# Technical Advisory

U.S. Department of Transportation
Federal Highway Administration

**Subject**

**Concrete Pavement Joints**

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| | **T 5040.30** |
| **Date:** | **January 2019** |
| **Responsible Office:** | **HIF** |

## 1. What is the purpose of this Technical Advisory?

This Technical Advisory contains guidance and recommendations relating to the design and construction of joints in jointed plain concrete pavements (JPCP).

## 2. Does this Technical Advisory supersede another FHWA Technical Advisory?

This Technical Advisory supersedes Federal Highway Administration (FHWA) Technical Advisory T 5040.30, Concrete Pavement Joints, dated November 30, 1990.

## 3. What information does this Technical Advisory Include?

This Technical Advisory provides information and guidance on the current state-of-the-practice regarding proper design and construction of joints in jointed concrete pavements.

## 4. How do concrete pavement joints affect pavement performance?

Concrete pavement joints serve one or more of several possible functions, including: control of cracking, provision of load transfer, isolation of structures that move or behave differently, and provision of lane or shoulder delineation. The placement of joints at appropriate locations is essential in preventing random pavement cracking.

Many jointed concrete pavement distresses either develop at the joints or are a result of improper joint design, construction, or maintenance. These distresses include faulting, pumping, spalling (due to any of several mechanisms), corner breaks, blowups, and mid-panel cracking (when caused by excessive joint spacing or improper joint construction).

The primary design, construction and maintenance factors that contribute to satisfactory joint performance include: the correct use of various types of joints, joint layout, the proper use of dowels (including size, location and alignment) and tie bars (including size and location), good concrete consolidation (especially around dowels and tie bars), proper joint cutting or forming techniques (including the timing, depth and width of saw cuts), and periodic inspection and maintenance of the joints (including the filler or sealant material, if used). Satisfactory joint performance also depends on the use of appropriate pavement design standards, quality construction materials, and good construction and maintenance procedures. Attention to all these factors is essential for producing pavement joints that will perform satisfactorily over the service life of the pavement.

## 5. Are there different types of concrete pavement joints?

Yes. Concrete pavement joints are commonly defined by their primary function (e.g., contraction or control joints, construction joints, isolation joints, and expansion joints). Within each of these types, they may be further described by their orientation (i.e., transverse or longitudinal). The most commonly used pavement joint types are defined and described below.

### a. Contraction or Control Joint

The most common type of joint in JPCP, typically created by sawing (in recently hardened concrete) a groove in the concrete slab to create a weakened vertical plane. This weakened plane is intended to control the location of slab cracking that develop due to the restraint stresses caused by moisture-related concrete shrinkage, thermal contraction, temperature curling and moisture warping. Contraction/control joints may be oriented transversely (i.e., perpendicular to the direction of traffic flow; see figure 1) or longitudinally (i.e., parallel to the direction of traffic flow; see figure 2).

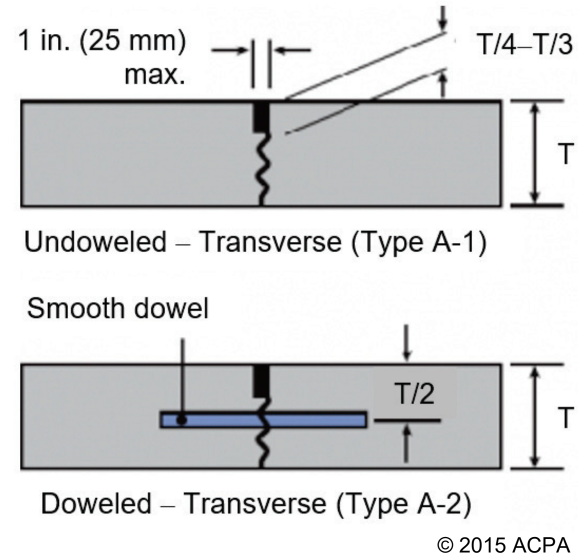


Figure 1. Example transverse contraction joint schematic (ACPA 2015).

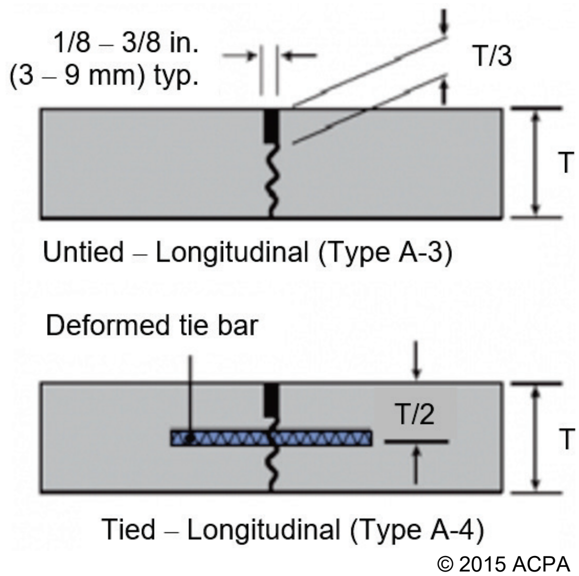


Figure 2. Example longitudinal contraction joint schematic (ACPA 2015).

**b. Construction Joint**

The joint that necessarily results from the placement of concrete next to hardened concrete without an effort to isolate the two placements. Construction joints may be oriented transversely (e.g., between consecutive paving placements in the same lane or lanes; see figure 3) or longitudinally (e.g., between adjacent lanes of pavement placed on different days; see figure 4). Transverse construction joints are typically placed at the end of each day of construction, but may also be used in the cases of weather- or equipment-related paving stoppages.

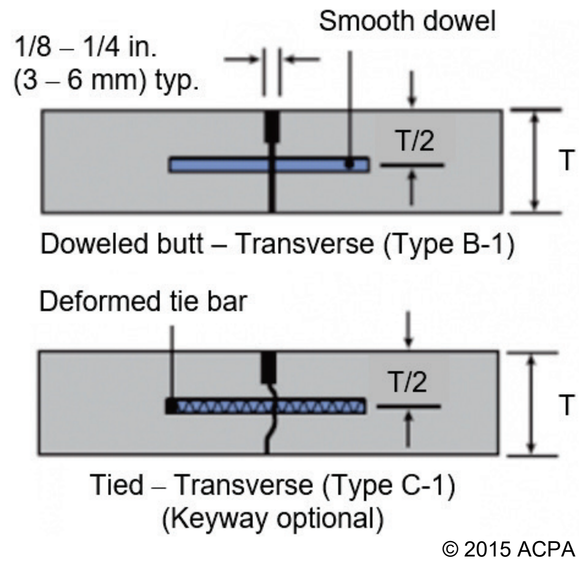


Figure 3. Example transverse construction joint schematic (ACPA 2015).

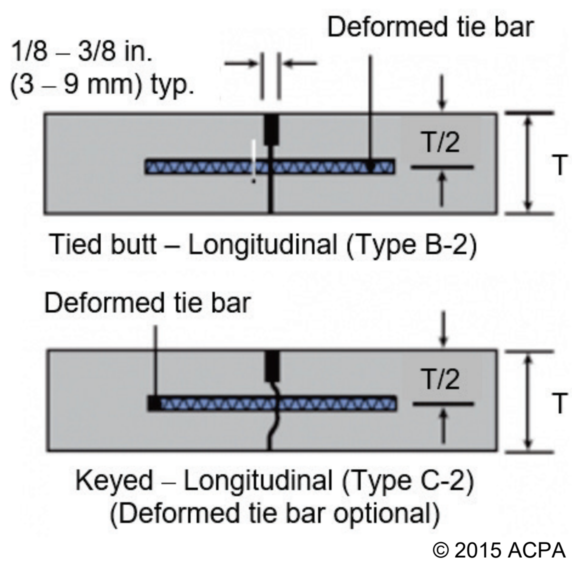


Figure 4. Example longitudinal construction joint schematic (ACPA 2015).

### c. Isolation Joint

A special-use joint placed between the concrete pavement and an adjacent pavement (e.g., an intersecting roadway) or other fixed structure (e.g., a median barrier) or embedded object (e.g., a manhole, utility riser, etc.) to allow the concrete pavement and the adjacent pavement, structure or embedded object to move independently in all directions without damage (see figures 5 and 6). Isolation joints typically include a full-depth compressible material and contain no load transfer devices, tie bars or other connections.

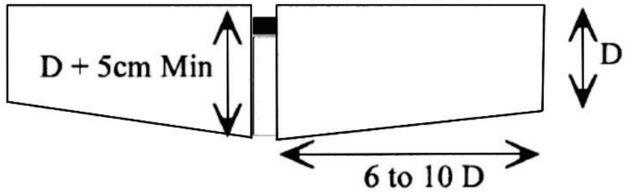




Figure 5. Example isolation joint schematic (with thickened edge) (ACI 2002).

