Practical Method for Ensuring the Success of Crack and Seat Operations Using the Falling Weight Deflectometer

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Cracking and seating (C&S) of rigid pavements before laying asphalt overlays has been extensively used in recent years to control reflective cracks. By inducing small hairline cracks in the portland cement concrete slabs, the potential for reflective cracks is decreased. The performance of the overlayed section highly depends on the cracking pattern developed in the C&S operation. Deflection testing has been used successfully in C&S operations to evaluate the developed cracking pattern. A mechanistic procedure for calibrating the hammer and the roller in C&S operations using falling weight deflectometer (FWD) measurements is presented. This procedure has two phases: (a) determine the hammer parameters (height and spacing) that develop good cracking patterns, full depth cracks with adequate aggregate interlock between the cracked segments and (b) determine the optimum number of passes of a rubber-tired roller. A three-dimensional, dynamic finite element method (3D–DFEM) was used in the analysis to study the effect of crack width and condition on surface deflections. A dynamic loading cycle was used to simulate the FWD loading cycle. Four crack conditions were considered in the analysis: no crack, minor surface cracks, hairline cracks, and wide cracks. A field validation study was conducted to validate the new approach. Four test sections were included in this study. The results of this study are found to be successful. A user-friendly computer program was developed to implement this method. The program can be loaded on the FWD computer. It reads the FWD raw data file and evaluates the cracking pattern. When the desired cracking pattern is achieved, the program searches for the optimum number of passes of the roller.

Cracking and seating (C&S) of rigid pavements before asphalt overlays has been extensively used in recent years to control reflective cracking in the overlays. This method involves cracking the existing portland cement concrete (PCC) slabs into small segments to reduce the relative movement of the slabs. By inducing small hairline cracks in the PCC slabs, the potential for reflective cracking is decreased.

The Federal Highway Administration (FHWA) *Pavement Rehabilitation Manual* (*1*) indicates:

> *The intent of pavement cracking and seating is to create concrete pieces that are small enough to reduce horizontal slab movements to a point where thermal stresses which contribute to reflective cracking will be greatly reduced, yet still be large enough and still have some aggregate interlock between pieces so the majority of the original structural strength of PCC pavement is retained. Seating of the broken slabs after cracking is intended to reestablish support between the subbase and the slab where voids may have existed.*

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Cracking a PCC pavement is the most important step of the rehabilitation technique. In Indiana, it has been found that C&S jobs that have performed well so far are those that have good cracking patterns. Techniques commonly used to evaluate slab cracking include (*2*): visual examination of dry and wet slabs, coring, picking up slabs for visual examination, and deflection testing. Visual inspection sometimes is misleading and does not guarantee that cracks are fully developed through the slab thickness. Coring and picking up slabs for visual examination are impractical and take a long time. Deflection testing has been used successfully in C&S operations and is recommended by many highway agencies. In Indiana, the Dynaflect is currently used for this purpose. Empirical criteria are involved in the evaluation process. During the last few years, the Indiana Department of Transportation (INDOT) has experienced some equipment-related problems with the Dynaflect. A decision was made to retire the Dynaflect and use the falling weight deflectometer (FWD) in C&S operations. The procedure used with the Dynaflect is not necessarily valid for the FWD.

This paper presents a mechanistic procedure for calibrating the hammer and the roller in C&S operations using FWD measurements. This procedure has two phases:

- Determine the hammer parameters, height, and spacing that develop good cracking patterns, full depth hairline cracks with adequate aggregate interlock between the cracked segments and
- Determine the optimum number of passes of a rubber-tired roller.

FACTORS THAT AFFECT THE CRACKING PATTERN

The cracking pattern must produce hairline cracks that break the PCC slabs into segments without loosening the aggregate interlock between these segments. The pavement strength is reduced by cracking, but the cracked slabs still function as a load-carrying layer. Excessive cracking can be detrimental to the pavement structure and turn the slabs into rubble, which is not desired. Figure 1 shows different cracking patterns. Factors that influence the cracking pattern include

- Type and size of hammer;
- Impact force of hammer, drop height, and spacing between drops;
- Thickness and strength of the existing PCC slabs; and
- Condition of the subgrade.

