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Evaluation of Structural Responses of Continuously Reinforced Concrete Pavement (CRCP) using Falling Weight Deflectometer

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Abstract

The objective of this study is to suggest reasonable structural evaluation method of continuously reinforced concrete pavement (CRCP) using Falling Weight Deflectometer (FWD). The effects of transverse crack spacing and temperature conditions were investigated in CRCP sections with various slab thicknesses and pavement ages. A total of 20 CRCP sections were selected throughout Texas and structural responses were evaluated from 2006 to 2013 for eight testing years. Test results show that transverse crack spacing has little effect on deflection and load transfer efficiency (LTE). LTE values were maintained at above 90%, regardless of crack spacing, temperature condition or pavement age. Temperature variations had small effects on deflections at cracks and the mid-slab, but almost no effects on LTE. Maximum deflections and back-calculated k-values appear to be better indicators of structural condition of CRCP than LTE. LTE is not the best indicator of structural condition of transverse cracks in CRCP. Deficiencies in slab support are the primary cause of full-depth distresses in Texas, and backcalculated k-values, which combine both a maximum deflection and the shape of deflection bowl from FWD testing, may be a better indicator of the structural condition of CRCP.

Keywords: structural responses; transverse crack; falling weight deflectometer; modulus of subgrade reaction; continuously reinforced concrete pavement; load transfer efficiency
1. Introduction

As of 2012, there are 17,336 lane miles of Portland cement concrete (PCC) pavement managed by the Texas Department of Transportation (TxDOT). Among those lane miles, 77% is continuously reinforced concrete pavement (CRCP) and the remaining 23% is jointed plain concrete pavement (JCP). Even though the PCC pavement in Texas is only 9.7% of the total lane miles, which is 196,821 lanes miles as of 2012, it is estimated that one quarter of the total traffic in Texas is carried by PCC pavement. Also, PCC pavement has been built where truck traffic is heavy. Accordingly, keeping PCC pavement in a good structural as well as functional condition is vital to the economy of Texas. To evaluate and maintain PCC pavement in a good condition, TxDOT evaluates almost all lane miles every year under the Pavement Management Information System (PMIS) program. PCC pavement evaluations under PMIS are primarily based on visual observations of the pavement condition, such as cracking and joint failures for JCP, and punchout and spalling for CRCP, as well as the number of asphalt or concrete patches. Based on these observations, a score called a distress score is developed. Ride quality is evaluated in terms of international roughness index (IRI), and a ride score is developed. A score, called a condition score, is derived from these two scores and assigned to each pavement section. However, a condition score (CS) is not necessarily an indication of the structural condition of the pavement. It is partly because not all distresses in CRCP are always due to structural deficiency of the pavement system; rather, they quite often develop from quality issues of materials and construction. Keeping the pavement in an adequate structural condition is a prerequisite to ensuring a good long-term performance of the pavement. Evaluating structural condition of pavement sections is not an easy task. One of the more feasible means for structural condition evaluations is the use of falling weight deflectometer (FWD).

The performance of CRCP in Texas has been quite satisfactory, with a lower number of distresses per mile than in JCP for pavements with a comparable age (Choi et al. 2013). At the same time, the ride quality of CRCP has been consistently better than that of asphalt pavement or JCP. Based on the historical information on the performance of JCP and CRCP, in 2000, TxDOT made it a policy to utilize CRCP for projects when a rigid pavement type is selected. Since then, most of the rigid pavements constructed in Texas have been CRCP, while the lane miles of JCP has steadily decreased primarily due to the asphalt overlays. Even though CRCP performs better than JCP, the initial
construction cost of CRCP is higher than that of JCP, and the repairs of distresses in CRCP are more complicated, expensive and time-consuming than those in JCP. Accordingly, it is quite important to have sound design and structural condition evaluation methodologies for CRCP in place, so that the incidents of CRCP distresses are minimized and preventive maintenance activities can be planned with adequate funding secured. To achieve these goals, TxDOT initiated a research study to investigate structural behavior of CRCP, with the goal of developing sound procedures for structural capacity evaluations of CRCP.