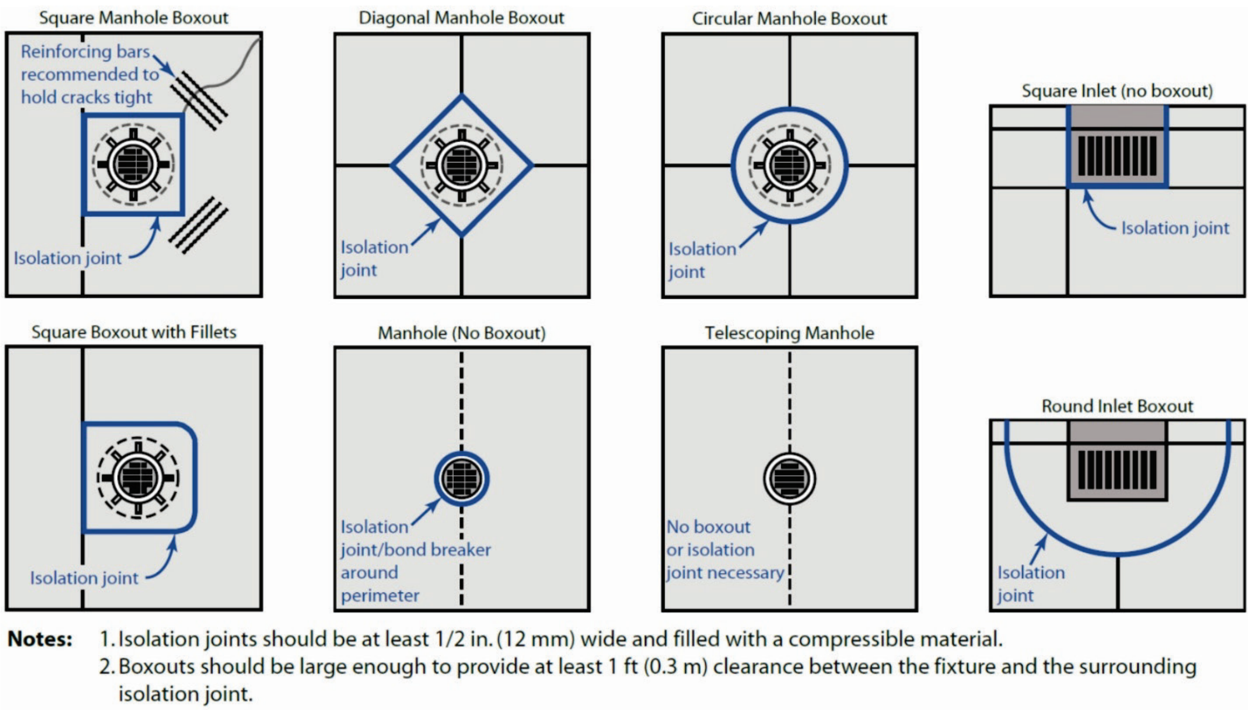




Figure 6. Example applications of isolation joints for embedded structures (ACPA 2007b).

**d. Expansion Joint**

A special-use joint that is constructed in new pavements to accommodate potential excessive slab expansion or movement without developing high compressive forces in the pavement that might otherwise result in joint spalling and blowups in the pavement or damage to adjacent structures (e.g., bridge decks and approach panels). Unlike isolation joints, which allow fully independent movement of adjacent structures, expansion joints typically include dowels or other load transfer devices and allow independent movement only in the direction of expansion (see figure 7). The overuse of expansion joints should be avoided because this may allow surrounding contraction joints to open over time, resulting in sealant or filler failure, infiltration of water and incompressibles, and loss of load transfer.

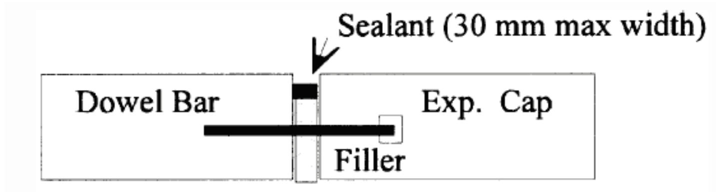


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Figure 7. Example expansion joint schematic (ACI 2002).

**e. Specialty Joints**

Joints designed for a specific purpose not previously described and less commonly used. The primary example is a joint that is used for transitions between concrete and asphalt pavements (see figure 8). A thickened pavement section may be used to help reduce edge stress levels that develop due to a lack of load transfer between the pavements. Other transition details are sometimes used, such as for the asphalt pavement to extend over a sloping and/or thinned concrete section to avoid the asphalt hump that sometimes develops at vertical transitions.

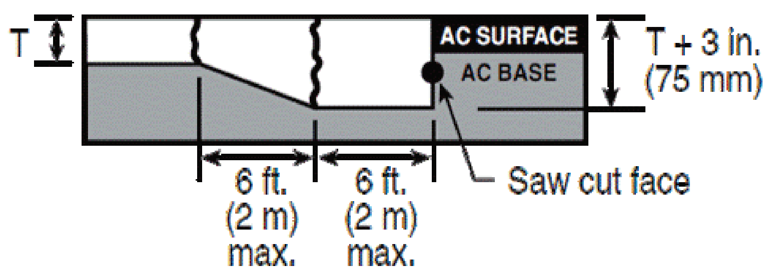


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Figure 8. Example "specialty" joint detail for transition between concrete and asphalt paving (ACPA 2015).

Concrete pavement joints can serve more than one function. For example, in addition to the primary functions listed above, joints may also provide load transfer or lane or shoulder delineation.

**6. Where should joints be located to control cracking?**

Uncontrolled cracking in JPCP generally can be avoided if:

- Longitudinal construction and contraction joints coincide with travel lane limits.
- Transverse construction and contraction joints are constructed perpendicular to the direction of paving at locations that line up across adjacent lanes and produce panels with appropriate dimensions (see 6a below).
- Independent adjacent structures (e.g., median barriers) are properly isolated from the pavement.
- Embedded structures (e.g., manholes) are isolated from the pavement structure and joint locations are adjusted to minimize the potential for cracking (see ACPA 2007a and ACPA 2007b for examples).

Experience in the United States has led to a general convergence of JPCP jointing practices around 15-ft panel lengths and 12-ft panel widths (except where the outside lane is striped at 12 ft but is constructed 13 to 14 ft wide to reduce edge stresses). However, some JPCP with panel lengths exceeding 15 ft have performed satisfactorily, and it may be necessary to use shorter panel lengths (and widths) when the designed slab thickness is less than 8 inches thick, especially when built on stabilized base. It is important to take local experience into account in designing panel size.

Joint spacing requirements depend on many factors, including: slab thickness, concrete characteristics (e.g., moisture and temperature response, strength, and elasticity), foundation support, and environmental conditions, as discussed below.

**a. Panel Dimensions: Limiting Maximum Size and Aspect Ratio**

Conventional panel dimensioning guidance for JPCP suggests that, to prevent uncontrolled panel cracking, the maximum panel dimension (in feet) should not exceed 1.5 to 2 times the slab thickness (in inches), or 18 to 24 times the slab thickness (non-dimensionally), with lower values selected for construction on higher-modulus (often stabilized) foundation materials and higher values chosen for placement on more compliant, lower-friction granular materials. In addition, the ratio of panel length and width should not exceed 1.5. For an 8-inch thick slab, for example, these guidelines would limit the maximum panel length to 12 to 16 ft, and the ratio of panel length-to-width for a 12-ft lane width would be 1.0 to 1.33, a range lower than the 1.5 limit.

Using these guidelines, thicker pavements could have significantly longer panels (especially when placed on softer, lower friction foundations), but experience and performance records have resulted in a cap of 15 ft on JPCP panel length to prevent spalling and panel cracking in many States.

Appropriate panel dimensions can also be developed using mechanistic-empirical tools that relate cracking to slab thickness, concrete properties, foundation properties and other factors. For example, research indicates there is a general relationship between the ratio of maximum panel length (L) to the radius of relative stiffness ($\ell$) and the development of panel cracking. The radius of relative stiffness is parameter that quantifies the relationship between the stiffness of the slab and the foundation as follows:

$$l = [\frac{Eh^3}{12k(1-\mu^2)}]^{0.25} \qquad \text{(Eq. 1)}$$

where:

$\ell$ = radius of relative stiffness, in

E = concrete modulus of elasticity, psi

h = slab thickness, in

k = modulus of foundation reaction (subgrade support), psi/in

μ = Poisson's ratio of the concrete, dimensionless

Research data indicate that transverse slab cracking increases when L/$\ell$ > 4.4 (ACI 2002), and the form of the model suggests that the maximum allowable panel length increases with increasing slab thickness and concrete stiffness, while it decreases with increased foundation stiffness.

The effects of joint spacing on pavement performance are considered directly in AASHTO Pavement ME Design. The AASHTO Pavement ME Design software considers the effects of many design, geometric, environmental, and traffic loading variables, including joint spacing, on the critical pavement responses (stress and deflection) to predict pavement performance.

In this approach, the joint spacing is typically selected based on the agency experience or policy, and the design analysis is conducted to determine the combination of slab thickness and design features that would satisfy the performance requirements for the specified material and site conditions.

Note that the guidelines above were developed to prevent uncontrolled cracking in unreinforced, cast-in-place concrete pavement, and the AASHTO Pavement ME Design software prediction models are also developed for JPCP. For jointed reinforced concrete pavement (JRCP), including precast concrete pavement systems, the panel length selection is based on policy, experience, economics and other factors, and the reinforcing system is designed for the given panel length to prevent the anticipated panel cracks from opening.

**b. Impact of Joint Spacing on IRI (Ride Quality) and Agency Costs**

Each transverse joint in JPCP has an associated construction cost (i.e., the cost of any included load transfer devices, joint sawing, and any joint filling or sealing) and an associated maintenance cost (e.g., periodic joint resealing, possible joint repairs, etc.). Therefore, the use of fewer joints (i.e., longer panels) may reduce agency life-cycle costs for the pavement.

