

Behavior and Performance of Continuously Reinforced Concrete Pavement

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Abstract

Continuously reinforced concrete pavement (CRCP) allows the concrete to form cracks to relieve stresses resulting from temperature and moisture variations. The cracks are held tight by longitudinal reinforcement. CRCP performance has been quite satisfactory in Texas and the Texas Department of Transportation (TxDOT) made it a policy to use CRCP when a rigid pavement is selected for a project. To further enhance CRCP performance, TxDOT sponsored several research studies; this paper presents the findings made so far. Extensive field evaluations found (1) almost no correlations between crack spacing and crack width, (2) crack widths decreasing over time, and (3) almost no changes in load transfer efficiencies at cracks between winter and summer. These findings contradict the hypotheses widely accepted in pavement research community. Existing punchout mechanisms were evaluated for their validity. It appears that other mechanisms are more prevalent. Many seeming punchouts are not truly structural distresses; rather, they are due to horizontal cracking at the mid-depth of the slab, which can be corrected by proper selection of materials and designs. Based on these findings, efforts are underway at TxDOT to improve design, material selection, and construction practices to further enhance the performance of CRCP.

Introduction

Portland cement concrete (PCC) pavement provides structural system superior to other pavement types partly due to the high stiffness of the pavement system and resulting low deflections. Low deflections in PCC pavement with adequate thickness and subbase support makes it possible for PCC pavement to provide longer service life with minimum

maintenance. In general, there are three types of PCC pavement, which differ in the way that volume changes due to temperature variations in concrete are addressed. The first type is jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), or precast concrete pavement, where concrete volume changes are accommodated by joints at a certain interval. The second type is cast-in place post-tensioned concrete pavement, where compressive stresses are applied to concrete while allowing concrete to move rather freely. The third type is continuously reinforced concrete pavement (CRCP), where transverse cracks are allowed to take place. In CRCP, longitudinal steel is used continuously throughout the project, except on bridges, and its function is to keep transverse cracks tight. Most of the transverse cracks in CRCP are formed within a few months after construction, primarily due to temperature variations and drying shrinkage (environmental loading). These cracks, unlike cracks in structural concrete members or in JPCP, do not represent defects, as they are kept quite tight and are not structurally weak areas. Rather, these cracks relieve stresses resulting from environmental loading.

The first CRCP in Texas was constructed in 1951 in the Fort Worth District. At the early days of CRCP usage, punchouts were the primary distress, caused by insufficient slab thickness, pumping due to erosion, and lack of edge support. Over the years, as TxDOT gained experience with and knowledge of CRCP behavior and performance, several changes were made. These included the use of thicker slabs (greater than 20 cm (8 inches)) and the use of non-erodible subbase, and tied concrete shoulder. These changes made CRCP perform extremely well, and punchouts are quite rare in CRCP built with these changes. Based on the excellent performance of CRCP, TxDOT made a policy in 2000 to utilize CRCP when a rigid pavement is selected for a project. In order to further enhance CRCP performance by improving CRCP designs, material selection, and construction methods, TxDOT has sponsored several research projects over the last few years. They include a project to develop a rigid pavement database that will be used to calibrate yet-to-be developed CRCP mechanistic models, a project to identify the causes of and develop recommendations to prevent horizontal cracking, a project to develop mechanistic-empirical CRCP pavement design procedures, and a project to improve subbase layer. A number of important findings have been made under these studies, and are under consideration for implementation at TxDOT. These findings are expected to further enhance CRCP performance and optimize the utilization of limited financial resources at TxDOT.

Research Significance

A study of rigid pavement database in Texas reveals that CRCP has provided much better performance than the currently available design programs predict. Currently, full-depth edge punchout is considered the only structural distress. However, changes made over the years to address edge punchouts, including the use of tied concrete shoulder or widened lanes and the use of non-erodible subbases, substantially reduced the occurrence of punchouts. This research study identified the benefits of those changes in improving CRCP performance, such as high level of load transfer efficiencies at transverse cracks regardless of temperature conditions and resulting low level of damages to concrete due to wheel loading applications. In Texas, a different form of distress resulting from

horizontal cracking at the depth of longitudinal steel was identified as more prevalent distress. Some form of this distress resembles edge punchouts and could be misdiagnosed as full-depth edge punchouts. A research study is underway to identify the causes of horizontal cracking and it appears that it can be prevented by proper design and material selection. This misdiagnosis might have resulted in the requirements of thicker CRCP than needed.

CRCP Structural Responses and Their Effects on Performance

As described earlier, in CRCP, concrete volume changes due to environmental loading are accommodated by naturally occurring transverse cracks, which are kept tight by longitudinal steel. Past research primarily focused on the effects of transverse cracks on punchouts. The premise made in the past research is that transverse cracks represent the weak link in CRCP and could be the primary contributor to punchouts. A few research studies were conducted to predict transverse crack spacing distribution (Won et al. 1991, Kim et al. 2003), as it was assumed that crack widths are closely related to crack spacing and slabs with certain crack spacing were assumed to be more prone to punchouts (AASHTO 1993, Won et al. 1991, ARA, Inc 2003). In addition, there have been other assumptions or premises made on CRCP behavior and performance. This paper presents overall discussions on CRCP behavior and performance issues primarily based on the findings made over the last few years under the research studies mentioned above, with the objectives of providing information for discussions, potential improvements for design, and future research. The authors plan to publish separate papers with in-depth information on these issues.

A. Transverse Crack Spacing and Crack Width

Tight crack widths will prevent water from getting into the cracks, minimizing the potential for subbase erosion and steel corrosion. Tight crack widths will also provide better load transfer efficiency (LTE), which reduces wheel load stresses. Thus, the importance of tight crack widths has been recognized, and efforts were made to predict crack widths based on crack spacing (Palmer et al. 1988, Won et al. 1991). That is one of the reasons efforts were made to predict crack spacing distributions. In this paper, transverse crack spacing is simply referred to as *crack spacing*. Field evaluations were made to evaluate the effects of crack spacing on crack widths. Figure 1-(a) shows the data collected in 1989 on relatively new CRCP (Suh et al. 1992). The section was less than one year old. Figure 1-(b) illustrates the data collected in 2004 (Nam 2005). These sections were less than two years old. In both evaluations, crack widths were measured on the surface using microscopes. Both show poor correlation between crack spacing and crack widths.

