EFFECTS OF CONSTRUCTION CURLING ON CONCRETE PAVEMENT BEHAVIOR

H. Thomas Yu, P.E.
Applied Pavement Technology, Inc.
3001 Research Road, Suite C
Champaign, IL 61822

Lev Khazanovich, Ph.D.
ERES Consultants,
A Division of Applied Research Associates, Inc.
505 West University Avenue
Champaign, IL 61820

ABSTRACT

Numerous factors can cause jointed plain concrete pavement (JPCP) slabs to develop a permanent upward curled shape (concave up) even when the slabs are not subjected to any temperature gradients. These factors include the temperature gradient locked into the slabs during construction (the temperature gradient at the time of concrete hardening), differential shrinkage, and moisture gradient. Pavement design features such as joint spacing, dowels, and base type, and material properties such as thermal coefficient and shrinkage characteristics affect the magnitude of construction curling.

This paper illustrates the effects of construction curling on critical stresses in JPCP and the consequent effects on slab cracking. The effects of construction curling on pavement deflections and surface profile are also discussed. Also presented is a procedure for estimating the magnitude of construction curling based on curling deflections monitored over a range of temperature conditions. Field data from I-80 Pennsylvania are presented to illustrate the effects of construction curling and the procedure for estimating the magnitude of construction curling.

INTRODUCTION

Over the past decade, several researchers have shown that JPCP slabs are not necessarily flat even when no temperature gradient is present, and that numerous factors favor the slabs being permanently curled up (Armaghani 1987; Eisenmann and Leykauf 1990a, 1990b; Janssen 1987; Yu et al. 1998; Byrum 2000). The presence of built-in upward curling is equivalent to having a built-in negative temperature gradient (slab cooler on the surface), and the effects are additive to those of the actual temperature gradients the pavements experience under service conditions. Thus, a built-in upward curling effectively reduces daytime temperature gradients (slab warmer on the surface) but adds to nighttime temperature gradients (slab cooler on the surface). If the magnitude of built-in curling is sufficiently high, multi-axle loading under nighttime temperature conditions becomes more critical, and the slabs can crack from top-down, rather than bottom-up.

Numerous factors can cause pavement slabs to have a built-in negative temperature gradient. One major source is the temperature gradient that is built into the pavement slabs. The temperature gradient the slabs are exposed to while the concrete is plastic becomes an effective built-in temperature gradient of the opposite sign. For example, if a pavement slab is exposed to a +10 °C (18 °F) gradient when the concrete hardened, the slab will curl up upon removal of this temperature gradient. The magnitude of curling will be the same as if the slab were exposed to a -10 °C (-18 °F) gradient. The slab will become flat again only when it is exposed to a +10 °C (18 °F) gradient. Effectively, the slab has a built-in temperature gradient of -10 °C (-18 °F). Since pavements are typically constructed during the daytime, the chances are very high that pavement slabs will have a significant built-in negative temperature gradient.

Differential shrinkage and moisture gradients also add to the built-in negative temperature gradients in pavement slabs. The moisture level in concrete below about 50 mm (2 in) from the surface remains at constant high level (greater than 80 percent), but the pavement surface can dry out, resulting in differential shrinkage (Janssen 1994). The effects of differential shrinkage can be represented in terms of equivalent temperature gradient and combined into built-in curling for analysis purposes.

Because stresses in JPCP are very sensitive to temperature gradients, accurate determination of the magnitude of built-in curling is very important in modeling JPCP performance. However, built-in curling is difficult to quantify, and the magnitude of built-in curling is likely to vary continuously throughout a project since the temperature gradients through PCC slabs vary continuously. The daily and seasonal variation in temperature gradients through PCC slabs is illustrated in figure 1. The main difficulty in quantifying built-in curling is that surface profile of PCC slabs alone may not be completely indicative of the support condition beneath the slabs.

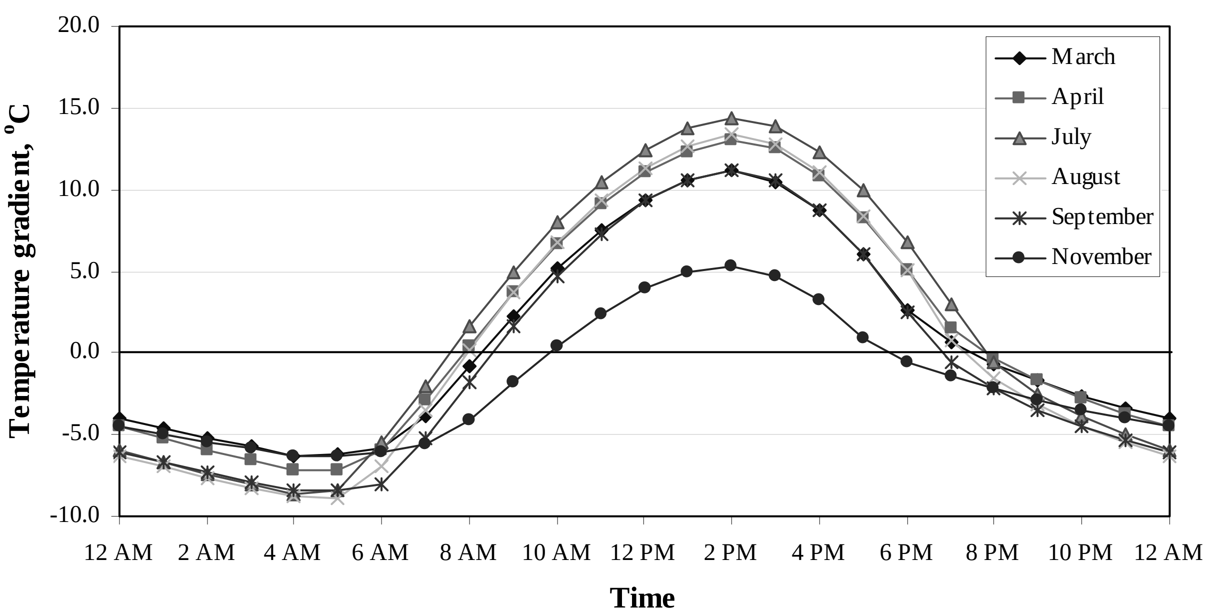

Figure 1. Daily and seasonal variation in temperature gradients through 330-mm (13-in) slab.