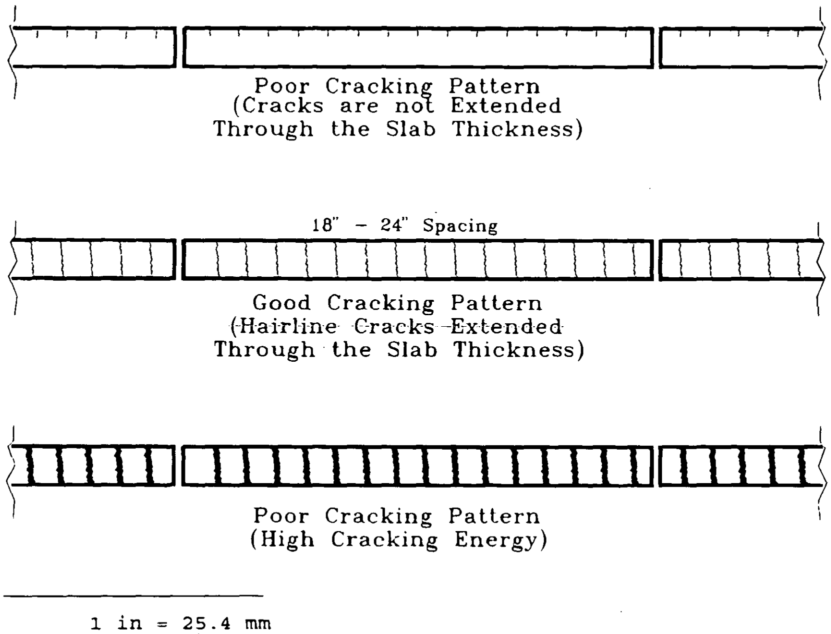


FIGURE 1 Different cracking patterns.

Types of hammer commonly used in C&S operations include the pile-driving hammer, the whip hammer, and the guillotine hammer (*3*). In a previous study conducted in Indian (*4*), the guillotine and whip hammers were compared. The results of this study showed that the guillotine hammer is superior to the whip hammer in terms of subsequent performance. Based on the results of this study, INDOT allows only guillotine hammers to be used in C&S operations. The current INDOT specifications require that PCC pavements be cracked into strips that are 45.72 to 60.69 cm (18 to 24 in.) wide, as shown in Figure 1. Cracking a pavement into smaller pieces (<45.72 cm) is not recommended because it may result in spalling and loss of structural strength. Only transverse cracks are allowed and should extend to the full depth and width of the PCC slabs.

Because of the variables listed above, at least one 120-ft test section is cracked to determine the impact force, height, and spacing of the hammer that will produce a good cracking pattern. The hammer parameters determined from one section may not be suitable for another section. For example, the pavement condition of one traffic direction could be different from that of the other traffic direction. Therefore, it is recommended that the hammer parameters (height and spacing) are determined independently for each direction.

INDOT CURRENT PROCEDURE

Currently, INDOT uses the Dynaflect and empirical criteria to evaluate cracking patterns and to determine the optimum number of passes of a rubber-tired roller to ensure adequate seating of the cracked slabs. In this method, three single-slab test sections are tested before cracking with the Dynaflect. After the hammer has cracked the first section, a second round of deflection testing is conducted. In this second round of deflection tests, the Dynaflect sensors are positioned so that a crack is located between Sensors 1 and 2. The cracking pattern is considered good if the differences in the deflections of Sensors 1 and 2 is greater than 11.

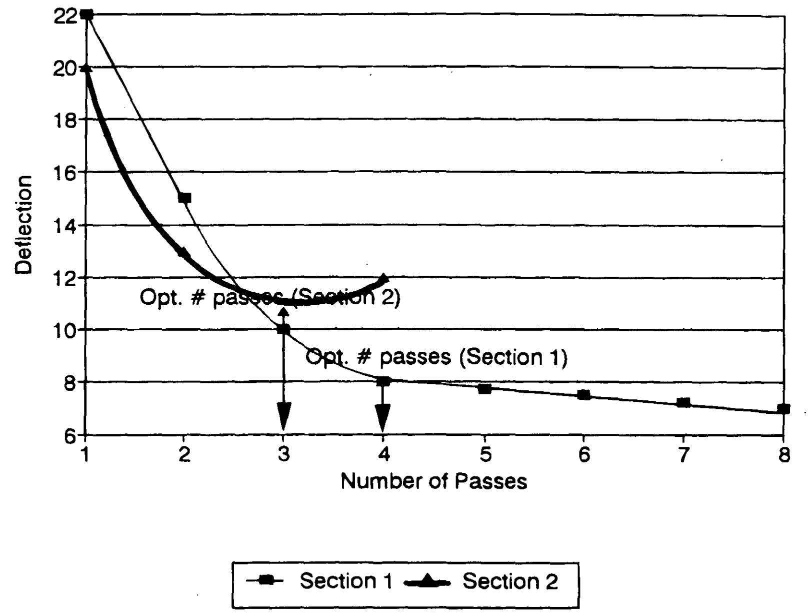
For the seating operation, the pavement deflection is measured after the first, third, and fifth passes of the rubber-tired roller. Readings of Sensor 5 (W_5) are plotted versus the number of passes. The number of passes after which the curve of W_5 and the number of passes starts to level off or increase is taken as the optimum number of passes, as shown in Figure 2.

