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Guide to Dowel Load Transfer Systems for Jointed Concrete Roadway Pavements

September 2011

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About This Guide

This guide provides a summary of the factors and design theories that should be considered when designing dowel load transfer systems for concrete pavement systems (including dowel basket design and fabrication) and presents recommendations for widespread adoption (i.e., standardization).

Development of the guide was sponsored by the National Concrete Consortium (NCC) with the goal of helping practitioners develop and implement dowel load transfer designs based on current research and best practices.

The NCC is a national forum for concrete pavement research and technology transfer initiatives. Its projects are supported through the Technology Transfer Concrete Consortium (Federal Highway Administration Pooled Fund TPF-5[159]), and its administrative and publications support services are provided by the National Concrete Pavement Technology Center at Iowa State University.

The overall goals of the NCC are to identify needed research projects, develop pooled fund initiatives, provide a forum for technology exchange between participants, communicate state agencies' research needs to FHWA and industry, and provide implementation assistance to the National Concrete Pavement Road Map.

NCC participating states include Alabama, California, Georgia, Iowa, Illinois, Indiana, Kansas, Louisiana, Michigan, Minnesota, Missouri, North Carolina, North Dakota, New York, Ohio, Oklahoma, Pennsylvania, South Dakota, Texas, and Wisconsin.

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Contents

List of Figures vii

List of Tables viii

Introduction 1

Dowel Load Transfer System Design: A Brief History 1

Dowel Load Transfer System Designs and Design Considerations 2

- Dowel Diameter/Cross-Section 2
- Dowel Bar Length 3
- Dowel Alignment Requirements 4
  - Vertical Translation 5
  - Longitudinal Translation 5
- Dowel Spacing and Number of Dowels 6
- Epoxy Coatings 6
- Alternate Dowel Materials and Coatings 7
  - Stainless Steel 8
  - Microcomposite Steel 8
  - Zinc Alloy-Sleeved Dowels 9
  - Fiber-Reinforced Polymer (FRP) and Glass Fiber-Reinforced Polymer (GFRP) Composite Dowels 10
- Dowel Bar Lubrication/Bond-Breaker Materials 10
- Use of Expansion Caps and Joint Forming Materials 11

Recommendations 11

- Dowel Bar Material 11
- Dowel Bar Diameter 11
- Dowel Bar Length 11
- Dowel Corrosion Protection 12
- Dowel Basket Height 12
- Recommendations for Standardized Basket Frame Design 13
  - Basket Stake Requirements and Other Anchoring Approaches 14
  - Cutting Tie or Spacer Wires Prior to Paving 14
  - Use of Bond-Breakers and Basket Pre-Coating 14

References 14
Additional Resources 15
Appendix A - The Mechanics of Joint Faulting 16
Appendix B - Design Factors Affecting Dowel-Concrete Bearing Stress (and Faulting) 18
Appendix C - Use of FWD Measurements in Measuring Dowel Effectiveness.....20
Appendix D - Evaluating Dowel Load Transfer Systems 22
Appendix E - Concepts for Optimizing Dowel Load Transfer System Design 24
Appendix F - Summary of Studies Concerning Use of FRP Dowels in PCC Pavements.....27

List of Figures

Figure 1a. Typical dowel basket assembly 1

Figure 1b. Dowel baskets positioned ahead of paver 1

Figure 2. Load transfer versus dowel embedment (observed and computed) 4

Figure 3. Effects of dowel embedment and diameter on dowel looseness after 600,000 repetitions of a 10,000 lb load 4

Figure 4. Photo of retrofit dowel bar assemblies, ready for repair material 4

Figure 5. Photo of epoxy-coated dowel bars in full-depth concrete pavement repair 4

Figure 6. Effect of concrete cover on dowel-concrete shear capacity for 1.25 in. and 1.5 in. dowels, based on both laboratory tests and finite element analyses 5

Figure 7. Effect of concrete cover on LTE for retrofit 1.5 in. steel dowels in 7.5 in. concrete slabs 5

Figure 8. Effect of embedment length on shear force and displacement for 1.25 in. diameter steel dowels. 6

Figure 9. Shear capacity versus embedment length for 1.5 in. diameter steel dowels. 6

Figure 10. Epoxy-coated dowels for retrofit application 7

Figure 11. Corroded (and non-corroded) dowels at in-service pavement joint 7

Figure 12. Various stainless steel dowel products 8

Figure 13. MMFX 2 (microcomposite steel) dowel after five years of service 9

Figure 14. Zinc alloy-sleeved dowel, as manufactured and after five weeks in sodium chloride bath with a 1 in. wide breach in the zinc 9

Figure 15. Experimental installation of FRP dowels in West Virginia 10

Figure A1. Illustration of pumping mechanism in jointed concrete pavement 16

Figure A2. Joint faulting and corner breaks 16

Figure B1. Sample computation of individual dowel shear loads within a dowel group 18

Figure C1. Placement of FWD load plate and first sensor on opposite sides of a transverse joint for the evaluation of LTE 20

Figure C2. Example of the relationship between deflection and stress load transfer efficiencies for a particular pavement design thickness and support condition 21

Figure E1. Screen capture of the dowel sizing module in DowelCAD 2.0 26

Figure E2. Screen capture of the dowel spacing module in DowelCAD 2.0 26

Figure F1. Lab test LTE histories for several dowel materials and diameters (7.5 in. PCC slab, 12 in. dowel spacing) 28

Figure F2. Differential deflection (loaded side of joint minus unloaded side of joint) for several dowel materials and diameters (7.5 in. PCC slab, 12 in. dowel spacing) 28

List of Tables

Table 1. State highway agency practices for dowel bar diameter (inches) by pavement thickness 2

Table 2. Sample dowel bar pullout test results 10

Table 3. Recommended standard basket heights for various round dowel diameters 13

Table F1. Sample sensitivity analysis of dowel deflection and bearing stress to dowel diameter and material (computed using Friberg's bearing stress analysis) 27

Introduction

Round steel dowels are the devices most commonly used for transferring loads across transverse joints in concrete highway pavements. In new pavement construction, dowels are often installed in wire basket assemblies that are intended to support and hold dowels in the desired position during paving operations. These baskets are generally pre-assembled, shipped to the project site, and anchored to the grade before the paver places the concrete (Figure 1).

State highway agency requirements for dowel baskets vary widely, even though the mechanics of dowel behavior and basket structural requirements are well-understood. The adoption of a standard set of dowel basket designs will reduce manufacturer set-up and production costs associated with producing many nonstandard designs, and will allow manufacturers to more easily maintain a larger inventory of fewer varieties of assembled dowel baskets. These manufacturing process changes should result in lower costs and improved dowel basket availability (i.e., fewer, if any, production delays) to highway agencies.

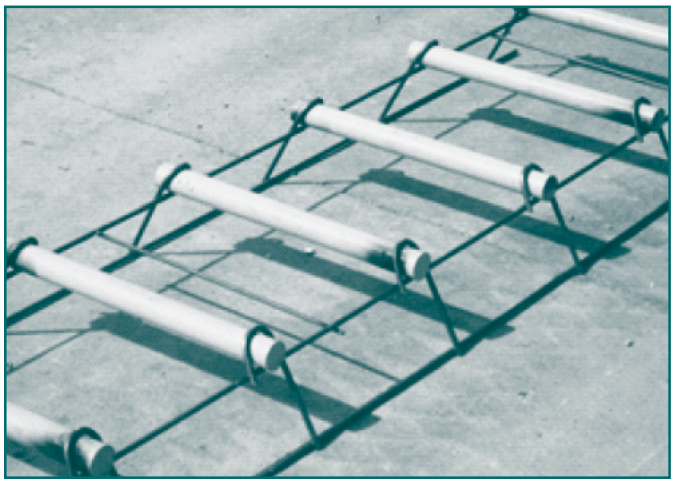

Figure 1a. Typical dowel basket assembly

Figure 1b. Dowel baskets positioned ahead of paver

This reference guide provides a summary of the factors and design theories that should be considered in dowel load transfer system design (including dowel basket design and fabrication) and presents recommendations for widespread adoption (i.e., standardization).

Dowel Load Transfer System Design: A Brief History

The potential benefits of using smooth, round steel bars across transverse joints as load transfer devices has been recognized for nearly 100 years. The first reported U.S. installation took place in the winter of 1917–1918 between two army camps near Newport News, Virginia, where four 3/4 in. diameter bars were used across the 20 ft pavement width with 2 dowels per 10 ft travel lane (Teller and Cashell 1958).

The use of steel pavement dowels spread rapidly in the United States in the years following World War I and, by 1930, nearly half of all states required their use. However, details concerning dowel diameter, length, and spacing varied considerably. In 1926, for example, one state required two 1/2 in. diameter bars, 4 ft long; another required four 5/8 in. diameter bars (also 4 ft long); and still another required eight 3/4 in. bars, 2 ft long.

In the following years, numerous dowel bar studies and tests were conducted by Westergaard (1928 and 1938), Bradbury (1932), Teller and Sutherland (1935, 1936, and 1943), and others, with the results leading to the use of dowels that were increasingly stiff (larger diameter), more closely spaced, and of shorter length. Repeated load testing of dowels in slabs performed at Bureau of Public Roads labs in the 1950s led to the development of design recommendations that eventually became the standard in the United States in the 1960s and 1970s: dowel diameter equal to 1/8 the slab thickness and spaced at 12 in. on center.

The minimum embedment required to achieve maximum load transfer was found to be 8 dowel diameters for dowels up to 3/4 in. diameter and 6 dowel diameters for larger dowels (i.e., embedment lengths of 6, 6, and 7.5 in. for 3/4 in., 1 in., and 1.25 in. diameter dowels, respectively). These recommendations were for dowels in expansion joints with widths up to 3/4 in., and it was noted that decreasing the joint width (i.e., use in a contraction joint) would decrease the dowel bending and bearing stresses and deflections and would give much better structural performance (Teller and Cashell 1958). In practice, dowel lengths generally settled at 18 in. to provide the recommended embedment length for maximum load transfer, even when joint location varied slightly with respect to the midpoint of the dowel.

In recent years, dowel length and spacing have generally remained at 18 in. and 12 in., respectively, although a few agencies have adopted 14 and 15 in. long dowels and some pavements have been constructed with dowels concentrated in the wheel paths. Standards for steel dowel diameter have grown less uniform, as some agencies have adopted the use of diameters that are larger than the 1/8 slab thickness recommendation as a result of performance studies that have shown decreased joint faulting with larger dowel diameter (i.e., lower dowel-concrete bearing stress), such as Darter et al. (1985). A summary of state practices (as of 2009) concerning dowel bar diameter as a function of pavement thickness is shown in Table 1.

There have also been efforts to improve dowel bar design through the use of alternate shapes (other than round) to further reduce dowel-concrete bearing stresses and/or to reduce steel requirements (and, therefore, cost) at the joints, and to use alternative materials and different coatings for improved corrosion-resistance. These are discussed briefly in later sections and Appendix E of this guide.

Dowel Load Transfer System Designs and Design Considerations

Dowel bars transfer load through both shear and moment mechanisms. However, many researchers have shown that the primary load transfer mechanism is shear (especially for joints that open less than 1/4 in.) and moment mechanisms can be neglected (Guo et al. 1996).

The earliest dowel load transfer system designs (circa 1920) were performed by "opinioneering" and later designs were developed based on combinations of analytical work and the experience gained from previous installations. The dowel diameter design "rule of thumb" of slab thickness divided by eight is an example of an empirical design rule that was developed based on many years of experience and a recognition of the fact that the accommodation of more loads and heavier loads required both thicker pavements and larger dowels (at least up to some practical limit).

Today's engineers have the benefit of nearly 100 years of accumulated pavement design and performance experience (including the construction of many test roads and several full-scale laboratory tests), a thorough understanding of most common failure mechanisms associated with dowel load transfer systems (which has resulted in the development of pavement performance models that consider the effects of load transfer system design), and sophisticated analytical tools for evaluating concrete pavements and load transfer systems design.

The following sections describe the factors that should be considered in a complete analysis or evaluation of dowel load transfer systems.

Dowel Diameter/Cross-Section

It can be shown that the maximum load transferred by the critical dowel in a typical highway pavement joint is generally less (and often much less) than 3,000 lb (see Appendix B). Given that the yield stress of steel used in dowels is at least 40,000 psi (and often much higher), it is clear that the design of steel dowel bar diameter or cross-section is not at all controlled by shear or bending considerations. However, dowel diameter (or cross-section) does strongly affect the behavior and performance of the dowel-pavement system. Increased dowel stiffness (either through increased dowel diameter/section modulus or the use of stiffer materials) reduces peak

Table 1. State highway agency practices for dowel bar diameter (inches) by pavement thickness (summarized from 2009 National Concrete Consortium questionnaire responses)

Slab Thickness (in.)	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11	11.5	12.0	12.5
California	1.250	1.250	1.250	1.250	1.250	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500
Iowa	0.750	0.750	0.750	0.750	1.250	1.250	1.250	1.250	1.500	1.500	1.500	1.500	1.500	1.500
Illinois	1.000	1.000	1.250	1.250	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500	1.500
Indiana	1.000	1.000	1.000	1.000	1.000	1.000	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.500
Michigan	1.000	1.000	1.000	1.000	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.500	1.500	1.500
Minnesota	1.000	1.000	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.500	1.500	1.500	1.500	1.500
Missouri	N/A	N/A	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.500	1.500	1.500	1.500	1.500
North Dakota	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.250	1.500	1.500	1.500	1.500	1.500
Ohio	1.000	1.000	1.000	1.000	1.000	1.250	1.250	1.250	1.250	1.500	1.500	1.500	1.500	1.500
Texas	N/A	N/A	N/A	N/A	1.000		1.125		1.250		1.375		1.500	
Wisconsin	N/A	N/A	1.000	1.000	1.250	1.250	1.250	1.250	1.500	1.500	1.500	1.500	1.500	1.500

and differential deflections and reduces dowel-concrete bearing stresses (thereby reducing the rate of development of joint faulting) when all other factors are held constant. Detailed discussions of the impact of dowel diameter (or cross-section) on dowel-concrete bearing stress and the development of joint faulting are presented in Appendices A and B.