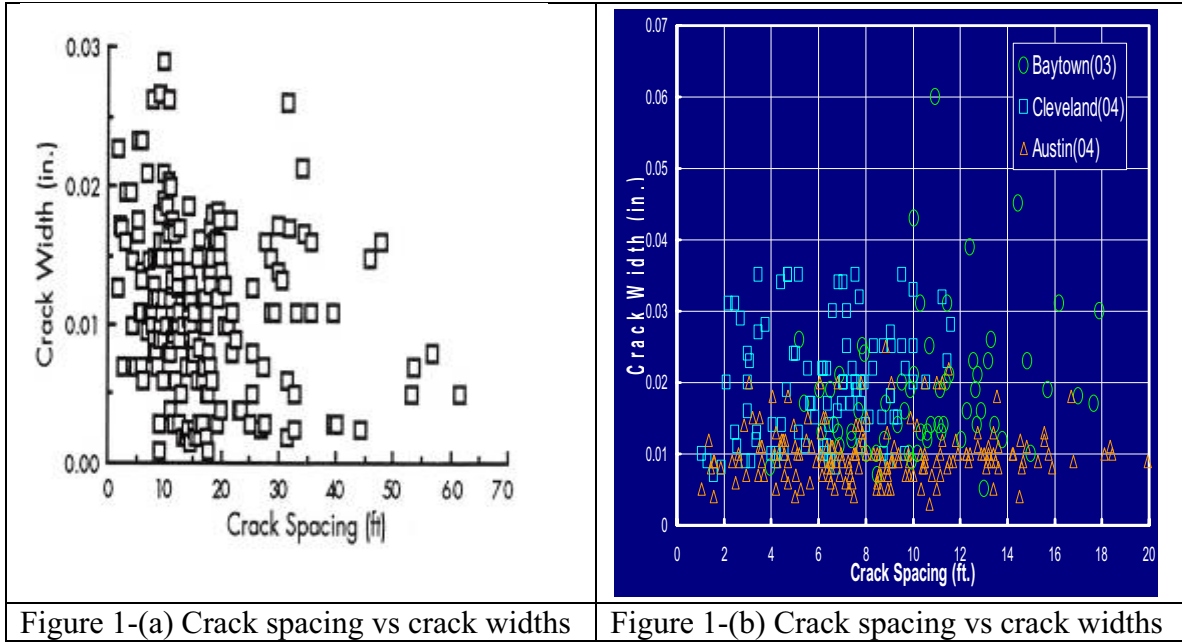


Figure 1-(a) Crack spacing vs crack widths

Figure 1-(b) Crack spacing vs crack widths

On the other hand, the crack width prediction model adopted in NCHRP 1-37(A), called the *mechanistic-empirical pavement design guide* (MEPDG), shows approximately linear correlation between crack spacing and crack width as illustrated in Equation (1). In this equation, crack width is the value at the depth of the longitudinal steel.

$$cw_i = CC \cdot \bar{L} \left(\varepsilon_{shri} + \alpha_{PCC} \Delta T_{\zeta m} - \frac{c_{2i} f_{\sigma i}}{E_{PCCi}} \right) \cdot 1000 \quad (1)$$

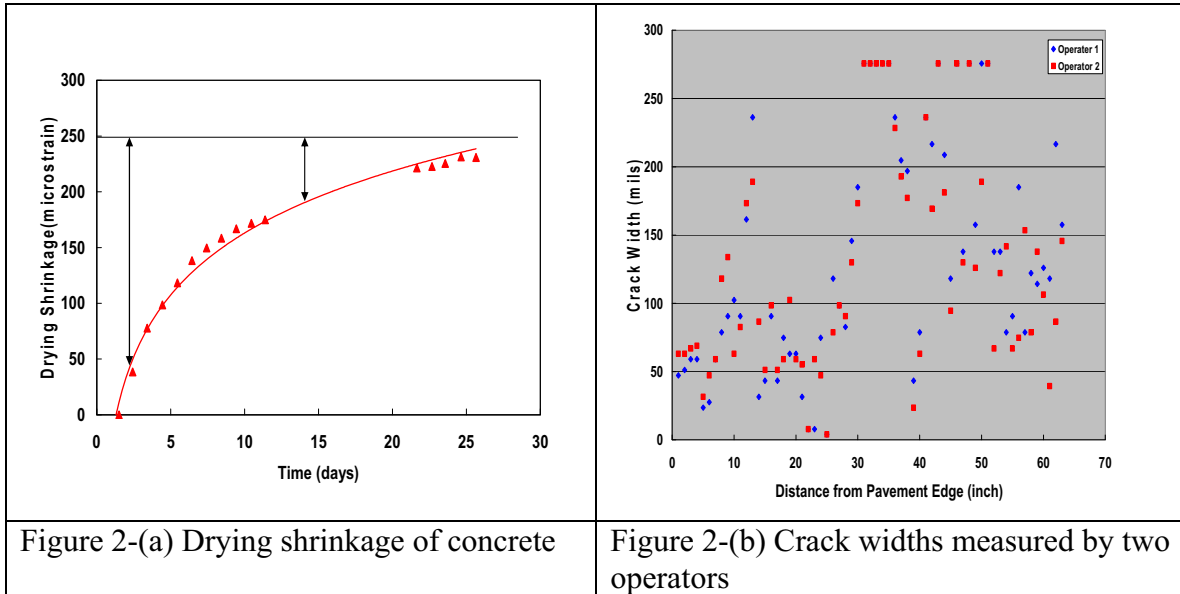
If $cw_i < 0$, $cw_i = 0$

where

- cw_i = average crack width at the depth of the steel for monthly increment i , mils
- CC = local calibration constant ($CC=1$ is used based on global calibration)
- $\bar{L}$ = mean crack spacing, inch
- ε_{shri} = unrestrained concrete drying shrinkage at the depth of the steel for monthly increment i , "strains"
- α_{PCC} = PCC coefficient of thermal expansion, $^{\circ}\text{F}^{-1}$
- $\Delta T_{\zeta m}$ = drop in PCC temperature from the concrete "set" temperature at the depth of the steel for each month m , $^{\circ}\text{F}$
- c_{2i} = second bond stress coefficient for monthly increment i
- $f_{\sigma i}$ = maximum longitudinal tensile stress in PCC at the steel level for monthly increment i
- E_{PCCi} = PCC elastic modulus for monthly increment i , psi

