Evaluation of PCC Joint Stiffnesses Using LTPP Data

Lev Khazanovich[1], Member ISCP, and Alex Gotlif[2]

Abstract

Shear stiffness of joints and cracks profoundly affects the performance of concrete pavements. This paper presents a systematic analysis of stiffnesses of joints in jointed concrete pavements (JCP) and cracks of continuously reinforced pavements (CRCP) using deflection data collected under the Long Term Pavement Performance (LTPP) program. To estimate joint behavior, representative load transfer efficiency (LTE) indexes were calculated for all LTPP sections and a trend analysis was performed to evaluate the effect of Falling Weight Deflectometer (FWD) load level on LTE. It was found that the majority of the joints did not show significant load-level dependency. This justifies use of a simple Tabatabae-Barenberg (TB) model for routine pavement analysis. The paper also discusses a backcalculation procedure for determination of TB model parameters. Joint stiffnesses were backcalculated from LTEs, coefficients of subgrade reactions, and radii of relative stiffness. As expected, it was found that cracks in CRCP usually have higher stiffnesses than joints of JCP, while non-doweled joints usually have much lower stiffness than doweled joints. It was also found that joint stiffness could vary significantly during the day.

Introduction

Shear stiffness of joints and cracks profoundly affects the performance of concrete pavements. Low joint stiffness results in low joint load transfer efficiency (LTE), may lead to longitudinal cracking and excessive faulting of plain and reinforced jointed concrete pavements (JCP), and could also accelerate punchout development in continuously reinforced concrete pavements (CRCP). These distresses could lead to roughness and poor ride quality. On the other hand, joints and tightly closed transverse cracks with high shear stiffness do not typically cause any pavement serviceability problems.

Mechanistic modeling of the load transfer mechanism is a complex problem.

[1] Associate Professor, Department of Civil Engineering, University of Minnesota Minneapolis, MN 55455; email: khaza001@umn.edu
[2] Research Engineer, Applied Research Associates, Inc., 505 W. University Avenue. Champaign, Illinois 61820-3915, email: agotlif@ara.com

Frieberg (1940) was one of the first researchers who attempted to tackle it. The introduction of a finite element method for analysis of JCP provided a significant boost to understanding load transfer mechanisms. Tabatabae and Barenberg used linear elastic spring and beam elements for modeling of joints and cracks of portland cement concrete (PCC) pavements in a finite element program ILLI-SLAB (Tabatabae and Barenberg, 1980).

Recently, many comprehensive finite element models have been developed (Scarpas et al, 1994; Parson et al, 1997; Shoukry and William, 1998; Davids and Mahoney, 1999; Jensen and Hansen, 2003). However, the development of a comprehensive, practical, and reliable model for rigid pavement cracks and joints is far from complete. Although the Tabatabae and Barenberg (TB) model have been intensively used for pavement analysis and was utilized in the 2002 Design Guide, there was no large scale effort to either confirm or reject this model (Darter et al. 2001). FWD deflection data collected under the Long Term Pavement Performance program (LTPP) offer a unique opportunity to investigate the applicability of the TB model for routine pavement analysis. An initial investigation of this method is presented below.

Mechanistic Modeling of Joint Shear Transfer

When a traffic load is applied near a joint in a PCC pavement, both loaded and unloaded slabs deflect, as a portion of the load applied to the loaded slab is transferred to the unloaded slab. As a result, deflections and stresses in the loaded slab may be significantly lower than if there was a free edge instead of a jointed slab. The magnitude of reduction in stresses and deflections by a joint compared to a free edge depends on the joint's LTE.

Traditionally, LTE at the joint is determined based on the ratio of the maximum deflection at the joint of the loaded slab and the deflection of the unloaded slab measured right across the joint from the maximum deflection (*8*). The following equation for the deflection LTE is used most often:

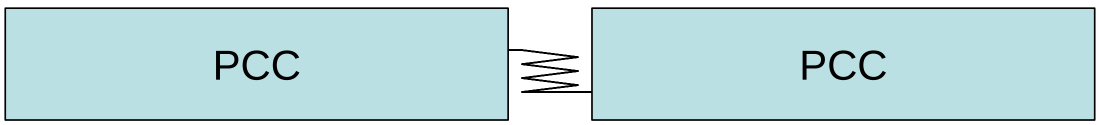
$$LTE = \frac{d_u}{d_l} * 100\% \quad (1)$$

where

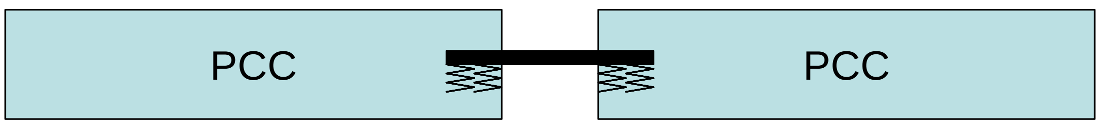
d_l is the maximum deflection at the joint of the loaded slab
d_u is the corresponding deflection at the joint of the unloaded slab
LTE is load transfer efficiency index.

If a joint exhibits a poor ability to transfer load, the deflection of the unloaded slab is much less than the deflection at the joint of the loaded slab and the LTE is close to 0%. If a joint's load transfer ability is very good, then the deflections at the both sides of the joint are virtually equal and the LTE is close to 100%.

Load transfer between the slabs can occur through shear mechanisms between aggregate particles of the fractured surface below the saw cut at a joint, through steel dowels (if they exist), and through the base and subgrade. Tabatabae and Barenberg (*1980*) proposed to address aggregate interlock between the adjacent slabs through a line spring along the joint (see figure 1a). They also proposed to treat dowels as Timoshenko beam elements supported by springs representing dowel-concrete interaction, as shown in figure 1b. As it was shown by Ioannides and Korovesis (*1990*), the bending load transfer efficiency of a dowel may be neglected in the majority of the cases and the TB model can be reduced to the concentrated spring.



