Guidelines for Dowel Alignment in Concrete Pavements

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Guidelines for Dowel Alignment in Concrete Pavements

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FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report presents proposed guidelines for dowel alignment in concrete pavements. These guidelines deal with the effects of dowel misalignment on performance and the measures for reducing misalignment and its adverse effect. The report will guide pavement and construction engineers in considering dowel misalignment in pavement design and identifying measures for reducing misalignment during construction or for dealing with misaligned dowels. The information contained in the report will be of immediate interest to state engineers and others concerned with concrete pavement design and construction.

Dowels are used in jointed portland cement concrete pavements to provide load transfer, reduce faulting, and improve performance. These dowels are placed either manually before concrete placement or during construction by automatic dowel bar inserters to expedite construction and reduce cost. Inspection of pavements in several states revealed that misalignment of dowels generally occurs regardless of the placement method. These inspections also revealed that slab cracking and other forms of distress may not always occur as a result of such misalignment. However, limited research has been performed to determine the extent of dowel misalignment in pavement construction and its effect on performance. Thus research was needed to (1) address the issues associated with dowel alignment and to develop approaches for estimating the effects of different levels and types of misalignment on performance, (2) identify a methodology for considering misalignment in the design of concrete pavements, and (3) prepare guidelines on dowel alignment appropriate for use in performance related specifications.

Under NCHRP Project 10-69, "Guidelines for Dowel Alignment in Concrete Pavements," University of Minnesota worked with the objective of recommending guidelines for dowel alignment in concrete pavements that consider the ranges of misalignment encountered during construction and the effects of misalignment on performance, and present a rational approach for considering misalignment in the analysis and design process. These guidelines were to address all forms and combinations of dowel misalignment. To accomplish this objective, the researchers reviewed available information pertaining to the alignment of dowels in concrete pavements, conducted measurements on more than 35,000 dowels in 17 states, investigated the effects of dowel misalignment on pavement performance in a series of laboratory tests, and calibrated a finite element model to facilitate the analysis of misalignment effects on performance. Based on this work, the researchers proposed a methodology for considering dowel misalignment in pavement design and analysis and provided related guidelines. The proposed methodology and guidelines will be particularly useful to highway agencies because their use will facilitate the consideration of misalignment in pavement design and help reduce misalignment during construction and mitigate its adverse effects.

Appendixes A through D contained in the research agency's final report provide detailed information on the literature review, laboratory and field test results, and finite element analysis. These appendixes are not published herein; but they are available online at http://trb.org/news/blurb_detail.asp?id=10299. These appendixes are titled as follows:

Appendix A: Review of Literature and Other Relevant Information
Appendix B: Field Testing Results
Appendix C: Laboratory Testing Results
Appendix D: Finite Element Analysis

CONTENTS

CHAPTER 1

Background

1.1 Problem Statement

Dowels are used in jointed portland cement concrete (PCC) pavements to provide load transfer, reduce faulting, and improve performance. These dowels are placed either manually before concrete placement or during construction by automatic dowel bar inserters to expedite construction and reduce cost. Inspection of pavements in several states revealed that misalignment of dowels generally occurs regardless of the placement method. These inspections also revealed that slab cracking and other forms of distress may not always occur as a result of such misalignment. However, limited research has been performed to determine the extent of dowel misalignment in pavement construction and its effect on performance.

This report presents the research conducted under NCHRP Project 10-69 to address the issues associated with dowel alignment and develop approaches for estimating the effects of different levels and types of misalignment on performance, thus improving the analysis and design of concrete pavements. The objective of this research is to develop guidelines for dowel alignment in concrete pavements. The research addresses all forms and combinations of dowel misalignment (i.e., vertical and lateral skew and displacement).

1.2 Scope of Study

The research was conducted to develop guidelines concerning dowel alignment in concrete pavements. The effects of dowel misalignment on pavement performance were evaluated through a literature review; laboratory tests of individual dowels; field measurements of misalignment levels, distresses, and joint performance; and finite element modeling of pavements with different types and levels of misalignment. The laboratory tests dealt with dowel-concrete interaction of individual dowels to evaluate the effects of specific types and levels of misalignment in a controlled environment. Pullout testing was conducted on individual dowels to identify the misalignment's effect on expansion and contraction of the concrete due to shrinkage and thermal effects. Individual shear-pull testing was conducted to determine the effect of different types and levels of misalignment on ultimate shear strength and stiffness. Finite element modeling was used to augment the results of the laboratory study. An equivalent dowel diameter concept was developed to facilitate quantifying the effects of dowel misalignment on pavement performance.

CHAPTER 2

Research Methodology

2.1 Introduction

This section describes the purpose of transverse joints and dowels in concrete pavements, introduces dowel misalignment terminology used in this study, and gives an overview of the dowel misalignment specifications used by various transportation agencies.

2.1.1 Joints and Dowels in Concrete Pavements

Joints are introduced in PCC pavements to allow for thermal expansion and contraction, as well as shrinkage after construction. To improve load transfer across the transverse joints (thus minimizing faulting and corner breaks), many transportation agencies place dowels at mid-depth between the pavement slabs using either basket assemblies or an automated dowel bar inserter (DBI) (McGhee, 1995). The load transfer concept is illustrated in Figure 2.1 (PCA, 1991). When a wheel load is applied to an undowelled joint, greater edge and corner deflections (and corresponding stresses) are experienced. Dowel bars reduce the critical deflections and stresses by transferring the load between the slabs. Several studies, including Yu et al. (1998), Khazanovich et al. (1998), and Hoerner et al. (2000), concluded that properly designed and installed dowels greatly reduce transverse joint faulting and corner cracking. Dowels should maximize vertical load transfer, minimize longitudinal restraint, and be durable (Lechner, 2005).

2.1.2 Terminology

Ideally, dowel bars should be placed such that the longitudinal axis is parallel to both the surface and centerline of the hardened PCC slab, and the geometric center of the dowel bar is directly below the joint. If dowel position in the hardened concrete deviates from this ideal position, it is said to be *misaligned*. Misalignment may result from misplacement (initially placing the dowels in an incorrect position or saw cutting at the incorrect location), displacement (movement during or following the paving operation), or both.

The following major categories of dowel misalignments were identified by Tayabji (1986) (see Figure 2.2):

- Longitudinal translation;
- Vertical translation;
- Horizontal skew; and
- Vertical tilt.

Vertical translation refers to the deviation of the position of the dowel relative to the reference mid-depth position. However, because concrete cover describes the distance between the dowel and slab surface, it also reflects the vertical positions of the dowel and its vertical translations.

2.1.3 Current Specifications

Different states have adopted different requirements for dowel bar tolerances with respect to longitudinal and vertical translation, horizontal skew, and vertical tilt (see Table 2.1). These tolerances can be expressed as absolute maximum measures or as percentages of the length of the dowel or thickness of the concrete. Many states have adopted the FHWA-recommended limits for horizontal skew and vertical tilt of ¼ in. over 12 in. (6.3 mm over 305 mm) or 2% (FHWA, 1990). FHWA recommended further studies to determine the validity of this 2% tolerance (FHWA, 1990). The American Concrete Pavement Association (ACPA) recommends limits of ⅜ in. over 12 in. (9.5 mm over 305 mm) or 3% based on NCHRP Synthesis 56 (ACPA, 2004; NCHRP, 1979).

The data provided in Table 2.1 were obtained from literature review (MCC, 2004; Lechner, 2005) and communications with state department of transportation (DOT) representatives. Table 2.2 gives the dowel bar alignment tolerances permitted in the construction specifications of the Ministry of Trans-

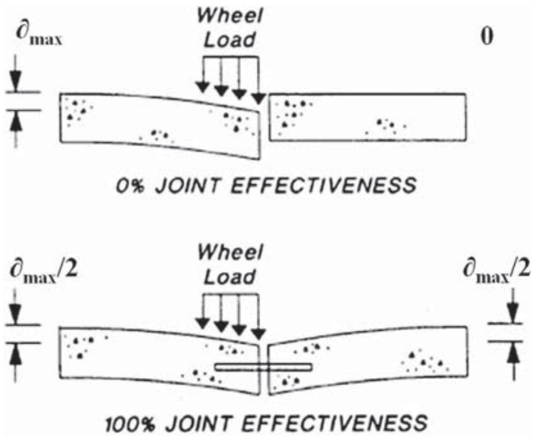

Figure 2.1. Effectiveness of load transfer (PCA, 1991).

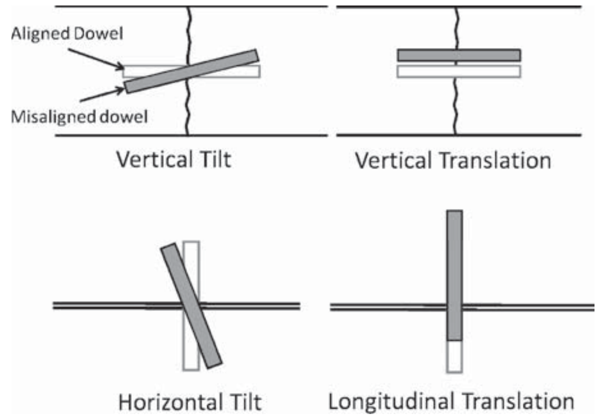

Figure 2.2. Types of dowel misalignment (adopted from Tayabji, 1986).

Table 2.1. Specified dowel misalignments limits.

Agency	Vertical Tilt	Horizontal Skew	Longitudinal Translation	Vertical Translation
	in. per 18 in.	in. per 18 in.	in. per 18 in.	in.
Arkansas	0.25	0.25	N/A	N/A
Connecticut				
Federal Aviation Administration				
Hawaii				
Idaho				
Kentucky				
Minnesota				
Texas				
Utah				
Wisconsin				
Nebraska				
Iowa				
Michigan				
Montana	0.25	0.25	0.50	0.50
North Dakota	0.25	0.25	0.25	0.25
Tennessee				
Ontario	0.24	0.24	0.59	0.59
Nevada	0.50	0.50	N/A	N/A
Missouri	0.50	0.50	0.50	1.00
Kansas	0.38	0.38	N/A	1/10 Pavement Depth
Indiana	0.38	0.38	N/A	N/A
North Carolina				
Illinois	0.19	0.19	N/A	N/A
Delaware				
South Carolina	0.56	0.56	3.00	0.75
Georgia	0.562	0.562	N/A	N/A
Germany	0.75	0.75	2.00	N/A
Alabama	0.25	0.69	N/A	N/A
Great Britain	0.39	0.39	N/A	N/A
New York	N/A	0.16	0.25	0.26
Ohio	N/A	N/A	0.50	0.50
Pennsylvania	0.23	0.23	1.00	1.00

Table 2.2. Specification limits for position and alignment of dowel bars (MTO, 2007).

Misalignment	Lower Limit (mm)	Upper Limit (mm)
Horizontal skew (mm per 450 mm dowel)	-15	15
Vertical tilt (mm per 450 mm dowel)	-15	15
Longitudinal translation (mm)	-50	50
Depth tolerance (for specified slab thickness):		
200 mm (mid depth - 6 mm/+6 mm)	94	106
225 mm (mid depth -12 mm/+15 mm)	100	127
250 mm (mid depth -15 mm/+25 mm)	110	150
260 mm (mid depth -15mm/+25 mm)	115	155

1 in. = 2.54 mm

portation of Ontario (MTO, 2007). The MTO tolerances are based on research performed in Ontario to determine the extent and effect of dowel misalignment in pavement construction. Recent guidelines developed by the FHWA also are based on the alignment and performance data (FHWA 2007).

2.2 Dowel Misalignment Assessment

This section summarizes available information on the state-of-the-art in field and laboratory testing, as well as analytical modeling, for dowel misalignment.

2.2.1 Field Testing

There have been a limited number of field studies of dowel misalignment (Tayabji and Okamoto, 1987; Yu et al., 1998). Devices used for identifying dowel misalignment include MIT Scan-2, the Profometer, and ground penetrating radar (GPR) (Khazanovich et al., 2003). In 2005, FHWA identified the MIT Scan-2 as a tool that could potentially improve the assessment of concrete pavements (FHWA, 2005). An assessment conducted by the Virginia DOT also identified MIT Scan-2 as a viable technology for construction quality control (Hossain and Elfino, 2006).

Inspection of pavements in several states revealed that the misalignment of dowels generally occurs regardless of the placement method. For example, significant dowel misalignment was identified in a pavement section constructed using dowel baskets on Highway 115 in Ontario (Leong, 2006) and in a pavement constructed using a DBI on I-16 in Georgia (Fowler and Gulden, 1983). Field studies also have shown variability in dowel position and alignment from one project to another (Yu, 2005). While a majority of dowel bars meet state specifications for alignment on most projects, there are a number of dowel bars that do not meet specifications.

The performance of some of these sections indicates that slab cracking and other forms of distress may not always occur as a result of such misalignment. Field studies have shown that the only type of misalignment that clearly had an effect on pavement performance was longitudinal translation (causing low embedment length). An example of the effect of low embedment length was observed on I-35 near Fergus Falls, Minnesota, where significant early faulting occurred when dowel embedment lengths were less than 2.5 in. [63 mm] (Burnham, 1999).

2.2.2 Laboratory Testing

Previous laboratory studies generally have been limited to dowel pullout tests that focused on dowel resistance to joint opening by measuring pullout force and by evaluating concrete distresses. These tests include standard pullout tests and slab pullout tests. In the former test, a dowel is pulled away from an anchored concrete slab. In the latter, a moving or "transient" slab is pulled away from an anchored or "stationary" slab to open a dowelled joint to a specified width. Up to five dowels are tested in the joint. Slab tests have been used by Tayabji (1986), Prabhu et al. (2006), and others to model slab expansion.

The standard pullout test data typically are presented as a plot of pullout force versus dowel horizontal displacement. The results of such tests have been used to calibrate a finite element model (Khazanovich et al., 2001). This well-controlled test provides valuable information related to dowel-PCC friction. More information on this test and modifications made to the test to better characterize the interaction between a misaligned dowel and the surrounding concrete are presented in Section 2.3.3 and Appendix C.

The slab pullout test data can be used to model the effects of several misaligned dowels on joint behavior during joint movement. The following trends have been observed (Prabhu et al., 2006; Tayabji, 1986):

- The force required to displace the dowel increased with the increased misalignment.
- Nonuniform misalignment had a greater effect on pullout force and distresses than uniform misalignment (non-uniform misalignment refers to dowels oppositely misaligned

and uniform misalignment refers to dowels all misaligned in the same direction).
- Slabs develop cracking only at significant misalignment levels (over ¾ in. [19 mm]) when the alignment of dowels along the joint is nonuniform and when excessive levels of joint opening (over 0.5 in. [13 mm]) are present.
- Minor spalling around dowels was found in slabs with uniform and nonuniform significant misalignment (Prabhu et al., 2006).

Because rotation of the beam in the direction of the misaligned dowel may occur during testing and affect test results, provisions must be made to ensure proper anchoring of the concrete (Tayabji, 1986). Nevertheless, slab testing is not expected to provide detailed information about the interaction between the dowel bar and the surrounding concrete (Prabhu et al., 2006).

2.2.3 Analytical Models

The two main categories of analytical models that can be used for assessing the effects of dowel misalignment are structural response models and performance prediction models.

2.2.3.1 Structural Response Models

Several finite element and finite difference models have been used to analyze the effects of dowel misalignment (Khazanovich et al., 2001; Davids, 2003; Leong, 2006; Prabhu et al., 2006). Some of the major findings include:

- Dowel misalignment increases PCC-dowel contact stresses.
- When embedment length falls below some critical level, bearing stresses increase.
- If several consecutive transverse joints are subject to lockup, stresses increase away from the joint, with high stresses developing at the mid-slab location.

The analytical models for predicting the effects of dowel misalignment on concrete pavement behavior can be classified according to the degree of detail used for modeling the dowels and their interaction with concrete as Types I and II.

Type I models provide detailed modeling of dowels and dowel-PCC interaction. These models include:

- ABAQUS 3-D model for a single dowel;
- ABAQUS 3-D model for several dowels; and
- FLAC-3-D model.

Type II models provide simplified modeling of dowel-PCC interaction. These models include:

- ISLAB2000;
- EVERFE; and
- ABAQUS-2D multiple slab model.

Type I models are suited for analyzing the effects of dowel misalignment on bearing stresses and joint stiffness, whereas Type II models are suited for multi-slab analysis to predict mid-slab stresses. These models were evaluated based on the following criteria:

- Ability to model dowel-PCC slip.
- Ability to model stress distribution around misaligned dowel.
- Ability to model subgrade and base support.
- Ability to model nonuniform misalignment.
- Ability to model multiple joints.
- Model flexibility.
- Input requirements.

Based on these criteria and experience, the ABAQUS 3-D models were selected for use and modification in this study.

2.2.3.2 Performance Prediction Models

Models for predicting jointed plain concrete pavement (JPCP) cracking, joint faulting, spalling, and roughness were identified and evaluated. The evaluation revealed that none of the performance models consider dowel alignment as an input parameter. However, mechanistic-empirical (ME) pavement performance models can be adapted to account for the effects of dowel misalignment.

Several faulting models relate concrete bearing stresses under the critical dowel with the rate of load transfer efficiency (LTE) deterioration and faulting development (Owusu-Antwi et al., 1997; Hoerner et al., 2000; Khazanovich et al., 2004). Higher bearing stress accelerates joint LTE deterioration and causes early faulting. Thus, if higher bearing stresses were observed for reduced dowel diameters and also observed for joints with misaligned dowels, levels of dowel misalignment could be equated to reduced dowel diameters when bearing stress is considered.

Cracking models relate PCC pavement longitudinal bending stresses developed at mid-slab with the percentage of cracked slabs. If dowel misalignment causes joint lockup, it may cause additional tensile stresses that should be accounted for in the cracking model.

Available performance prediction models that can be used for development of guidelines for dowel alignment were evaluated based on the accuracy of predictions, simplicity of use, and simplicity of integration with the dowel misalignment analysis. The evaluations indicated the following:

- The Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO, 2008) faulting model was appropriate for prediction of the long-term effects of dowel misalignment on joint faulting.
- The MEPDG cracking model was the most comprehensive model available for cracking prediction.

- None of the identified spalling models could be used for analyzing the effects of dowel misalignment on joint spalling.

Based on these evaluations, the MEPDG faulting and cracking models were selected for modification in this study and the MEPDG International Roughness Index (IRI) model was adapted for roughness prediction.

2.3 Research Approach

The following section describes the approach used in conducting field and laboratory tests, analytical modeling, and developing performance predication models for JPCP with misaligned dowels.

2.3.1 Field Testing

The field testing included (a) evaluation of typical dowel alignments observed across the United States for a variety of construction projects and (b) identification of short-term and long-term effects of dowel misalignment on pavement performance.

2.3.1.1 Alignment and Performance Database

A database of the dowel alignment and pavement performance was assembled from the evaluation of 37 pavement sections and information on 23 additional pavement sections reported in other studies (Yu, 2005). These 60 pavement sections are located in Arizona, California, Colorado, Georgia, Indiana, Illinois, Kansas, Michigan, Minnesota, Missouri, Nevada, North Carolina, Ohio, South Dakota, Virginia, Washington, and Wisconsin.

The candidate sections for field data collection were identified with assistance from state DOTs. Another source of projects for field evaluation was the Long Term Pavement Performance (LTPP) database, particularly the Seasonal Monitoring Program (SMP) sections because they included information on joint opening and historical time series on distress, faulting, LTE, etc. Seventeen of the 37 pavement sections surveyed in this study are LTPP test sections. Appendix B lists all pavement sections, summarizes their design features, and describes the testing operations performed on each. These sections represent broad ranges of design, construction, climate and traffic variables:

- Climatic region: 8 sections in dry-freeze, 24 sections in dry-nonfreeze, 22 sections in wet-freeze, 6 sections in wet-nonfreeze.
- Pavement thickness: 5 sections with thickness ≤ 8 in. [203 mm], 5 sections with thickness between 8 and 9 in. [203 and 229 mm], 10 sections with thickness between 9 and 10 in. [229 and 254 mm], 20 sections with thickness between 10 and 11 in. [254 and 279 mm], and 20 sections with thickness ≥ 11 in. [279 mm].
- Dowel size: 16 sections with 1.25-in. [32 mm] diameter dowels, 42 sections with 1.5-in. [38 mm] diameter dowels, and 2 sections with dowels of other diameters (1 and 1.125 in. [25 and 29 mm]).
- Dowel installation procedure: 35 sections were constructed using basket assemblies, 23 sections using DBI, and 2 sections were retrofitted.
- Construction year: 4 sections were constructed before 1991, 22 sections between 1991 and 1995, 10 sections between 1995 and 2000, 20 sections between 2000 and 2006, and 4 sections in 2007.
- Average daily traffic (ADT): 16 sections had ADT ≤ 15000, 12 sections had ADT between 15000 and 30000, 19 sections had ADT between 30000 and 60000, 12 sections had ADT ≥ 60000, and 1 section (on MnROAD) had 100,000 passes of 80 kip (35.6 kN) truck.

2.3.1.2 Data Collection

Every joint in each pavement section was tested using MIT Scan-2, and MagnoProof (MIT Scan-2 PC software) was used to quantify dowel alignment and position in the pavement section.

In addition to the dowel alignment and position data, faulting of each transverse joint was measured using a faultmeter reading to the nearest 0.01 in. (0.25 mm). Readings were taken in the outer wheel path (approximately 18 in. [450 mm] from the edge of the lane) and at the slab corner. Thus, for a 500-ft. (150-m) section with 15-ft. (4.6-m) joint spacing, over 30 faulting measurements were made. A complete distress survey of each pavement section also was conducted in accordance with the LTPP Distress Identification Manual (Miller and Bellinger, 2003); the extent and severity of cracking, spalling, corner breaks, and so on were noted. At each transverse joint, the overall extent of joint deterioration was noted and the severity was rated as None, Low, Medium, or High. The condition of the joint seal (if present) also was noted. Digital photographs were taken to document the overall condition of each test section and typical distresses (if any), as well as the site conditions. On some sections, joint LTE was measured using the Falling Weight Deflectometer (FWD).

2.3.2 Laboratory Testing

Laboratory testing was conducted on pavement slabs in a controlled environment to determine the effects of dowel misalignment. Performance parameters such as maximum required pullout force, dowel shear stiffness, and ultimate dowel shear capacity were measured. The standard pullout test was modified to eliminate the influence of beam rotation. Also, shear pull tests were conducted to address the effect of misalignment on shear performance.

2.3.2.1 Laboratory Setup

Each specimen consisted of a 4-ft. wide [1.2 m], 8-in. thick [203 mm], and 18-in. [457 mm] tall concrete beam containing four 1.25- or 1.5-in. [32 or 38 mm] diameter dowels placed 12 in. [305 mm] apart, with the end dowels 6 in. [152 mm] away from the edge (Figure 2.3). Test specimen dimensions were selected with consideration to the capabilities of the available test apparatus and the planned finite element modeling.

Beam thickness was based on a general design of a thin (8-in. [200-mm] thick), doweled PCC pavement. The width was chosen as the most efficient width for casting and testing the dowels using the available testing apparatus and the height was selected to ensure that the test beam adequately represents a "long" PCC slab (i.e., the specimen has sufficient length in the direction of dowel embedment such that boundary conditions do not significantly influence test results). The finite element simulation of the modified pullout test indicated that increasing the beam height beyond 18 in. [457 mm] would not provide any advantage but would increase specimen weights and make it difficult to handle.

The 1.25- and 1.5-in. [33- and 38-mm] dowel diameters were chosen because they are commonly used in the United States. The distance between the dowels was selected to ensure that (1) the specimen clamps could be placed on the beam at sufficient distances from each dowel being tested to avoid influencing the test results and (2) the damage of the beam after a pullout test on one dowel would not affect the adjacent dowels.

To ensure precision in installing the dowels with the intended misalignment, a dowel jig was fabricated and a procedure was used for setting dowels with precisely the desired type and amount of misalignment. Each jig featured two holes that were

Figure 2.3. Test specimen.

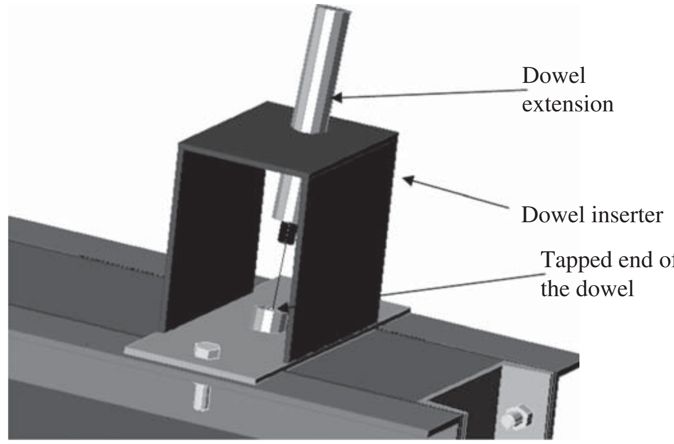

Figure 2.4. Dowel extension and alignment jig.

offset to provide the desired misalignment (see Figure 2.4). The top end of each dowel was tapped to allow a dowel extension to be screwed into place. The extended dowel was inserted through the jig holes and set at the proper embedment length and angle. After the concrete had been placed and cured sufficiently, the dowel extension and jig were removed.

