temperature gradient at set will generally result in either downward curling of the slab or significantly lower curled-up shape.
- Cooler concrete temperature at placement (18°C [65°F]) had only a very marginal effect on slab temperature gradients, regardless of daytime (7 AM start) or nighttime (7 PM start) paving.
- Base temperature had a significant effect on the slab temperature gradient at final set. For the scenario with 49°C (120°F) base temperature, the temperature gradient at set was -8.6°C (-15.5°F), while it was only -4.7°C (-8.5°F) for the scenario with 32°C (90°F) base temperature.

While this analysis showed the effect of certain factors on slab temperature gradients, it is difficult to establish a single best practice as paving conditions for any project change throughout the day. General best practice, however, is to help minimize the temperature gradient in the pavement slab by taking into account the actual construction conditions. If paving on a hot, dry day, delaying paving until night can help reduce the built-in temperature gradient. Also, when paving over a base which tends to get hotter due to solar radiation, such as a bituminous material, measures to help cool the base will also help minimize the temperature gradient.

Mechanistic-Empirical Analysis. The results from the M-E analysis revealed that varying the built-in slab temperature gradient input showed the most significant difference in performance predictions using the AASHTO Pavement ME Design Guide. The predicted slab temperature gradients from HIPERPAV resulted in failing cracking performance at 40 years, with transverse cracking in 19 percent of slabs (CDOT failure criteria is 7 percent). And as expected, using a higher assumed initial IRI of 1.34 m/km [85 in/mi] (versus the CDOT upper limit for full pay of 1.06 m/km [67 in/mi]) resulted in higher predicted terminal IRI, but still passed the CDOT terminal criteria of 3.16 m/km (200 in/mi).

Conclusions

While the initial intent of this study centered on identifying the cause of differences in roughness between the EB and WB lanes of the US 34 project, the principal outcome from the study was a detailed evaluation of the effects of JPCP slab curling on roughness. This issue is very important for JPCP construction and specification practices as jointed concrete pavement curling affects both functional performance (smoothness) as well as the long-term structural performance of jointed concrete pavements.

Quantifying slab curvature from profile data using the 2GCI methodology provided much more insight into the effect of changes in slab curvature on roughness than the evaluation of roughness alone. The slab curvature analysis allowed curvature-related roughness to be separated from non-curvature-related roughness, so that the effect of slab curling could clearly be seen. Depending on the time of day of profiling, up to 0.63 m/km [40 in/mi] (HRI) of roughness can be attributed to slab curling on the US 34 project. While it may not be practical to compute slab curvature indices in regular practice, there are some practical recommendations from this study that should be considered for improving construction practice and the collection of smoothness data on jointed concrete pavements, as summarized below.

Recommendations

Implementation Recommendations for Construction Practices. Through the HIPERPAV analysis, the effect of base temperature and time of day of paving appears to have greatest impact on slab temperature gradients. Some potential modifications to current construction practice that should be considered, particularly for hot weather paving conditions, include:

1. Nighttime Paving and/or Maximum Ambient Temperature Restrictions. Consider a requirement for night paving under certain hot weather paving conditions, or alternatively, consider restricting paving based on ambient conditions, not just concrete temperature at placement.
2. Maximum Base Temperature - Consider a requirement for maximum base temperature for paving. This is particularly important for paving over bituminous base materials (either asphalt-treated base or reclaimed asphalt), which absorb significant heat from solar radiation during daytime hours. Lime-slurry solutions or white-pigmented curing compound provide solutions for helping to lower the base surface temperature.
3. Membrane Curing Compound – Consider a requirement for more effective curing compounds for hot weather paving conditions, such as Poly-Alpha Methylstyrene (PAMS). Minnesota DOT testing found that PAMS had 5 to 10 times less water loss at 1 and 3 days than conventional (wax or resin-based) membrane curing compounds (Zeller 2014). Testing by Oklahoma State University also found PAMS to provide the best performance in terms of water loss and curling from shrinkage (Hajibabaee and Ley 2015).

Implementation Recommendations for Collection of Profile Data. The evaluations completed under this project confirms what is well-known about most jointed concrete pavements – that smoothness changes throughout the day, sometimes dramatically, as a result of slab curling. This should somehow be reflected in the profile data collected on jointed concrete pavement projects, but to date there are no known state DOT specifications which address this issue. The following recommendations should provide a reasonable method to ensure this issue is addressed in pavement smoothness specifications.

For overall smoothness acceptance, a requirement for simply profiling under the "worst case" condition (generally early morning), without adjusting smoothness specification thresholds to account for this, could potentially unduly penalize contractors, while a requirement for profiling under the "best case" condition (generally early afternoon) effectively ignores the fact that early-morning levels of roughness better reflect slab curling effects that impact both user (driver) satisfaction and pavement structural performance. To balance these factors, the recommended modification to collection of profile data for jointed concrete pavements includes the following two components:

1. *Collect profile during at least two times of the (same) day for acceptance.* Ideally, profile data would be collected during the early AM and early PM time periods to capture the potential "worst case" and "best case" conditions. Early AM profiling should be completed just prior to sunrise, regardless of the season of the year. Early PM profiling will vary depending on the season of the year, but a window between 1 PM and 3 PM will likely capture the other extreme condition.

2. *Set acceptance thresholds for ride quality based on two parameters:*
   - Average roughness (HRI) for the two profiles that were collected at different times of the day. This threshold will likely need to be higher than current acceptance thresholds.
   - Maximum absolute difference in HRI between the two profiles. This parameter is perhaps the biggest indicator of the effect of slab curling on roughness. By setting a limit on the difference between the two extreme conditions, this can help eliminate accepting any pavement with very extreme diurnal differences that may in fact meet the average HRI value. A recommended starting point for this would be 0.24-0.32 m/km (15-20 in/mi) maximum absolute difference per lot.

There are, of course, many challenges to implementing these recommendations for the collection of construction acceptance pavement smoothness data. There will need to be consistency in the timing of profile data collection (across all projects), synchronization of repeat profiles, assessment of localized roughness, and setting appropriate thresholds. These issues are discussed in more detail elsewhere (Merritt 2015), and ultimately a series of pilot projects and working closely with the concrete paving industry will be required in order to fine tune the recommendations.

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