However, the effects of concrete pavement curling and warping generally increase with increasing panel length. The use of longer panels may also adversely impact pavement ride quality under some conditions (e.g., in dry or cold climates for pavements with relatively high coefficients of thermal expansion and contraction). This reduced ride quality may drive higher user costs and/or earlier and more frequent diamond grinding of the pavement surface. More closely spaced joints can also adversely affect ride quality and tire/pavement noise.

**c. Use of “Random” Joint Spacing**

The use of “random” joint spacing (typically a repeated pattern of four panel lengths, e.g., 12-13-18-17 ft) has been used (often in conjunction with skewed joint orientation) to eliminate roughness patterns from uniform panel lengths that might cause harmonic vehicle responses, resulting in exceptionally poor ride quality. This type of joint pattern is no longer recommended due to concerns with constructability and performance. In addition, properly constructed conventional 15-ft JPCP panel lengths do not seem to generally produce severely objectionable ride quality.

**d. Matching Transverse Joint Locations in Adjacent Lanes**

Transverse joint locations should be matched across all pavement lanes (including concrete shoulders), particularly if the adjacent lanes are to be tied together, to ensure that joint movements in one lane are not restrained by the adjacent lane. When transverse joints are not aligned across adjacent lanes, cracks often propagate from working joints across the adjacent lane panels (see figure 9) unless the panels are isolated from each other (typically by eliminating tie bars and providing foam board sheets or other isolation material along the longitudinal joint) between the two transverse joints to allow unrestrained movement due to thermal expansion and contraction along the longitudinal joint. Additional steps may be necessary during construction to prevent restraint-related cracking when adjacent lanes are constructed at significantly different times (e.g., in different construction seasons), as described under Question 13 of this advisory.



Figure 9. Propagation of crack due to misaligned transverse joints.

### e. Longitudinal Joints Within Travel Lanes

Longitudinal joints generally should coincide with pavement lane lines whenever feasible because it is believed that traffic flow is improved by limiting the chances of driver error in mistaking a longitudinal joint for a lane line. However, it is sometimes necessary (and even desirable) to locate longitudinal joints away from the pavement lane lines. Common examples include:

- The use of travel lanes that are constructed wider than normal and striped at normal lane width to prevent wheel loads from traveling along the joint or the pavement edge, thereby reducing critical edge stresses.
- The addition of longitudinal joints down the center of slip ramps and loop ramps that have widths significantly greater than 12 ft (to avoid uncontrolled longitudinal cracking).
- The use of small pavement panels (typically 6 ft square) on thin concrete pavements (particularly concrete overlays, but including new thin pavement construction as well).

Less common situations include the need to place longitudinal construction joints within travel lanes due to construction staging requirements in tightly constrained work areas. In these cases, particular attention must be paid to the structural design of these joints (i.e., edge support conditions provided by tie bars, dowels, keyways, etc.) when they are located within or near the wheel paths.

### f. Joint Layout

The basic guidance on jointing provided above is not sufficient for developing good joint layouts for atypical (but common) paving plans, such as intersections, roundabouts, cul-de-sacs, lane adds and drops, and diverging diamond interchanges. In addition, it is often necessary to adjust standard joint layout patterns to accommodate embedded structures (e.g., manholes, drainage inlets, utility access ports, etc.) in a manner that avoids creating weakened sections that will crack easily.

Joint layout plans should be developed and reviewed prior to commencing paving, especially for projects or project areas with non-standard jointing requirements. ACPA has developed several resources that provide multi-step procedures for developing joint layouts for specific situations as well as guidance in making necessary joint adjustments (ACPA 2007a; ACPA 2007b; ACPA 2016b). Reasonable field adjustments to the joint layout plan should be allowed during construction (e.g., to accommodate changed conditions).

**7. What should be considered in the design of transverse contraction joints?**

The primary design considerations are:

- Selection of joint locations.
- Selection and design of the load transfer system.
- Determining the depth of saw cut, tooling, joint former or other device to initiate cracking.
- Designing an appropriate system for filling or sealing the joint (if that is to be done).

Panel size and joint location considerations are discussed in Question 6; timing and depth of saw cuts are discussed in Question 13; and the design and construction of sealed and filled joints are presented in Questions 20 and 21. Thus, the response to this question focuses on the selection and design of load transfer systems.

**a. The Need for Load Transfer**

Traffic loadings must be effectively transferred from one slab to the next to reduce edge and corner deflections and stresses, and to help ensure satisfactory pavement performance by preventing the development of certain distresses (e.g., pumping, faulting, cracking and corner breaks).

Figure 10 illustrates the concept of deflection-based load transfer efficiency (LTE), which is commonly computed as the ratio of the deflections on the unloaded and loaded sides of a joint when the load is placed adjacent to the joint (generally either in a wheel path or at a slab corner). Joint deflections are easily measured and can provide an indication of the effects of load transfer systems on pavement performance. Slab stresses cannot be measured directly, but can be estimated or computed and are highly correlated with deflections.

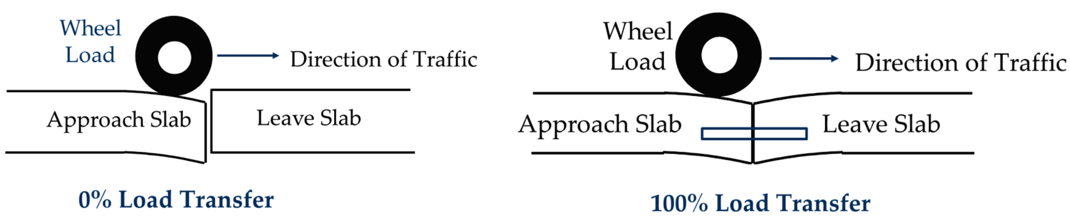




Figure 10. Computation of deflection-based load transfer efficiency (NHI 2001).

Pavement foundation stiffness influences the magnitude of pavement deflections and LTE values, but has little impact on the actual mechanisms of joint load transfer, which are better indicated by the difference in deflections across the joint.

The two principal mechanisms for transferring loads across transverse joints in concrete pavements are aggregate interlock and mechanical load transfer devices (generally smooth-surfaced dowel bars), which are discussed below.

$$\mathrm{LTE}(\%) = \frac{\mathrm{Deflection}_{\mathrm{UNLOADED}}}{\mathrm{Deflection}_{\mathrm{LOADED}}}\ X\ 100 \qquad \text{(Eq. 2)}$$

**b. Aggregate Interlock**

Aggregate interlock load transfer is achieved through shear at the irregular faces of the crack that forms beneath the sawed or formed portion of the joint, as shown in figure 11. The degree of load transfer that can be achieved by this mechanism depends on many factors, including: the gradation, hardness and angularity of the aggregate (large, durable, angular aggregate is desirable); concrete mixture proportions (more aggregate is better); concrete strength at the time of joint activation; whether the crack face is vertical or sloped; width of the joint at the fractured concrete face; and more. Of these factors, the joint width may be most important because the degree of interlock and shear capacity decreases rapidly as joint width increases above 0.03 inches. In addition, repeated heavy traffic loadings can abrade and smooth the texture of the joint face, resulting in a loss of load transfer efficiency over time. Therefore, it is recommended that reliance on aggregate interlock without dowels for load transfer only be considered for low-volume local roads and streets that carry few heavy trucks in areas with moderate climate (to avoid large joint openings in cold weather). Low-volume roadways may be considered as those carrying fewer than 100 trucks per day.

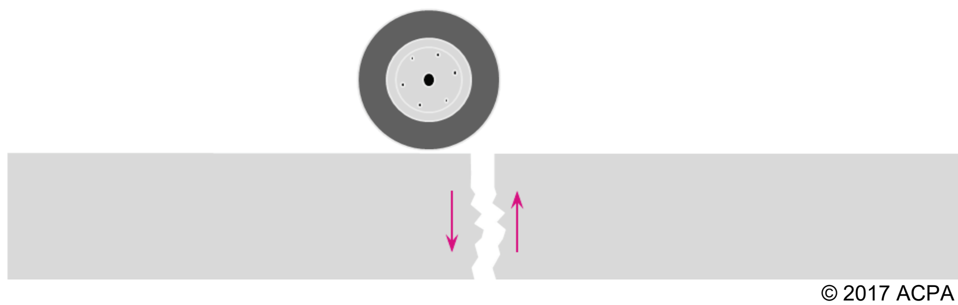


Figure 11. Illustration of aggregate interlock load transfer mechanism (Snyder 2017).

**c. Dowel Load Transfer Systems**

The purpose of dowels is to transfer loads across a joint without restricting joint opening and closing in response to daily and seasonal changes in temperature and moisture conditions, which cause the slabs to expand or contract. Studies indicate that the use of dowels is beneficial for all conventional jointed concrete pavements in providing load transfer and maintaining the horizontal and vertical alignment of the slabs. The use of dowel bars is recommended for all roadways.

*i. Conventional U.S Practice*

The conventional practice in the United States has evolved to the use of 18-inch long cylindrical carbon steel dowels with diameter that is at least 1/8 of the pavement thickness (often, 1.25 inches for pavement thickness of 10 inches or less and 1.5 inches for thicker pavements) and placed 12 inches apart across the joint at mid-depth of the slab (see figures 12 through 14).

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Figure 12. Conventional dowel placement, 12 dowels per lane.