To achieve the objective of the study, structural behavior of CRCP was investigated by extensive FWD testing in the field. Load transfer efficiency (LTE) at transverse cracks has been cited as a primary indicator of CRCP structural condition, as the loss of LTE over time due to traffic and environmental loading was considered as a major deterioration mechanism of distresses in CRCP (ARA 2004, Miller and Bellinger 2003, Selezneva et al. 2003). To evaluate the effects of transverse crack spacing and temperature conditions on LTE and investigate the validity of the distress mechanism of CRCP sections with various slab thicknesses and pavement ages were selected throughout Texas and structural responses were evaluated with FWD from 2006 to 2013 for eight years.

2. Transverse cracks in CRCP

In CRCP, most of the transverse cracks develop at early ages due to temperature and moisture variations (environmental loading) in concrete. These cracks are intentional and kept quite tight by longitudinal reinforcement, and normally do not represent weak elements in the pavement system. Since concrete undergoes continued drying shrinkage over time, the widths of cracks in CRCP are expected to increase as well, especially near the surface of the slab. What is not clearly known is whether the widths of cracks near the depth of longitudinal steel will increase as well and will affect LTEs and long-term performance of CRCP (ARA 2003a, b). The volume change potential of concrete near the depth of longitudinal steel is substantially smaller due to higher relative humidity and lower temperature variations than at the surface of the concrete. Also, since the volume changes near the longitudinal steel are restrained by longitudinal reinforcement, it is expected that creep of concrete will be more than at the surface, which will result in the smaller crack widths than at the concrete surface, and potentially might help maintain a higher level of LTEs at transverse cracks. On the other hand, in CRCP design algorithms adopted in the
mechanistic-empirical pavement design guide (MEPDG) (ARA 2004), the increase in crack widths over time due to continued drying shrinkage of concrete and resulting loss of LTE at transverse cracks, which increases wheel loading stress, is the punchout mechanism (ARA 2003a, b). In that algorithm, it is further assumed that crack width is almost linearly proportional to transverse crack spacing, which implies that large crack spacing is not desirable. Considering the punchout mechanism adopted in MEPDG, understanding of the characteristics and behavior of transverse cracks in CRCP is essential to the proper evaluation of structural performance, and in-depth investigations of transverse cracks were first conducted in the field investigations.

Fig. 1(a) presents a transverse crack with a large crack width on the surface, but the crack stops a few inches from the slab surface. The section was built in 1977 with a 10-in (254 mm) thickness of CRCP, and longitudinal saw-cut was made for widening operations, which provided an opportunity to observe how deep the transverse crack progressed. It is observed that even though the crack width on the slab surface was large, the crack did not propagate very deep, which implies that the visual condition of transverse cracks, more specifically crack widths on the pavement surface, may not be a good indicator for LTE and long-term performance of CRCP, since LTE at this crack will be 100 % and this crack does not present discontinuity from a structural standpoint. In CRCP, some transverse cracks propagate all the way through the slab depth, as shown in Fig. 1(b). This pavement was constructed in 1971, and the slab thickness was 8-in (203 mm). If the structural capacity of CRCP is deficient for the given traffic loading in terms of slab thickness, slab support, and longitudinal steel reinforcement, slab deflections could be large and longitudinal steel might not be able to hold the cracks tight. In these cases, cracks propagate through the slab depth and crack width could become large, which could result in the loss of aggregate interlock. However, for CRCP built lately with adequate slab support, an adequate amount of longitudinal steel and slab thickness, transverse cracks with a large width and resulting loss of aggregate interlock are quite rare, except for locations of localized deficient slab support.