The mold was stripped from the specimen after the concrete was cured sufficiently (a minimum of 24 hours) to avoid damage. Each beam was then cured under water for 6 days before testing. One ungreased 6-in. [153-mm] dowel was included and tested in each beam to provide a reference between beams. A compressive strength test was conducted 7 days after beam casting.

The MinneALF structure was modified to accommodate the modified pullout and shear pull tests (Khazanovich et al., 2005). These modifications included adjustment of the actuator positions and installation of the beam clamping mechanism.

2.3.2.2 Test Procedure

The dowel pullout testing was conducted after the test beams had been water-cured for 7 days. Because concrete pavement can experience contraction and shrinkage within several hours after concrete setting, the 7-day curing time was selected to ensure uniformity of the test beams. Dowels with various levels of misalignments were tested as follows:

1. Each dowel was tested individually by pulling it vertically with respect to the concrete beam, along the ideal axial direction of a properly aligned dowel in a displacement-controlled mode at a rate of 0.003 in./sec (0.076 mm/sec) until the dowel had translated (pulled out) 0.25 in. (6 mm) relative to the concrete. Pullout force and displacement were recorded continuously.
2. A post-test examination was conducted to evaluate the concrete surrounding the dowels (visible damage was recorded).

After the pullout test was completed, the beam was rotated 90 degrees so that it was lying on its side (Figure 2.5). The beam then was clamped to the test stand and a shear load was applied to selected dowels in a direction perpendicular to the plane of the slab surface. The dowel was pulled in a displacement-controlled mode until failure.

Dowels with various levels of misalignments were tested as follows:

1. Each dowel was tested individually by pulling it vertically with respect to the concrete beam, in a displacement-controlled mode until the concrete surrounding the dowel failed. During the testing, the shear pull force and displacements of the dowel and concrete were recorded continuously.
2. After testing each beam, an examination was conducted. The concrete surrounding the dowels was evaluated and the failure mode was recorded.

The effect of misalignment also was evaluated in repeated shear load tests with the following parameters:

- Magnitude of loading: 3 kips [13.3 kN].
- Load frequency: 2 Hz.
- Rest period: 0.5 seconds. To reduce the residual effect ("bouncing"), a static "seating" load of 500 lb [2.2 kN] was present between loading cycles.
- Measurement frequency: every 0.1 seconds.
- Number of load cycles: at least 10,000.

The laboratory process and setup for the repeated load test was the same as that used for the static test, except that a repeated 3-kip [13.3 kN] load was applied for at least 10,000 cycles. In this manner, the effect of a one-time load to failure on strength and stiffness could be related to the effect of a repeated load fatigue test.

2.3.2.3 Testing Factorial

The levels of misalignment used in the tests were selected based on a review of previous misalignment investigations, which showed that dowel rotational misalignments of up to 1 in. [25 mm] cause only small changes in distress and resistance to joint opening (Tayabji, 1986; Prabhu et al., 2006). Tests of dowels with up to 4 inches [102 mm] in vertical tilt showed no significant differences in behavior for the various levels of misalignment (Tayabji, 1986). Other tests found no distresses for levels of skew and tilt of up to 1 in. [25 mm] for vertical and horizontal misalignment and up to ¾ in. [19 mm] for combined tilt and skew (Prabhu et al., 2006).

In this study, tests were conducted on dowels with rotation ranging from 0 in. (i.e., properly aligned) to 4 in. per 18 in. [102 mm per 457 mm], embedment length ranging from 2 to 9 in. [51 to 229 mm], and concrete cover ranging from 1.25 to 3.375 in. [32 to 86 mm]. Because a typical dowel is 18 in. [229 mm] long, all dowel rotations are expressed as the vertical or horizontal displacement of one end of the dowel per 18 inches [229 mm] in length.

Pullout tests were conducted on specimens, each containing four dowels with various types and levels of misalignment. After the test, the two dowels on the outside of the beam were tested in shear or repeated shear (Appendix C presents the dowel alignments for each dowel tested in this study).

Shear testing of the first two beams revealed difficulties in testing four dowels within a single test beam due to the occurrence of horizontal cracks. It was concluded that only the outside dowels could be tested to measure the ultimate shear load capacity of a given dowel because testing of the interior dowels would result in horizontal cracks that would influence the shear pull test results of adjacent dowels. Therefore, all of the dowels were tested in pullout but only the outside dowels were tested in shear, as noted in Figure 2.6.

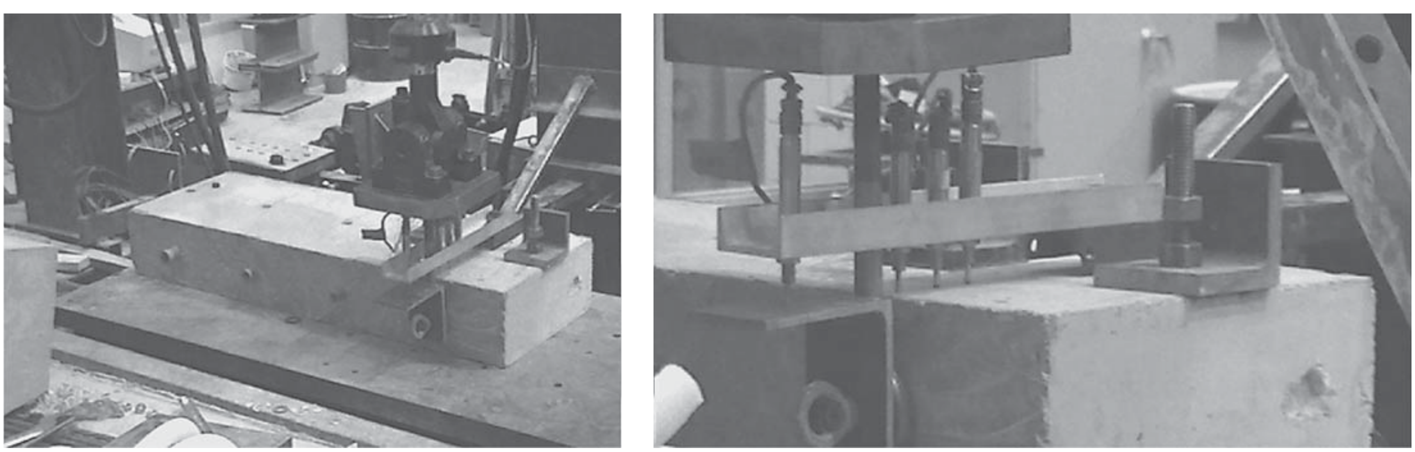

Figure 2.5. Setup for vertical shear test (also for repeated shear testing).

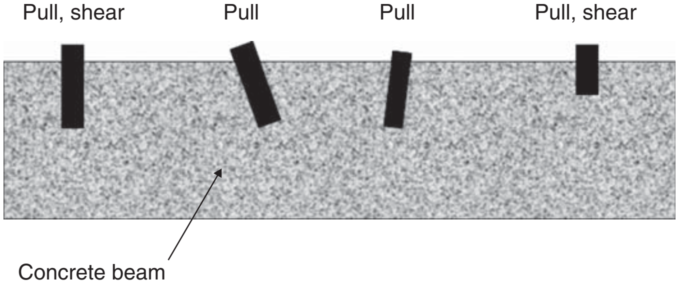

Figure 2.6. Tests conducted on individual dowels in a beam.

2.3.2.4 Results Interpretation

Modified Pullout Tests. During pullout testing, the pullout force and displacements were recorded continuously. Figure 2.7 shows an example of the two types of curves recorded. Throughout the pullout testing, a majority of the dowels showed a monotonically increasing force-displacement curve (i.e., the pullout force increased with dowel displacement) and others showed discontinuous force-displacement curves, similar to those shown in Figure 2.7. The behavior illustrated by the properly aligned curves is characterized as "static-slip" because it appears that the dowel "slips" slightly each time enough force is generated to exceed the static friction conditions.

In these tests, maximum pullout force for a dowel with a given combination of misalignments was increased and then used to evaluate the effects of dowel misalignment on dowel resistance to joint opening and joint lockup.

It should be noted that the measured pullout forces in this study were higher than the pullout forces reported from forensic studies in which the doweled joints were extracted from pavements and tested in the lab. The difference is probably because the laboratory-prepared specimens were cured for 7 days before testing whereas the in situ dowels were subjected to joint movements at a much earlier age.

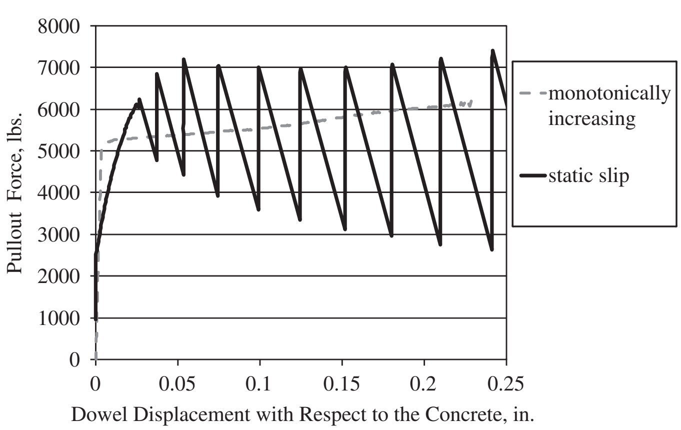

Figure 2.7. Examples of the typical pullout test results.

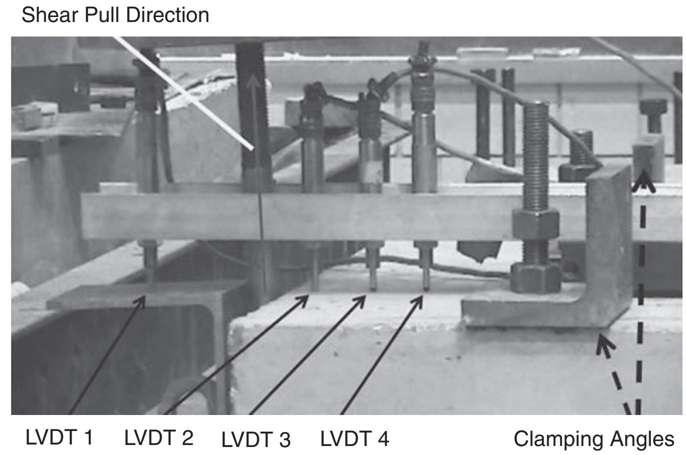

Figure 2.8. Locations of displacement measurements.

Shear-Pull Tests. Figure 2.8 shows the locations at which vertical displacement measurements were recorded. The first linear variable differential transformer (LVDT1) measures the displacement of the metal angle above the dowel, giving a measure of absolute dowel displacement. LVDT2 measures the displacement at the edge of the concrete beam closest to the dowel, LVDT3 measures the beam displacement 2 in.[51 mm] from the edge, and LVDT4 measures the beam displacement 4 in. [102 mm] from the edge. All four LVDTs are located in the vertical plane of the dowel (i.e., directly above the dowel).

The shear-pull force and displacements of the dowel at the joint face (LVDT1) and at the three locations on the beam (LVDTs 2 through 4) were recorded continuously during testing. Figure 2.9 shows an example of the recorded displacements and shear force for a 1.5-in. [38-mm] diameter dowel that was vertically tilted by 2 in. per 18 in. [51 mm per 457 mm] of dowel length.

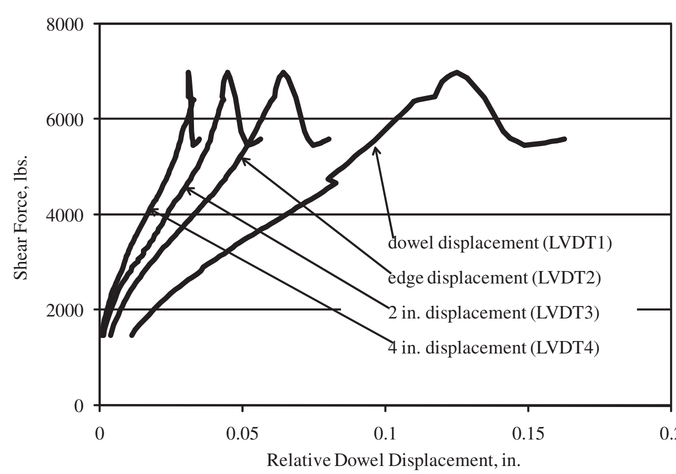

Figure 2.9. Force versus displacement for a 2 in. vertically tilted dowel.

To conduct analyses of the effects of dowel misalignment on the stiffness of the dowel-concrete interaction, the relative vertical displacement of the dowel end with respect to the surrounding concrete was estimated by subtracting the calculated dowel displacement due to the rigid body rotation of the beam from the actual dowel displacement. The calculated dowel displacement was determined from the displacements of LVDT2 and LVDT4 (Figure 2.8) and the specimen geometry. These displacements were used to calculate the slope of the rigid body motion of the beam, Δ_{rb} as follows:

$$\Delta_{rb} = \frac{\partial_2 - \partial_4}{l_{24}} \tag{1}$$

where

- l_{24} = the distance between LVDT2 and LVDT4;
- ∂_2 = the vertical displacement at the edge of the beam (measured by LVDT2); and
- ∂_4 = the vertical displacement 4 inches [102 mm] from the edge (measured by LVDT4).

The slope of the rigid body could then be used to calculate the position of the dowel, assuming rigid body motion (i.e., that the beam rotates under load without bending) as follows:

$$\partial_{calc} = \partial_4 + \Delta_{rb} l_{14} \tag{2}$$

where

- l_{14} = the distance between LVDT1 and LVDT4; and
- ∂_{calc} = calculated dowel displacement assuming rigid body motion.

To check the accuracy of the rigid body motion calculation, the displacements at LVDT3 were calculated similarly and compared to the actual LVDT3 measurements. Figure 2.10 shows a typical example of the calculated versus measured displacements at the 2 in. [51 mm] location for the same dowel.

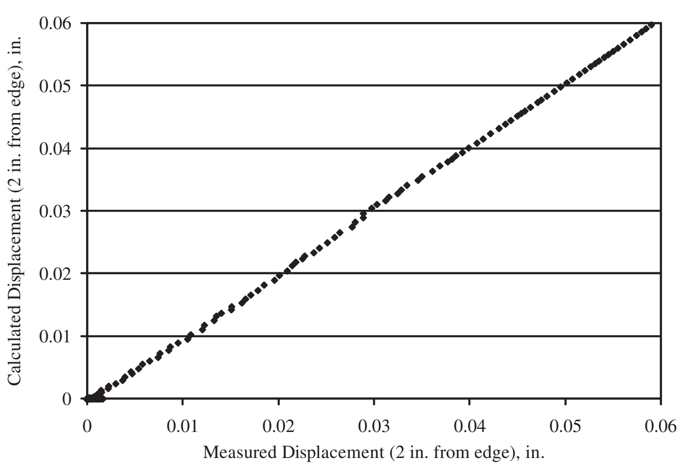

Figure 2.10. Verification of the rigid body slope.

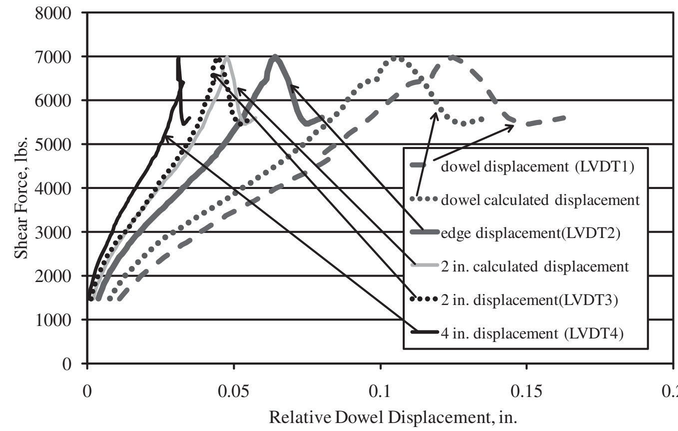

Figure 2.11. Measured and calculated force versus displacement for a 2 in. vertically tilted dowel.

This plot confirms appropriateness of the rigid body assumption for the rotation of the concrete beam.

Figure 2.11 shows the calculated values for LVDT1 and LVDT3 for the example illustrated in Figure 2.9. The plot shows that, while the beam surface displacements can be described as rigid body motion (i.e., the measured and calculated data points at 2 in. [51 mm] from the joint face are similar), the dowel exhibits additional displacements with respect to the concrete beam surface.

The relative dowel displacement can be computed as:

$$\partial_{rel} = \partial_{meas} - \partial_{calc} \tag{3}$$

where

- ∂_{rel} = the dowel displacement due to the compression of the concrete around dowel;
- ∂_{calc} = the calculated rigid body displacement; and
- ∂_{meas} = the dowel displacement measured by LVDT1.

Figure 2.12 shows a plot of applied shear force versus relative dowel displacement. The relative dowel displacement was used

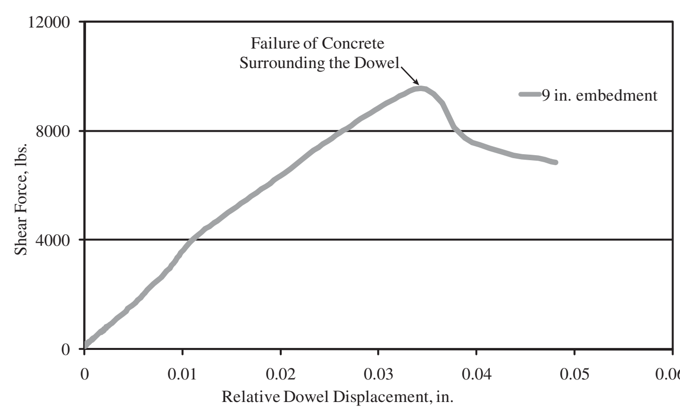

Figure 2.12. Example of shear force versus relative displacement.

to estimate the degree of deformation of the concrete during testing. The shear force that caused failure of the concrete surrounding the dowel was considered the ultimate shear strength of the dowel, which indicates the ability to sustain overloading and maintain stiffness under a large number of repeated loads. In addition, the slope of the curve characterizes the stiffness of the tested dowel-concrete interaction. The ultimate shear and stiffness associated with each dowel indicate how the load transfer efficiency might be affected by dowel misalignment.

2.3.3 Analytical Modeling

This section provides a brief overview of the finite element modeling conducted in this study (a more detailed description is provided in Appendix D).

2.3.3.1 Finite Element Models

To model the effects of dowel misalignment on concrete pavement behavior, the following 3-D ABAQUS models were developed using the approach developed by Khazanovich et al. (2001):

- Beam model replicating the laboratory test with individual dowels.
- Slab model with four dowels for analysis of the effect of nonuniform dowel rotation on joint load transfer efficiency.

The beam model for dowel-concrete interaction was calibrated using results of the laboratory tests. The calibrated model then was used to investigate misalignment cases and magnitudes that were not tested. To analyze the effect of multiple dowels, a slab model was built using this dowel-concrete interaction model.

Based on the results of the finite element modeling, the concept of an equivalent dowel diameter was developed. The effects of dowel misalignment on long-term pavement performance were then estimated using this concept and the MEPDG performance prediction models.

Beam Model. A single finite element model was used to simulate both modified pullout and shear pull laboratory tests. In the lab, shear testing always was conducted after the pullout testing to model the effect of joint opening prior to wheel loading. In a similar manner, the finite element beam model was set up to apply the pullout test prior to applying the shear pull test, therefore accounting for damage in the concrete beam. Thus, it was necessary to add or remove the clamping mechanism when changing the simulation from pullout to shear testing. This was accomplished by modeling the horizontal and vertical clamping mechanisms with a temperature-sensitive stiffness.

The beam model consists of 8700 elements of type C3D8R (8-node, reduced-integration 3-D linear brick element). A finer mesh was modeled for the dowels and concrete around the dowel to allow for a more detailed analysis of the critical sections surrounding the dowel. Although more computational time is needed for the finer mesh, the higher mesh density allows for more accurate analysis of the strains, stresses, and deflections at the most relevant points. A coarser mesh was assigned to the concrete not surrounding the dowel because less precision was needed in this area and to reduce the computational time without significantly decreasing the accuracy of analysis.

Two separate material models were employed to model the concrete. Following Prabhu et al. (2006), the concrete surrounding the dowel was modeled using the "concrete damaged plasticity" option available in ABAQUS. The inelastic behavior of concrete was modeled using the concept of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity (ABAQUS, 2007). This model accounts for the loss of elastic stiffness due to plastic straining of the concrete in tension and compression. The concrete away from the dowel was modeled as a linear elastic material.

The dowel was modeled as an elastic isotropic material, with 20 elements along its length and 20 elements in the cross-section. A finer mesh in the dowel compared to the surrounding concrete was necessary to improve the stability of the dowel-concrete interaction that was modeled as a surface-to-surface contact defined between two deformable bodies.

Initially for the pullout testing, the clamping mechanism was set to be very stiff, and the shear-pull clamp was set at a very low stiffness. A stable friction contact between the dowel and the surrounding concrete was ensured using the procedure developed by Khazanovich et al. (2001). This was followed by the application of the prescribed pullout displacement at the end of the dowel to simulate the displacement-controlled mode of the laboratory testing. After the dowel reached the maximum prescribed displacement, the displacement at the end of the dowel was deactivated to simulate the removal of the test load.

After the pullout test simulation was completed, the properties of both clamping mechanisms were changed to simulate stiff shear-pull clamping fixtures and negligible stiffness of the pullout fixtures. This was followed by the application of the prescribed shear-pull displacement at the end of the dowel.

Model Validation. To validate the finite element dowel-concrete interaction model, the simulated deflections from the beam model were analyzed in the same manner as the deflections measured in the tests. The relative vertical displacements of the dowel end (with respect to the surrounding concrete) were estimated. These laboratory-measured relative displacements and shear force data were used to validate the

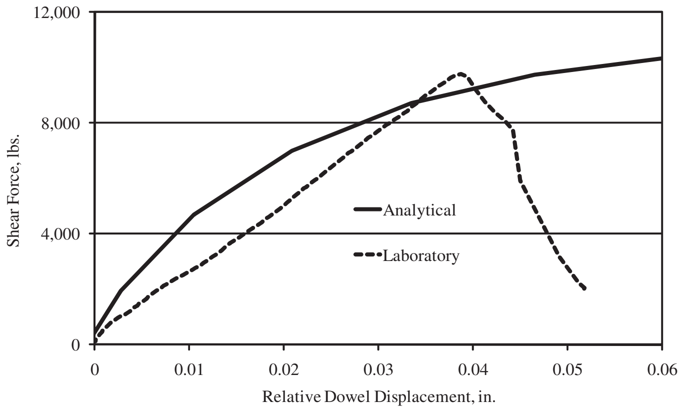

Figure 2.13. Laboratory and analytical shear versus displacement for an aligned dowel.

Table 2.3. ABAQUS-computed versus laboratory-measured shear capacities for various dowel embedment lengths.

Embedment Length (in.)	Shear Capacity (lb) ABAQUS Calculated	Shear Capacity (lb) Laboratory Measured
2	4870	5360
3	6590	5930
4	7950	7050
5	9070	N/A
6	9890	9770
9	10,370	9570

finite element model. The displacement measurement locations used in the laboratory also were used in the finite element model calculations so that the relative dowel displacement data obtained in the lab could be compared directly to the finite element results. By comparing the results of the shear-pull tests to those of the ABAQUS model, rational parameters were established for the dowel-concrete interaction model.

Figure 2.13 shows the shear force versus relative displacements for an aligned dowel tested in the laboratory and for a simulated dowel using ABAQUS. The figure shows some agreement between the model and laboratory results. Similar observations were made for the other alignment conditions.

The shear capacity was used to compare the performance of the dowels in the ABAQUS simulations to that obtained from laboratory measurements. Figure 2.14 illustrates the shear force versus relative displacement for a reduced embedment length of 6 in. [152 mm] and the most extreme case of reduced embedment length of 2 in. [51 mm] for both laboratory and analytical estimates. The figure indicates similar shear stiffness for the model and laboratory data with respect to the shear capacity. The shear force at failure was used in the laboratory analysis while the shear force required to cause 0.05 in. [1.27 mm] of relative displacement was used in the finite element analysis.