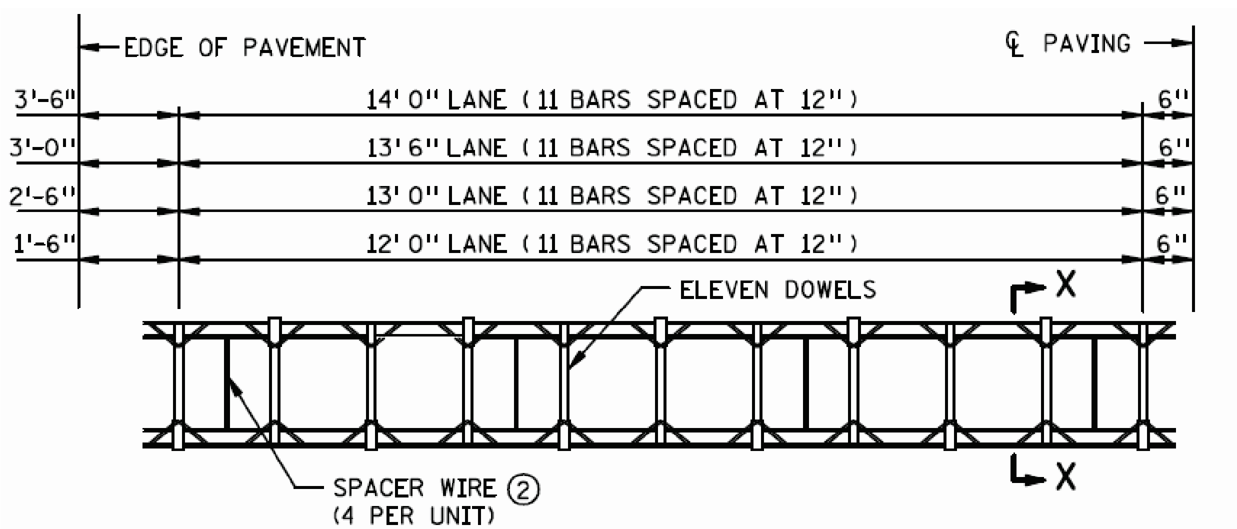


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Figure 13. Schematic of conventional contraction joint dowel placement with 11 dowels per lane to reduce potential for conflicts between edge dowels and paving machine.



Figure 14. Use of 11-dowel baskets in Minnesota.

*ii. Tied and Widened Lanes and Tied Shoulders*

The use of widened outside lanes (e.g., a 14-ft wide lane that is striped at 12 ft) is typically considered to be a structural enhancement for preventing transverse panel cracking due to edge stress fatigue. However, the use of a widened lane also provides the opportunity to provide additional dowels in the transverse joint using the same dowel spacing, thereby increasing the number of dowels that transfer the outer wheel load across the joint. This reduces the critical dowel-concrete bearing stress and reduces differential joint deflections, which should improve pavement performance potential. The use of tied longitudinal joints between travel lanes and concrete shoulders provides a similar benefit.

*iii. Alternate Dowel Load Transfer Systems*

Recent analytical research and innovations in dowel bar designs and materials are leading to a much broader range of practices that include the use of:

- Alternate dowel materials (e.g., glass fiber-reinforced polymer (GFRP), stainless steel and other metallic alloys, etc.).
- Alternate dowel shapes (e.g., hollow dowels, sleeved or clad cylindrical dowels, a wide range of flat plate dowel shapes, and dowels with reduced length).
- Nonuniform spacing of dowels along the joint, often more concentrated in the anticipated wheel paths (see figures 15 and 16).

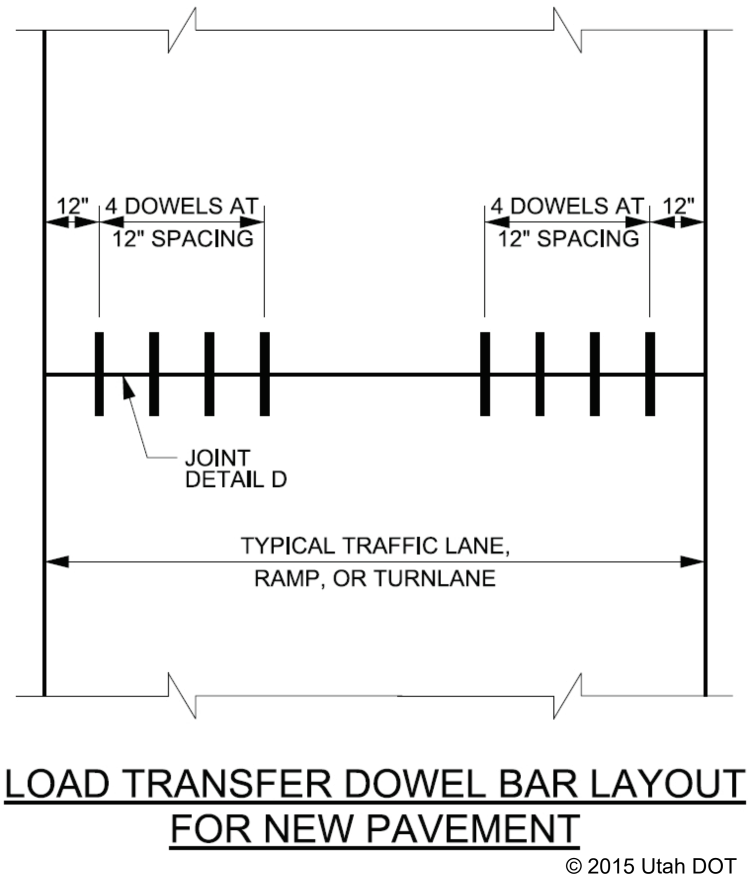


Figure 15. Utah DOT standard dowel bar layout (4 dowels per wheel path).

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Figure 16. Illinois State Toll Highway Authority use of 5-dowel “mini-baskets” in each wheel path.

These newer materials, shapes and spacing arrangements are being driven by competitive efforts to reduce initial material costs (through the use of more efficient sections and systems), to provide improved dowel corrosion resistance and durability, and/or to provide lower resistance to joint opening and closing (through tapered sections and lower-friction coatings) without sacrificing potential pavement performance. The potential performance of any dowel load transfer system design should be verified by field or laboratory evaluations before use (Snyder 2011).

iv. *Dowel Corrosion Protection*

Any dowel load transfer system used in concrete pavements must have sufficient corrosion resistance to withstand the environment in which it will be used over the projected performance life of the pavement structure. Dowels with damaged barrier-type corrosion protection systems (e.g., nicks or cuts in coatings of plastic or epoxy) with nicks or cuts must be repaired to restore the barrier before paving. It is not necessary to coat the ends of the dowels.

**8. What should be considered in the design of longitudinal contraction joints?**

Longitudinal contraction joints are induced in concrete pavement to control the locations of cracks that might otherwise form due to the restraint of temperature- and moisture-related movements (i.e., shrinkage, thermal contraction, curling and warping). When possible, longitudinal contraction joints are generally cut at locations that coincide with (or are close to) pavement lane lines to facilitate lane delineation and traffic control. Longitudinal contraction joints should not be confused with longitudinal construction joints, which are the result of adjacent placements of concrete pavement (although these two joint types share many design features and functional characteristics).

The primary design considerations for longitudinal contraction joints are:

- Selecting of joint locations.
- Selecting and designing the load transfer system.
- Determining the depth of saw cut, tooling, joint former or other device to initiate cracking.
- Designing an appropriate system for filling or sealing the joint (if that is to be done).

Aspects of panel size and joint location pertaining to prevention of panel cracking are discussed in Question 6, but longitudinal joint location and panel width can also impact transverse joint behavior and other aspects of pavement performance. Widened outside lanes (and tied concrete shoulders) can be used to move vehicle loads farther from unsupported pavement edges and provide additional dowels for transferring critical loads, thereby reducing critical dowel-concrete bearing stresses and differential joint deflections. Tied concrete shoulders can be used to similar benefit. These are very important options to consider for roads that will be subjected to very high volumes of heavy traffic loads over their service lives.

Considerations for the timing and depth of saw cuts are discussed in Question 13, and the design and construction of sealed and filled joints are presented in Questions 20 and 21. Thus, the rest of the response to this question focuses on the selection and design of load transfer systems for longitudinal contraction joints.

**a. Load Transfer**

Load transfer at longitudinal contraction joints is achieved mainly through aggregate interlock, which is effective only if the joint remains tightly closed. Tie bars are generally recommended to ensure that the joints remain tight, although they may be omitted for very low volume roadways or those that are laterally confined (by curb and gutter, for example). Tied contraction joints are sometimes referred to as “hinge joints” because they allow a small amount of rotation helping to ensure resistance to relative vertical and horizontal of the panels on either side of the crack.

### b. Tie Bar System Design Considerations

#### *i. How many lanes can be tied together?*

Longitudinal joints should be tied to prevent lane separation and/or faulting and to maintain the aggregate interlock. It is commonly recommended that no more than three lanes (including the concrete shoulder) be tied together (ACI 2002). ACPA (1992) has recommended limiting the width of tied roadway to about 48 ft based on subgrade drag theory, but notes that there has been good field performance in some instances with up to 70 ft of tied pavement. Mallela et al. (2009) concluded that concrete stresses do not increase significantly when three or more lanes are tied together, and experience in some States suggests that at least four lanes can be tied together without inducing uncontrolled longitudinal cracking.