Fig. 1(c) shows two transverse cracks observed on the side of a CRCP slab, one apparently from top to bottom and the other from bottom to top, with both cracks stopped at the middle depth of the slab. This 10-in (254 mm) thick CRCP section was completed in 1980, and it appears that the top-down crack was caused by environmental loading.
The bottom-up crack could have been by environmental or wheel loading, or a combination of both. This type of cracks - two vertical cracks at a location, with one top-down and the other bottom-up - are observed in new CRCP sections before they are open to traffic, which shows that the cracks developed due to environmental loading. Fig. 1(c) indicates that (1) transverse cracks in CRCP are caused by warping and curling actions of concrete slab, which implies that the crack widths might vary through the slab depth, and (2) transverse cracks in CRCP could be quite stable, as these two cracks did not join or propagate through the slab depth under more than 35 years of environmental loading. Fig. 1(d) shows a distress in CRCP, which is not a typical punchout, as it did not occur at the edge of the pavement. One the other hand, this distress shares common characteristics of punchout as it contains deteriorated transverse cracks and longitudinal cracks. The area outlined in red chalk was cut and removed to investigate the causes of this distress. Fig. 1(e) shows the slab removed. It shows a horizontal crack at the depth of steel and transverse cracks that stopped at the depth of the horizontal crack. It indicates that the distress shown in Fig. 2(d) was caused by fragmentation of concrete surrounded by a horizontal crack at the mid-depth, and transverse and longitudinal cracks. Fig. 1(e) does not provide information on, between longitudinal and horizontal cracks, which crack occurred first. Fig. 1(f) shows that a transverse crack was initiated at the mid-depth of the CRCP slab after a horizontal crack developed. Transverse cracks that develop following this mechanism are quite different in many aspects from normal transverse cracks that develop due to temperature and moisture variations. It appears that this cracking process is a part of a segmentation process of concrete slab, which results in partial depth distress.

The discussions made with respect to Fig. 1 indicate that normal transverse cracks develop due to warping and curling of the concrete slab. However, it also illustrates that not all transverse cracks are the same in terms of the depth and width of the cracks, and that transverse cracks could be initiated at the mid-depth of the slab, after a horizontal crack developed, which could result in partial depth distresses. The investigation of the process involved in partial depth distresses was out of the scope of this study. In this study, field testing with FWD was conducted primarily to evaluate CRCP behavior as affected by transverse cracks that developed from normal process. Test sections did not contain any distresses, either partial depth or full depth distresses. The testing program thus developed was expected to provide both valid and valuable information regarding the effects of transverse cracks on structural behavior of CRCP.
3. FWD testing

3.1 Description of FWD testing

FWD is designed to impart a load pulse to the pavement surface, which simulates the load produced by a rolling vehicle wheel. Setup of the FWD device for testing is composed of setting the sensor spacing and the drop heights to obtain the target load levels.

In the present study, TxDOT’s Dynatest 8000 FWD device, with a 1 ft (30 cm) diameter loading plate, was used for deflection data collection. The seven velocity transducers (geophones) were spaced at every 1 ft (30.5 cm) from the center of the loading plate, and an extra geophone for LTE evaluation was placed on the other side of the loading plate, as shown in Fig. 2, denoted as G8. To measure a deflection of CRCP, three target load levels, which are 9,000 lbs (40.0 kN), 12,000 lbs (53.4 kN), and 15,000 lbs (71.2 kN), were applied at each test section.

3.2 LTE evaluation method

As discussed earlier, LTE is considered as one of the most important CRCP structural behaviors that determine pavement performance, as wheel load stresses in concrete slabs will be greatly influenced by LTE (ARA 2003a). LTE depends on crack widths and it is assumed that the crack spacing and concrete temperatures have substantial effects on crack widths. Accordingly, it follows that LTE will depend on those two variables – crack spacing and concrete temperature.

There are several different ways to evaluate LTEs in JCP. The most widely used methods in JCP are as follows (eq. 1 and eq. 2) (American Concrete Pavement Association 1998):

\[
\text{LTE} = \frac{d_u}{d_l} \times 100\% \quad - - - \text{ (eq. 1)} \quad \text{and} \quad \text{LTE}^* = \frac{2d_u}{d_l + d_u} \times 100\% \quad - - - \text{ (eq. 2)}
\]

where, \( d_l \) = the maximum deflection at the joint of the loaded slab

\( d_u \) = the corresponding deflection at the joint of the unloaded slab
These two formulations are related as both include only $d_l$ and $d_u$ as independent variables. In LTE analysis in JCP, $d_l$ and $d_u$ are measured across a transverse contraction joint. Fig. 3(a) illustrates the LTE measurements in JCP. $d_l$ is the deflection measured directly under the loading plate, while $d_u$ is the deflection at 1 ft (30.5 cm) away from the loading plate across the joint. The assumption made in these two formulations is that the maximum deflection will be at the joint, not at the loading plate.