Aggregate interlock model



Dowel model

Figure 1. Tabatabae-Barenberg model of PCC joints and cracks.

The main advantage of the TB models is their simplicity. The aggregate interlock model requires only one parameter, an AGG factor, which described shear stiffness of the unit length of the joint. If the bending transfer efficiency is neglected, then the TB dowel model is also reduced to one composite parameter, composite dowel shear stiffness, *D*, which can be computed from the PCC-dowel interaction factor, dowel properties, and joint opening. TB models, with minor improvements proposed by Guo et al. (*1996*), are used in many popular finite element programs for analysis of concrete pavements, including ILLI-SLAB and ISLAB2000 (Tabatabae and Barenberg, 1980; Khazanovich et al. 2000). Nevertheless, in spite of widespread use of the TB model for more than 25 years, there are no widely accepted, validated recommendations for assignment of the AGG factor or composite dowel shear stiffness *D*.

The TB models predict that, if the PCC slabs remain in full contact with the foundation, the shear force transferred by the joint is proportional to the magnitude of the applied load. As a result, the joint load transfer does not depend on the magnitude of the applied load. More sophisticated joint models predict more complex relationships between applied loading and LTE under certain conditions. Therefore, it is important to evaluate load-level dependency of LTE using field deflection data to investigate the applicability of the TB models. If LTE depends on the magnitude of the applied load, the TB models are not applicable. Moreover, the applicability of the LTE index as defined by equation 1 for characterization of joint performance becomes quite questionable. The Falling Weight Deflectometer (FWD) deflection data collected under the LTPP program can be used to evaluate the applicability of the TB model for routine pavement analysis.

LTPP LTE Deflection Data

As part of the on-going LTPP program, deflection measurements are being taken with the FWD. This deflection testing program is being conducted periodically to obtain the load-response characteristics of the pavement structures at critical points in time, depending on the experiment. In this study, the deflection data were downloaded during the summer of 2001 from the MON_DEFL_DROP_DATA table in the LTPP database. Only the LTE test data were used. For the LTE testing, the FWD load is applied at one side of the joint or crack along the mid-lane path, and the deflections are measured at both sides of the discontinuity. The LTE testing with the load plate placed at the leave side of the joint requires deflection sensors placed at 0 and 305 mm from the center of the load plate. Likewise, LTE testing with the load plate placed at the approach side of the joint requires deflection sensors placed at 0 and -305 mm from the center of the load plate. The load sequence for rigid pavement testing, as stored, is presented in table 1.

No. of Drops	Target Load, kN	Acceptable Range, kN
4	40.0	36.0 to 44.0
4	53.3	48.1 to 58.7
4	71.1	64.1 to 78.3

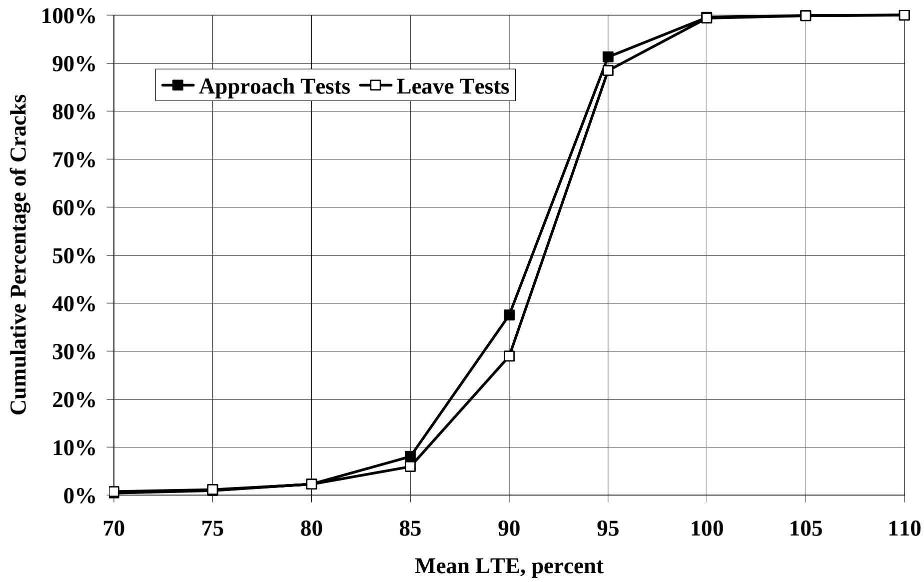
Table 1. Load sequence for FWD testing of LTPP rigid pavements

A total of 850,791 raw deflection basins were extracted from the LTPP database for 581 JCP sections and 116 CRCP sections. The extracted data were examined to ensure their consistency and reasonableness, and some data were excluded from the analysis. The data were rejected on three grounds: incorrect FWD sensor configuration, incorrect testing time or location, or insufficient number of data points for a section.