#### *ii. How are tie bar systems designed?*

Tie bar size, spacing and length can be designed taking into account pavement thickness, the number of lanes being tied together, the location of the joint in question and its distance to the nearest free (or untied) pavement edge, the foundation stiffness, the properties of the concrete and steel, and the environment in which the pavement is being constructed. AASHTO (1993) and NCHRP (2004) provide relatively simple approaches to tie bar system design (bar diameter and spacing) that are based on the force required to pull the pavement across the foundation. ACPA (Mallela et al. 2009) provides a more complex mechanistic-empirical approach to tie bar system design that considers the physical and mechanical properties of the pavement system components and the effects of local temperature and moisture conditions on stresses in the steel.

Although tie bar size and spacing requirements can vary significantly on a given project (joints that are closest to free edges require less tie bar reinforcing than those that are farther away), the design for the joint farthest from a free edge is commonly used for all longitudinal joints to simplify construction. A typical tie bar system design may include Grade 40 or 60 steel, #4 or #5 bars (1/2 or 5/8 inches diameter) on 30-inch centers, which results in 4 or 5 tie bars per longitudinal joint in a 15-ft panel.

It is important to design the tie bar system (using one of the procedures described above) rather than to use a single standard design for all pavements to avoid potential pavement performance problems. For example, the use of Grade 60 #5 bars on 30-inch centers may be appropriate for a 13-inch concrete pavement on granular base. The same tie bar design used in a 6-inch concrete overlay or city street may prevent the joint from activating, resulting in a longitudinal crack near the ends of the tie bars (see Figure 17). Similarly, a tie bar design developed for a relatively thin two-lane pavement may be inadequate for holding tight the middle longitudinal joint of a thick four-lane pavement.

Tie bars should not be placed within 6 inches of the ends of transverse joint dowels (i.e., within 15 inches of transverse joints when 18-inch long dowels are used) to avoid corner spalling and other potential interference effects (ACPA 2015). Depending on panel length and required tie bar spacing, it may be necessary to reduce tie bar spacing slightly to provide the required number of tie bars in each panel while avoiding conflicts with transverse joint dowels.

Tie bar length is generally selected to develop the allowable working strength of the tie bar using equations such as can be found in AASHTO (1993) and ACI (2002). These equations typically result in the use of tie bar lengths of 24 to 30 inches. Shorter lengths may provide acceptable service if the design does not require the full working strength of the steel.

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Figure 17. Photo of longitudinal cracking off ends of oversized tie bars in bonded concrete overlay of asphalt pavement in Iowa with widening (original pavement joint under longitudinal joint nearest stripe) – revised design calls for 1/2-in maximum tie bars in similar cases.

iii. *Must tie bars be installed at mid-depth of the slab?*

Tie bars should generally be installed at mid-depth to maximize concrete shear capacity above and below the bar. However, some deviation in placement depth may be desirable for improved constructability (e.g., in super-elevation areas where cross slope of the new pavement surface will be greater than that of the supporting layer such that the use of baskets results in placements greater than mid-depth and the use of inserters results in placements less than mid-depth). Experience indicates that placement within 2 inches of mid-depth will result in good performance provided at least 3 inches of cover is maintained and the bars are not tilted (Khazanovich, Hoegh, and Snyder 2009). Even greater deviations from mid-depth may be possible (particularly in thick pavements or in concrete overlays of asphalt pavements [Harrington and Fick 2014]), but the shear capacity of critical concrete above or below the tie bar should be evaluated with respect to the tie bar capacity or expected tensile load. When the tie bars are placed significantly above the mid-depth of the slab, adequate cover must be verified to ensure that the bars will not be cut during the sawing of the longitudinal joint,

iv. *What about corrosion protection?*

In areas where deicing salts are commonly used, the use of corrosion-resistant tie bars (e.g., epoxy-coated tie bars) is recommended. Corrosion can reduce the structural adequacy of tie bars.

**9. How are dowel and tie bars typically installed in joints?**

Dowels and tie bars can be pre-placed using basket assemblies and chairs (see figure 18), or may be mechanically inserted in the plastic concrete by a component of the paving train (e.g., a dowel bar inserter [DBI] or tie bar inserter [TBI], as shown in figures 19 and 20, or a side bar inserter [SBI], as shown in figure 21). The placement or insertion must be performed so that the devices are properly positioned and aligned within acceptable tolerances (particularly for dowels) to ensure proper location relative to the joint (for adequate embedment on each side of the joint after sawing or forming) and to function as intended. Basket assemblies, chairs and insertion devices all offer the potential for adequate placement accuracy when used properly. The measurement and evaluation of dowel location and alignment are discussed later in this advisory.



Figure 18. Dowel baskets on grade before paving.

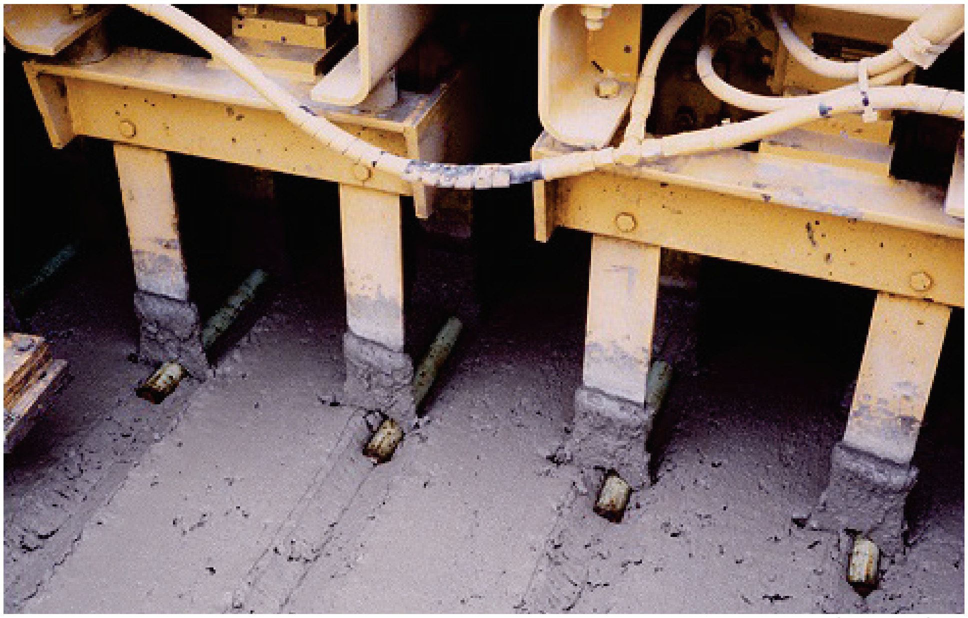




Figure 19. Typical dowel bar inserter (DBI) system (ACPA 2018).



Figure 20. Typical vertical tie bar inserter (TBI) system.



Figure 21. Typical side bar insertion (SBI) system.

Dowel baskets are typically welded wire assemblies that provide a stable base and support system for the included dowels. They must also be designed to withstand transport, handling, and placement conditions. Recommendations for standardized dowel basket wire sizes, basket height and anchoring requirements can be found in Snyder (2011).

Dowel baskets must be securely anchored to the grade using the correct type and length of anchor device (suitable types and lengths vary with subbase type) to prevent their movement during paving operations. Recommendations for dowel basket anchoring have been provided by Voigt and Ferrebee (2016) and include:

- Longer basket anchor pins or stakes are typically necessary for weaker subbase or subgrade materials.
- Practices vary with State requirements and contractor preferences, but a minimum of eight fasteners is typically used for a standard 10- to 12-ft lane. Weaker subbases and subgrades may require additional fasteners while stabilized subbases may require only six fasteners.
- Fasteners should be evenly spaced with half being placed on each side of the basket, with the placement of anchor pins on the leave side of the basket wires to help prevent pushing of the basket in the direction of paving by the concrete head.
- Additional strategies for ensuring that baskets remain secured during placement include avoiding the discharge of concrete directly on the baskets and using additional basket bracing devices.

Basket shipping wires add stability to the assemblies and are typically small enough that they do not need to be cut (to reduce joint restraint) after the basket is anchored to the subbase. However, these wires reduce the ability of some pulse-induction-type dowel alignment measurement devices to accurately locate the dowels; therefore, the shipping wires may need to be cut when the use of those devices is planned.

A stable, workable concrete mixture is also essential for helping to ensure good dowel alignment. Stiff, unworkable mixtures that flow poorly exert higher pressures on dowel baskets and anchoring systems, making them more susceptible to displacement during paving operations. Unstable mixtures that are highly plastic when vibrated may result in translation or rotation (or both) of dowels placed using DBIs.

DBIs and tie bar insertion devices must be well maintained (e.g., all bar feed, distribution and insertion equipment functioning properly) and properly set up for installation at the correct locations and to the correct depth. When properly set up and operated with a good paving mixture, DBIs ensure acceptable dowel positioning and alignment.