The surface profile of PCC slabs can be accurately measured using a Dipstick. Byrum (2000) showed that built-in curling could also be determined using high-speed profile data. Given the potential variability in built-in curling throughout a project, Byrum's approach of using high-speed profile data solves an important practical problem. The measured pavement surface profiles have to be adjusted for the temperature gradient at the time of measurement to determine built-in curling. Both Dipstick measurements and high-speed profile data show that many PCC pavements have very significant amount of built-in curling, as much as equivalent of -44 °C (-80 °F) temperature gradient in extreme cases. Some of the LTPP sections also have built-in downward, or positive, curling (Byrum 2000).

If PCC slabs are founded on a flat surface, the effects of built-in curling on PCC pavement response and performance can be determined based on pavement surface profile alone. However, curling deflections measured from instrumented slabs, and PCC pavement performance in general, suggest that the support condition under the slab edges and corners may be much better than that suggested by the surface profile data. That is, the surface of the foundation supporting PCC slabs is not flat but follows the contour of the slab to some extent, providing much better support. These results suggest that the effects of built-in curling cannot be determined based on pavement surface profile alone. To determine the magnitude of the effective built-in curling, data that reflects the actual pavement response (such as curling deflections) are needed.

Presented in the following is a discussion of the effects of built-in curling on critical stresses in JPCP and consequent effects on slab cracking. The analysis was conducted using ISLAB2000 finite element analysis program. Pavement profile data and curling deflections measured from I-80, Pennsylvania are used to demonstrate various points in the discussion. Also presented is a suggested procedure for estimating the magnitude of built-in curling using curling deflections monitored over a range of temperature conditions.

EFFECTS OF BUILT-IN CURLING ON JPCP RESPONSE AND PERFORMANCE

The procedure for incorporating the effects on built-in curling on JPCP response is simple. The temperature-gradient equivalent of the built-in curling may be simply added to the actual temperature gradients. Therefore, built-in upward curling (which is equivalent to having a built-in negative temperature gradient) has the effect of reducing stresses under daytime, positive temperature gradients, but increasing stresses under nighttime, negative temperature gradients.

Without built-in curling, the critical stress in JPCP will almost always occur under daytime conditions, because edge-load (figure 2) stresses are about 50 percent greater than corner-load stresses and the magnitude of daytime temperature gradients are typically much higher than that of nighttime temperature gradients (figure 1). The critical loading condition for top-down stresses is shown in figure 3. Multiple-axle loading is required to produce high top-down stresses, because without the restraint provided by the axles placed at opposite ends of the slab, the slab can rotate to relieve significant amount of the stress. It should be noted that the loading condition shown in figure 3 will cause transverse cracking at about midslab, very similar to the cracks caused by bottom-up stresses.

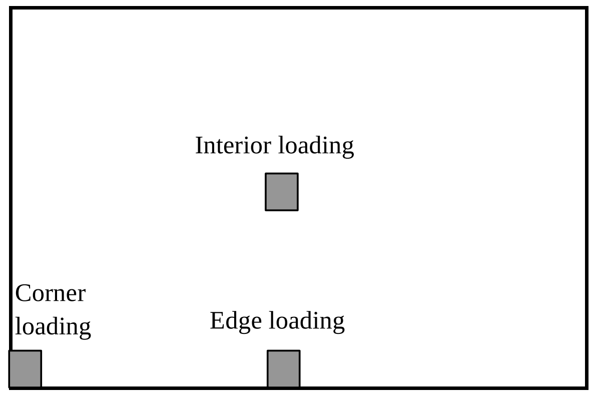

Figure 2. Critical loading conditions for JPCP.

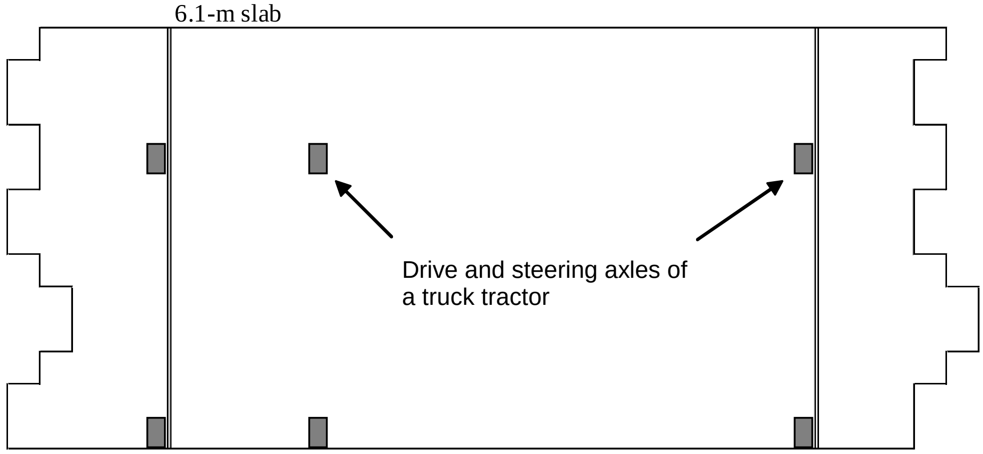

Figure 3. Critical loading condition for top-down stresses.

