Project No. 10-69

Guidelines for Dowel Alignment in Concrete Pavements

APPENDIX A
REVIEW OF LITERATURE AND OTHER RELEVANT INFORMATION

Prepared for
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APPENDIX A. REVIEW OF LITERATURE AND OTHER RELEVANT INFORMATION

This Appendix contains information related to:

- Dowel placement in concrete pavements to identify
  - problems with alignment,
  - extent of misalignment,
  - methods for determining misalignment, and
  - effect of misalignment on performance;
- Factors contributing to dowel bar misalignment;
- Available approaches for estimating the effects of misalignment on pavement performance.

A.1. PROBLEMS WITH DOWEL PLACEMENT

Dowel bars are typically placed at the mid-depth of the slab and should be parallel to the pavement surface and parallel to the direction of travel. The center of the dowel bar should be below the joint. If dowel placement deviates from the desired position, it is said to be *misaligned*. Tayabji (1986) identified the following categories of dowel misalignment (see figure A.1):

- horizontal translation;
- longitudinal translation;
- vertical translation;
- horizontal skew; and
- vertical tilt.

Misalignment may result from misplacement (initially placing the dowels in an incorrect position), displacement (movement during the paving operation), or both. Dowel bars are typically placed in the joints using either basket assemblies or an automated dowel bar inserter (DBI).

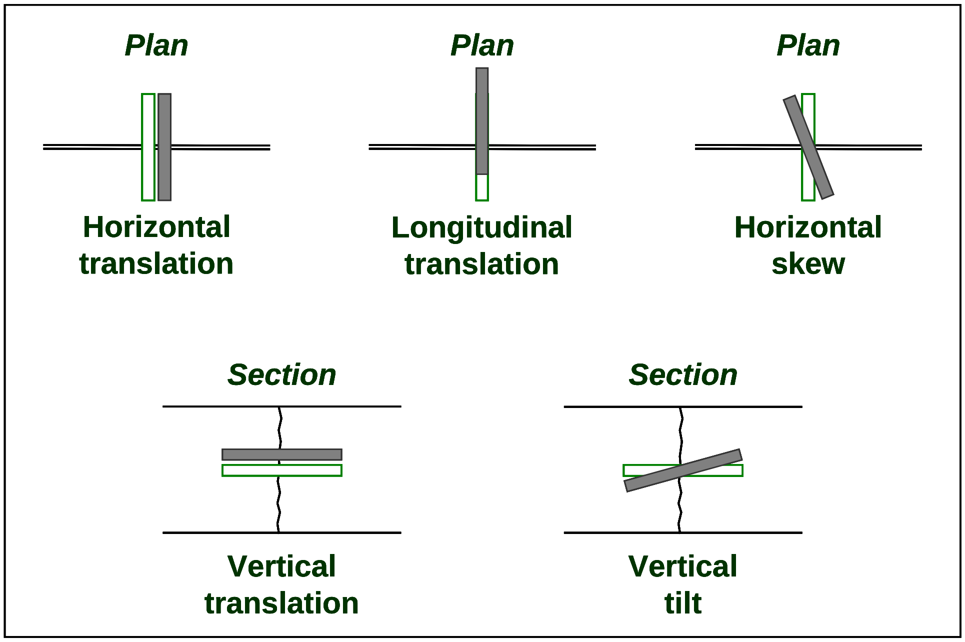

Figure A.1. Types of dowel misalignment (Tayabji, 1986).

Dowel bar tolerances vary with respect to horizontal, longitudinal, and vertical translation, horizontal skew, vertical tilt, and embedment length. Different states have adopted differing standards with respect to dowel bar alignment and positioning tolerances. 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 Federal Highway Administration (FHWA)-recommended limits for horizontal and vertical alignment (rotation) of ¼ in over 12 in (6.3mm over 305mm) or 2% (FHWA 1990). The American Concrete Pavement Association (ACPA) recommends limits of 3/8 in over 12 in (9.5mm over 305mm) or 3% based on National Cooperative Highway Research Program (NCHRP) Synthesis 56 and an FHWA memo from 1989. FHWA recommended further studies to determine the validity of their 2% tolerance.

Table A.1 shows the variation of dowel bar misalignment tolerances for several states. The maximum rotation column is an absolute maximum for the horizontal skew and vertical tilt. The data for the Midwest states were gathered from the 2004 state representatives' reports (MCC, 2004). The data from Georgia, North Carolina, and South Carolina were gathered by e-mail from each state representative. The information from the Munich Technical University paper was obtained from an agency's research paper (Lechner, 2005).

Table A.1. Variation in dowel misalignment tolerances from state to state.

Location	Maximum Rotation (in.)	Vertical Translation (in.)	Longitudinal Translation (in.)	DBI	Source
Illinois	3/16	NA	NA	not allowed	Illinois DOT Rep., Spring 2004
Indiana	3/8	NA	NA	not allowed	Indiana DOT Rep., Spring 2004
Iowa	1/4	NA	NA	not allowed	Iowa DOT Rep., Spring 2004
Kansas	3/8	1/10 of pavement Depth	NA	allowed	Kansas DOT Rep., Spring 2004
Michigan				allowed	Staton, Michigan DOT, Spring 2004
Basket	1/8	1/2	NA		
DBI	1/4	NA	2		
Minnesota	1/4	NA	NA	allowed	Minnesota DOT Rep., Spring 2004
Missouri	No specs.	NA	NA	not allowed	Missouri DOT Rep., Spring 2004
Nebraska	1/4	NA	NA	allowed	Nebraska DOR Rep., Spring 2004
Ohio	No specs.	NA	NA	allowed	Ohio DOT Rep., Spring 2004
Georgia	9/16	NA	NA	-	Fowler et al., May 1983.
				-	Gulden, Georgia DOT 2005
North Carolina	3/8	NA	NA	-	Pace, NC DOT 2005
South Carolina	9/16	3/4	3	-	Johnson, SC DOT 2005
German Agency	3/4	NA	2	-	FGSV, 2001

One limitation of existing specifications and guidelines on dowel placement tolerances is that they all focus on individual dowel bars and do not fully consider the effects on pavement behavior. Different types of misalignments have different effects on pavement performance. The translational misalignments (misplacements), including longitudinal translation (which determines the dowel embedment length), affect the effectiveness of individual dowel bars (i.e., load transfer capacity). As such, the individual-bar evaluation is appropriate for misplacement errors. However, even in this case, the location of the dowel bars may be considered. For example, the dowel bars in the wheelpath are more critical, whereas the load transfer capacity is not critical for the bars outside of the wheelpath. The rotational misalignments (horizontal and vertical misalignments) govern joint movements, and a joint-by-joint evaluation may be warranted.

Dowel bars are expected to resist differential vertical movement between the slabs while allowing expansion and contraction in the horizontal direction due to thermal contraction and expansion of the concrete. Highway agencies specify dowel alignment tolerances to prevent joint malfunctions due to misalignment. Commonly believed mechanisms for these malfunctions include the following:

- If the dowels are not placed accurately in the wheel paths (i.e., there is horizontal translation), it reduces their effectiveness and their ability to provide adequate joint load transfer efficiency (LTE).
- If the dowel does not have sufficient embedment length on the both sides of the joint due to longitudinal translation, concrete bearing stresses will be increased, which may cause the development of dowel looseness and result in premature loss of LTE.
- Horizontal skew and vertical tilt may restrain joint movements due to thermal contraction and expansion of the concrete. This restraint increases slab tensile stresses and may increase their cracking potential. This restraint may also induce significant additional localized stresses around the dowels, which can

lead to spalling and/or dowel looseness, with an accompanying decrease in the joint LTE. It is also hypothesized that dowel rotation can increase resistnce to joint opening causing joint lockup and transverse cracking.
- Vertical translations of the dowel may result in insufficient concrete cover, which can lead to joint spalling and loss of LTE.

The potential impacts of various types of dowel misalignment on pavement performance, as identified by Tayabji (1986), are summarized in table A.2. It should be noted that, although loss of LTE is not a distress per se, poor LTE is a contributing factor in other distresses, such as premature joint faulting (Khazanovich and Gotlif, 2003).

Table A.2. Effect of each type of misalignment (Tayabji, 1986).

Type of Misalignment	Effect on Spalling	Cracking	Load Transfer
Horizontal translation	no	no	yes
Longitudinal translation	no	no	yes
Vertical translation	yes	no	yes
Horizontal skew	yes	yes	yes
Vertical tilt	yes	yes	yes

Although many transportation agencies specify alignment tolerances, relatively few laboratory and field studies have been conducted to evaluate the effects of various types and levels of misalignment on concrete pavement performance.

Several studies have evaluated the effects of dowel misalignment on restricting joint movement due to thermal contraction and expansion of the concrete. One such study was conducted by Segner and Cobb at the University of Alabama (1967). This study used dowel pull-out test results to show that vertical tilt was more critical to pavement performance than horizontal skew. The study showed that a horizontal skew of 19.1 mm did not increase the pullout force required. However, a vertical tilt of 6.4 mm was sufficient to significantly increase the pullout force required to achieve the same joint opening. Significant spalling failures were observed with vertical tilt of 25.4 mm and with horizontal skew measures of 76 mm (Leong, 2006).

Another study, using data from slab pullout tests with 2 oppositely misaligned dowels, found that horizontal skew and vertical tilt of less then 1 in. per 18-in. bar allowed horizontal movements up to values that would not be exceeded in the field, and pullout loads were relatively low for these dowel misalignment levels. Table A.3 shows the force required to create a joint opening of 0.25 in. for various levels of misalignment after different concrete cure times (Tayabji, 1986).

Table A.3. Maximum Pullout loads for Tayabji's slab pullout tests (Tayabji, 1986).

Test Series	Misalignment (in.)	Maximum Pullout Load (lb) by Test			
		1 Day	3 Days	7 Days	28 Days
A	0 horizontal	1,030	840	1,020	1,640
B	1/4 horizontal	890	670	980	2,000
C	1/2 horizontal	1,160	1,270	1,410	1,890
D	1 horizontal	1,460	1,280	1,020	NA

Note: NA = not available. Slab thickness = 8 in. Maximum joint opening = 0.25 in. Maximum aggregate size = 1 in.

More recently, laboratory experiments at Michigan State University were completed using slab pull-out tests with up to 5 dowels per joint (Prabhu et al., 2006). This study found that, while dowel misalignment has only a small influence on initial debonding shear stresses, it has a significant influence on post-slip horizontal displacements. Structural distresses such as concrete spalling and cracking increased in severity with the number of misaligned dowel bars at the joint. The misalignments measured in this study were all rotational (i.e., horizontal skew, vertical tilt, or a combination of both). The distresses caused by the different tests, types of misalignment, and magnitudes of misalignment are shown in tables A.4 and A.5. It should be noted that the distresses reported in these tables occurred only after unrealistically high joint openings.

Table A.4. Two-dowel slab pullout data (Prabhu et al., 2006).