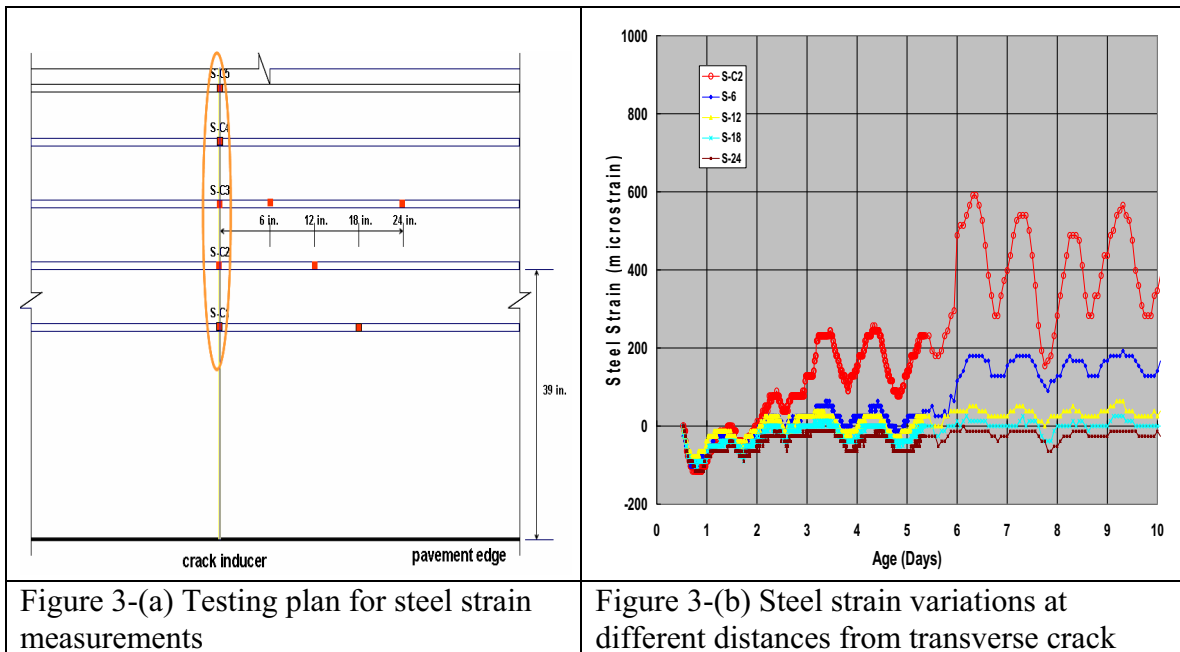
A number of reasons present themselves for the discrepancy between Equation (1) and the field observations as shown in Figures 1-(a) and 1-(b). One reason could be that the drying shrinkage effect as a function of when the crack occurs was not included in Equation (1). If cracks take place at early ages, subsequent drying shrinkage will make the crack widths larger compared with cracks that take place much later, when drying

shrinkage is almost complete. Figure 2-(a) shows the actual drying shrinkage measured in the field (Nam 2005) using unrestrained concrete prism with vibrating wire strain gages embedded. For a crack that occurred at 2 days after concrete placement, there will be additional 200 micro-strains of drying shrinkage at 30 days. On the other hand, if a crack occurred at 14 days after concrete placement, additional drying shrinkage at 30 days will be about 70 micro-strains, and some portion of the drying shrinkage up to the 14th day (in this case, about 180 micro-strains) could be absorbed by creep of concrete. The resulting width of the crack that occurred at 14 days will be smaller compared with the width of crack that occurred at 2 days.



Another reason for the discrepancy could be that crack widths on the surface are not uniform along the crack. Figure 2-(b) shows crack widths measured by two operators on a single transverse crack in CRCP section that was about 20 years old. Crack widths were measured every inch from the pavement edge for up to 1.6 meters (63 inches) along a single transverse crack. For accurate evaluations, locations of the crack width readings were clearly marked and two operators measured crack widths using the same microscope within a few minutes of each other. Even though the variations between the two operators are relatively small in most locations, there are locations where the difference is quite high. Also observed is that the variations of crack width on the surface along a single crack are quite large. Generally, locations of small crack widths coincide with the locations of longitudinal steel. The spacing for longitudinal steel was 180 mm (7 inches), and it is noted that, even though there are exceptions, minimum crack widths are repeated at approximately 180 mm (7 inches). This rather large variability makes correlations of crack widths with other variables less accurate. Another reason for the poor correlation between crack spacing and width might be that restraints on concrete volume changes by longitudinal steel are limited to about 305 mm (12 inches) from transverse cracks, even though this distance might vary depending on the environmental loading. Steel strains were evaluated in longitudinal steel as shown in Figure 3-(a) (Nam 2005). Steel strain gages were installed at 0-mm (0-in), 152 mm (6-in), 305 mm (12-in),

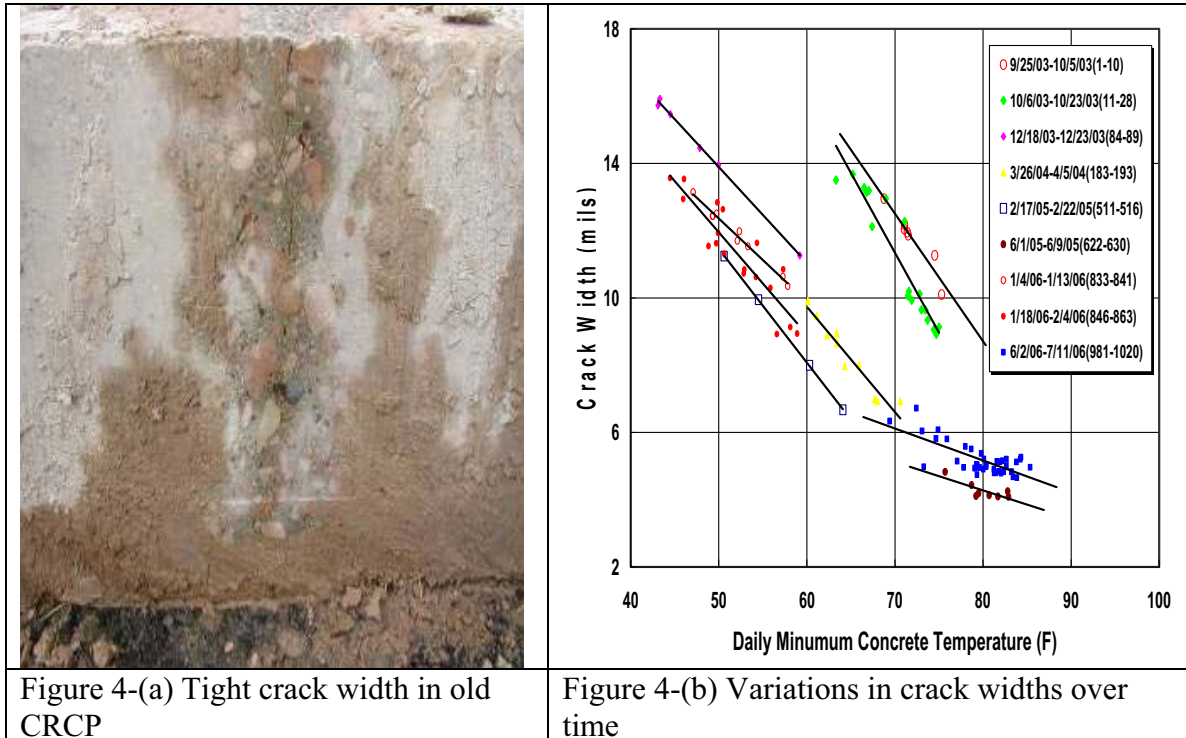
457 mm (18-in), and 610 mm (24-in) from the induced transverse crack. Figure 3-(b) illustrates the steel strains at different distances from a transverse crack. It shows that steel strains remain almost zero beyond 305 mm (12 inches) from the transverse crack. This indicates that concrete volume changes contributing to crack widths at the steel depth is limited to about 305 mm (12 inches) from a transverse crack. In other words, as long as crack spacing is larger than 61 cm (2 ft), the effect of crack spacing on crack width will be negligible.