The presence of built-in upward curling has the effect of shifting the temperature gradients to the negative side, because the effects of built-in curling are directly additive to those of actual temperature gradients. If the magnitude of the built-in upward curling is sufficiently high, the multiple-axle loading under a high negative temperature gradient becomes more critical than edge loading under daytime conditions, as shown in figure 4. In this example, figure 4 shows that top-down stresses are more critical than bottom-up stresses under tandem-axles if built-in curling is greater than about -8.2 °C (-15 °F). Thus, built-in curling can change the mode of failure of JPCP slabs.

In terms of JPCP fatigue cracking, the effects of built-in curling are even greater than that indicated by figure 4. For both top-down and bottom-up modes of cracking, the critical damage location is the longitudinal edge, and the critical stress is at a maximum when the load is placed at the pavement edge. As the load is moved away from the pavement edge, the critical stress at the pavement edge drops off rapidly for the bottom-up case (figure 5). However, for the top-down case the stress drops off much more gradually as the load is moved away from the pavement edge.

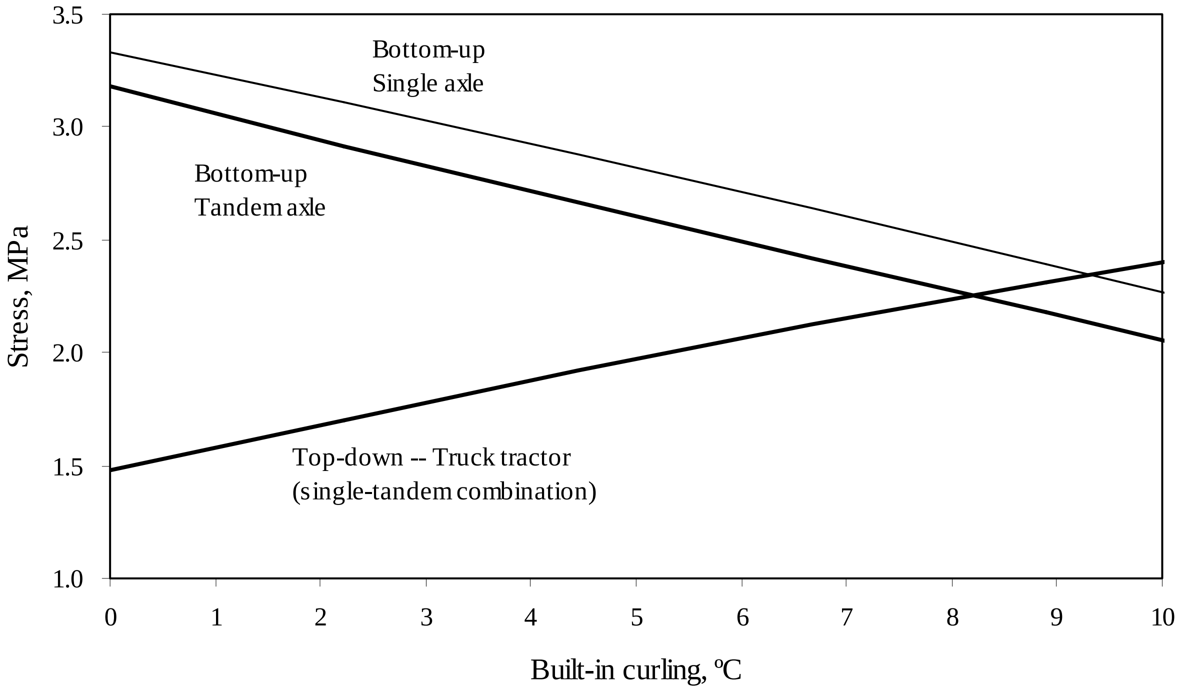

Figure 4. Effects of built-in curling on top-down and bottom-up stresses.