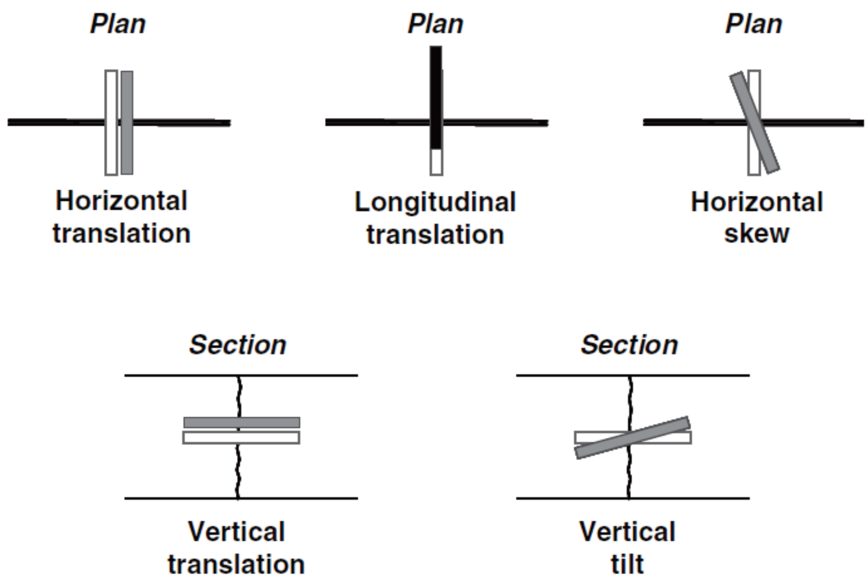
Tie bars across longitudinal joints should not be placed or inserted within 15 inches of doweled transverse joints (ACPA 2008; ACPA 2015); closer placements may result in transverse joint restraint, lockup and corner spalling.

Tie bars and dowel bars may also be anchored in holes drilled in hardened concrete using epoxy or cementitious mortar anchor materials. This is not typical construction practice, but is sometimes necessary due to construction staging and other issues.

### 10. What is the impact of dowel alignment and location on concrete pavement performance?

Dowel bars should be placed parallel to both the pavement surface and the longitudinal axis of the pavement to minimize restraint of the transverse joints. Dowels are typically placed at mid-depth of the concrete and the joint is sawed or formed over the longitudinal center of the dowel. Dowels are typically spaced 12 inches apart either over the entire length of the joint or may be placed in clusters of 3, 4 or 5 that are centered over the wheel paths (as illustrated previously in figure 15).

Dowel alignment and location quality can be characterized in terms of five measures, as illustrated in figure 22: horizontal translation, vertical translation, longitudinal translation (also called “side shift”), horizontal skew and vertical tilt.




Source: FHWA

Figure 22. The five types of dowel bar misalignment and mislocation (FHWA 2007a).

The alignment of dowel bars (i.e., **horizontal skew and/or vertical tilt**) is important because significant misalignment of dowel bars in a doweled joint may prevent that joint from properly opening/closing. Isolated joints that do not open/close effectively will not necessarily result in a mid-panel crack or another pavement defect, but the risk of panel cracking and joint distress increases with each successive joint with limited opening/closing capabilities (FHWA 2007a). In extreme cases, badly misaligned dowels may cause joint spalling (figure 23) or may extend through the pavement surface (figure 24). **Longitudinal translation or "side shift"** must be limited to ensure that dowels are sufficiently embedded on both sides of the joint to provide adequate long-term load transfer. **Vertical translation or "depth deviation"** must be limited to ensure that there is enough concrete over the steel to mitigate the corrosion of uncoated steel dowel bars and to prevent the development of shear cracking or spalling above or below the dowels as loads are transferred across the joint. **Horizontal translation** is of concern when a dowel is located far enough from its intended location that loads are redistributed and joint performance may be affected.



Figure 23. Photo of joint spalling caused by misaligned/mislocated dowel.

Source: FHWA

Figure 24. Misaligned dowels causing surface distress (Voigt and Ferrebee 2016).

Recent research has found no clear relationships between moderate levels of dowel misalignment or mislocation and pavement performance (in terms of joint faulting, spalling or panel cracking. However, laboratory testing and analytical models suggest that dowel misalignment can reduce load transfer capabilities (Khazanovich, Hoegh, and Snyder 2009). Based on these findings, it is recommended that dowel alignment and location acceptance tolerances be relatively tight and established at levels that are achievable with reasonably good construction practices Also, since limited amounts of misaligned bars are tolerable, specification requirements based on percent-within-limits may be appropriate for dowel bars on a joint-by-joint basis (e.g., using Joint Scoring concepts).

**11. Is guidance available concerning the specification, measurement and evaluation of dowel alignment?**

Before the early 2000s, no major studies of the relationship between dowel alignment/position and long-term pavement performance had been performed so there was no well-documented basis for developing realistic specifications concerning dowel alignment and location. Dowel positioning and alignment specifications at that time were often not strictly enforced because it was difficult to quickly and accurately measure dowel position and alignment. Guidance and specifications from this time frame may be unrealistic and should be used with caution.

There are now several devices that can be used to measure and report the position and alignment of dowel bars using magnetic imaging tomography (MIT), ground penetrating radar (GPR), and ultrasonic technologies (figures 25 through 30). The most commonly used device is the MIT-SCAN2-BT, a magnetic imaging tomography device that can be used to measure the position and alignment of all dowels in a joint (FHWA 2007a).

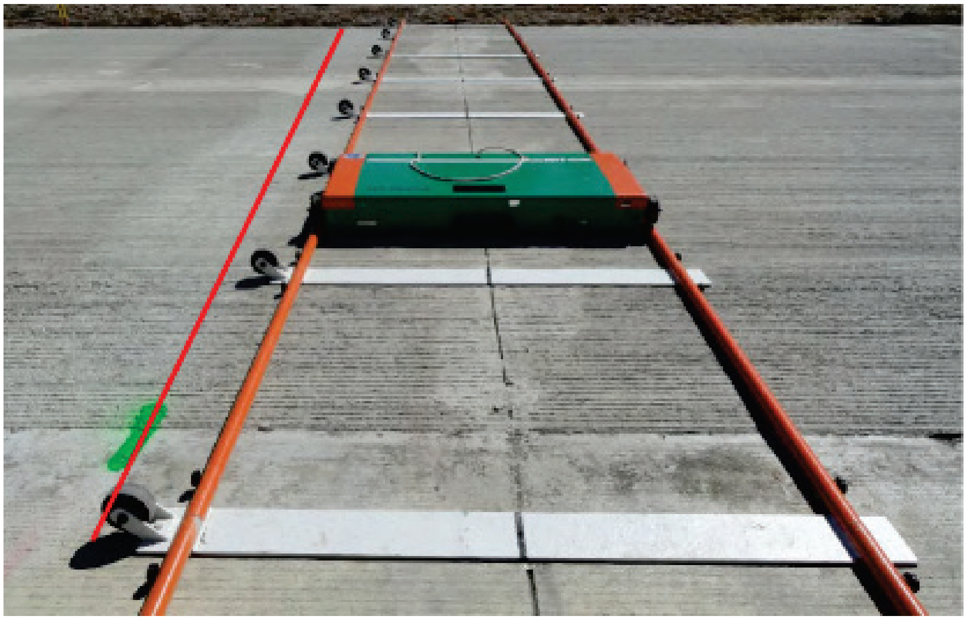




Figure 25. MIT-SCAN2-BT device.

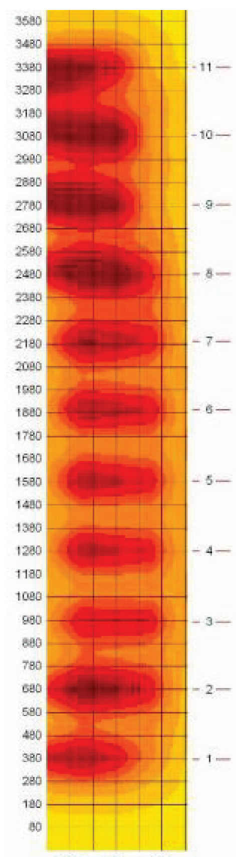





Figure 26. Example dowel imaging output from MIT-SCAN2-BT.



Figure 27. Example ground-penetrating radar device for pavement and bridge deck applications.

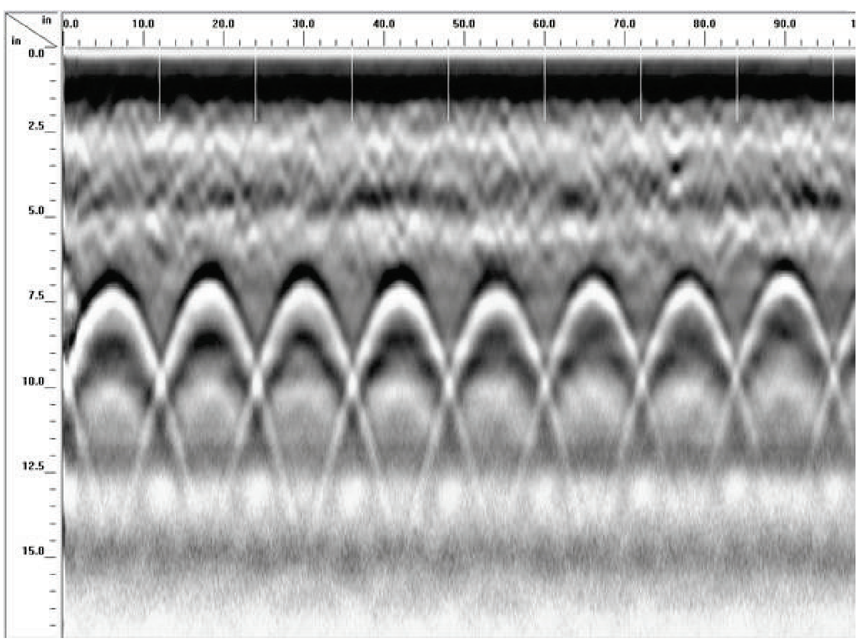





Figure 28. Example ground-penetrating radar output images – parabolas indicate dowel locations and elevations.



Figure 29. MIRA ultrasonic testing device.

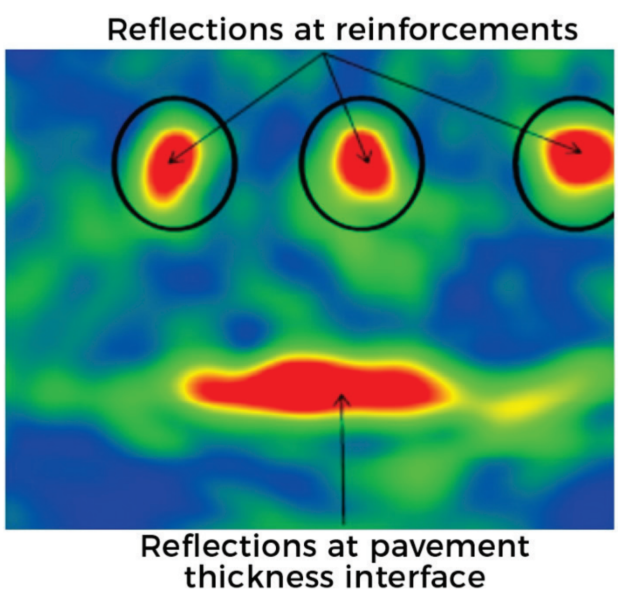





Figure 30. Example MIRA ultrasonic testing output image.

The MIT-SCAN2-BT device has been used in two nationwide studies of dowel alignment (Yu 2005; Khazanovich, Hoegh, and Snyder 2009), as well as several local studies. Information from these studies has been used to develop improved specifications and requirements for dowel alignment.

One example is the Ministry of Transportation of Ontario (MTO) dowel alignment specification, which establishes different acceptance and rejection criteria for various dowel alignment measures along with lot-based percent within limits (PWL) pay adjustments to encourage construction practices that result in better dowel placement (Lane and Kazmierowski 2006). More recently, ACPA developed a complete dowel bar alignment guide specification that has been used as a basis for specifications on several projects and which has been modified and refined as a result of those implementation experiences (ACPA 2016a).

FHWA (2007a) recommends that dowel placement specifications be developed by: 1) establishing reasonably constructible acceptance criteria (i.e., relatively tight alignment tolerances that should be easily met with good construction practices); 2) establishing rejection criteria based on the expected impacts of misalignment and mislocation on pavement performance; and 3) establishing a PWL criteria for dowels that fail to meet acceptance criteria but also do not exceed rejection criteria.

## 12. What is the impact of tie bar alignment and location on concrete pavement performance?

Tie bars in longitudinal contraction or construction joints should be placed parallel to the pavement surface and perpendicular to the plane of the longitudinal joint. Tie bars are typically placed at mid-depth of the concrete with the center of the bar coinciding with the joint location.

Tie bar alignment and location quality can be characterized similarly to the way that dowel alignment and location are described with translation in each of three directions and rotational misalignment both vertically (tilt) and horizontally (skew).

The alignment of tie bars (i.e., horizontal skew and/or vertical tilt) has little impact on pavement performance as long as the misalignment does not result in shallow cover of the tie bar (e.g., one end near the pavement surface where it could cause surface spalling) because the deformed bars are designed to hold the joint tight and additional restraint due to misalignment only serves to reinforce that behavior. It should be noted that some States allow the installation of construction joint tie bars with up to a 45-degree bend at the joint, and retrofit tie bars (i.e., cross-stitch bars) are commonly installed across longitudinal joints and cracks at angles of up to 45 degrees.

*Longitudinal translation* (along the length of the tie bar) must be limited to ensure that the bars are sufficiently embedded on both sides of the joint to develop the design capacity of the bar (typically 75 percent of the yield strength) or at least the required capacity based on the distance to the nearest free edge and the friction or bond between the slab and the underlying foundation layer (”subgrade drag”, as described under Question 8). Inadequate embedment may result in tie bar pullout and opening of the joint, along with other distresses that may result from the loss of edge support and entry of water and incompressibles.

While it is not essential that tie bars be located exactly at mid-depth of the slab, *vertical translation or depth deviation* must be limited to ensure that there is enough concrete over the steel to mitigate the corrosion of uncoated steel tie bars and to prevent shear failure in the concrete (with subsequent pullout of the tie bar). Adequate cover is also essential to ensure that the bars are not cut during the sawing of the joints. In general, 3 inches or more of concrete cover is desirable.

Modest amounts of *horizontal translation* (along the length of the longitudinal joint, up to several inches) are of little concern in terms of joint behavior and pavement performance, although the required amount of steel per joint should be maintained and the maximum distance between tie bars should not exceed 48 inches.

## 13. What are the best practices for constructing contraction joints in concrete pavements?

The best-designed joint systems will not perform to their potential and pavement life may be significantly shortened without proper construction. Good joint construction practices can be grouped into three phases: pre-paving, paving and joint sawing. Details concerning joint sealing practices are discussed in Questions 20 and 21.

The following is an overview of selected key considerations and "best practices" for constructing concrete pavement joints. Expanded discussions and additional considerations, details, and recommendations are available elsewhere (ACPA 2008; ACPA 2010; ACPA 2015; FHWA 2007b; Taylor et al. 2012).

### a. Pre-paving

When pavements are constructed on lean concrete base (LCB) or similarly stiff stabilized base material, cracks may exist (or develop) in the base and reflect to the pavement surface. This reflective cracking can be prevented by placing a nonwoven geotextile fabric separator layer between the base and concrete pavement.

Load transfer dowels should be lightly coated with a suitable bond-breaker material (e.g., form oil or a very thin layer of grease) over their entire length. Thick coatings of grease or graphite may result in large voids in the concrete surrounding the dowels, which may reduce their effectiveness.

When using dowel basket assemblies, the condition of the baskets should be checked before placement to ensure that the baskets are undamaged and the dowels are properly aligned. Basket assemblies and tie bar support chairs (if used) must be securely anchored to the base to ensure that the dowels and tie bars remain properly positioned and aligned throughout the paving operation. Secure anchoring requires the use of the correct type, length and number of anchors, as described by Voigt and Ferrebee (2016). Basket transport tie wires do not need to be cut for performance reasons (ACPA 2005). See Question 9 for more details.

The tying of new concrete pavement to jointed concrete pavement that is older (even by only a few months) may result in the development of cracks in the older pavement (see figure 31) or crushing of the new concrete if the old pavement joints are open at the time of paving (causing the new pavement to restrain slab expansion in old pavement). Minimize the width of joint opening in the older pavement (e.g., minimize the time between placements or pave during warmer weather) when paving new adjacent tied paving lanes or shoulders.

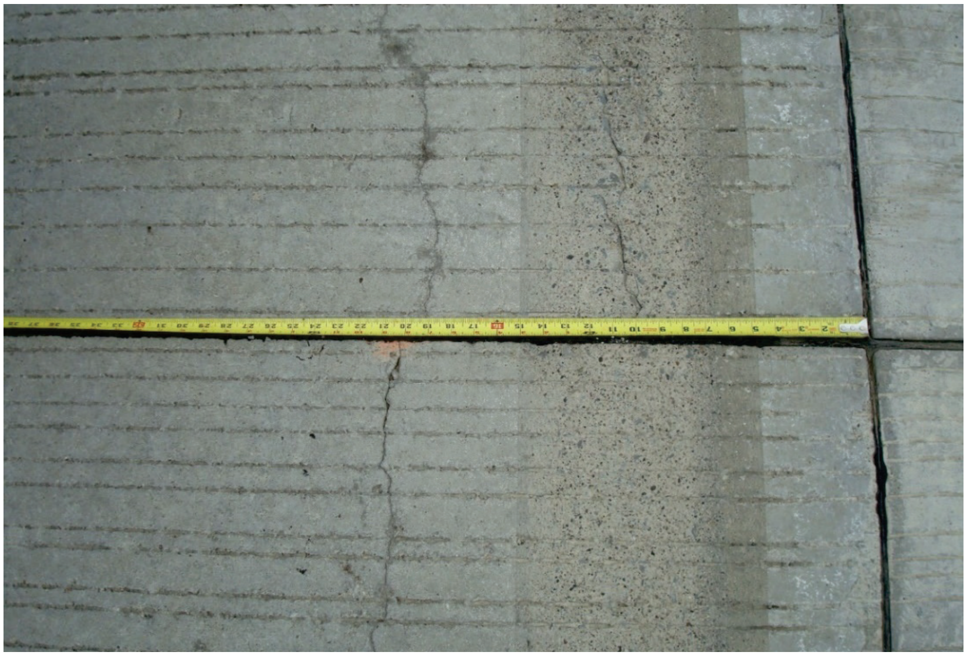




Figure 31. Restraint cracking at transverse joint after placement of new concrete shoulder in the next construction season.

Another potential failure mechanism when placing new concrete pavement next to existing pavement is the intrusion of mortar or incompressibles in the open transverse joints of the existing pavement, which could prevent the joints from closing normally during slab expansion and may lead to joint spalling in the existing pavement. It is recommended that backer rod, tape, or other material be placed on the vertical face of transverse joints between adjacent lanes to prevent mortar from intruding into existing joints during paving.