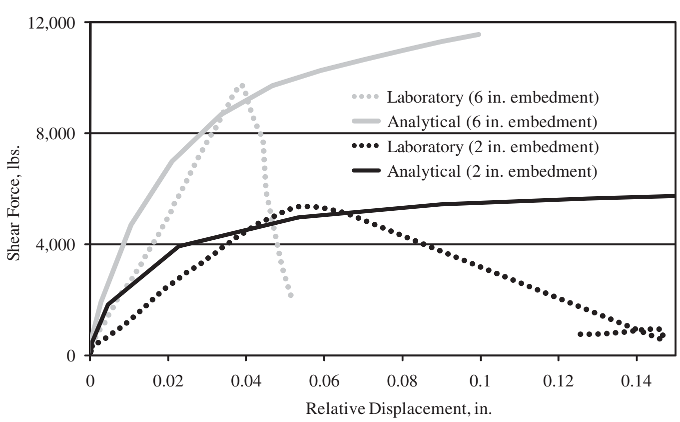

Figure 2.14. Laboratory and analytical sheer versus displacement for misaligned dowels.

Table 2.3 compares the shear capacities obtained from the lab testing to those estimated from the calibrated analytical model for all of the embedment lengths. There is a consistent agreement between the laboratory testing and analytical model results with the largest difference being less than 1 kip [4.45 kN]. Thus, the analytical model can be applied to those cases for which lab testing was not feasible.

Slab Model. Although the beam finite element model is an effective tool for analyzing the effects of longitudinal and vertical translations on the behavior of individual dowels, previous laboratory and analytical studies indicated that the effects of dowel rotational misalignments (in the form of horizontal skew and vertical tilt) are affected by the misalignments of other dowels in the joint (Tayabji, 1986; Khazanovich et al., 2001; Prabhu et al., 2006). To investigate this phenomenon, the beam model was expanded to simulate a slab with multiple dowels in the joint and to consider temperature expansion and contraction, as well as wheel loading at the joint.

The slab model consists of two slabs connected by four dowels at the joint and resting on an elastic Winkler foundation. Each slab is 60 in. [1524 mm] wide and 90 in. [2286 mm] long. The symmetrical boundary conditions along one of the longitudinal slab edges make the effective slab width 120 in. [3 m]. These boundary conditions also reduce the model run time by more than half (with respect to a full-scale model) without affecting accuracy. To limit the effect of the reduced slab length in the longitudinal direction, the ends of the slab along the outside longitudinal edges were constrained by springs. A comparison of this model with a full-scale, four-slab ISLAB2000 model (Khazanovich et al., 2000) found that the difference in LTE at the slab corner was within one percent.

As in the beam model, a finer element mesh was used for the dowels and the concrete surrounding the dowels; a total of 30,464 type C3D8R elements (8-node, reduced-integration 3-D linear brick, continuum element) were used in this model. The model design was selected to optimize the computational time without significantly influencing the accuracy. However, each individual slab simulation required 4 hours or more of run time on a supercomputer. The concrete and dowel materials, as well as the interface between the dowel and concrete, were assumed to have the same properties as those used in the beam model. Each dowel could be rotated about the vertical or horizontal axes to simulate uniform and different types of nonuniform misalignments.

To initiate the dowel-concrete contact, the same procedure used in the beam model was used. After that, prescribed longitudinal displacements were applied at opposite transverse edges of the modeled slab to simulate temperature contraction of the concrete slabs. The resulting joint opening induced damage in the concrete surrounding the misaligned dowels. The analysis showed that misalignment of 2 in. per 18 in. [51 mm per 457 mm] of vertical tilt causes higher stresses in the concrete surrounding the dowels than the aligned dowels.

After the joint opening was simulated, the prescribed displacements were deactivated, and the simulated wheel load was then applied at the corner of the slab causing displacements of the system. The ratio of displacements of the loaded and unloaded slabs provides a measure of the LTE for different levels of dowel rotation.

2.3.3.2 Performance Prediction Models

The MEPDG (AASHTO, 2008)does not include an input parameter for dowel misalignment. However, the laboratory and field data and analysis conducted in this study provide a means for incorporating the effect of dowel misalignment in the MEPDG. The following section discusses approaches for accounting for the effects of dowel misalignment in the models used in the MEPDG for JPCP joint faulting, transverse cracking, joint spalling, and IRI models.

Faulting Model. Dowel diameter is one of the most important parameters of the faulting model. Dowel design has a major effect on the LTE of JPCP joints. If all other parameters are equal, a joint with a greater dowel diameter will have a higher LTE, which according to the MEPDG faulting model should reduce the rate of faulting development. The laboratory and analytical studies showed that dowel misalignment may affect dowel shear capacity and cause accelerated development of joint faulting.

In the absence of an input parameter for dowel misalignment in the faulting model, the use of the *equivalent dowel diameter* concept to account for the effects of dowel misalignment is proposed. The *equivalent dowel diameter* is the dowel diameter that will yield the same dowel shear capacity of a misaligned dowel. This equivalent dowel diameter can then be used to investigate the effect of dowel misalignment on the long-term pavement performance using the MEPDG procedures.

The equivalent dowel diameter concept postulates that, with regard to joint faulting, a joint with misaligned dowels behaves as a joint with aligned dowels with a diameter, d_{eq}, as defined by the following equation:

$$d_{eq} = r_{emb} \times r_{cc} \times r_{vt} \times r_{hs} \times d_0 \qquad (4)$$

where

r_{emb} = the adjustment factor for a reduction in embedment length;
r_{cc} = the adjustment factor for a reduction in concrete cover;
r_{vt} = the adjustment factor for vertical tilt;
r_{hs} = the adjustment factor for horizontal skew; and
d_0 = the nominal dowel diameter.

The adjustment factors can have values ranging from 0 to 1, where the value is inversely related to the level of misalignment. For a perfectly aligned dowel, all adjustment factors are equal to 1 and the corresponding equivalent dowel diameter is the same as the design dowel diameter. Conversely, dowels that are extremely misaligned in some way will have adjustment factors that approach zero. For example, if the dowel embedment length is equal to zero, then the adjustment factor r_{emb} is zero, making the equivalent dowel diameter zero, and the MEPDG faulting model would treat it as an undowelled pavement. Derivations of each individual dowel adjustment factor are presented in Chapter 3.

Transverse Cracking Model. The field, laboratory, and finite element investigations conducted in this study could not link dowel misalignment with transverse cracking.

Spalling Model. The MEPDG spalling model accounts only for the damage due to combinations of concrete degradation (controlled by the inputs of air content, water/cement ratio, and climate), and ability of incompressibles to penetrate the joint (controlled by the inputs of sealant type). The MEPDG spalling model does not contain any parameters related to dowel diameter or misalignment in either of these factors. The model addresses only spalling due to concrete degradation and age.

Since dowel misalignment due to reduced concrete cover does not greatly influence the aging or wearing of joints, incorporating dowel misalignment into the original MEPDG spalling model could not be rationally suggested. On the other hand, dowel misalignment that reduces the concrete cover to the extent that the dowels are exposed at the surface is a roadway safety concern and is therefore considered in this study (recommendations for concrete cover to minimizing the risk of such critical spalling are presented in Chapter 3).

IRI Model. The MEPDG IRI model considers changes in ride quality over time as a degradation of the initial smoothness due to transverse cracking, spalling, faulting, and pavement site conditions. The general equation for the IRI model is presented below to illustrate the compound effect of predicted transverse cracking, spalling, and faulting on prediction of pavement ride quality (AASHTO, 2008):

$$IRI = IRI_I + C1\ CRK + C2\ SPALL + C3\ TFAULT + C4\ SF \qquad (5)$$

where

C1 through C4 = weighting factors or coefficients and
IRI = predicted IRI, in./mi;
IRI_I = initial IRI, in./mi;
CRK = % slabs with transverse cracks (all severities);
SPALL = % joints with spalling (medium and high severities);
TFAULT = total joint faulting cumulated per mi, in.; and
SF = site factor.

If each of these components is affected by dowel misalignment in some fashion, then the IRI model will account for the effects of dowel misalignment on IRI. Therefore, the MEPDG IRI model can be adopted in its current form to account for the effects of dowel misalignment.

CHAPTER 3

Findings and Applications

This chapter describes the results of field studies, laboratory testing, and analytical modeling conducted in this project. These results were used to develop the design and construction guidelines provided as Attachment A to this report.

3.1 Field Testing

MIT Scan-2 data from 60 projects located in 17 states were used to evaluate typical values of dowel alignment and position. These data included measurements of over 2,300 one- or two-lane joints and more than 28,000 dowel bars. Data that appeared to have been affected by nearby metallic objects, such as tie bars or traffic loops, were not included in the analyses.

The relationship between dowel misalignment and pavement performance also was evaluated. Dowel misalignment was characterized by its type (e.g., embedment length, vertical translation or concrete cover, and rotational tilt) and magnitude. Pavement performance was characterized by observed distresses such as transverse joint faulting and transverse cracking. The performance of some joints also was evaluated using FWD testing. The results of these analyses are presented below.

3.1.1 Typical Misalignment

The misalignment levels measured in this study give insight into the level of alignment that can be achieved using current construction practices. The achievable level for which there is no observable effect on performance is used in the development of the guidelines. All rotational misalignments (i.e., horizontal skew and vertical tilt) are expressed as a deviation from alignment over 18 in. [457 mm], which is the length of a typical dowel.

3.1.1.1 Vertical Translation

Dowel bars are assumed to be embedded at the mid-depth of a slab. A vertical deviation from this position is considered vertical translation. Negative vertical translation indicates that the dowel bar is closer to the surface and positive vertical translation indicates that the dowel bar is closer to the base.

Average measured vertical translation for individual projects ranged from −1.1 in. to +0.9 in. [−28 mm to 23 mm]; the distribution of these averages is presented in Figure 3.1, which shows that, although 63% of the projects are within the typical DOT-specified vertical translation limits of ± 0.5 in. [±13 mm], it is possible for entire projects to have an average vertical translation level of more than 0.5 in [±13 mm]. Over 95% of the projects have an average vertical translation level within ± 1.0 in. [± 25 mm] of the slab mid-depth. This can be a result of using dowel baskets of incorrect height, the use of an improperly set DBI and/or concrete mix-related issues, or the placement of pavement that is thicker (or thinner) than specified. The vertical translation distribution of the dowel bars within each nominal thickness is shown in Table 3.1.

When absolute values are considered, the average vertical depth deviation for all projects is 0.46 in. [12 mm] and the standard deviation is 0.6 in. [15 mm].

As mentioned previously, some of the variability in vertical translation or concrete cover is due to differences between designed and as-built slab thicknesses, and the computation is based on the nominal design thickness. For example, if the design thickness is 10 in. [254 mm], then the dowel bar is expected to be located at a depth of 5 in. [127 mm]. However, if the as-built thickness is 10.24 in. [260 mm] and the dowel bar is located at mid-depth (5.12 in. [130 mm] from the pavement surface), then a deviation of +0.12 in. [3 mm] would be assumed. The vertical translation manifests itself most notably in reduction of the concrete cover either from the top or the bottom surface. Table 3.2 shows the average concrete cover, dowel depths, and corresponding standard deviations for various projects with nominal concrete thickness ranging from 8 to 12 in. [203 to 305 mm].

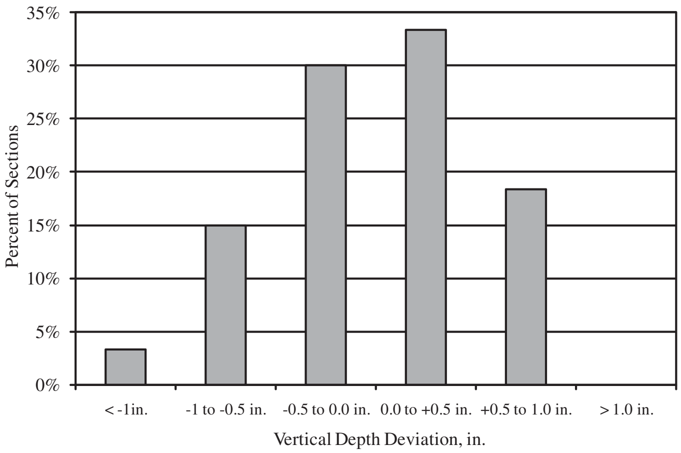

Figure 3.1. Measured vertical translation distribution.

3.1.1.2 Longitudinal Translation

The longitudinal center of a dowel bar is designed to be at the location of the transverse joint saw cut. Therefore, any deviation in longitudinal dowel placement with respect to the joint axis is considered longitudinal translation (i.e., reduced dowel embedment on one side of the joint). Key factors influencing longitudinal translation are joint marking and saw cut operations.

The average longitudinal translation for all projects was 0.86 in. [22 mm], and the standard deviations within individual projects ranged from 0.4 in. to 1.9 in. [9 mm to 49 mm]. This suggests that the dowel bars were placed in their accurate longitudinal positions in some projects and in varying longitudinal positions in other projects. The average standard deviation for all projects was 0.9 in. [23 mm]. The maximum average longitudinal translation was 1.9 in. [49 mm], resulting in a lowest average embedment length of 7.1 in. [180 mm] for the 18-in. [457-mm] long dowels.

The standard deviation of longitudinal translation for all of the individual dowels was 1.2 in. [30 mm]; Figure 3.2 shows the longitudinal translation distribution. Over 91 and 98% of all bars are within ±2 in. [50 mm] and ±3 in. [75 mm] from the transverse joint, respectively.

3.1.1.3 Horizontal Skew

The MIT Scan-2 unit determines the positions of the two ends of a dowel bar and computes the horizontal skew as a deviation from the longitudinal axis over the length of the dowel. The horizontal skew can be positive or negative depending on the horizontal angle of the dowel bar relative to the longitudinal joint. The absolute values were used for mean analysis and the actual values were used for standard deviation analysis.

Average absolute horizontal skew for individual projects ranged from 0.13 in. to 0.41 in. [3.3 mm to 10.4 mm], and the average absolute horizontal skew for all projects was 0.23 in. [5.9 mm]. The horizontal skew standard deviations for individual projects ranged from 0.1 in. to 0.34 in. [2.6 mm to 8.7 mm], and the average standard deviation was 0.19 in. [4.7 mm].

The average horizontal skew for all bars from all projects was 0.24 in. [6.1 mm] with a standard deviation of 0.21 in. [5.3 mm]. Less than 80% of all bars were within ⅜ in. [9 mm]. Figure 3.3 shows the horizontal skew distribution for all bars from all projects. Almost 90, 98, and 99.5% of the dowel bars have horizontal skew less than 0.50 in. [13 mm], 0.75 in. [19 mm], and 1.0 in. [25 mm], respectively.

3.1.1.4 Vertical Tilt

The MIT Scan-2 unit pinpoints the vertical positions of the two ends of a dowel bar and determines the vertical tilt as the vertical deviation from the longitudinal axis with respect to

Table 3.1. Vertical dowel translation for sections with different thicknesses.

		Concrete Thickness (in.)				
		8	**9**	**10**	**11**	**12**
Dowel Bar Statistics	**# of Projects**	3	7	11	26	5
	# of Dowel Bars	1036	4847	7321	9529	2388
	Dowel Diameter, in.	3 X 1.25	4 X 1.25; 3 X 1.5	3 X 1.25; 8 X 1.5	2 X 1.25; 24 X 1.5	5 X 1.5
	Construction	3 Basket	2 Basket; 5 DBI	1 Basket; 10 DBI	20 Basket; 6 DBI	3 Basket; 2 DBI
	Average Depth, in.	3.76	4.56	5.13	5.47	5.94
	Standard Deviation	0.38	0.57	0.49	0.69	0.46
Dowel Bar Deviation Distribution	**< -1 in.**	0.0%	0.0%	9.1%	3.8%	0.0%
	-1.0 to -0.5 in.	25.0%	10.0%	0.0%	23.1%	0.0%
	-0.5 to 0 in.	50.0%	40.0%	18.2%	23.1%	40.0%
	0 to 0.5 in.	25.0%	30.0%	54.5%	30.8%	40.0%
	0.5 to 1.0 in.	0.0%	20.0%	18.2%	19.2%	20.0%
	>1 in.	0.0%	0.0%	0.0%	0.0%	0.0%

Table 3.2. Measured depth of dowel bars from slab surface for various concrete thicknesses.

		Concrete Thickness (in.)				
		8	**9**	**10**	**11**	**12**
Dowel Bar Statistics	**Projects**	3	7	11	26	5
	Dowel Bars	1036	4847	7321	9529	2388
	Dowel Diameter, in.	3 X 1.25	4 X 1.25; 3 X 1.5	3 X 1.25; 8 X 1.5	2 X 1.25; 24 X 1.5	5 X 1.5
	Construction	3 Basket	2 Basket; 5 DBI	1 Basket; 10 DBI	20 Basket; 6 DBI	3 Basket; 2 DBI
	Average Depth, in.	3.76	4.56	5.13	5.47	5.94
	Standard Deviation	0.38	0.57	0.49	0.69	0.46
Dowel Bar Depth Distribution	**< 2.0 in.**	0.0%	0.0%	0.0%	0.0%	0.0%
	2.0 to 2.5 in.	0.1%	0.1%	0.0%	0.0%	0.0%
	2.5 to 3.0 in.	1.0%	2.8%	0.0%	0.0%	0.0%
	3.0 to 3.5 in.	26.4%	3.3%	0.8%	0.1%	0.0%
	3.5 to 4.0 in.	42.7%	5.4%	2.9%	1.4%	0.0%
	4.0 to 4.5 in.	27.2%	29.1%	3.9%	8.1%	0.4%
	4.5 to 5.0 in.	2.7%	38.3%	27.7%	16.3%	1.2%
	5.0 to 5.5 in.	0.0%	19.0%	46.1%	23.8%	13.1%
	5.5 to 6.0 in.	0.0%	1.6%	16.1%	28.5%	44.7%
	6.0 to 6.5 in.	0.0%	0.2%	2.2%	15.2%	27.9%
	6.5 to 7.0 in.	0.0%	0.1%	0.2%	5.8%	11.4%
	7.0 to 7.5 in.	0.0%	0.0%	0.1%	0.8%	1.3%
	7.5 to 8.0 in.	0.0%	0.0%	0.0%	0.0%	0.1%
	> 8.0 in.	0.0%	0.0%	0.0%	0.0%	0.0%

the length of the dowel. Although the vertical tilt can be positive or negative depending on the vertical angle of the dowel bar relative to the surface of the slab, the absolute values were used for mean analysis, and the actual values were used for standard deviation analysis.

Average absolute vertical tilt for individual projects ranged from 0.11 in. to 0.51 in. [2.9 mm to 13.1 mm], and the average vertical tilt for all projects was 0.24 in. [6.1 mm]. The standard deviation for individual projects ranged from 0.1 in. to 0.53 in. [2.7 mm to 13.5 mm], and the average standard deviation for all projects was 0.19 in. [4.9 mm].

The average vertical tilt for all bars from all projects is 0.23 in. [6 mm] with a standard deviation of 0.21 in. [5.4 mm]. These values are nearly identical to the horizontal skew values. Approximately 80% of all bars were within ⅜ in. [9 mm]. Figure 3.4 shows the vertical skew distribution for all bars from all projects. About 91, 98, and 99% of dowel bars had vertical tilt less than 0.50 in. [13 mm], 0.75 in. [19 mm], 1.0 in. [25 mm], respectively.

3.1.2 Effect on Pavement Performance

Distress data were collected for 37 pavement sections, many of which had almost no distresses. Some projects exhibited minor shallow surface spalling (less than 0.5 in. [13 mm] deep) that apparently did not result from dowel misalignment but

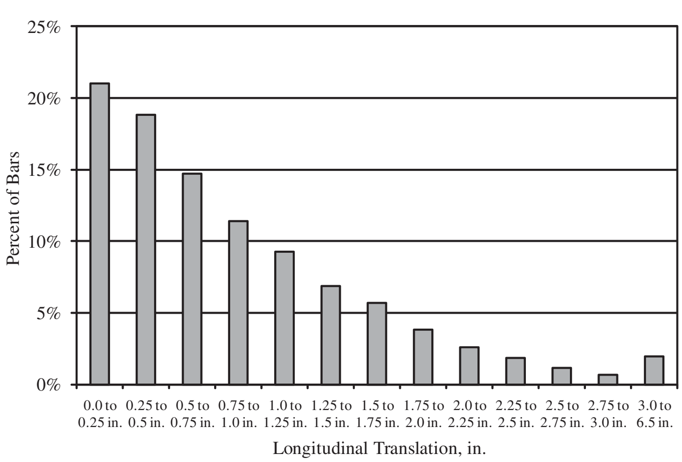

Figure 3.2. Distribution of longitudinal translation.

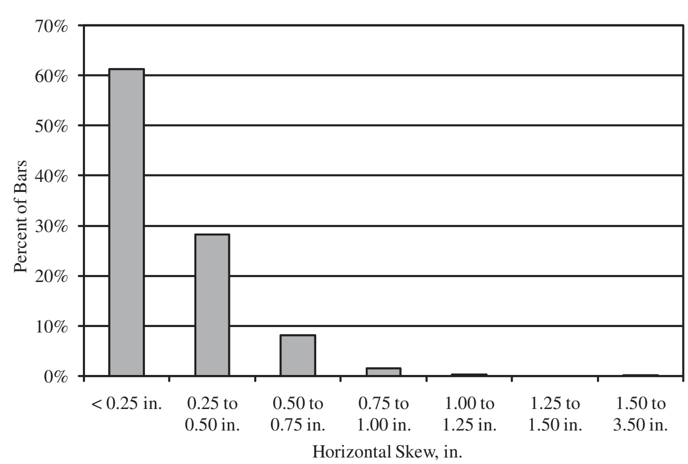

Figure 3.3. Distribution of horizontal skew.

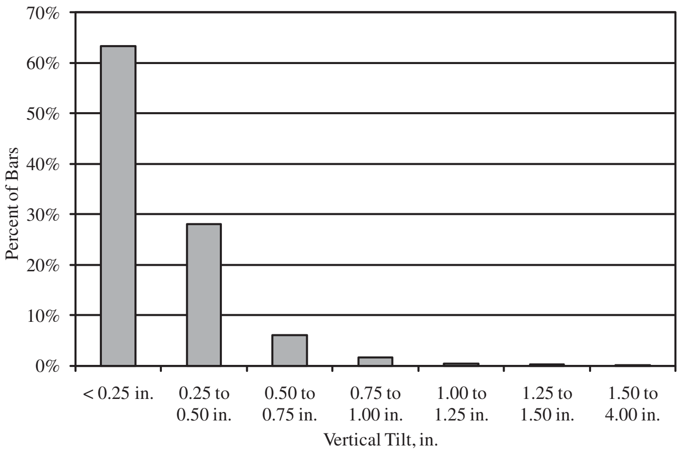

Figure 3.4. Distribution of vertical tilt.

was more likely due to saw cut timing. To evaluate the effect of dowel misalignment, the performance of sections with high and low levels of misalignments were compared.

3.1.2.1 Comparison of Section Performance

Dowel alignment of the 37 projects was classified in Groups A, B, and C with regards to the four misalignment categories: (1) vertical depth deviation, (2) longitudinal translation, (3) horizontal skew, and (4) vertical tilt. For analysis purposes of each misalignment category, projects with placement accuracy in the bottom third were placed in group C, projects with placement accuracy in the top third were placed in Group A, and the rest were placed in Group B.

Only two sections were included in Group C in all four categories, eight sections were included in Group C in three of the four categories, only one section was included in Group A in all four categories, and seven sections were included in Group A under three of the four categories.

Tables 3.3 and 3.4 give the percentage of slabs with different distresses for the different projects of Groups A and C, respectively. No clear trend was observed with respect to any of the distresses between the Group A and Group C sections. In fact, the only project that was included in Group A under all four categories (1-OH3) had the highest amount of transverse cracking (48% of the slabs).

Because of the differences between the projects in factors such as design, traffic, age, climate, and materials, project-level analyses were conducted to examine the development of distresses in the different slabs of a specific project containing joints with varying degrees of dowel misalignment.

3.1.2.2 Project-Level Analysis

Dowel alignment levels are not uniform within each project, so the effects of dowel misalignment on the distribution of distresses within the sections were analyzed. Two types of project-level analyses were conducted. In one analysis, joints or slabs with high levels of distresses and joints or slabs with no significant distresses were identified, and the dowel misalignments for the two groups of joints were then compared. The second analysis involved sorting the joints with respect to misalignment level from highest accuracy to lowest accuracy and comparing the distresses of those joints or adjacent slabs. Examples of these analyses for transverse cracking and joint faulting are presented here. Appendix B provides more detail on the analysis for these distresses and joint opening.