Slab Dimensions	Number of Dowels	ID	Misalignment	Magnitude (in rad.)	Distress Observed
2 slabs each 1220 x 610 x 250 mm (48 x 24 x 10 in.)	2 (Uniform)	2A	Aligned	0	None
		2V9U	Vertical	$+\frac{1}{9}$; $+\frac{1}{9}$	Spalling at end
		2V18U		$+\frac{1}{18}$; $+\frac{1}{18}$	None
		2H9U	Horizontal	$+\frac{1}{9}$; $+\frac{1}{9}$	Spalling at end
		2H18U		$+\frac{1}{18}$; $+\frac{1}{18}$	None
		2C9U	Combined	$+\frac{1}{9}$; $+\frac{1}{9}$	Spalling at end
		2C18U		$+\frac{1}{18}$; $+\frac{1}{18}$	None
	2 (Non - Uniform)	2V9NU	Vertical	$+\frac{1}{9}$; $-\frac{1}{9}$	Spalling at end
		2V12NU		$+\frac{1}{12}$; $-\frac{1}{12}$	Spalling at end
		2V18NU		$+\frac{1}{18}$; $-\frac{1}{18}$	Spalling at end
		2V36NU		$+\frac{1}{36}$; $-\frac{1}{36}$	Spalling at end
		2H9NU	Horizontal	$+\frac{1}{9}$; $-\frac{1}{9}$	Spalling and Transverse Cracking @ 17mm joint opening
		2H12NU		$+\frac{1}{12}$; $-\frac{1}{12}$	Spalling and Transverse Cracking @ 18mm joint opening
		2H18NU		$+\frac{1}{18}$; $-\frac{1}{18}$	Spalling at end
		2H36NU		$+\frac{1}{36}$; $-\frac{1}{36}$	Spalling at end
		2C9NU	Combined	$+\frac{1}{9}$; $-\frac{1}{9}$	Spalling and Transverse Cracking @ 11mm joint opening
		2C12NU		$+\frac{1}{12}$; $-\frac{1}{12}$	Spalling and Transverse Cracking @ 24mm joint opening
		2C18NU		$+\frac{1}{18}$; $-\frac{1}{18}$	Spalling at end
		2C36NU		$+\frac{1}{36}$; $-\frac{1}{36}$	Spalling at end
	2 (One Bar Misaligned)	2V12AM	Vertical	$\frac{1}{12}$; 0	None
		2V18AM		$\frac{1}{18}$; 0	None
		2H12AM	Horizontal	$\frac{1}{12}$; 0	None
		2H18AM		$\frac{1}{18}$; 0	None
		2C12AM	Combined	$\frac{1}{12}$; 0	None
		2C18AM		$\frac{1}{18}$; 0	None

Table A.5. Three- and five-dowel slab pullout data (Prabhu et al., 2006).

Slab Dimensions	Number of Dowels	ID	Misalignment	Magnitude (in rad.)	Distresses Observed
2 slabs each 2440 x 915 x 250 mm (96 x 36 x 10 in.)	3 (Non - Uniform)	3V18NU	Vertical	$+\frac{1}{18}$; $-\frac{1}{18}$; $+\frac{1}{18}$	Spalling around the dowel bars
		3H18NU	Horizontal		
		3C18NU	Combined		
	5 (Non - Uniform)	5V18NU	Vertical	$+\frac{1}{18}$; $-\frac{1}{18}$; $+\frac{1}{18}$; $-\frac{1}{18}$; $+\frac{1}{18}$	Spalling @ 23mm joint opening
		5H18NU	Horizontal		Spalling and Transverse Cracking @ 22mm joint opening
		5C18NU	Combined		Spalling and Transverse Cracking @ 22mm joint opening
	5 (Alternate Misaligned)	5V18AM	Vertical	$+\frac{1}{18}$; 0; $-\frac{1}{18}$; 0; $+\frac{1}{18}$	Spalling around the outer and center dowel bars
		5H18AM	Horizontal		
		5C18AM	Combined		

While dowel misalignment in the form of tilt and skew are the most common misalignments tested using laboratory techniques, a Minnesota Department of Transportation (Mn/DOT) sponsored study evaluated the effect of vertical translation. The study used Minne-ALF (an accelerated loading system) to test the effect of vertical dowel translation (i.e., reduced concrete cover) on long-term LTE. While the study was conducted using retrofitted dowels, the variables being evaluated (i.e., shallow dowel placement and lack of concrete cover) are consistent with the problems that can arise from vertical translation in new pavement construction. This study concluded that reduced concrete cover did not significantly affect the LTE performance of pavement. As figure A.2 shows, the slab with only 2 inches of concrete cover between dowel and surface performed as well as the slab with 3 inches of cover for up to 10 million load cycles (Odden et al., 2004).

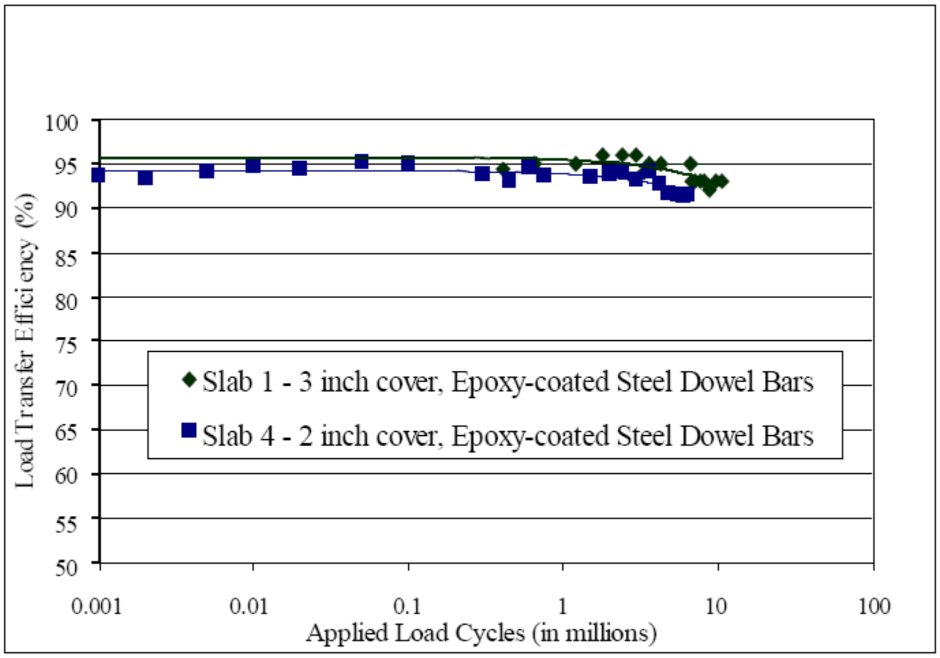

Figure A.2. Effect of concrete cover on pavement performance (Odden et al., 2004).

In the recent field, laboratory, and analytical studies conducted at Munich Technical University, the effects of dowel misplacement were studied extensively. One laboratory study conducted by Leykauf and Freudenstein found a maximum allowable skew or tilt of 20 mm and maximum longitudinal translation of 50 inches. They also found that there are significant increases in contact pressure and decreases in load transfer for embedment lengths less than 50 mm, while changes in embedment length above 100 mm have little effect (Lechner, 2005).

The effect of dowel misplacement on pavement performance was also the subject of several field studies. As with the laboratory testing, the field studies have yielded varying and sometimes contradictory results, as described below.

In 1979, the Wisconsin Department of Transportation conducted a study of pavement sections that used dowel baskets during construction. The field evaluation found that the effect of dowel misalignment on pavement performance was not easy to quantify. Judging from the accuracy of dowel placement during construction, they concluded that 3.5% in horizontal skew and 2.0% in vertical tilt are attainable tolerances, but are not necessarily acceptable. Incidences of vertical tilt frequently involved individual bars, while horizontal misalignment typically involved the entire assembly (Ross, 1979).

An investigation of dowel bars by the Georgia Department of Transportation found that, despite a high percentage of misaligned dowels (as shown in Table A.6), there was no pavement distress related to dowel bar misplacement after being exposed to 3 years of traffic.

Table A.6. Percentage of dowels that did not meet specification requirements (Fowler and Gulden, 1983).

PROJECT	TYPE INSTALLATION	DEPTH(1)	VERTICAL ROTATION(1)	HORIZONTAL ROTATION (1)	HORIZONTAL ROTATION (2)	LONGITUDINAL ALIGNMENT (1)	LONGITUDINAL ALIGNMENT (2)
A	Implant	24	20	9	10	65	68
B	Implant	72	17	25	15	75	66
C	Implant	83	28	20	22	63	62
D	Basket	0	5	0	4	57	54
E	Basket	0	0	5	10	21	22

The results of evaluation of pavement sections located on Highway 115 in Ontario, Canada are presented by Leong (2006). The data showed that the pavement sections were in good condition despite problems that affected dowel bar alignments and joint saw cut depth (over 80% of the dowels were vertically tilted or horizontally skewed more than 12mm). Observed distresses included cracks, corner breaks, and spalling of the joints, but dowel bar misalignment could not be correlated with the observed distresses.

The effects of longitudinal translation on pavement performance was also a subject of field evaluations. One such study was conducted on I-35 near Fergus Falls, Minnesota. Heavy rain during pavement construction created problems in joint location during saw cutting, resulting in longitudinal displacement of the dowels with respect to the joint and a subsequent short embedment lengths. Twelve years after construction, Mn/DOT found that the short embedment lengths contributed greatly to premature faulting. Ten of fifteen joints evaluated were found to have dowel embedment lengths of less than 2 in., and the saw cut completely missed the dowels in five of the ten. Several of these joints had faulting more than 0.25 in, with a maximum faulting measurement of 0.50 inches. The LTE values, determined from FWD testing, ranged from 30% to 87%, with higher embedment lengths resulting in higher LTE values. The study found that significant early faulting occurs when dowel embedment lengths are less than 2.5 inches (Burnham, 1999).

The third method of evaluating the effect of dowel misalignment on pavement performance involves analytical modeling, as was done in a recent Michigan Department of Transportation-sponsored study (Khazanovich et al., 2001). The study showed that while uniform vertical misalignment does not cause significant resistance to joint horizontal movements, non-uniform misalignment may cause joint lock-up (Khazanovich et al., 2001). Non-uniform misalignment also caused increases in concrete bearing stresses, which can result in dowel looseness and loss of LTE. Past studies have demonstrated that JPCP with low levels of load transfer develop significant faulting more rapidly than sections with higher levels of LTE, as shown by figure A.3 (Khazanovich and Gotlif, 2003).

