The Need for Improved Specifications on Dowel Bar Placement Tolerance

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Abstract

While the importance of achieving good dowel alignment is widely recognized, determining the alignment of dowel bars encased in hardened concrete had been a difficult and costly process prior to the availability of MIT Scan-2. MIT Scan-2 is a state-of-the-art, nondestructive testing (NDT) device, which allows for efficient and accurate measurement of dowel alignment. Because of the past difficulties in measuring dowel alignment, the magnitude of misalignment at which the poor dowel alignment becomes a pavement performance issue is not well known. Nevertheless, nearly every State has tight specifications on dowel placement tolerance. With the availability of a new, practical method of measuring dowel alignment, there is a critical need to review the effects of dowel misalignment on pavement performance and develop rational guidelines on dowel placement tolerance.

A comprehensive national study is underway (National Cooperative Highway Research Program [NCHRP] Project 10-69, Guidelines for Dowel Alignment in Concrete Pavements) that is aimed at evaluating the effects of dowel alignment on pavement performance and developing guidelines for dowel placement tolerance. In the interim, the findings from several recent studies could be put into practice. Based on the lessons learned from recent dowel-alignment-related studies and field observations, this paper provides recommendations on dowel placement tolerances. An important change proposed is the consideration of dowel alignment on joint-by-joint basis and the inclusion of the provision to allow a limited number of isolated locked joints.

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INTRODUCTION

Dowel bars are used in jointed concrete pavements (JCP) to prevent pumping and faulting, as well as cracking. Dowel bars provide positive load transfer across pavement joints to greatly reduce critical deflections and stresses. In the past, roughness caused by excessive faulting had been a major problem on non-dowelled pavements subjected to heavy truck traffic (Gulden 1974; Smith et al 1990). Studies have shown that large-diameter dowel bars are highly effective in preventing faulting (Snyder et al 1989; Smith et al. 1990; Yu et al. 1998). The effectiveness of dowel bars in reducing faulting is also clearly demonstrated in the effectiveness of retrofit dowel bars (in combination with diamond grinding) in extending the service life of pavements that had developed severe faulting (Snyder et al 1989; FHWA 1997; Pierce et al. 2003).

The use of large-diameter (minimum 32 mm [1.25 in]) dowel bars is highly recommended for JCP subjected to high volumes of heavy truck traffic (FHWA 1989; AASHTO 1993). In these recommendations it is assumed that the dowel bars will be placed in proper alignment and positions. Improper placement may not only reduce the effectiveness of dowel bars, but also contribute to spalling and cracking. Recognizing the importance of good dowel alignment, most states have stringent requirements on dowel placement accuracy. However, these requirements are not enforced rigorously in most States, because there had been no practical means of measuring dowel alignment.

The past difficulties in measuring dowel alignment had at least two important consequences on concrete pavement construction in the U.S.:

- Possibility of excessively stringent dowel placement tolerance – the existing specifications are based on limited laboratory testing and analytical evaluation results, and they do not reflect field experience.
- Limited usage of dowel bar inserters (DBI) – because of the concern over the dowel alignment DBIs are not widely used in the U.S., and many highway agencies specifically prohibit their use, although DBI may offer advantage in construction cost and speed.

Today, dowel alignment can be measured efficiently and accurately using MIT Scan-2 (figure 1), a state-of-the-art nondestructive testing (NDT) device for measuring the position and alignment of dowel bars (Khazanovich et al. 2003). The device is easy to use, and the results can be printed using the on-board printer immediately after scanning. Up to 400 or more joints can be tested in an 8-hr work day using MIT Scan-2. This device was evaluated extensively under an FHWA study (Yu and Khazanovich 2005) and was found to provide accurate results. For the rotational misalignment (horizontal and vertical misalignment), the overall standard deviation of measurement is 3 mm (0.12 in).

With the availability of this new capability, questions are being raised as to the adequacy of the current standards on dowel placement tolerances. Many questions remain on what dowel alignment is needed to ensure good pavement performance, and based on the information from recent studies, there seems to be an urgent need for improved specifications on dowel placement tolerances. A comprehensive study is underway (NCHRP Project 10-69, Guidelines for Dowel Alignment in Concrete Pavements) that is aimed at providing the answers to those questions and developing improved guidelines on dowel placement accuracy. In the interim, the findings from recent studies could be put into practice. Based on the lessons learned from recent studies and field observations, this paper provides recommendations on dowel placement tolerance.
EFFECTS OF DOWEL MISALIGNMENT

Dowel bars need to be placed parallel to the pavement surface and to the longitudinal joint to enable free, uninhibited opening and closing of the joints resulting from expansion or contraction of the pavement slabs in response to temperature changes, as well as initial shrinkage. The bars should also be placed centered on the joint to ensure adequate embedment in both approach and leave slabs for load transfer. To ensure adequate concrete cover at top and bottom of the slab (for both corrosion considerations and to avoid spalling), the bars should be placed near the mid-depth. The position of the bars along the joint is also important to ensure the bars are placed where they are needed to provide load transfer. Any deviations in dowel bar position from the ideal position may be defined misplacement or misalignment. Tayabji (1986) identified the following categories of dowel misalignment (figure 2):

- Horizontal translation
- Longitudinal translation (side shift)
- Vertical translation (depth error)
- Horizontal skew (horizontal misalignment)
- Vertical tilt (vertical misalignment)

The rotational misalignments affect the free joint movements, while the translational misalignments (or misplacements) affect the effectiveness of individual dowel bars in performing the intended function (i.e., provide load transfer). In general, the margin for placement error is much greater on translational misalignments than on rotational misalignments.

Horizontal Translation

The horizontal translation may be the least critical type of misalignment. Adequate number of dowel bars should be provided under each wheelpath to ensure adequate load transfer. The dowel bars should be evenly spaced, but the exact position of the bars along the joint is not critical, since the traffic wanders laterally. The margin for placement error for horizontal translation may be in the order of 10s of mm (inches).

Vertical Translation

The main concern with vertical translation is the concrete cover. Inadequate cover may lead to spalling or corrosion problems. In most States, the dowel bars are specified to be placed at mid-depth plus or minus 25 mm (1 in). Typical minimum cover requirement is 75 mm (3 in). On a 200-mm (8-in) pavement, mid-depth minus 25 mm (1 in) would result in cover depth less then the minimum required. However, in a thick pavement (e.g., 330 mm [13 in]), there may be ample margin for additional placement error. Thus, the tolerance on vertical translation may be better given in terms of minimum cover, rather than deviation from the mid-depth.

Longitudinal Translation

Longitudinal translation (or side shift) determines the embedment length of the dowel bars in the slabs on either side of the joint. The embedment length relates directly to the load-transfer effectiveness of dowel bars. Historically, a minimum embedment length of 150 mm (6 in) was thought to be the minimum needed to ensure full load transfer. The standard dowel bar length of 450 mm (18 in) was meant to provide a minimum embedment of 150 mm (6 in) and placement tolerance of ±75 mm (3 in). However, the tolerance on longitudinal translation is 50 mm (2 in) or less in most states.
At least two recent studies showed that the embedment length needed to obtain full load transfer may be significantly less than previously thought. A study conducted by Minnesota Department of Transportation (MnDOT) showed that the embedment length required may be as little as 64 mm (2.5 in) (Burnham 1999). Figure 3 shows the effects of embedment length on load-transfer effectiveness of dowel bars from the Minnesota study. A laboratory and analytical evaluation conducted in Germany (Lechner 2005) showed a significant increase in contact pressure and decreases in load transfer for embedment lengths less than 50 mm (2 in), but no change for embedment length above 100 mm (4 in). The study concluded that there is no benefit for providing embedment greater than 100 mm (4 in).

Further validation is needed to ensure that the above findings are applicable to pavements subjected to heavy traffic (high volume of heavy trucks) over the entire design life of the pavement. In the mean time, the use of more conservative requirements may be prudent. However, even based on the original intent for using 450-mm (18-in) bars the placement tolerance could be relaxed to some extent. For example, a tolerance of ±75 mm (3 in) is very conservative. For the bars outside the wheelpath, the tolerance may be further relaxed to ±100 mm (4 in) without any adverse effects.

**Rotational Misalignments**

Horizontal and vertical misalignments affect free joint movements. Severe horizontal or vertical misalignments are thought to cause spalling or cracking. Dowel misalignment is often cited as the suspected cause when premature cracking or spalling occurs. However, there are no conclusive evidences linking dowel misalignment to spalling or cracking in the field. In laboratory studies, spalling and cracking have been produced, but the distresses only developed at displacements several times greater than the joint movement that occur in the field, even for severely misaligned dowel bars (50-mm [2-in] misalignment).

An investigation of dowel bars by the Georgia DOT found that, despite a high percentage of misaligned dowel bars with misalignments in excess of 25 mm (1 in), no pavement distress related to dowel bar misplacement occurred after being exposed to 3 years of traffic (Fowler and Gulden 1983). The same pavement section surveyed 20 years later also exhibited no pavement distresses that could be related to dowel bar alignment, except that very poor joint load transfer was noted (Yu 2005).

A study conducted by Michigan State University (Prabhu et al. 2006) showed that at small displacements (e.g., less than 5 mm [0.2 in]), even significantly misaligned dowel bars (up to 50-mm [2-in] misalignment) do not result in spalling or cracking. In the laboratory study, displacements in excess of 17 mm (0.67 in) were needed to produce distresses. The typical joint movement for 4.6-m (15-ft) slabs is 2-3 mm (0.08 to 0.12 in), even in colder areas. Figures 4 and 5 show the results from the Michigan State University study. The series in the plots are labeled as follows:

- Number of dowel bars (e.g., “2” in 2H9NU)
- Type of misalignment: H = horizontal; V = vertical; C = combined (resultant); A = aligned (control)
- Amount of misalignment in radians (e.g., “9” I 2H9NU) – 9 means 1/9 radian.
- Uniform or non-uniform misalignment (U or NU) – uniform misalignment means all misaligned bars are parallel to each other.
In Figure 4 the series labeled 2A is the control specimen, in which the bars are perfectly aligned; other series are labeled with the amount of misalignment given in radians. On 450-mm (18-in) bars, 1/9 radian rotation corresponds to 50-mm (2-in) misalignment and 1/18 radian to 25-mm (1-in) misalignment. Figure 4 shows that for displacements up to about 2 mm (0.08 in), neither the amount nor type of misalignment has any significant effect on the pull-out force. The difference is only moderately higher for the non-uniform misalignment at 3-mm (0.12-in) displacement. As noted earlier, the typical joint-movement for 4.6-m (15-ft) slabs is 2-3 mm. Figures 4 and 5 show that that a substantially greater amount of displacement was needed to produce distresses. Based on these results, spalling or cracking due to dowel misalignments does not seem very likely in the field. This is consistent with field observations.

The findings from the Michigan State University study include the following (Parabu et al. 2006):

- Nonuniform misalignment is more critical than uniform misalignment.
- Number of misaligned bars affects the pull-out force – the greater the number of misaligned bars present, the higher the force (per bar) needed to open the joint.

The second point above is an indication that a joint can lock if it contains enough bars with significant misalignment. However, a review of performance of in-service pavements showed that the presence of occasional, isolated, locked joints do not have any adverse effects on pavement performance (Yu 2005).

The specifications on rotational misalignments (horizontal and vertical misalignment) range from 5 to 13 mm (3/16 to ½ in). Figure 6 shows distribution of current specifications in 23 different states. Prior to 1989, the prevailing recommendations were to specify 3 mm (1/8 in) per 305 mm (1 ft) of dowel bar. The 5-mm (3/16 in) specification for the standard 450-mm (18-in) dowel bars is based on these recommendations. In 1989, the FHWA relaxed the recommendations for dowel placement tolerance to 6 mm (1/4 in) per 305 mm (1 ft) based on more recent research findings. These recommendations remain the prevailing guidelines on dowel bar placement tolerance today.

**LIMITATIONS OF CURRENT SPECIFICATIONS**

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 wheelpaths are more critical; whereas, the load transfer capacity is not critical for the bars outside the wheelpaths.

The rotational misalignments govern joint movements. As such, a joint-by-joint evaluation is important in evaluating the potential impact of rotational misalignments on pavement performance. On short jointed pavements, free joint movement is not necessary at every joint. In fact, pavement designs incorporating so called “hinge joints” have been used on experimental pavements, with dowelled joints at every 2nd or 3rd transverse joints (Smith et al. 1997). Field studies have also shown that occasional locked joints have no adverse effects on pavement performance. However, consecutive locked joints are not desirable, because of the potential for
the build up of restraint stresses in the locked group of slabs and excessive joint movements at the first working joint.

In one recent study, a simple weighted-score system was used to conduct a joint-by-joint evaluation of dowel alignments (Yu 2005). The Joint Score, as defined in this evaluation, is a measure of the combined effects of misaligned dowel bars at a joint. Joint Score is determined by summing the product of the weights (given in table 1) and the number of bars in each misalignment category and adding 1. For example, if a joint has 4 misaligned bars in the range 15 to 20 mm (0.6 to 0.8 in), the joint score is 9; if a joint has 1 misaligned bar in the range 15 to 20 mm (0.6 to 0.8 in) and 1 bar in the 25 to 38 mm (1 to 1.5 in) range, the score is 8. A Joint Score of 10 is the critical level, above which the risk of joint locking is considered high.

Figure 7 is an illustration of how dowel bar alignment is viewed today: on a bar-by-bar basis. This does not provide any information about the distribution of the critical, severely misaligned bars. A joint-by-joint look, using Joint Score is shown in figure 8, which clearly identifies the joints that are at risk of being locked.

The weighting factors given in table 1 were determined based on field observations and the findings of previous studies. Further research is needed to refine these values, but the Joint Scores determined using the values given in table 1 are adequate for the purposes of identifying the joints that may be locked and the distribution of potentially locked joints.

**RECOMMENDATIONS**

The available information on the effects of dowel misalignment suggests that dowel placement tolerances could be relaxed to some extent. The basic premise for the standard should be that dowel bars placed in accordance with the specification should not have any adverse effects on pavement performance. Another important factor for consideration is that there may be cases where even grossly misaligned dowel bars have no adverse effect on pavement performance (e.g., occasional, isolated locked joint). In such cases, “do nothing” can be the best repair option. Based on these considerations, the following approach is recommended:

- Establish a relatively tight acceptance criteria – no further evaluation is needed if the acceptance criteria are met.
- Establish rejection criteria considering the effects on pavement performance – determine the need for remedial action on joint locking based on joint-by-joint evaluation using Joint Score; on embedment length, consider location of dowel bars – additional allowance could be given for dowel bars outside the wheelpath.

The recommended interim guidelines for dowel placement tolerance are as follows:

**Acceptance Criteria**

- **Horizontal alignment:** 15 mm (0.6 in)
- **Vertical alignment:** 15 mm (0.6 in)
- **Side shift:** 50 mm (2 in)
- **Depth:** mid-depth ± 25 mm (1 in)
Rejection Criteria

- Horizontal and vertical alignment – evaluate on joint-by-joint basis, using the Joint Score.
  - Isolated locked joints (as indicated by Joint Score greater than 10) may be allowed, provided the adjacent joints have Joint Score less than 10.
  - It may be permissible to allow up to 2 or 3 consecutive locked joints (joints with Joint Score greater than 10), depending on joint spacing and climate. Establish the maximum allowable consecutive locked joints based on maximum joint movement, not to exceed 5 mm (0.2 in).
  - Reject any bars in the wheelpath with misalignment greater than 38 mm (1.5 in).

- Side shift
  - Dowel bars in the wheelpath – 75 mm (3 in) for 450-mm (18-in) dowel bars, or a minimum embedment length of 150 mm (6 in).
  - Dowel bars outside the wheelpath – 100 mm (4 in) for 450-mm (18-in) dowel bars, or a minimum embedment length of 125 mm (5 in).

- Depth – a minimum cover of 75 mm (3 in), top or bottom.

Based on the available information, the above guidelines are conservative. More robust guidelines will be developed under NCHRP Project 10-69, Guidelines for Dowel Alignment in Concrete Pavements.
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Figure 5. Laboratory testing results showing the effects of the number of misaligned bars on the pull out force (Prabhu et al. 2006).

Figure 6. Current specifications on rotational misalignments from 23 states.

Figure 7. Example distribution of dowel misalignment (maximum horizontal or vertical) by range of misalignment.

Figure 8. Example Joint Score plot – a score greater than 10 indicates a high potential for joint locking.
Table 1. Weighting factors used to determine Joint Score.

<table>
<thead>
<tr>
<th>Range of misalignment</th>
<th>Weight</th>
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<tr>
<td>10 mm &lt; d ≤ 15 mm</td>
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<tr>
<td>15 mm &lt; d ≤ 20 mm</td>
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<tr>
<td>20 mm &lt; d ≤ 25 mm</td>
<td>4</td>
</tr>
<tr>
<td>25 mm &lt; d ≤ 38 mm</td>
<td>5</td>
</tr>
<tr>
<td>38 mm &lt; d</td>
<td>10</td>
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