Transverse Cracking and Joint Spalling. Of the 37 sections surveyed, 26 projects did not exhibit any transverse cracking, and 33 projects did not exhibit any high-severity spalling at the joints. Only six projects (1-AZ3, 1-AZ9, 1-CA3, 1-IL2, 1-OH3, and 1-WI2) had a considerable amount of transverse cracking or high-severity joint spalling (greater than 10% of slabs or joints); they could be considered for project-level analysis. All other projects could not be used for project-level analysis because they did not have significant amounts of such distresses.

1-OH3 was not used for project-level analysis because it had an unusually high percentage of slabs with transverse cracking (48%), such that no difference in joint and slab performance could be attributed to the varying levels of misalignment (nearly all joints had a cracked adjacent slab). 1-CA3 was excluded from the analysis because it included dowel retrofitted joints, and most of the cracking probably occurred

Table 3.3. Slabs with distresses in Group A sections.

	Slabs with distress, percent									
Project	1 - AZ 8	1 - AZ 6	1 - WI 1	1 - MN 2	1 - MN 1A	1 - OH 1	1 - AZ 4	1 - WI 3	1 - IL 2	1 - MN 1B
Slabs Cracked (Transverse)	0	0	6	0	0	0	3	7	14	0
Spalling (Major)	0	0	0	0	0	0	0	15	3	0
Corner Breaks	0	0	0	0	0	0	0	0	0	0
Slabs Cracked (Longitudinal)	0	3	0	6	0	0	3	0	3	0
Joint FDR	0	0	12	0	0	0	0	0	0	0
Midpanel FDR	0	0	0	0	0	0	0	0	0	0

Table 3.4. Slabs with distresses in Group C sections.

	Slabs with distress, percent							
Project	**1 - NC 1**	**1 - NC 4**	**1 - OH 4**	**1 - WI 2**	**1 - NC 3**	**1 - IN 2**	**1 - CA 3**	**1 - OH 3**
Slabs Cracked (Transverse)	0	0	0	0	0	0	24	48
Spalling(Major)	0	3	0	40	0	0	0	0
Corner Breaks	0	0	0	0	0	0	6	0
Slabs Cracked (Longitudinal)	0	0	0	0	0	0	0	0
Joint FDR	0	0	0	0	0	0	0	0
Midpanel FDR	0	0	0	0	0	0	0	6

before the joints were retrofitted. Therefore, the analysis was performed on the other four projects (1-AZ3, 1-AZ9, 1-IL2, and 1-WI2).

Thirty percent of the slabs in project 1-AZ3 exhibited transverse cracking, and none of the joints had any major spalling. A statistical analysis was conducted to compare the dowel alignment of joints adjacent to slabs that exhibited transverse cracks with that of joints adjacent to slabs that did not exhibit any transverse cracking. The test section had 33 joints, 16 of which were adjacent to slabs with transverse cracking (Group A) and 17 of which were adjacent to slabs without any transverse cracking (Group B). Student's *t*-tests were conducted to determine whether there were any statistically significant differences between the two sets of joints with regard to the average absolute values of vertical and longitudinal translation, vertical skew, and horizontal tilt at the individual joints.

There was no statistical difference in average vertical translation, average longitudinal translation, or average vertical tilt between joints that are adjacent to slabs exhibiting transverse cracking and joints adjacent to intact slabs. However, there was a statistically significant difference between the two groups with respect to horizontal skew. Contrary to expectations, the joints adjacent to the intact slabs had higher levels of average horizontal skew than the joints adjacent to cracked slabs. This suggests that factors other than misalignment contributed to cracking. Moreover, the actual levels of misalignment of both groups are less than 0.32 in. [8 mm], which is well within typical specification tolerances, and should not cause joint lockup.

The analyses for test sections 1-AZ9, 1-IL2, and 1-WI2, presented in Appendix B, also showed that there is no statistically significant difference between the alignments of dowels in joints adjacent to cracked slabs and alignments of dowels adjacent to uncracked slabs for these sections.

Therefore, the results of the project-level analyses suggest that, within the nonextreme limits of dowel translations (vertical and horizontal) and rotations (vertical tilt and horizontal skew) measured in this study, there appear to be no differences in the amounts of transverse cracking and joint spalling as a result of dowel misalignment.

Faulting and LTE Analyses. Many of the evaluated projects had only small levels of faulting ranging from 0 to 0.1 in. [0 to 3 mm] at most of the joints. The low faulting could be attributed to the use of relatively large dowel bars (1.25- and 1.5-in. [35- and 38-mm] diameter) and the young age of the pavement sections. For the faulting analyses that follow, only older pavements (> 10 years) that exhibited some significant amount of faulting (mean faulting > 1 mm) were considered. Faulting measurements were taken in the wheel path and at the slab edge, and the maximum of the two values was used for analysis.

Vertical Translation. Analysis was conducted to compare faulting and LTE at joints with dowels that were centered within ±0.25 in. [±6 mm] (on average) of mid-depth with those that had dowels centered more than 1.0 in. [25 mm] closer (on average) to the pavement surface. The average vertical translation at each joint in each project was computed with respect to the mid-depth of the pavement. For a given project, the average faulting of all joints with the smaller level of vertical translation (Group 1) was paired with the average faulting of all joints with the higher level of vertical translation (Group 2). Ten projects were considered in this analysis. The same analysis procedure was used for joint LTE; five projects were considered.

The relatively high P-values suggest that there are no statistically significant differences in faulting or LTE between the two groups (i.e., joints with average vertical translation < ±0.25 in. [±6 mm] and joints with average vertical translation > 1.0 in. [25 mm] closer to the slab surface). Note that the faulting levels considered in this study were extremely low, and the vertical translations greater than 1.0 in. [25 mm] closer to the surface were observed on thick slabs with sufficient cover (i.e., the dowels were still 4 to 5 in. [102 to 127 mm] from the surface of the slab).

Longitudinal Translation. Analysis was conducted to compare faulting and LTE at joints with dowels that were centered within ±0.5 in. [13 mm] (on average) of the transverse joints with those that had dowels that were centered greater than 2.0 in. [51 mm] (on average) from the transverse joints. Although longitudinal translations over 3 in. [76 mm] were observed on some newly constructed pavements, these projects were not included in the performance analysis because of their age.

For a given project, the average faulting of all joints in Group 1 (joints with dowels that were centered within ±0.5 in. [±13 mm], on average, of the transverse joints) was paired with the average faulting of all joints in Group 2 (joints that had dowels that were centered greater than 2.0 in. [51 mm], on average, from the transverse joints). The same analysis was conducted for joint LTE. Fourteen projects were considered in this analysis, but only four projects provided sufficient data points for this paired *t*-test.

The high P-values suggest that there is no statistically significant difference in faulting or LTE between the two groups (i.e., joints with average longitudinal translation < ±0.5 in. [±13 mm] of the transverse joint and average longitudinal translation > ±2.0 in. [±51 mm] of the transverse joint). Note that the faulting levels measured in this study were extremely low, and none of the joints considered in this study had significant levels of average longitudinal translation (> 3 in. [76 mm]); the average minimum embedment length was 7 in. [178 mm] or more. Therefore, the effects of higher longitudinal translation on faulting and LTE cannot be determined on the basis of this data set. However, other studies (Burnham, 1999) showed that embedment lengths of 2.5 in. [64 mm] or less resulted in higher levels of faulting at these joints.

Vertical Tilt. Analysis was conducted to compare faulting and LTE at joints with dowels that had vertical tilts less than ±0.25 in. [±6 mm] (on average) with those that had dowels with vertical tilts greater than ±0.75 in. [±19 mm] (on average).

The average vertical tilt at each joint at each project was computed. For a given project, the average faulting of all joints in Group 1 (joints with dowels that had vertical tilts less than ±0.25 in. [±6 mm]) was paired with the average faulting of all joints in Group 2 (joints that had dowels with vertical tilts greater than ±0.75 in. [±19 mm]). The same analysis was conducted for joint LTE. Fourteen projects were considered in the analysis, but only four projects provided sufficient data points for this paired *t*-test.

The P-value of 0.024 calculated for faulting suggests that there is a statistically significant difference in faulting between the two groups (joints with average vertical tilt < ±0.25 in. [±6 mm] and joints with average vertical tilt > ±0.75 in. [±19 mm]). The joints with higher average vertical tilts had higher levels of average faulting. Note that the faulting levels are extremely low, and only a small number of joints at each section had average tilt > ±0.75 in. [±19 mm]. However, there was no statistically significant difference in LTE between the two groups as indicated by the relatively high P-value of 0.474.

Horizontal Skew. Analysis was conducted to compare faulting and LTE at joints with dowels that had horizontal skews of less than ±0.25 in. per 18 in. [± 6 mm per 457 mm] (on average) with those that had dowels with horizontal skews greater than ±0.75 in. per 18 in. [±19 mm per 457 mm] (on average).

The average horizontal skew at each joint at each project was computed. For a given project, the average faulting of all joints in Group 1 (joints with dowels that had horizontal skews of less than ±0.25 in. per 18 in. [± 6 mm per 457 mm]) was paired with the average faulting of all joints in Group 2 (those that had dowels with horizontal skews greater than ±0.75 in. per 18 in. [± 19 mm per 457 mm]). The same analysis was conducted for joint LTE. The same procedure was followed for joint LTE, where the average LTE of all joints in Group 1 was paired with the average LTE of all joints in Group 2 for each project. Fourteen projects were considered in this analysis, but only four projects provided sufficient data points for this paired *t*-test.

The P-value of 0.45 calculated for faulting suggests that there is no statistically significant difference in faulting between the two groups (joints with average horizontal skew < ±0.25 in. [± 6 mm] and joints with average horizontal skew > ±0.75 in. [± 19 mm]). The P-value of 0.11 calculated for LTE, however, suggests that there is moderate statistical significance in the differences in LTE between groups of joints with these different levels of horizontal skew. The joints with higher average horizontal skews had slightly lower joint LTE. It should be noted that (1) the faulting levels are extremely low, (2) only a small number of joints at each section had average skew > ±0.75 in. [±19 mm], and (3) a small number of sections provided data for LTE comparisons.

3.1.3 Summary of Field Study Analyses

Review of the field data from 60 projects indicated the following ranges for dowel misalignments in the majority of joints:

- Vertical translation: ± 0.5 in. [± 13 mm] for pavement that is 12-in. [305-mm] thick or less;
- Horizontal skew: ± 0.5 in. per 18 in. [± 13 mm per 457 mm];
- Vertical tilt: ± 0.5 in. per 18 in. [± 13 mm per 457 mm]; and
- Longitudinal translation: ± 2 in. for 18-inch dowels [± 51 mm per 457 mm].

These ranges of misalignment represent tolerances that are easily achieved in the field. Furthermore, dowel misalignment within these ranges on slightly higher levels does not appear to affect pavement performance significantly.

3.2 Laboratory Testing

This section summarizes the results of dowel pullout and shear tests conducted to evaluate the effects of dowel misalignment on joint lockup and dowel efficiency.

3.2.1 Modified Pullout Testing

3.2.1.1 Results Overview

It was observed that greasing or not greasing the dowels greatly influences pullout force as shown in Figure 3.5 for dowels embedded 6 in. in the same beam. Ungreased dowel requires a significantly higher force to cause pullout failure.

Embedment length also had a significant effect on pullout force. Figure 3.6 shows the pullout force versus relative dowel and displacement for two aligned dowels (to illustrate the variability in pullout force) and for a dowel with 3 in. [76 mm] of embedment. The figure shows that the dowel with lower embedment length required a lower pullout force than either of the aligned dowels and illustrates the large variability in pullout force.

Inspection of the interface between the dowel and concrete surface after each pullout test indicated slight surface paste chipping for dowels embedded with 1 in. [25 mm] of tilt and spalling damage for dowels embedded with 2 in. [51 mm] of rotation.

Figure 3.7 presents the distribution of the maximum forces required to pull out dowels embedded with different types and levels of misalignment in 4 groups. One group includes properly aligned, ungreased dowels with 6 in. [152 mm] of embedment. Another group includes properly aligned dowels, dowels with 2 in. [51 mm] of rotation, and dowels with 4 in. [102 mm] of rotation, all greased with 9 in. [229 mm] embedment. The third group is similar to the second group, except the dowels had 6 in. [152 mm] of embedment. The fourth group includes unrotated greased dowels with 2 and 4 in. [51 and 102 mm] embedment length and dowels with 3 in. [76 mm] of embedment and 2 in. [51 mm] of rotation.

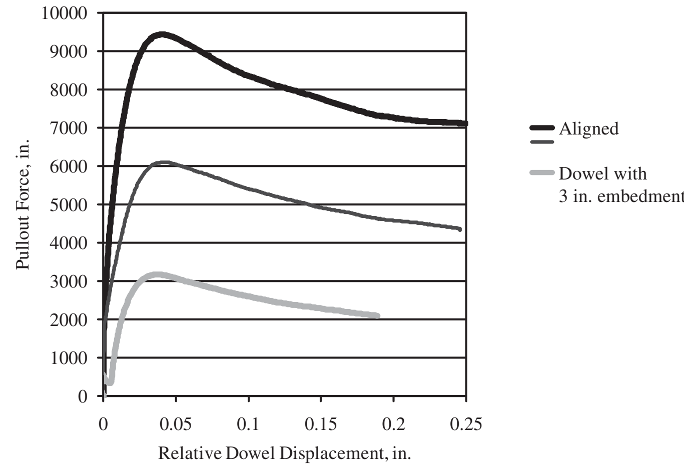

Figure 3.6. Effect of embedment length on pullout force versus displacement.

3.2.1.2 Trends

To test for statistically significant differences in pullout forces between the various groups of dowels, Student *t*-tests were conducted (details of all these tests are provided in Appendix C). The analysis confirmed that greased dowels with 6 in. [152 mm] of embedment require significantly lower pullout forces than similarly embedded ungreased dowels, and even greased dowels with 9 in. [229 mm] of embedment require a lower mean pullout force than that of ungreased dowels with 6 in. [152 mm] of embedment.

It can be observed in Figure 3.7 that rotational misalignment up to 2 in. per 18 in. [51 mm per 457 mm] dowel length did not have a significant effect on pullout force, but rotational

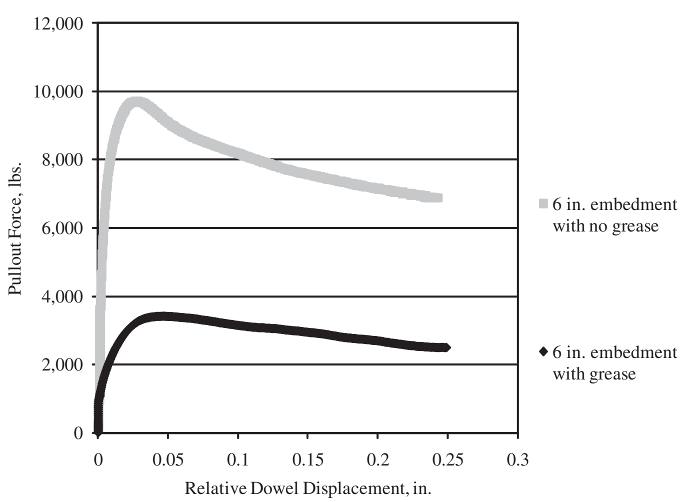

Figure 3.5. The effect of greasing dowels on pullout force versus displacement.

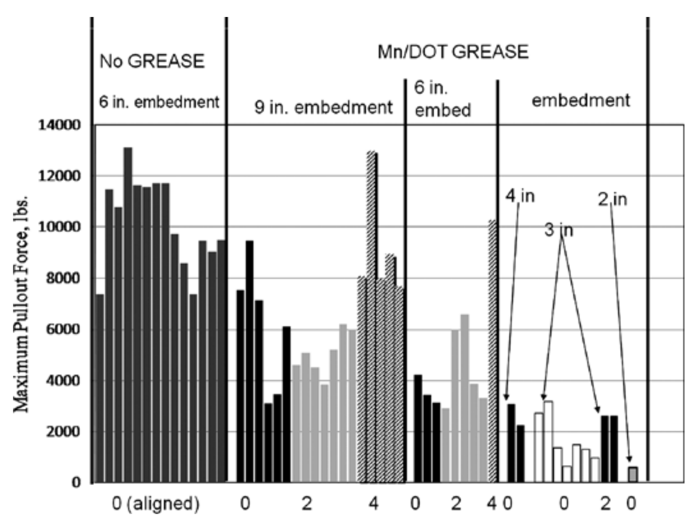

Figure 3.7. Distribution of maximum pullout forces for greased and ungreased dowels with varying degrees of misalignment.

misalignments of 4 in. per 18 in. [102 mm per 457 mm] dowel length had a significant effect. The analysis further illustrated that there is no statistically significant difference between the means of pullout forces for the aligned and 2 in. [51 mm] rotated dowels, while the 4 in. [102 mm] rotated dowels required significantly larger pullout forces. This suggests that dowels that are not properly greased or dowels that experience extreme rotation would increase longitudinal restraint at the joints.

Also, because of the reduced dowel-concrete contact area, a lower pullout force is required for a reduced embedment length. For example, the 9-in. [229-mm] embedded dowels require a significantly larger pullout force than the 3-in. [76-mm] embedded dowels.

It has been reported that some distresses may develop prematurely due to joint lockup caused by dowel misalignment (Tayabji, 1986). However, analysis of the pullout data obtained in this study has shown that moderate misalignment of individual dowels did not have a significant effect on the maximum required pullout force, and greasing the dowels prior to embedment reduced the required pullout force significantly.

3.2.2 Shear-Pull Testing

Although dowels transfer load through shear and moment mechanisms, numerous studies have shown that the shear mechanism dominates and the moment transfer mechanism can be neglected (Guo et al., 1996). The MEPDG structural analysis model assumes that dowels transfer the load in shear only.

The shear-pull test was used to evaluate the ability of dowels with various misalignments to resist a shear load after being subjected to the pullout test, and it simulates the ability of a dowel to transfer a wheel load (in shear) after the joint has been opened due to slab contractions caused by temperature change or shrinkage. Shear performance measures (such as shear stiffness and shear capacity) were used to evaluate the effectiveness of each dowel-concrete system in resisting applied shear loads. Shear capacity is defined as the load at which the concrete around the dowel experiences shear failure. Shear stiffness is defined as the relationship between changes in shear force in relation to changes in relative dowel displacement.

An example of shear force versus relative dowel displacement for dowels with 2, 3, 4, and 9 in. [51, 76, 102, and 229 mm] of embedment is shown in Figure 3.8, which illustrates how the ultimate shear can be affected by dowel misalignment. The figure shows that a 9-in. [229-mm] embedded dowel has a higher ultimate shear force than any of the dowels with a lower embedment length. Also, there is no loss of shear stiffness in the dowel with 4 in. [102 mm] of embedment until the system fails at a load of about 7 kips [31 kN]. For the 2 and 3 in. [51 and 76 mm] embedment cases, the dowel not only has a lower ultimate shear capacity (about 5 kips [22 kN]) but there is also a loss in shear stiffness from almost the beginning of load application.

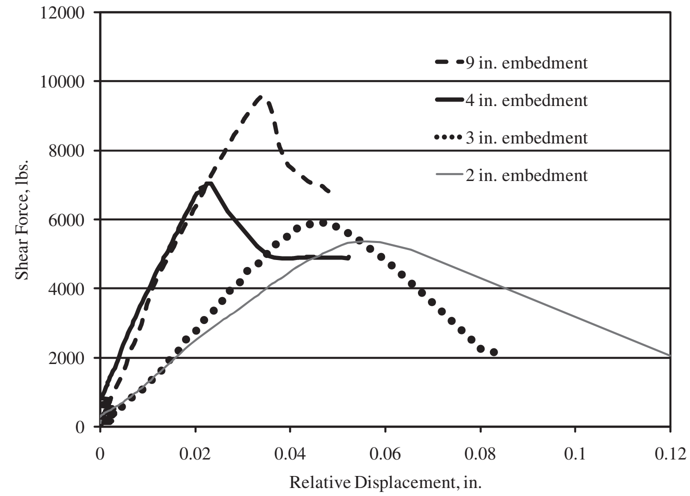

Figure 3.8. Illustration of reduced ultimate shear capacity and loss of stiffness with increased dowel misalignment.

3.2.2.1 Trends

Shear stiffness and ultimate shear capacity can be used to compare the effects of different types and levels of misalignments. For example, Figure 3.9 shows that vertical tilt of up to 2 in. [51 mm] did not have a significant effect on shear stiffness or ultimate shear capacity while 4 in. [102 mm] of vertical tilt greatly reduced the shear stiffness and ultimate shear capacity. This suggests that the shear capacity decreases as vertical tilt increases above 2 in. [51 mm].

Because the shear test was performed after the pullout test, the extreme loss in stiffness experienced by the 4-in. [102-mm] vertically-tilted dowel was probably caused in part by the

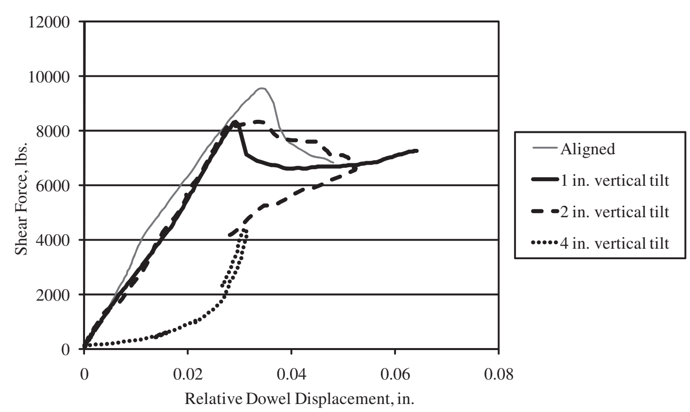

Figure 3.9. Vertical tilt shear pull shear capacity.

damage at the dowel-concrete interface that occurred during the pullout test.

Figure 3.10 shows the relative dowel displacement versus shear force for dowels with various embedment lengths. This figure shows that reducing the embedment length from 9 in. [229 mm] to 6 in. [152 mm] had little effect on dowel shear behavior, reducing the embedment length further to 4 in. [102 mm] had little effect on shear stiffness but resulted in a large reduction (26%) in shear capacity. Further reducing the embedment to 3 in. [76 mm] produced an additional 12% reduction in shear capacity (38% total reduction with respect to the 9-in. [229 mm] embedment condition) and a 63% reduction in shear stiffness. The reduction in embedment to 2 in. [51 mm] resulted in shear capacity and shear stiffness of 56% and 30%, respectively, of the values for 9 in. [229 mm] embedment.

The average shear capacity values for aligned dowels and dowels with concrete cover reduced from 3.25 to 1.25 in. [83 to 32 mm] due to vertical translation of 2 in. [51 mm] were 9.3 and 4.3 kips (42.2 and 19.1 kN, respectively). Thus, the ultimate shear capacity was reduced by more than 50% due to this reduction in concrete cover.

When comparing the shear force versus relative dowel displacements for an aligned dowel to that for a dowel with reduced embedment length, a dowel with reduced concrete cover, and a dowel with both reduced embedment length and reduced concrete cover, a compounding effect of misalignments is observed. The decrease in concrete cover results in a large decrease in ultimate shear capacity with little loss of shear stiffness while the reduction in embedment results in modest losses of both shear capacity and stiffness. However, the combination of both misalignments results in large reductions in both ultimate shear capacity and shear stiffness.

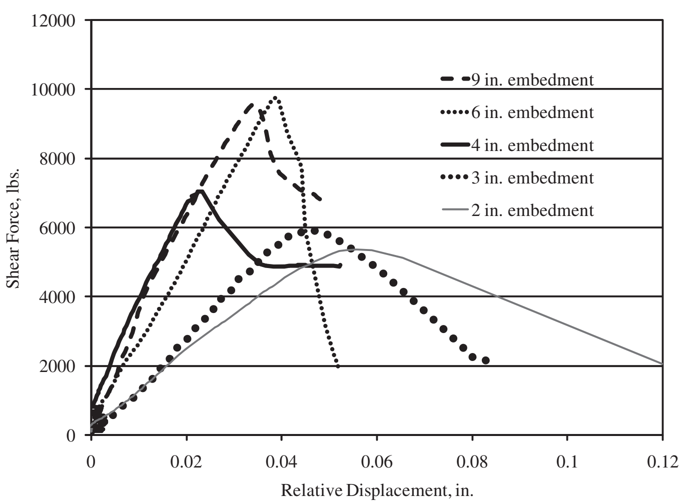

Figure 3.10. Effect of embedment length on shear force versus displacement.