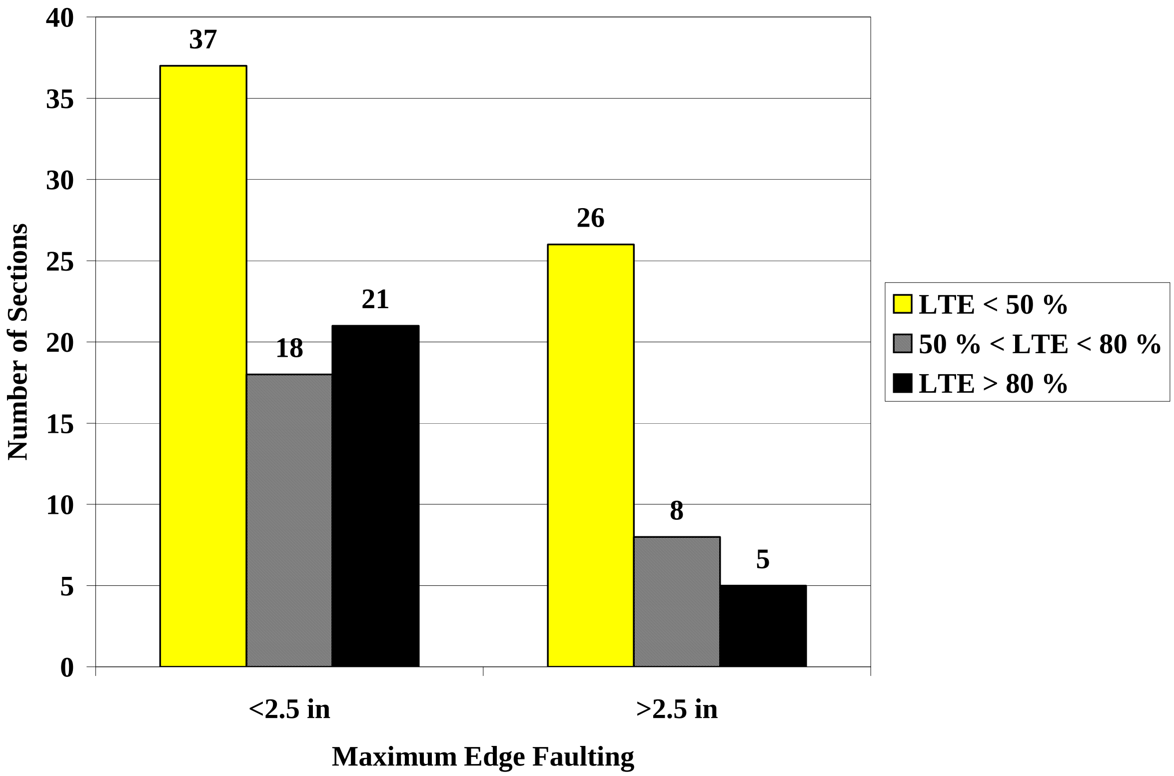

Figure A.3. Effect of LTE on faulting (Khazanovich and Gotlif., 2003).

A.2. FACTORS THAT MAY CONTRIBUTE TO MISALIGNMENT

Design and construction factors can have significant effect on dowel alignment achieved in concrete pavements. A number of broad factors include:

- plastic concrete properties;
- concrete placement practice;
- construction quality control;
- handling, placement, and anchoring of dowel baskets (baskets); and
- equipment type, adjustments, and operator (DBI).

The method of dowel bar placement determines which factors are more critical. In current practice, the dowel bars are placed using either pre-fabricated dowel baskets or a DBI, as shown in figures A.4 and A.5, respectively.

Figure A.4. Placement of dowels in dowel baskets prior to paving.

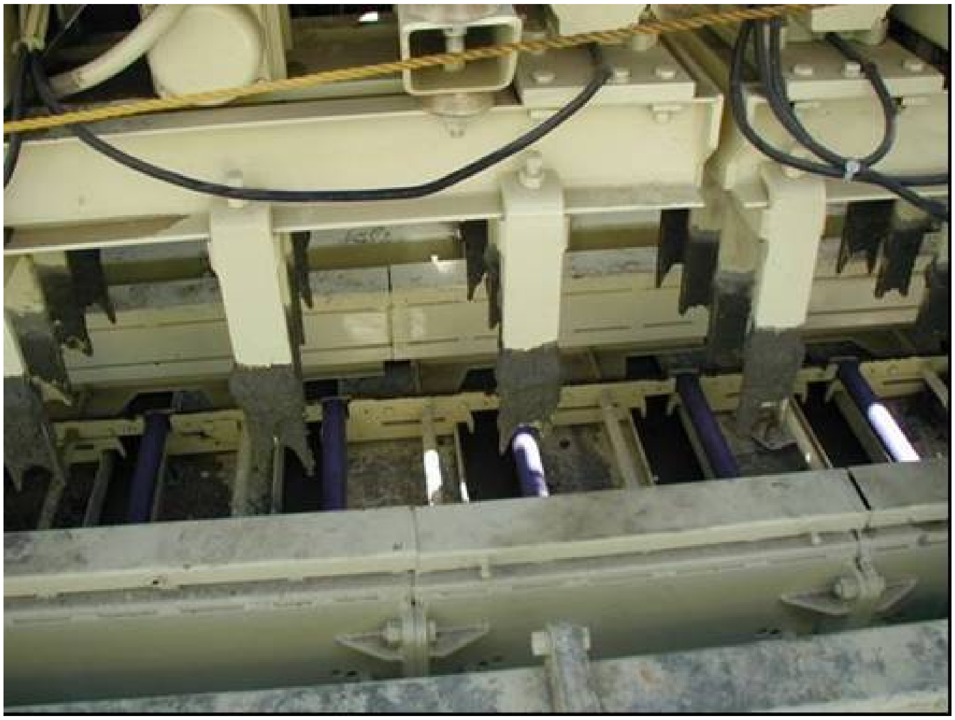
Figure A.5. Placement of dowels using a DBI.

In the U.S. dowel bars are placed most commonly using dowel baskets. In this approach, prefabricated dowel baskets are placed on prepared base at the planned joint locations and anchored in place using nails or stakes prior to paving. For dowel baskets, the most critical factor is the manner in which the baskets are secured to the subbase prior to paving. If the baskets are securely anchored, such that the baskets don't move or deform in any way during paving, very good results are usually obtained. However, if the baskets are not adequately anchored, the baskets can deform, move, rotate, or burst open during paving, resulting in extreme dowel misalignments. The importance of proper dowel installation prompted the Iowa State University PCC Center to develop the following recommended procedure for installing dowel baskets prior to paving (figure A.6):

Recommended Procedures

- After the subgrade has been prepared for paving, dowel assemblies can be placed. Set out pins or paint marks on either side of the roadway to mark locations.
- Align dowels exactly centered over the joint line.
- Anchor dowel baskets securely into the subgrade. For 12' or 14' lane widths, typically a minimum of 4 stakes are installed on the leave side of both basket legs.
- Do not place bent dowel baskets. Do not leave bent dowel baskets in place.
- As a final check, make sure
  - All dowels are parallel to the center line of the roadway
  - All dowels are parallel to the base
  - All baskets are properly pinned
  - The center of each basket (i.e., the joint location) is clearly marked

Figure A.6. Procedure for dowel basket installation (Iowa State University, 2005)

Other factors that can affect the alignment of dowels placed using baskets include the following (Fowler and Gulden, 1983; Tayabji, 1986; Leong, 2006):

- basket rigidity;
- quality control during basket fabrication;
- care during basket transportation and placement;
- fastening of basket to the base/subbase;
- location of saw cut over basket;
- paving operations;
- location of saw cut over implanted dowels; and
- field inspection during construction.

For dowel bars placed in baskets, care during both the transportation and placement of the baskets is important to achieving good results, since any misalignments present prior to paving will add to any that may be introduced during paving. The baskets may also get bent during concrete placement by being walked on or by excessive concrete pressure placed on the basket. To ensure that the joint saw-cuts are made at the proper locations, the dowel baskets must be placed on the survey marks and the joints clearly marked.

Fowler and Gulden (1983) identified saw-cut misplacement as the main cause of longitudinal translation misalignment.

The alternative to using baskets is to directly insert dowel bars into plastic concrete during paving. DBIs were developed in the late 1970s in an attempt to improve the efficiency of dowel placement operation. DBIs are widely used in Europe, but the use of DBIs has been very limited in the U.S. The concerns over dowel alignment and adequate consolidation of concrete over the inserted bars had been the principal reasons for the reluctance to use DBIs in the United States. Also, poor results obtained in some of the earlier attempts at adoption are reasons for the limited use of DBIs in this country.

While concerns over dowel alignment may have been valid when DBI technology was first introduced, significant advances were made over the years in both equipment design and construction practices, with consequent improvements in the results obtained. Investigations of dowel alignment in in-service pavements using ground penetrating radar (GPR) in the mid-1980s showed that DBIs are capable of placing dowel bars within specified placement tolerances and that the inserter placement was comparable to basket placement (Bock and Okamoto, 1989; Tayabji and Okamoto, 1987). In 1996 the FHWA officially encouraged the use of DBIs as an acceptable alternate means of dowel bar placement in jointed concrete construction (Missouri Department of Transportation, 2003); however, as indicated in table A.1, the use of DBI is still banned in some states.

Recently, the Texas, Wisconsin, and Missouri departments of transportation concluded that dowel bars can be placed as accurately using a DBI as baskets in separate investigations (Missouri Department of Transportation, 2003). Yu (2005) concluded that the use of dowel baskets does not guarantee good dowel bar alignment, and excellent results can be achieved using a DBI. Rao (2005) also drew similar conclusions based on an evaluation of dowel alignments in five DBI and seven basket projects located in six States across the United States. These evaluations showed that comparable results can be obtained using either method of construction, as long as the procedures necessary to achieve accurate dowel bar alignment are followed.

Although good results can be obtained using a DBI, close attention must be paid to several factors to obtain good results. The factors that can lead to dowel bar misalignment when using a DBI include the following:

- plastic concrete properties;
- DBI design and adjustment;
- implanting operation (operator);
- concrete placement practice;
- location of saw cut over implanted dowels; and
- field inspection during construction.

When using a DBI, PCC mix design is extremely important to ensure that the PCC mix is sufficiently stable to hold the bars in place after the bars are in inserted. According to one equipment manufacturer, the same properties needed to produce smooth pavement are needed to pave using a DBI (Guntert, 2004). Guntert favors the Shilstone approach (Shilstone, 1990). Shilstone's method is focused on the optimization of the grading of aggregates. To ensure uniform blends without major gaps, especially in the N4 and N8 sieve sizes, Shilstone uses of the coarseness chart (figure A.7), the 0.45 grading power chart (figure A.8), and the mortar factor (Shilstone, 1990; Shilstone and Shilstone, 2002).

Basically, gap-grading should be avoided. Any segregation can lead to problems because of the instability of the mix at random locations. The significant difference in the vibration energy needed to insert the bars in the area dense with aggregate, compared to the area composed mostly of cement paste, is also a major problem. If the same energy is used, the bars can drop to the bottom in the slab.

In figure A.8 (Shilstone and Shilstone, 2002) aggregate gradations for concrete mixes are divided in five zones. The diagonal bar, which separates Zone V from the others, also separates rocky mixtures from sandy mixes. Mixtures in Zone I are prone to segregation. Mixtures in Zone IV have too much fine aggregate and are likely to crack, yield low strength, and segregate during vibration. Zone II is the desirable zone. Zone III is an extension of Zone II for maximum aggregate size of 13 mm (0.5 in) or less. For paving using DBI, the mixtures in Zones II or III are recommended.