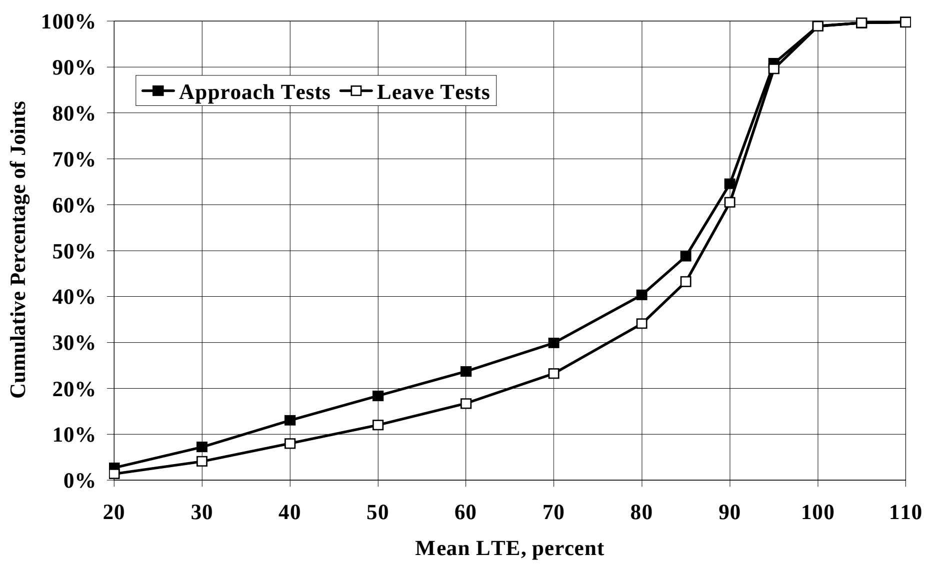
Approximately two percent of the basins (17,214 basins) were eliminated from the analysis. LTEs were calculated for the remaining 833,577 basins, but 13,181 of them were identified as questionable and excluded from calculation of representative statistical indexes for joint and section LTEs. The rationale for these rejections was inconsistency with other measurements for the same time of testing, joint, load plate location, and load level.

From the deflection basins accepted after initial screening, representative statistical summaries of LTE parameters were calculated for each deflection basin, for each joint, and for each FWD pass.

Figures 2a and 2b present cumulative frequency curves for mean LTE of joints in the LTPP JCP sections and cracks in the LTPP CRCP sections, respectively. These frequency curves are based on the results of the analysis of mean values of LTE for individual cracks and joints performed for the same FWD pass from multiple drops and FWD load levels. In the LTPP FWD load-testing program, the FWD loads were applied at both sides of the joints, so the resulting LTEs were grouped by load plate positions. Since the LTPP sections vary in age, design features, and site conditions, it is not surprising that the resulting LTEs vary from very low (less than 20 percent) to very high (close to 100 percent).



a. CRCP sections



b. JCP sections

Figure 2. Distribution of crack and joint LTE mean values for JCP and CRCP sections, respectively.

Load-Level Dependency Analysis of LTE Using LTPP Data

The most fundamental difference between very simple TB models of joints and cracks and more sophisticated joint models is that the TB models predict that the analytical load transfer efficiency as defined by equation 1 does not depend on the FWD load level. LTPP data allow for examination of this effect. This analysis is important not only for assessing validity of the TB models, but also for assessing usefulness of the load transfer efficiency index itself. If found to be load-level dependent, the LTE index would need to be replaced by a more applicable parameter that is sensitive to the load level.

In this study, the LTEs of joints/cracks of all LTPP sections were classified as load independent if the mean LTE for the lowest load level was less than 5 percent different from the mean LTE for the highest load level because the lesser difference might be attributed to measurement error. Table 2 presents the summary of this analysis. The majority of LTEs of cracks in CRCP were classified as load-level independent (more than 96 percent for both leave and approach tests). A higher percentage of LTEs of JCP joints were classified as load-level dependent (decreasing or increasing with the FWD load level): 9 percent for approach slab tests and 16 percent for leave slab tests.

Test Type	Percentage of Joint with LTE –Load-level Relationship			
	Independent	Decreasing with Load Increasing	Decreasing with Load Decreasing	Not Defined
CRCP cracks (approach)	96.8	2.0	1.0	0.2
CRCP cracks (leave)	96.4	1.9	1.5	0.2
JCP joints (approach)	90.0	5.0	4.1	0.9
JCP joints (leave)	82.9	1.2	15.2	0.8

a. Individual joints

Test Type	Independent, percentage of FWD passes	Decreased, percentage of FWD passes	Increased, percentage of FWD passes
CRCP cracks (approach)	99.7	0.0	0.3
CRCP cracks (leave)	98.9	0.3	0.8
JCP joints (approach)	97.2	1.4	1.4
JCP joints (leave)	89.6	0.2	10.2

b. LTPP sections

Table 2. LTE load-level dependence

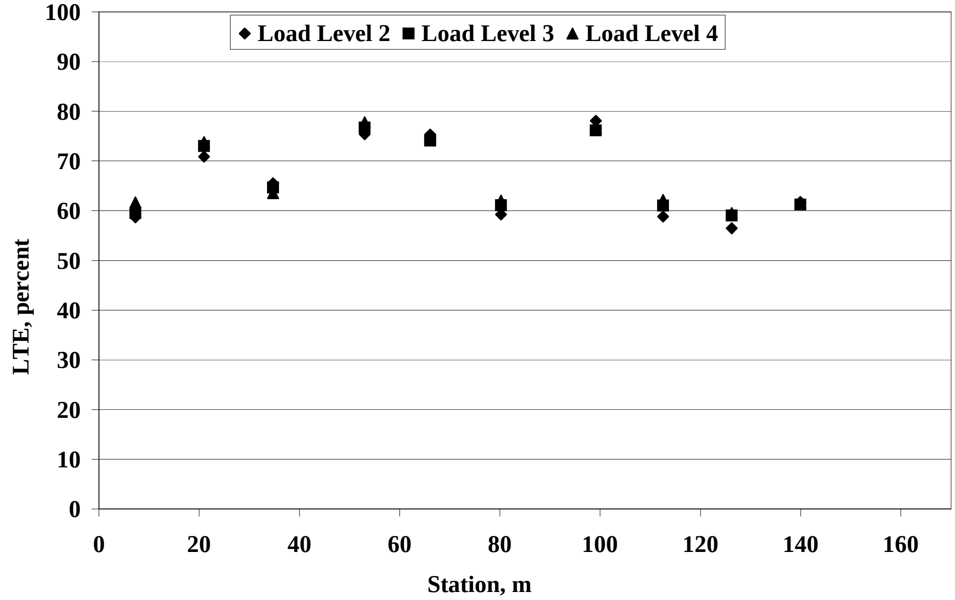
It is interesting to note that, for approach slab testing, the number of joints exhibiting an increase in LTE level with load level is almost equal to the number of joints that exhibited a decrease in LTE with increase in load level. At the same time, for the leave slab testing, almost all load-level dependent LTEs increase with load level.