To verify whether JCP slabs at a contraction joint behave as shown in Fig. 3(a), a field testing was conducted using FWD. An FWD trailer was placed in such a way that the center of the loading plate was at 15.5-in (394 mm) from a contraction joint, as shown in Fig. 3(b). With the FWD trailer fixed at the same location, the G8 sensor attached to the extension bar was moved, on average 1-in (25 mm) at a time, from the far end of the extension bar toward the loading plate with each drop of the loading. In this setup, the deflection readings of G8 indicate the deflection shape of the concrete slab near a joint. Fig. 3(c) shows the testing results, indicating that the deflection is the largest at the contraction joint. In Fig. 3(c), there are 11 data points, and if 11 geophone sensors had been placed at distances indicated in Fig. 3(b), the same deflection bowl would have been obtained, even though placing 11 sensors with small spacing is physically impossible. The deflection bowl obtained is quite similar to the shape shown in Fig. 3(a), which indicates the assumption made for LTE eqs. (1) and (2) for JCP is correct.

However, it is not clear whether the same system should be applied to LTE evaluations for CRCP. Transverse cracks in CRCP are quite different from transverse contraction joints in JCP as far as structural continuity is concerned. In a transverse contraction joint in JCP, one-third or one-quarter of the slab depth is saw cut, and a crack develops under the saw cut. Even though dowel bars are placed and aggregate interlock is present at transverse contraction joints, especially at high temperatures, the degree of structural continuity at contraction joints in JCP may not be comparable to that in CRCP. To estimate structural continuity at transverse cracks in CRCP, experiments were conducted in CRCP where the loading plate was placed at about 12-in (305 mm) from a transverse crack. With the loading plate fixed at that location, geophone G8 was moved from right next to the edge of the loading plate to about 19-in (483 mm) from the center of the loading plate, in the same manner as described above for JCP, also shown in Fig. 4(a). Loadings were dropped as the geophone sensor G8 was moved to a new location. Testing results from the
experiment are shown in Fig. 4(b), which illustrates quite different slab deflection behavior at a transverse crack than at a contraction joint, which is illustrated in Fig. 3(c). This deflection behavior, which is quite similar to that of a continuous slab, is believed to be due to the tight crack widths, as shown in Fig. 1(a), and the continuity of longitudinal steel. From the experiment, as long as longitudinal steel is not ruptured and cracks are maintained tight, slab deflection behavior near transverse cracks can be illustrated as shown in Fig. 4(c). Slab deflection behavior at a transverse crack as shown in Fig. 7 demonstrates that the LTE eqs. (1) or (2) with the $d_l$ and $d_u$ setup as shown in Fig. 3(a) are not applicable to CRCP, as LTEs will always be less than 100%, even when the structural continuity at a transverse crack is perfectly maintained. Instead, for the LTE evaluations at transverse cracks in CRCP, two geophone sensors should be placed at the opposite side of the loading plate at an equal distance from the loading plate, as shown in Fig. 4(c). It should be noted that LTE values in JCP are sensitive to the location of the loading plate relative to a transverse contraction joint, while those in CRCP are not as sensitive, primarily because the location of maximum deflection is always under the loading plate in CRCP, while in JCP, maximum deflection is at the joint. In the present study, LTE was calculated using eq. 1, with $d_l$ evaluated at 12-in (305mm) from the center of the loading plate in the same side of a crack, while $d_u$ evaluated at the other side of the crack.

4. Field testing plan

To evaluate slab support conditions in CRCP with various ages, slab thicknesses, and environmental conditions, a total of 27 sections were selected and detailed field evaluations including FWD testing and visual surveys conducted under TxDOT research projects (Choi et al. 2013, Medina-Chavez and Won 2006). The length of each test section was 1,000 ft (305 m), with a transverse construction joint (TCJ) at the middle of the section, and FWD testing conducted on the outside lane. A total of 12 transverse cracks – two of each small, medium, and large crack spacing at each side of the TCJ – were selected for each test section. Small crack spacing ranged from 2 to 3 ft (0.6-0.9 m), medium crack spacing from 4 to 6 ft (1.22-1.8 m), and large crack spacing from 7 to 10 ft (2.13-3.1 m). To evaluate the behavior of a transverse crack with a specific crack spacing, two slab segments with comparable spacing at both sides of a crack were selected. Fig. 5(a), (b), and (c) shows slab segments selected for the evaluation of small, medium, and large crack spacing, respectively. Fig. 5(d) shows the loading plate and sensor locations for LTE.
evaluation at a transverse crack. Field data collection consisted of measuring deflections with FWD at every 50 ft (15.2 m) from the beginning to the end of a test section (a total 21 FWD drop locations) and LTE. For LTE evaluations, FWD drops were made at the mid-slab of the upstream of a crack, at the upstream of a crack, at the downstream of a crack and at the mid-slab of the downstream of a crack. This setup was used for slab segments (two slabs on either side of a crack) with medium and large crack spacing.