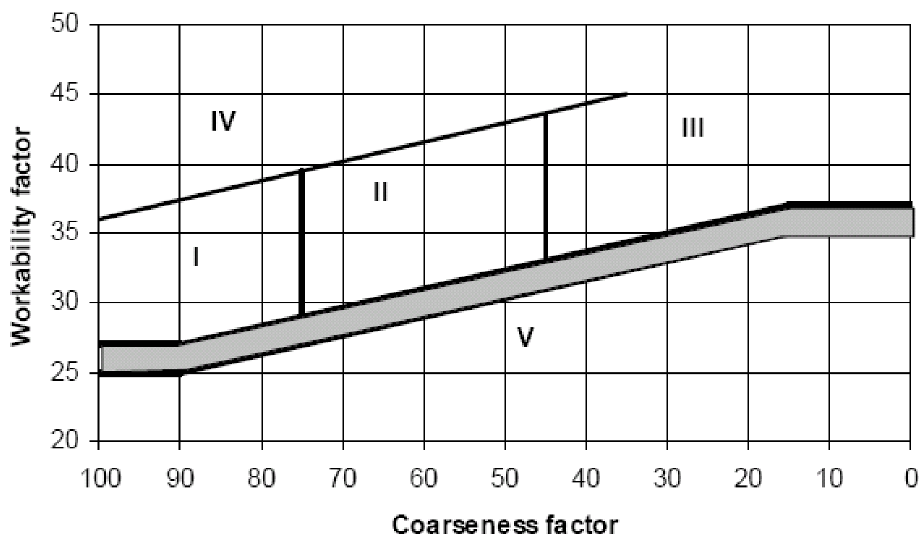

Figure A.7. Coarseness chart as proposed by Shilstone (Shilstone and Shilstone, 2002).

For grading, Shilstone recommends using the 0.45 power grading chart. Figure A.8 shows the 0.45 power chart for maximum aggregate size of 1 in (Pedro and Fowler, 2004). In this chart the horizontal axis scale is obtained by raising the sieve opening size to the 0.45 power. A good grading is one that does not deviate significantly from the straight line, as in the case of the example gradation shown in figure A.8.

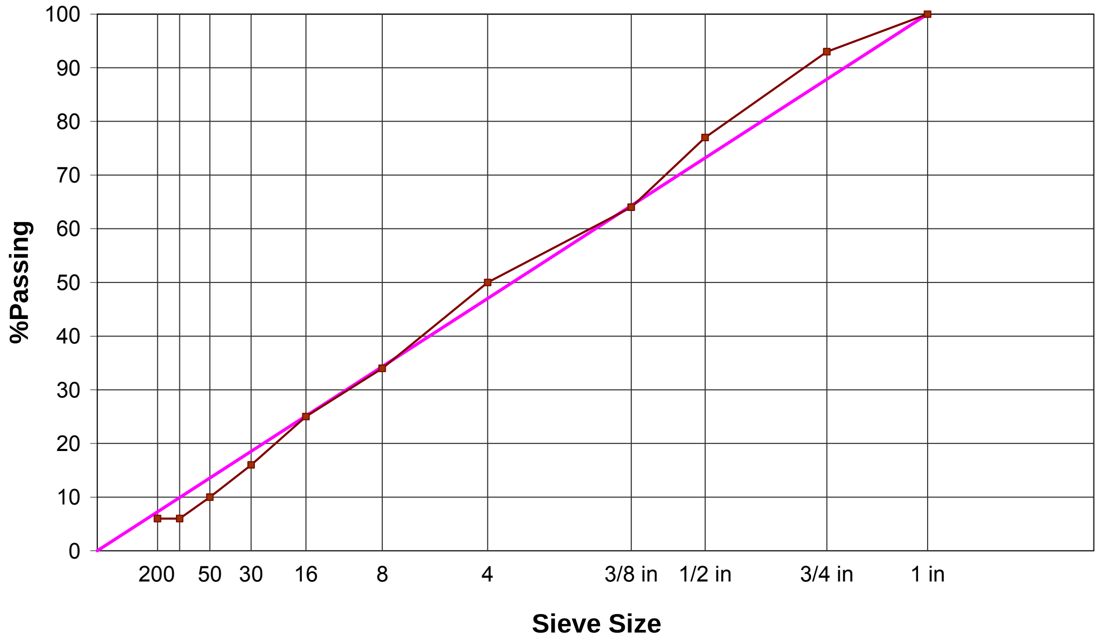

Figure A.8. The 0.45 power grading chart (Shilstone and Shilstone, 2002).

In general, a mixture with desirable properties (good workability and density) can be obtained using Shilstone's guidelines. Pedro and Fowler (2004) found the following:

> "The 0.45 power chart combined with the coarseness chart seems to lead to reasonable results. In this investigation, it was found that mixtures slightly above the straight line of the 0.45 power chart and not too far below, and in Zone II of the coarseness chart generally produced workable mixtures. Mixtures above the straight line tended to be stiff, and required high amounts of water reducers to reach the target slump. These mixtures usually were in Zone IV of the coarseness chart. Mixtures far below the line tended to be coarse, unstable and prone to segregation."

One drawback of the Shilstone method is that the aggregate shape and texture is not considered. As a result, mixtures with exactly the same grading can behave differently (Pedro and Fowler, 2004).

Mix optimization is very important to obtain good results using a DBI. Figure A.9 shows the effects of mix optimization on dowel alignment (Yu and Khazanovich, 2005). The Shilstone method was used to optimize the concrete mix on this project. Figure A.9 show the improvement with each iteration of mix adjustment in terms of the percentage of bars in compliance. The dowel alignment data were obtained using MIT Scan-2.

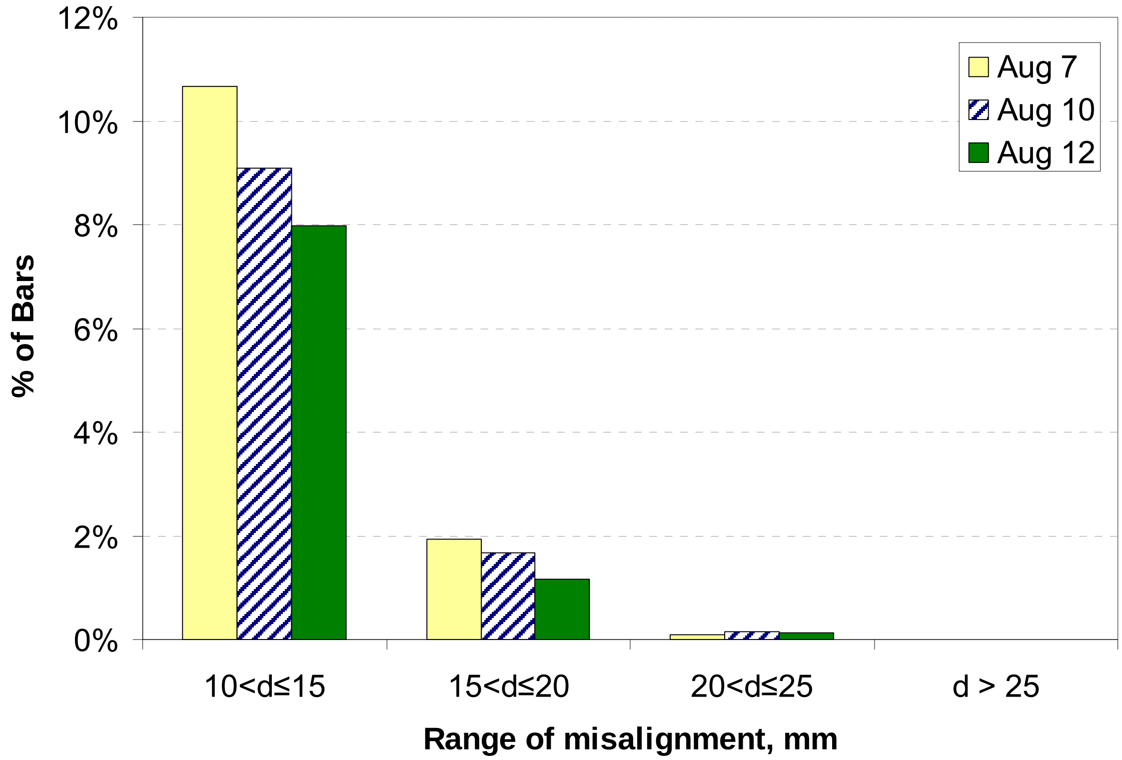

Figure A.9. The effects of mix optimization on dowel alignment on the US-64 Bypass project (Yu and Khazanovich, 2005).

When using a DBI, monitoring the dowel alignment is very important to ensure that the construction process is working to produce good dowel alignment. Misalignments can result from improper equipment adjustments, as well as any problems with the concrete mix. Consistent problems at one dowel bar location indicate the problem with the equipment adjustment; whereas random problems indicate the mix stability problem.

Several equipment factors can also be important to obtaining good results using a DBI. The number of forks and vibrating frequency affect dowel alignment, as well as consolidation of concrete around the dowel bars and above the bars. Guntert (2004) points out that the dowel bars must act as the vibrator to move and consolidate the concrete in its path around the dowel bar as the bar is lowered into concrete, because the inserter forks do not have the surface needed to vibrate the concrete after releasing the bars. In some DBI designs, metal forms are placed on the pavement surface and only narrow slots are left open for inserting the dowel bars (see figure A.5). Guntert (2004) placed importance on the confinement provided by the metal forms to ensure that the concrete displaced by the dowel bars move around the dowel bar to fill the void above the bar as the bar is lowered into the concrete.

Accurately locating joint location can be more of a problem for DBI than baskets, because the joint locations are marked using the paint marks automatically placed by the paver. The paint mark has a relatively large diameter (about the same size as the typical specifications on longitudinal misalignment [2 in]), and the marks may get lost if the joint locations are not marked using nails or other more permanent markers shortly after paving.

A.3. FIELD EVALUATION OF DOWEL MISALIGNMENT

Field evaluations are usually performed on a case-by-case basis when dowel misalignment is suspected due to poor joint performance, such as excessive faulting or spalling. In the past, it was not common to measure dowel placement position in newly constructed PCC pavements because, until recently, there was no simple way to perform this operation.

Under a Caltrans-sponsored project, Khazanovich et al. (2003) identified the devices that were available for estimating or measuring dowel position in 2003:

- Impact echo
- Profometer
- Micro Covermeter
- Covermaster
- Rebar locator
- Fisher MODEL M-101 Rebar Locator
- Refor 3, Ferroscan
- Ground Penetrating Radar (GPR)
- MIT-Scan-2
- Kansas State University dowel bar locator

Of these, the only devices frequently used for identifying dowel misalignment are the MIT Scan-2, Profometer, and Ground Penetrating Radar (GPR). The other devices can be used for locating dowels or reinforcement in concrete.