Different percentages of load-level dependent joints for leave and approach tests for the same type of pavement indicate that the same joint may exhibit load-level dependent behavior for FWD tests on one side of the joint and load-level independent behavior for another side of the joint. Figure 3 gives an example of such a behavior. The joints of LTPP section 370201 in North Carolina exhibited very low load-level dependency for the approach test on November 27, 1995. During the same FWD pass, the leave test indicated that joint LTE increased with the load level.
To further evaluate this phenomenon, mean LTEs were computed for each LTPP section for individual FWD passes and load levels. Similar to what was discussed above for LTE of individual joints, load-level dependency for each FWD pass was determined. A section was identified to exhibit a load-level independent behavior for a certain FWD pass and test type (leave or approach) if a Student t-test found LTEs from the lowest and highest load level statistically different and mean values for the lowest and highest load level LTE differed by more than 5 percent.

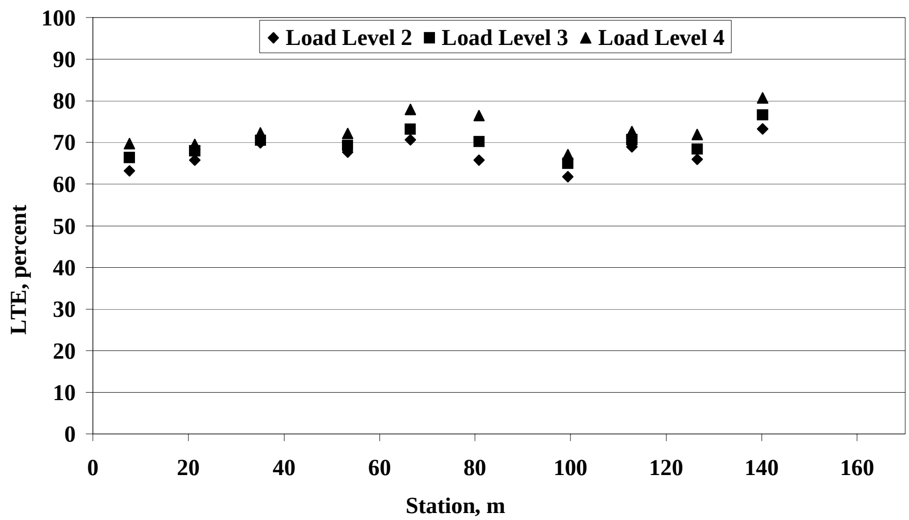
Table 2 presents a summary of load dependency indexes for all FWD passes evaluated. The vast majority of LTPP sections were classified as having a load-level independent LTE (99.7 and 98.9 percent of FWD passes of CRCP sections for approach and leave tests, respectively, and 97.2 percent of approach test FWD passes for JCP sections). At the same time, more than 10 percent of FWD passes of leave tests in JCP sections resulted in a load-level dependent LTE (mostly, LTE increasing with FWD load increasing).

To evaluate whether load-level dependency is a repeatable effect, sections with multiple FWD visits were evaluated. For each section that exhibited load-level dependent LTE behavior on at least one FWD visit, the ratio of the visits that resulted in load-level dependent behavior to the total number of FWD visits of that section was calculated. The averages of those ratios were then computed and found to be 0.36 and 0.52 for approach and leave tests, respectively. This means that if a section exhibited load-level dependent LTE for the leave test, there is only about a 50 percent chance that the next FWD visit will find the LTE for this section load-level dependent again.

On the other hand, such low repeatability can be explained by variability from visit to visit in LTE measurements themselves. LTE level may vary from one visit to another due primarily to changes in temperature conditions. FWD passes with higher mean LTE have lower overall variability than passes with lower mean LTE. Therefore, an increase in LTE level from one pass to another may make the difference in LTEs from different load levels statistically insignificant.



a. Approach test



b. Leave test

Figure 3. LTE for section 370201 on November 27, 1995.

To eliminate this effect, the analysis of load dependency variability was repeated for FWD passes with mean LTEs less than 80 percent and for FWD passes with mean LTEs less than 70 percent. The results of those analyses are summarized in table 3. If only passes with low LTEs are considered, the repeatability of load-level dependency for the leave test increases to 82 percent. Therefore, it is quite likely that load-level dependency is a repeatable effect for the leave test. However, no explanation was found as to why the same trend was not observed for approach tests.

The results of the LTE load-level dependency using LTPP data allows for the conclusion that a simple TB model adequately describes joint behavior for the majority of practical cases. Therefore, it is important to provide a procedure for rational determination of parameters for this model.

Test Type	Average Repeatability Ratio		
	All Passes	Passes with Mean LTE Lower than 80 Percent	Passes with Mean LTE Lower than 70 Percent
JCP joints (approach)	0.36	0.42	0.45
JCP joints (leave)	0.52	0.73	0.82

Table 3. Repeatability ratios for different LTE level dependency

Joint Stiffness – LTE Relationship

The TB model characterizes aggregate interlock and dowel shear load transfer through a shear stiffness by unit length of an aggregate interlock factor, AGG, and a shear stiffness of a single dowel, D (including dowel-PCC interaction). Ioannides and Korovesis (*1990, 1992*) made significant contribution toward improvement in joint stiffness characterization. They identified the following nondimensional parameters governing joint behavior:

Non-doweled joints:

$$AGG^* = \frac{AGG}{k\,\ell} \qquad (2)$$

Doweled joints:

$$D^* = \frac{D}{s\,k\,\ell} \qquad (3)$$

where

*AGG** is nondimensional stiffness of a non-doweled joint
*D** is nondimensional stiffness of a doweled joint
AGG is a shear stiffness by unit length of an aggregate interlock mechanism
D is a shear stiffness of a single dowel (including dowel-PCC interaction)

ℓ is a PCC slab radius of relative stiffness
k is a coefficient of subgrade reaction
s is dowel spacing.