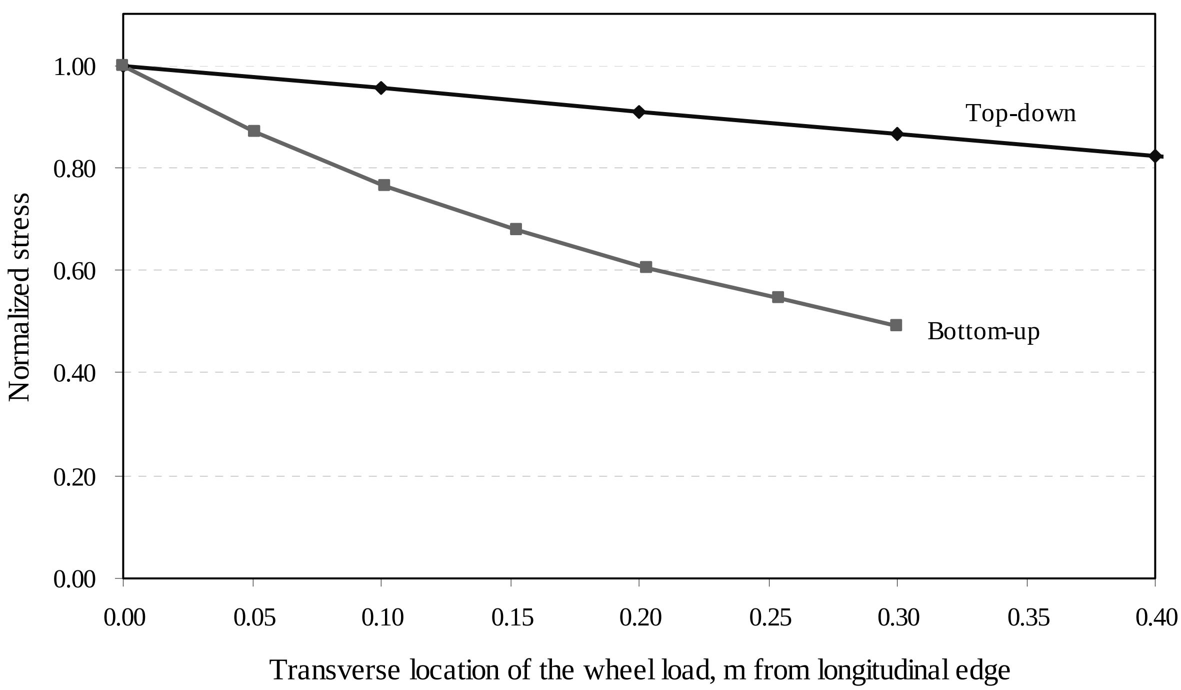

Figure 5. Effects of load placement on critical top-down and bottom-up stresses.

For bottom-up cracking, only a small fraction of the applied traffic (less than 5 percent) that wanders close to pavement edge causes stresses that are significant to fatigue cracking. For top-down cracking, a much greater percentage of applied traffic causes significant fatigue damage. When the traffic wander effects are considered, top-down cracking becomes more critical at a lower amount of built-in curling, as shown in figure 6.

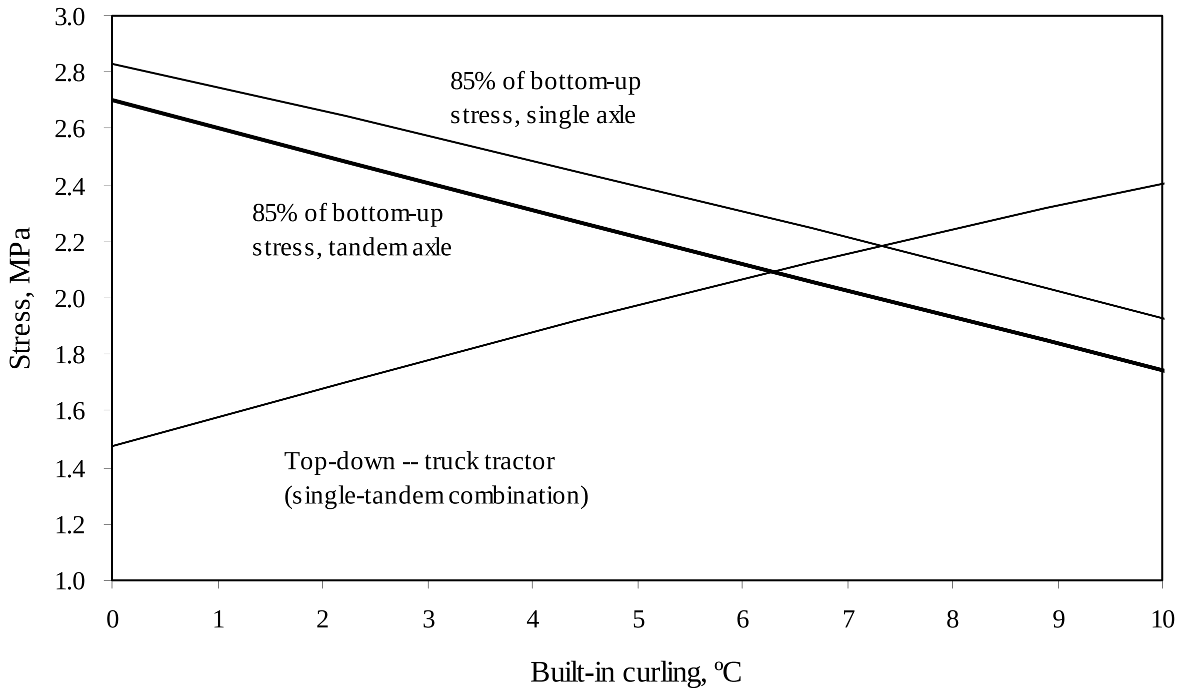

Figure 6. Effects of built-in curling on top-down and bottom-up stresses adjusted for greater effective traffic coverage under top-down loading condition.

ANALYSIS OF PAVEMENT SURFACE PROFILE DATA

In this section, the JPCP surface profile data obtained from I-80, Pennsylvania are examined. The pavement structure for this section of I-80 consists of 330-mm (13-in) slab constructed on permeable aggregate (PAGG) or permeable asphalt treated base (PATB) with 6-m (20-ft) joint spacing. The profile data was obtained using Dipstick. The PAGG section on this project developed premature cracking, and the testing had been a part of investigation into the cause of cracking.