MIT Scan-2. MIT Scan-2 was developed by MIT GmbH of Dresden, Germany, and was created specifically for locating steel dowels and tie bars in concrete pavements. The device has features that make it superior to all other devices:

- In one scan, the device determines the location and alignment of all dowels along an entire joint (up to three lanes wide).
- Preliminary results can be printed immediately after the measurements are taken; more comprehensive analyses can be performed later.
- Multiple sensors and innovative data interpretation software make the device extremely accurate.

For dowel bars placed in baskets, the presence of the metal basket interferes with MIT Scan-2 results. However, if the transport ties in the basket are cut, good results can be obtained, even without any special considerations for the dowel basket. With specific calibration a similar level of accuracy can be obtained for dowel baskets as for bare bars.

MIT Scan-2 is an easy-to-use device that permits high productivity in terms of both measurements and data analysis. A two-person crew can use the device to test 400 or more joints in an 8-hour shift, and the field data analysis is fully automated, with results produced less than a minute after scanning. In addition, the onboard computer is equipped with a printer to provide printed output in the field.

The MIT Scan-2 is designed for use on construction sites without any special protection from the environment. Both the sensor unit and the onboard computer are adequately protected against dust, and they can be used in adverse weather conditions, including rain and low temperatures. The test results are not influenced by weather conditions and the operating temperature range is from 23°F to 122°F (-5°C to 50°C).

Test data are stored on a PCMCIA flash memory card. Data for up to 600 joints (single lane) can be stored on the 32-megabyte (MB) memory card provided with the device. The test results (produced by MagnoNorm software) are accurate for the following conditions:

- mean dowel depth 150 $\pm$ 40 mm (4.3 to 7.5 in.);
- maximum vertical misalignment $\pm$ 20 mm (0.8 in.);
- maximum horizontal misalignment $\pm$ 20 mm (0.8 in.); and
- maximum lateral position error (side shift) < 50 mm (2 in.).

For other conditions, the accompanying PC software (MagnoProof) can be used to conduct a more comprehensive analysis. MagnoProof is also highly automated and easy-to-use, but it allows more manual control of the analysis process. For example, the automatic process for detecting dowel bar locations may not pick up a bar that is placed much deeper than the others because of the weaker signal. MagnoProof allows users to insert or delete bars based on their interpretation of the signal-intensity plot, which is shown on the screen. The user may also restrict the analysis region to cut out any parts containing strong influence from foreign objects that cannot be analyzed. The output options include a signal-intensity contour map and an illustration of the analysis results that shows the specified bar locations and the actual bar positions.

GPR. Ground Penetrating Radar (GPR) has been also used for determining dowel positions. GPR sends a short burst electromagnetic energy into the concrete, where some of this energy is reflected at the boundary between the concrete and dowel. Detection and measurement of the echoes from this reflection give information about the size and shape of the dowel and the degree of discontinuity at the boundary (Geophysics, 2004).

A recent study conducted by the Missouri Department of Transportation (2003) demonstrated that GPR can be used to accurately assess dowel bar alignment. The researchers reported a measurement accuracy of ±3 mm (0.1 in.) on vertical alignment and ± 10 mm (0.4 in.) on lateral positioning.

The GPR method of detecting dowel alignment has significant drawbacks, however, including:

- The method is sensitive to the dielectric constant of concrete, which is a function of many factors, including concrete moisture content and temperature, and antenna frequency. Therefore, this method cannot be used on fresh concrete or when the concrete surface is wet.
- This lack of a fixed reference can exaggerate or minimize the actual dowel misalignment.
- GPR data processing is quite involved. An experienced operator must be available to interpret the GPR output.
- GPR techniques have relatively high operation and data analysis costs.

KSU device. A team of researchers from Kansas Statue University (KSU) recently developed the Kansas State University dowel bar locator, a device based on principles similar to those used in the MIT-SCAN-2 (DeVault et al., 2005). The main purpose of the Kansas device is to verify the depth of dowel bars and tie bars. In its current configuration, the device was not intended for higher-precision measurements needed to evaluate dowel bar alignment. The advantage of the Kansas device is that it runs on wheels, rather than rails, which makes it more convenient for taking continuous measurements along the longitudinal joints.

Other devices. Profometer, Micro Covermeter, Covermaster, Rebar locator, Fisher MODEL M-101 Rebar Locator, Refor 3, Ferroscan were mainly designed for locating reinforcement in concrete structures and determining the depth of concrete cover. They work on the same basic principle as the MIT Scan-2. All of the devices have a similar configuration, with one or more sensors for detecting an induced magnetic field. Based on the duration or intensity of the induced magnetic field, the location of embedded metal is determined. All of the devices provide measures of the concrete cover and the horizontal distance to the bar.

To determine dowel alignment, the ends of the dowel bar must be located by finding the location where the signal drops off abruptly, and the location is then marked manually on the pavement surface. The horizontal alignment is determined from the marked positions, and the depths measured at those locations are used to determine vertical alignment. This process is slow and is subject to errors associated with manual pavement marking and taking readings precisely at the bar ends. These devices may be effective for random checks of dowel alignment, but they are not practical for evaluating the alignment of all bars in a joint, which is needed to assess whether improperly placed dowels will interfere with the proper functioning of the joint.

Comparison of devices. Several recent studies dealt with the evaluation of devices for determining in situ dowel position in pavements. A Caltrans-sponsored study

(Khazanovich et al., 2003) reviewed various devices that can be used for determining dowel misalignment. It compared the accuracy of the devices available in 2003 including: MIT-Scan-2, Profometer, Micro Covermeter, Covermaster, Rebar locator, Fisher MODEL M-101 Rebar Locator, Refor 3, Ferroscan, Ground Penetrating Radar, and the Kansas State University dowel bar locator. It was found that the MIT-Scan-2 device was the most reliable and accurate in locating the position of DBI-inserted dowel bars (Khazanovich et al., 2003).

In the last few years, the Kansas State University (KSU) and the Kansas Department of Transportation have enhanced the KSU dowel bar locator and have conducted field evaluations of the latest system. It was found that the latest system was a significant improvement over the original KSU dowel bar locator and that the new apparatus provides a low-cost approach for lower resolution measurements, but that the MIT-Scan-2 should be used for high-resolution measurements (DeVault et al., 2005).

An FHWA-sponsored study also clearly demonstrated that MIT Scan-2 is a reliable tool for determining of the extent of dowel misalignment in both newly constructed and older PCC pavements (Yu and Khazanovich, 2005). In another study (sponsored by the Ontario Ministry of Transportation) researchers tested the accuracy of the MIT-Scan-2 and found no statistical difference between MIT-Scan-2 measurements and hand measurements, or between repeated MIT-Scan-2 measurements (Leong 2006).

Although the MIT-Scan-2 was found to be very accurate, it was also found to have some limitations. For example, metallic objects within about 1 meter of the dowel bars will invalidate the test results (Yu and Khazanovich, 2005). Therefore, while the MIT-Scan-2 works for dowel basket assemblies with cut wires, only limited information can be obtained for uncut baskets (Khazanovich et al., 2003). For this reason, the MIT-Scan-2 is applicable only to pavements in states that allow or require the cutting of dowel basket tie wires.

Based on the observations made above, it was decided to use MIT SCAN-2 for field testing in this study.

A.4 LABORATORY EVALUATION OF DOWEL MISALIGNMENT

Laboratory testing is an important tool for investigating how dowel misalignment affects pavement performance and for determining what types of distresses develop if one or more dowels are misaligned.

In the past, laboratory testing of dowel bars dealt mainly with the testing of dowel shear transfer efficiency and damage of the concrete surrounding the dowels due to repeated shear load applications. Very few laboratory studies have been conducted to investigate the effect of dowel misalignment on the behavior of surrounding concrete. These studies involved the use of pull-out tests of single or multiple dowel installations, as described below:

- Dowel pull-out test (Figure A.10)
  - One of the first laboratory methods used to evaluate dowel misalignment in a controlled environment
  - Involves pulling an individual dowel out of a concrete block or slab while measuring the force required to initiate and continue dowel movement.

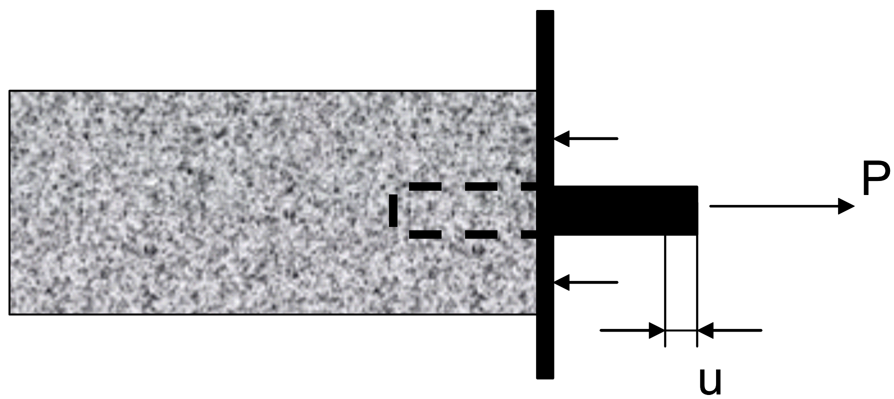

Figure A.10. Schematic of a dowel pull-out test.

- Slab pull-out test (Figure A.11)
  - Used by Tayabji (1986), Michigan State University (Prabhu et al., 2006), and others in an attempt to more realistically model slab expansion and contraction behavior than is possible with the single dowel pull-out test
  - A moving or “transient” slab is pulled away from an anchored or “stationary” slab to open a dowelled joint to a specified width
  - Has been used with up to five dowels in the joint

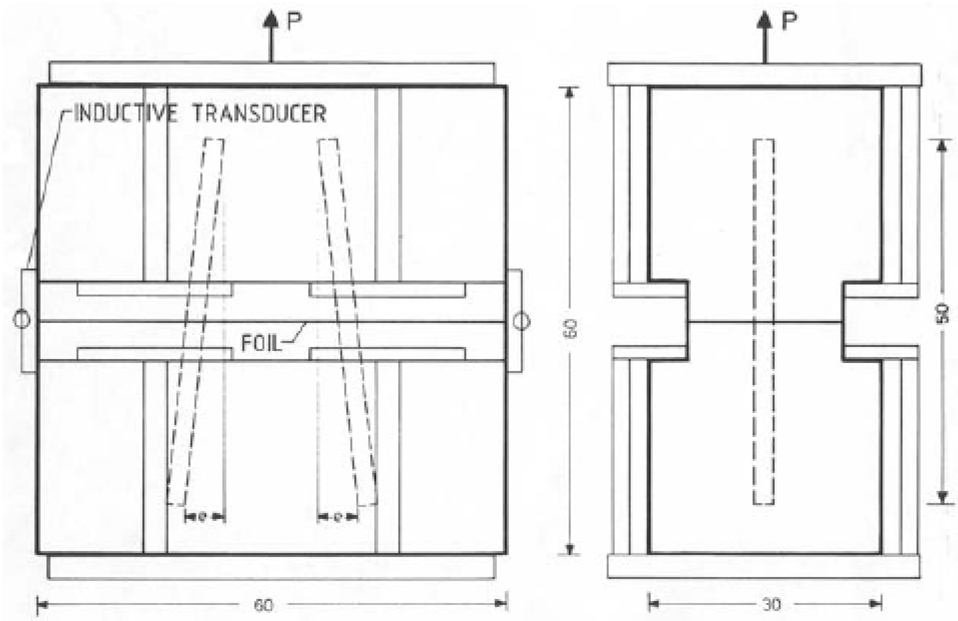

Figure A.11. An example of the slab pullout test. This particular test used two oppositely misaligned dowels and was conducted at TU Munich (Lechner, 2006).