Using the finite element program ILLI-SLAB, Ioannides and Korovesis also identified a unique relationship between nondimensional stiffnesses and LTE (see figure 4). The following assumptions were made in derivation of these relationships:

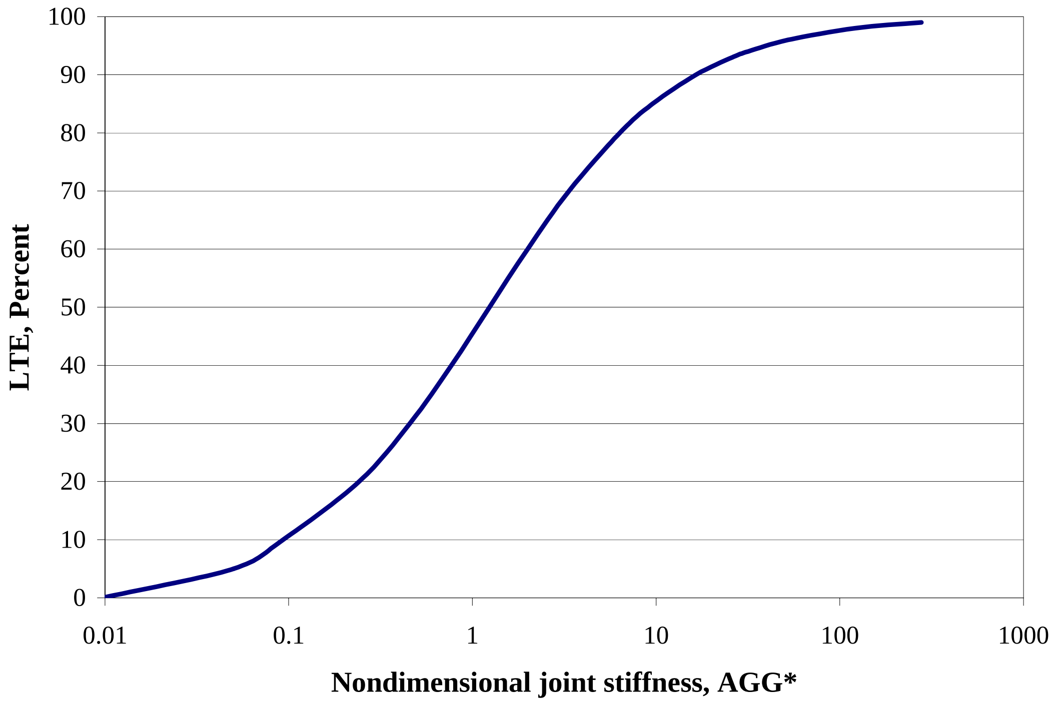


Figure 4. LTE versus nondimensional joint stiffness.

Prior to loading, PCC slabs are flat and in full contact with the foundation. A PCC joint propagates through the base layer (if present). No load transfer occurs through the base layer. The subgrade is modeled as a Winkler foundation, which assumes no load transfer through the subgrade. The PCC joint has uniform LTE across its width. The entire load transfer in non-doweled joints occurs through aggregate interlock, whereas the entire load transfer in doweled joints occurs through dowels (no aggregate interlock).

The relationships identified by Ioannides and Korovesis form a basis for backcalculation of joint aggregate interlock stiffness of non-doweled joints or dowel shear stiffness of doweled joints if their LTEs are known. In both cases, however, the backcalculated stiffness overestimates real aggregate interlock stiffness or dowel stiffness since the entire joint stiffness is attributed to a single (although prevailing) component. The reason of this limitation is the inability of the ILLI-SLAB model to distinguish between load transfer mechanisms. However, this limitation does not cause a significant problem, as the backcalculated joint stiffness provides sufficient information for accurate joint modeling in the forward analysis. Moreover, if the additional information is available, individual components can be determined more accurately.

For example, if AGG_{tot} is the backcalculated stiffness of a doweled joint and D is the known dowel stiffness, the "true" aggregate interlock factor, AGG_0, for this joint can be determined from the following relationship:

$$AGG_0 = AGG_{TOT} - D\,s \tag{4}$$

where s is dowel spacing. In this study, Ioannides and Korovesis's relationship was further investigated and an efficient backcalculation procedure for joint stiffness determination was developed.

The relationship identified by Ioannides and Korovesis was further elaborated by Crovetti (1994), Zollinger et al. (*1999*), and Ioannides et al. (*1996*). Crovetti proposed the following relationship between nondimensional joint stiffness and LTE:

$$LTE = \frac{100\%}{1 + 1.2 * \left(\dfrac{AGG_{tot}}{k\,\ell} \right)^{-0.849}} \tag{5}$$

where

AGG_{tot} is the total stiffness

ℓ is the PCC slab radius of relative stiffness

k is a coefficient of subgrade reaction (k-value).

Zollinger's model for this relationship has the following form:

$$LTE = \frac{100\%}{1 + 10^{\left[\frac{0.214 - 0.183\frac{a}{\ell} - \log\left(\frac{AGG_{tot}}{k\,\ell}\right)}{1.18} \right]}} \tag{6}$$

where a is the equivalent radius of the applied load.