The repeated shear load testing also revealed that the shear capacity of a dowel subjected to repeated loading was significantly lower than that for a dowel subjected to a single displacement-controlled loading. A comparison of shear force versus displacement for a 2 in. [51 mm] vertically translated dowel (i.e., with concrete cover of 1.25 in. [32 mm]) to that of an aligned dowel (i.e., with concrete cover of 3.25 in. [83 mm]) shows that (1) the shear stiffness of both dowels was reduced after 14,000 load cycles and (2) the stiffness of the 2 in. [51 mm] vertically translated dowel exhibited a secondary decrease as the load approached 3 kips [13 kN] (as shown by the rapid decrease in slope of shear load versus displacement curve above 2.5 kips [11 kN]). This observation suggests that failure of the dowel with reduced concrete cover and subjected to repeated loading started at loads approaching 3 kips [13 kN], which is significantly lower than the failure due to single load application of 4.7 kips [21 kN].

Single load tests showed that reduced dowel diameter causes lower shear stiffness. Similar shear performance trends were noted for aligned dowels and dowels with reduced concrete covers. As expected, lower shear capacity and shear stiffness were measured for the 1.25-in. [32-mm] diameter dowels than those for 1.5-in. [38-mm] diameter dowels with the same alignment.

The effects of dowel misalignment on performance observed in the laboratory study can be summarized as follows:

- Presence of greasing significantly affects pullout force.
- Dowel rotation as extreme as 2 in. per 18 in. [51 mm per 457 mm] does not affect dowel shear capacity.
- Reduction of dowel embedment length to 3 in. [76 mm] or less significantly affects shear capacity.
- Reduction in concrete cover from 3.25 to 1.25 in. [83 to 32 mm] causes large reduction in ultimate shear force.
- The combined effect of low concrete cover and low embedment length is greater than the effect of either one of the two misalignments.

3.3 Analytical Modeling

The ABAQUS beam-dowel model presented in Chapter 2 was used to perform computer simulations to augment the results of the laboratory study and to further investigate the effects of dowel misalignment on joint behavior.

3.3.1 Finite Element Beam Model

A validated beam model will allow consideration of dowel misalignment cases other than those tested in the laboratory. The shear force required to cause 0.05 in. [1.3 mm] of relative displacement was defined as the dowel shear capacity because the shear force required to cause this displacement according to the analytical model was similar to the shear capacity level

Table 3.5. Shear capacities for different levels of misalignment.

Longitudinal Translation		Vertical Translation		Vertical Tilt		Dowel Diameter	
Embedment, in.	Shear Capacity, lbs.	Concrete Cover, in.	Shear Capacity, lbs.	Rotation, in./18 in.	Shear Capacity, lbs.	Diameter, in.	Shear Capacity, lbs.
2	4900	3.25	10400	0	10400	1.0	5600
3	6600	4.25	12000	0.5	10300	1.125	6800
4	8000	5.25	13400	1.0	10200	1.25	8000
5	9100	7.25	14600	1.5	10300	1.375	9200
6	9900			2.0	9700	1.5	10400
9	10400						

causing failure in the laboratory (see Figure 2.13). Therefore, the ultimate shear forces for dowel misalignments that could not be investigated in the laboratory can be estimated analytically as the shear force corresponding to 0.05 in. [1.3 mm].

Table 3.5 gives the ultimate shear capacities for different levels of longitudinal translation, concrete covers, vertical tilt, and dowel diameter. The table shows that the shear capacity of a dowel is reduced by increasing levels of longitudinal translation (reduced embedment length), increased by increasing concrete cover, and not affected by the magnitude of vertical tilt. These results are similar to those observed from the laboratory tests except for the case of 4 per 18 in. [102 per 457 mm] tilt. It also should be noted that the beam test does not account for the effect of interaction with multiple dowels which could be important for vertical tilt. The data also show that reductions in dowel diameter reduce the shear capacity and shear stiffness.

3.3.2 Finite Element Slab Model

The laboratory tests indicated that dowel rotations up to 2 in. [51 mm] or less per 18 in. [457 mm] of dowel length did not result in significantly different dowel-concrete system responses under loading. A similar trend also was observed from the analytical simulations. However, previous studies (Khazanovich et al., 2001) have shown that rotations of adjacent dowels or multiple dowels in a single joint can influence the behavior of the joint. To investigate this effect, a slab model with multiple embedded dowels was considered. The material parameters obtained from the beam model were used to simulate dowel performance using the slab model for the following four cases of rotational combinations:

Table 3.6. LTE predictions for various levels of dowel rotation.

	LTE, percent			
Dowel Tilt, in./18 in.	**Case 1**	**Case 2**	**Case 3**	**Case 4**
0.5	84.5	86.0	85.7	84.9
0.75	84.1	85.3	85.3	84.4
1	82.0	83.5	85.1	83.2
1.25	81.0	82.9	85.1	-
1.5	79.5	82.1	85.2	82.3
Average LTE	82.2	84.0	85.3	83.7

- Case 1: All dowels rotated by the same amount, but adjacent dowels are rotated in opposite directions.
- Case 2: Each dowel tilted with the same magnitude and in the same direction.
- Case 3: The dowel in the wheel path aligned properly, and each other dowel rotated with the same magnitude and direction.
- Case 4: The dowel at the wheel path rotated, and each other dowel aligned properly.

For each case, joint LTE was calculated as the ratio of the corner deflection of the unloaded slab to the corner deflection of the loaded slab. Table 3.6 shows LTE for these four cases with different levels of dowel rotation. LTE is lower for the oppositely misaligned dowels especially as the dowel tilt exceeds 1 in. per 18 in. [25 mm per 457 mm]. Thus, although the mean misalignment level of Case 2 was higher than Case 1 (the mean misalignment is zero in Case 1), Case 1 results in a lower joint LTE. Therefore, the mean misalignment level is required for characterizing the translational misalignments, but the standard deviation of the dowels is required to describe the rotational joint misalignment. Table 3.6 also shows that, for the same magnitude of dowel tilt, the LTE is lower for Case 4 than for Case 3, especially at the higher misalignment levels. Thus, the alignment of the dowel in the wheel path (critical dowel) has a more significant effect on the LTE than the alignment of the other dowels in the joint.

3.4 Pavement Performance Modeling

3.4.1 Faulting

The equivalent dowel diameter concept requires the consideration of adjustment factors for each type of misalignment. The development of such factors is presented in this section.

3.4.1.1 Embedment Length Adjustment Factor

The finite element model was used to obtain the embedment length adjustment factor. A series of finite element runs were

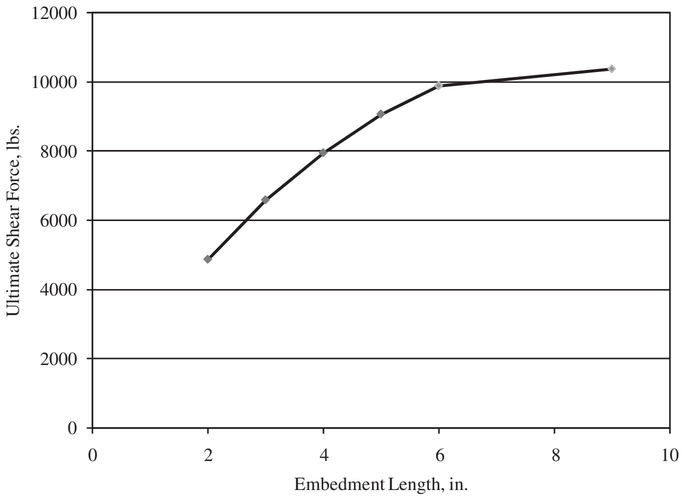

Figure 3.11. Dowel shear capacity versus embedment length for 1.5-in. [38 mm] diameter dowels.

made. The first series was performed for a 1.5-in. [38-mm] diameter dowel with embedment lengths varying from 2 to 9 in. [51 to 229 mm] and for dowel diameters ranging from 1.0 to 1.5 in. [25 to 38 mm] with a 9 in. [229 mm] embedment. Figures 3.11 and 3.12 present the relationships between embedment length and shear capacity and between dowel diameter and shear capacity, respectively.

By equating the shear capacity of a misaligned dowel with the shear capacity of an aligned dowel of reduced diameter, an equivalent reduced dowel diameter could be determined. For example, a 1.5-in. [38-mm] dowel with embedment of 5 in. [127 mm] has a shear capacity of 9000 lb [40 kN] (Figure 3.14), which is equivalent to that of a 1.4-in. [36-mm] diameter dowel with embedment of 9 in. [229 mm]. The adjustment factor then is calculated by dividing the corresponding dowel diameter by the nominal dowel diameter. Therefore, the adjustment factor for an embedment length of 5 in. [127 mm] is 1.4/1.5 = 0.933. Figure 3.13 presents the computed adjustment factor r_{emb} for a range of the embedment lengths L_{emb}. This relationship can be presented by the following equation:

$$r_{emb} = -0.010 L_{emb}^2 + 0.167 L_{emb} + 0.324 \qquad (6)$$

where L_{emb} is the embedment length in inches.

Equation 6 is applicable for embedment lengths between 2 and 6.9 in. [51 and 175 mm]. An adjustment factor of 1 should be assumed for embedment lengths greater than 6.9 in. [175 mm] and 0 for embedment lengths less than 2 in. [51 mm].

In cases where the embedment length of the dowels varies along the joint, this procedure will result in a different equivalent dowel diameter for each dowel in the joint. However, because the MEPDG faulting model assumes the same diameter for all dowels, a single equivalent dowel diameter that accounts for all dowels needs to be estimated.

Finite element modeling shows that the LTE of the joint is affected by misalignment of the dowel in the wheel path approximately as much as the combined effect of the same level of misalignments for all of the other dowels in the joint (see Table 3.6). Therefore, the following procedure should be used for a joint with variable dowel embedment lengths:

1. Compute an adjustment factor for each dowel in the joint.
2. Determine the mean adjustment factor for all of the dowels in the joint.
3. Determine the mean adjustment factor for the three dowels in the critical wheel path (for example, the right wheel path in the truck lane).
4. Use the average of the two values obtained in Steps 2 and 3 as the adjustment factor for the joint.

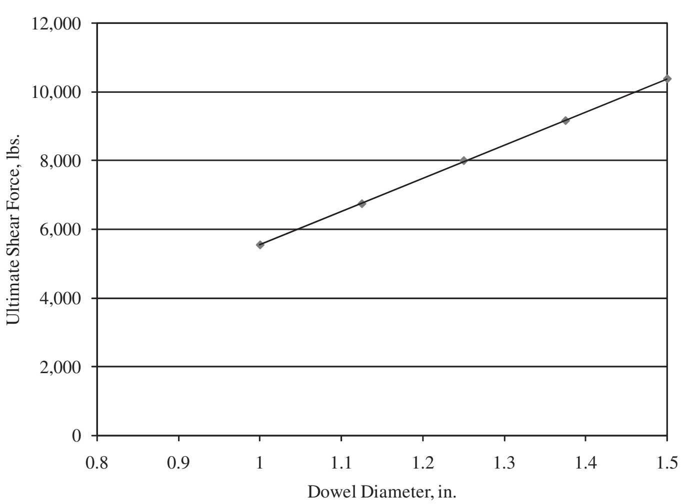

Figure 3.12. Dowel shear capacity for various dowel diameters (embedment length equal to 9 in. [229 mm]).

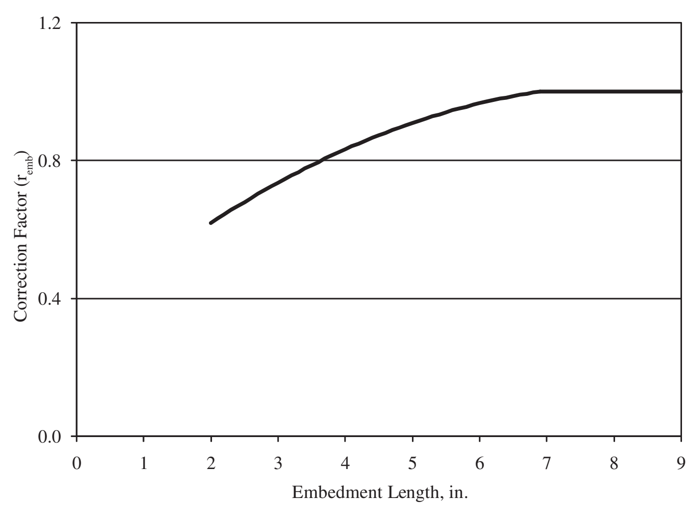

Figure 3.13. Adjustment factor (r_{emb}) versus embedment length.

3.4.1.2 Vertical Translation (Low Concrete Cover) Adjustment Factor

Laboratory beam testing was conducted only for nonvertically translated dowels and dowels with a vertical translation of 2 in. [51 mm] (representing concrete covers ranging from 1.25 in. to 3.375 in. [32 mm to 86 mm]). The finite element beam model was used to extend the results of the laboratory tests to concrete covers up to 7.25 in. [184 mm]. Dowels 1.25 in. and 1.5 in. [32 mm and 38 mm] in diameter were used in the analysis for concrete covers of less than 5.25 in. [133 mm], and only 1.5-in. [38-mm] diameter dowels were used for concrete covers of 5.25 in. [133 mm] and greater (because 1.5-in. [38-mm] diameter dowels are commonly used in thick pavements that result in these large concrete covers). This analysis produced the following relationship between dowel shear capacity and concrete cover:

$$DSC = \left(-153.3\,CC^2 + 2503\,CC\right) d_0 \qquad (7)$$

where
- DSC = the dowel shear capacity in lbs;
- d_0 = the dowel diameter in inches; and
- CC = the concrete cover in inches.

Figure 3.14 presents the relationship between concrete cover and shear capacity for two dowel diameters obtained from model simulations and the laboratory test data.

Figure 3.14 illustrates the reduction in shear capacity due to a reduction in concrete cover. The field measurements conducted in this study showed that vertical translation of up to 0.5 in. [13 mm] should be expected for concrete thicknesses of 12 in. [305 mm] or less, and a study conducted by MTO (MTO, 2007) concluded that translation of up to 1 in.

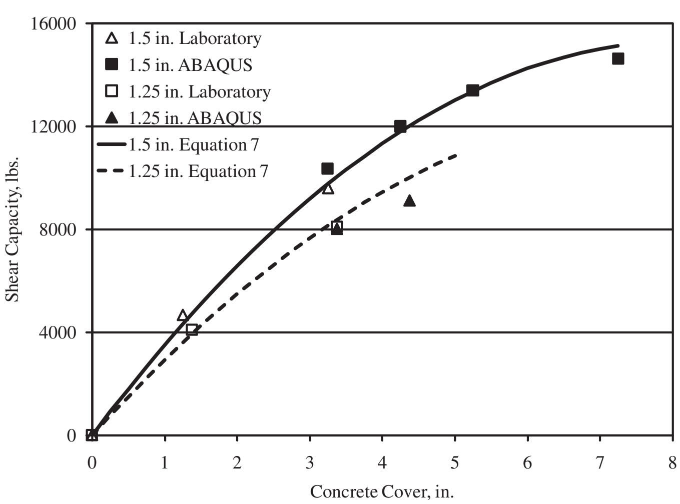

Figure 3.14. Shear capacity versus concrete cover.

[25 mm] should be expected for concrete thicknesses above 12 in. [305 mm]. Therefore, reduction in shear capacity should be considered only if the reduction in concrete cover exceeds the normal variability level, as represented by the following equation:

$$\Delta DSC = \left[-153.3\left(CC_{ref}^2 - CC^2\right) + 2503\left(CC_{ref} - CC\right)\right] d_0 \qquad (8)$$

where
- ΔDSC = the change in dowel shear capacity in pounds due to reduction in concrete cover beyond normal variability;
- CC = the concrete cover in inches; and
- CC_{ref} = the reference level concrete cover in inches.

CC and CC_{ref} can be computed as follows:

$$CC_{ref} = H_{PCC}/2 - d_0/2 - 0.5, \quad \text{for } H_{PCC} \le 12 \text{ in.}$$
$$CC_{ref} = H_{PCC}/2 - d_0/2 - 1.0, \quad \text{for } H_{PCC} > 12 \text{ in.} \qquad (9)$$
$$CC = H_{PCC}/2 - d_0/2 - \left|H_{PCC}/2 - D_{depth}\right|$$

where
- H_{PCC} = the designed PCC thickness in inches;
- d_0 = the designed dowel diameter in inches; and
- D_{depth} = the depth of the dowel in inches.

However, if the computed $CC_{ref} > 3.5\,d_0$, then $3.5\,d_0$ should be used as the CC_{ref}. This maximum value was selected based on the results showing no increase of dowel shear capacity for concrete cover exceeding 3.5 times the dowel diameter.

If CC is equal to or greater than the reference concrete cover (CC_{ref}), no reduction in effective dowel diameter should be considered (i.e., $r_{cc} = 1.0$). If CC is less than 2 in. [51 mm], the adjustment factor should be considered to equal 0 (i.e., $r_{cc} = 0$) because of high spalling potential. Effective dowel diameters should be considered for intermediate values.

Figure 3.15 presents the relationship between dowel diameter and dowel shear capacity obtained from finite element analysis for H_{PCC} equal to 8 in. [203 mm]. The relationship between the reduction in normalized shear capacity and the reduction in dowel diameter from d_0 to d is presented as follows:

$$\Delta DSC = 9628\left(d_0 - d\right) \qquad (10)$$

Thus, the adjustment factor for concrete cover r_{cc} can be presented as follows:

$$r_{cc} = \frac{d}{d_0} = 1 - \frac{1}{9628}\frac{\Delta DSC}{d_0} \qquad (11)$$

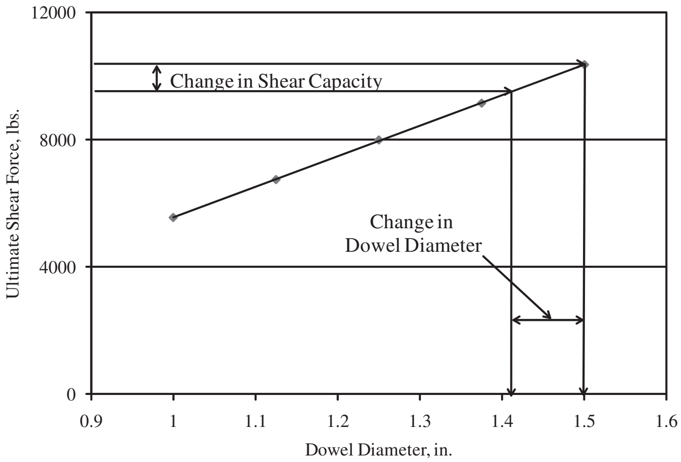

Figure 3.15. Shear capacity versus dowel diameter.

Substituting Equation 8 into equation 11 results in the following adjustment factor for each individual dowel:

$$r_{cc} = 1 - \left[-153.3 * (CC_{ref})^2 + 2503 * (CC_{ref}) + 153.3 (CC)^2 - 2503 * (CC) \right] / 9628 \quad (12)$$

However, the adjustment factor should be assumed to be zero for concrete covers less than 2 in. [51 mm] because low concrete cover can cause spalling around the dowel. Even if spalling is not visible, the ability of the dowel to transfer the load will be diminished. Figure 3.16 presents the calculated dowel diameter adjustment factors versus vertical translation for combinations of PCC thickness and dowel diameter. The figure indicates that the adjustment factor decreases as the vertical translation increases; the decrease is less drastic for thicker concrete slabs because of the larger concrete cover.

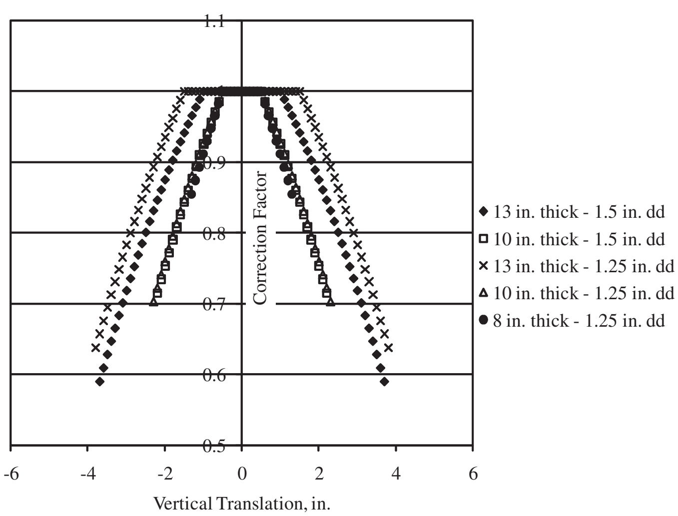

Figure 3.16. Concrete cover adjustment factors (r_{cc}) versus vertical translation for combinations of dowel diameter and PCC thickness.

Finite element analysis showed that the LTE near the slab corner is affected by the dowel in the wheel path as much as all of the other dowels in the joint combined. Therefore, the following procedure should be used for a joint with variable concrete cover:

1. Compute an adjustment factor for each dowel in the joint.
2. Determine the mean adjustment factor for all of the dowels in the entire joint.
3. Determine the mean adjustment factor for the three dowels in the critical wheel path (for example, the right wheel path in the truck lane).
4. Use the average of the two values obtained in Steps 2 and 3 as the adjustment factor for the joint.

3.4.1.3 Rotation (Horizontal or Vertical Tilt) Adjustment Factor

Dowel rotation in the form of vertical tilt and horizontal skew can have adverse effects on the performance of concrete pavement joints. Increased restraint to joint opening and closing due to dowel rotation may cause micro-damage and minor spalling around dowels (as observed in the laboratory tests) that reduce joint LTE. Laboratory tests and analyses have shown similar effects for vertical tilt and horizontal skew. Therefore, the equivalent dowel diameter concept can be applied in a similar manner to both types of misalignment.

The equivalent dowel diameter concept used to account for the effects of translational misalignments also is used to account for the effects of rotational misalignments. As noted earlier, relative rotations of dowels (e.g., opposite misalignment) have a greater effect on the joint performance than rotational magnitude. The effect of rotational misalignments on joint LTE was determined by analyzing slabs with multiple dowels. In this analysis, the corner deflections of the loaded and unloaded slabs were computed for various combinations of dowel misalignment. The joint LTE was calculated by dividing the unloaded slab corner deflection by the loaded slab corner deflections, and the nondimensional joint stiffness, *JStiff*, was determined using the following equation (Khazanovich and Gotlif, 2002):

$$JStiff = \left(\frac{\frac{1}{LTE} - 0.01}{0.012} \right)^{-1.17786} \quad (13)$$

in which LTE is expressed as a percentage.

Finite element analysis was performed for each of the four rotational misalignment cases described in Section 3.3.2, and the joint stiffness was determined. Linear regression analysis was used to develop the following relationship:

$$JStiff = JStiff_0 - 0.20623 \times MeanTilt - 0.61796 \times StDTilt - 0.86862 \times WPTilt \quad (14)$$

where

MeanTilt = the average tilt of the dowels in the joint in inches per 18 in.;
StDTilt = the standard deviation of the tilt of the dowels in the joint in inches per 18 in.; and
WPTilt = the maximum dowel tilt in the critical wheel path in inches per 18 in.

$JStiff_0$ is the computed stiffness of the joint with aligned dowels; this value is presented in Table 3.7 for each dowel diameter. These joint stiffness values account for the contributions of the dowels to the stiffness of the joint, but not those of aggregate interlock, foundation support, or other factors.

The joint LTE can be predicted using the following equation (Crovetti, 1994):

$$LTE = \frac{100\%}{1 + 1.2 * (JStiff)^{-0.849}} \quad (15)$$

Figure 3.17 presents the load transfer efficiencies using Equations 14 and 15 versus the load transfer efficiencies computed from the finite element analysis. These values correlate well.

Figure 3.18 shows the sensitivity of predicted LTE to the level of tilt for uniformly and oppositely tilted 1.25-in. [32-mm] diameter dowels in a joint. The LTE decreases with increases in tilt level. The LTE values are lower for oppositely tilted dowels than for uniformly tilted dowels. Similar observations were noted in earlier studies (Khazanovich et al., 2001).

The field study showed that construction practices should permit the installation of dowels with tilt no greater than 0.5 in. per 18 in. [13 mm per 457 mm] of dowel length. Such a level of misalignment did not affect pavement performance.

Table 3.7. Computed stiffness for various dowel diameters.