Figure 7 shows the Dipstick data from a PAGG section measured under different temperature conditions. The temperature difference between the top and bottom of the slab was -6.7 °C (-12 °F) at 7:00 a.m. and 13.3 °C (24 °F) at 2:00 p.m. The data had been adjusted for longitudinal slope. Dipstick is a very sensitive instrument, and any surface irregularity (such as surface texture) can cause erratic jumps in measurements at this level of resolution. A best-fit

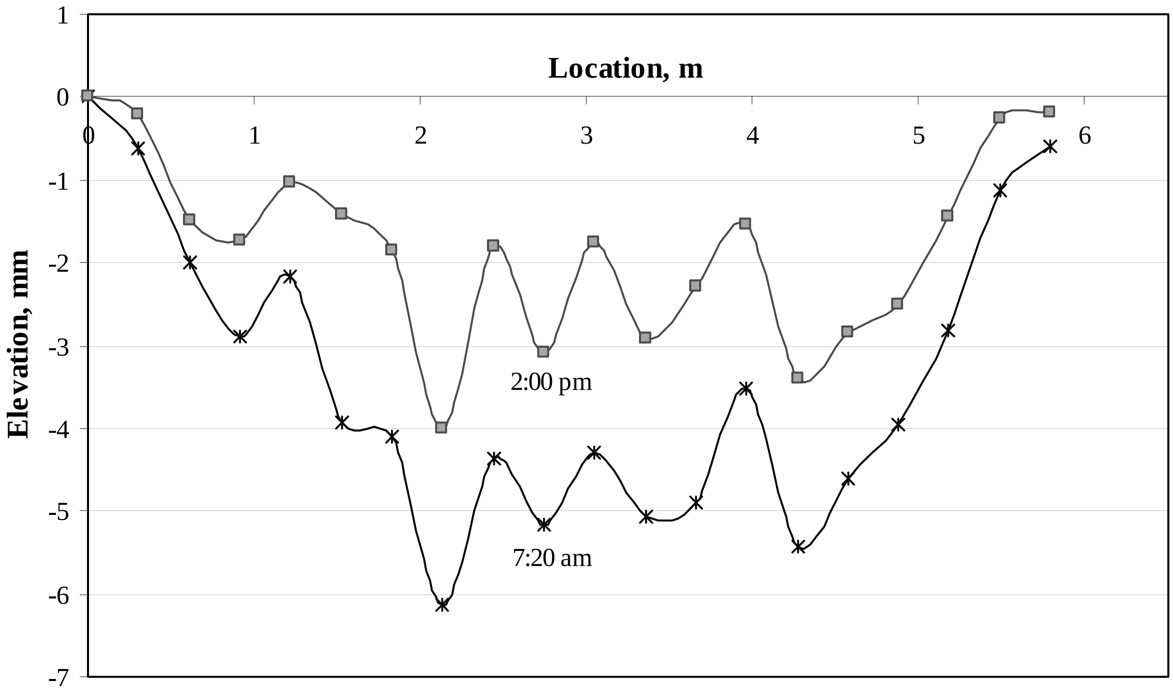

Figure 7. Dipstick measurements taken from a permeable aggregate base section on I-80, Pennsylvania.

quadratic curve drawn through the data points provides a reasonable representation of the actual profile of the pavement surface. Figures 8 and 9 show the surface profiles obtained using this approach for slabs in PAGG and PATB sections.

Figures 8 and 9 indicate a substantial amount of built-in curling in both PAGG and PATB sections. The magnitude of built-in curling is so much that even under a high positive temperature gradient (13.3 °C [24 °F]) both slabs are curled up significantly. The amount of built-in curling in PAGG section is significantly higher (about 70 percent greater) than that in PATB section. One possible explanation for this difference is the bonding that may have occurred between PATB and PCC slab in the PATB section.

Figure 10 shows the relationship between temperature gradient and amount of curling, which is represented as the difference in curling deflection between slab corner and longitudinal edge (at midslab). The amount of curling in the PAGG section at 7:20 a.m. is about 5.2 mm (0.20 in). An ISLAB2000 analysis showed that the temperature gradient required to produce this magnitude of curling is about -44 °C (-79 °F). At the time of Dipstick measurement, the actual temperature gradient through the slab was about –6.7 °C (-12 °F). Subtracting the actual temperature gradient from the temperature gradient needed to produce 5.2-mm (0.20-in) curling leaves a built-in curling of -37 °C (-67 °F). The use of the 2:00 p.m. data produces the same result (-24 °C – 13.3 °C = -37 °C [-43 °F – 24 °F = -67 °F]).