The neural network model developed by Ioannides at al. (*1996*) cannot be expressed as a simple equation, but rather takes the form of a computer program. Although this model is more accurate than the regression models, it is less convenient for joint stiffness backcalculation and was not evaluated in this study.

To evaluate the Crovetti and Zollinger models, a factorial of 375 runs was performed to simulate FWD testing at the PCC joint. Figure 5 presents comparisons of the LTEs calculated from the ISLAB2000 results and LTEs from Crovetti's and Zollinger's equations. Although Crovetti's equation is simpler than Zollinger's, it better corresponds with ISLAB2000 analytical LTEs. In this study, the Crovetti model was selected as a basis for backcalculation of joint stiffnesses.

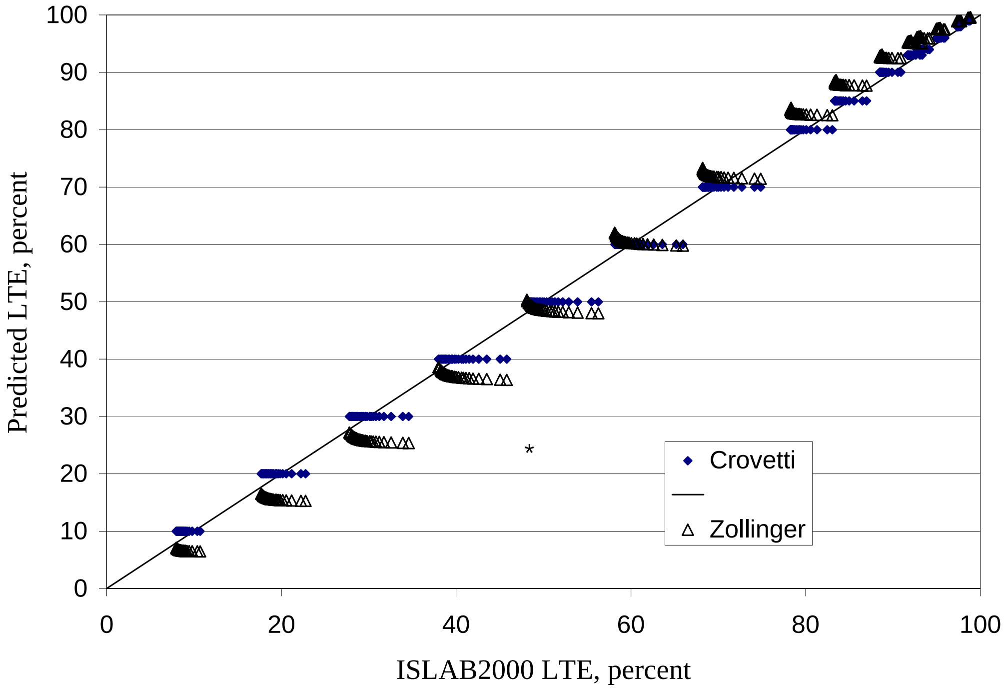


Figure 5. Comparison of LTE calculated from ISLAB2000 results with predictions using Crovetti's and Zollinger's models.

Joint Stiffness Backcalculation and Analysis

Joint Stiffness Backcalculation. Crovetti's equation can be used for backcalculation of the joint stiffness if the following information is available:

- Joint/crack LTE
- Coefficient of subgrade reaction, k
- PCC slab radius of relative stiffness.

An inversion of equation (5) leads to the following equation:

$$AGG = k\,\ell \left(\frac{\frac{1}{LTE} - 0.01}{0.012} \right)^{-1.17786} \tag{7}$$

It should be noted that Crovetti's equation is a regression model, and therefore its inversion does not necessarily produce a reliable relationship. To verify the obtained equation, an analysis of the ISLAB2000 deflection data presented in figure 6 demonstrates that these equations adequately predict nondimensional joint stiffness for a wide range of values. Therefore, the resulting joint stiffness can be used for a forward analysis using a popular finite element program for rigid pavement analysis such as ISLAB2000, ILLI-SLAB, or J-SLAB.

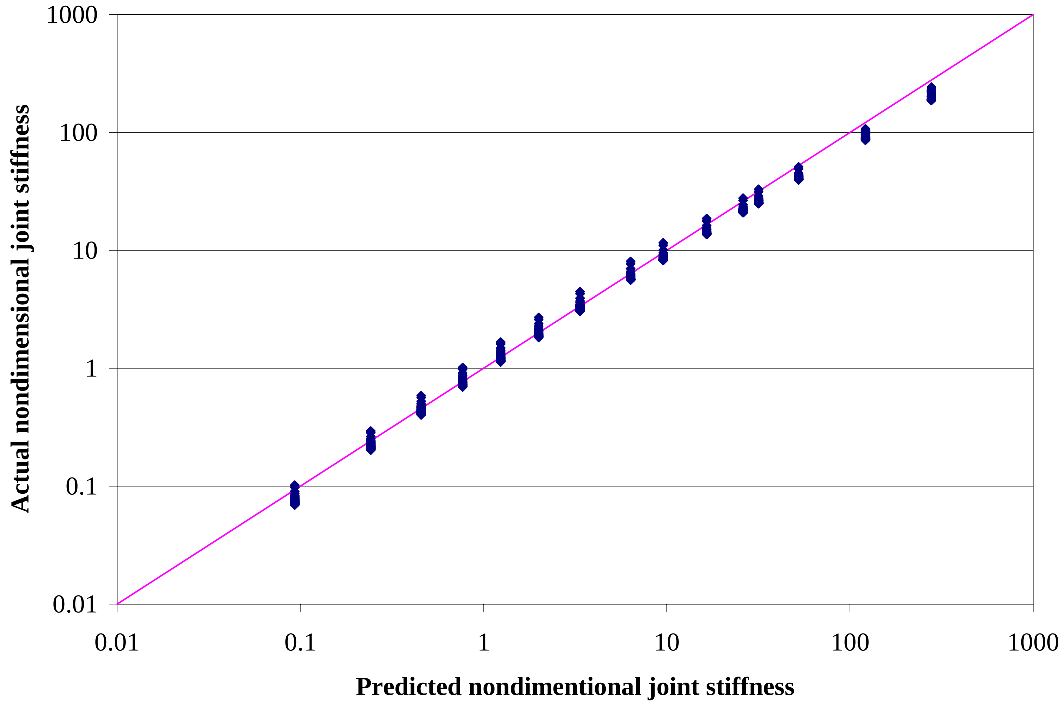


Figure 6. Predicted versus actual ISLAB2000 nondimensional joint stiffness.