Dowel Diameter (in.)	$JStiff_0$
1	6.537
1.125	7.447
1.25	8.461
1.375	9.601
1.5	10.894

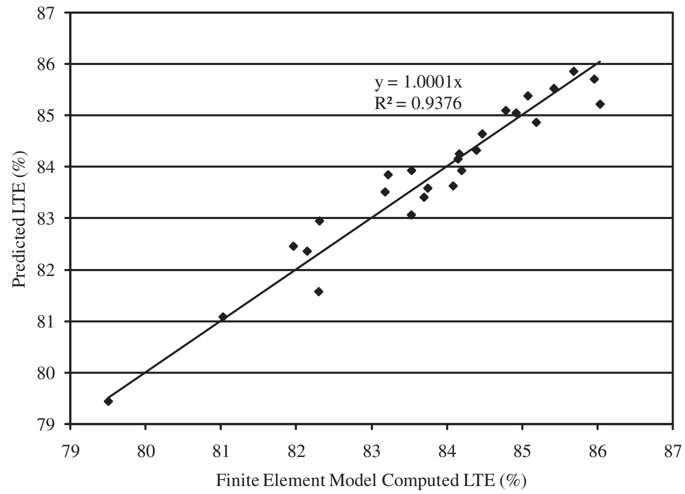

Figure 3.17. Computed versus predicted LTEs for various rotational misalignments.

Based on these observations, joints with oppositely misaligned dowels with rotation of 0.5 in. per 18 in. [13 mm per 457 mm] dowel length were used to represent the nominal condition. Thus, any combination of dowel misalignment that results in a LTE equal to or greater than the nominal LTE will not affect the pavement performance; rotations that result in less than the nominal LTE will have adverse effects on the joint performance.

Table 3.8 gives the nominal load transfer efficiencies obtained from the finite element slab model for various dowel diameters; lower LTE is obtained for smaller dowel diameters. The predicted LTE can be expressed in terms of the diameter of a properly aligned dowel, using the following relationship:

$$d = 0.0103e^{0.0582\,LTE} \quad (16)$$

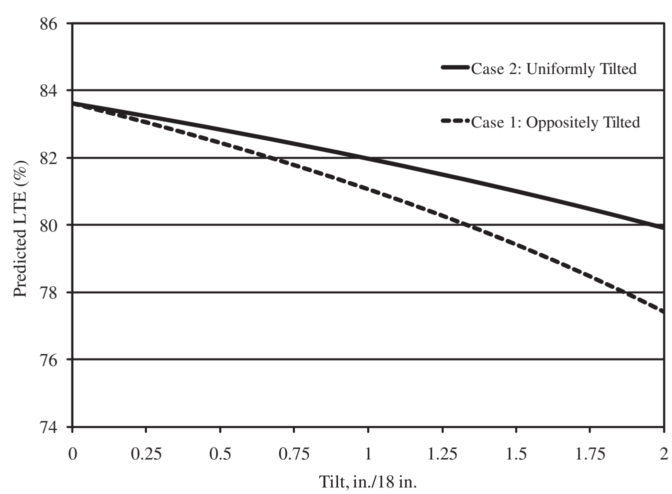

Figure 3.18. Predicted LTEs for oppositely and uniformly tilted dowels.

Table 3.8. LTE versus dowel diameter for slab model simulations.

Dowel Diameter, in.	LTE
0.75	0.73
1	1.01
1.125	1.14
1.25	1.26
1.375	1.36
1.5	1.46

By substituting Equation 15 into Equation 16, the adjustment factor for rotational misalignment (vertical tilt or horizontal skew), r_{rot}, is obtained as follows:

$$r_{rot} = \frac{d}{d_0} = \frac{0.0103}{d_0} \exp\left(0.0582\ LTE\right) \tag{17}$$

If the adjustment factor r_{rot} is greater than 1, a value of 1 should be assumed.

3.4.1.4 Faulting Prediction

After computing the adjustment factors for all misalignment types, the equivalent diameter for the doweled joint should be computed using Equation 4. The effect of dowel misalignment on the reduction of pavement life with respect to faulting and/or the reduction in predicted faulting reliability then can be determined using the MEPDG faulting model.

3.4.2 JPCP Cracking

Joint lockup can cause transverse cracking. As discussed in Section 2.3.3, if joint lockup causes significant longitudinal stresses, then it can be accounted for by the MEPDG cracking model.

Earlier studies identified the possibility of high longitudinal stresses as a result of rotationally misaligned dowels. One of these studies (Khazanovich et al., 2001) did not consider concrete damage in the immediate area of the dowel and overestimated the joint capacity to resist opening. Another study (Prabhu et al., 2006) indicated the possibility of large longitudinal stresses for unrealistically large joint openings.

To consider the effect of possible joint lockup on longitudinal stresses, the mid-slab stresses for aligned and misaligned dowels were considered. For the misaligned case, each dowel was tilted by 2 in. [51 mm] over its 18 in. [457 mm] length, and the dowels were configured so that adjacent dowels were rotated in opposite directions to provide the greatest potential for joint lockup. Figure 3.19 presents the computed longitudinal stresses for various joint openings that represent different degrees of thermal contractions.

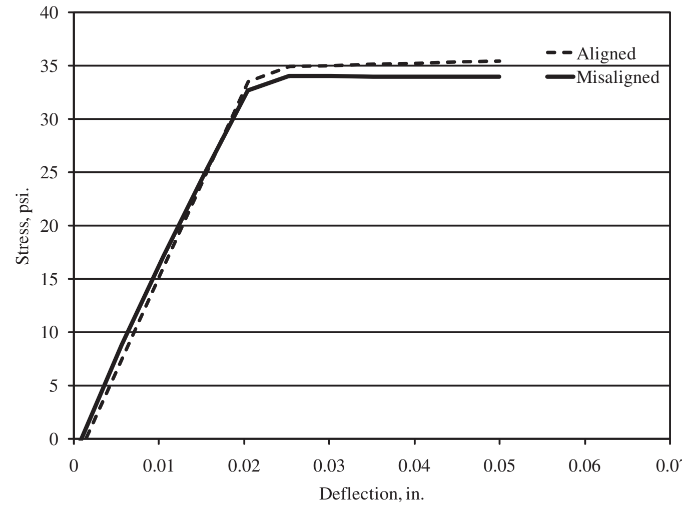

Figure 3.19. Longitudinal stresses for slabs between joints containing aligned and rotationally misaligned dowels.

For small joint openings, the slab with misaligned dowels experienced slightly higher stresses than the slab with aligned dowels at the joint. However, above a certain amount of joint opening, the slab with aligned dowels experiences consistently higher stresses than the slab with misaligned dowels. This phenomenon is caused by damage in the concrete surrounding the misaligned dowels, which reduces the ability of the joint to resist opening.

Based on these observations, it can be concluded that dowel misalignment itself is not a sufficient cause for joint lockup and it does not cause significant additional stresses in the longitudinal direction. Also, the MEPDG cracking model can be used without modification to account for dowel misalignment.

Several conditions were evaluated using the finite element slab model to investigate the effect of friction at the dowel-PCC interface. These conditions included a joint with aligned dowels and a joint with two levels of misalignment (0.25 in. [6 mm] over 18 in. [457 mm] and 2 in. [51 mm] over 18 in. [457 mm]) for very high friction between the dowel and PCC. Figure 3.22 shows the computed longitudinal stresses for these cases and the low friction cases for both an aligned and a misaligned dowel.

Figure 3.20 indicates that aligned dowels with high friction result in significantly higher longitudinal stresses and higher resistance to joint opening than misaligned dowels with low friction. Also notice that both the low and high friction cases for misaligned dowels did not converge for the entire range of joint openings (due to failure of concrete around the dowels). The analysis showed very high stress concentrations at the surface in the vicinity of the dowels, which may cause microcracking or micro-spalling in the concrete around the dowels and lead to joint lockup.

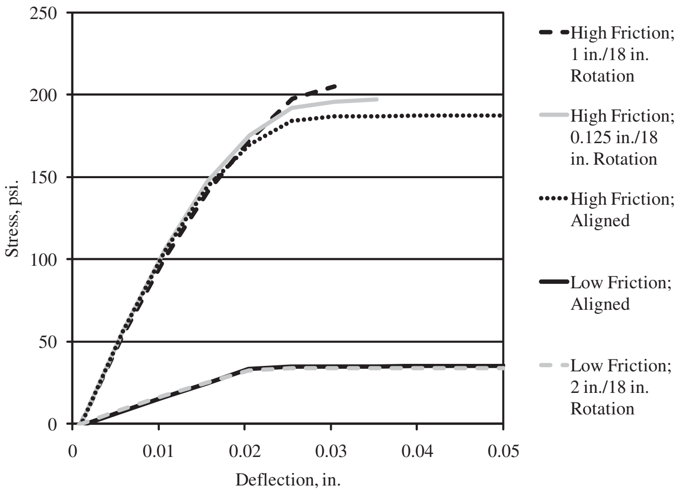

Figure 3.20. Effect of dowel-PCC friction on longitudinal concrete stresses.

While misalignment can result in higher longitudinal stresses, joint lockup is more greatly affected by friction between the dowel and PCC. The laboratory tests identified the lack of dowel grease as a cause for higher dowel-concrete interface friction and significant increase of the maximum pullout force.

3.4.3 Joint Spalling

In addition to joint performance considerations, the location of dowels with respect to the top PCC surface may present constructability and safety concerns. In some cases, joints are not saw cut to the prescribed depth to avoid cutting through the dowels located too close to the surface. In this case, joints will not be formed and random cracking occurs. Also, a combination of vertical translation and tilt may result in low concrete cover at the end of the dowel. This condition may cause a high stress concentration in the concrete at the dowel end, possibly leading to spalling and exposure of the dowel to the pavement surface.

To address safety concerns related to the low concrete cover, it is recommended to saw cut through the dowels at the joint if any dowel end is located within 2 in. [51 mm] of the top pavement surface. This minimum concrete cover requirement is supported by the findings of a full scale laboratory study in which a slab with 2 in. [51 mm] of concrete cover above the dowel performed as well as a slab with 3 in. [76 mm] of cover for up to 10 million load cycles (Odden et al., 2003). Also, the laboratory testing conducted in this project showed that a dowel with 1.25 in. [32 mm] of concrete cover sustained a shear force of 4.5 kip [20 kN], which is greater than the force required to be transferred by the critical dowel in a pavement joint loaded by a 60-kip [267 kN] tandem axle load (based on ISLAB2000 analysis).

The minimum recommended concrete cover should allow for adequate consolidation of concrete around dowels and may be increased for aggregate with maximum size greater than 1 in. [25 mm] based on local experience. Also, the minimum concrete cover may be increased if high possibility for dowel corrosion exists. If the concrete cover is less than the minimum required concrete cover, the equivalent dowel diameter should be set equal to zero (i.e., undowelled joint is assumed.)

3.4.4 Pavement Performance Prediction

The procedure for predicting pavement performance based on the measured dowel misalignment level requires that an equivalent dowel diameter be determined for each joint in a pavement using the MEPDG procedures. The following observations were considered in formulating the performance prediction procedure:

- The MEPDG prediction models were calibrated using the data contained in the LTPP database for 500-ft [152-m] long pavement sections.
- Joints with severe dowel misalignment that are concentrated in a certain portion of the pavement section will have a greater effect on performance than similar joints distributed randomly along the pavement project.
- Nondestructive dowel location devices could be used to investigate dowel misalignment in pavement projects.
- The equivalent dowel diameter of each joint can be determined using the equations provided in Chapter 3.
- The mean value of a pavement design parameter (pavement thickness, subgrade resilient modulus, etc.) along the section is used.

The following procedure is suggested for analyzing the effects of dowel misalignment on the performance of a uniform pavement project:

1. Use dowel alignment measurements to calculate the equivalent dowel diameter in each joint of the pavement project using the procedure described in Section 3.4.1.
2. Establish “uniform sections” approximately 500 ft. [152 m] long for the purposes of analysis and evaluation such that all joints in the section have similar equivalent dowel diameters. A series of several joints in any section with relatively uniform equivalent dowel diameters that are substantially different from the others in uniform sections may be evaluated as a separate uniform section.
3. Compute the mean equivalent dowel diameter for each section. Two or more adjacent sections with no significant difference in equivalent dowel diameters can be combined into a single section.

4. Perform MEPDG computations for each uniform section using the calculated mean equivalent dowel diameter for the section.

If certain adjustment measures such as dowel retrofitting are performed, the effective dowel diameters of the retrofitted joints should be recalculated and the pavement performance predictions computed.

3.5 Examples of Application of The Equivalency Concept

3.5.1 Example 1. Assessment of a Single Joint

The following example illustrates the calculation of the effect of dowel misalignment on joint performance for a joint in an 11-in. thick pavement. The joint is assumed to contain 12 dowels with 18 in. [457 mm] length and 1.5 in. [38 mm] diameter with the following features:

1. The saw cut is 4 in. [102 mm] away from the designed location, resulting in 4 in. [102 mm] of longitudinal translation and 5 in. [127 mm] of embedment length for all dowels.
2. The dowel basket used for the placement was 0.75 in. [19 mm] taller than was required for the mid-depth dowel placement, resulting in 0.75 in. [19 mm] vertical translational displacement towards the pavement surface and reduced concrete cover from 4.75 in. to 4 in. [121 mm to 102 mm] for all dowels.
3. The dowels were placed with the rotational misalignment (vertical tilt and horizontal skew) given in Table 3.9.

The procedure for determining the equivalent dowel diameter for this joint involves the calculation of four adjustment factors corresponding to the types of dowel misalignment assumed in this example.

Table 3.9. Assumed dowel misalignments.

Dowel Bar Number	Vertical tilt, in./18 in.	Horiz. Skew, in./18 in.
1	-0.44	-0.26
2	0.50	-0.32
3	-0.34	-0.32
4	-0.80	-0.38
5	-0.54	-0.48
6	1.46	-0.27
7	-0.54	-0.39
8	0.46	-0.33
9	-0.54	-0.47
10	-0.54	-0.43
11	-0.54	-0.44
12	-0.54	-0.42

3.5.1.1 Embedment Length Adjustment Factor

Since the embedment length is greater than 2 in. [51 mm] and less than 6.9 in. [175 mm], the adjustment factor for the longitudinal translation and related reduction in embedment length is calculated using Equation 6 as follows:

$$r_{emb} = -0.010(5)^2 + 0.167(5) + 0.324 = 0.909$$

3.5.1.2 Vertical Translation (Low Concrete Cover) Adjustment Factor

The reference concrete cover and the actual concrete cover (CC) are calculated using Equation 9, as follows:

$$CC_{ref} = \frac{11}{2} - \frac{1.5}{2} - 0.5 = 4.25 \text{ in.}$$

$$CC = \frac{11}{2} - \frac{1.5}{2} - \left|\frac{11}{2} - 4.75\right| = 4 \text{ in.}$$

CC_{ref} is also limited to a maximum of three times the dowel diameter, or 4.5 in. [114 mm] in this example. Thus, the calculated value for CC_{ref} of 4.25 in. [108 mm] is used. The adjustment factor for the loss in concrete cover is calculated using Equation 12 as follows:

$$r_{cc} = 1 - \left[-153.3 * (4.25) + 2503 * (4.25) + 153.3 * (4)^2 - 2503 * (4)\right] / 9628 = 0.968$$

3.5.1.3 Vertical Tilt Adjustment Factor

For the vertical tilt values provided in Table 3.10, mean vertical tilt of 0.2 in. [5 mm], standard deviation of the vertical tilt of 0.633 in. [16 mm], and wheel path dowel vertical tilt of 0.5 in. [13 mm] were calculated. The joint stiffness can be calculated using Equation 14 as follows:

$$JStiff = 10.8942 - 0.20623 \times (0.2) - 0.61796 \times (0.633) - 0.86862 \times (0.5) = 10.03$$

The LTE of the joint can be calculated using Equation 15 as follows:

$$LTE = \frac{100}{1 + 1.2(10.03)^{-0.849}} = 85.51\%$$

The adjustment factor for vertical tilt can be obtained from Equation 17 as follows:

$$r_{vt} = \frac{0.0103}{1.5}\exp(0.0582 \times 85.51) = 0.995$$

3.5.1.4 Horizontal Skew Adjustment Factor

For horizontal skew values provided in Table 3.10, mean horizontal skew of 0.38 in. [10 mm], standard deviation of the horizontal skew of 0.073 in. [1.9 mm], and maximum wheel path dowel horizontal skew of 0.32 in. [8 mm] were calculated. The joint stiffness can be calculated using Equation 14 as follows:

$$JStiff = 10.8942 - 0.20623 \times (0.38) - 0.61796 \times (0.073) - 0.86862 \times (0.32) = 10.49$$

The LTE of the joint can be calculated using Equation 15 as follows:

$$LTE = \frac{100}{1 + 1.2(10.49)^{-0.849}} = 85.98$$

The adjustment factor for horizontal skew can be obtained from Equation 17 as follows:

$$r_{hs} = \frac{0.0103}{1.5}\exp(0.0582 \times 86.03) = 1.02$$

Because the adjustment factor should not exceed 1, an adjustment factor of 1.0 should be assumed.

3.5.1.5 Assembly of Calculated Adjustment Factors

The equivalent dowel diameter (d_{eq}) for the joint is obtained by multiplying the original dowel diameter (d_0) by the adjustment factors for concrete cover, embedment length, vertical tilt, and horizontal skew as follows:

$$d_{eq} = r_{emb} \times r_{cc} \times r_{vt} \times r_{hs} \times d_0 = 0.909 \times 0.968 \times 0.996 \times 1 \times 1.5 = 1.31 \text{ in.}$$

Since the concrete cover for each dowel was greater than the minimum required concrete cover, no further reduction of the equivalent dowel diameter is needed. Therefore, to account for the effects of the misalignment in this joint, the pavement should be treated as if it had dowels with a diameter of 1.31 in. [33 mm] (and not the actual 1.5-in. [38-mm] diameter).

3.5.2 Example 2. Assessment of a Pavement Section

The following example illustrates the calculation of the effect of dowel misalignment on the performance of a 540-ft. [165-m] pavement section with an 11 in. [279 mm] thickness. The pavement section has 30 joints, each of which contains 12 dowels with 18 in. [457 mm] length and 1.5 in. [38 mm] diameter. The pavement was designed for the following performance criteria (after 20 years at 90 percent reliability):

- Transverse cracking not to exceed 12% of cracked slabs.
- Mean joint faulting not to exceed 0.12 in. [3 mm]
- IRI not to exceed 190 in./mile [3.0 m/km].

The equivalent dowel diameters were calculated for each joint (results are shown in Table 3.10). Because the pavement section is less than 1000 ft [305 m], the mean equivalent dowel diameter was computed for the entire pavement section resulting in 1.41 in. [36 mm]. This equivalent dowel diameter was then used in an MEPDG simulation to predict faulting and IRI for the project. Figures 3.21. and 3.22 present the predicted faulting and IRI, respectively, for the as-designed pavement (dowel diameter of 1.50 in. [38 mm]) and for a similar pavement with 1.41 in. [36 mm] dowels.

These results indicate that the predicted faulting and IRI of the project are within the specified acceptance thresholds. However, analysis of the MEPDG run output files (not presented here) showed that because of dowel misalignment the reliability of faulting and IRI not exceeding the performance threshold decreased from 96.7 to 91.9% and from 92.5 to 91.0%, respectively.

Table 3.10. Equivalent dowel diameter for each joint in the pavement section.

Joint #	Equivalent Dowel Diameter (in.)	Joint #	Equivalent Dowel Diameter (in.)	Joint #	Equivalent Dowel Diameter (in.)
1	1.31	11	1.5	21	1.21
2	1.5	12	1.22	22	1.5
3	1.41	13	1.5	23	1.5
4	1.14	14	1.5	24	1.27
5	1.5	15	1.49	25	1.5
6	1.1	16	1.5	26	1.5
7	1.5	17	1.5	27	1.5
8	1.5	18	1.23	28	1.5
9	1.5	19	1.05	29	1.37
10	1.5	20	1.5	30	1.5

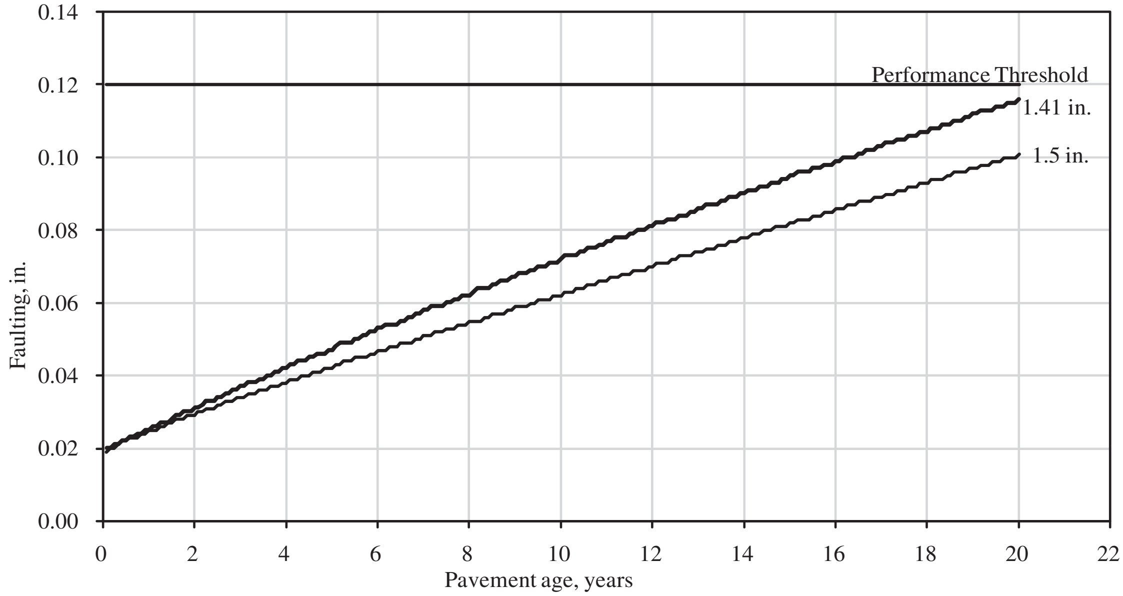

Figure 3.21. Predicted faulting for the as-designed pavement project.

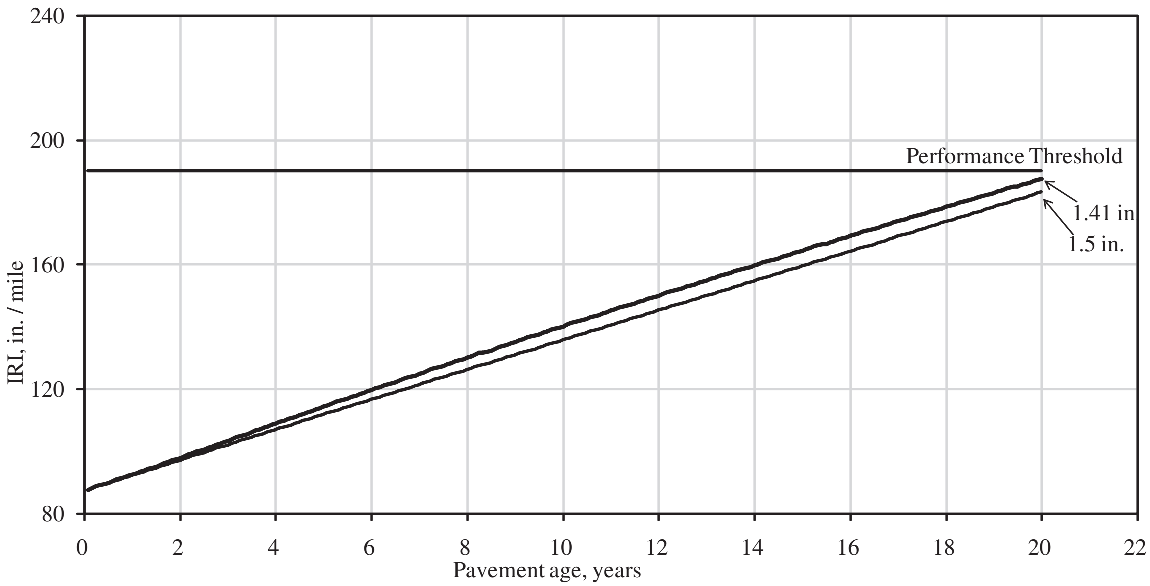

Figure 3.22. Predicted IRI for the as-designed pavement project.

CHAPTER 4

Conclusions and Suggested Research

4.1 Conclusions

This report documents the field evaluation, laboratory testing, finite element modeling, and methodology used to develop mechanistic-based dowel alignment guidelines suitable for use by highway agencies, consultants, contractors, and others involved in the design and construction of concrete pavements.

Measurement of misalignment (and associated distress) of more than 35,000 dowels in more than 2,300 transverse joints of 60 projects in 17 states indicated the following ranges for dowel misalignment of most joints:

- Longitudinal translation: ± 2 in. [51 mm] over 18 in. [457mm] dowels.
- Vertical translation: ± 0.5 in. [13 mm] for pavements 12 in. [305 mm] or less in thickness.
- Rotational components (horizontal skew and vertical tilt): each less than 0.5 in. [13 mm] over 18 in. [457 mm] dowels.

These levels of misalignment generally have no significant effects on pavement performance.