FWD testing was conducted in accordance with this testing scheme twice a year, once in the summer and again in the winter. The objective of two cycles of testing a year was to identify the effects of temperature on LTE and other behavior. The summer testing was conducted from June through September and the winter testing cycle was conducted from December through February. This testing scheme provided a valuable data set for the analysis of the effects of temperature and crack spacing, as well as traffic, on LTE and overall condition of CRCP. The dataset obtained from the eight-year long experiment was analyzed and, out of 27 sections originally selected, it was determined that datasets from 20 sections contained large enough data to make the analysis results meaningful. In this paper, the analysis results from the 20 sections are presented. Table 1 shows the list of those 20 sections, and the locations are also illustrated, which shows that the sections are located in four different environmental regions – wet-freeze, wet-no freeze, dry-freeze, and dry-no freeze in Texas.

5. Test results and discussions

5.1 Effect of crack spacing on deflections

Fig. 6(a) illustrates overall average deflections obtained in all 20 sections, evaluated near cracks (upstream and downstream) at small, medium and large crack spacing in summer and winter. Accordingly, the deflections shown here include all the deflections at upstream and downstream of cracks, with slab thicknesses from 8-in (203 mm) to 15-in (381 mm). Illustrating information on a specific test section may not represent the overall trend, and all the data points were combined to minimize statistical bias. Fig. 6(a) also shows average deflections at TCJs, the averages of both upstream and downstream deflections. It is observed that, in general, (1) the differences in deflections among crack spacing are small, (2) for a given crack spacing, the differences in deflections in the summer and winter are also small, even though deflections in the winter are consistently larger than those measured
in the summer, and (3) deflections at TCJ are larger than those at transverse cracks. It is postulated that the little
effects of crack spacing on deflections are due to a high level of structural continuity at transverse cracks as shown
in Fig. 2(a). Larger deflections obtained in the winter might be explained by curling up of concrete slabs due to the
lower temperature at the concrete surface compared to the temperature at the bottom, as well as overall contraction
of concrete. At TCJs, less aggregate interlock is provided than at cracks, which might explain larger deflections at
TCJs than at cracks. In addition, built-in curling that occurs at concrete poured in the late afternoon side might
contribute to the larger deflections at TCJs. It is interesting to note that even though 50 % more steel is provided at
TCJ, the additional steel doesn’t seem to overcome the loss of aggregate interlock or possibly built-in curling. It
should be noted that the deflections in the winter for large crack spacing are smaller than those for small or medium
crack spacing, which is somewhat contradictory to the assumption made in the development of MEPDG - crack
widths are almost linearly proportional to crack spacing, and larger crack widths will reduce LTE. The information
obtained in this study does not support validity of the assumption.

Fig. 6(b) illustrates the average deflections at mid-slabs between two adjacent cracks of slab segments with small,
medium and large spacing. As discussed earlier, FWD drops were not made at mid-slab for small crack spacing, and
accordingly, deflections at cracks are identical to those at mid-slab. It is observed that, compared with deflections at
cracks, (1) deflections at mid-slabs are slightly smaller, especially for winter measurements, (2) there are smaller
temperature effects for all crack spacing, and (3) the larger the crack spacing, the smaller the deflections. Larger
deflections at cracks than at mid-slabs are more pronounced in the winter than in the summer. As a matter of fact,
the difference in deflections at cracks and mid-slab is almost negligible in the summer. Crack width observed on the
side of the CRCP as shown in Fig. 1(a) is quite tight near longitudinal steel, even in the winter. Accordingly, it is
postulated that the larger deflections at cracks than at mid-slab in the winter is by the curling effect rather than the
increase of crack widths and loss of aggregate interlock, at least in Texas weather conditions, even though a slight
increase in crack width near the slab surface in the winter might reduce crack stiffness and contribute to larger
deflections. Smaller temperature effects at mid-slabs than at cracks are explained by better continuity of slabs at
mid-slab than at cracks. Smaller deflections at mid-slab for slab segments with larger crack spacing can be explained
similarly – by the greater distance from cracks.
Fig. 6(c) presents a typical example of deflection basins obtained from FWD testing in the winter at small, medium, and large cracking spacing, including TCJ. The graph is well matched with the deformed shape illustrated in Fig. 4(c), which indicates the LTE evaluation method adopted in this study is reasonable. It is noted that deflection basins among three different crack spacings are quite similar. The finding also indicates that deflection at TCJ is larger than those at cracks.