Assessment of Joint/Crack Stiffnesses for LTPP PCC Sections. In this study, calculated LTEs for cracks and joints were used to backcalculate joint stiffnesses for those LTPP sections and FWD visits for which the backcalculated k-values and radii of relative stiffness were backcalculated in a separate study (Khazanovich et al. 2001). This resulted in representative crack stiffness for 134 visits of 72 CRCP sections and 910 visits of 250 JCP sections.

Figure 7 shows a frequency distribution of crack stiffness for CRCP sections. For more than two-thirds of the cases, the backcalculated CRCP crack stiffnesses ranged between 800 and 1600 MPa. The mean crack stiffness value for all cases was 1240 MPa.

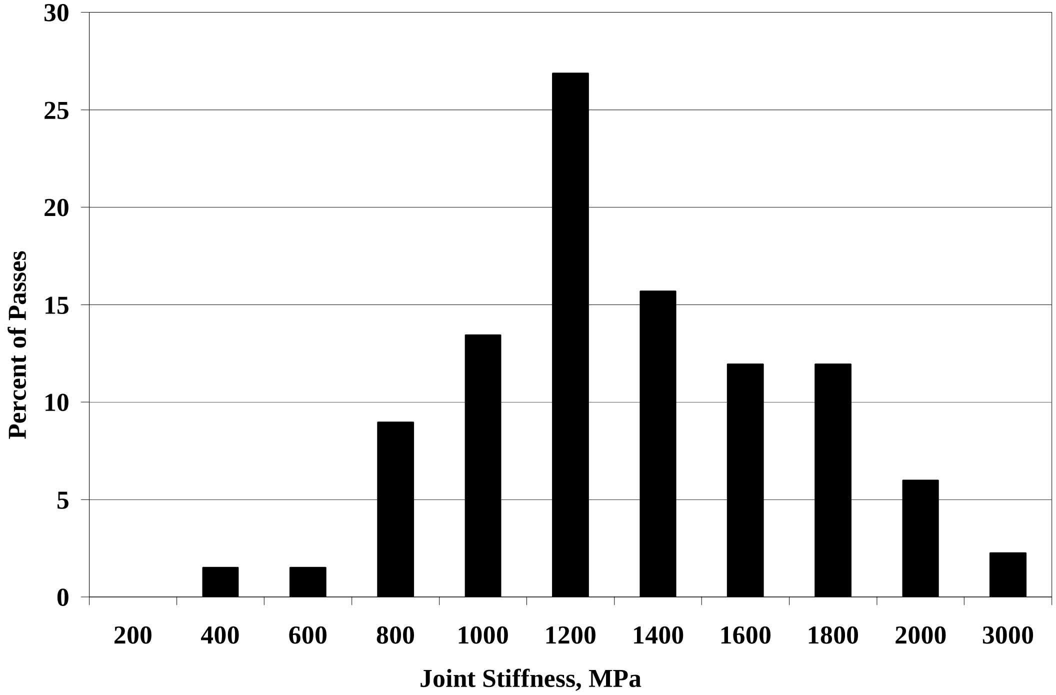


Figure 7. Frequency distribution of representative CRCP crack stiffnesses.

Frequency distributions of representative joint stiffness of joints of doweled and non-doweled JCP pavements are presented in figure 8. Comparison of these distribution shows that non-doweled joints usually have much lower stiffness than doweled joints. More than half of backcalculated stiffnesses for non-doweled joints were less than 200 MPa, and the average value from all cases was 470 MPa. At the same time, more than 60 percent of doweled joints had stiffnesses greater than 600 MPa, with the average value equal to 730 MPa.

The LTE of cracks and joints varies with time, as do joint and crack stiffnesses. Figure 9 presents a comparison of joint stiffnesses backcalculated from the FWD deflections obtained on the same day of testing but from different FWD passes. Significant variability exists for some joints, especially for those that exhibited lower stiffness at the time of the first FWD pass. This means that the time of day of FWD testing may significantly affect joint LTE. This effect is most likely due to temperature variations and the resulting joint movement and slab curling. Therefore, accounting for the effect of PCC slab curling is very important for reliable interpretation of FWD deflection data.