B. Variations of Crack Widths over Time

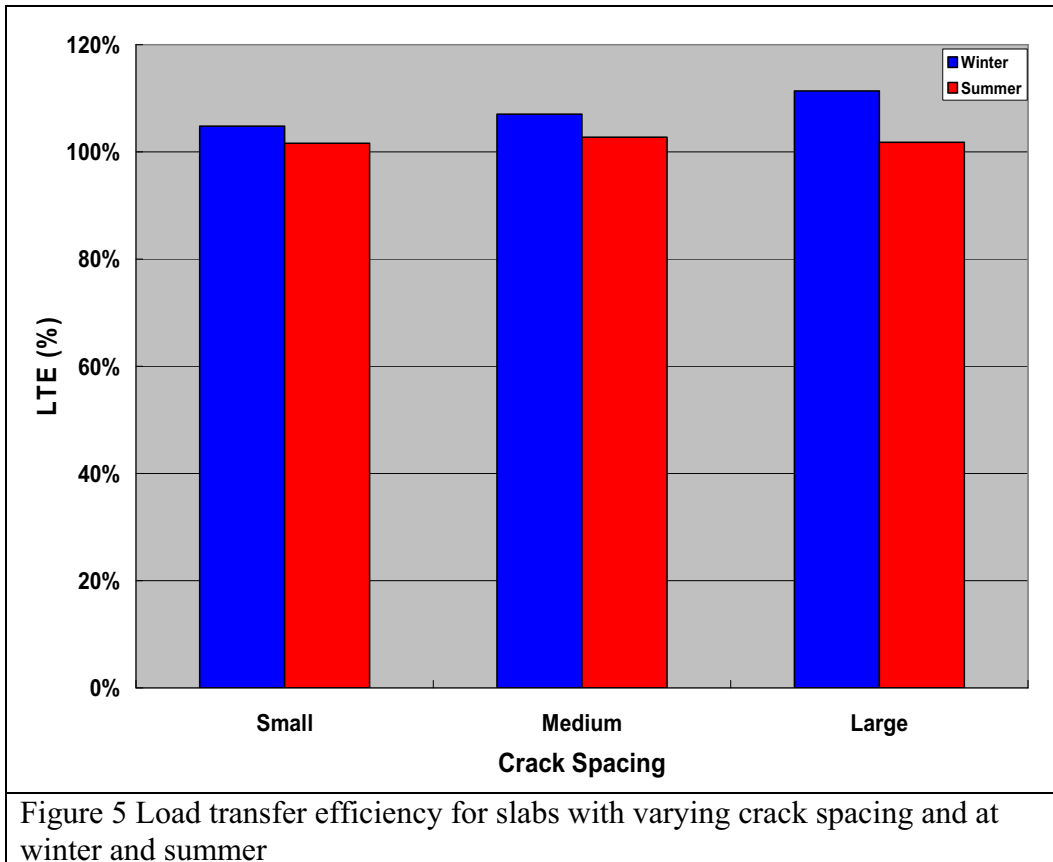
It's been assumed that crack widths increase over time, primarily due to the continued drying shrinkage of concrete, as suggested by Equation (1). However, evaluations of transverse cracks in old CRCP sections revealed that cracks remained quite tight after many years of service. Figure 4-(a) illustrates crack width variations through the slab depth for 35-year-old CRCP on IH35 in the Dallas District. It is observed that even though crack width is large on the surface, the crack almost disappears as it goes down few inches below the surface. Tight crack widths in old CRCP have been observed in a number of projects. To identify variations in crack widths over time, vibrating wire strain gages (VWSG) were installed in three projects; each in north, central, and south Texas. Three gages were installed in each project: at top, middle, and bottom of the concrete slab. A transverse crack was induced at the location of the vibrating wire gages. Crack widths were calculated by the product of strains recorded in VWSG and gage length. In this calculation, tensile strains in concrete due to stresses within the gage length of VWSG are ignored. In other words, the crack widths estimated by this method might slightly over-predict actual crack widths. Figure 4-(b) shows the crack widths values at mid-depth over about a three-year-period in a project in central Texas. Concrete was placed on September 25th, 2003 on US183 in Austin, Texas. It consists of 280 mm (11-in) CRCP

over 100 mm (4-in) asphalt stabilized base on top of a flexible base. Figure 4-(b) illustrates that crack widths vary almost linearly with concrete temperatures. It also illustrates that crack widths decreased over time. Data from the other two projects show quite similar trend. There is a good agreement between tight crack widths observed in old CRCP and the information shown in Figure 4-(b). Redistribution of stresses and displacements in CRCP as more cracks form is considered one of the mechanisms of the reduction of crack widths over time. However, there might be other mechanisms for this and research efforts are underway to identify the mechanisms for the decrease of crack widths over time.



C. Load Transfer Efficiency in CRCP

Load transfer efficiency (LTE) is considered one of the most important variables in determining PCC pavement performance (ARA Inc 2003). Crack widths and longitudinal reinforcement, along with subbase support, are considered to have effects on LTE in CRCP. LTEs in CRCP have been evaluated in 27 CRCP sections in Texas. For each section, which is 305 m (1000-ft) long, a total of 12 cracks were selected; 4 each for small (up to 91 cm (3 ft)), medium (152-183 cm ((5 -6 ft)), and large crack spacing (over 213 cm (7 ft)). LTE testing was conducted twice at the same locations; one in hot summer, and the other in cold winter. The sections included slab thickness from 20 cm (8 inches) to 38 cm (15 inches). Figure 5 shows LTE evaluated in more than 20-years old CRCP with 30 cm (12-in) slab thickness. As can be seen, LTEs were maintained at quite a high level, both in the summer and winter, and for all crack spacing ranges.



D. Effect of Transverse Crack on Deflections

Punchouts mechanisms adopted in MEPDG assume that transverse cracks will deteriorate over time due to the increase of crack widths and drop in LTEs. As discussed, crack widths in this study appear to decrease over time and LTEs are maintained at quite a high level. To evaluate the effects that transverse cracks have on the structural capacity of CRCP, deflections were measured at the middle of the slab between two transverse cracks and on a transverse crack as shown in Figure 6-(a). Deflections were measured at 30 cm (1 ft) intervals from the pavement edge between 9 am and 10 am in June 2003. Figure 6-(b) shows that little difference exists in deflections measured at the transverse crack and at the middle between two transverse cracks. This finding illustrates that transverse cracks in CRCP do not necessarily represent weak elements. This finding is corroborated by the findings described earlier – cracks remain quite tight and LTEs at a high level.