5.2 Effect of crack spacing on LTE

As discussed earlier, LTE has been assumed as the most important structural response of CRCP that is responsible for punchout development (ARA 2003a, b, 2004). In this study, LTEs at cracks were evaluated, and Fig. 7(a) illustrates the information obtained in this study. The LTE values are the average of all the values obtained for a specific condition. LTE values of all the cracks evaluated in this study were near 100 percent, regardless of crack spacing and temperature condition. It is noted that, when a LTE value greater than 100 % was obtained, a value of 100 % was assigned. Data obtained in this study indicates negligible effects of temperature on LTE in CRCP; however, it has been demonstrated that the temperature effect is quite pronounced for LTEs at transverse contraction joints in JCP (Smiley and Hansen 2007). Also, it should be noted that the LTE values presented are averages of eight-year data, which implies that LTE values have been maintained at almost 100 % throughout eight years, and pavement age or traffic applications for those eight years had little effects on LTE. Compared with cracks, TCJs provide smaller LTEs in the winter. The reason for the lower LTE values in TCJs in the winter is due to the low LTEs of two sections out of 20 test sections as presented in Fig. 7(b). On the other hand, LTEs at the other 18 sections of 20 were measured at almost 100%. Fig. 7(c) and (d) shows the conditions of TCJs that correspond to the LTE values shown in Fig. 7(b). The condition of the two TCJs is quite similar to that of JCP as shown in Fig. 7(e). It appears that debonding occurred between longitudinal steel and surrounding concrete at TCJs, which was not able to restrain concrete volume changes effectively, and aggregate interlock was almost non-existent in the winter due to larger joint widths. With small aggregate interlock at these 2 TCJs, the LTE values obtained - 62 and 73 % - might be due to the base support and longitudinal reinforcement at TCJs. Out of 20 TCJs evaluated, LTEs at the other 18 TCJs were maintained quite high, which implies that the 2 TCJs are exceptions. Previous research discovered that
distresses at TCJs were one of the most frequently observed distresses in CRCP (Saraf et al. 2013). The primary reasons for the distresses at TCJs were inadequate concrete consolidation or poor concrete material qualities at TCJs.

There is data available on crack spacing and LTE from the LTPP database (Tayabji et al. 1999). The report notes that there is no correlation between crack spacing and LTE. It is interesting to note that LTE values were maintained quite high for pavements that were in service. The other two reports also noted that the LTEs were maintained at quite a high level, and there is no effect of concrete temperature on LTE (Kohler 2005, Roesler and Huntley 2009).

Another premise made in CRCP research is that crack widths and LTE depend on the concrete temperature. MEPDG illustrates that crack widths increase over time due to continued drying shrinkage of concrete, and vary depending on the temperature of concrete, i.e., crack widths get smaller in summer and larger in winter (ARA 2003a). However, the information collected in this study shows that LTE values of all the cracks evaluated remained constant regardless of the season of the testing and the age of the pavement.

The punchout model adopted in MEPDG assumes that increases in crack width due to continued drying shrinkage will reduce LTE, which will initiate the punchout process. In other words, transverse cracks in punchout distress should have low LTE values. To evaluate the validity of this model, a location of CRCP that was at an initial stage of punchout was identified. The location was monitored for about two years, and when the distress was at a medium stage of punchout, with spalling developing at transverse cracks, transverse cracks that surrounded the punchout were evaluated for LTE, as shown in Fig. 8. LTE was almost at 100 percent; however, deflections at cracks were quite higher than those in nearby transverse cracks, which implies that LTE is not a good indicator for structural condition of transverse cracks in CRCP. High LTEs could be achieved as long as deflections at both sides of a transverse crack are comparable, regardless of how large the deflections are. This issue could be resolved if LTE in CRCP is defined in a different way, such as the ratio of the deflections at mid-slab to a crack. However, this definition of LTE does not resolve a situation where base support is poor and deflections are relatively high at both mid-slab and crack. Maximum deflection, not LTE, might be a better indicator of structural condition of CRCP.