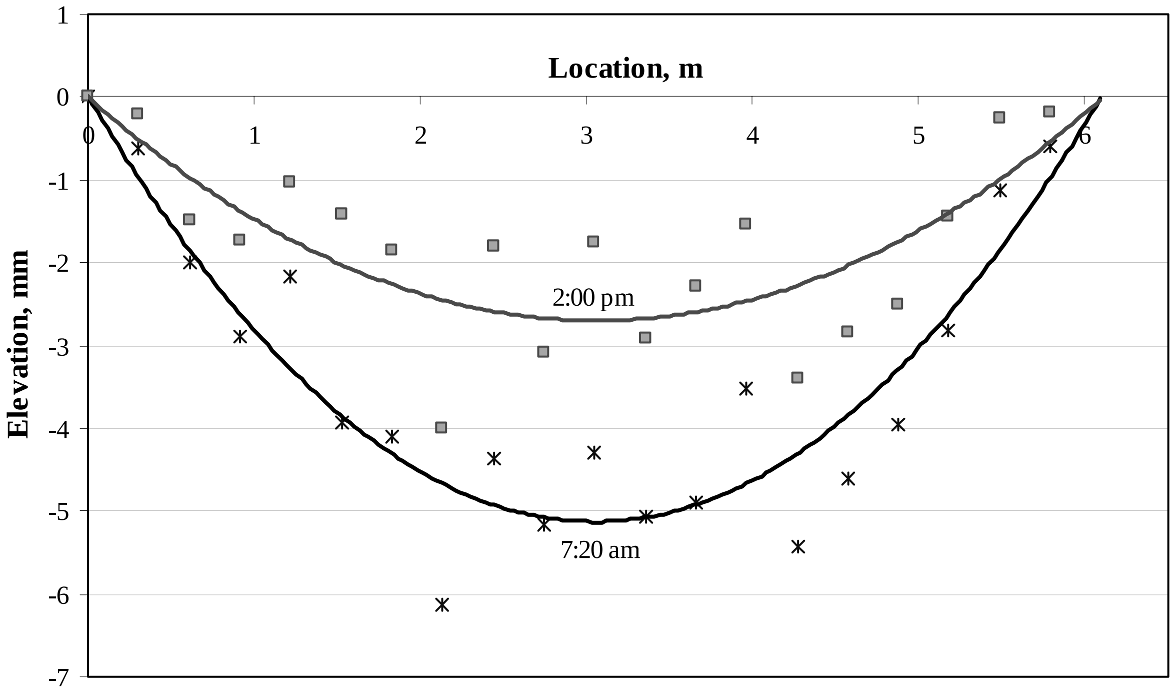

Figure 8. Surface profile of a permeable aggregate base section on I-80, Pennsylvania.

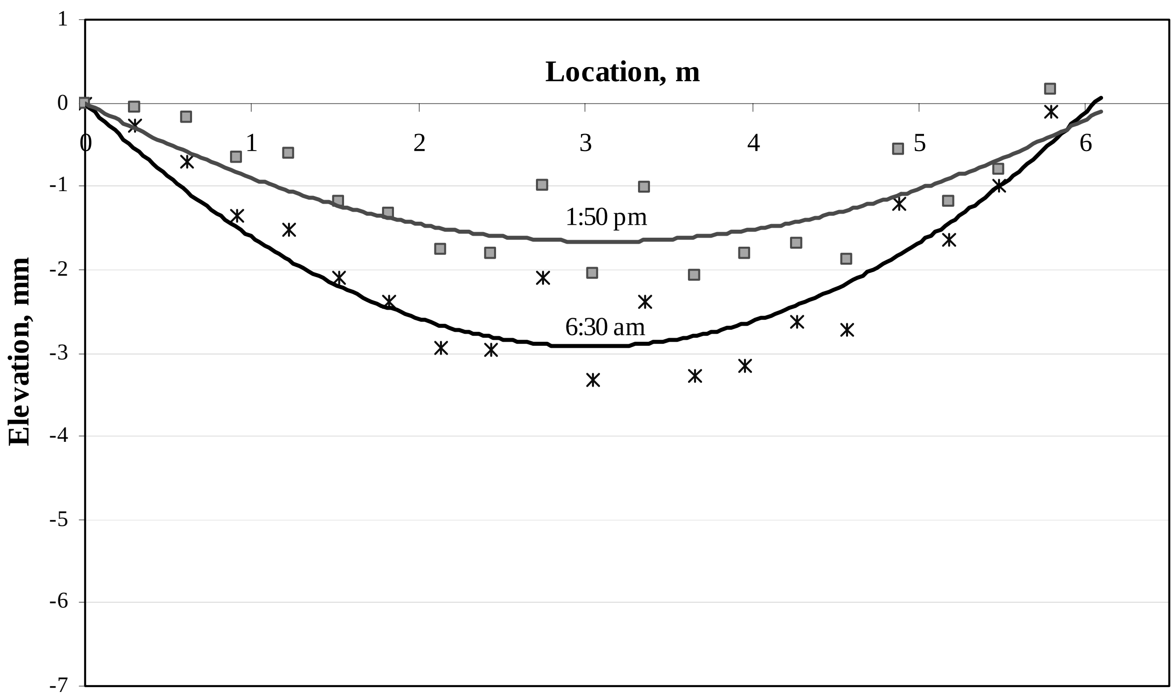

Figure 9. Surface profile of a permeable asphalt-treated base section on I-80, Pennsylvania.