Dowel diameter requirements may increase or decrease when dowels are spaced nonuniformly across a joint. For example, larger dowels may be required if dowel spacing remains constant and dowels away from the wheel paths are eliminated (forcing the remaining dowels to carry additional load), and smaller dowels may be permissible if the spacing of dowels is decreased in the wheel paths. Dowel diameter requirements are often significantly greater when lower-modulus materials are used as dowels (e.g., fiber-reinforced polymer, which may have an elastic modulus that is only a fraction of that of mild steel). Appendix B provides the information necessary to evaluate these types of design cases.

The diameter of a round dowel (and other cross-sectional properties of a non-round dowel) also directly controls the primary aspects of the dowel's structural capacity—shear, bending, and tension, although these are never of concern for typical design loads and steel dowels of the sizes normally used today.

Dowel Bar Length

Today's dowel bar length practices have evolved from practices in the late 1920s that typically featured the use of 3/4 in. dowels measuring 3 ft in length and spaced 18 to 36 in. apart. By the late 1930s, 24 in. dowel lengths were more common, and the benefits of using larger diameters and closer spacings were beginning to be recognized.

The analytical roots of pavement dowel design are found in the work of Timoshenko and Lessels (1925), who developed the original analysis of dowel bars embedded in concrete by considering the dowel as having semi-infinite length. In 1938, Friberg showed that the effect of cutting the dowel at the second point of contraflexure (typically less than 7 in. into the concrete for 1 in. dowels and less than 8.5 in. into the concrete for 1.25 in. dowels) resulted in a net change in the maximum bearing pressure at the face of the concrete of less than 0.25 percent. Based on this finding, he concluded that dowel lengths could be further reduced (to values less than 24 in.).

This work, along with the results of laboratory and field studies, including work begun at the Bureau of Public Roads in 1947, led the American Concrete Institute Committee 325 (Concrete Pavements) in 1956 to recommend the use of 18 in. long dowels spaced 12 in. apart—a practice that has been widely adopted and remains the most common practice today. These recommendations were given for steel dowels between 3/4 in. and 1.25 in. in diameter used in pavements with thicknesses between 6 and 10 in.

Based on the above, it can be noted that today's dowel lengths were originally selected to be long enough to ensure that the resulting bearing stresses at the joint face would be very close to values that would be obtained with dowels of semi-infinite length (i.e., the analysis originally performed by Timoshenko and Lessels in 1925). They do not seem to be based on the results of data that relate dowel embedment length to dowel performance, although such data have been available since at least 1958, when Teller and Cashell first published the results of the Bureau of Public Roads repeated shear load testing of full-scale pavement joints.

Based on the results of repeated load tests, Teller and Cashell (1959) determined that the length of dowel embedment required to develop maximum load transfer (both initially and after many hundreds of thousands of cycles of repetitive loading) for 3/4 in. dowels could be achieved with an embedment of about 8 dowel diameters (6 in.) while 1 in. and 1.25 in. dowels required only 6 diameters of embedment (6 in. and 7.5 in., respectively). Their test data suggest that even shorter embedment lengths (i.e., 4 dowel diameters or less) may still result in acceptable performance (bearing stresses and dowel looseness appear to increase only marginally and load transfer loss is less than 1 percent, as illustrated in Figures 2 and 3). As a point of interest, it was this same study that resulted in the recommendation that "dowel diameter in eighths of an inch should equal the slab depth in inches."

Khazanovich et al. (2009) performed a laboratory study of dowel misalignment conditions (including longitudinal translation, which results in reduced dowel embedment) and found that the shear capacities and relative displacements of 1.25 in. and 1.5 in. diameter steel dowels were probably acceptable, even when embedment was reduced to 4 in. or less. This study is described in the section about dowel alignment requirements.

Burnham (1999) evaluated the field performance and behavior (after 12 years of service) of several pavement joints on a Minnesota concrete pavement where the joints were not sawed at the proper locations, resulting in reduced embedment lengths. He concluded that "a minimum dowel bar embedment length of 64 mm (2.5 in.) is needed to prevent significant faulting and maintain reasonable load transfer efficiency across a joint."

Field experience and the analytical work and lab tests described above all seem to indicate that dowel embedment requirements could be reduced from current levels (resulting in dowel bars that are significantly shorter than 18 in.) and

still have good pavement joint performance while reducing pavement construction costs. Any dowel bar length selected should reflect both embedment requirements and variability in dowel placement and joint location (which is usually lower in pavement repair and dowel bar retrofit applications (Figures 4 and 5) than in new construction and might justify the use of even shorter bars in repairs).

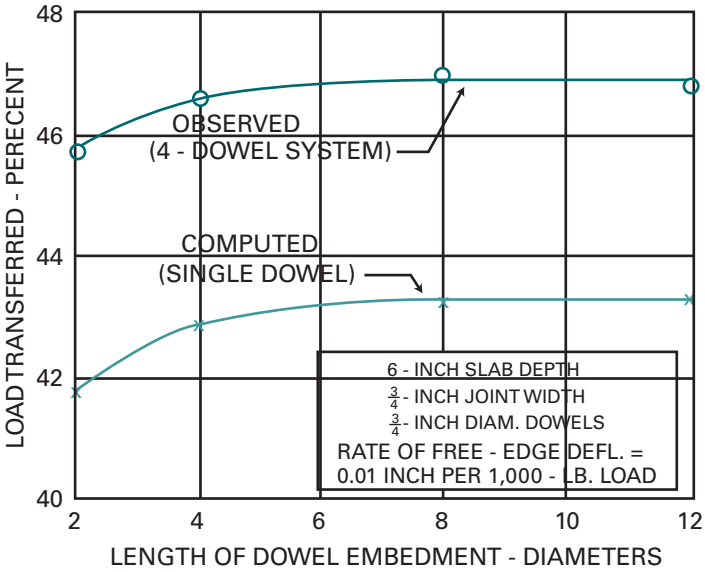

Figure 2. Load transfer versus dowel embedment (observed and computed), after Teller and Cashell (1959)

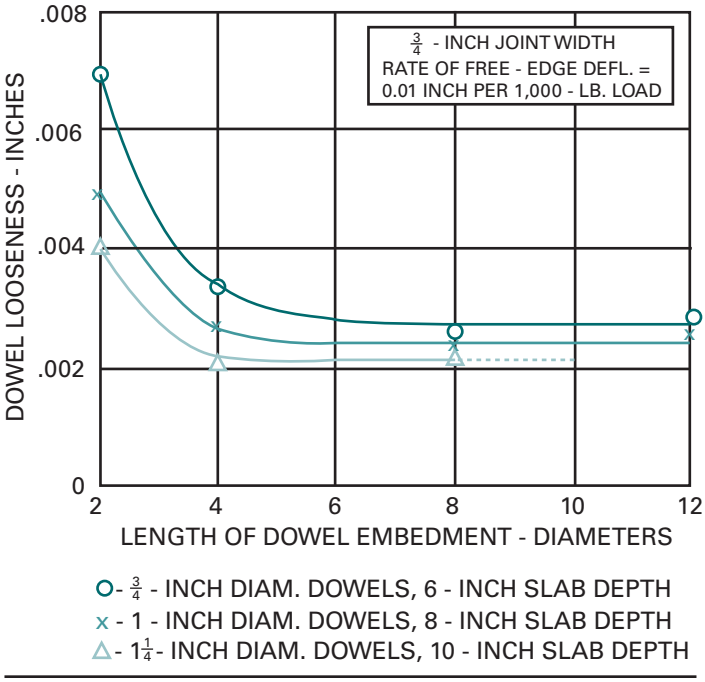

Figure 3. Effects of dowel embedment and diameter on dowel looseness after 600,000 repetitions of a 10,000 lb load (after Teller and Cashell 1959)

Dowel Alignment Requirements

Most highway agencies have fairly close tolerances on dowel bar placement and alignment. A report by ARA (2005) noted that most states have adopted the Federal Highway Administration-recommended limits on dowel rotation (horizontal skew or vertical rotation) of 1/4 in. per ft of dowel bar length or two percent (FHWA 1990). It also noted that there was no evidence that this level of tolerance was required to ensure good field performance.

Poor dowel alignment does not necessarily result in the development of slab cracking and spalling. If a single joint locks up, adjacent joints may provide sufficient stress relief to prevent the development of distress. The number of consecutive joints that must lock to produce distress depends on many other factors, including climate conditions, pavement structural design, concrete properties, restraint provided by the slab-subbase interface, and other factors (ACPA 2005).

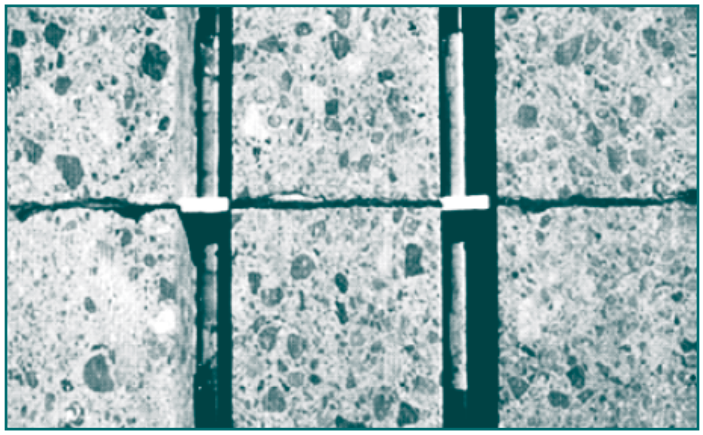

Figure 4. Photo of retrofit dowel bar assemblies, ready for repair material (photo credit: International Grooving and Grinding Association)

Figure 5. Photo of epoxy-coated dowel bars in full-depth concrete pavement repair (photo credit: www.pavementinteractive.org)

For example, Fowler and Gulden (1983) found similarly poor dowel alignment conditions on two comparable portions of I-20 located less than one mile apart from each other in Georgia, but a recent condition survey of those sections (ARA 2005) found one in excellent condition while the other exhibited substantial cracking. ACPA recommends limiting dowel rotational misalignment to three percent of the bar length (i.e., 3/8 in. per 12 in. or 9/16 in. for an 18 in. long dowel) based on NCHRP Synthesis 56 (ACPA 1998; NCHRP 1979).

For the purposes of this reference guide, it is assumed that a properly designed and manufactured dowel basket will hold the dowels in positions that assure adequate rotational alignment and stability. Findings of studies of vertical- and horizontal-translation forms of misalignment are discussed below, because they impact discussions of basket height and dowel length requirements.

Vertical Translation

Khazanovich et al. (2009) analyzed field performance data to compare faulting and load transfer efficiency (LTE) at joints with dowels centered within 1/4 in. of slab mid-depth with those of joints with dowels that were more than 1 in. closer to the pavement surface. They found no statistically-significant differences in faulting and LTE between the two groups.

They also performed laboratory tests of single dowels and conducted finite element analyses to examine the effects of concrete cover (which is affected by vertical translation) and dowel diameter on the shear capacity of the dowel-concrete system. Figure 6 summarizes the results of these studies and shows that the shear capacity of the system exceeds 5,000 lb when the cover over either 1.25 in. or 1.5 in. dowels is greater than 2 in. Recalling the maximum design shear loads in the critical dowel, it is clear that significant vertical dowel translation (up to the point where less than 2 in. of cover are provided) will still provide sufficient shear capacity for typical design load conditions. Khazanovich et al. further suggest that concrete cover exceeding 3.5 times the dowel diameter (i.e., 3.5 in. for a 1 in. dowel, 4.375 in. for a 1.25 in. dowel, or 5.25 in. for a 1.5 in. dowel) provides no significant increase in shear capacity.

Full-scale repeated load testing performed at the University of Minnesota confirmed that the reduction of performance associated with reduced dowel cover (vertical translation) was minimal (Odden et al. 2003). Three epoxy-coated steel dowels (1.5 in. diameter, 15 in. length) were retrofit in the wheel paths of each of two 7.5 in. thick concrete slabs—at mid-depth in one slab (resulting in 3 in. of concrete cover) and with two in. of cover in the other. Figure 7 presents LTE measurements obtained over more than 10 million applications of a 9,000 lb simulated wheel load, and shows that both installations provided good performance and exhibited similar rates of deterioration, although the shallow cover installation had slightly lower LTE values (and slightly higher apparent dowel looseness, as indicated in other portions of the report).

Longitudinal Translation

Khazanovich et al. (2009) also compared faulting and LTE data for joints with dowels that were placed with their centers within 1/2 in. of the joint versus those placed with more than 2 in. of longitudinal translation. They found no statistically-significant differences in faulting and LTE between the two groups.