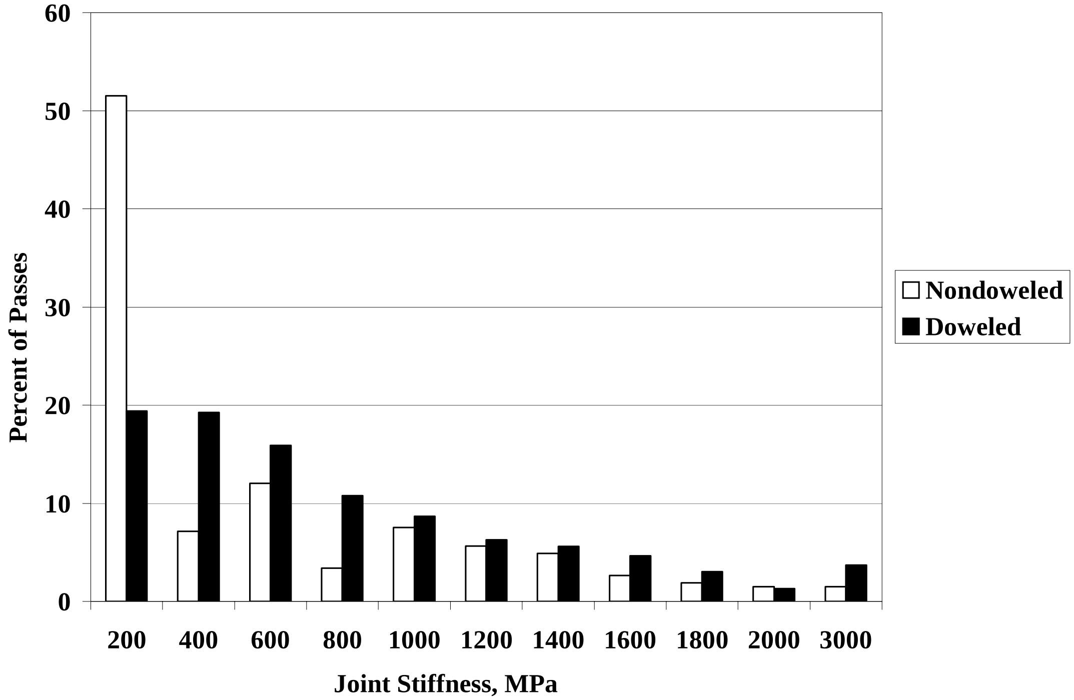


Figure 8. Frequency distributions of representative joint stiffnesses for joints of doweled and non-doweled JCP.

Currently, very little guidance is available for selecting joint and crack stiffness parameters for analysis of rigid pavement using finite element programs like ILLI-SLAB or JSLAB. Based on the results of this study, recommendations were made for the selection of joint stiffness values, if such stiffnesses cannot be obtained from other sources. They are summarized in table 4. However, more research is needed to validate these recommendations.

Pavement Type	Recommended Ranges, MPa
Non-doweled JCP	100-500
Doweled JCP	400-1000
CRCP	800-1400

Table 4. Recommended joint/crack stiffnesses for different types of pavements.

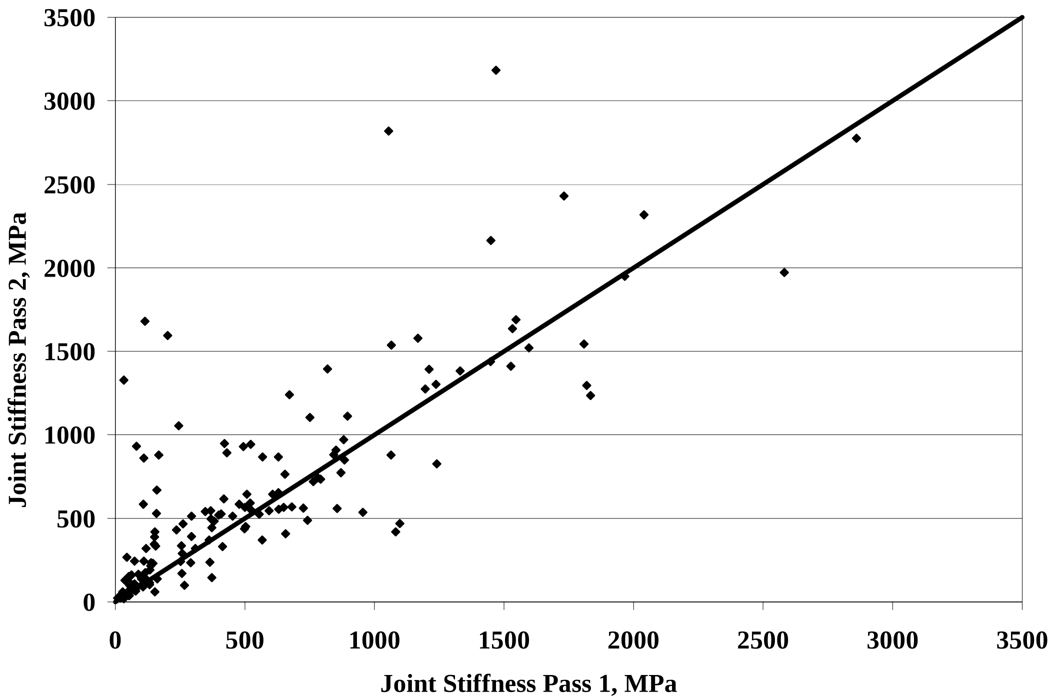


Figure 9. Comparison of backcalculated joint stiffness from two FWD passes on the same day of testing.

Conclusions

The analyses reported in this paper were intended to evaluate load-level dependency of load transfer efficiency of JCP joints and CRCP cracks and backcalculate stiffnesses of cracks and joints of PCC pavements from deflection measurements. It was found that, for the majority of the observations in the LTPP database, LTE is not load-level dependent and therefore a simple linear Tabatabae-Barenberg (TB) model is adequate for routine pavement analysis. A backcalculation procedure for joint stiffnesses was also developed based on Crovetti's equation. From the results of backcalculation for the LTPP sections, typical ranges were recommended for selection of joint stiffnesses for CRCP cracks as well as doweled and non-doweled joints for use in finite element analysis.

It should be also noted that in some cases load-level dependent behavior was observed which would require a more complex joint model to better depict this mechanism. Such a model should be capable of describing load position dependent behavior and provide better understanding of the effect of joint/crack opening and PCC slab curling on LTE. This will significantly improve the fundamental understanding of rigid pavement behavior and contribute toward the improvement of mechanistic-empirical design procedures.

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