Pull-out testing is the easiest way to test the dowel-PCC bond strength and friction in a laboratory. This test is used by many state departments of transportation for forensic studies of dowelled pavement joints (ACPA, 2005). The test involves using a jack or other device to pull an embedded dowel out of a concrete slab, block or beam that has been mounted on a stiff plate, as shown in figure A.10. Pullout force and displacement are monitored during the test. A typical value for a pull-out force on a typical 1.25-in dowel is about 2000 lb (Buch et al., 2001). If the pull-out force is too small, it may indicate that the concrete around the dowel is either poorly consolidated or damaged. If the pull-out force is too high, it may indicate that the bond breaker between the dowel and concrete is not effective.

Although the pull-out test can provide valuable information for forensic analyses, it is important to note that it has significant limitations:

- Jacking forces applied to the steel face plate are transferred to the concrete as compressive stresses that can provide lateral confinement to the embedded dowel, resulting in possible overestimation of dowel resistance to pullout and joint opening.
- The pull-out test does not provide information on how a misaligned dowel resists joint opening and what kind of damage the horizontal dowel displacement induces in the surrounding concrete.

These limitations make the pull-out test deficient for characterizing the behavior of misaligned dowels.

A.5 ANALYTICAL EVALUATION OF DOWEL MISALIGNMENT

There are two main categories of analytical models that are useful for assessing the effects of dowel misalignment on pavement performance:

- Structural response models
- Performance prediction models

Structural response models. Dowel–concrete slab interaction is a complex problem. Properly designed, manufactured, and installed dowels should provide desirable shear LTE between the adjacent slabs and, at the same time, not resist the slab's horizontal movements during temperature- and moisture-related contraction and expansion. Although some dowel coatings can significantly reduce friction and bonding between the dowel and the surrounding concrete, results of pullout tests show that some resistance to pullout usually remains and must be considered in the analysis.

Finite element and finite difference methods permit the development of structural models that satisfy these requirements. A variety of finite element programs are available to pavement engineers today. These programs may be either general-purpose finite element programs or finite element codes developed specifically for the analysis of pavement systems.

Several of these analytical tools have been used to develop structural models of pavement systems with misaligned dowels, including:

- Three-dimensional (3D) ABAQUS model of a single misaligned dowel (Khazanovich et al., 2001)
- 3D ABAQUS model of multiple misaligned dowels
- 3D FLAC model of multiple misaligned dowels (Leong, 2006)
- Two-dimensional (2D) ABAQUS model of multiple joints with misaligned dowels (Khazanovich et al., 2001)
- 3D EVERFE model of multiple joints with misaligned dowels (Davids, 2003)
- 3D ISLAB2000 model of multiple joints with misaligned dowels (Khazanovich et al., 2000)

These models can be classified according to the degree of detail used for modeling the dowels and their interaction with concrete, as follows:

- Detailed modeling of dowels and dowel/PCC interaction (i.e., the first three models from the list above)
- Simplified modeling of dowel/PCC interaction (i.e., the last three models from the list above)

The models from the first group treat dowels as 3D bodies and use comprehensive contact models to describe dowel/concrete interaction. Khazanovich et al. (2001)

developed a 3D finite element model for a single misaligned dowel (see figure A.12) using ABAQUS.

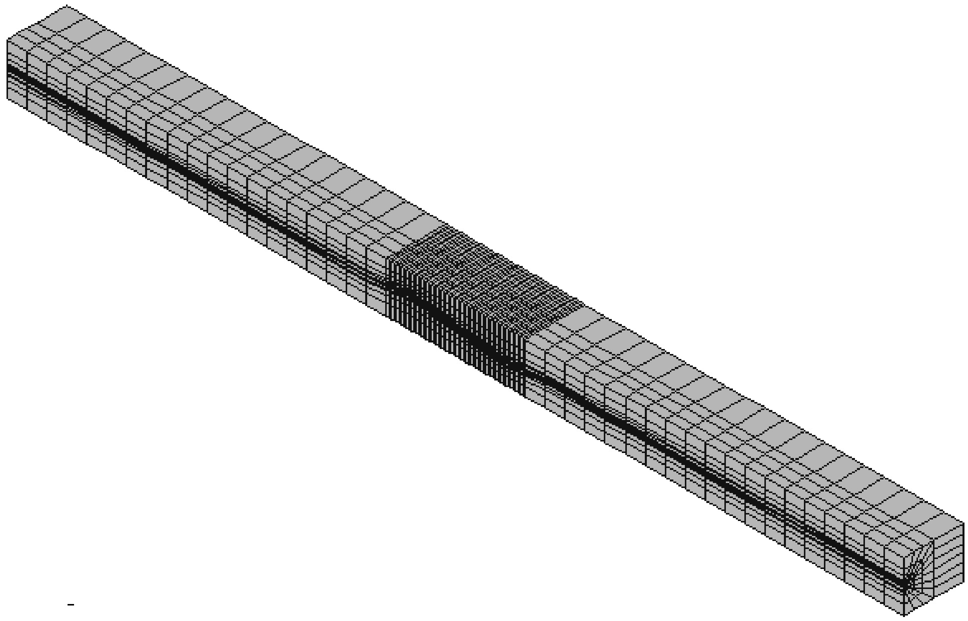

Figure A.12: ABAQUS 3D model of a vertically misaligned dowel. (Khazanovich et al., 2001)

Khazanovich et al. (2001) considered the following cases in the model from figure A.12:

- All dowels in the joint misaligned in the same way and to the same extent (uniform misalignment).
- All dowels in the joint are misaligned to the same extent, but adjacent dowels are misaligned in opposite directions (e.g., if the left end of a dowel is misaligned downward, then the left ends of two adjacent dowels are misaligned upward).
- Only one dowel in the joint is misaligned and all other dowels are perfectly aligned.

This model was later generalized by ARA, Inc. Under a Michigan Department of Transportation-sponsored study, the modified model was used for analyzing cases with three randomly misaligned dowels (see figure A.13).

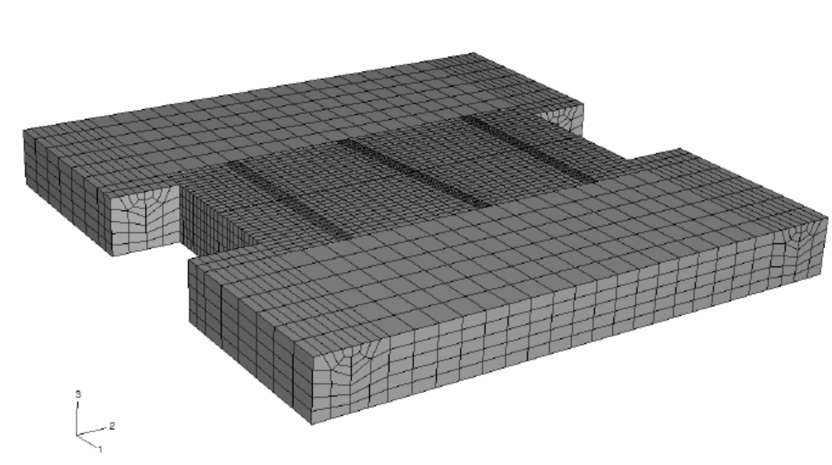

Figure A.13: ABAQUS 3D model of three vertically misaligned dowels.

Leong (2006) used the finite difference-based general purpose program FLAC to analyze misaligned dowels. Figure A.14 shows the FLAC model of 3 misaligned dowels.

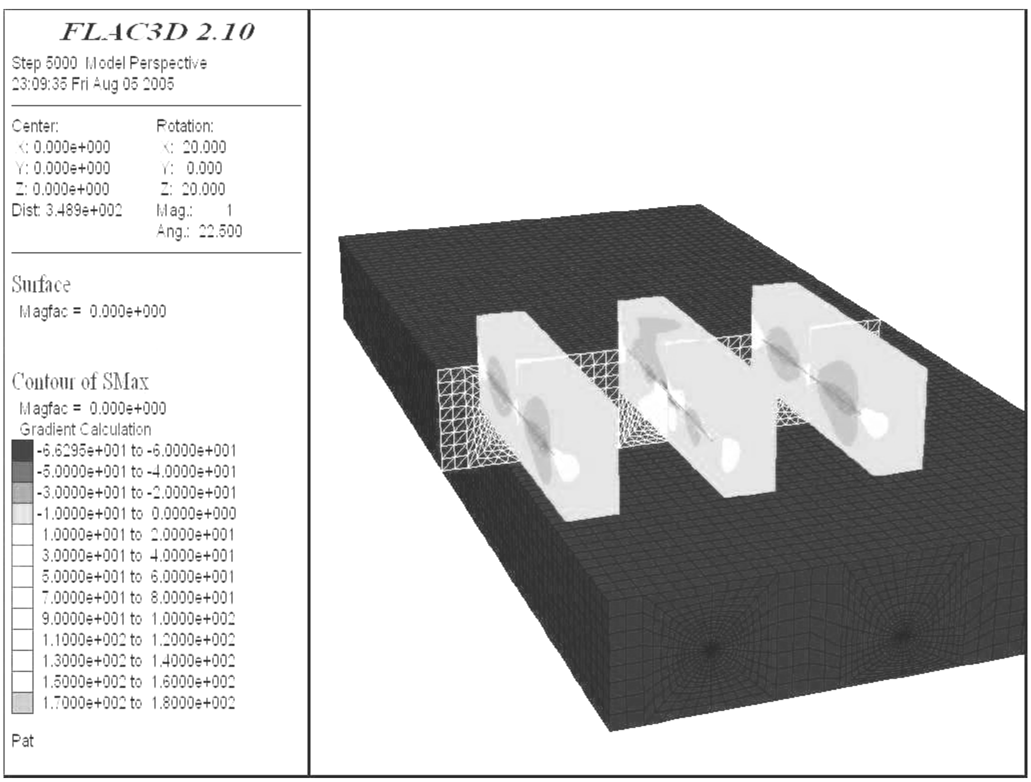

Figure A.14. Section view of stress distribution for 3 misaligned dowels (Leong, 2006).

Although these models are capable of providing detailed information on the stress distribution around a single dowel or a part of a joint, they are also very expensive computationally. This is why simplified models have been developed for analyzing multiple slab systems.