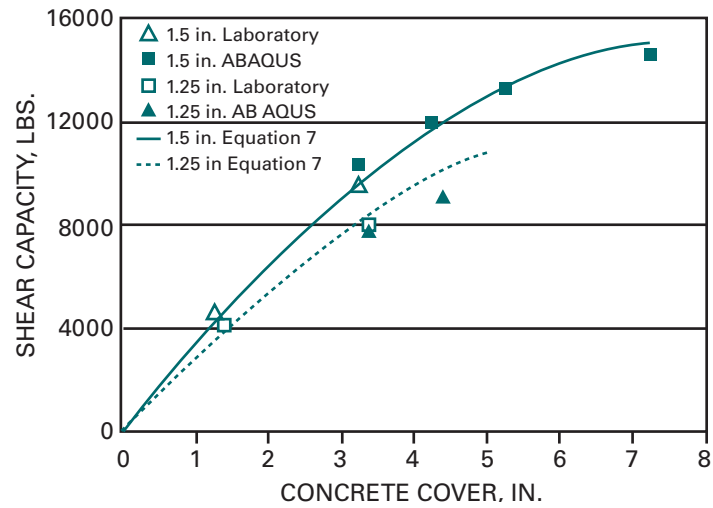

Figure 6. Effect of concrete cover on dowel-concrete shear capacity for 1.25 in. and 1.5 in. dowels, based on both laboratory tests and finite element analyses (after Khazanovich et al. 2009)

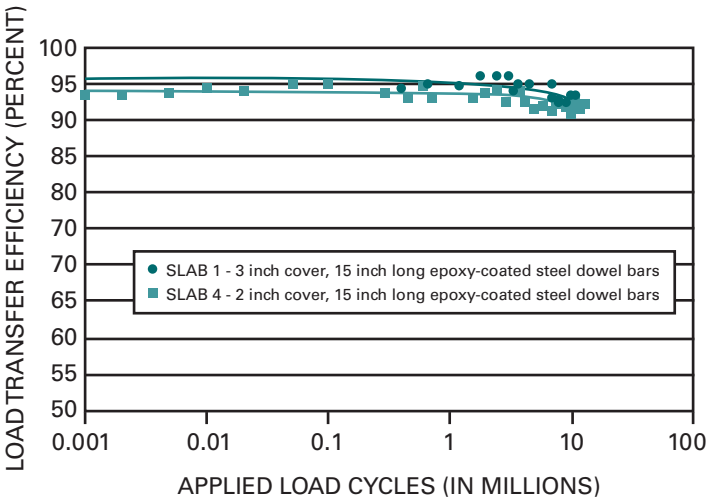

Figure 7. Effect of concrete cover on LTE for retrofit 1.5 in. steel dowels in 7.5 in. concrete slabs (after Odden et al. 2003)

In laboratory shear pull tests of dowels with varying amounts of embedment, Khazanovich et al. found no significant loss of shear capacity until embedment length fell to 4 in., and embedment lengths of as little as 2 in. provided shear capacity of more than 5,000 lb, which is more than sufficient for the critical dowel under typical highway design conditions (Figures 8 and 9). It should be noted, however, that the initial stiffness of the dowel-concrete system decreased by 60 percent or more when dowel embedment decreased to 3 in. or less, which would result in higher differential deflections and increased potential for pumping and faulting.

Khazanovich et al. also found that the combined effects of low concrete cover and low embedment length was greater than either of these two individual misalignment effects.

Dowel Spacing and Number of Dowels

A minimum distance of 12 in. between dowels has been standard practice in the US since the 1950s and has worked well, providing each dowel with sufficient shear capacity without creating a fracture plane along the line of dowels (except in cases where dowel bar corrosion contributed additional stress). It is likely that a slightly closer spacing of dowels could be used in areas of high load concentration (i.e., the wheel paths) without adverse effect, if it is beneficial to do so. However, there is anecdotal evidence to suggest that spacings of 6 in. or less (such as those that have resulted when drilling or retrofitting dowels between existing dowels) may result in the formation of a failure plane through the dowels. It is recommended that any dowel system with spacings less than 12 in. be analyzed to ensure it will perform as expected.

Many states have reported misalignment problems caused by the paver catching the dowel basket during paving and shoving or twisting it to result in severely displaced baskets. While some of these problems might have been avoided with improved anchoring of the baskets, a more reliable solution is to place the outside dowel 9 to 12 in. from the pavement edge and longitudinal joint (instead of 6 in.). This practice was recommended by Khazanovich et al. (2009) in their study report of dowel misalignment problems, and can be shown to result in only a small increase in pavement corner stress (see Appendix E). It offers the added benefit of reducing the cost of the basket assembly (one less dowel will be used if spacing remains constant at 12 in.).

Guidance on optimizing the location of dowels (i.e., the use of different and/or nonuniform dowel spacing) is provided in Appendix E.

Epoxy Coatings

Historically, most pavement dowels have been made primarily of carbon steel, which will corrode readily, especially in the presence of deicing chemicals. Dowel corrosion can cause or increase the rate of development of several types of pavement distress. For example, when dowel corrosion begins at the joint and progresses back into the adjacent slabs, the gap (or looseness) between the concrete and dowels increases the effective width of the joint, slab deflections and stresses increase (resulting in more rapid accumulation of fatigue damage), and load transfer is reduced (facilitating pumping, possible loss of foundation support, and more rapid development of faulting). A second corrosion-related distress mechanism is the expansion of corrosion products around the dowel, which can cause severe joint spalling or the formation and/or deterioration of mid-panel cracks.

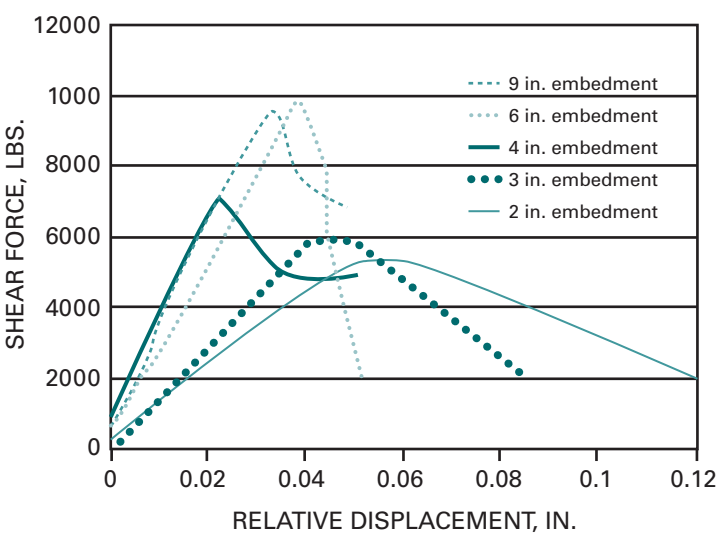

Figure 8. Effect of embedment length on shear force and displacement for 1.25 in. diameter steel dowels

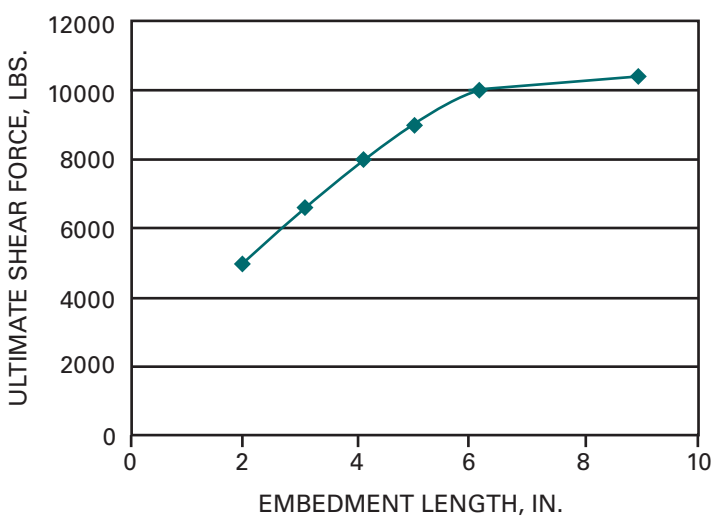

Figure 9. Shear capacity versus embedment length for 1.5 in. diameter steel dowels

Carbon steel dowels have typically been coated with grease, paint, epoxy, or plastic to inhibit corrosion, with epoxy coating meeting AASHTO M284 being the treatment most widely and effectively used. The epoxy provides a barrier between the steel and corrosive elements. Additional materials, such as grease or oil, are often applied to the epoxy coating to act as a bond breaker between the dowel and the concrete to facilitate horizontal joint movement in response to temperature and moisture changes.

Epoxy coatings used in paving dowels have typically been flexible (green) epoxies conforming to AASHTO M284. These coatings also meet ASTM A775/A775M and are applied using an electrostatic spray technique. A few projects have been constructed using "nonflexible" (purple or grey) fusion-bonded epoxies conforming to ASTM A934/A934M (Figure 10). Epoxy coatings produced under ASTM A934 and ASTM A775 are required to meet identical abrasion resistance criteria when tested using ASTM D4060; however, field experience suggests that ASTM A934 epoxies seem to have greater abrasion resistance than ASTM A775 epoxies. Mancio et al. (2008) found no significant difference in the degree of corrosion protection provided by either of these types of epoxy in dowel bar applications.

Epoxy coating of dowels is relatively inexpensive, and this treatment has historically been the most widely used corrosion protection treatment for dowel bars. However, the long-term performance of epoxy coating (and the other barrier methods mentioned above) has varied widely with environmental conditions, coating properties and durability, construction practices, and other factors. These types of coatings have sometimes proven unreliable for long performance periods (i.e., more than 20 years) in locations where deicing salts are used, because small defects in the coating (caused during manufacture, transport, or construction site handling) may provide a corrosion initiation site, reducing the dowel performance. Once established, the corrosion may spread (Figure 11).

To reduce the potential for corrosion problems, the epoxy specified for use must be sufficiently durable and resistant to the types of damage that will always be part of normal transport and site handling processes. Transport and handling should be conducted in a manner consistent with the requirements of ASTM D3963 ("Standard Specification for Fabrication and Jobsite Handling of Epoxy- Coated Steel Reinforcing Bars") or as described in the Appendix of ASTM A775 ("Standard Specification for Epoxy-Coated Steel Reinforcing Bars"). It is also recommended that plants selected for manufacturing epoxy-coated dowel bars be audited by an independent certification program for epoxy coating applicator plants, such as that provided by the Concrete Reinforcing Steel Institute.

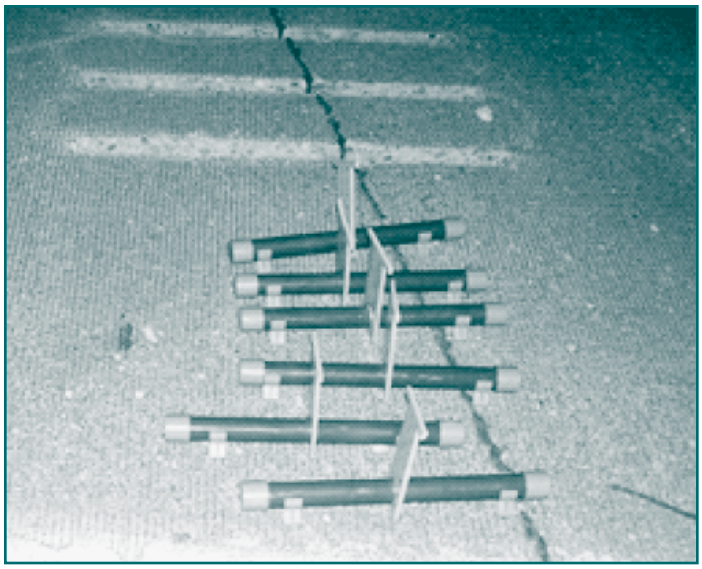

Figure 10. Epoxy-coated dowels for retrofit application (source: Washington State DOT)

Figure 11. Corroded (and non-corroded) dowels at in-service pavement joint (photo credit: Washington State DOT Pavement Guide)

Coating thickness specifications must call for enough thickness that normal variability in coating does not result in areas with coating that is too thin. Standardization of these items will help to make the dowel manufacturing process more efficient and will improve the field performance of epoxy-coated dowels.

Alternate Dowel Materials and Coatings

In recent years, dowels have been manufactured using corrosion-resistant and noncorroding materials, such as stainless steel, microcomposite steel, zinc-sleeved steel (passive cathodic protection), and (glass) fiber-reinforced

polymer (FRP/GFRP) products. These products offer better corrosion resistance than epoxy-coated carbon steel dowels (unless the epoxy coating is flawless), but these materials may have other drawbacks (e.g., reduced stiffness, increased cost, concerns about durability). These products and their uses are described briefly below.

Stainless Steel

Various types of stainless steel have been considered for use as dowel bars and dowel coatings or sleeves, but only Type 316/316L/316LN has proven to provide the corrosion resistance desired in long-life concrete pavements, especially in areas where deicing chemicals are used. This is the type of stainless steel recommended for use by the FHWA (Larson and Smith 2005).

Stainless steel offers the advantages of superior corrosion resistance (it is essentially the "gold standard" for metallic dowels) and engineering properties that are sufficiently similar to those of carbon steel, so they can be used without need to change the dowel size or spacing when replacing carbon steel dowels. If prepared with a smooth or polished finish, they may bond only weakly with the concrete, resulting in lower pullout forces.

Offsetting these clear benefits are relatively high cost (unit prices are several times that of carbon steel and have been somewhat volatile in recent years) and the production of hazardous gasses when being welded (e.g., to the dowel basket). In addition, stainless steel is more "noble" than carbon steel and can cause accelerated corrosion of nearby carbon steel if an electrochemical cell is formed in the presence of an electrolyte (e.g., salt water).

The most common uses of stainless steel in highway pavement dowels are: 1) solid stainless steel dowels, 2) hollow stainless steel (pipe) dowels, 3) stainless steel-clad carbon steel dowels, and 4) stainless steel-sleeved carbon steel dowels, which are shown in Figure 12.

Solid stainless steel dowels were used on a few long-life concrete paving projects in Minnesota between 2000 and 2002, but their high expense led the Minnesota DOT to consider the use of more economical corrosion-resistant products.

Hollow stainless steel tube (pipe) dowels offer the advantages of reduced cost over solid stainless steel, while reducing the weight and cost of the dowel and sacrificing some of the dowel stiffness. A sample use can be found in the Minnesota DOT high-performance concrete paving specification, which allows the use of 1.25 in. diameter Schedule 40 316LN stainless steel pipe (nominal diameter = 1.66 in., wall thickness = 0.14 in.) and which must either be filled with cement grout

Figure 12. Various stainless steel dowel products (clockwise from upper left): solid stainless steel (source: Cogne Stainless Reinforcement), hollow stainless steel pipe (source: Energy Engineered Products), stainless steel clad carbon steel dowels (source: www.pavementinteractive.org), and stainless steel-sleeved epoxy-coated carbon steel dowel (source: Construction Materials, Inc.)

or urethane, or must have end caps to prevent intrusion of paving concrete. These have been used on at least one high-performance concrete pavement in Minnesota.