E. Edge Condition on Deflections

The CRCP section originally constructed in 1966 on IH35 in the Dallas District had both asphalt and tied concrete shoulders. It was observed that traditional edge punchouts took place only in the area with asphalt shoulder. No punchouts were observed in the area with tied concrete shoulder.

Deflections were measured at the pavement edges as shown in Figure 7-(a) (asphalt shoulder) and 7-(b) (tied concrete shoulder).

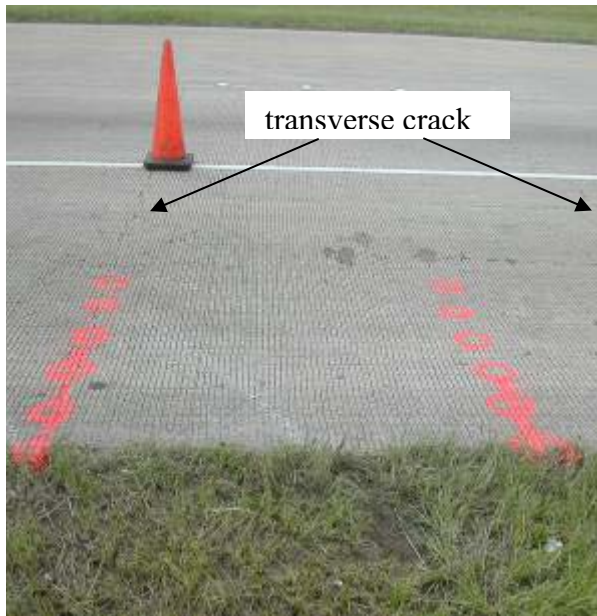


Figure 6-(a) FWD testing on crack and mid-slab

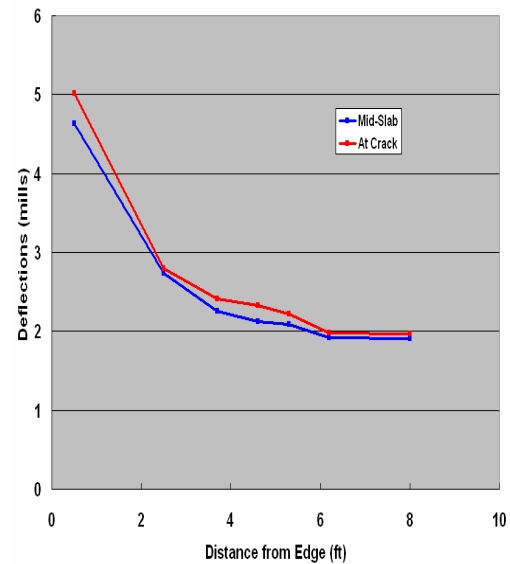


Figure 6-(b) FWD deflections at crack and mid-slab



Figure 7-(a) Edge deflection measurement with asphalt shoulder



Figure 7-(b) Edge deflection measurement with tied concrete shoulder

Figure 8-(a) shows that edge deflections with an asphalt shoulder are almost three times higher than those with tied concrete shoulder. Figure 8-(b) shows punchouts that took

place in CRCP with an asphalt shoulder. The evidence of pumping is also noted. It is noteworthy that two transverse cracks in the inner half of the lane were kept quite tight, even though the two transverse cracks in the outer half of the lane deteriorated substantially. Also observed is that the punchout is the shape of a half moon. Based on these observations, it could be concluded that the punchouts took place in accordance with the following sequence: (1) large edge deflections in CRCP with the asphalt shoulder caused degradation of subbase, pumping, and voids, (2) repeated applications of wheel loading and larger deflections further degraded the subbase and caused fatigue damage in concrete, (3) a half moon shape longitudinal top-down cracking took place and the half moon slab segment started experiencing even larger deflections, causing two transverse cracks within the half moon slab segment to deteriorate further, and finally (4) punchout took place. Most of the punchouts observed in Texas that meet traditional definitions appear to follow this mechanism. Kohler also observed this cracking and punchout mechanism (Kohler 2005). Figures 9-(a) shows a half-moon-shaped longitudinal crack that formed at pavement edge. Note that asphalt shoulder was used. It is also noted that transverse cracks in the outer half of the lane are still as tight as those in the inner half of the lane, and larger crack widths and low LTEs may not be the cause of this half-moon-shaped crack. Eventually, due to large deflections in the half-moon-shaped slab segment, transverse cracks within that segment will deteriorate and punchouts will result. In structurally deficient CRCP with an asphalt shoulder, the half-moon-shaped longitudinal crack would occur even when there were no transverse cracks. It follows that transverse cracks are not necessarily the cause of the structural deficiency and eventual punchouts, as long as they are kept tight.