Khazanovich et al. (2001) used ABAQUS to evaluate the effect of misalignment of one or more dowels in a multi-slab system on the behavior of the entire system. A 2D finite element model was used to evaluate a system of three PCC slabs connected with doweled joints. The center slab was modeled as a full-length slab, while only half of the right and left slabs were modeled directly because their centers were restrained from longitudinal movement (see figure A.15). The PCC slabs were modeled using 2D plane stress elements and the dowels were modeled using spring elements. The stiffness of those springs was determined using the pullout force-joint opening relationships obtained from the 3D model.

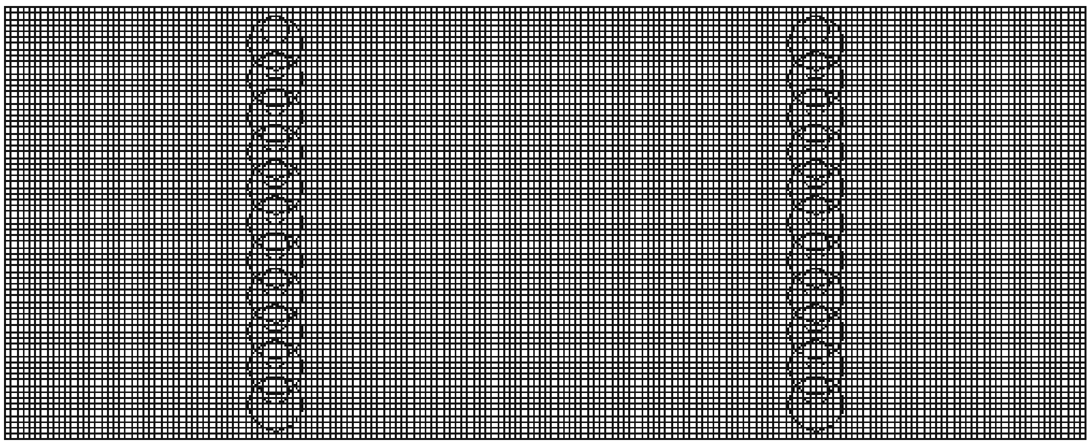

Figure A.15. 2D ABAQUS model of a multi-slab system (Khazanovich et al, 2001).

A similar model was incorporated into the finite element program ISLAB2000 (figure A.16). Unlike other 2D pavement-specific programs, ISLAB2000 has special 20 degree-of-freedom elements that are capable of modeling both bending and concrete slab compression/tension. It also features horizontal spring elements that permit modeling of the effects of restraint to joint opening/closing due to dowel misalignment.

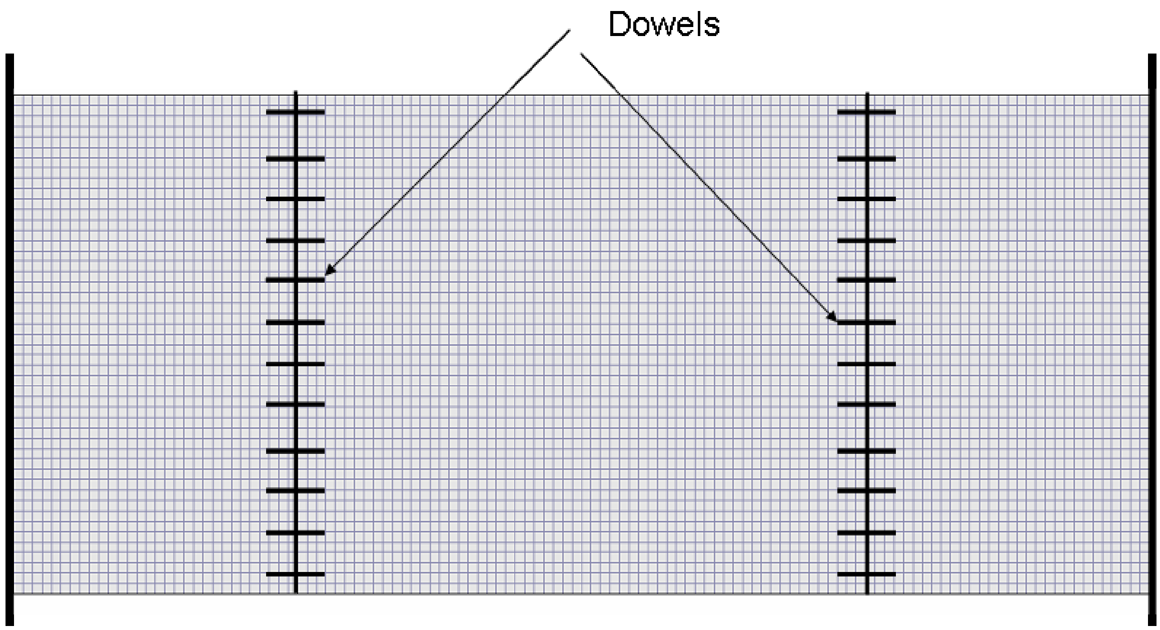

Figure A.16. 2D ISLAB2000 model of a multi-slab system (Khazanovich et al, 2000).

The finite element program EVERFE can analyze multi-layered pavement systems using 3D-continuum brick elements for the PCC and base layers. EVERFE also allows the simulation of dowel misalignment. The user is allowed to input the shift of each individual dowel along and across the joint *x*- and *z*-axes, and is also allowed to define its angular misalignment in the horizontal and vertical planes (Figure A.17). It should be noted that although EVERFE performs comprehensive modeling of concrete slabs, it models dowels using beam elements and requires input of dowel support and restraint moduli. The lack of an option for realistically modeling the friction between the PCC slab and dowels makes EVERFE similar to ISLAB2000 when the effects of dowel misalignment are analyzed.

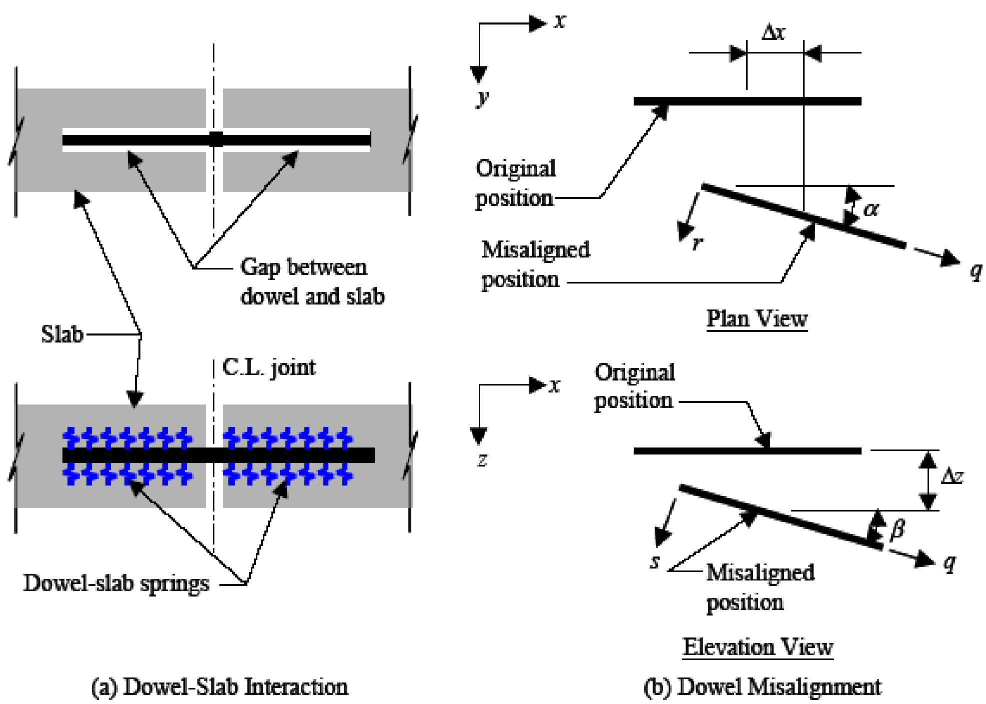

Figure A.17. Dowel modeling in EVERFE (Davis, 2004).

A.5.1. Performance prediction models

Under certain conditions, even severe dowel misalignment does not cause immediate distresses, but still reduces useful pavement life. For example, if dowels (or a sawcut) are so severely displaced in the longitudinal direction that dowels are embedded entirely on one side of the joint, then the pavement will not fail immediately but will instead behave as though undoweled. That will lead to premature faulting and will require earlier restoration or rehabilitation. Another example can be partial locking of joints, which may cause relatively small tensile stresses in concrete that are much lower than the concrete's tensile strength. However, when superimposed with the stresses caused by vehicle loading, curling, and warping, they may accelerate transverse cracking.

In this research, the available performance prediction models that can be used for development of guidelines for dowel alignment, were evaluated based on the following criteria:

- accuracy of predictions;
- simplicity of use; and
- simplicity of integration with the dowel misalignment analysis.

The research team identified available performance prediction models for the following distress indicators:

- JPCP cracking;
- JPCP joint faulting;
- JPCP spalling; and
- roughness.

JPCP Cracking models. Transverse cracking is a key measure of concrete pavement performance for JPCP. The deterioration of a transverse crack in JPCP often leads to roughness and additional cracks in the slab, eventually becoming a shattered slab that requires replacement. Slab replacement is costly and can lead to early rehabilitation of the pavement as more and more cracking occurs. Transverse cracking in concrete pavements can occur as a result of either very high stresses in the slabs or fatigue failure. The high stress levels are usually caused by the combined effects of the restraint forces (the restraint against the contraction of PCC in response to either shrinkage or temperature change), thermal curling, moisture warping, and traffic loads. Transverse cracking can initiate either at the top surface of the PCC slab and propagate downward (top-down cracking) or vice versa (bottom-up cracking), depending on the loading and environmental conditions at the project site, as well as material properties and conditions during construction.

When the truck axles are near the longitudinal edge of the slab midway between the transverse joints, a critical tensile bending stress occurs at the bottom of the slab. This stress increases greatly when there is a high positive temperature gradient through the slab. Repeated loadings of heavy axles result in fatigue damage along the edge of the slab that eventually results in micro-cracks that propagate to the slab surface and transversely across the slab.

When the truck steering axle is near the transverse joint and the drive axle is within 10 to 20 feet and still on the same slab, a high tensile stress occurs at the top of the slab between the axles at some distance from the joint. This stress increases greatly when there is a negative temperature gradient through the slab, a built-in negative gradient from construction, or significant drying shrinkage at the top of the slab (all of these are common).

The modeling of JPCP transverse cracking has been the focus of numerous field and laboratory investigations over the past 30 years. The FHWA-sponsored Design of Zero-Maintenance Plain Jointed Concrete Pavement study was the first mechanistic-based study to demonstrate a direct correlation between accumulated fatigue damage and transverse cracking. This approach was later expanded in several FHWA and NCHRP-sponsored studies. The following JPCP cracking models have been identified under this study:

- PEARDARP Cracking model (Van Wijk, 1985);
- COPES Cracking Model (Darter et al., 1985);
- FHWA-RD-89-137 Cracking Model (Smith et al., 1990);
- NCHRP 1-26 Cracking model (Salsilli et al., 1993);
- SHRP P-020 Cracking Model (Simpson et al., 1994);

- FHWA-RD-95-11 JPCP Cracking Model (Yu et al., 1998a);
- FHWA PAVESPEC 3.0 Cracking Model (Khazanovich and Yu, 2001); and
- MEPDG Cracking Model (NCHRP, 2004).