5.3 Evaluation of modulus of subgrade reaction
One of the assumptions made in the development of the AREA method for the back-calculation of k-values (Hall et al. 1997, Ioannides et al. 1989) is that the slabs on which deflections are measured are continuous, and deflections are evaluated at a sufficient distance from any discontinuities. In CRCP, there are numerous transverse cracks, and it is almost impossible to place geophone sensors at a sufficient distance from transverse cracks. However, the findings in Fig. 6(a) and (b), which indicates a small difference in deflections at mid-slab and at a crack, indicate the locations of FWD drops or locations of geophone sensors in relation to transverse cracks, might not have substantial effects on back-calculated k-values from the AREA method. Fig. 9(a) shows the comparison of back-calculated k-values from deflections measured at every 50 ft (15.2 m) and deflections measured at the middle of large crack spacing. It is noted that large crack spacing in this study is in the range of 8 to 10 ft (2.4 to 3.0 m), and deflection measurements at mid-slab leave the 4th geophone sensor at least 1 ft (0.3 m) from a transverse crack, which might be considered satisfactory to one of the assumptions made in the back-calculation method. As shown in Fig. 9, the differences in k-values from the two deflection measurement schemes are not large, especially from a practical standpoint. Fig. 9(b) illustrates the back-calculated k-values obtained from deflections measured at small crack spacing and at the middle of large crack spacing. It is shown that, except for few data points, in general, there is a good correlation between the two data sets. The analysis results indicate that the back-calculated k-values are somewhat insensitive to the locations of FWD drops with respect to transverse cracks. It might be, as discussed earlier, due to small differences in deflections evaluated at near transverse cracks and midway between two adjacent transverse cracks.

Fig. 10(a) shows k-values obtained with the AREA method for CRCP sections with different ages. Information from special sections evaluated in the database project was included. The figure indicates an overall decrease in k-values as CRCP becomes old. Information on the initial k-values after CRCP construction of these sections is not available, and therefore, the k-values presented are in-situ values at the time of FWD testing. Even though the interpretation of the data may require caution, most of the base types in these projects are of the two types currently used in TxDOT – either 4-in (102 mm) hot mix asphalt, or 1-in (25 mm) hot mix asphalt on 6-in (152 mm) cement stabilized base, and it appears that the modulus of subgrade reaction deteriorates with time. This finding is supported by deteriorated base materials observed during CRCP repairs, as shown in Fig. 10(b). As discussed earlier, most of
the full-depth distresses in CRCP in Texas are due to deficiencies in the slab support, and more research effort needs to be made in the design and construction of the durability aspect of base layers.

6. Conclusions

The objective of this study was to develop reasonable structural evaluation procedures of continuously reinforced concrete pavement (CRCP) using Falling Weight Deflectometer (FWD). Punchout is a major structural distress in CRCP, and the punchout mechanism adopted in the mechanistic-empirical pavement design guide (MEPDG) is based on the assumption that load transfer efficiency (LTE) deterioration at transverse cracks over time is primarily responsible for punchout development. A total of 27 test sections with varying slab thicknesses and pavement age, and in different environmental regions, were selected throughout Texas and FWD testing was conducted twice a year, once in the summer and again in the winter. The test sections were from 9 years to 43 years old when the testing program terminated. Each section is 1,000-ft long, and in each section, 12 cracks were selected, four each of small, medium and large crack spacing, and FWD testing conducted at upstream and downstream of cracks and at mid-slab between two adjacent cracks. This testing scheme allowed evaluations of effects of certain variables such as crack spacing and concrete temperature on LTE and other structural responses, as well as the condition of slab support. Detailed analysis conducted on the data obtained from the test sections over an eight-year time period point to the following conclusions:

1) Not all transverse cracks are the same in terms of their depth of propagation and their development mechanism. Most cracks in CRCP in Texas with adequate slab support, slab thickness and longitudinal reinforcement do not propagate throughout the slab depth. Cracks can be developed from top to bottom or from bottom to the top, or initiated at the middle of the slab depth if a horizontal crack exists.