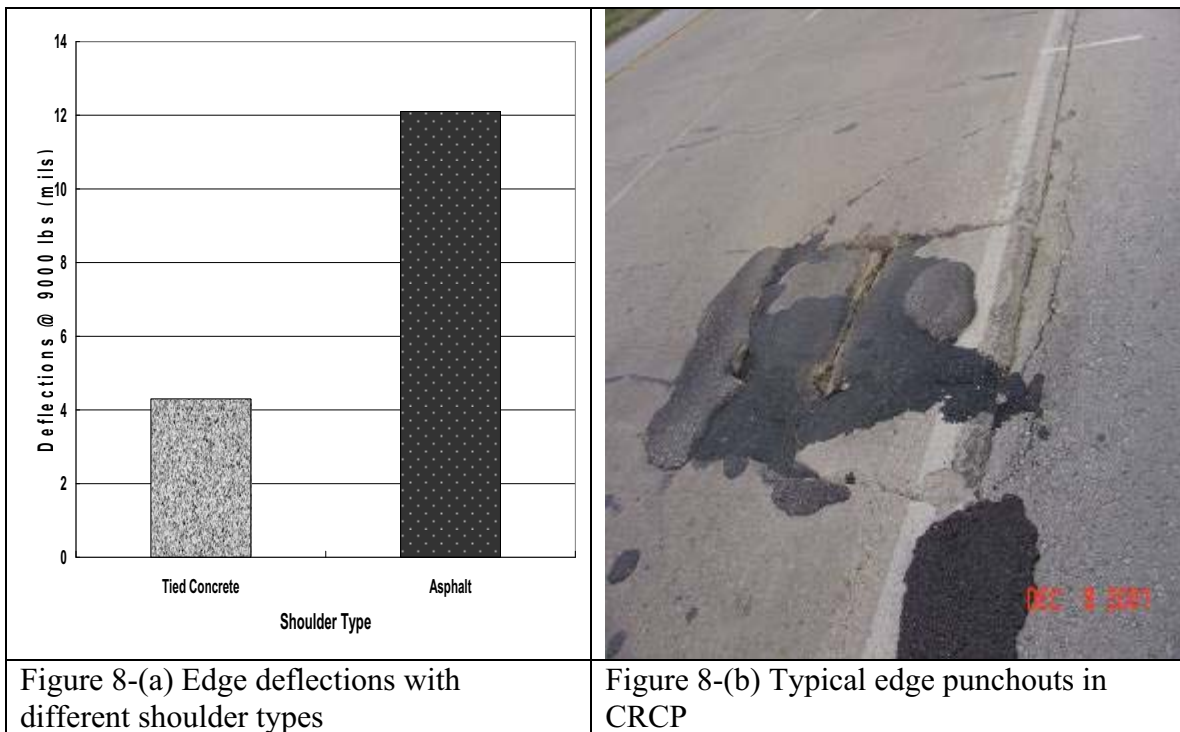




Figure 9-(a) Half moon shape longitudinal crack

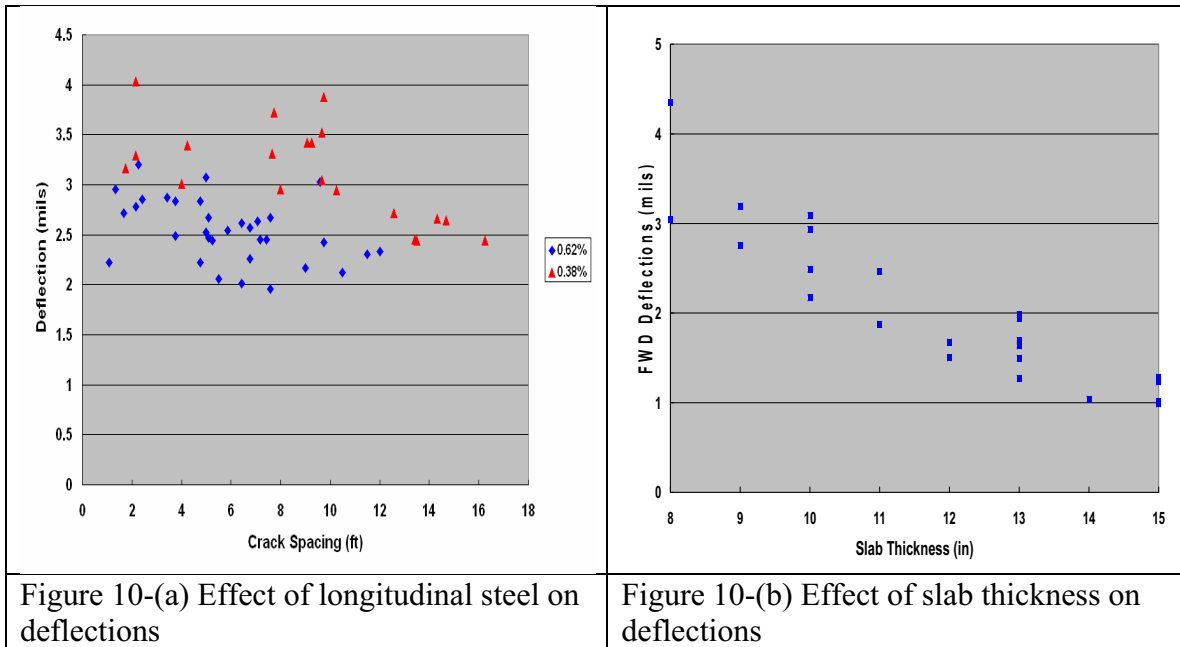


Figure 9-(b) Severe pumping in CRCP with asphalt shoulder

Figure 9-(b) shows severe pumping of the CRCP which is about 40 years old with heavy truck traffic. Note that asphalt shoulder was used in this project, and the edge of the concrete slab was depressed about one and a half inches, indicating voids underneath the slab edge. No deterioration was observed in transverse cracks yet. It is expected that a half-moon longitudinal crack might eventually form here.

F. Slab Thickness and Percent Steel on Deflections

The longitudinal steel in CRCP, more specifically temperature steel in PCC pavement, is assumed to contribute little to structural capacity of the pavement. The effect of longitudinal steel amount on CRCP deflections was evaluated on the test sections that were placed in 1989 in Houston. The objectives of the test sections were to evaluate the effects of various factors such as coarse aggregate type, the amount of longitudinal steel, and placement seasons, on CRCP performance (Suh et al. 1992). Figure 10-(a) shows the deflections measured by a falling weight deflectometer (FWD) on sections with high and low amounts of steel. Both sections have the same slab thickness (10-in) over 1-in asphalt stabilized subbase (bond breaker) on top of 6-in cement stabilized subbase. The loading was applied in the middle of the slab between transverse cracks and between wheel paths. The length of each section was 70 m (230 ft). Figure 10-(a) shows that the section with higher steel content has smaller deflections. Also noted is that the average crack spacing is smaller in the section with higher steel content, which is expected. The low deflections in the section with higher steel content indicate the increased slab stiffness due to the longitudinal steel, even though there were more transverse cracks in that section.