Extensive laboratory testing was conducted to evaluate the effect of dowel misalignment on performance parameters such as pullout force, shear capacity, and shear stiffness. These tests indicated the following:

- Extreme longitudinal and vertical translation can cause significant reductions in shear capacity.
- A combination of low concrete cover and low embedment length has a more adverse effect on dowel performance than either one of the two misalignments.
- Dowel rotations of up to 2 in. over 18 in. [51 mm over 457 mm] length have a negligible effect on pullout and shear performance measures.
- Pullout of ungreased dowels requires a significantly higher force than for greased dowels, suggesting that a lack of grease may restrain a doweled joint from opening and closing and cause joint lockup.

Using the data derived from the laboratory tests, a finite element model was calibrated and used to analyze a broader range of dowel misalignment combinations and magnitudes. The field evaluation indicated no strong links between small amounts of dowel misalignment and performance in terms of faulting, spalling, or panel cracking. However, the laboratory testing and analytical modeling determined that dowel misalignment could reduce dowel shear capacity and its ability to transfer a load and can have the following effect on pavement distresses:

- Transverse cracking. Dowel misalignment is not a primary cause or contributor to the development of transverse cracking. The increase in longitudinal stresses caused by dowel misalignment has a smaller effect in cracking than variability in other parameters (concrete slab thickness, concrete strength, joint spacing, dowel-concrete friction, etc.).
- Joint faulting. Any type of dowel misalignment (translational or rotational) above a certain magnitude contributes to an increase in faulting potential. The dowel shear capacity and joint stiffness decreases as the level of misalignment increases. Dowel misalignment has a similar effect on joint performance as a reduction in the diameter of dowels. Therefore, the *equivalent dowel diameter* concept is appropriate for predicting performance for pavements with misaligned dowels.
- Joint spalling. A reduction in concrete cover because of vertical translation and/or tilt beyond a critical level increases the potential for spalling development.
- IRI. Because dowel misalignment increases faulting and spalling potential, it will affect ride quality and IRI.

An MEPDG-based procedure was developed to quantify the effect of dowel misalignment on pavement performance. In this procedure, an equivalent dowel diameter is calculated for the joint based on type and level of dowel misalignment in a joint. The mean equivalent dowel diameter is calculated for each section and is used in MEPDG analysis to predict pavement distresses.

Guidelines for dowel alignment have been prepared and are included as Attachment A to this report. These guidelines provide information on measuring dowel misalignment, quantifying the effects of misaligned dowels on pavement performance, determining critical levels of dowel misalignment, and the means for preventing dowel misalignment and mitigating or remedying the effects of misaligned dowels.

The finite element analysis confirmed the findings of the laboratory testing that PCC-dowel friction and/or bond strength due to lack of proper bond breaker or dowel corrosion may cause more restrain to joint opening and closing than dowel rotational misalignment of typical levels.

4.2 Suggested Research

Although the findings of this project were based on a significant amount of field and laboratory measurement and finite element analysis, additional studies would help improve these findings and the recommended guidelines. Such studies may include the following:

1. Evaluation of in-service pavement sections with high misalignment levels after they have been exposed to traffic to determine the effect of these misalignments on the long-term pavement performance and further evaluate the equivalent dowel diameter concept.
2. Laboratory investigations of the influence of concrete mixtures, curing procedures, and other construction factors on misalignment.
3. Investigation of approaches and concepts for improving dowel placement.
4. Investigation of the mechanisms associated with joint lockup and the premature cracking and spalling in the proximity of transverse joints.

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ATTACHMENT A

Recommended Guidelines for Dowel Alignment in Concrete Pavements

The proposed guidelines are the recommendations of NCHRP Project 10-69 staff at the University of Minnesota. These guidelines have not been approved by NCHRP or any AASHTO committee or formally accepted for adoption by AASHTO.

Introduction and Background

Transverse joints are designed to allow slab movements due to shrinkage and thermal expansion/contraction while controlling the location and shape of slab cracks. Dowels are installed in these joints to improve load transfer capacity across the joints, thereby reducing slab deflections and stresses.

Dowels must be properly sized and placed to carry applied loads and minimize longitudinal restraint (i.e., to allow joints to open and close, as needed) and they must be fabricated for durability (e.g., be resistant to corrosion or chemical attack). Dowels that are not located or oriented properly are called "misaligned" dowels. Misaligned dowels may not provide adequate load transfer capacity and/or may prevent the joint from opening and closing properly, resulting in premature pavement deterioration (e.g., joint faulting, spalling, etc.).

Pavement dowels are generally installed using pre-fabricated baskets or cages (which are placed on grade before concrete placement) or by using a mechanical dowel bar inserter (mounted on the paving machine). Inspections of pavements in several states have shown that dowel misalignment generally occurs with both installation methods. These inspections have also shown that typical levels of misalignment do not always result in premature pavement distress.

Requirements for dowel alignment were recently introduced based on limited in-service alignment and performance data (MTO, 2007; FHWA, 2007). The guidelines presented here are based on findings from field performance evaluation, laboratory testing, and analytical modeling and address the following topics:

- Measuring dowel misalignment;
- Quantifying the effects of misaligned dowels on pavement performance;
- Determining critical levels of dowel misalignment that may result in lower levels of pavement performance;
- Preventing dowel misalignment; and
- Mitigating or remedying misaligned dowels in practice.

Types and Definitions of Dowel Misalignment

Dowel bars should be placed parallel to both the pavement surface and the longitudinal axis of the pavement in order to minimize longitudinal restraint of the transverse joints. Dowels are typically placed at mid-depth (to provide maximum shear load transfer capacity in the concrete slab) and the dowel bar should be centered longitudinally on the transverse joint. Misalignment is deviation in dowel placement from the prescribed position as a result of inaccurately placing the dowel, saw cutting in an incorrect position, dowel movement during the paving operation, or a combination of these factors.

The five major categories of dowel misalignment, as illustrated in Figure 1, are horizontal translation, longitudinal translation, vertical translation, horizontal skew, and vertical tilt (Tayabji, 1986).

Causes of Dowel Misalignment

Common causes of dowel misalignment when using basket placement include:

- Use of basket assemblies that are bent or are otherwise faulty due to inadequate rigidity (design), poor quality control during fabrication, or improper handling during transport and placement;
- Failure to anchor the basket assembly to the grade prior to paving, thereby allowing the assembly to rotate, tip, or slide as the concrete is placed;

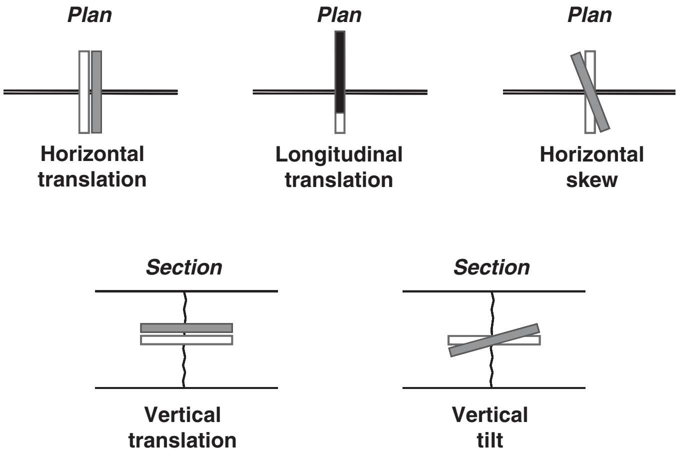

Figure 1. Types of dowel misalignment (Tayabji, 1986).

- Use of improperly sized basket assemblies (i.e., too tall or too short);
- Mishandling dowels or baskets during concrete placement (e.g., workers stepping on dowel baskets);
- Inappropriate basket or cage width or placement that interferes with slipform paver operation, resulting in rotation or sliding of the assembly;
- Improper location of basket assembly; and
- Improper location of sawed or formed joint.

The most critical factor in using dowel basket assemblies is probably the number and type of pins used to secure the basket. When an insufficient number of pins (or inadequate pins) are used, the baskets may shift, rotate, or burst resulting in misalignment problems (ACPA, 2006).

Common causes of misalignment when using dowel bar inserters (DBI) include:

- Settlement of dowels in the concrete mass after insertion (due to mix fluidity, excessive vibration, etc.);
- Movement of inserted dowels due to mishandling after placement;
- Improper DBI operations; and
- Improper location of sawed or formed joint.

The most critical factor in maintaining dowel alignment when using DBI is probably the concrete mixture because it affects the ability of the DBI to accurately place dowels and control the dowel location and orientation in the plastic concrete (ACPA, 2006).

Detection/Measurement of Dowel Misalignment

Many magnetometers, ground-penetrating radar units, and other devices can provide indications of dowel alignment with various degrees of accuracy. Because of the potential sensitivity of pavement performance to relatively small magnitudes of misalignment, measurement devices must be capable of providing high precision.

Among the devices used for measuring misalignment is the MIT Scan-2 (FHWA, 2007; FHWA, 2005; Yu and Khazanovich, 2005). Such measurement is performed by pulling the rail-mounted device along the joint while the device emits a weak, pulsating magnetic signal and detects the transient magnetic response signal. The included software which uses methods of tomography then determines the positions of the metal bars (ACPA, 2006). Available software can produce output in either numerical or graphical forms. A recent evaluation concluded that such a device measures dowel placement with an accuracy of ± 0.2 in. [5 mm] per 18 in. [457 mm] dowel length with 95 percent reliability on rotational alignment (FHWA, 2005).

Typical Dowel Misalignments and Effects on Pavement Performance

Dowel misalignment is expected to occur on every project. For example, variations in constructed slab thickness will result in variability in concrete cover over the dowels. Also, the accuracy of basket placement or insertion points during construction or joint sawing or forming operations will influence embedment lengths. The following sections summarize the typical misalignment levels observed in the field in this study.

Longitudinal Translation

Field measurements indicated an average longitudinal dowel bar translation of 0.86 in. [22 mm], with project standard deviations ranging from 0.4 to 1.9 in. [9 to 49 mm], and 1.2 in. [30 mm] standard deviation for all individual dowels.

The overall distribution of longitudinal translation measurements for individual dowels presented in Figure 2 shows that more than 91 percent of all bars measured were within 2 in. [51 mm] of being centered on the transverse joint and about 98 percent were within 3 in. [76 mm].

Vertical Translation

Dowel bars are generally designed and assumed to be embedded at the mid-depth of the slab. Dowels that are closer to the pavement top surface are considered to have a negative vertical translation and those that are closer to the bottom surface are considered to have a positive vertical translation.

The average absolute value of vertical translation for the individual dowels measured for a large number of dowels was 0.46 in. [12 mm] with a standard deviation of 0.6 in. [15 mm]. The distribution of vertical translations of individual dowel

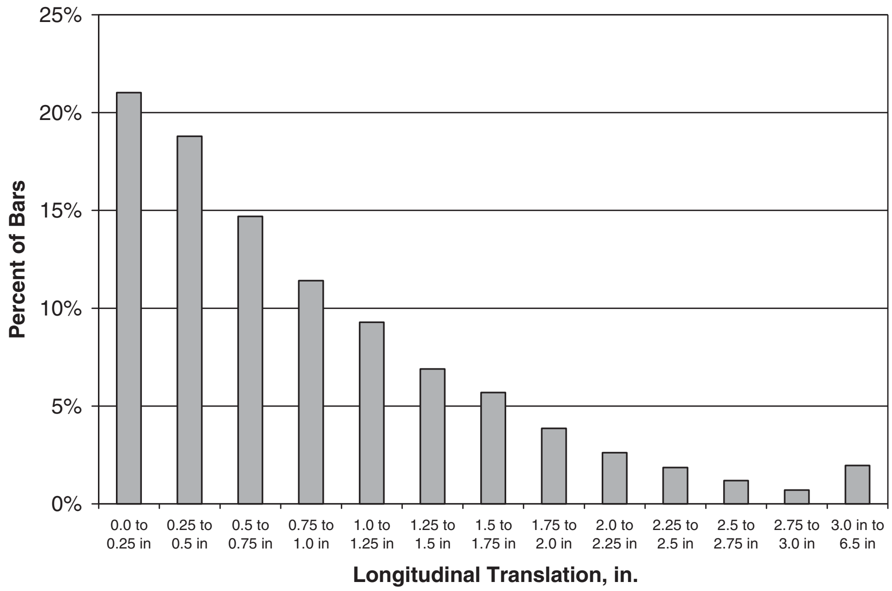

Figure 2. Distribution of longitudinal translation for field study measurements.

bars shown in Figure 3 indicates that about 96 percent of all bars were within ±1.0 in. [±25 mm] of the mid-depth location; the remaining dowels were more than 1 in. [25 mm] closer to the top or bottom pavement surface.

Dowel Rotation

Dowel rotations about the horizontal and vertical axes (axial rotation is irrelevant for round dowels) are two forms of rotation that may significantly impact concrete pavement performance.

Measurements on a large number of dowels indicated an average horizontal skew of 0.24 in. [6 mm] per 18 in. [457 mm] dowel with a standard deviation of 0.21 in. [5 mm]. Figure 4 presents the horizontal skew distribution for all dowels and shows that more than 60 percent of the bars were skewed by more than ¼ in. [6 mm] per 18 in. [457 mm]. About 2 percent of the bars had horizontal skew values exceeding 0.75 in. [19 mm] and about 0.5 percent had horizontal skew values exceeding 1.0 in. [25 mm].

Vertical tilt averaged 0.23 in. [6 mm] per 18 in. [450 mm] dowel with a standard deviation of 0.21 in. [5.4 mm]. Figure 5 presents the vertical tilt distribution and shows a very similar distribution to that of the horizontal skew. About 9, 2, and 1% of dowel bars had vertical tilt more than 0.50 in. [12 mm], 0.75 in. [19 mm], and 1.0 in. [25 mm], respectively

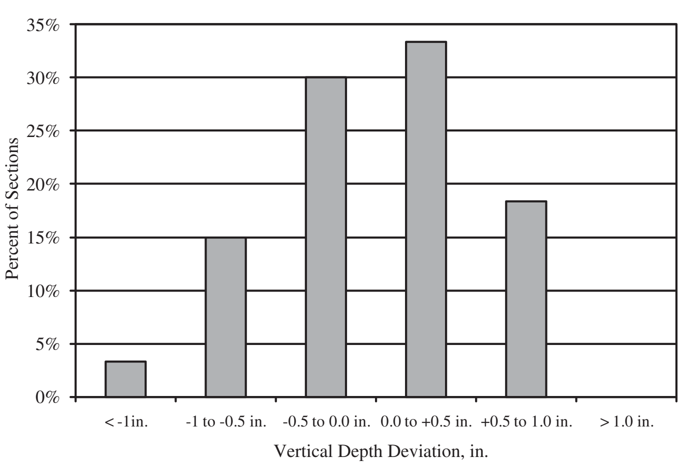

Figure 3. Distribution of vertical dowel bar translations.

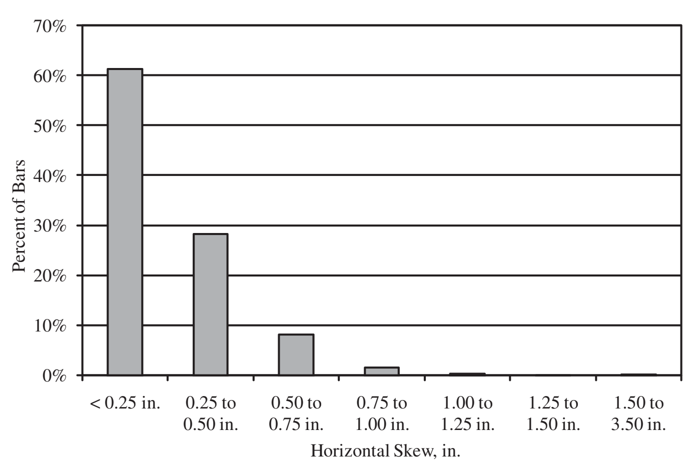

Figure 4. Distribution of the horizontal skew.

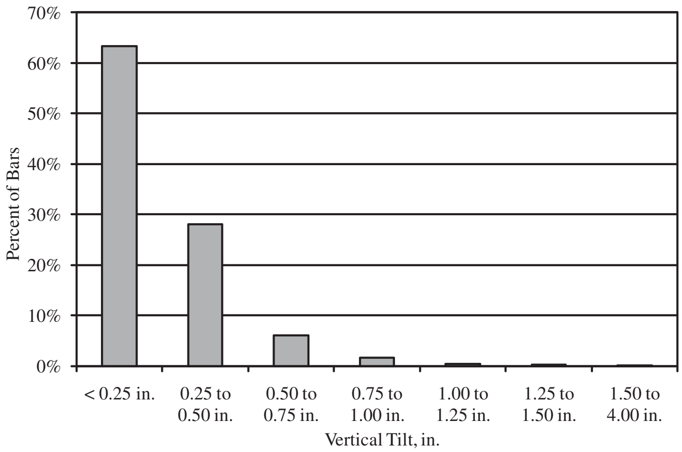

Figure 5. Distribution of vertical tilt.

Summary of Misalignment Values

An analysis of data from 60 project sites indicates that most joints had dowel misalignments within the following ranges:

- Longitudinal translation: ±2 in. [±51 mm] over 18-in. [457-mm] dowels.
- Vertical translation: ±0.5 in. [±13 mm] for pavements 12 in. [305 mm] or less in thickness.
- Rotational components (horizontal skew and vertical tilt): each less than 0.5 in. [13 mm] over 18-in. [457-mm] dowels.

Measures for Reducing Dowel Misalignment

Several measures can be taken to reduce the potential for dowel misalignment, as discussed in the following sections.

Design Issues

- Dowel baskets should be designed to withstand the rigors of transport, handling, and placement. Baskets that are not sufficiently rigid may bend or allow the dowels to be moved during construction.
- The use of narrower baskets, with the outside dowels located 9 to 12 in. [229 to 305 mm] from the pavement edge and longitudinal joint (instead of 6 in. [152 mm]) reduces the cost of the basket (one less dowel is used if spacing remains constant) and reduces the probability of the paver catching the dowel basket and shoving or twisting it during paving.

Construction Issues

- Proper care must be taken in the storing and handling of dowel baskets at the job site to prevent bending of the basket or misalignment of the dowels. All dowel baskets should be inspected prior to and during the paving process. Damaged baskets should be removed and replaced prior to placement of concrete.
- The correct locations for dowels should be marked along both edges of the pavement for either basket or DBI placement methods. The marks must be placed accurately and must be easy for the saw crew to locate after the paver has passed (ACPA, 2005).
- Dowel baskets must be accurately placed in proper alignment on the survey marks. A thorough inspection of basket and dowel alignment prior to paving is extremely important.
- Dowel baskets must be firmly staked or anchored to ensure that they do not move or tip during paving. Low anchor points help to prevent shoving and sliding of the basket while high anchor points help to prevent tipping of the basket (ACPA, 2005).
- The types of anchors used and the frequency of their use should be selected based on the type and thickness of base used. For example, a 6-in. [152-mm] pin may be used to firmly anchor the basket to an asphalt-treated base (ATB), but it may need to be installed on a skew if the layer thickness is 4 in. [102 mm].
- There is no consensus with regard to the treatment of dowel basket tie or spacer wires during construction. The FHWA recommends that these wires should be removed, citing concerns that failing to cut the wires may contribute to joint lockup and subsequent slab cracking and notes that properly anchored baskets do not need these wires for stability (FHWA, 1990). The American Concrete Pavement Association (ACPA) recommends that dowel basket tie wires should not be cut after basket placement and prior to paving because cutting the tie wires may destabilize the basket, allowing it to come apart during paving and result in misaligned dowels. ACPA also states that analyses show that concerns about the contribution of tie/spacer wires to joint lock-up and subsequent slab cracking are unfounded (ACPA, 2005).
- Care must be taken during construction to avoid stepping on the dowel baskets and dowels, especially during paving.
- When using a DBI, concrete mixtures should be selected to ensure stability of the dowel bars during placement and subsequent paving operations (i.e., vibration, screeding, etc.)
- To eliminate possible confusions between tie bars that are placed between adjacent lanes and/or shoulders and dowel bars that are placed at transverse joints, tie bars should not be placed within 2 ft [0.6 m] of transverse joints.

Misalignment Limitations

While no clear relationship was found between moderate levels of dowel misalignment and pavement performance in terms of faulting, spalling or panel cracking, laboratory testing and analytical modeling determined that dowel misalignment could reduce dowel shear capacity and its ability to transfer a load. Therefore, limitations on dowel misalignment can be based upon their effects on load transfer effectiveness, and by the minimum acceptable concrete cover (with respect to either the top or bottom of the slab) or the depth of joint saw cuts.

Dowel alignment guidelines and specifications should stipulate requirements that are achievable with good construction practices and have no significant adverse impact on pavement performance. However, specifications and guidelines should encourage placement that is as accurate as is reasonably possible, and also recognize that certain levels of misalignment may not significantly affect pavement performance.

The following approach will help establish dowel placement specifications:

1. **Establish constructible acceptance criteria.** Establishing a relatively tight (but constructible) placement tolerance will promote the placement of properly aligned dowel bars and eliminate the need for further evaluation or remedial actions. Examples of such tolerances may include the following:
   - Horizontal or vertical rotational alignment: 0.5 in. [13 mm] over 18.0 in. [457 mm].
   - Vertical translation: ± 0.5 in. [13 mm] for pavements 12 in. [305 mm] or less in thickness; ± 1.0 in. [25 mm] for pavements greater than 12 in. [305 mm] in thickness.
   - Longitudinal translation: 2.1 in. [55 mm] over 18-in. [457 mm] dowels.
   - Horizontal translation: 1 in. [25 mm].
2. **Establish rejection criteria.** Rejection criteria should be established on the basis of measured, predicted, or expected pavement performance or behavior. For example, remedial action may be required due to inadequate depth of placement (considering concrete cover requirements and saw cut depth), inability to achieve specified performance thresholds (e.g., predicted faulting or IRI), or obvious placement flaws (e.g., interference from misplaced tie bars). For example, a dowel, joint, or section may be rejected if any of the following conditions occur:
   - Concrete cover at any end of the dowel is 2 in. [51 mm] or less from the top surface.
   - Concrete cover from the dowel to the top surface is less than the sawcut depth.
   - Rotational misalignment is 3 in. [75 mm] or more per 18 in. [457 mm] dowel length.
   - Agency-specified performance prediction measures are not met.

The following procedure may be used for analyzing the effects of dowel misalignment on the performance of a uniform pavement project:

1. Use dowel alignment measurements to calculate the equivalent dowel diameter in each joint of the pavement project, using the procedure described under "Joint Effectiveness Evaluation".
2. Establish "uniform sections" approximately 500 ft [153 mm] in length for the purpose of analysis and evaluation such that all joints in the section have similar equivalent dowel diameters. A series of several joints in any 500-ft [153-mm] section with equivalent dowel diameters that are relatively uniform but substantially different from the rest of the section may be evaluated as a separate uniform section.
3. Compute the mean equivalent dowel diameter for each section. Two or more adjacent sections with no significant difference in equivalent dowel diameters can be combined into a single section for analysis purposes.
4. Perform MEPDG computations for each uniform section using the calculated mean equivalent dowel diameter for the section, and compare the performance and distress predictions for each section with the prescribed performance thresholds or the as-designed pavement performance prediction.

A decision about the acceptance, rejection, correction factors, etc. can be made for each pavement section based on the results of the computations and stipulated threshold values. If correction measures (such as dowel retrofitting) are performed, the effective dowel diameters of the affected joints should be recalculated and the pavement performance predictions for those joints reassessed.

Corrective Measures

The following corrective measures may be considered appropriate for dowels or doweled joints that fail to meet the acceptance criteria:

- Dowel bar(s) with inadequate concrete cover or excessive rotational misalignment can be corrected by removing and replacing the misaligned bars (retrofitting).
  - Bar(s) in the wheel path that cannot be removed can be corrected by removing and replacing the entire joint using a doweled full-depth repair.
  - Bar(s) not in the wheel paths that cannot be removed can be corrected by cutting completely through.
- Individual dowel bars with inadequate embedment or that are missing can be corrected by retrofitting additional dowels.
- Average initial joint load transfer efficiency should not be less than 70 percent after corrective measures have been performed.

Joint Effectiveness Evaluation

The equivalent dowel diameter concept assumes that a joint with misaligned dowels behaves as a joint with perfectly aligned dowels of a smaller effective diameter. The equivalent dowel diameter, d_{eq}, is defined by the following equation:

$$d_{eq} = r_{emb} \times r_{cc} \times r_{vt} \times r_{hs} \times d_0$$

where
- r_{emb} = adjustment factor for a reduction in embedment length;
- r_{cc} = adjustment factor for a reduction in concrete cover;
- r_{vt} = adjustment factor for vertical tilt (dowel rotation);
- r_{hs} = adjustment factor for horizontal skew (dowel rotation); and
- d_0 = nominal dowel diameter.