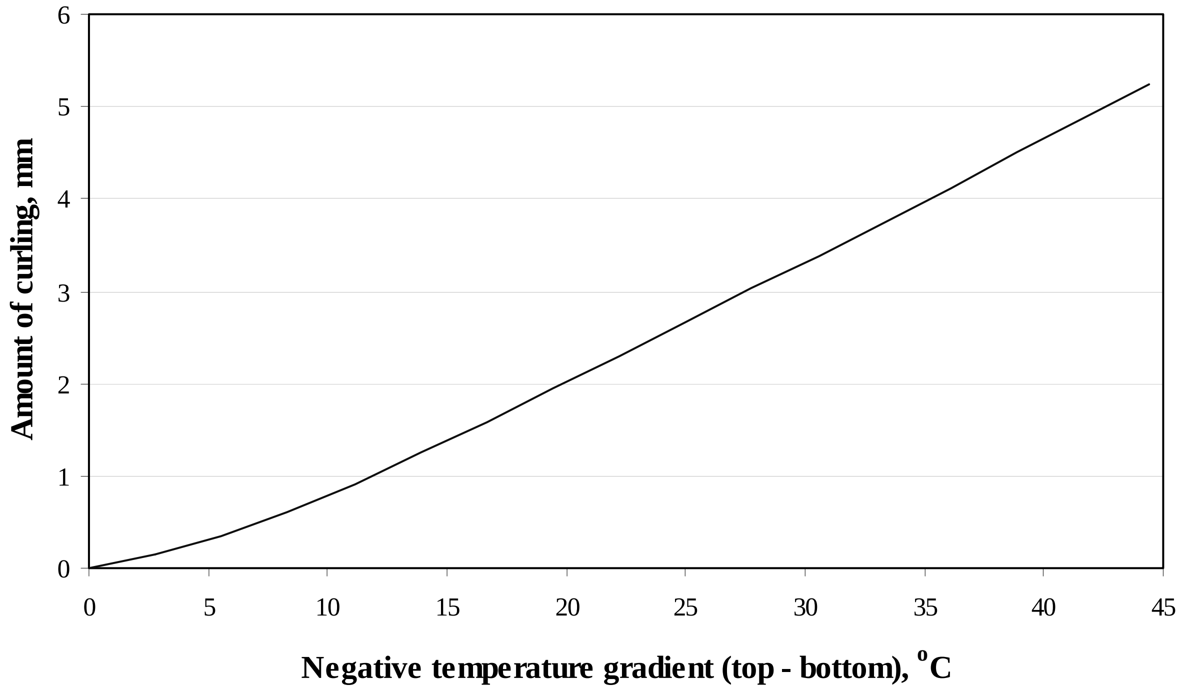

Figure 10. Sensitivity of the amount of curling (corner-edge deflection) to temperature gradient for the PAGG section on I-80, Pennsylvania.

If the amount of built-in curling determined based on the profile data were representative of the support condition under the pavement slab, all slabs in PAGG sections should have cracked shortly after construction. An analysis conducted using ISLAB2000 showed that the maximum top-down stress under nighttime temperature conditions with the -37-°C (67-°F) built-in curling is in excess of 3.5 MPa (500 psi) even without the consideration of nonlinear temperature distribution. For top-down stresses, nonlinear temperature distribution can drastically amplify thermal stresses. When the effects of nonlinear temperature distribution are considered the stresses far exceed the PCC strength.

Although premature cracking was considered a problem on this section of I-80, the cracking did not occur until the pavement sections have been in service for 5 or 6 years. The traffic on I-80 is very heavy, and the pavement sections carried more than 8 million ESALS before the cracking became a noticeable problem. Had the effective built-in curling been even half that suggested by surface profile (18 °C [32 °F]) the slabs would have cracked within the first year. For the slabs on I-80 to have lasted as long as they had, the support condition under the slabs had to be significantly better than that suggested by the surface profile.

ANALYSIS OF CURLING DEFLECTION DATA

Curling deflections measured under different temperature conditions provide a means of evaluating pavement response to temperature changes. The measurement of curling deflections involve anchoring a reference rod well below the surface (e.g., 2 m [6.5 ft]) and isolating it from the movements of the upper layers by placing it in a tube, and then measuring the movements of the slab corner relative to the reference rod. The movements can be monitored using either a dial gauge or LVDT attached on the slab corner. On I-80, LVDTs were used.

The curling movements of PCC slab corners can be used to determine the support condition under the slabs because of the differences in the restraint imposed on curling deflections by the slab self-weight between upward and downward curling. For a pavement slab to curl up, only the slab corners need to be lifted, and the lifting of the slab corners is resisted only by the self-weight of the part being lifted. However, for a pavement slab to curl down, the slab corners have to push against the foundation, and the movement is resisted by the weight of the entire slab. The presence of built-in curling affects the amount of curling deflections because it changes the initial condition from which upward or downward curling takes place.

If a pavement slab is initially curled up, the slab corners can curl down when subjected to a positive temperature gradient without having to push against foundation until the slab corners are back in contact with the foundation. The downward curling that takes place while the slab corners are out of contact with foundation occurs without any resistance. However, once the slab corners are back in contact with foundation, any additional downward curling is resisted by the weight of the entire slab. Therefore, the amount of curling deflections that takes place under a given positive temperature gradient is related to the support condition under the slab.

This relationship between the amount of curling deflections and built-in curling can be used to quantify the support condition under PCC slabs in terms of effective built-in curling. The effective built-in curling may be defined as the part of built-in curling that is representative of the support condition under the slab. It is important to note that pavement response is influenced by the support condition under the slab, not the surface profile.

The following outlines the procedure for determining the effective built-in curling based on curling deflections measured under different temperature conditions:

1. Using the curling deflections measured under the most positive and the most negative temperature gradients, determine the magnitude of curling deflection that took place between the two temperature conditions. For the I-80 PAGG section, the total curling movement that took place at a slab corners between –6.7 °C (-12 °F) and +13.3 °C (+24 °F) ranged from about 2.0 to 2.4 mm (80 to 95 mils), depending on the slab.
2. Run a series of analysis using a finite element analysis program for a range of values of built-in curling (e.g., 0 °C to -25 °C [0 °F to 45 °F]) for the negative temperature-gradient condition (-6.7 °C [-12 °F]) and the positive-temperature condition (+13.3 °C [+24 °F]) and develop a chart similar to figure 11. The total curling movement is the corner deflection under the negative temperature gradient minus the corner deflection under the positive temperature gradient.
3. Estimate the effective built-in curling as the point where the analytical curling deflection matches the observed. The estimated value of effective built-in curling for the I-80 PAGG section ranges from –5.5 to -10 °C (-10 to -18 °F).