THREE-DIMENSIONAL DYNAMIC FINITE ELEMENT ANALYSIS

A three-dimensional, dynamic finite element method (3D–DFEM), ABAQUS (*5*), was used to simulate the FWD testing during crack and seat operations and to develop a criterion to evaluate the cracking pattern in the field.

Features of the Finite Element Model

A jointed reinforced concrete pavement (JRCP) cross section similar to the typical cross section of an Indiana highway was modeled in this analysis as two 365.76 cm (2-ft) lanes plus 243.84 cm (8-ft) shoulders on either side. The pavement structure consists of three layers: concrete slab, granular subbase, and subgrade. Asphalt shoulders were used in the analysis to be consistent with the typical cross section of an Indiana highway. A three-dimensional finite element mesh (3D–FEM) with variable size openings was created to model the pavement structure. Variable size openings were used to reduce the computer memory requirements and computational time. A smaller mesh spacing was used to provide detailed response predictions where needed.



1 in = 25.4 mm

FIGURE 2 Effect of the number of passes on surface deflection (Dynaflect).

The pavement structure was modeled as a set of layers. Figure 3 shows one of the 3D-FEM meshes used in the analysis. In this example, the subgrade thickness was represented by three elements, the concrete slab was represented by two elements, and the granular subbase thickness was represented by one element. Longitudinal and transverse joints were modeled using gap elements with an initial opening of 9.53 mm (3/8 in.). Depending on the deformed shape of the slabs after loading, the slabs might come in contact and develop friction. Two types of pavements were considered in the analysis: a plain concrete pavement without dowel bars and a reinforced concrete pavement with dowel bars. Dowel bars and temperature steel were modeled and located at the mid-depth of the slab. The bond stress of one-half of the dowel bar was set to zero. Details of the finite element features used in this analysis are reported by Zaghloul and White (*6*).

Three conditions were considered for cracks (as shown in Figure 1): minor surface cracks extended only few inches in the PCC slabs; hairline cracks extended through the full depth of the concrete slab, with full friction along the crack sides; and wide cracks with openings not less than 2.54 mm (0.1 in.), with no initial friction but

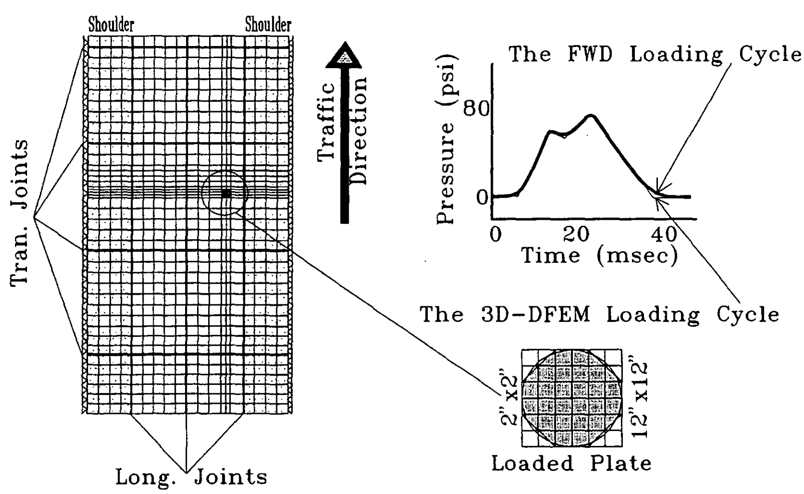


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FIGURE 3 The 3D-DFEM configuration.

with possible contact between the crack sides, depending on the deformed shapes.