These models represent continuous improvements in JPCP cracking prediction technology over more than 30 years. All of the models relate cracking to the maximum tensile stress at the mid-slab part of the longitudinal edge. All the models use Miner's fatigue hypothesis to accumulate damage from multiple load applications and use empirical relationships to correlate damage and the percentage of cracked slabs.

The MEPDG cracking model is clearly the most comprehensive performance prediction model available today. It was developed based on the experience obtained in developing the other cracking models, retaining all of their positive features and adding many advanced features. Table A.8 demonstrates that the MEPDG model has many advantages when compared to the PAVESPEC 3.0 model.

The common drawback of all the available cracking models, including the MEPDG model, is that they account only for the bending stresses in the slab and ignore the in-plane stresses. Dowel misalignment may have an effect on these stresses if it restrains joints from opening and closing. The magnitude of these stresses depends on the magnitude and type of dowel misalignment and magnitude of variation in the mean PCC slab temperature stresses. However, the climatic inputs to the MEPDG cracking models (PCC temperature distribution) predicted by the EICM are exactly the same inputs required for analyzing the effect of dowel misalignment. That will greatly simplify integration of the prediction of the long-term effects of dowel misalignment on JPCP cracking.

This and other positive features prompted the research team to select the MEPDG cracking model for analyzing the long-term effects of dowel misalignment on JPCP cracking.

Table A.8. Comparison of PAVESPEC 3.0 and MEPDG cracking models.

Model Feature	PAVESPEC 3.0	MEPDG
Basis of Model	Fatigue Consumption	Fatigue Consumption
Modes of Loading	Traffic, Temperature	Traffic, Temperature, Moisture
Traffic Characterization		
Wheel Loading	18-kip ESALs	Axle Load Spectra All FHWA truck classes 24-hour truck count
Traffic Wander	Only critical loading position (at pavement edge) considered	Wheel wander effects fully considered in incremental damage process
Climatic effects considered	Thermal gradients considered (approximated from standard table as a function of thickness and LTPP climatic zone)	Effects of climate on curling/warping, base modulus, and subgrade support value are fully considered
Structural layers modeled	PCC and base layer. All other layers modeled using the k-value.	No limitation on the number of input layers
Materials Characterization	28-day PCC modulus and flexural strength	PCC modulus and strength gain over time
Types of Damage Computed	Bottom-up damage	Bottom-up and Top-down damage
Stress Computation	Closed-form solutions for stresses (based on a database of finite element solutions)	Neural network solutions (based on a database of finite element solutions)
Calibration data set	LTPP (GPS-3) and RPPR	LTTP (GPS-3 and SPS-2) & RPPR
Cracking Model		
Stress ratio	Only PCC modulus of rupture at 28 days considered	Actual values of PCC modulus of rupture for current pavement age considered
Allowable number of load repetitions	From the fatigue model for assigned temperature gradient values	From the fatigue model for each pavement age, season, axle type, load level and traffic path
Pass-to-Coverage-Ratio	Regression equations for each stress ratio	Direct accounting for traffic wander
Frequency distribution of temperature gradient	Standard tables for climatic zone and effective thickness	Actual temperature gradients and traffic data considered
Applied number of load repetitions	Standard frequency values, pass-to-coverage-ratios and ESALS considered	Actual frequency values for each season, temperature gradient, axle type, load level and traffic path considered
Cumulative fatigue damage	Sum of damages for 22 increments for each values of temperature difference	Sum of the damage increments for each condition (age, season, temperature difference and traffic wander). Bottom-up and Top-down damage
Percent of slabs cracked	Regression model	Regression model for Bottom-up and Top-down cracking. Total amount of cracking calculation

JPCP faulting models. Transverse joint faulting is defined as the difference in elevation between adjacent slabs at a transverse joint. The development of faulting is often attributed to a combination of repeated heavy axle loads, insufficient load transfer between the adjacent slabs, free moisture in the pavement structure, and the presence of an erodible base or subgrade material. Significant joint faulting causes loss of ride quality and triggers early rehabilitation

Transverse joint faulting has been the focus of several field and laboratory investigations, which have resulted in many faulting models, including the following:

- SHRP P-020 JPCP Transverse Joint Faulting Model (Simpson et al., 1994);
- FHWA-RD-95-11 JPCP Transverse Joint Faulting Model (Yu et al., 1998a);
- ACPA JPCP Transverse Joint Faulting Model (Wu et al., 1993);
- FHWA NAPCOM JPCP Transverse Joint Faulting Model (Owusu-Antwi et al., 1997);
- NCHRP 1-34 Model (Yu et al., 1998b) ;
- LTPP Data Analysis Study JPCP Transverse Joint Faulting Model (Titus-Glover et al., 1999);
- PRS 3.0 Transverse Joint Faulting Model (Horner et al., 2000); and
- MEPDG (Khazanovich et al., 2004).

These models can be divided into 3 groups:

- Empirical models - SHRP P-020 and FHWA RPPR 1997
- Simplified mechanistic-empirical (ME) models - (FHWA NAPCOM, NCHRP 1-34, LTPP, and PAVESPEC 3.0); and
- the MEPDG model.

None of the models can account directly for dowel misalignment. Therefore, the effort required to integrate dowel misalignment analysis into the model should be an important criterion for evaluation. Since the empirical models are applicable only within the inference space, they are not well suited for extrapolation. Therefore, preference should be given to the mechanistic-empirical models.

Although the ACPA model is a mechanistic-empirical model and it uses the Power concept for the analysis of damage caused by repeated vehicle loading, it accounts for dowel effects empirically. Therefore, the ACPA model is not a good candidate for integration in the dowel misalignment analysis.

Other simplified ME models are based on the Differential Energy (DE) concept (Khazanovich et al., 2004). This concept recognizes that significant differential deflections of adjacent slabs impart energy to the underlying pavement materials. These deflections cause the movement of the saturated underlying pavement material as equilibrium is reestablished, resulting in erosion and pumping. The differential energy across the joint or crack is amplified by several factors, including heavy wheel loads and inadequate load transfer. Since dowels reduce DE, they reduce faulting. However, since dowel misalignment may cause greater damage around dowel, it may reduce dowel efficiency and increase faulting potential.

Although the simplified ME models are theoretically sound, they have the following disadvantages:

- They use “average” pavement parameters (LTE, PCC slab properties, subgrade support conditions).
- The models neglect seasonal and environmental effects on faulting development.

Developed under the NCHRP 1-37A study, the MEPDG faulting model is also based on the DE concept, but it incorporates several major improvements compared to the simplified mechanistic-empirical models. A detailed list of the positive feature of the MEPDG model is presented elsewhere (Khazanovich et al., 2004). Only the most relevant advantages of this model are presented below:

- The MEPDG model accounts for incremental deterioration of transverse joints. This is important because joint deterioration reduces joint LTE, increases the magnitude of differential PCC slab deflection across the joint, and therefore increases the magnitude of differential energy of subgrade deformation.
- The model recognizes that the total deflection LTE includes the contribution of three major mechanisms of load transfer:
    - Load transfer by PCC aggregates
    - Load transfer by joint dowels (if applicable)
    - Joint transfer by the base/subgrade

  Modeling of each of these LTE mechanisms is performed separately. This simplifies incorporation of the effects of dowel misalignment, which requires adjustment of the effectiveness of the dowel component of the LTE.

- The model accounts for the effects of monthly variations in joint opening (assuming that the dowels are aligned). This is important because the predicted joint openings may be also used for analyzing the effects of dowel misalignment on JPCP cracking.

- The MEPDG software integrates the faulting model with the EICM

These features along with other positive features (such as more accurate prediction of structural responses [loaded and unloaded slab deflections], accounting for axle spectrum distribution versus ESALs, a calibration involving the largest, most comprehensive data set) make the MEPDG faulting model the model of choice for the integration of the prediction of the long-term effects of dowel misalignment on joint faulting.

Spalling models. Transverse joint spalling is the chipping or fracturing of the slab edges at the joint, extending from a few inches to a few feet from the joint. Transverse joint spalling usually does not extend vertically through the entire slab thickness, but rather is limited to the upper portion of the slab. Transverse joint spalling can be caused by a variety of factors, including:

- the presence of incompressible materials in the joints that cause excessive stresses at the joint as the slab expands in warm weather;
- poor durability of the concrete, either due to an inadequate air void system or to aggregate durability problems such as D-cracking or reactive aggregate;
- inadequate consolidation of the concrete at the joint; and
- misaligned and corroded load transfer devices.

The following spalling models were identified:

- COPES Joint Deterioration Model (Darter et al., 1985);
- SHRP P-020 JPCP Spalling Model (Simpson et al., 1994);
- FHWA-RD-89-137 Spalling Model (Smith et al., 1990);
- Texas Transportation Institute Spalling Model (Senadheera and Zollinger, 1994);
- FHWA-RD-95-11 JPCP Spalling Model (Yu et al., 1998); and
- MEPDG Cracking Model (NCHRP, 2004).

Although several spalling models were identified in this study, none of them is useful for analyzing the effect of dowel misalignment on joint spalling. Indeed, five out of six models are empirical and none of them has dowel misalignment as an input parameter. The only mechanistic-empirical spalling model (TTI Spalling Model) does not incorporate mechanistic responses which can be affected by the misalignment level.

Roughness models. The international roughness index (IRI) is an indicator of pavement ride quality that is calculated from longitudinal profile data and is reported in English units of in/mi. IRI has been shown to correlate very well with the subjective user ratings of ride quality (i.e. present serviceability rating [PSR]) and is strongly correlated with the presence of pavement distresses. The IRI over the design period depends upon the initial as-constructed profile of the pavement, the subsequent development of distresses such as joint faulting and slab cracking, and any future settlement of the slab that affects longitudinal profile over time.

The following IRI models were identified under this study:

- SHRP P-020 JPCP IRI Model (Simpson et al., 1994);
- FHWA-RD-89-137 IRI Model (Smith et al., 1990);
- FHWA-RD-97-147 IRI Model (Perera et al., 1998);
- FHWA-RD-95-11 JPCP IRI Model (Yu et al., 1998); and
- PRS 3.0 IRI Model (Hoerner et al., 2000).

None these models directly account for the effect of dowel misalignment, but many of them can account for this effect indirectly through correlation between IRI and the individual distresses (faulting, cracking, and spalling). All the roughness models are empirical models related to pavement distresses (i.e., cracking, faulting, and spalling) and site conditions. Their empirical nature, however, is not a drawback for this study because misalignment may affect the ride quality mainly through increases in the incidence and severity of individual distresses. Since the MEPDG faulting and cracking models were selected for modification is this study, it was decided to adopt the MEPDG IRI models for roughness prediction.

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