Stainless steel-clad dowels have also been used on a small number of highway paving projects. These dowels typically feature a thin layer (7 to 15 mils thick) of stainless steel that has been fusion-bonded (clad) to a carbon steel dowel. The principal performance problems with these dowels have involved inadequate or nonuniform cladding thicknesses, which have become apparent after time in exterior storage when corrosion products have been observed on the dowel surfaces. Stainless steel-clad dowels are approved for use in several states and have been used on a handful of construction projects.

Stainless steel-sleeved dowels have been produced by press-fitting a carbon steel dowel (sometimes with epoxy coating) into a thin-walled stainless steel tube to produce a single dowel structure. This approach provides a thicker corrosion barrier than the stainless-clad dowels, is less expensive than solid stainless steel, and may be less expensive than stainless steel tube (pipe) dowels. This product has been used on a handful of projects in Minnesota.

Microcomposite Steel

Microcomposite steel is a through-alloy low-carbon, chromium steel (described in ASTM A1035) that typically offers higher strength, ductility, and corrosion resistance than tra-

Figure 13. MMFX 2 (microcomposite steel) dowel after five years of service (source: Wisconsin DOT)

ditional carbon steel. MMFX 2 is an example of this type of material that is widely marketed for dowel bar applications and has been approved for use in several states (Figure 13). It has been used most widely in Washington State and is present in several trial installations in other states.

Given that increased strength and ductility are of little value in highway pavement dowel bars (because bearing stress typically controls design), the primary benefit offered by microcomposite steel dowels is improved corrosion resistance over uncoated carbon steel and coated carbon steel with coating defects. The corrosion resistances of each of the other products described in this section have been shown to be superior to that of microcomposite steel for long-life pavement applications, but the relatively low cost of microcomposite steel dowels has resulted in their approval and use in many states.

Microcomposite steel appears to be a good material for use in reinforcing steel applications (where the benefits of increased strength and ductility can be utilized and direct exposure to the corrosive effects of chlorides, moisture, and oxygen is small due to embedment and cover, unless the concrete is cracked). The corrosion resistance of microcomposite steel in dowel bar applications would probably be improved to levels comparable to those of stainless steel if they were also epoxy-coated.

Zinc Alloy-Sleeved Dowels

Zinc alloy-sleeved dowels are produced by mechanically bonding a layer of zinc strip (approximately 40 mils thick, in practice) to a standard carbon steel dowel. The resulting product is a dowel bar that has a thick barrier to corrosive agents and oxidation and that also acts as a passive cathodic protection system (where the zinc corrodes to protect the carbon steel) to protect the steel in case of any breach in the barrier. The effectiveness of this system in preventing corrosion of the steel can be seen in Figure 14, which shows a zinc-sleeved dowel (with a strip of zinc removed to expose the underlying carbon steel) after several weeks in a salt water solution. The presence of zinc oxide is apparent, but there is no evidence of steel corrosion.

Several large long-life concrete paving projects have been constructed using these dowels in Minnesota and Wisconsin, and demonstration installations have been placed in Ohio and other locations.

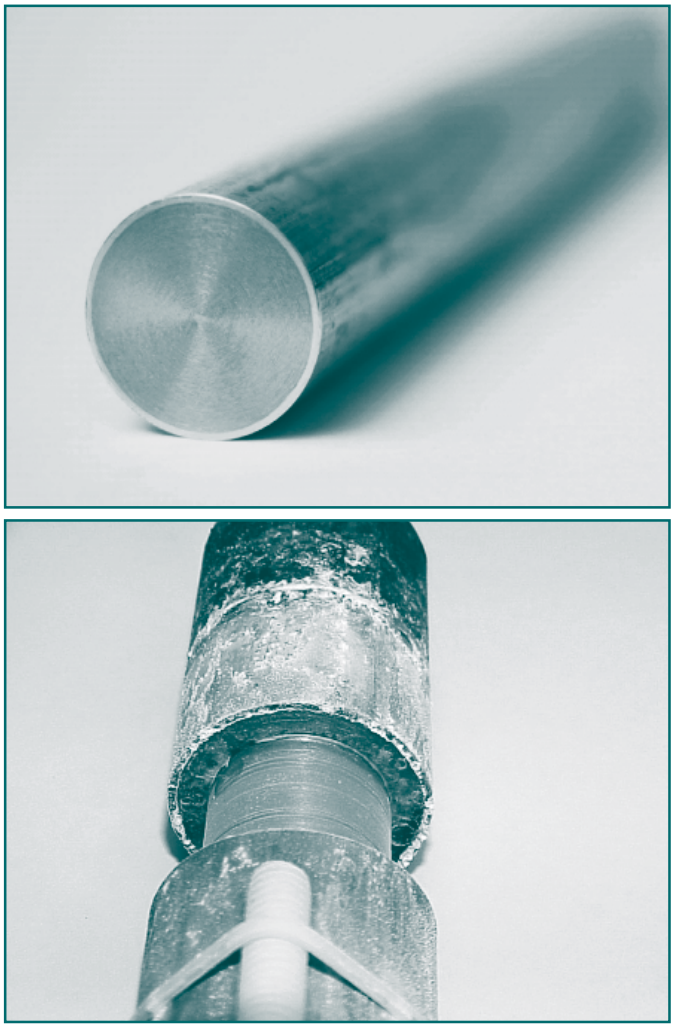

Figure 14. Zinc alloy-sleeved dowel, as manufactured and after five weeks in sodium chloride bath with a 1 in. wide breach in the zinc (source: Jarden Zinc Products, Inc.)

Fiber-Reinforced Polymer (FRP) and Glass Fiber-Reinforced Polymer (GFRP) Composite Dowels

FRP and GFRP composites comprise a matrix binder (made up of a resin or polymer material, such as polyester, vinyl ester, or epoxy), a strong reinforcing element (such as fiberglass, carbon fiber, or graphite fiber) and inert filler materials (such as calcium carbonate, clay, or hydrated alumina) (RJD 1999). These bars are often manufactured by a process called pultrusion, in which the reinforcing elements are pulled through a resin impregnation bath and then through a shaping die, where the resin is cured. FRP/GFRP has not been widely approved for use in highway pavement applications, but several trial installations are in place and under study throughout the US, and one major Interstate project was recently constructed using GFRP dowels in Idaho. Figure 15 shows a sample installation of FRP dowels.

FRP and GFRP materials are lightweight, relatively inexpensive (when compared with other corrosion-resistant products described in this section), noncorroding, and nonmagnetic (an advantage for applications near magnetic sensors for detecting vehicles at toll plazas and other locations). The principal drawback in the use of these products for dowel load transfer systems is that their elastic modulus is typically about 20 percent of that of steel, which results in significantly higher bearing stresses and differential joint deflections when all other factors are held constant (Murison et al. 2005; Cable and Porter 2003; Crovetti 1999). The reduced dowel stiffness makes the behavior of FRP-doweled joints much more sensitive to joint width and foundation stiffness. Much larger dowels and/or much closer spacing of dowels is required to produce the same bearing stresses and deflections that would be produced with any given size of round metallic dowel.

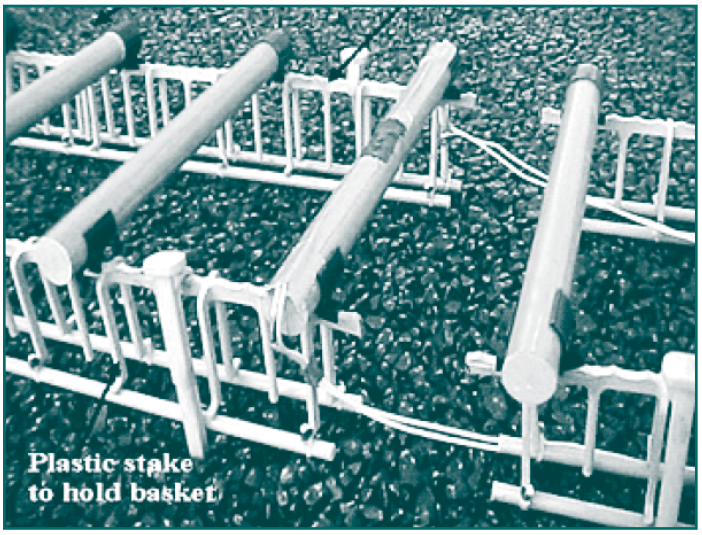

Figure 15. Experimental installation of FRP dowels in West Virginia (source: FHWA)

A brief summary of recent studies concerning the use of FRP dowels in PCC pavements is presented in Appendix F.

Dowel Bar Lubrication/Bond-Breaker Materials

Dowels must be fabricated and installed in a manner that permits the joints to open and close with slab contraction and expansion. This is typically accomplished with a relatively smooth dowel surface and generally requires the application of a bond-breaker material (i.e., a lubricant) prior to paving. Even though most dowels are manufactured with relatively smooth surfaces, there are occasionally minor imperfections due to machining, handling, etc., which provide a degree of mechanical interlock with the surrounding concrete. In addition, concrete bonds better with some dowel coatings (epoxy, plastic, etc.) than with others. Thus, different dowel products provide varying degrees of resistance to slip along their length.

AASHTO T 253 "Standard Method of Test for Coated Dowel Bars" (also referred to as "the pullout test") provides a procedure for testing the resistance of concrete-embedded dowels to slip along their length. Test results are reported in terms of the peak load required to extract the dowel at a constant rate of movement. At least one state (Michigan) uses an alternate test (Michigan Test Method 614) and reports both peak load and shear bond stress (peak load divided by embedded dowel cylindrical surface area) and specifies a limit on the bond stress.

The allowable limit for dowel pullout tests varies between highway agencies. For example, the Michigan DOT standard construction specifications (Section 914.07) limit bond stress to 60 psi (i.e., the pullout force limitation varies with dowel diameter and length), while the 2007 Kansas DOT Standard Specifications (section 1718) limit pullout force to 3,400 lb. Most dowels should be lubricated with form oil, grease, or synthetic materials prior to paving to ensure that they meet

Table 2. Sample dowel bar pullout test results (ACPA 2005)

Dowel Bar Coating	Pullout Load Avg. of 3 Tests	
	Lb	% of control
TECTYL 164	700	5%
TECTYL 506	930	7%
Asphalt MC-250	970	7%
SAE 30 Oil	1,600	12%
Grease	2,350	18%
Meadows Duo-Guard	6,670	50%
CONTROL - Uncoated	13.350	100%

these requirements. Table 2 provides an example of the effectiveness of various types of dowel lubrication materials on dowel pullout forces.

Dowel lubrication/bond-breaking agents must be applied uniformly over at least half the length of each dowel to maximize the effectiveness in reducing pullout force. Coating the full length of each dowel will help to ensure proper dowel function. It is also important that semi-solid coatings (grease, graphite, Tectyl, etc.) are applied in a relatively thin layer. A thick layer may result in an apparent loss of load transfer due to the softer support provided by the material (or by the void that results when the material wears or washes away). For example, the Kansas DOT specifies that coating thickness not exceed 24 mils.

Use of Expansion Caps and Joint Forming Materials

In new construction, expansion caps should be provided on dowel ends only at expansion joints; they are not necessary (or desirable) at contraction and construction joints. Joint-forming materials should also be used only at expansion joints.

When used at expansion joints, the caps should be installed on the unwelded end of each dowel in the basket (alternating dowel ends across the joint). Expansion caps should also be used in dowel bar retrofit installations.

Recommendations

Dowel Bar Material

Structural and behavioral considerations favor the continued use of metallic dowels that have engineering properties similar to those that have been in use for nearly 100 years: carbon steel of an appropriate grade and conforming to AASHTO M227/ASTM A663, ASTM A615 or ASTM A36. This includes the use of solid stainless steel dowels, appropriately designed hollow stainless steel dowels, stainless-clad and stainless-sleeved dowels, zinc-sleeved dowels, and microcomposite steel dowels, when long-term durability (corrosion) considerations dictate. Depending on the environmental and design conditions present, plain carbon steel and microcomposite steel dowels may not offer sufficient corrosion resistance without the use of an epoxy coating or other effective barrier to prevent corrosion.

GFRP and FRP dowels have engineering properties that are significantly different from those of metallic dowels (e.g., Young's modulus values about 80 percent lower than that of carbon steel). When used as direct replacements (in terms of dowel diameter or cross-section and length), they may induce unacceptable pavement behaviors and structural responses. In addition, field studies and laboratory tests have shown that the use of GFRP or FRP dowels of comparable size and spacing to standard steel dowel load transfer systems results in higher deflections (overall and differential), lower initial load transfer efficiency, and more rapid loss of load transfer efficiency under repeated loads. Significant increases in dowel diameter or reductions in dowel spacing may address these problems, but these approaches may cause other problems (e.g., slab cracking or delamination along the plane of the dowels at the joint). In addition, the long-term (more than 20 years) performance of pavements constructed using FRP/GFRP dowels has not yet been established. Therefore, the use of GFRP and FRP dowels should be approached with great caution.

Dowel Bar Diameter

Dowel bar diameter is an integral part of the design of the rigid pavement structural system and should be determined as a part of the overall pavement design/evaluation process because it directly affects key measures of pavement performance (e.g., pumping, faulting, ride quality). Dowel diameter should not be selected independently of pavement design, nor even as a simple function of pavement thickness. Therefore, no recommendation concerning design dowel diameter is provided here.

The manufacturers of all types of dowels should be encouraged to produce products with finished diameters that conform to those of standard epoxy-coated dowels for which baskets are designed, and it is recommended that dowel bars be manufactured in 1/4 in. diameter increments.