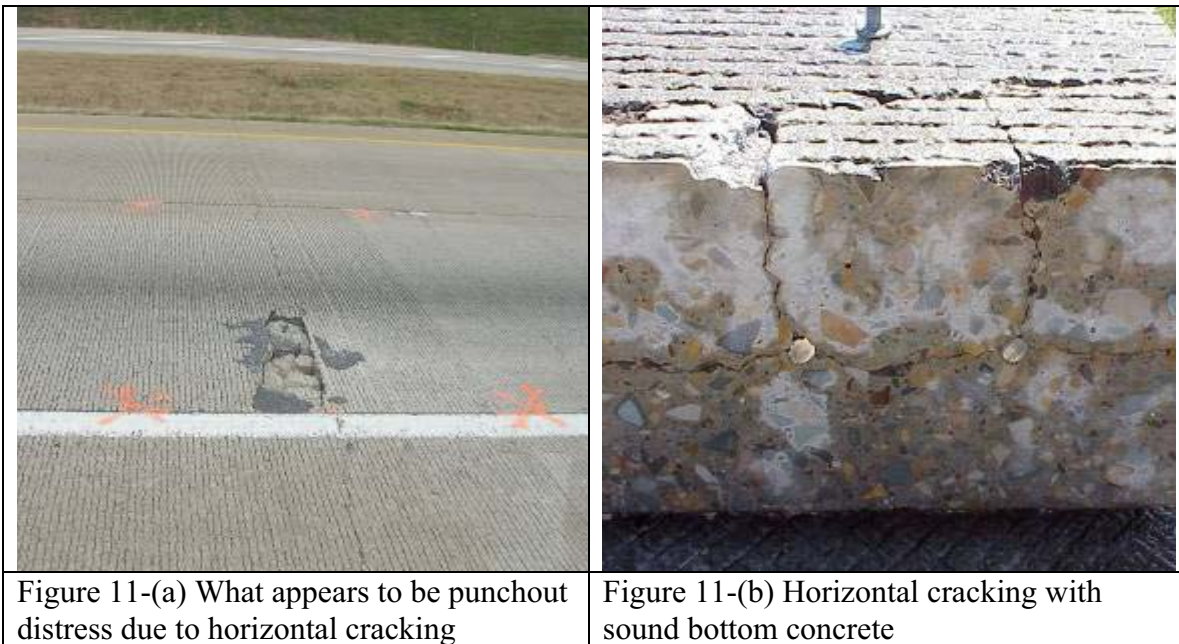


The effect of slab thickness on deflections was evaluated in 27 projects throughout Texas. FWD loading was applied at 15 m (50 ft) intervals for 305 m (1000 ft) test sections. Loading was applied in between wheel paths. Figure 10-(b) shows, as expected, inverse relationship between slab thickness and deflections. Each point in the figure is an average of 20 deflections in each test section. Also, test sections vary in pavement age and subbase types. Two subbase types used in all 27 projects are either 2.5 cm (1 in) asphalt stabilized later over 15 cm (6 in) cement stabilized subbase or asphalt stabilized subbases with various thicknesses, both of them sitting on top of subgrade. Considering the variability in age and subbase types, the trend indicates the substantial effects of concrete slab thickness on pavement deflections.

G. Horizontal Cracking in CRCP

One type of little-known CRCP distress is caused by horizontal cracking (HC) at the depth of longitudinal steel. This distress was not recognized until it was first discovered in 1999 in Texas. In 2001, Elfino et al reported its occurrence in Virginia. Since then, HC was observed in many full-depth repair projects, and it was concluded that a substantial number of distresses identified as punchouts in the past were actually caused by horizontal cracking. Figure 11-(a) shows typical distress due to horizontal cracking. At this point, this type of failure is recorded as punchouts in TxDOT's pavement management information system (PMIS) as well as in long-term pavement performance (LTPP) database. The unique nature of distresses caused by HC is that, in many cases, the bottom half of the slab is quite solid, as shown in Figure 11-(b). It is noted that the longitudinal cracks took place above the longitudinal steel and stopped at the mid-depth, indicating that these cracks are not due to structural deficiency of the pavement system. It is quite possible that state highway agencies (SHAs) over the years increased the required slab thicknesses due to the distresses caused by horizontal cracking, being unaware that this distress is not caused by structural deficiencies of the pavement system.

Rather, it appears to be due to the interactions between concrete material properties and environmental loading (temperature and moisture variations in concrete). Recognizing that distresses due to HC represent a significant portion of pavement distresses, TxDOT initiated a research study to identify the causes of HC and measures to minimize or prevent this distress. Findings so far indicate HC is due to the interactions among a high coefficient of thermal expansion of concrete, longitudinal steel, and environmental loading at early ages. HC can be minimized or eliminated by modifications to longitudinal steel design and/or selection of proper concrete materials. Also observed is that HC took place at early ages before the pavement is open to traffic, indicating that HC is not due to structural deficiencies of the pavement. The research is still ongoing, and further findings will be reported elsewhere.



H. Distresses due to Inappropriate Designs

Distresses also take place in CRCP, not due to structural deficiency, but due to inappropriate design practices. Figure 12-(a) shows distresses that could take place at transverse construction joints. The concrete was placed in the direction from left to right. Note that the transverse crack, about 60 cm (2-ft) away from the joint, is parallel to the transverse construction joint. This type of failure is not uncommon, and field investigation was conducted to identify the causes. Figure 12-(b) illustrates the installation of LVDTs in the longitudinal direction. This section was completed Friday, August 26, 2005. Note the addition of extra longitudinal bars, about 60 cm (2 ft) from the end of completed paving section.



Figure 12-(a) Distress due to improper use of additional rebars

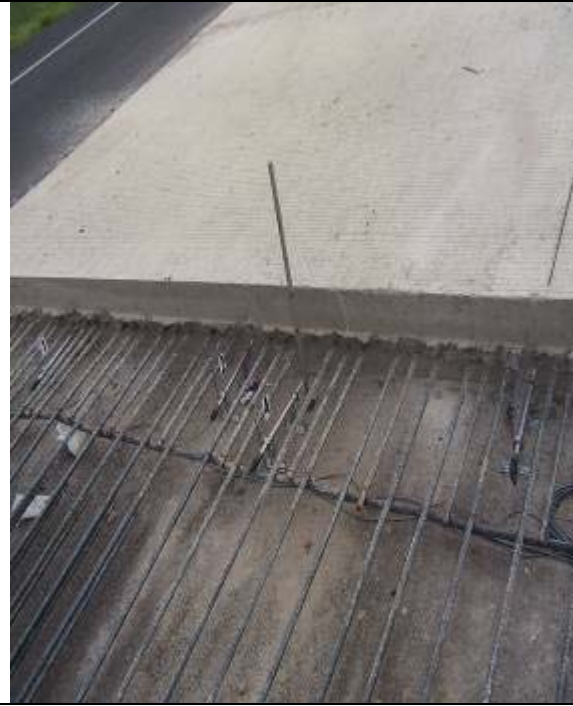


Figure 12-(b) Measurements of slab displacements at construction joint

Three LVDTs were installed to measure slab movements in the longitudinal direction. Air temperature was also recorded. Figure 13 shows the measured data. It is noted that slab contracted by more than 2.5 mm (0.1 inches) within 24 hours, and almost by 5.0 mm (0.2 inches) within 48 hours. Figure 13 also shows that the air temperature increased by more than 17°C (30°F) Saturday, but the slab expanded by less than 0.8 mm (0.03 inches). This illustrates the dominant effects of drying shrinkage over thermal volume changes at early ages as far as slab movements are concerned at the transverse construction joint. The gages were removed Sunday afternoon. Once the new concrete is placed next to this concrete, the new concrete will undergo drying shrinkage and try to shrink. Meanwhile, there will be a large difference in concrete stiffness between previously and newly placed concretes at early ages. This imbalance in stiffness or force between two concretes could cause a transverse crack at the end of the extra longitudinal bars in the newly placed side. When the previously placed concrete is trying to contract, it will pull the extra longitudinal bars with it, potentially causing a transverse crack at the end of the extra longitudinal bars.