Pavement materials included in the analysis were divided into four groups: PCC, asphalt concrete, granular materials, and cohesive soils. Elastic-plastic material models were used to model the portland cement concrete, the cohesive soils, and the granular subbase, and a visco-elastic model was used to model the asphalt mixtures of the shoulder. Details of these material models were reported by Zaghloul (*7*).

Loading Cycle

Figure 3 shows an actual FWD loading cycle. This loading cycle was modeled using the straight line segments shown in the same figure. The loading cycle was applied as a distributed load on an approximation of a circle, as shown in Figure 3. A set of 3D, 6-node triangle elements was used to approximate the loaded area.

Finite Element Model Verification

Several verification studies were conducted to verify the 3D–DFEM nonlinear, dynamic analysis capabilities. Some of these verification studies are mentioned below. Details of these studies were reported by Zaghloul and White (*6,8,9*).

The dynamic response was verified by comparing field-measured pavement deflections from loads moving at different speeds and the 3D-DFEM predictions for similar conditions (pavement structure, load magnitude and configuration, and speed). The predictions were in good agreement with measurements (R^2 = 0.998). Figure 4 shows the result of this comparison (*6*).

In another study, the dynamic analysis capabilities of the 3D–DFEM were verified using a FWD data set. Excellent results were obtained from this study. The predicted peak deflections were found to match the measured ones. Also, the deflection history curves (deflection with time) at different offset distances were found to be in good agreement with the measured ones. The absolute sum of errors between the measured and predicted deflections was 6 percent. Figure 5 shows the measured and predicted deflection basins (*9*).

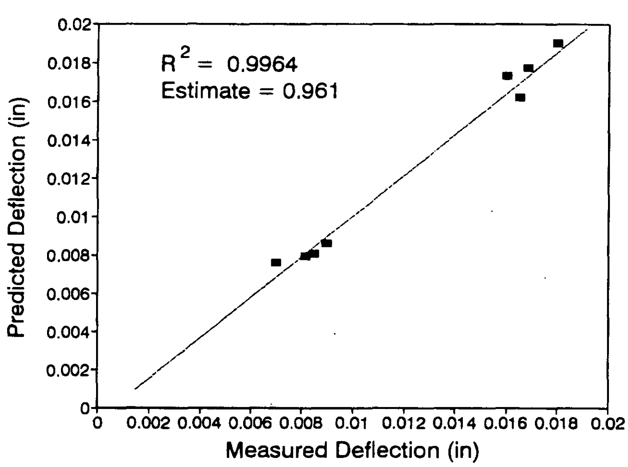

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FIGURE 4 Dynamic analysis verification (moving loads).

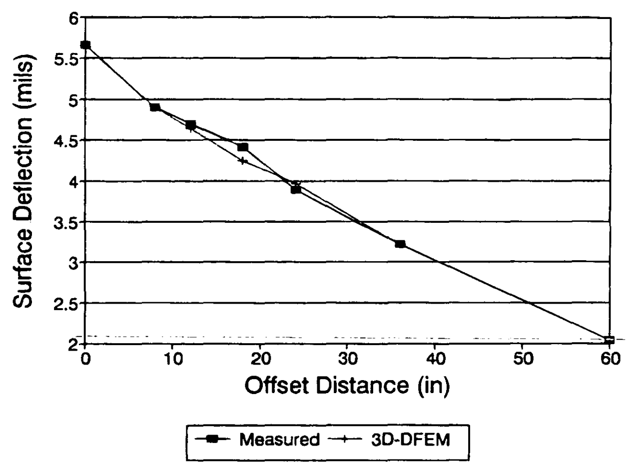

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FIGURE 5 Dynamic analysis verification (FWD).

EVALUATION OF THE CRACKING PATTERN USING THE FWD

The effect of cracks/joints on surface deflections as measured using the FWD is shown in Figures 6 and 7. Two sensor configurations were used in the analysis, as shown in Figures 6 and 7. In both configurations, the deflection of two adjacent slabs were measured to evaluate the load transfer efficiency across the crack/joint. For Configuration 1, the ratio of D_2 to D_1 is a good indication of the load transfer efficiency, while for Configuration 2, the ratio of D_3 to D_2 can be used instead. It was found that Configuration 1 is more practical, and it has been used in the subsequent analysis.