Dowel Bar Length

The recommended length for highway pavement dowels has been 18 in. since the 1950s. As described previously, this length was established primarily based on a desire to maximize potential shear capacity, even though this capacity was typically many times higher than design shear loads. Full-scale tests, field studies, and analytical work going back to the 1950s show that reduced dowel embedment lengths (as little as 4 in. and sometimes less) will provide adequate structural performance while reducing pavement material costs.

Based on the body of available research work and experience cited previously, it is recommended that round metallic dowel systems be designed to provide a minimum of 4 in. of embedment on each side of the joint. **Overall dowel bar length should be selected to provide the desired minimum dowel embedment on both sides of the joint, plus additional dowel length to account for variances in dowel placement across the joint**. Sources of placement variance include tolerances in the marking and sawing of joints in

new pavement construction, which could add several inches to the required overall dowel length.

Less variation in dowel placement can be assumed for dowel bar retrofit and full-depth repair applications, where the location of the dowel within the joint can be easily controlled. In these applications, acceptable performance can be expected to result from the use of dowels that are significantly shorter than those used in current practices.

It should be noted that dowel basket manufacturers indicate that dowel bar length can be varied without significantly affecting the manufacturing process, so it is not essential that dowel bar length requirements be standardized.

Dowel Corrosion Protection

Epoxy coating remains the least expensive, potentially effective alternative for corrosion protection of carbon steel dowels (and for additional protection for other metallic dowels). However, the durability of epoxy-coated dowels is reduced if defects in the epoxy develop during transport, construction, or service.

Assuming that transport and handling of any epoxy-coated dowel is done in a manner that minimizes the potential for introducing defects in the coating, the use of epoxy coatings with great abrasion and impact resistance should be considered. Some agencies have used epoxy coatings that were developed for use with prefabricated steel reinforcing under ASTM A934; these materials typically are either purple or grey in color. Coatings meeting ASTM A775 and ASTM A934 are required to meet identical abrasion resistance criteria when tested using ASTM D4060; however, field experience suggests that ASTM A934 epoxies seem to have greater abrasion resistance than ASTM A775 epoxies.

Epoxy coatings used in other applications (e.g., for coating pipelines) have been developed with significantly greater abrasion and impact resistance than the commonly-used AASHTO M284 (ASTM A775) green epoxy coating. Such abrasion-resistant coatings do not have the flexibility of the materials meeting AASHTO M284 (ASTM A775), which was originally developed for reinforcing bars that are to be bent after coating. Epoxy flexibility is probably not important for dowel bar applications.

Any epoxy used for dowel bars must be applied uniformly and with sufficient thickness to provide the desired protection of the dowel. AASHTO M254 requires coating thicknesses to be 7 +/- 2 mils, as this was the thickness range required for epoxy-coated reinforcing bars when the specification was first developed. Since then, the most commonly used ASTM specification for epoxy-coated reinforcing bars (ASTM A775) has increased the coating thickness to allow a range of 7 to 16 mils for bars with diameters greater than 3/4 in. Many agencies require significantly thicker reinforcing bar coatings than those required by the current AASHTO M254 specification.

To set a standard for the thickness of epoxy coating for highway pavement dowels, one can consider practices that are currently accepted by state DOTs and select the minimum thickness that is greater than or equal to the minimum thickness accepted by all state DOTs.

According to the results of a 2009 survey by the National Concrete Consortium, a value of 10 mils would satisfy this as a standard. It should be noted that AASHTO M284 and ASTM A775 require that "no single recorded coating thickness measurement shall be less than 80 percent of the specified minimum thickness," so measurements as low as 8 mils would be accepted when the specified minimum thickness is 10 mils.

With this in mind, it is recommended that the average epoxy coating thickness should be 10 mils or more (with all individual thickness measurements greater than 8 mils).

This recommendation will result in a slight increase in minimum allowable thickness for some agencies, but that increase is easily justified. Most epoxy coating thickness specifications are based on deformed reinforcement applications where the bars will see little (if any) movement and associated abrasion, and where too much epoxy will reduce pullout test values. Smooth dowel bars are intended to slide easily and are subject to continued abrasion and wear over time, so thicker epoxy coating is warranted than for rebar applications.

The use of too much epoxy coating would, theoretically, produce a softer support layer surrounding the dowel, which would result in increased differential joint deflections; however, this effect is believed to be minimal. In addition, manufacturer profit motives should prevent the use of excessive amounts of epoxy, so it probably isn't necessary to specify a maximum coating thickness.

Additional corrosion protection is not necessary for dowels manufactured using only 316L stainless steel (solid or hollow dowels), FRP or GFRP, or carbon steel dowels with adequate thicknesses of stainless steel or zinc alloy cladding/sleeving. Dowels manufactured using microcomposite steel and lower grades of stainless steel may develop some corrosion under pavement joint exposure conditions; their performance potential could probably be improved with the use of good epoxy coatings.

Dowel Basket Height

The following recommendations (Table 3) are for basket heights (from base to center of dowel bar) for dowel

diameters between 3/4 and 2 in., in 1/4 in. increments. The largest dowel diameters listed exceed those commonly used for metallic highway pavement dowels, but might be appropriate for some FRP or GFRP replacements of common highway dowels.

The basket height for each dowel diameter has been selected to result in placement of the dowel exactly at mid-depth for slab thicknesses at the lower end of each thickness range, and placement slightly below mid-depth for slab thicknesses at the upper end of each thickness range. The table reflects a preference for reduced cover on the bottom of the slab (where any resulting distress will not directly affect pavement ride quality or appearance) rather than the top. Note that the proposed cover of each dowel ranges from 2.125 in. (for the 3/4 in. dowel in a 5 in. slab) to 4.25 in. or more for the 1.5 in. dowel.

While an "intended slab thickness" is listed for each dowel bar diameter/basket height combination, it is recognized that larger or smaller dowels could be used for any given pavement thickness. The use of any proposed standard dowel diameter/basket height combination in slab thicknesses that are no more than one column to the left (i.e., the use of "oversized" dowels) results in a vertical translation of 0 to 1 in. (higher than mid-depth), while the use of the same basket in slab thicknesses that are no more than one column to the right (i.e., the use of "undersized" dowels) results in a vertical translation of 1 to 2 in. lower than mid-depth.

For example, Table 3 assumes the use of 1.25-in. diameter dowels in a standard basket (4 in. from base to mid-dowel, 1/4 in. from mid-depth) for an 8.5-in. pavement. However, some agencies (e.g., Indiana, per its current practice) might prefer to use 1.0-in. diameter dowels; the standard basket would place those dowel center 3 in. from the base and 1.25 in. from mid-depth. Other states (e.g., Illinois and Texas, per their current practices) might prefer to use 1.5-in. diameter dowels; the standard basket would place those dowel centers 5 in. from the base and 3/4 in. from mid-depth. Analytical, laboratory, and field studies have all shown that these ranges of displacement will still provide good performance, as described previously.

Recommendations for Standardized Basket Frame Design

The following recommendations are based on the information received from the 22 states surveyed by the National Concrete Consortium in 2009, as well as information obtained from contractors, manufacturers, and other industry representatives:

- The basket rail wire diameter should be a minimum of 0.306 in. (1/0 gauge).
- Loop wires should be "U" or "V" style and should be a minimum of 0.243 in. diameter (3 gauge).
- **Basket height (distance from bottom of base rail wire to dowel center) should be standardized according to dowel bar diameter,** as shown in Table 3.
- Standard basket loops should be spaced 12 in. (+/- 1/2 in.) on center.
- Loop wire legs may be installed on either the inside or outside of the rail wires.
- "Spacer" or "tie" wires (used to provide basket stability during shipping and handling) should have a diameter of 0.177 in. (7 gauge wire).
- Four equally spaced tie wires should be used in full lane-width basket assemblies; two tie wires should be used in mini-basket assemblies.
- All wire intersections must be welded.
- Baskets should be manufactured so that all dowels are horizontally mounted, parallel to each other, and oriented in the direction of expected slab movement (i.e., parallel to the direction of paving).
- **Standard baskets for full-lane applications should provide 11 dowels on 12 in. centers (i.e., basket length nominally 10 ft)**, with the intent that the distance from the edge of paving to the first dowel will be a minimum of 9 in. Nonstandard basket lengths can be specified and produced as needed for special projects.
- Epoxy-coating of baskets should be left to the discretion of the specifying agency.

Table 3. Recommended standard basket heights for various round dowel diameters

Dowel Bar Diameter, in.	0.75	1	1.25	1.5	1.75	2
Height to Dowel Center, in.	2.5	3	4	5	6	6
Intended Slab Thickness, in.	5–6	>6–8	>8–10	>10–12	>12	>12
Distance Between Dowel Center and Slab Mid-Depth, in.	0–0.5	0–1	0–1	0–?	0-?	0-?

Basket Stake Requirements and Other Anchoring Approaches

Inadequate anchoring of the dowel basket can lead to sliding, tipping, or pulling apart of the basket as the paver passes, which can result in severe dowel misalignment. Therefore, the degree to which the baskets are secured to the subbase or subgrade prior to paving is one of the most critical factors affecting dowel basket performance.

Basket rails should be anchored to the grade to provide maximum resistance to both tipping and sliding. Simple pins are commonly used for granular materials and soil, while power-driven anchors may be more effective for use in stabilized bases. Different foundation types may also require different pin or stake lengths (e.g., asphalt-treated base versus silty-clay soil), and layer thickness may dictate orientation of the anchor (e.g., a 6 in. pin cannot be placed vertically in a 4 in. granular layer that overlays a rigid layer).

It is recommended that a minimum of eight anchors be used to stabilize full-lane-width dowel baskets. It is common practice to place four anchors on each side of full-lane-width baskets, but some engineers believe that placing more (or all) of the anchors on the side of the basket that the paver first approaches will reduce the potential for basket tipping. Mini-baskets (e.g., short baskets used for small groups of dowels, often concentrated in wheel paths) should be installed with a minimum of four anchors. Mini-basket anchor locations can also be placed on one or both sides of the basket, as described above for full-lane-width baskets.

Cutting Tie or Spacer Wires Prior to Paving

ACPA recommends that dowel basket spacer/tie wires should not be cut after basket placement and prior to paving. The wires serve to brace and stiffen the baskets during paving and help to prevent basket movement as the paver passes.

Proponents of cutting the wires cite concern that the tie wires will restrain joint movement, but this has not been shown to be a problem and simple analyses of pavement contraction forces indicate that tie wires sized and spaced as recommended previously will either yield or will fail at the welds to the basket and will not significantly restrain pavement joint movements (ACPA 2005). It has also been reported that the MIT-SCAN-2 magnetic tomography device for measuring dowel alignment provides more accurate readings when the basket wires are cut (Khazanovich et al. 2009).

Use of Bond-Breakers and Basket Pre-Coating

The use of bond-breaker materials is typically specified and applied in the field, as necessary, to ensure that pullout forces do not exceed some maximum value (as described previously). Some states allow (or require) precoating of the entire dowel basket with a protective agent that doubles as a bond-breaker (e.g., Tectyl 506). Basket precoating is an additional step that is not critical to the control of the manufacturing process, so it is recommended that this requirement be left to individual states.

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Additional Resources

Dowel Bar Presentations from 2009 Spring NCC Meeting: http://www.cptechcenter.org/t2/ttcc_ncc_meeting.cfm

Innovative Concrete Pavement Dowel Design Guidelines and Dowel Cad2.0 from ACPA: http://www.pavement.com/dowelcad/

Appendix A - The Mechanics of Joint Faulting

Transverse joint faulting is one of the main distresses that affect the serviceability or ride quality of jointed concrete pavements. It is defined as the difference in slab elevations across the joint and is the result of a combination of heavy axle loads, insufficient load transfer between adjacent slabs, free moisture beneath the pavement, and erosion of the supporting base or subgrade material from beneath the slab.

Erosion occurs when excess moisture is ejected from beneath the leave slab corner as it is loaded by a vehicle. The moisture that is ejected carries base and/or subgrade fines with it, resulting in the development of a void beneath the pavement at the leave slab corner (Figure A1). In addition, there may be a corresponding deposit of this material under the approach slab. Due to the build-up of material beneath the approach slab and the loss of support under the leave corner, faulting and corner cracking can develop (Figure A2).

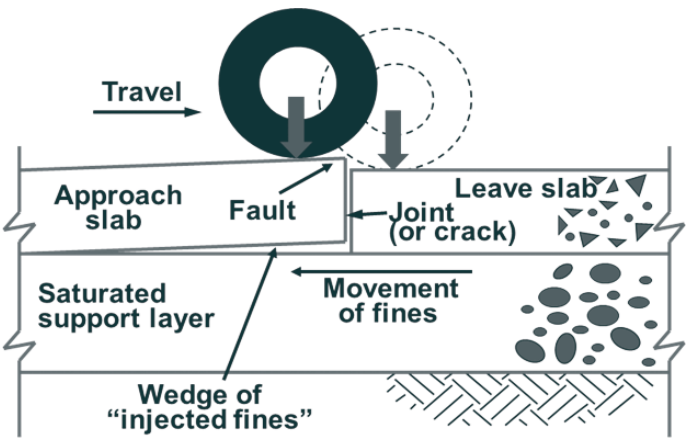

Figure A1. Illustration of pumping mechanism in jointed concrete pavement (source: NHI 1993)

Transverse joint faulting is an important deterioration mechanism for jointed concrete pavements (JCPs), because of its highly negative impact on ride quality. Significant joint faulting has a major impact on the life cycle costs of the pavement in terms of rehabilitation and vehicle operating costs.

Pavement design features that have been found to have a significant impact in models of joint faulting include: slab thickness, dowel diameter or bearing stress, drainage type, joint spacing, base type, and presence of a tied concrete shoulder. Two climatic variables (precipitation and freezing index) are also highly correlated with the development of faulting for non-doweled concrete pavements, but are less relevant for doweled pavements.

The AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) faulting models are highly dependent on the magnitude of the differential energy (DE) density at the slab corner. The DE is defined as the energy difference in the elastic subgrade deformation under the loaded slab (leave) and the unloaded slab (approach) and can be computed as:

$$DE = \frac{k}{2}\left(w_L + w_{UL}\right)\frac{1-\frac{LTE}{100}}{1+\frac{LTE}{100}}$$

where k is the modulus of subgrade reaction ("k-value"), LTE is the measured deflection load transfer efficiency, w_L is the deflection of the loaded side of the joint, and w_{UL} is the deflection of the unloaded side of the joint.

Figure A2. Joint faulting (left, source: Louisiana DOT) and corner breaks (right, source: www.pavementinteractive.com)

As DE increases, the potential for pumping and faulting increase greatly as well.

LTE, deflections and differential energy all depend, at least in part, on the deflection and deformation of the dowel-concrete system. The deflections and deformations depend upon the magnitude of the applied load, the dowel-concrete system structure (i.e., dowel diameter and embedment and concrete cover), the physical properties of the concrete and dowel (i.e., strength, elastic modulus, etc.), and the looseness of the dowel within the concrete – both initially and the increase after repeated load applications. The increase in dowel looseness (and corresponding increase in differential deflections and energy and loss of load transfer) are strongly influenced by the dowel-concrete bearing stress. The factors affecting the dowel-concrete bearing stress are discussed in Appendix B.

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Appendix B - Design Factors Affecting Dowel-Concrete Bearing Stress (and Faulting)

To determine critical dowel-concrete bearing stress first requires identification of the portion of the design load that is carried by the critical (most heavily loaded) dowel.

The total shear load carried by a dowel group cannot be more than 50 percent of the applied load (which corresponds to 100 percent deflection load transfer conditions) and is a function of many factors, including the spacing, length, and diameter (or other section characteristics) of the dowels, thickness of the slab, width of the joint (which influences the behavior of the dowel system), stiffness of the supporting pavement layers, and "looseness" in the dowel bars (due to initial conditions and the effects of repeated loads). Studies by Tabatabaie (1978) and others have established that, for design purposes, values of 40 to 50 percent transferred load are appropriate. Heinrichs et al. (1987) found that this value is generally between 41 and 43 percent.

Friberg (1938) studied the theoretical behavior of dowels in rigid pavements and concluded that all dowels within a distance of 1.8ℓ of the point of load application (where ℓ is the radius of relative stiffness of the pavement-foundation system) would carry a portion of the load, with the magnitude of load carried being inversely proportional to the distance from the applied load. Westergaard (1925) had previously defined the radius of relative stiffness as follows:

$$\ell = (E_C h^3/12k(1 - \mu^2))^{0.25}$$

where E_C is the concrete modulus of elasticity, k is the modulus of foundation support (k-value), and μ is the concrete Poisson's ratio. For typical concrete slabs (thickness ranging from 8 to 12 in. and elastic modulus ranging from 3 to 6 million psi) constructed on granular subbases and subgrade soils with an effective k of 200 psi/in., the radius of relative stiffness ranges from about 28 to 45 in.

The introduction of finite element methods in the late 1970s offered a new tool for analyzing concrete pavement joints, and several researchers (Tabatabaie 1978, Tabatabaie et al. 1979, and Barenberg and Arntzen 1981) re-examined the distribution of loads at the pavement joint and found that the distribution of shear forces should be restricted to 1.0ℓ or less to reflect values computed using finite element analyses. This revised distribution assigns a much higher load to the critical dowel and results in higher bearing stresses. Heinrichs et al. (1987) confirmed these findings and further stipulated that the figure should decrease to about 0.6ℓ as the load approaches the slab corner. Figure B1 illustrates how the effect of the design load on the critical dowel can be estimated using the information above.

Once the load on the critical dowel has been determined, the bearing stress can be computed using an equation developed by Friberg (1940) based on work done by Timoshenko and Lessels (1925):

$$\sigma_b = Ky_0 = KP_t(2 + \beta z)/4\beta^3 E_d I_d$$

where K = modulus of dowel-concrete interaction (similar to k-value for soils), which is typically assumed to be 1,500,000 psi/in.; y_0 = deformation in the concrete under the dowel at the joint face; P_t = the magnitude of the transferred load in this dowel; z = joint width at the dowel bar; E = modulus of elasticity of the dowel; I_d = moment of inertia of the dowel (= $\pi d^4/64$ for round dowels, where d is the diameter of the dowel); and β = the relative stiffness of the dowel embedded in the concrete and is computed as follows:

$$\beta = (Kd/4E_d I_d)^{0.25}$$

Assumptions:

Wheel load = 9,000 lb

Transferred load = 42 percent of applied load (P_t = 9000x0.42 = 3,780 lb/wheel)

Dowel spacing, s = 12 inches

Slab thickness, h = 10 inches

Effective modulus of subgrade support = 200 psi/in.

PCC Modulus of elasticity = 4.0×10^6 psi

PCC Poisson's Ratio = 0.17

Radius of Relative Stiffness, $\ell = (E_C h^3/12k(1 - \mu^2))^{0.25}$ = 36.19 in.

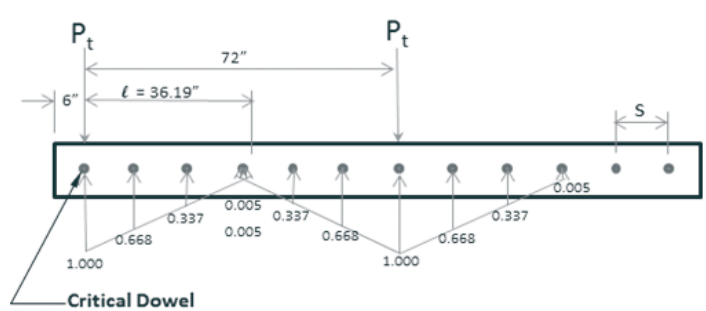

Figure B1. Sample computation of individual dowel shear loads within a dowel group

Calculation of effective dowels:

Dowel directly beneath load: 1.0 effective dowels

Dowels 12 in. from load: 24.19/36.19 = 0.668 effective dowels

Dowels 24 in. from load: 12.19/36.19 = 0.337 effective dowels

Dowels 36 in. from load: 0.19/36.19 = 0.005 effective dowels

Edge load is carried by 1.0 + 0.668 + 0.337 + 0.005 = 2.010 effective dowels

Mid-panel load is carried by 1.0 + 2(0.668) + 2(0.337) + 2(0.005) = 3.020 effective dowels

Critical dowel carries 3780(1.000/2.010) = 1881 lb

Adjacent dowel carries 3780(0.668/2.010) = 1256 lb

Other dowel loads can be computed similarly.

From these equations, it is clear that dowel bearing stress is directly proportional to the magnitude of the transferred load, as well as the joint width and the modulus of dowel-concrete interaction. It can also be inferred that bearing stress increases with decreasing dowel elastic modulus and moment of inertia (or diameter, for round dowels). Because bearing stress is directly related to y_0 (deformation in the concrete under the dowel at the joint face), factors that increase bearing stress also increase differential deflection across the joint and increase the potential for pumping and faulting. Furthermore, repeated applications of higher-bearing stresses result in more rapid increases in dowel looseness, which further increase differential deflections and potential for pumping and faulting.

While ACI Committee 325 (Concrete Pavements) currently makes no recommendations concerning limits for dowel bearing stress, in 1956 they published a document containing the following recommendation (which resulted in factors of safety of 2.5 to 3.2 against bearing stress-related cracking) (American Concrete Institute 1956):

$$f_b = f'_c(4 - d)/3$$

where f_b = allowable bearing stress, f'_c = concrete compressive strength and d = dowel diameter (in.).

Appendix C - Use of FWD Measurements in Measuring Dowel Effectiveness

The most common way to evaluate joint load transfer efficiency is through the use of a Falling Weight Deflectometer (FWD), which simulates the passage of vehicle loads on the pavement. The FWD load plate is placed at the point of interest (in this case, directly over the critical dowel, which is usually the one closest to the pavement edge, on one side of the joint), operating the FWD to simulate the passage of the design wheel load (typically 9,000 lb for highway pavements), and measuring the resulting deflections on each side of the pavement joint, as shown in Figure C1.

Deflection-based load transfer efficiency (LTE) is most commonly computed as:

$$LTE(\%) = 100\frac{\Delta_{UL}}{\Delta_L}$$

where Δ_{UL} is the deflection of the unloaded side of the joint and Δ_L is the deflection of the loaded side of the joint. In theory, LTE values can range from 0 to 100 (where 0 represents complete isolation of the two sides of the joint and 100 represents equal movements on both sides of the joint); however, variability in test measurements sometimes results in LTE values that are slightly greater than 100. Slab bending correction factors are sometimes applied to the LTE equation above to account for the fact that the measured deflections would not be expected to be exactly equal, even if there were no joint present, because the sensor in the load plate should always be at the deepest point in the deflection basin.

Deflection values (and, therefore, computed load transfer values) are affected by many factors, including pavement structural parameters (such as slab dimensions, foundation support, joint opening, and dowel design) and environmental conditions (such as average slab temperature and temperature and moisture gradients in the slab), which can vary hourly, daily, and seasonally. Therefore, deflection testing and load transfer evaluation should be performed under conditions that result in a realistic assessment of load transfer capability. It is generally accepted that concrete pavement joint load transfer testing should be conducted only when the slab temperature is 70°F or less to avoid conditions where thermal expansion results in joint closure and unusually high LTE values. Similarly, testing should not be done during times when the slab is significantly curled upward (especially on stabilized foundation layers), because measured deflections may be unusually high at these times.

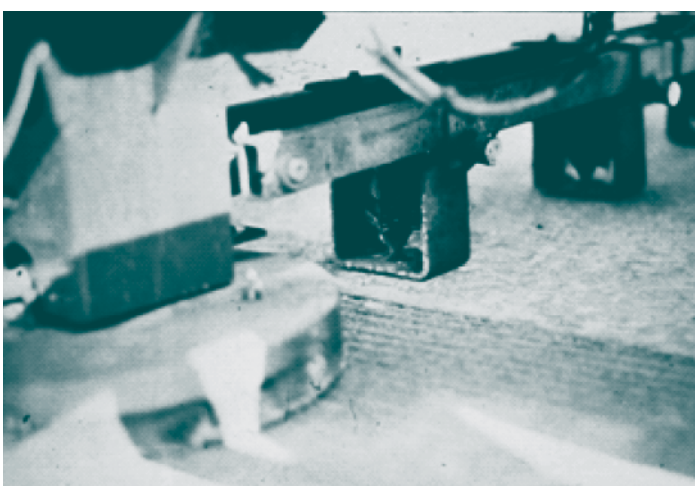

Figure C1. Placement of FWD load plate and first sensor on opposite sides of a transverse joint for the evaluation of LTE (photo source: NHI 1993)

LTE has often been used as the sole measure of the effectiveness of the joint load transfer system and of the need for restoration activities, such as load transfer restoration (dowel bar retrofit), undersealing, and joint replacement (patching). Typical "action" thresholds range from 50 to 70 percent LTE. Unfortunately, LTE alone does not tell the whole story.

Consider the case of a well-supported pavement structure, where FWD testing results in only 5 mils of deflection under the load and 2 mils on the unloaded side of the joint. The resulting LTE is 100*2/5 = 40%, which would be considered a failure using the LTE criteria described previously, even though the deflections are very small , so load-related slab stresses should also be small and the difference in deflections across the joint is probably not enough to cause significant pumping problems.

Conversely, consider the case of a poorly supported pavement structure, where FWD testing results in 30 mils of deflection under the load and 21 mils on the unloaded side of the joint. The resulting LTE is 100x21/30 = 70%, which would be considered acceptable under the LTE criteria described previously. In this case, however, total deflections are very high (due to the weak pavement support or voids under the joint) and the difference in deflections across the joint is high (and may be a source of the loss of support if pumping is taking place).

Clearly, joint evaluation cannot be based on LTE values alone. The additional consideration of maximum deflection or differential deflection (DD = Δ_L - Δ_{UL}) is probably appropriate. For example, Larson and Smith (2005) suggest that "doweled joints with LTE of 85 percent or less and/or a different deflection greater than 0.13 mm (5 mils) in five years or less are unlikely to provide satisfactory long-term

performance. The maximum differential deflection criteria of 0.13 mm (5 mm) may help evaluate dowel looseness or the possibility of delaminations in the concrete at the dowel bar level." Some states have adopted similar (but less stringent) criteria. For example, the Pennsylvania DOT specification for slab stabilization (Section 679) requires patching and stabilization of any joint or crack having a corner deflection of more than 20 mils and LTE of 65 percent or less (PennDOT 2007).

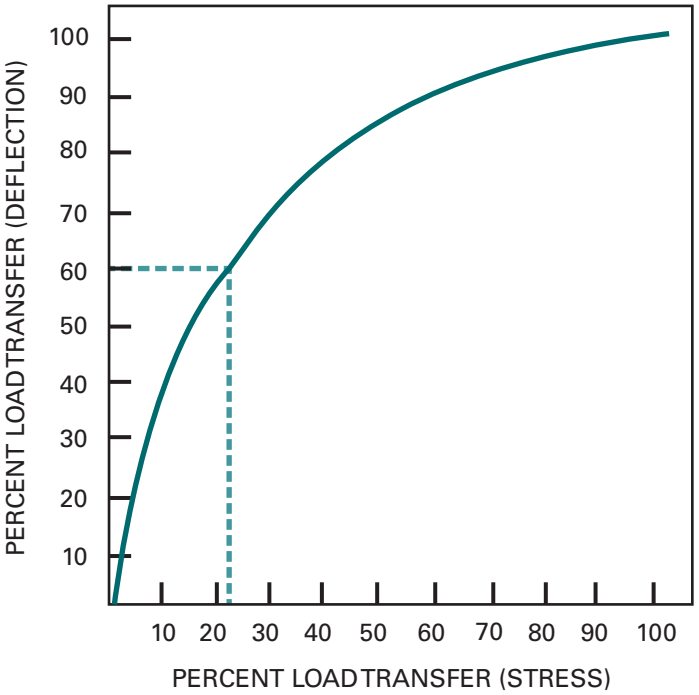

Figure C2. Example of the relationship between deflection and stress load transfer efficiencies for a particular pavement design thickness and support condition (source: FHWA 1997)

In establishing a limiting LTE standard, consideration should be given to the fact that concrete slab edge stresses change at a much different rate than do deflections. Stress transfer efficiency (STE) can be computed using an equation similar to the LTE equation presented previously:

$$STE(\%) = 100\frac{\sigma_{UL}}{\sigma_L}$$

where σ_{UL} is the stress in the unloaded side of the joint and σ_L is the stress in the loaded side of the joint. Figure C2 presents an example of an approximate relationship between deflection and stress load transfer efficiencies and shows that for the typical threshold deflection LTE value of 60 percent, stress transfer efficiency is only approximately 20 percent. Thus, it may be appropriate to consider the adoption of deflection LTE criteria that are 80 percent or higher to achieve stress transfer efficiencies of at least 50 percent.

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Appendix D - Evaluating Dowel Load Transfer Systems

The evaluation of individual or competing dowel load transfer systems must consider both structural and functional parameters and their influence on pavement behavior and performance. The effects of various structural parameters (dowel shape, size, spacing, material type, etc.) are briefly discussed in Appendix E. This appendix briefly discusses some key measures of load transfer system structural capacity or effectiveness that can be used to evaluate the suitability and performance potential of any given dowel load transfer system.

It should be noted that any dowel load transfer system being considered must have sufficient corrosion resistance to withstand the environment in which it will be used over the projected performance life of the pavement structure. It can also be assumed that the shear and moment capacity of any typically-sized dowel bar fabricated from typical steel or FRP material will be sufficient (considering that the peak dowel load in the critical dowel is generally less than 4,000 lb and that contraction joint openings are typically less than 1/4 in.). Finally, it is assumed that any dowel load transfer system under consideration has been laid out to avoid potential conflicts with paving machines and other slab reinforcing (i.e., tie bars) and will be constructed with adequate concrete cover for shear transfer and with proper alignment (as discussed in the main body of this guide).

Dowel-Concrete Bearing Stress. Excessive dowel-concrete bearing stress is believed to be responsible for the development of dowel looseness (and subsequent loss of load transfer, higher slab deflections, pumping, loss of joint support, and faulting) under repeated heavy loads. It can also cause concrete cracking in the vicinity of the dowel bar.

The computation of dowel bearing stress is presented in Appendix B, which shows that bearing stress increases with decreasing dowel elastic modulus and moment of inertia (or diameter, for round dowels). Bearing stress is also strongly affected by dowel spacing; close spacing in the area of loading reduces the peak load (and resulting bearing stress) on the critical dowel, while the opposite is true for increased dowel spacing.

There are currently no specific recommendations concerning dowel bearing stress limitations, although it seems intuitive that such limits would be linked to the strength of the surrounding concrete. In 1956, American Concrete Institute published a document containing the following recommendation (which resulted in factors of safety of 2.5 to 3.2 against bearing stress-related cracking)(American Concrete Institute 1956):

$$f_b = f'_c(4 - d)/3$$

where f_b = allowable bearing stress, f'_c = concrete compressive strength, and d = dowel diameter (inches). The use of this limit seems to have been generally effective in preventing bearing stress-related failures. Research is needed to update and refine dowel-concrete bearing stress requirements.

Load Transfer Efficiency. The use of Falling Weight Deflectometer (FWD) deflection test data to evaluate pavement joint behavior is discussed in Appendix C. Deflection-based load transfer efficiency (LTE) can be computed from FWD test results, and action threshold values typically range from 50 to 70 percent. However, since stress transfer efficiency values lag far below deflection transfer values (e.g., deflection LTE = 60 percent corresponds to a stress LTE of only about 20 percent, as described in Appendix C), it may be appropriate to consider much higher action threshold values for deflection LTE. In addition, computed LTE values should be considered in combination with overall and/or differential deflection values because it is possible to have high (acceptable) LTE values for systems with poor deflection characteristics, and it is also possible to have low (unacceptable) LTE values for systems that can be expected to perform well because of their very low deflections.

Joint Deflection (Peak and Differential). As described in Appendix C, joint deflection measurements (either peak deflection under the applied load or differential deflection on either side of the joint) provides a useful indication of the effectiveness of a joint load transfer system and are especially useful in properly interpreting deflection load transfer efficiency (LTE) values. It is difficult to find published recommendations for joint deflection criteria, but there seems to be anecdotal support for limiting peak corner deflections to 25 mils or less and differential deflections to 5 mils or less. For example, Larson and Smith (2005) suggest that pavements having less than 85 percent deflection-based LTE and more than 5 mils differential deflection after five years of service are unlikely to provide good long-term performance. Further research may help to provide better guidelines for using joint deflection data to differentiate the performance potential of alternative dowel load transfer systems.

Joint Stiffness. Dowel load transfer systems that have reduced stiffness (through the use of more flexible dowel

materials, reduced dowel bending stiffness, greater dowel spacing, etc.) will provide less restraint of slab curling and warping movements, regardless of the deflection-based LTE that is achieved. Some pavement engineers believe that this is a positive effect because less joint restraint means lower stresses due to curling and warping and correspondingly lower combined load and environmental stresses. Others argue that curl/warp restraint stresses are mitigated by creep effects over time and that failing to restrain the joints from rotation results in loss of slab support and higher load-related stresses and fatigue accumulation.

Research is needed to examine and resolve this issue and provide better load transfer design guidance.

Appendix E - Concepts for Optimizing Dowel Load Transfer System Design

Pavement dowels provide structural support to pavement joints while allowing those joints to open and close to accommodate temperature and moisture effects. In providing edge support, they provide for the transfer or sharing of applied loads across the joint, which reduces stresses and deflections and the accumulation of fatigue and cracking in the slab where the load is applied. They also reduce the independent vertical movements (differential deflections) of the slabs on each side of the joint, which reduces the potential for distresses such as pumping and faulting.

Dowel load transfer systems have traditionally consisted of smooth, round steel bars that have been spaced uniformly along a pavement joint, and the size (diameter) of the dowels has been selected (at least in recent years) to reduce dowel-concrete bearing stresses to levels that are believed to avoid the development of significant dowel looseness over time. However, the analyses presented in Appendix B make it clear that dowels located away from the load paths carry very little load. It follows that the most efficient reduction of pavement stresses and deflections can be accomplished by concentrating the dowels in the immediate vicinity of the applied loads. This can be accomplished by eliminating one or more dowels that are located away from the wheel paths, by more closely spacing dowels within the wheel paths, or both.

For any given dowel pattern, it is possible to strive for further performance improvements and efficiencies through the use of non-round dowels (e.g., elliptical or flat plate shapes), changes in dowel size (i.e., cross-section area for any given shape), the use of different dowel materials (e.g., various solid or hollow metallic dowels versus various solid or hollow fiber-reinforced polymer dowels), and/or the use of shorter dowel bars, as was discussed in the main body of this reference guide. There is also interest in improving pavement constructability at some expense of structural performance by moving basket-mounted dowels slightly further from the slab edge to avoid possible basket displacements caused by conflicts with the paver during concrete placement.

This Appendix provides brief discussions of the considerations and effects associated with each of the dowel load transfer system design modifications mentioned above. More in-depth analyses and discussions can be found in many of the references cited in the main body of this document, as well as in Transtec 2008.

Dowel Shape

The primary reason for considering the use of non-round dowels has been to reduce concrete bearing stresses by presenting a larger steel bearing surface while reducing (or holding constant) cross-sectional area (and, therefore, cost). This has been achieved occasionally through the use of elliptical dowels (mainly on highway pavements) and flat plate dowels (historically, for industrial floor slab and pavement applications).

It is clear that elliptical dowels and plate dowels can result in reduced bearing stress when compared to round dowels of similar sectional area. Reduced bearing stress means reduced deformation of the concrete surrounding the dowel and resulting smaller deflection of the dowel within the concrete slab. However, it must also be considered that many of these non-round dowels have much lower bending stiffness in the plane of loading, which means that differential deflections across the joint or crack width will be higher (and corresponding load transfer efficiencies will be lower) than would be expected for round dowels of similar area.

The reduced bending stiffness of the non-round dowels means that the joint will also have less bending stiffness and restraint of slab curl and warp will be reduced. Some researchers consider this to be a good thing, because the restraint of curling and warping induces stresses that may combine with load-related stresses to create conditions that accelerate the development of slab cracking. Other researchers, however, point out that the slab restraint stresses decrease over time due to "slab creep" effects, and that the higher deflections and subsequent fatigue caused by loads being applied to poorly-supported corners and edges is more damaging than the effects of loading on restrained slabs. Foundation stiffness (e.g., the use of granular versus stabilized subbase material) also influences the effect of restraining slab curl.

There have also been concerns about the proper installation of elliptical dowels (particularly where the use of a dowel bar inserter is used, rather than prefabricated dowel baskets) to ensure that they are oriented properly. In most cases, a 90 degree rotation of the dowel about the longitudinal axis will present a much smaller bearing area and substantially higher bearing stresses.

A second benefit of some plate dowels (i.e., those with tapered/diamond shapes or other design features that allow

lateral displacement) is their ability to accommodate slab movements in two directions, such as are experienced in airport aprons, parking lots and other area paving applications.

Dowels shaped like small I-beams have also been used on some older highway paving projects in New York (presumably with a goal of more efficient use of steel, rather than to significantly reduce bearing stress). It is likely that it was difficult to consolidate concrete around these unusually shaped bars, and their use has long been abandoned.

Dowel Size

For most dowel shapes (other than plates), increased dowel size results in reduced bearing stress and increased joint stiffness (along with associated reductions in overall deflection and differential deflection and increased restraint of slab curling and warping) when dowel spacing is held constant. Increased plate dowel width also reduces bearing stresses and increases joint stiffness, and increased plate dowel thickness further increases joint stiffness.

Dowel unit costs tend to increase rapidly with size, so it is important to use a dowel size that is no larger than is necessary to limit bearing stress and slab deflections to acceptable levels.

Dowel Material

The most widely used dowels are of solid metallic construction, generally using some form of steel that is either highly corrosion resistant (i.e., 316L stainless steel) or less corrosion resistant but coated with a protective barrier, such as epoxy, stainless steel or zinc alloy cladding/sleeving, paint, or plastic. Solid dowels fabricated using these types of materials have similar Young's modulus properties (~29×10^6 psi) and can be expected to produce similar system behavior (i.e., similar bearing stresses, joint stiffness, curl/warp restraint, and slab deflections).

The use of hollow stainless steel dowels has been investigated and is approved in at least one state (Minnesota, which allows the use of 1.25 in. nominal diameter Schedule 40 stainless steel pipe for dowels, with end caps or filler [grout or urethane]). This design was proposed to reduce the high costs associated with the use of 316L stainless steel. While these dowels have a slightly "softer" response to applied loads than do solid dowels, they have been shown to have adequate structural capacity and sufficiently low bearing stresses to perform well.

Fiber-reinforced polymer (FRP) dowels have been proposed for use in recent years and they have been the subject of many theoretical, lab, and field studies. FRP dowel manufacturer literature suggests that most of these products have a Young's modulus that is about 80 percent lower than that of steel, and theory and research show conclusively that the reduced stiffness of FRP dowels results in significantly higher bearing stresses and deflections when all other design factors are held constant. Therefore, FRP dowels must be larger and more closely spaced than metallic dowels to provide similar slab behavior. Appendix F provides a more detailed summary of the behavior of FRP dowels in highway pavement applications.

Dowel Spacing

When dowel spacing decreases, bearing stresses and deflections also decrease and joint stiffness increases. Thus, reduced dowel spacing (within limits) can be an effective way to reduce bearing stresses to acceptable levels in wheel paths and near slab edges. There are limits to how closely dowels can be spaced without inducing a horizontal plane of weakness in the concrete at the joint face, as has been observed in some installations where dowel spacings were 8 in. or less.

Conversely, when dowel spacing increases, bearing stresses and deflections increase while joint stiffness decreases. However, because bearing stresses are generally expected to be lower in areas that are not within the wheel paths, dowel spacing can be significantly increased in these areas (often by eliminating one or more dowels, with resulting cost savings) without increasing bearing stresses above critical levels and without significantly increasing slab deflections.

The two considerations described above can be combined and used to develop non-uniform dowel distributions along the joint face that feature slightly reduced spacing in the wheel paths and greater spacing near the center of the lane. Sample analyses of these types of systems are presented in Transtec 2008, which examines the predicted bearing stresses and slab deflections associated with several alternate dowel patterns and found that removing two, four, and six dowels from the center of the lane (i.e., leaving ten, eight, or six dowels to carry the load) resulted in edge deflection increases of only 2 to 10 percent and increases in peak dowel bearing stress of only 1 to 5 percent.

Distance from Edge to First Dowel

The dowel closest to the outside pavement edge has often been placed as closely as possible to the edge (usually about 6 in. away) to maximize the support to the joint at this critical location. However, when dowel baskets are used (rather than dowel bar inserters), it is not uncommon for the paving equipment to catch the edge of the basket and twist or

displace it, causing severe dowel misalignment. For this reason, many states have begun to increase the distance from the edge to the first dowel from 6 in. to 9 or 12 in. (often reducing the number of dowels in the joint by one at the same time, as an added cost savings).