2) LTE values were maintained at a quite high level, regardless of crack spacing, temperature condition or pavement age. Also, no appreciable variations were observed in LTE over the eight-year time period.
   a. High level of LTE at all cracks evaluated indicates practically no effect of crack spacing on LTE. The assumption that a crack width is almost linearly proportional to crack spacing, and LTE decreases with larger crack spacing, may not be valid.
b. High level of LTE evaluated in the winter and in the summer suggests almost no effect of concrete temperature on LTE. The assumption of a crack width getting larger at lower temperature and resulting in reduced LTE does not appear to be valid.

c. In a transverse crack that went through the punchout process, LTE was maintained at almost 100 percent. It appears that LTE is not a good indicator for structural condition of cracks in CRCP.

3) Crack spacing had little effect on average deflections at cracks. On the other hand, temperature effect on average deflections at cracks was larger than that of crack spacing, even though it was small.

   a. Little effect of crack spacing on deflections at cracks indicates almost constant structural continuity at transverse cracks regardless of crack spacing.

   b. There was a small effect of temperature on deflections at cracks. It appears that the curling effect, not the crack width variations due to temperature changes, is responsible for that effect.

4) Deflections at mid-slab between two adjacent transverse cracks decreased with increasing crack spacing, but varied little for temperature changes.

5) Modulus of subgrade reaction (k-value) evaluated with FWD and by the AREA method decreased with pavement age. Locations of geophone sensors in relation to transverse cracks have, from a practical standpoint, little effect on backcalculated k-values.

Based on the above findings, LTE is not the best indicator of structural condition of transverse cracks in CRCP. Deficiencies in slab support are the primary cause of full-depth distresses in Texas, and backcalculated k-values, which combine both a maximum deflection and the shape of deflection bowl from FWD testing, may be a better indicator of the structural condition of CRCP. FWD testing for LTE is quite time-consuming, primarily because of placements of geophone sensors at specific locations with respect to cracks. Since the locations of geophone sensors in relation to transverse cracks or temperature have little effect on backcalculated k-values, the use of FWD for structural evaluation of CRCP in terms of backcalculated k-values can be not only more reasonable, but also more efficient, than LTE evaluations.
References


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**Table 1.** List of Level I test sections
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<table>
<thead>
<tr>
<th>Test section ID</th>
<th>District</th>
<th>Highway</th>
<th>Construction year</th>
<th>Slab thickness [in.]</th>
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Fig. 10. k-value variations with pavement age and deteriorated base materials
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(a) Half-depth transverse cracks  (b) Full-depth transverse cracks

(c) Top-down and bottom-up cracks  (d) Partial-depth distress

(e) Half-depth crack with horizontal cracking  (f) Transverse crack at the mid-depth

**Fig. 1.** Transverse cracks and their effect on CRCP
Fig. 2. Location of geophones
Fig. 3. LTE evaluation for JCP
(a) FWD testing for deflection bowl evaluation in CRCP

(b) Deflection shape of CRCP slab near a transverse crack

(c) LTE evaluation for CRCP

Fig. 4. LTE evaluation for CRCP
<table>
<thead>
<tr>
<th>a. Crack with short crack spacing</th>
<th>b. Crack with medium crack spacing</th>
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<td>c. Crack with large crack spacing</td>
<td>d. LTE evaluation at downstream</td>
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**Fig. 5.** FWD test for small, medium, and large crack spacing
(a) Average deflection at cracks [standard error of 5 percent]

(b) Mid-slab deflections at cracks (Level-I test sections) [standard error of 5 percent]

(c) Deflection basin [1 mil = 0.0254 mm]

Fig. 6. Average deflections at cracks and mid-slab
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Fig. 8. Punchout evaluation on IH 45
Fig. 9. Back-calculated k-value comparisons [1 psi/in = 0.271 kPa/mm]
(a) k-value variations with pavement age [1 psi/in = 0.271 kPa/mm]

(b) Deteriorated base materials at full-depth distress location

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