Deflection basins of mid-slab and joint loadings are presented in Figure 6. Because of the PCC slab rigidity, the mid-slab deflection basin is almost a straight line. The shape of the mid-slab deflection basin suggests that:

$$DR = \frac{(D_1 - D_7)}{(D_2 - D_7)} = \frac{X_7}{(X_7 - X_2)}$$

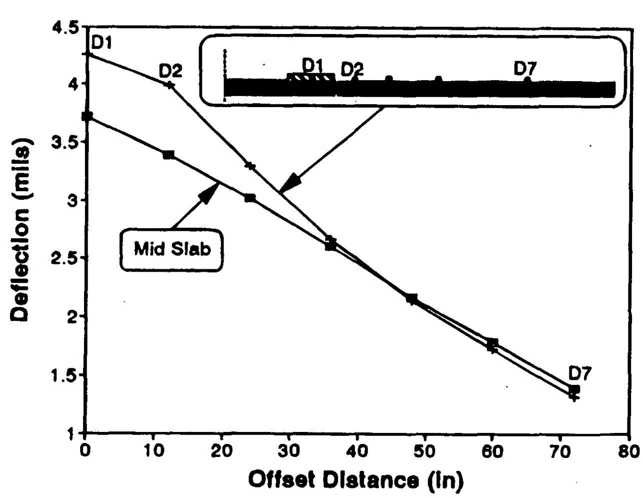

FIGURE 6 Effect of cracks/joints on surface deflection (Configuration 1).

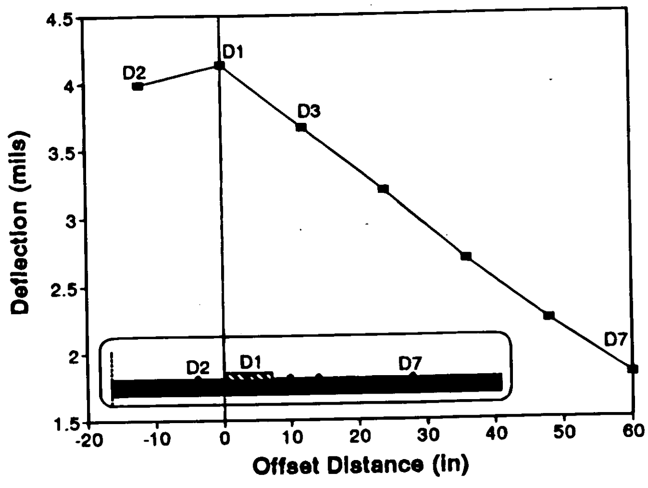

FIGURE 7 Effect of cracks/joints on surface deflection (Configuration 2).

where

DR = deflection ratio,
D_i = deflection of the ith sensor, and
X_i = distance between the center of the load plate and the ith sensor.

The above equation can be rearranged as follows:

$$CDR = \frac{(D_1 - D_7)}{(D_2 - D_7)} \times \frac{(X_7 - X_2)}{X_7}$$

where CDR = corrected deflection ratio.

The CDR value of a sound, uncracked pavement is expected to approach 1.0, while the corresponding value for a cracked pavement is expected to be significantly different from 1.0. Figure 8 shows four deflection basins as measured with the FWD. Two of these deflection basins are for crack-free slabs and the other two are for slabs with cracks located somewhere between Sensors 1 and 2 of the FWD. The CDR values for the crack-free slabs are 0.96 and 0.97. The corresponding values for the cracked slabs are 0.78 and 0.83. In the same figure, the theoretical ideal deflection basins, straight lines connecting D_1 and D_7, are shown. As can be seen from this figure, the actual deflection basins of the crack-free slabs are very close to the theoretical ideal deflection basins, while the actual deflection basins of the cracked slabs are significantly different from the theoretical ideal ones. This significant difference was reflected on the CDR values.

A sensitivity study was conducted using the 3D–DFEM to evaluate the effect of crack width and condition on the CDR value. In this study, the FWD configuration shown in Figure 6 was used. Four crack conditions were considered in the analysis:

- Cracks with zero opening (no cracks),
- Minor surface cracks at the top 5.08 cm (2 in.) of the PCC slabs,
- Full-depth hairline cracks with openings less than 1.25 mm (0.05 in.) and with full friction between the crack sides, and
- Wide cracks with openings greater than 1.25 mm (0.05 in.) and with no friction along the crack sides.