Transtec (2008) performed a sensitivity analysis on edge deflections and peak bearing stress for edge loads when this dowel is moved away from the edge, and found that the increases in edge and corner deflection were close to zero, but that the peak bearing stress increased substantially (by up to 31 percent for 14 in. slabs and a 12 in. distance to the first dowel). The increased potential bearing stress under edge loads should be considered before adopting a large increase in edge distance for the first dowel. If the estimated stress exceeds target levels, the use of larger dowels, closer dowel spacing, and/or higher-strength concrete (to increase the acceptable stress level) should be considered.

DowelCAD 2.0 – A Tool for Evaluating Alternate Dowel Designs

Engineers that are interested in evaluating potential alternate dowel load transfer designs (including consideration of reduced numbers of dowels, alternate dowel locations and spacings, and various dowel shapes) may find useful tools in the Dowel CAD 2.0 software and accompanying Innovative Concrete Pavement Dowel Design Guidelines (both available at no charge from the American Concrete Pavement Association at http://www.pavement.com/dowelcad/).

DowelCAD 2.0 includes two dowel load transfer evaluation modules: the first evaluates the effects of varying dowel bar shape (round versus elliptical) and size on predicted joint load transfer and bearing stress (Figure E1); the second provides an assessment of the impacts of dowel shape, size and spacing alternatives on peak bearing stress, slab edge stress and deflection and slab corner stress (Figure E2). It is important to note that DowelCAD 2.0 assumes that all dowels analyzed have properties that are similar to steel; the results obtained are not generally applicable to consideration of FRP dowel options, which exhibit significantly different structural and mechanical behavior, as is discussed in Appendix F.

Reference

Transtec. 2008. *Innovative Concrete Pavement Dowel Design Guidelines.* Document prepared for and published by the American Concrete Pavement Association. Skokie, IL.

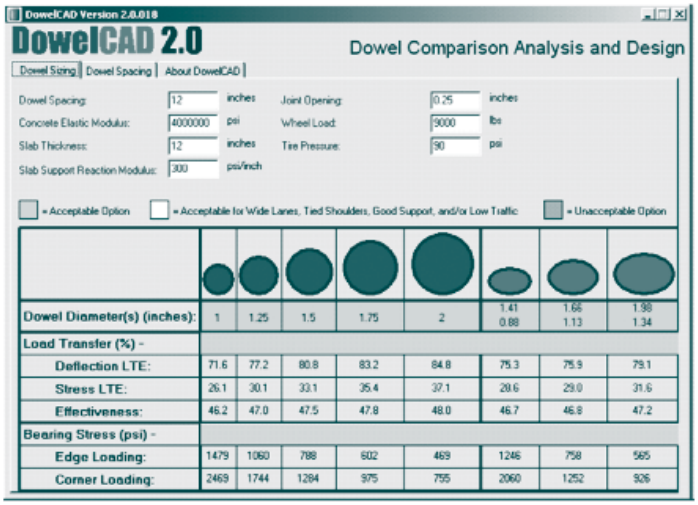

Figure E1. Screen capture of the dowel sizing module in DowelCAD 2.0 (source: Transtec 2008)

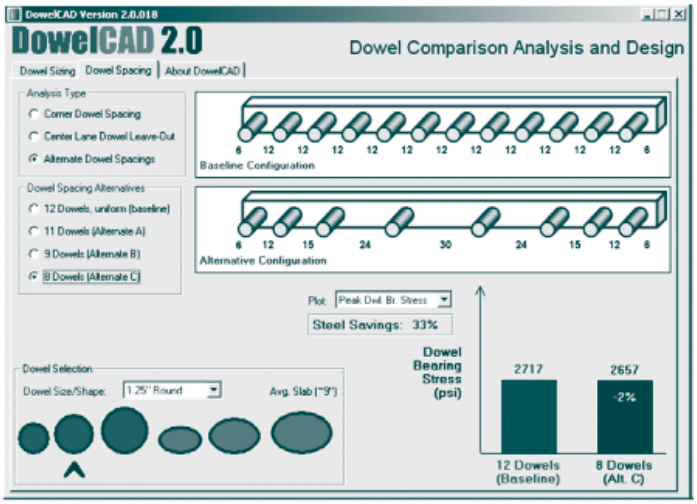

Figure E2. Screen capture of the dowel spacing module in DowelCAD 2.0 (source: Transtec 2008)

Appendix F – Summary of Studies Concerning Use of FRP Dowels in PCC Pavements

FRP and GFRP materials are lightweight, relatively inexpensive, noncorroding, and nonmagnetic. The principal drawback in the use of these products for dowel load transfer systems is that their elastic modulus is typically about 20 percent that of steel, which results in significantly higher bearing stresses and differential joint deflections when all other factors are held constant (Murison et al. 2005, Cable and Porter 2003, Crovetti 1999). The reduced dowel stiffness makes the behavior of FRP-doweled joints much more sensitive to joint width and foundation stiffness. Much larger dowels and/or much closer spacing of dowels are required to produce the same bearing stresses and deflections that would be produced with any given size of round metallic dowel.

For example, it can be shown (using analysis techniques described in Appendix B) that the use of FRP dowels will result in dowel-concrete bearing stresses that are 50 percent higher and dowel deflections that are about 60 percent higher than those associated with the use of metallic dowels when all other factors are held constant. To match the dowel deflection and bearing stress of 1.5 in. diameter steel dowels on 12 in. centers in a particular pavement system, it is necessary to use either 1.92 in. diameter FRP dowels on 12 in. centers or 1.5 in. dowels on 8 in. centers (Table F1). Dowels spaced as closely as 8 in. apart have been associated with joint spalling and cracking/delamination of the concrete along the weakened plane of the closely spaced dowels (Larson and Smith 2005).

Several laboratory test studies support the trends observed in Table F1 and provide additional insight into the differences in performance between pavements constructed using metallic dowels and those built using GFRP/FRP dowels. Several of these studies were summarized by Larson and Smith (2005). For example, Davis and Porter (1998) conducted a laboratory study that showed similar joint LTE behavior when using 1.75 in. diameter FRP dowels spaced at 8 in. and conventional 1.5 in. steel dowels spaced at 12 in. Another lab study by Melham (1999) showed that 1.5 in. FRP dowels performed comparably to 1 in. steel dowels in repeated load testing.

Odden et al. (2003) and Popehn et al. (2003) performed full-scale repeated load tests of several types of dowels (including FRP dowels) at the University of Minnesota and observed significantly higher deflections and more rapid loss of load transfer for the slab containing 1.5 in. diameter FRP dowels than for those containing 1.5 in. metallic dowels. When the FRP dowel diameter was increased to 1.75 in., they found that they behaved more similarly to the smaller metallic dowels. The researchers concluded that the FRP dowels would need to be about 2 in. in diameter to provide slab behavior and load transfer values similar to those provided by the 1.5 in. metallic dowels. Representative graphs from the report that illustrate these points are provided in Figures F1 and F2.

Field studies have also documented the differences in joint behavior and performance between FRP and metallic dowels. For example, several experimental pavement projects were built in the late 1990s and early 2000s using FRP dowels under the FHWA TE-30 program:

- In Illinois, a 2004 evaluation determined that the sections were all performing well, but that the LTE data for the sections containing FRP dowels were lower and more variable than the data for sections containing epoxy-coated steel dowels (Gawedzinski 2004).
- Iowa researchers (Cable and Porter 2003) found (after five years of performance) that the FRP dowels tested needed to be spaced not more than 8 in. apart to provide similar load transfer performance to the epoxy-coated steel dowels at 12 in. spacings. However, at this spacing, a horizontal delamination was observed in a core retrieved adjacent to one of the FRP dowels. The Iowa study also noted that FRP dowels were susceptible to "floating" to the pavement surface when placed using a dowel bar inserter.

Table F1. Sample sensitivity analysis of dowel deflection and bearing stress to dowel diameter and material (computed using Friberg's bearing stress analysis)

Dowel Type	Diameter (in.)	Dowel Modulus, E (psi)	Applied Shear Force (lb)	Dowel Deflection at Joint Face (in)	Bearing Stress (psi)
Metallic	1.5	29,000,000	1940 (12 in. spacing)	0.0009	1421.4
FRP	1.5	5,600,000	1940 (12 in. spacing)	0.0015	2185.8
FRP	1.92	5,600,000	1940 (12 in. spacing)	0.0009	1405.5
FRP	1.5	5,600,000	1260 (8 in. spacing)	0.0009	1419.7

- The Wisconsin DOT constructed two experimental projects containing FRP dowels in 1997. Early deflection testing (Fall 1997 and Fall 1998) indicated significantly reduced LTE for the composite dowels (Crovetti 1999, Smith 2002). None of the test sections appears to have developed distress related to differences in LTE at this time

In summary, while the FHWA TE-30 program indicated no early pavement distress problems associated with the use of FRP dowels, the projects constructed were very young when last evaluated (prior to 2005) and longer-term performance monitoring (20 years or more) should be considered in evaluating the performance potential of FRP dowels, particularly when the designs used result in significantly higher deflections and lower LTE values than for metallic dowels. Larson and Smith (2005) observed that "the large number of joints with low LTEs of FRP dowels in less than five years is a serious concern."

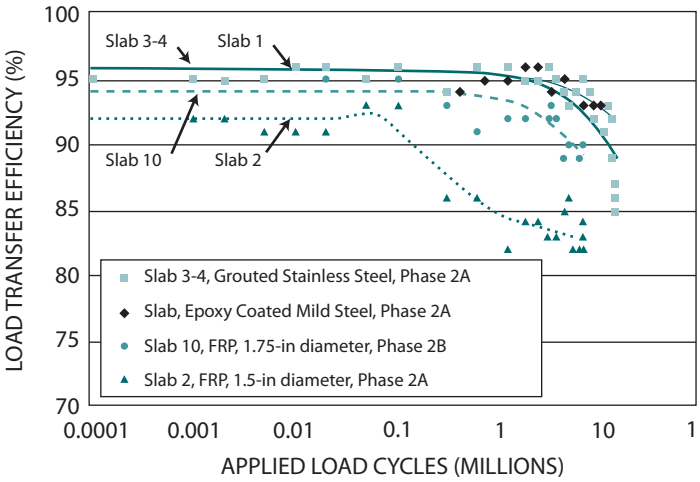

Figure F1. Lab test LTE histories for several dowel materials and diameters (7.5 in. PCC slab, 12 in. dowel spacing) (after Popehn et al. 2003)

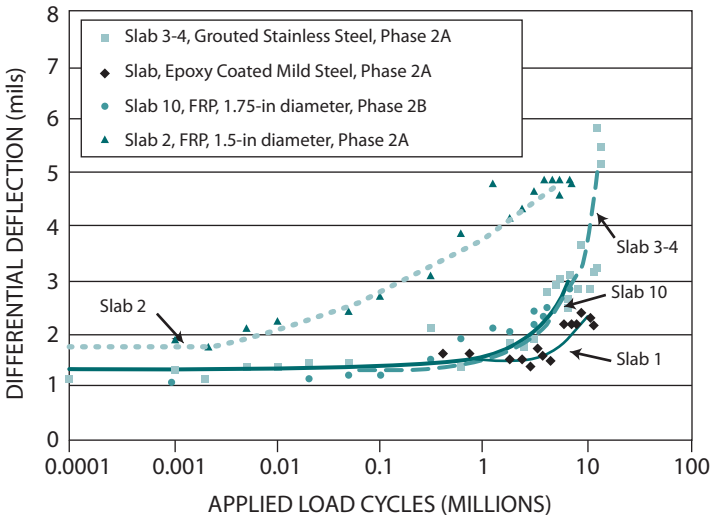

Figure F2. Differential deflection (loaded side of joint minus unloaded side of joint) for several dowel materials and diameters (7.5 in. PCC slab, 12 in. dowel spacing) (after Popehn et al. 2003)

The University of West Virginia is performing a congressionally mandated study of FRP dowels in jointed concrete pavement. This study includes analytic work as well as laboratory tests and field studies. While this study is continuing at present, the authors have published the results of tests conducted to date, which include LTE data after five million cycles of fatigue tests under simulated heavy truck traffic (Vijay et al. 2009). Some of the study findings to date include:

- Laboratory tests suggest that the performance of FRP-doweled joints was acceptable when the supporting foundation was in good condition, but that LTE values dropped to unacceptable levels (~ 50 percent, versus 90 percent for steel-doweled joints) when the foundation condition deteriorated. When joint widths increased from 0.25 in. to 0.4 in., FRP-doweled joint LTEs fell significantly (from 94 percent to 72 percent for 1 in. dowels at 6 in. spacing after two million load cycles).
- FRP dowels result in higher bearing stress, 56 percent higher dowel shear deflection, and 95 percent higher total dowel deflection than steel dowels when all other factors are held constant (1.5 in. diameter dowels spaced at 12 in.).
- Based on considerations of bearing stress using current analytical models, 1.5 in. FRP dowels should be spaced no more than 7.5 in. apart. Similarly, 1 in. FRP dowels should be spaced no more than 4 in. apart.
- Based on the location of dowel inflection points under load, length requirements for FRP dowels can be significantly reduced (e.g., to 11 in. for 1.5 in. FRP dowels or to 9 in. for 1 in. FRP dowels versus 17 in. and 13 in., respectively, for steel dowels).
- FRP dowels were generally found to provide adequate LTE values (greater than 75 percent) in the configurations evaluated (i.e., spacings less than 8 in.) when joint widths are 0.25 in. and foundation conditions are good.
- Some lab test specimens developed cracking away from the joint along the dowel edges.

Recommendations for further study include evaluation of the durability of FRP dowels and continuation of long-term monitoring of the field sections.

Based on the analytical, lab testing, and field records described above, it can be concluded that the use of FRP dowels in highway pavements should be approached with caution and that FRP load transfer system design requires the use of larger dowels and/or more closely spaced dowels in conjunction with good foundation support and narrow joint widths (i.e., short panel lengths) to produce joint systems that behave similarly to those constructed using metallic dowels.