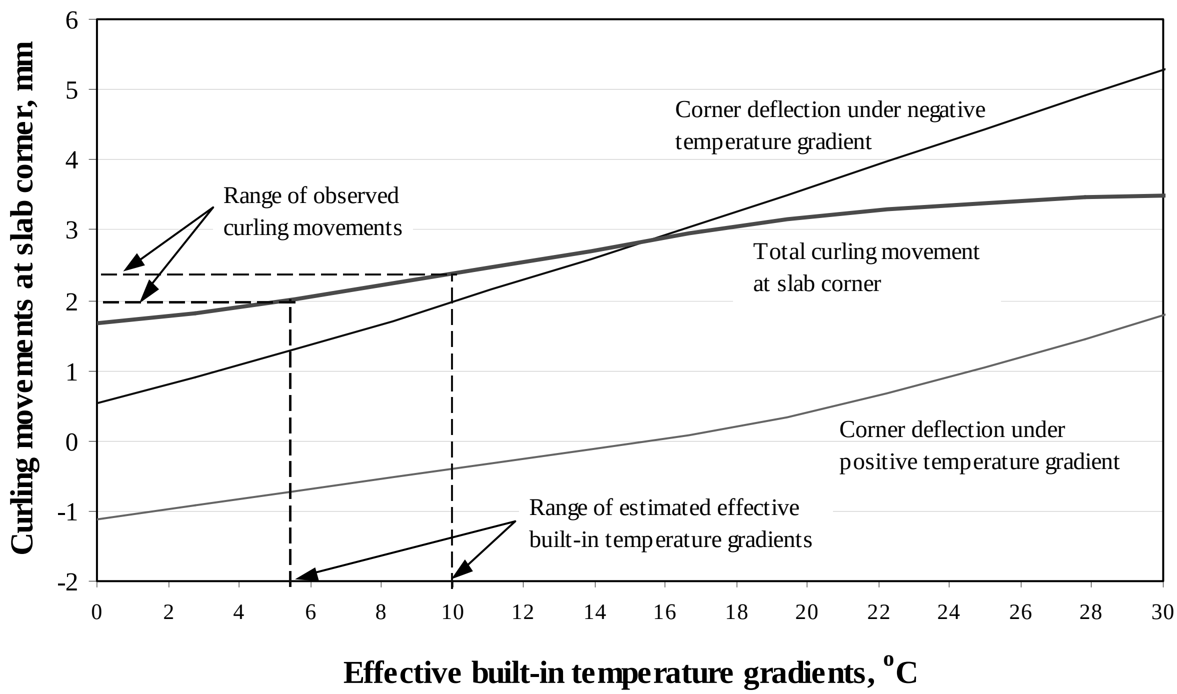

Figure 11. Illustration of the use of calculated and measured curling movements at slab corners to estimate the magnitude of effective built-in temperature gradient.

The procedure outlined above is in effect a backcalculation procedure for determining the effective amount of built-in curling. Curling deflections are direct pavement responses to changes in temperature conditions. Therefore, the effective built-in curling deflection determined using this procedure reflects the actual support condition under PCC pavements. In this procedure the moisture gradient during the testing was assumed to remain constant. Moisture conditions in PCC slabs remain relatively uniform after initial drying of the surface. There may be some seasonal changes in moisture gradients, but in short-term the variability in moisture gradients is not significant.

Figure 11 shows that at some point the total curling movement vs. effective built-in curling curve becomes flat. This is because when a slab has so much built-in curling the slab corners never comes in contact with foundation, and there is no appreciable difference in the support condition between the two temperature conditions (extreme positive and extreme negative temperature gradients). However, the PAGG section on I-80 represents an extreme case, and the effective built-in curling is usually much less than -10 °C (-18 °F). Therefore, the flat part of the curve does not pose a practical limitation. One limitation of this procedure is that the results are very sensitive to the observed curling movements. Therefore, the procedure requires very accurate measurements of curling deflections.

A small difference in effective built-in curling has a very significant effect on fatigue of JPCP. Even 0.5-°C (1-°F) difference is significant. The variability in built-in curling based on surface profile is in the order of 10s of °C. This magnitude of variability in built-in curling leads to extreme variability in calculated stresses which is not consistent with observed pavement performance. The average effective built-in curling determined based on curling movements for I-80 sections were -8.9 °C (-16 °F) for the PAGG section and -6.7 °C (-12 °F) for the PATB section. Fatigue analysis conducted using these values provided reasonable explanation of the cracking problem observed on PAGG sections.

CONCLUSIONS

This paper presents a discussion of the effects of construction curling on structural response of JPCP and the consequent effects on pavement performance. The relationship between pavement surface profile and curling deflections was also discussed, and a procedure was presented for estimating the effective built-in curling based on measured curling deflections. The following is a summary of the points made in this paper:

- Numerous factors can cause pavement slabs to have a permanent upward curling.
- The presence of built-in upward curling is equivalent to having a built-in negative temperature gradient (slab cooler on the surface), and the effects are additive to those of the actual temperature gradients the pavements experience under service conditions.
- Many in-service JPCP sections have significant amount of built-in upward curling. The amount built-in upward curling determined based on surface profile can be as much as an equivalent temperature gradient of -44 °C (-80 °F).
- If sufficiently high built-in upward curling is present, the stress caused by multi-axle loads (e.g., truck tractor) under a high negative temperature gradient becomes critical, and the slabs can crack from top-down.
- The pavement surface profile does not necessarily reflect the actual support condition under PCC slabs, and for pavement performance only the part of built-in curling that represents the support condition beneath PCC slabs are significant.
- The amount of curling deflections that takes place under a given positive temperature gradient is related to the support condition under the slab.
- The relationship between the amount of curling deflections and built-in curling can be used to quantify the support condition under PCC slabs in terms of effective built-in curling. The effective built-in curling may be defined as the part of built-in curling that is representative of the support condition under the slab.
- The results of fatigue analyses conducted using effective built-in curling agree well with observed pavement performance.

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