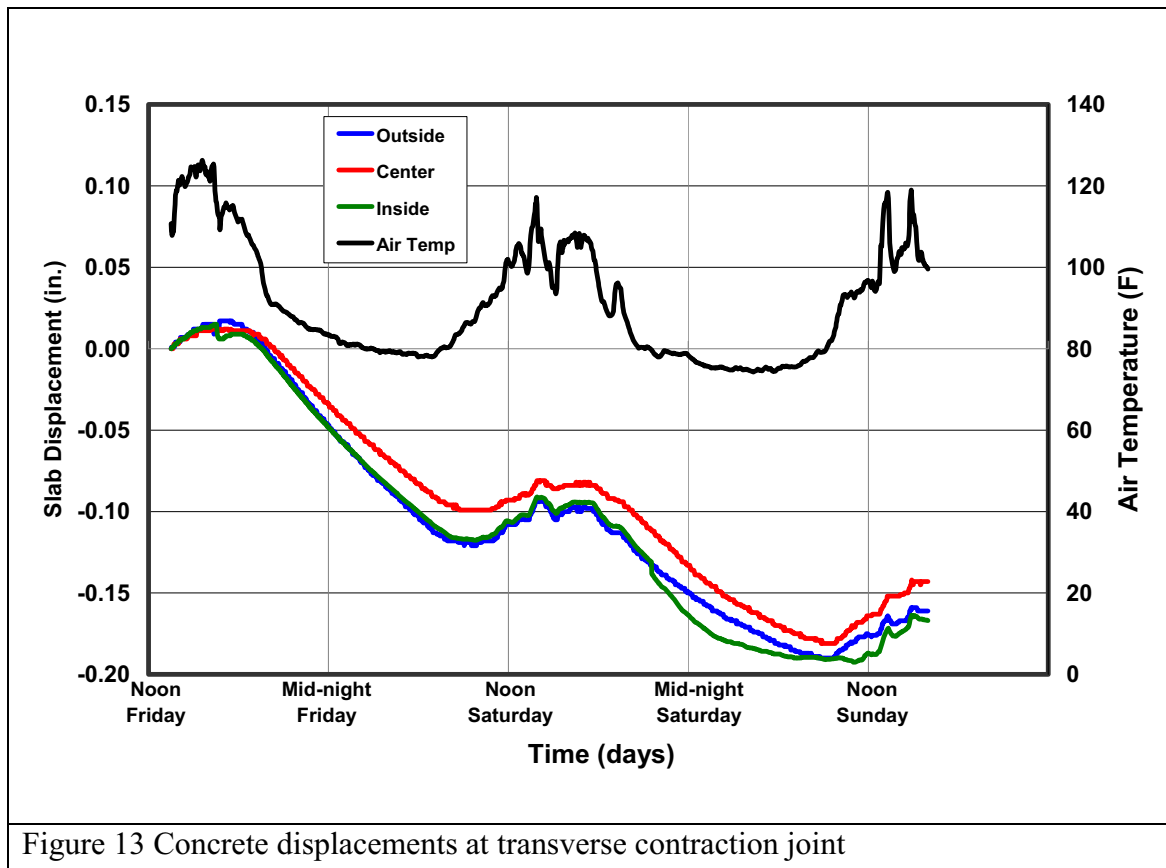


Figure 13 Concrete displacements at transverse contraction joint

Because the first concrete poured in the morning at the construction joint is placed mostly by hand, which sometimes requires the addition of water to improve workability, the quality of the material and construction could be compromised. Also, the temperature of concrete placed in the early morning increases more than that of concrete placed in the late morning or in the afternoon. Accordingly, there is a large thermal strain and stress developed near the transverse construction joint, which could lead to more cracks and sometimes distresses. The placement of extra longitudinal bars might not address the real cause of distresses near transverse construction joints. Rather, stricter quality control of materials and construction might help resolve the performance issues near transverse construction joints. If extra longitudinal bars are to be used, the ends of the bars in the new concrete side should not end at the same line. They should end in different locations by using different lengths of bars.

Conclusions

This paper presents general discussions of the behavior and performance of CRCP with reviews of existing assumptions and their validities, with the objectives of providing information for discussions, potential improvements for design and construction practices, and future research. The findings presented in this paper are based on the results of a number of research studies sponsored by the Texas Department of Transportation (TxDOT). The findings provide good evidence for the excellent performance of CRCP. The findings can be summarized as follows:

- 1) Crack widths decrease over time. Evaluations of crack widths in old CRCP show tight cracks, especially near the mid-depth of the slab. This explains high level of load transfer efficiency (LTE) in quite old CRCP. Even though crack widths increased in the winter, there was no practical difference in LTEs measured at the same location between summer and winter. The reason for the decrease in crack widths over time is not known at this point, and a research study is currently ongoing to identify the cause.
- 2) In properly designed and constructed CRCP, transverse crack does not represent weak element. Deflection measurements using a falling weight deflectometer (FWD) at a transverse crack and midway between two transverse cracks show little difference in deflections. In fact, the majority of transverse cracks do not go through the slab depth; rather, they almost disappear near the mid-depth where longitudinal steel is located, which explains the behavior of practically continuous structural member. The efforts to try to predict the performance of CRCP by evaluating transverse crack spacing distributions may not be valid.
- 3) Edge deflection is one of the most significant performance indicators of punchouts in CRCP. CRCP with tied concrete shoulder experiences much less edge deflections than CRCP with asphalt shoulder. Larger edge deflections with an asphalt shoulder could result in pumping of subbase materials and eventual punchouts.
- 4) Even though longitudinal steel is placed at mid-depth of the slab in Texas and it is assumed that steel does not contribute to the structural stiffness of the slabs, CRCP with 0.68% steel provided less deflection than CRCP with 0.38%. This indicates the contribution of longitudinal steel to the structural stiffness of CRCP. There were decent correlations between slab thickness and deflections as expected, even though the ages of the pavements and the subbase types used were different.
- 5) One of the primary causes of severe distresses in CRCP is partial-depth failure due to horizontal cracking. Horizontal cracking appears to be due to the interactions among a high coefficient of thermal expansion of concrete, longitudinal steel, and environmental loading at early ages. Horizontal cracking is not due to structural deficiency of the pavement. Observations made during full-depth repair projects indicate that substantial portions of the repairs were due to partial-depth failures caused by horizontal cracking. It appears that this distress has been identified as full-depth punchouts in many databases including TxDOT's pavement management information systems (PMIS) and long-term pavement performance (LTPP). On going research effort indicates HC can be minimized or eliminated by modifications to longitudinal steel design and/or selection of proper concrete materials.
- 6) In Texas, additional longitudinal rebars have been used at transverse construction joints. These bars have the same lengths and transverse cracks formed at the end of these rebars, resulting in distresses. These cracks are due to the imbalance in stiffness of concretes placed at different days and volumetric changes in concrete due to temperature and moisture variations. These additional rebars may not be needed. If additional longitudinal rebars are used, it is recommended that rebars

be staggered to avoid having the ends of all the rebars at the same transverse location.

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