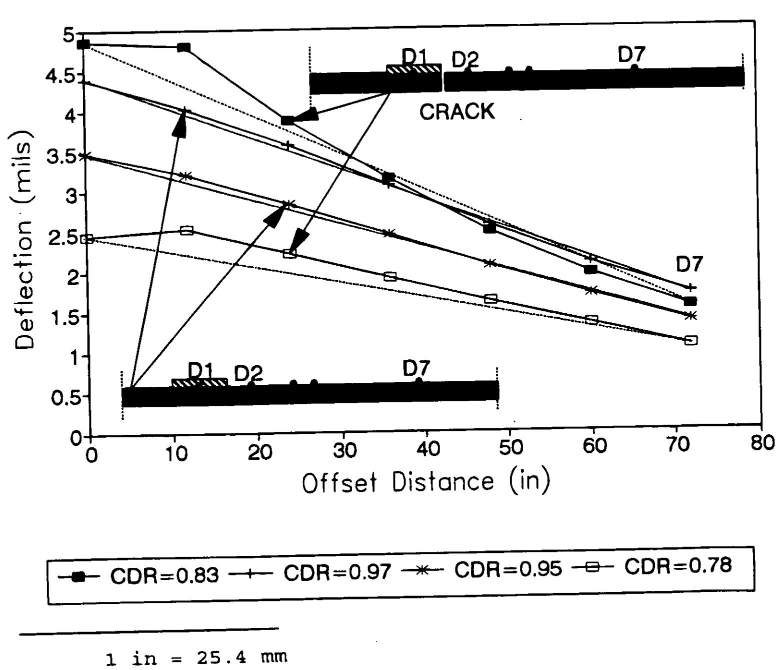

FIGURE 8 Effect of crack conditions on surface deflection.

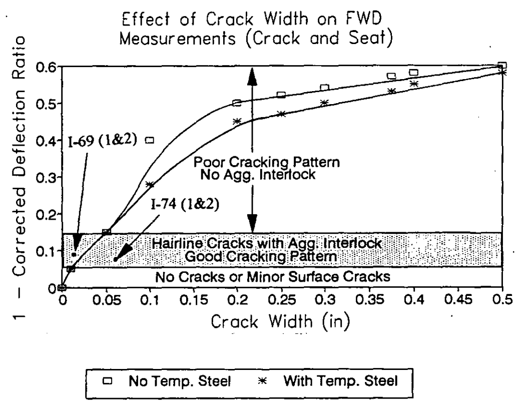

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FIGURE 9 Effect of crack width on FWD measurements.

The effect of the crack condition on CDR as predicted using the 3D–DFEM is shown in Figure 9. It was found that as the crack width increases, the CDR value significantly differs from 1.0, as expected. The effect of temperature steel was found to be significant only for wide cracks, as can be seen from Figure 9.

A field validation study was conducted on the CDR ranges predicted from the 3D–DFEM sensitivity analysis. In this study, a pavement section located on I–74 in Indiana was tested with the FWD. Two cases were considered in the analysis: crack-free midslab deflections and joint deflections, with the joint located between Sensors 1 and 2. For the former case, the CDR values ranged from 0.96 to 1.003; for the latter case, the CDR values ranged from 1.2 to 1.3. These numbers agree with the results of the sensitivity study.

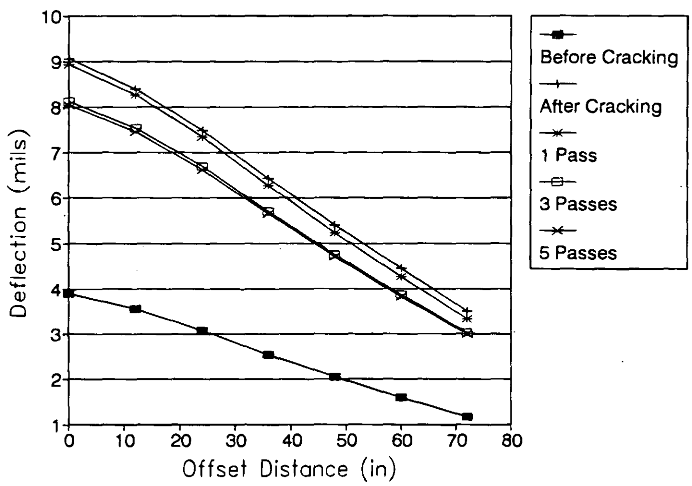
IMPLEMENTATION OF THE CDR METHOD

A pilot implementation study was conducted to test the CDR method. Four test sections were included in this study. Two of these sections are located on I–69 and the other two are located on I–74 in Indiana. The four pavement sections were tested with the Dynaflect and the FWD. The current INDOT C&S evaluation procedure was used, as well as the CDR method. The after-cracking CDR were calculated and are presented in Figure 9. It was found that the CDR values were in the range of hairline cracks. These results agree with the results obtained from the current INDOT C&S evaluation procedure.