The procedure for selecting appropriate adjustment factors for the different misalignment forms is described below.

Embedment Effect (Longitudinal Translation)

Figure 6 can be used to estimate the adjustment factor r_{emb} (or dowel diameter ratio), for dowel embedment length, L_{emb}. No reduction or adjustment is assumed for embedment of 6.9 in. [175 mm] or more, and embedment of 2 in. [51 mm] or less should be treated as undoweled (i.e., $r_{emb} = 0$). The relationship shown in Figure 6 is given by the following equation for embedment lengths between 2 and 6.9 in.:

$$r_{emb} = -0.010 L_{emb}^2 \times 0.167 L_{emb} \times 0.324$$

For example, the adjustment factor, r_{emb}, for an 18-in. [457-mm] dowel that is longitudinally translated by 3.9 in. [99 mm] (i.e., 5.1 in. [130 mm] of embedment), is 0.916.

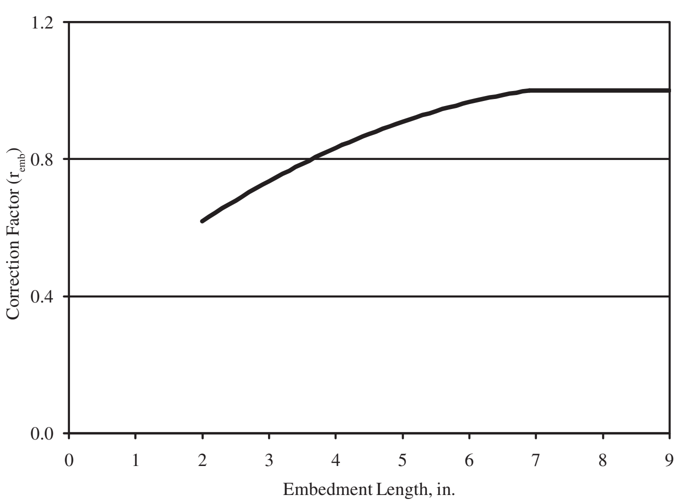

Figure 6. Adjustment factor for embedment length.

Joint load transfer efficiency (LTE) is generally most affected by the dowel(s) closest to the applied load (generally in the wheel path), and the dowels in the wheel path affect LTE as much as the combined effects of all other dowels in the joint. The following procedure should be used if dowel embedment varies along the joint:

1. Compute the adjustment factor for each dowel in the joint.
2. Determine the mean adjustment factor for all of the dowels in the joint.
3. Determine the mean adjustment factor for the three dowels in the critical wheel path (for example, the right wheel path in the truck lane).
4. Use the average of the two values obtained in Steps 2 and 3 as the adjustment factor for the joint.

Concrete Cover Effect (Vertical Translation)

When the dowel is translated vertically, the amount of concrete cover is reduced either above or below the dowel, which reduces the shear load capacity of the concrete and of the dowel-concrete system. The reduced shear load capacity can be represented by a dowel diameter reduction factor for concrete cover, r_{cc}, which is the ratio of the diameter of a dowel placed at mid-depth having the same shear capacity as the vertically translated dowel in question to that of the diameter of the misaligned dowel. The reduction in effective dowel diameter depends upon the amount of vertical translation, the typical amount of variation in vertical translation, and the assumed basic or reference amount of concrete cover. A reduction should be applied only when vertical translation exceeds normal variability and the resulting concrete cover is lower than a specified reference level of concrete cover.

The actual concrete cover (CC) for a given dowel can be calculated as follows:

- $CC = y - d_0/2$, where y is the measured depth of the center of the dowel and d_0 is the nominal dowel diameter if the longitudinal axis of the dowel is above mid-depth of the pavement
- $CC = H_{PCC} - y - d_0/2$, where H_{PCC} is the slab thickness if the longitudinal axis of the dowel is below mid-depth of the pavement (i.e., the dowel is closer to the bottom of the slab).

Alternatively, CC can be computed equivalently using the following single equation:

$$CC = H_{PCC}/2 - d_0/2 - |H_{PCC}/2 - y|$$

The reference level of concrete cover, CC_{ref}, can be considered as the amount of cover above which there is no appreciable increase in dowel-concrete shear capacity (or below which there is a decrease in dowel-concrete shear capacity). For any pavement thickness, the maximum possible concrete cover, CC_{max}, is developed when the dowel is located at the exact mid-depth of the slab:

$$CC_{max} = H_{PCC}/2 - d_0/2 = (H_{PCC} - d_0)/2$$

Because there is some expected variability in concrete cover due to variances in constructed slab thickness, finished base profile, etc., the maximum possible value of concrete cover should be reduced by this amount of variability to serve as a basic reference level of concrete cover for evaluating the effects of vertical dowel misalignment. Thus, one possible value of CC_{ref} is given as:

$$CC_{ref} = H_{PCC}/2 - d_0/2 - \Delta_{typ} = (H_{PCC} - d_0)/2 - \Delta_{typ}$$

where Δ_{typ} = the typical variance in vertical dowel translation, which is estimated to be 0.5 in. (13 mm) for slab thickness of ≤ 12 in. (305 mm) and 1.0 in. (25 mm) for slab thickness greater than 12 in (305 mm).

Finite element analysis indicates that increasing concrete cover beyond approximately 3.5 times the diameter of the dowel bar does not improve the shear capacity of the dowel-concrete system. Therefore, the reference level of concrete cover can be defined as the lesser of the theoretical amount of concrete cover for a dowel at mid-depth of the slab less the typical vertical translation, or 3.5 d_0. This is expressed as follows:

$$CC_{ref} = \mathrm{Min}(H_{PCC}/2 - d_0/2 - 0.5,\ 3.5\, d_0) \quad \text{for slab thickness} \le 12 \text{ in. } [305 \text{ mm}].$$

$$CC_{ref} = \mathrm{Min}(H_{PCC}/2 - d_0/2 - 1.0,\ 3.5\, d_0) \quad \text{for slab thickness} > 12 \text{ in. } [305 \text{ mm}].$$

If the actual CC is greater than or equal to the reference level of concrete cover (CC_{ref}), no reduction in dowel diameter should be considered (i.e., $r_{cc} = 1.0$). If the actual CC is less than 2 in. [51 mm], then the adjustment factor should be assumed to be equal to 0 (i.e., $r_{cc} = 0$). If the actual concrete cover is less than the reference value (but greater than 2 in. [51 mm]), a reduction in effective dowel diameter should be considered. Laboratory testing and finite element analyses of dowels embedded in 8-in. [203-mm] concrete slabs have provided the following relationship:

$$r_{cc} = 1 - \left[-153.3 * (CC_{ref})^2 + 2503 * (CC_{ref}) + 153.3 * (CC)^2 - 2503 * (CC)\right] / 9628$$

For example, the adjustment factor due to vertical translation of a 1.5-in. [38-mm] dowel in a 11 in. [279-mm] thick concrete slab by 1.75 in. [44 mm] (i.e., concrete cover is decreased from a reference or "nominal" level of 4.25 in. [108 mm] to 3.0 in. [76 mm]) would be:

$$r_{cc} = 1 - \frac{-153.3 * 4.25^2 + 2503 * 4.25 + 153.3 * 3.0^2 - 2503 * 3.0}{9628} = 0.82$$

The following procedure is recommended for determining the "average" effective diameter for dowels with variable concrete cover at a particular transverse joint:

1. Compute an adjustment factor for each dowel in the joint.
2. Determine the mean adjustment factor for all of the dowels in the joint.
3. Determine the mean adjustment factor for the three dowels in the critical wheel path (for example, the right wheel path in the truck lane).
4. Use the average of the two values obtained in Steps 2 and 3 as the adjustment factor for the examined joint.

Rotational Effects (Vertical Tilt and Horizontal Skew)

The effects of vertical tilt and horizontal skew have been observed to be similar in both laboratory tests and analytical modeling. Therefore, the two adjustment factors, r_{vt} and r_{hs}, are computed in the same manner but separately.

Determining adjustment factors for vertical tilt and horizontal skew requires the measurement of vertical tilt and horizontal skew for each dowel in the joint. These data are used to compute the mean tilt or skew, standard deviation of the tilt or skew, and the maximum tilt or skew of the dowels in the critical wheel path. This information can then be used to estimate the stiffness of the joint and the joint load transfer efficiency (LTE). LTE can be related to the average diameter of properly aligned dowels to compute r_{vt} and r_{hs}, as illustrated below.

The following relationship between dowel tilt and nondimesional joint stiffness was developed:

$$JStiff = JStiff_0 - 0.20623 \times MeanTilt - 0.61796 \times StDTilt - 0.86862 \times WPTilt$$

where

$JStiff$ = nondimensional stiffness of a joint with rotationally misaligned dowels;

$JStiff_0$ = the predicted nondimensional stiffness of a joint with aligned dowels (see Table 1);

$MeanTilt$ = absolute value of the average tilt (or skew) of the dowels in the joint, in. per 18-in. dowel;

Table 1. Nondimensional joint stiffness values (*JStiff*$_0$) for aligned dowels of various dowel diameters.

Dowel Diameter (in.)	$JStiff_0$
1	6.537
1.125	7.447
1.25	8.461
1.375	9.601
1.5	10.894

StDTilt = standard deviation of the tilt (or skew) of the dowels in the joint; and
WPTilt = maximum absolute value of the tilt (or skew) of the dowels in the wheel path, in. per 18-in. dowel.

Example: Assume that the average measured horizontal skew of 1.5-in. [38-mm] diameter dowels in a joint is 0.2 in. [5 mm], with a standard deviation of 0.633 in. [16.1 mm] and that the maximum horizontal skew of the wheel path dowel is 0.8 in. [20 mm]. The resulting nondimensional stiffness value would be 9.767.

The nondimensional stiffness can be used to calculate LTE using the following relationship (Crovetti, 1994):

$$LTE = \frac{100\%}{1+1.2\left(JStiff\right)^{-0.849}}$$

Thus for a nondimensional stiffness value of 9.767, the LTE would be 85.2 percent. This value then can be used to determine the adjustment factor due to rotational misalignment, r_{rot}, as follows (0.98 in this example):

$$r_{rot} = \frac{0.0103}{d_0}\exp\left(0.0582\,LTE\right)$$

Combined Effect

The equivalent dowel diameter concept assumes that a joint with misaligned dowels behaves as a joint with perfectly aligned dowels of a smaller effective diameter, d_{eq}, as defined by the following equation:

$$d_{eq} = r_{emb} \times r_{cc} \times r_{vt} \times r_{hs} \times d_0$$

For the example illustrated above, the equivalent dowel diameter for the misaligned 1.5 in. dowels (assuming all of the misalignments occur concurrently and that there is no vertical tilt) would be:

$$d_{eq} = 0.916 \times 0.82 \times 1.0 \times 0.98 \times 1.5 = 1.10 \text{ in.}$$

Example for Calculating the Equivalent Dowel Diameter

This example assumes an 11-in. [279-mm] thick pavement with joints containing 12 dowels with 18 in. [457 mm] length and 1.5 in. [38 mm] diameter, with the following conditions:

1. The saw cut was incorrectly made 4 in. [102 mm] away from the designed location, resulting in 4 in. [102 mm] of longitudinal translation and 5 in. [137 mm] of embedment length for all 12 dowels.
2. The dowel basket was 0.75 in. [19 mm] taller than was required for the mid-depth dowel placement, resulting in 0.75 in. [19 mm] vertical translational displacement towards the pavement surface and reduced concrete cover for all 12 dowels in the joint from 4.75 to 4 in. [121 to 102 mm].
3. The rotational misalignments (vertical tilt and horizontal skew) for all 12 dowels in the joint are given by Table 2. The dowels are numbered according to their distance from the truck lane shoulder (i.e., dowel Number 1 is the closest to the shoulder). The first three dowels are considered to be wheel path dowels.

Calculation of Equivalent Dowel Diameter

Embedment Length Adjustment Factor

Because the embedment length is greater than 2 in. [51 mm] and less than 6.9 in. [175 mm], the adjustment factor due to the longitudinal translation and reduced embedment length, r_{emb}, is computed as:

$$r_{emb} = -0.01 * L_{emb}^2 + 0.167 * L_{emb} + 0.324$$

$$r_{emb} = -0.010\left(5\right)^2 + 0.167\left(5\right) + 0.324 = 0.909$$

Table 2. Assumed dwell misalignments in the joint.

Dowel Bar Number	Vertical tilt, in./18 in.	Horiz. Skew, in./18 in.
1	-0.44	-0.26
2	-0.50	-0.32
3	-0.34	-0.32
4	-0.80	-0.38
5	-0.54	-0.48
6	1.46	-0.27
7	-0.54	-0.39
8	0.46	-0.33
9	-0.54	-0.47
10	-0.54	-0.43
11	-0.54	-0.44
12	-0.54	-0.42

Vertical Translation (Reduced Concrete Cover) Adjustment Factor

The reference and actual concrete cover values (CC_{ref} and CC, respectively) are computed as:

$$CC_{ref} = \text{the smaller of}\left(\mathrm{H_{PCC}}/2 - \mathrm{d_0}/2 - 0.5\right) \text{ and } 3.5\mathrm{d_0}$$
$$= \left(11/2 - 1.5/2 - 0.5\right) \text{ or } 3.5 * 1.5$$
$$= 4.25 \text{ in. or } 5.25 \text{ in.} = 4.25 \text{ in.}$$

$$\mathrm{CC} = \mathrm{H_{PCC}} - \mathrm{d_0}/2 - \left|\mathrm{H_{PCC}}/2 - \mathrm{y}\right|$$
$$= 11/2 - 1.5/2 - \left|11/2 - 4.75\right| \text{ in.}$$
$$= 4.00 \text{ in.}$$

Using these values of and CC, the adjustment factor due to the loss in concrete cover, r_{cc}, can be calculated as follows:

$$r_{cc} = 1 - \left[-153.3 * (4.25)^2 + 2503 * (4.25) + 153.3 * (4)^2 - 2503 * (4)\right] / 9628 = 0.968$$

Vertical Tilt Adjustment Factor

For the vertical tilt measurements provided in Table 2, the following misalignment parameters are calculated:

- Mean vertical tilt = 0.2 in. [5 mm].
- Standard deviation of vertical tilt = 0.633 in.[16 mm].
- Maximum absolute value of wheel path dowel vertical tilt = 0.5 in. [13 mm].

The nondimensional joint stiffness is calculated as follows:

$$JStiff = JStiff_0 - 0.20623 \times MeanTilt - 0.61796 \times StDTilt - 0.86862 \times WPTilt$$

$$JStiff = 10.8942 - 0.20623 \times (0.2) - 0.61796 \times (0.633) - 0.86862 \times 0.5 = 10.03$$

The LTE of the joint can be estimated as:

$$LTE(\%) = \frac{100}{1 + 1.2(JStiff)^{-0.849}}$$

$$LTE = \frac{100}{1 + 1.2(10.03)^{-0.849}} = 85.51\%$$

The vertical tilt adjustment factor associated with this load transfer efficiency can then be estimated as:

$$r_{vt} = \frac{0.0103}{d_0}\exp(0.0582\, LTE)$$

$$r_{vt} = \frac{0.0103}{1.5}\exp(0.0582 \times 85.51) = 0.995$$

Horizontal Skew Adjustment Factor

For the horizontal skew measurements provided in Table 2 the following misalignment parameters are calculated:

- Mean horizontal skew = 0.38 in. [10 mm].
- Standard deviation of horizontal skew = 0.073 in. [2 mm].
- Maximum absolute value of wheel path dowel horizontal skew = 0.32 in. [8 mm].

The nondimensional joint stiffness can be calculated as:

$$JStiff = JStiff_0 - 0.20623 \times MeanTilt - 0.61796 \times StDTilt - 0.86862 \times WPTilt$$

$$JStiff = 10.8942 - 0.20623 \times (0.38) - 0.61796 \times (0.073) - 0.86862 \times 0.32 = 10.49$$

The LTE of the joint can be estimated as:

$$LTE(\%) = \frac{100}{1 + 1.2(JStiff)^{-0.849}}$$

$$LTE = \frac{100}{1 + 1.2(10.49)^{-0.849}} = 85.98\%$$

The horizontal skew adjustment factor associated with this load transfer efficiency can then be estimated as:

$$r_{hs} = \frac{0.0103}{d_0}\exp(0.0582\, LTE)$$

$$r_{hs} = \frac{0.0103}{1.5}\exp(0.0582 \times 85.98) = 1.02$$

Because the maximum allowable adjustment factor cannot exceed 1.0, an adjustment factor of 1.0 will be assumed.

Computation of Overall Effective Dowel Diameter

The equivalent or effective dowel diameter is the original dowel diameter (d_0) multiplied by the adjustment factors for concrete cover, embedment length, vertical tilt, and horizontal skew:

Table 3. Equivalent dowel diameter for each joint in the pavement section.

Joint #	Equivalent Dowel Diameter (in.)	Joint #	Equivalent Dowel Diameter (in.)	Joint #	Equivalent Dowel Diameter (in.)
1	1.31	11	1.5	21	1.21
2	1.5	12	1.22	22	1.5
3	1.41	13	1.5	23	1.5
4	1.14	14	1.5	24	1.27
5	1.5	15	1.49	25	1.5
6	1.1	16	1.5	26	1.5
7	1.5	17	1.5	27	1.5
8	1.5	18	1.23	28	1.5
9	1.5	19	1.05	29	1.37
10	1.5	20	1.5	30	1.5

$$d_{eq} = r_{emb} \times r_{cc} \times r_{vt} \times r_{hs} \times d_0 = 0.909 \times 0.968 \times 0.996 \times 1 \times 1.5$$
$$= 1.31 \text{ in.}$$

Therefore, to account for the effects of the misalignment in this example, the pavement should be treated as if it had a dowel diameter of 1.31 in. [33 mm] (and not 1.5 in. [38 mm] diameter).

Assessment of a Pavement Section

Problem Statement

The following example illustrates the calculation of the effect of dowel misalignment on the performance of a 540-ft. [165-m] pavement section with an 11 in. [279 mm] thickness. The pavement section has 30 joints, each of which contains 12 dowels with 18 in. [457 mm] length and 1.5 in. [38 mm] diameter. The pavement was designed with the following performance criteria after 20 years at 90 percent reliability:

- Transverse cracking not to exceed 12% of cracked slabs.
- Mean joint faulting not to exceed 0.12 in. [3 mm].
- IRI not to exceed 160 in./mile [2.5 m/km].

The equivalent dowel diameters were calculated for the dowel alignments of each joint; results are shown in Table 3. Because the pavement section is less than 1000 ft [305 m], the mean equivalent dowel diameter is computed for the entire pavement section resulting in 1.41 in. [36 mm]. This equivalent dowel diameter was then used in an MEPDG simulation to predict faulting and IRI for the project. Figures 7 and 8 present the predicted faulting and IRI, respectively, for the as-designed

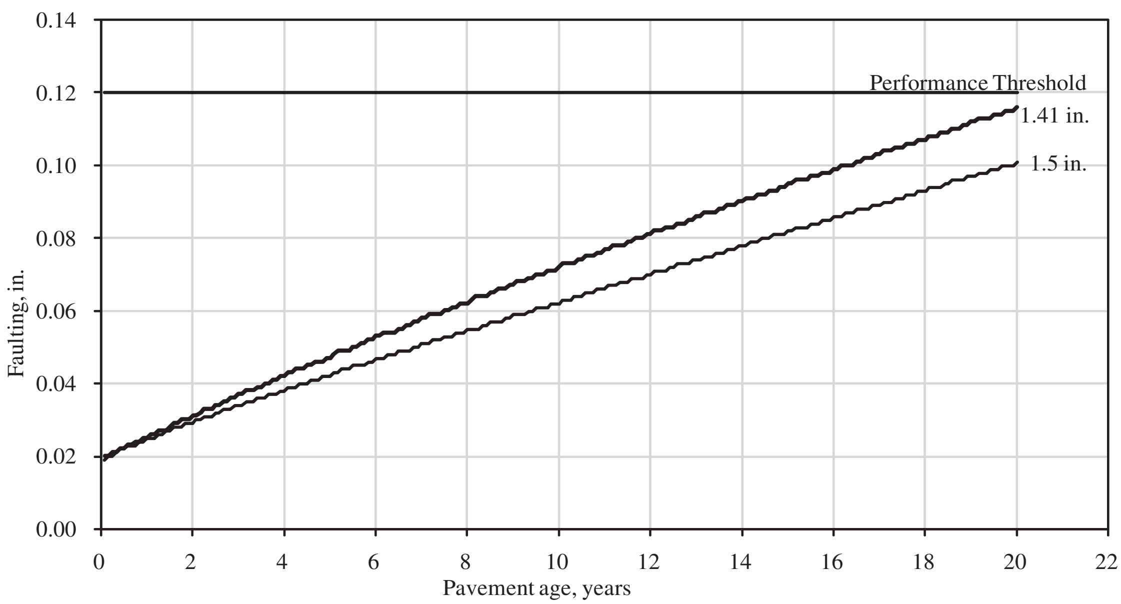

Figure 7. Predicted faulting for the as-designed pavement project.

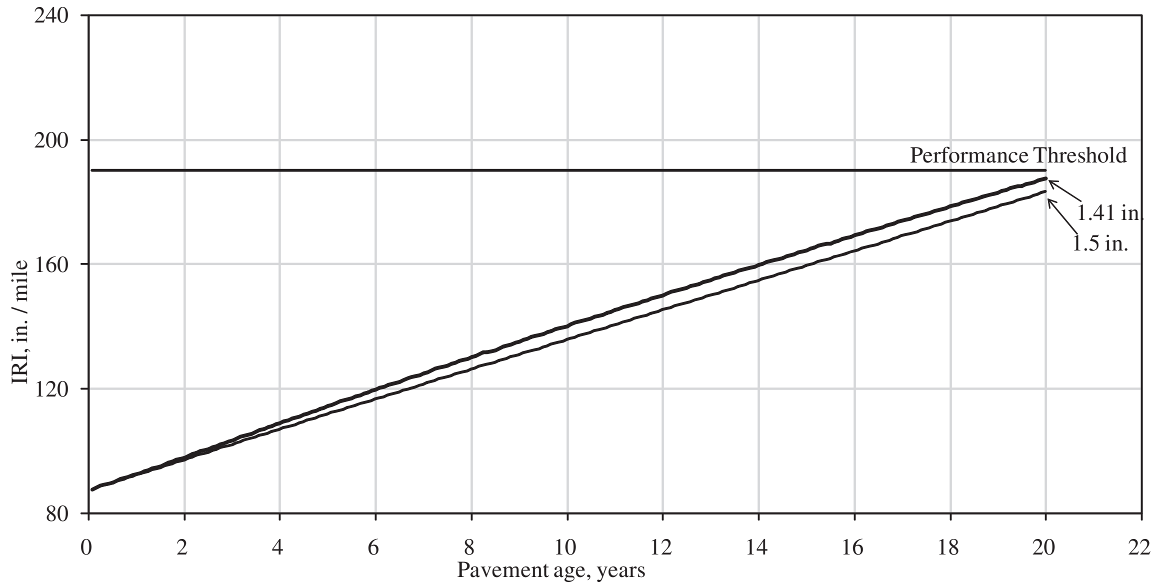

Figure 8. Predicted IRI for the as-designed pavement project.

pavement (dowel diameter of 1.50 in. [38 mm]) and for a similar pavement with 1.41 in. [36 mm] dowels.

The predicted faulting and IRI of the project after considering the dowel misalignment effects are within the specified acceptance thresholds. However, analysis of the MEPDG run output files (not presented here) showed that because of dowel misalignment, the reliability of faulting not exceeding the performance threshold was reduced from 96.7 to 91.9%, and the IRI reliability was reduced from 92.5 to 91.0%.

Concluding Remarks

The guidelines provide a simple methodology to account for the effects of dowel misalignment in estimating pavement performance. The methodology uses an equivalent diameter concept in which dowel diameter is reduced to account for the effects of misalignment. The dowel diameter reduction factor depends on the type and level of misalignment. Equations for determining the reduction factor for different types of misalignments were developed based on the results of field, laboratory, and finite element analysis. Pavement performance can then be estimated using pavement analysis predictions (e.g., the MEPDG) for the reduced dowel diameter.

Attachment A References

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APPENDIXES

Appendixes A through D contained in the research agency's final report provide detailed information on the literature review, laboratory and field test results, and finite element analysis. These appendixes are not published herein, but they are available online at http://trb.org/news/blurb_detail.asp?id=10299.

These appendixes are titled as follows:

Appendix A: Review of Literature and Other Relevant Information
Appendix B: Field Testing Results
Appendix C: Laboratory Testing Results
Appendix D: Finite Element Analysis

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation