USE OF DOWELS FOR LOW VOLUME ROADS AND STREETS

The performance of portland cement concrete (PCC) pavement for low volume roads and streets (LVRS) depends on its design and construction. The two most important aspects of concrete pavement design are slab thickness and jointing. While thickness is always designed for the project, joint design is often taken from standards that may not be adequate for the project at hand. An inadequate joint design nearly always leads to poor performance. Proper joint design for PCC pavements requires a holistic treatment of the site and design factors for a given project.

The purpose of this technical brief is to explain the importance of, and provide guidance on the use of, load transfer in LVRS. For the purposes of this document, a LVRS pavement is one that carries up to 100 trucks and buses per day in one direction based on the Federal Highway Administration (FHWA) class 4 classification or greater.

Need for Load Transfer at Joints

Transverse joints are required in unreinforced jointed concrete pavements to prevent uncontrolled slab cracking. They provide relief from excessive stress build-up due to temperature and moisture gradients through the PCC slab and the imposed traffic loadings. Transverse joint spacing for LVRS pavements may vary depending upon slab thickness – from about 12 ft for 6-in slabs to 15 ft for thicker slabs. Thus, a joint is placed every 12 to 15 ft to control cracking. This joint then becomes the most critical location in the slab. Much higher stresses and deflections occur at the joints than at the slab interior when heavy truck axle loads pass over the pavement. However, an advantage of providing planned joints (which are actually induced cracks) is that load transfer mechanisms can be provided, as needed, to reduce high stresses and deflections.

Joint Load Transfer

Concrete pavements built on LVRS typically rely on aggregate interlock to provide the necessary load transfer efficiency (LTE). Aggregate interlock provides LTE through shear forces developed at the rough joint interface by the shape, size and hardness of the coarse aggregate, as illustrated in Figure 1. Unfortunately, this only happens during warm weather when the joint is tightly closed (small joint opening). During the rest of the year there is very little LTE at the joint.

In contrast, the load transfer mechanism of dowel bars does not rely on warm weather or closed joints to transfer load across the joint. As a result, doweled joints are effective throughout the entire year. **Dowel bars are smooth and round or elliptical-shaped. They are placed across transverse joints parallel to the traffic direction to transfer load across two adjacent slabs, as shown in Figure 1.**

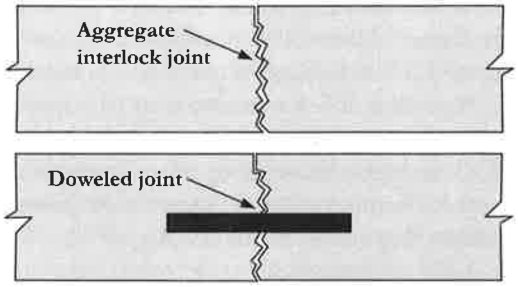


Figure 1. Contraction joint types

LTE is defined as the portion of load that is transmitted from the loaded slab across the joint to the unloaded slab. The most common way of evaluating LTE is to measure deflection on both sides of a joint that is loaded on one side by a truck axle as follows:

$$\mathrm{LTE} = \frac{\delta_U}{\delta_L} \times 100$$

Where,

δ_U: pavement deflection on the unloaded side

δ_L: pavement deflection on the loaded side

An LTE of 100 percent indicates that the deflection on the unloaded side is equal to the response on the loaded side. This results in a zero "differential" deflection ($\delta_L = \delta_U$) as a truck axle crosses the joint and causes very little pumping beneath the slab. An LTE of 0 percent occurs when the deflection on the unloaded slab is 0 and the deflection on the loaded side is high. This results in a large "differential" deflection ($\delta_L >> \delta_U$) and high potential for pumping beneath the joint. Also, the provision of 100 percent of LTE reduces edge stress by half and corner deflections by one-third. Low volume PCC pavements often have no base or only an untreated aggregate base that provides at most about 20 to 30 percent LTE of an open joint. When the joints are closed during a hot summer day, the LTE can be as high as in a doweled joint. However, when the joints are widely opened during a cold winter day, the LTE can be as low as 10 percent.

A recent study based on a comprehensive analysis of LTE data from the Long-Term Pavement Performance (LTPP) program [1] showed that 80 percent of all tested doweled sections had a LTE greater than 70 percent, whereas only 50 percent of nondoweled section had such high LTE. As a result, it was concluded that doweled joints have much higher LTE than nondoweled joints. In addition, LTE of doweled joints is consistently high, regardless of temperature at the time of testing, whereas LTE of joints with aggregate interlock is highly dependent on temperature [2]. A good LTE mechanism is required to minimize pavement responses at joints (Figure 2). When poor LTE is provided at a joint, the heavy repeated truck axles will eventually cause the joint to fault (Figure 3) if free water and erodible materials are available beneath the slab. In addition, wet and soft subgrade conditions also contribute to faulting.

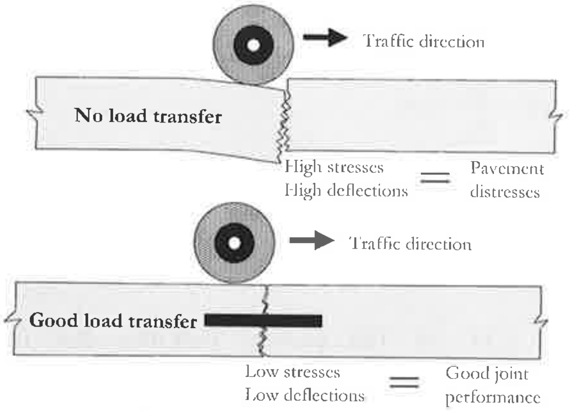


Figure 2. Effect of load transfer on pavement joint responses

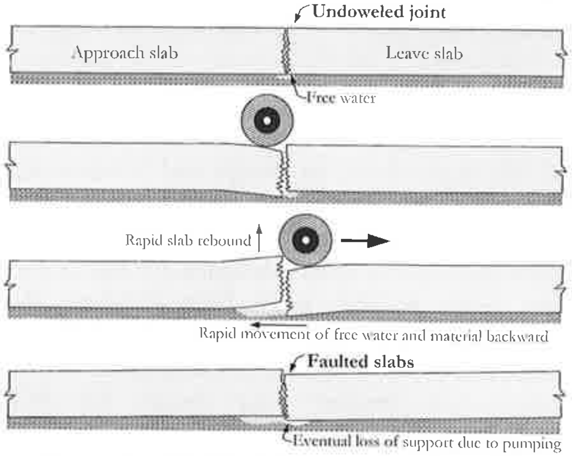


Figure 3. Joint faulting progression with repeated heavy axle loadings

Joint faulting directly affects smoothness and ride quality. Faulting is caused by pumping of the underlying materials from beneath the leave joint, causing loss of support, which may eventually result in increased corner and diagonal cracking. This material is pumped backwards beneath the approach joint, causing it to raise up. **Faulting is the difference in elevation between two adjacent slabs, whereas pumping is the ejection of fine materials from beneath the slab.** A picture of joint faulting and pumping of in-service pavement is shown in Figure 4, which also illustrates erosion at the longitudinal joints with the asphalt shoulder due to pumping of water out under pressure.

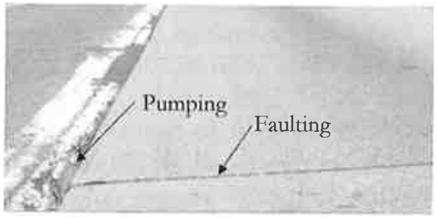


Figure 4. Joint faulting and pumping

Dowels consistently provide higher load transfer than aggregate interlock, which prevents faulting, in addition to helping maintain the slab alignment. Several studies have concluded that dowels also prevent corner breaks or diagonal cracks [3, 4, 5 and 6]. **In summary, nondoweled joints typically show progressive faulting as the number of heavy axle load repetitions increases, since they do not have a high and**

constant LTE. Doweled joints provide a high and constant LTE, so faulting and roughness problems are mitigated. In addition, the occurrences of corner breaks and diagonal cracks is significantly reduced.

Performance of Projects With and Without Dowels

Field performance studies [3, 4, 5, 7, 8, and 9] from the 1970's through the 1990's found that slabs without dowels at the joints showed substantially more faulting than doweled ones at the same location. As early as the late 1970's, faulting was considered "the most serious distress" [8] because it had a significant effect on ride quality when it developed to a significant level requiring maintenance. It was found that nondoweled pavement developed far more faulting than doweled pavement.

The importance of dowel bars is further underscored when one considers what was discovered for one improperly constructed transverse joint at the AASHO Road Test, where all joints were doweled. A Special Pavement Research Report about the AASHO Road Test [6] states the following:

> "Faulting at joints was notably absent throughout the project. One transverse joint faulted seriously, but the investigation showed that the joint had been accidentally sawed at some distance beyond the end of the dowels intended to protect it. Over the 2-yr period of the test there were no other cases of measurable faulting at joints, all of each were doweled."

Figure 5 presents a hypothetical scenario of what might have happened at the Road Test if some of the pavements within a given loop were left nondoweled and others doweled. This analysis was performed using the design procedures developed under the National Cooperative Highway Research Program (NCHRP) Project 1-37A [7] and assuming the cross-section, traffic, climate, and materials information from the Road Test. It is noted that nondoweled joints could have had up to seven times more faulting than doweled ones and resulted in faulting greater than the maximum allowable faulting for LVRS of 0.15 inches [7].

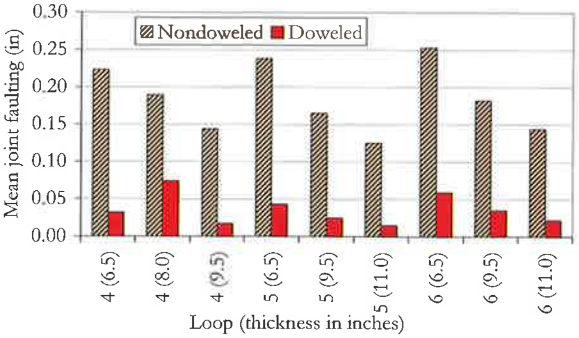


Figure 5. Predicted joint faulting of AASHO Road Test pavements after 1 million axle loads

Based on the analysis of several sections from the LTPP program, another study [5] found that the use of dowel bars significantly reduced the amount of faulting for untreated aggregate and treated bases. As truck traffic has increased so dramatically over several decades, nearly all States now require dowel bars on State highways. According to the FHWA [10], research conducted in Florida, Georgia, and Wisconsin indicated the incidence of less faulting in doweled pavements compared to pavements without dowels. Figure 6 shows a comparison between joint performance data from a major field study conducted in the U.S. in the late 1980's based on the results presented for pavement sections in Minnesota [4]. It shows that the effect of dowel bars seems to be more pronounced for thinner slabs. Khazanovich et al. [9] also showed the beneficial decrease in joint faulting due to the use of dowel bars based on an LTPP study. **In summary, many studies have clearly shown that faulting is significantly reduced once mechanical load transfer devices (dowels) are used.**

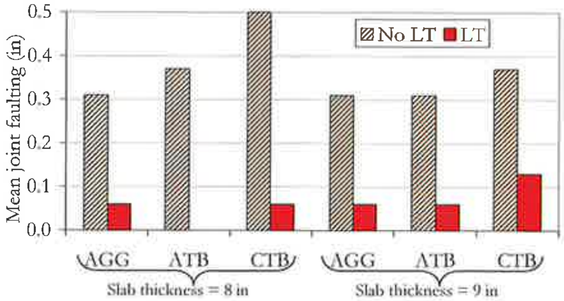


Figure 6. Effect of load transfer device on faulting based on a direct comparison of Minnesota testing sections [4]

Need for Dowels in LVRS?

The preceding performance data are based on highways with relatively high truck volumes and thicker pavement sections. LVRS, by most definitions, carry up to 500 vehicles per day [11]. Heavy trucks and buses represent a portion of this daily amount of vehicles, which if high enough volume, can lead to pumping, faulting, and unacceptable roughness for nondoweled joints. The question is, at what truck and bus volume should dowels be used to prevent significant faulting and roughness? **Clearly, dowels are not needed on all LVRS with lower levels of truck traffic, but when the predicted truck traffic exceeds a certain level, dowels will be needed to prevent excessive joint faulting and possible slab cracking due to loss of support.** The recommendations for the use of dowel bars are provided after discussing the current practice. It is based on the predicted level of truck traffic for a given slab thickness, base or soil type, and climatic zone.

Current Practice

The design of dowel bars consists of specifying their length, diameter, and spacing. Most design recommendations are based solely on pavement thickness. As most LVRS thickness designs do not exceed 8 in, a description of current design practices will be limited to that value. As a rule of thumb, the American Concrete Pavement Association (ACPA) suggests the use of dowel bars for slabs 8 inches thick or more. However, depending on the combination of other design and site factors (e.g., base type, precipitation, design life), pavements thinner than 8 inches may also need dowels to prevent premature faulting of joints. McGhee [12] indicated that, by 1995, most States required dowel bars. For those that did not, faulting was primarily the cause of concrete pavement failure. Currently, dowels are used in almost all States in the U.S. and also in some cities and counties. In fact, several States are performing dowel bar retrofitting on projects where dowels were not originally placed, to prevent faulting after diamond grinding. This has shown to be very effective in controlling joint faulting and prolonging the life of pavements.

Dowel diameter

All joints at the AASHO Road Test included dowels properly sized for the loadings, and none of these joints exhibited faulting. In addition, based on the analysis of AASHO Road Test pavements that were in service for 12 years and subjected to many additional heavy traffic loadings, it was found that an increase in dowel diameter has a major effect on controlling faulting.

As a general guideline, the American Association of State Highway and Transportation Officials (AASHTO) suggests that the dowel diameter should be equal to 1/8 of the slab thickness [13]. This was used for all slab thicknesses (3.5-in used 0.5-in dowels, 5-in used 0.625-in, 6.5-in used 0.875-in, 8-in used 1.00-in, and so on) at the AASHO Road Test. FHWA [14] also recommends this guideline but limits the dowel diameter to a minimum of 1.25 in for highways. Similarly, the ACPA [15] recommend the use of 1.25-in dowel diameter for slabs thinner than 10 in. Other dowel diameter recommendations are based on the traffic level. According to an ACPA survey, the average dowel bar diameter is 1.25 in. Another survey performed in 1992 [12] indicated that most State highway agencies used a dowel diameter of at least 1 in. Since slab thickness on LVRS generally does not exceed 8 in, 1-in-diameter dowel bars or the small elliptical dowel bars (discussed in a later section of this publication) are recommended.

Dowel length and spacing

Similar to the AASHTO pavement design guide, a recent joint design guide [16] recommended dowel length and spacing of 18 and 12 inches, respectively. These are by far the most used dimensions according to a database of State highway agency practices compiled by ACPA [12].

A study conducted in the late 1950's concluded that the dowel embedment length required to provide full load transfer was five or more times the bar diameter [17]. Based on this study, 1-in-diameter bars would need a minimum embedded length of 5 in. A recent study by the Minnesota DOT [18] indicated that an embedded length of only 2.5 in is sufficient to keep faulting at an acceptable level of 0.25 in and provide an LTE with less variability. This study has led Minnesota to the use of dowels 15 in long. **Based on these studies, dowels 15 in long spaced at 12-in intervals are adequate for LVRS.**

Dowel alignment

It is important to place dowel bars with reasonable rotational alignment to avoid joint lock-up and potential cracking. Translation in dowel bar location beyond the joint, on the other hand, would result in a nondoweled joint. As a result, specification tolerances must be established to limit dowel bar misalignment. The major dowel alignments that must be controlled are vertical and horizontal rotation, which are usually measured from the end of the dowels, as illustrated in Figure 7. Vertical and longitudinal translations should be controlled as well. The importance of controlling longitudinal translation is to guarantee appropriate dowel embedment length and unrestricted adequate opening and closing of the joint.

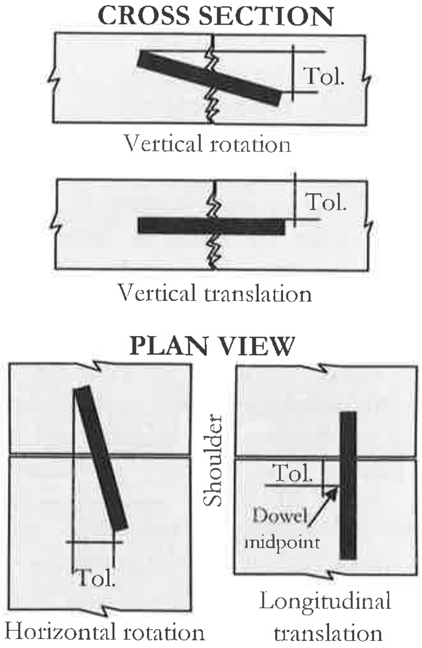


Figure 7. Diagram of how to measure dowel bar misalignment

Georgia DOT studied the effect of dowel bar misalignment on PCC pavement performance [19]. At that time, their vertical and horizontal rotation tolerances were 0.375 and 0.75 in/ft, respectively. Currently, their specification calls for 0.375 in/ft regardless of the direction [20]. The maximum vertical and horizontal rotations measured were 1 and 2.3 in/ft, respectively, and they were still working as designed. Georgia's study cites a study performed by the Alabama Highway Department in 1967 that concluded that misalignment up to 0.25 in, regardless the type, was not a concern for good pavement performance. Coincidentally, 0.25 in/ft was the tolerance limit established by FHWA in the late 1980's [10]. FHWA has considered relaxing this tolerance based on State experiences. In contrast, the ACPA recommends a tolerance limit of 0.375 in/ft [21].

Wisconsin performed a study in the late 1980's [22] that found 90 percent of the tested dowels were within their rotation tolerance of 0.33 in/ft. In Missouri, a study performed in 2003 [23] found average vertical and horizontal rotations of 0.17 and 0.30 in/ft, respectively.

Based on pullout tests performed in the laboratory, Tayabji [24] concluded that pullout loads were relatively low if the misalignment of two opposite dowels was kept below 0.67 in/ft and maximum joint opening kept to 0.25 in. A theoretical analysis of rotational misalignment [20] concluded that dowel misalignment of 0.17 in/ft or less did not cause significant restraint, which is about 25 percent of the acceptable level suggested by Tayabji [24]. **A tolerance of 0.375 in/ft for rotational misalignment is feasible and within the range of suggested values for rotational misalignment; therefore, this level is appropriate for LVRS when short joint spacing is used.**

Georgia DOT had a tolerance of ± 1 in for both vertical and horizontal translational alignment [19]. Their study verified that more than half of the bars had longitudinal misalignment more than the specified value. In fact, some dowels were completely out of the joint. **As the recommended dowel length is 15 in and as the required embedded length is approximately five times the dowel diameter, the acceptable horizontal translational misalignment is ±2.5 in. The vertical translational misalignment should be at most ± 1.0 in.**

Use of elliptical dowels

Dowels perform well as long as they are not "loose." This occurs when a void space is created where the dowel contacts the surrounding concrete. This is due to a repeated stress concentration or bearing stress, which crushes and wears away the concrete around the dowel bar. When this occurs, dowels lose their effectiveness in transferring load. The advantage of using elliptical dowels is because they reduce the bearing stresses compared to round dowels for the same cross sectional area. As the stress concentration occurs at the top and bottom of the dowels, their sides do not assist in the distribution of load. Elliptical bars are placed at the mid-depth of the slab with their major axis parallel to the ground, as shown in Figure 8. As a result, elliptical bars provide more bearing area for stress distribution. Porter et al. [25] conducted a study to evaluate the performance of elliptical dowels. Figure 9 shows the elliptical bar dimensions used in his evaluation and Figure 10 presents the variation in calculated bearing stress compared to a round bar of 1.25 in diameter [25]. Increasing the diameter from round 1.25 in to 1.50 in, increases the sectional steel area by 44 percent and decreases the stress of about 25 percent. In contrast, going from a 1.25-in round to a medium elliptical dowel increases the sectional steel area by 20 percent but decreases the stress of about 22 percent. As a result, the decrease in stress provided by the medium elliptical dowel was the same as the larger round dowel, but the increase in area of elliptical dowel was only half of the round dowel. Small elliptical dowels have approximately the same area as 1-in round dowels but bearing stresses on elliptical dowels are about 20 percent less. **In conclusion, elliptical bars are effective because they reduce dowel bearing stress compared to round bars for the same cross sectional area or result in similar bearing stresses with a smaller cross sectional area.**

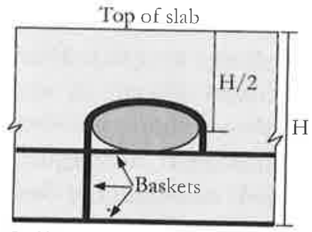


Figure 8. Placement of elliptical dowels

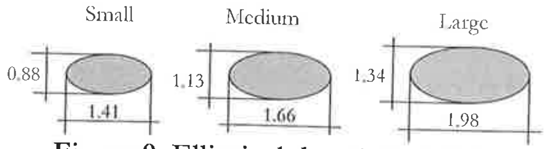


Figure 9. Elliptical dowel sizes (in)

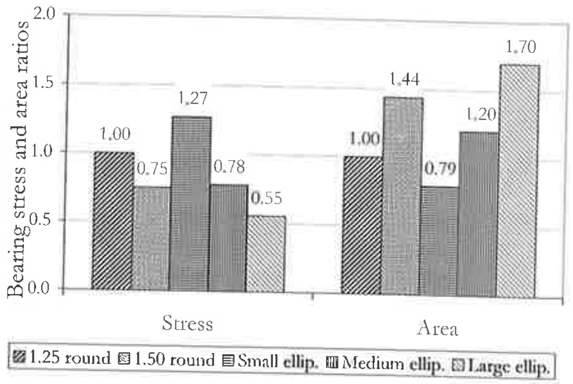


Figure 10. Bearing stress and area ratios compared to a round bar of 1.25-in diameter

Cost Analysis

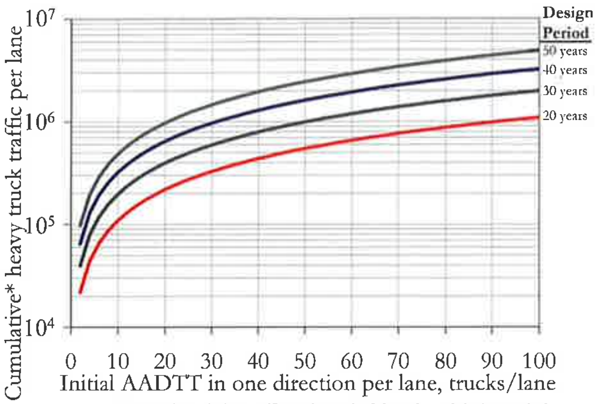
A recent review of highway agency practices indicated that the increase in cost of using dowels is small when compared to the significant reduction in probability of pavement failure [16]. However, even a small increase in cost must be justified in terms of improvement of service life. To analyze costs of different design features, construction cost must be considered but so must future maintenance costs. A technique that has been applied to decide between different pavement design features is life cycle cost analysis (LCCA). Methodologies based on LCC have been developed to evaluate the benefits and costs of various jointed plain concrete pavement design features. One of these methodologies [26] consisted of predicting pavement distresses, applying maintenance and rehabilitation policies based on performance indexes, and computing LCC during a design period for a given design relative to a reference design.

This methodology was applied to several design features, including the use of dowel bars. For lower traffic levels, this study showed that **the use of dowel bars increases the pavement life by about 60 percent and results in total LCC similar to not using dowels.** More simplistic cost analyses that account for only initial construction costs have also been employed. For instance, one of these analyses [27] compared the change in initial cost and load carrying capacity (number of axles carried) to analyze the effectiveness of different design features. This study concluded that **doweled projects increased the initial cost between 5 and 8 percent**[*] **compared to nondoweled projects but increased the load carrying capacity over 100 percent.** A similar conclusion was reached in a recent survey [28] that indicated that the use of dowels increases performance by 70 percent, while increasing cost only 6 percent.

Design Recommendations

The design recommendations presented in this section are based on past research studies and on the new Mechanistic-Empirical Pavement Design Guide (M-E PDG) [7]. These recommendations focus on the need for dowels in LVRS. As a result, the analyses shown in this section were performed assuming up to 100 heavy trucks in the design lane per day in the first year of a 30-year design period (DP). The assumed traffic distribution was comprised basically of busses and single-unit trucks. Figure 11 can be used to convert from initial year average annual daily truck traffic (AADTT) to cumulative traffic, and vice-versa, for different design periods.

The previous sections demonstrated that the most prominent advantage of using dowels is reduction in faulting, and consequently, maintaining smoothness. To illustrate these effects using the Design Guide, Figure 12 shows predicted mean joint faulting versus initial year AADTT for doweled and nondoweled joints, whereas Figure 13 shows the same analysis focusing on smoothness. These figures can also be used to determine the amount of traffic that the pavement can carry before a given performance parameter is reached. The use of 1-in-diameter dowel bars greatly reduces faulting, especially for traffic higher than 50 trucks per day, assuming the selected thickness. The use of 1.25-in dowels further reduces faulting, and the additional increase in diameter does not provide much benefit for the design conditions considered herein. Similarly, concrete pavement ride (smoothness) is enhanced with the use of dowel bars. This improvement can be up to 80 in/mi for the selected conditions.



*Note. Cumulative traffic at the end of the selected design period

Figure 11. Cumulative traffic versus initial AADTT (compound traffic growth = 4%)

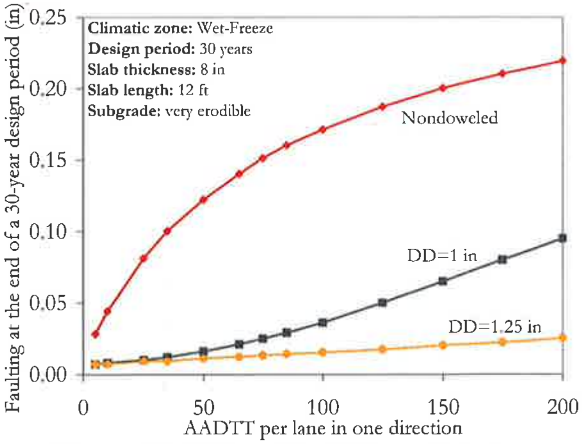


Figure 12. Effect of dowels on faulting

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[*] **Example – Initial Cost Increase Calculation**
Using current market prices, the price of plain concrete is approximately \$20/yd². Assuming a 15-ft long and 12-ft wide slab, the price per slab would be about \$400. If four 1-in dowels were placed in each wheel path, the price per joint would be approximately \$24, including baskets. As a result, the total doweled concrete pavement price would be \$424 per slab or \$21.2/yd², which represents an increase of 6 percent. Based on this example, the use of dowel bars increase the initial cost by 6 percent compared to nondoweled projects, but they increase pavement life by about 60 percent. If the use of dowels is not carefully considered, it is likely that dowel bar retrofitting would be required which would be a more expensive alternative.

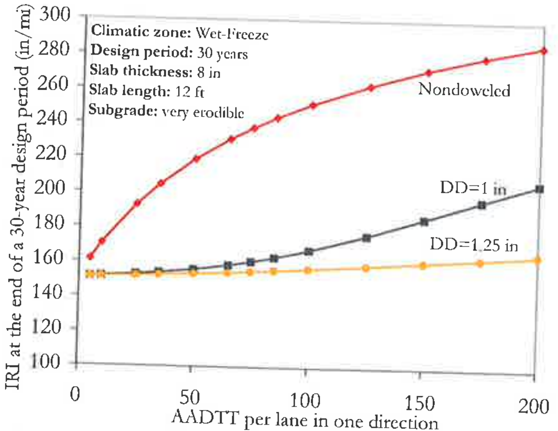

Figure 13. Effect of dowels on smoothness

The design criteria selected herein were based on the recommendation for LVRS in the M-E PDG [7]. The criteria for using dowels were based solely on faulting and smoothness, whose threshold values for acceptable designs were selected to be 0.15 in and 200 in/mi, respectively. The daily number of heavy trucks (and buses) that would lead to the selected design criteria at the end of the design period was determined for different slab thickness, subgrade conditions, and climatic zones. A range between 6 and 8 in was evaluated because these are typical thicknesses for LVRS. Climatic zones were divided according to the LTPP zoning criteria – Wet-Freeze (WF), Wet-Nonfreeze (WNF), Dry-Freeze (DF) and Dry-Nonfreeze (DNF), as shown in Figure 14. To account for different subgrade types, the Erodibility Index (EI) was varied from very erodible (EI=5) slab placed on fine-grained soils to erosion resistant (EI=3) good quality granular base course.

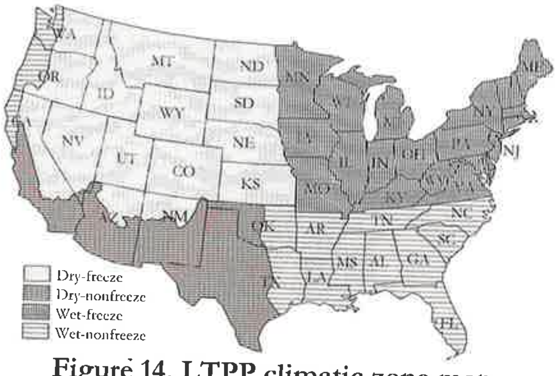

Figure 14. LTPP climatic zone map

Figure 15 shows the recommendation of dowel bar use for very erodible subgrade, assuming a reliability level of 75 percent. A similar analysis for erosion resistant subgrade is shown in Figure 16. Examples illustrating how to use these design charts are as follows:

- Consider the local streets in central Illinois cities (WF), where the slab on compacted subgrade is standard practice. A study [29] showed that urban streets in the area carry the following number of heavy vehicles per lane per day in one direction: 36 (bus route with 7-in slab) and 11 (not a bus route with 6-in slab). For collector routes (7-in slab), these numbers are: 53 (bus route) and 28 (not a bus route). Assuming the slab is placed directly on a very erodible subgrade (e.g., silty clay), Figure 15 shows that dowels are needed on both the local bus or non-bus route street to carry 30 years of traffic. Collector streets would also require dowels to control faulting. If the same conditions were applied to the Atlanta climate (WNF), dowels would not be required for local or collector routes for a 30-year design life, regardless is it was or not a bus route. This example illustrates the importance of accounting for climatic area when designing pavement to prevent faulting.
- Another example is a rural road in western Kansas (DF) that has an initial truck volume of 8 per day and a 7-in slab placed on a fine-grain compacted subgrade. Figure 15 indicates that no dowels are required over a 30-year life. However, it is likely that an industrial plant will soon be constructed along the road and that this will increase truck traffic to 25 trucks per day. Figure 15 shows that this would definitely require dowel bars to control faulting and roughness over 30 years.

The design charts presented in this section can be used to decide whether dowel bars are needed in LVRS. This decision depends on the daily traffic level, slab thickness, climate, and subgrade type.

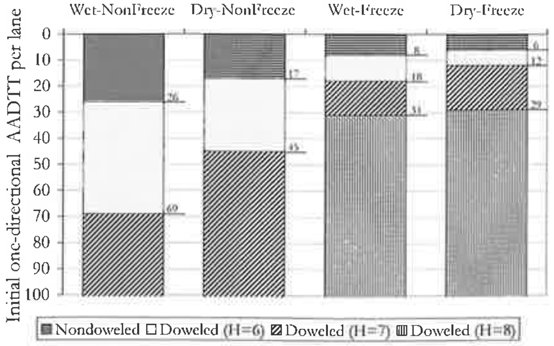

Figure 15. Dowel use recommendation for very erodible subgrade (design period = 30 years)

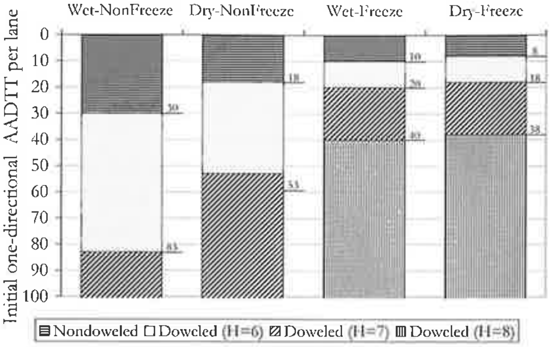

Figure 16. Dowel use recommendation for erosion resistant subgrade (design period = 30 years)

Conclusions

- Doweled joints provide high and constant LTE, controls faulting, improves ride quality, and reduces corner breaks and diagonal cracks.
- Many performance studies have shown that faulting is significantly reduced if dowel bars are used.
- Dowels 15 in long at 12-in intervals are adequate for LVRS.
- The recommendation for dowel bars alignment in short jointed LVRS is the following: 0.375 in/ft for rotation, ± 2.5 in for horizontal translation, and ± 1.0 in for vertical translation (Figure 7).
- Elliptical bars are more effective than round bars because they reduce dowel bearing stress for the same cross sectional area or result in similar bearing stresses with a smaller cross sectional area.
- Doweled projects increase the initial cost between 5 and 8 percent compared to nondoweled projects but increase the pavement life more than 60 percent.
- Design charts were presented to allow user to decide whether dowel bars are needed in LVRS to control faulting and roughness based on the daily traffic level, slab thickness, climate and subgrade type.

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References

[1] Khazanovich, L., and A. Gotlif, 2003. "Evaluation of Joint and Crack Load Transfer – Final Report," Report No. FHWA-RD-02-088, Federal Highway Administration.

[2] Rufino, D., J. Roesler, and E. Barenberg, 2004. "Effect of Pavement Temperature on Concrete Pavement Joint Responses," *Proceedings*, Paper No. P-29, 2004 Federal Aviation Administration Worldwide Technology Transfer Conference, Atlantic City, New Jersey, April.

[3] Darter, M. I., J. M. Becker, M. B. Snyder, and R. E. Smith, 1985. "Portland Cement Concrete Pavement Evaluation System – COPES," NCHRP Report 277, Transportation Research Board, Washington, D.C.

[4] Smith, K. D., D. G. Peshkin, M.I. Darter, A. L. Mueller, and S. H. Carpenter, 1990. "Performance of Concrete Pavements, Volume I: Evaluation of Concrete Pavement Performance and Design Features," Report No. FHWA-RD-89-136, Federal Highway Administration.

[5] Smith, K.D., M. J. Wade, D. G. Peshkin, L. Khazanovich, H. T. Yu, and M. I. Dater, 1998. "Performance of Concrete Pavements, Volume II: Evaluation of In-Service Concrete Pavements," Report No. FHWA-RD-95-110, Federal Highway Administration.

[6] Highway Research Board, 1962. "The AASHO Road Test – Report 5," Special Report 61E about Pavement Research, Publication No. 954, Division of Engineering and Industrial Research, Washington D.C.

[7] ARA, Inc., ERES Division, 2004. "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures," Final Report of Project No. 1-37A, National Cooperative Highway Research Program.

[8] Darter, M. I., 1977. "Design of Zero-Maintenance Plain Jointed Concrete Pavement," Report No. FHWA-RD-77-111, Federal Highway Administration.

[9] Khazanovich, L., M. Darter, R. Bartlett, and T. McPeak, 1998. "Common Characteristics of Good and Poorly Performing AC Pavements," Report No. FHWA-RD-97-131, Federal Highway Administration.

[10] Federal Highway Administration, 1989. "The Benefits of Using Dowel Bars," Technical Paper No. 89-03, Washington, D.C.

[11] Federal Highway Administration, 1992. "Local Low-Volume Roads and Streets," Publication No. FHWA-SA-93-006, Washington, D.C.

[12] McGhee, K. H., 1995. "Design Construction, and Maintenance of PCC Pavement Joints," Synthesis of Highway Practice 211, National Cooperative Highway Research Program, Washington, D.C.

[13] AASHTO, 1993. "Guide for Design of Pavement Structures," Published by the American Association of State Highway and Transportation Officials.

[14] Federal Highway Administration, 1990. "Concrete Pavement Joints," Technical Advisory T 5040.30, Washington, D.C.

[15] American Concrete Pavement Association, 1991. "Design and Construction of Joints for Concrete Highways," Publication No. TB010-01P.

[16] Ambroz, J. K., W. J. Seiler, and M. I. Darter, 1996. "Load Transfer Design and Benefits for Portland Cement Concrete Pavements," Report Number 96-128-E1, ERES Consultants, Inc.

[17] Teller, L. W., and H. D. Cashell, 1959. "Performance of Doweled Joints Under Repetitive Loading," Bulletin 217, Highway Research Board, Washington D.C.

[18] Burnham, T., 1999. "A Field Study of PCC Joint Misalignment Near Fergus Fall, Minnesota," Final Report No. MN/RC-1999-29, Minnesota Department of Transportation.

[19] Fowler, G., and W. Gulden, 1983. "Investigation of Location of Dowel Bars Placed by Mechanical Implantation," Georgia DOT and Federal Highway Administration, Report No. FHWA/RD-82/153.

[20] Khazanovich, L., N. Buch, and A. Gotlif, 2001. "Evaluation of Alignment Tolerances for Dowel Bars and Their Effects on Joint Performance," Draft Report prepared for Michigan DOT.

[21] American Concrete Pavement Association, 2004. "Understanding Sawed Joints and Dowel Bar Alignment," Concrete Pavement Progress, Volume 40, No. 4.

[22] Parry, J., 1989. "Dowel Bar Placement: Mechanical Insertion Versus Basket Assemblies," Final Report, Study No. 88-10, Wisconsin Department of Transportation.

[23] Donahue, J., 2003. "Investigation of Dowel Bar Placement Accuracy with a Dowel Bar Inserter," Report No. RDT03-009, Missouri Department of Transportation.

[24] Tayabji, S., 1986. "Dowel Placement Tolerances for Concrete Pavements," Transportation Research Record 1062, Transportation Research Board, pp. 47-54.

[25] Porter, M., L., R. J. Guinn, and A. L. Lundy, 2001. "Dowel Bar Optimization: Phases I and II," Center for PCC Pavement Technology, Iowa State University, Final Report.

[26] Gharaibeh, N. G., and M. I. Darter, 2001. "Benefits and Costs of Jointed Plain Concrete Pavement Design Features," Transportation Research Record 1778, Transportation Research Board, pp. 1-8.

[27] Smith, K. D., A. L. Mueller, M. I. Darter, and D. G. Peshkin, 1990. "Performance of Concrete Pavements, Volume II: Evaluation and Modification of Concrete Pavement Design and Analysis Models," Report No. FHWA-RD-89-137, Federal Highway Administration.

[28] Hoerner, T. E., K. D. Smith, and J. E. Bruinsma, 2004. "Incremental Costs and Performance Benefits of Various Features of Concrete Pavements," Report No. FHWA-HRT-04-045, Federal Highway Administration.

[29] ERES Consultants, 1994. "Review of Design and Construction Standards for New Subdivision Streets," Part 2, Final Report prepared for City of Champaign.

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