OPTIMUM NUMBER OF ROLLER PASSES

After a PCC pavement is cracked as specified, the concrete is seated or embedded into the subbase with a heavy pneumatic roller. The purposes of the seating operation are to ensure that the cracked slabs will not rock or move under traffic loads and to establish support between the cracked slabs and the subbase. A 30- to 50-ton, rubber-tired roller is commonly used for this purpose. In general, three to five coverage of a heavy roller are adequate to seat the cracked slabs. A large number of passes are not recommended because over-rolling the cracked pavement may distort the interlock between the individual segments.

The optimum number of roller passes is the minimum number of passes after which no significant reduction in the deflection could be achieved by increasing the number of passes. To determine the optimum number of passes, the deflection is measured at different stages: before cracking; after cracking; and after one, three, and five passes. Figure 10 shows the deflection basins of one of the four test sections included in the implementation study. As can be seen from this figure, the reduction in the deflection when the number of passes increased from three to five is negligible. Therefore, the opti-



1 in = 25.4 mm

FIGURE 10 Effect of the number of passes on surface deflection (FWD).

mum number of passes for this example is 3. Also, there is a significant difference between the before- and after-cracking deflections. It was found from previous C&S jobs that the deflection of a PCC pavement increases by at least 50 percent when a good cracking pattern is achieved. Therefore, the difference between the before- and after-cracking deflections is used as a second check that slabs are adequately cracked.

RECOMMENDATIONS

The optimum values of the hammer and roller parameters in C&S operations can be determined using the FWD. The following steps are recommended in crack and seat operations:

1. Before cracking, three 120-ft test sections are marked and tested using the FWD to determine the pre-cracking deflection.
2. The hammer height and spacing are adjusted to initial values. These initial values are assumed based on similar crack and seat jobs.
3. After the first test section is cracked, using the initial setup of the hammer, a light spray of water or flour should be applied to highlight the cracking pattern.
4. A second round of deflection testing is conducted in which cracks are located between two deflection sensors, as shown in Figure 6. The purpose of these deflection tests is to ensure that full-depth hairline cracks are developed in the slabs, as well as to ensure that there is still good aggregate interlock among the slab segments. The results of this deflection test are evaluated based on the average CDR.
5. If the deflection tests show that the desired cracking pattern has not been achieved, the hammer height and spacing are changed and another test section is cracked. The new hammer height and spacing are selected based on the results of the previous test section. The above steps are repeated until the desired cracking pattern is achieved. The after-cracking deflection should be at least 50 percent higher than the corresponding before-cracking deflection. If this condition is not satisfied, the cracking operation has to be repeated.
6. After achieving the desired cracking pattern, the seating is started. The rubber-tired roller rolls the pavement five times. Deflection tests are conducted after one, three, and five passes of the roller. A plot of the pavement deflection versus the number of passes is developed to determine the optimum number of passes.

A user-friendly computer program is developed to implement this method. The program reads the FWD data file and calculates the CDR values. If the CDR values are in the range of hairline cracks, the program compares the before- and after-cracking deflection basins. If the after-cracking deflections are at least 50 percent higher than the corresponding before-cracking deflections, the cracking operation is considered successful. The deflection basins after one, three, and five passes are compared, and the program searches for the optimum number of passes using the approach outlined earlier.

SUMMARY

A procedure is developed to use the FWD measurements to calibrate the hammer and roller during C&S operations. 3D–DFEM was used in the analysis to study the effect of crack width and condition on surface deflections. The 3D–DFEM predictions were verified in previous studies with field measurements. In this analysis, a dynamic loading cycle was used to simulate the FWD loading cycle. Four crack conditions were considered in the analysis: no crack, minor surface cracks, hairline cracks, and wide cracks. Also, a method to select the optimum number of passes of a rubber-tired roller is presented. A field validation study was conducted to validate the new approach. Four test sections were included in this study. The results of this study are found to be successful. A user-friendly computer program was developed to implement this method. The program can be loaded on the FWD computer. The program reads the FWD raw data file and evaluates the cracking pattern. When the desired cracking pattern is achieved, the program searches for the optimum number of passes of the roller.

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