**b. Paving**

Ensure that concrete mix designs are developed to balance mixture workability and stability. Mixtures that are too stiff may place undue pressures on dowel baskets and basket anchoring systems during placement, causing basket displacement and dowel misalignment. Mixtures that are unstable may result in mislocation and misalignment of dowels placed using a DBI.

Provide high-quality concrete at the joints. Concrete placed at the joints must be of the same high quality as concrete used in the rest of the slab. Modifying the mix at the joints is not recommended.

Properly consolidate concrete at the joints to ensure good joint performance. Load transfer across a doweled joint is greatly affected by the quality of concrete consolidation around the dowels. Inadequate consolidation can leave voids around the dowels, resulting in reduced load transfer capacity. Over-consolidation can reduce concrete strength and durability by segregating the mixture and changing the air void system characteristics. Low concrete strength and low air entrainment at the joints can result in structural or durability-related spalling and joint deterioration.

Take steps to ensure that dowels are properly located and aligned during placement operations. Monitor the concrete head in front of slipform pavers as they approach dowel baskets because excessive head may exceed the capacity of the anchors to hold the basket in place as the paver passes. A mechanical pre-spreader can help to prevent the development of excessive concrete head at the paver and subsequent movement of dowel baskets.

Verify the location and alignment of dowels as soon as paving begins and as paving progresses so that any construction-related problems are identified and corrected as quickly as possible. Dowel position and alignment can be verified during placement using probing or the magnetic, GPR and ultrasonic devices described previously.

### c. Joint Sawing

#### *i. General*

The most common technique for constructing contraction joints is to saw the concrete to some minimum depth at each joint location to produce a “weakened plane” in the concrete that will crack from the bottom of the saw cut through the remaining pavement thickness. A second cut may be made at a later time to accommodate joint filler or sealant materials. The design and construction of the sealant or filler reservoir is discussed under Question 19.

Alternate joint-inducing techniques have not been successfully or broadly adopted. Thus, it is recommended that all contraction joints be sawed. Only joint sawing practices are discussed further in this advisory.

#### *ii. Marking Joint Locations*

It is essential that joint locations are marked accurately before joint sawing to ensure that the resulting panel dimensions are as designed, and that sawed joints are located over the midpoints of dowels and tie bars. Figures 32 and 33 show the use of nails and washers or paint (placed on the shoulders before paving) to establish the sawing line. Figure 34 shows the use of a magnetic imaging device to locate the dowels near the pavement edges so that a saw line can be established over the centers of the as-installed dowels. Other options are also available.

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Figure 32. Use of nail and washer in shoulder (see circled area, left) to mark desired joint line.

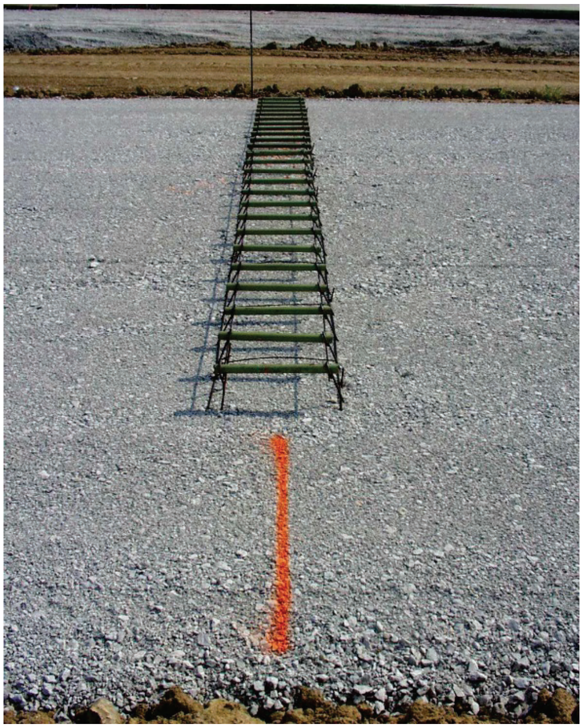




Figure 33. Use of paint stripe to mark desired joint line (ACPA 2018).



Figure 34. Use of magnetic imaging equipment to identify dowel locations at pavement edge before sawing (ACPA 2018).

*iii. Sawing Equipment*

Two types of saws that are commonly used for cutting concrete pavement joints: conventional and early-entry saws (also known as green concrete saws). Conventional saws are typically large-diameter, water-cooled, walk-behind saws (see figure 35) while early-entry saws are generally smaller-diameter, lighter-weight, dry-cut saws that are operated with a slotted plate in contact with the pavement surface to help prevent damage to the concrete adjacent to the saw cut (see figure 36).



Figure 35. Typical conventional water-cooled concrete saw.




Figure 36. Typical early-entry saw with vacuum.

Saw blades are typically either steel with diamond-infused cutting segments, which require cooling water during use, or carborundum (abrasive), which can be used for dry cutting and rapidly decrease in diameter with use. The blades used should be matched to the concrete aggregate hardness and the power output of the saw (APCA 2010; ACPA 2015). ACPA (2010) presents additional practical details concerning the sawing of joints using both conventional and "early-entry" saws. A tech brief concerning the use of early-entry saws is available from FHWA (2007b).

iv. *Saw Cut Timing*

- General

To prevent uncontrolled cracking in either the transverse or longitudinal directions, pavement joints must be sawed before the stresses generated due to restraint of temperature and moisture effects exceed the concrete strength. However, joints cannot be sawed until the concrete has gained sufficient strength to allow sawing without damaging or weakening the concrete along the joint (figure 37). This creates a "sawing window," as illustrated in figure 38. The size and timing of this sawing window are affected by all of the factors that affect both pavement stress and strength at early ages.




Figure 37. Typical joint raveling from sawing at various times relative to the sawing window (ACPA 2010).

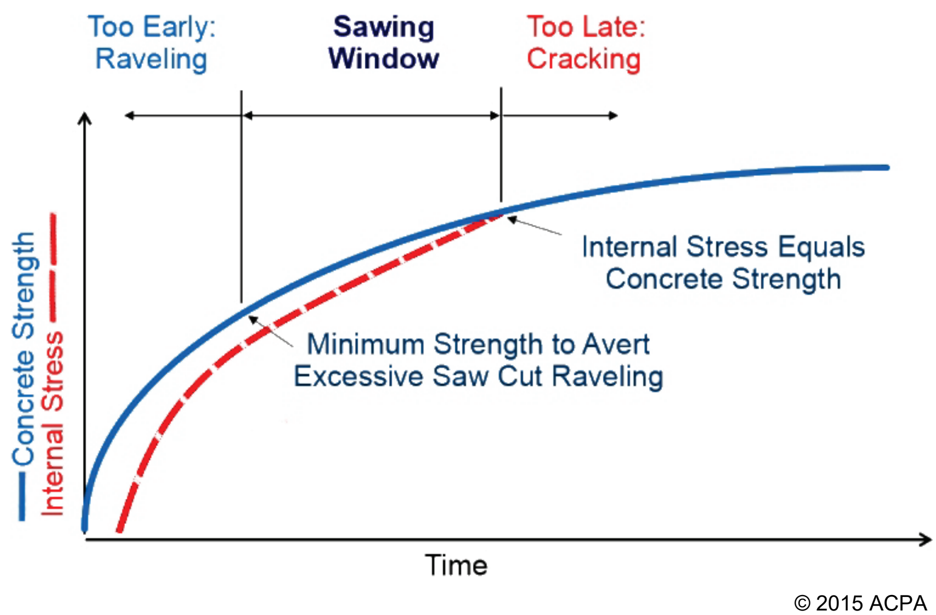



Figure 38. Illustration of concrete pavement joint sawing window concept (ACPA 2015).

- **Procedures**
  - Sawing should begin as soon as the concrete is strong enough to both support the sawing equipment and to prevent raveling during the sawing operation. There is no standard test for identifying the beginning of the saw cut window, although many experienced sawing contractors often use a tool to scratch the pavement surface to determine whether it has enough strength to resist spalling or raveling. Okamoto et al. (1993) developed minimum concrete compressive strength guidelines for mixtures with various aggregate geometry (crushed vs. rounded), aggregate hardness and cement contents for sawing without raveling (see table 1) and provided guidance on using pulse velocity and maturity monitoring techniques for nondestructively determining early age concrete compressive strength.

Table 1. Required Compressive Strength for Acceptable Levels of Saw Cut Raveling for Different Concrete Mixtures (after Okamoto et al. 1993).

| Aggregate Geometry | Aggregate Hardness | Cement Content (lb/c.y.) | 3 Saw Cut Rating* | 4 Saw Cut Rating* |
|---|---|---|---|---|
| Crushed | Soft | 500 | 480 psi | 720 psi |
| Crushed | Soft | 650 | 320 psi | 540 psi |
| Crushed | Hard | 500 | 930 psi | 1300 psi |
| Crushed | Hard | 650 | 700 psi | 1000 psi |
| Rounded | Soft | 500 | 280 psi | 460 psi |
| Rounded | Soft | 650 | 140 psi | 300 psi |
| Rounded | Hard | 500 | 620 psi | 910 psi |
| Rounded | Hard | 650 | 450 psi | 700 psi |

*Rating of 3 = acceptable level of raveling if sealant reservoir is to be widened; Rating of 4 = good

- Joint sawing generally must occur sooner in warm, dry or windy weather when shrinkage develops rapidly, especially if the pavement is constructed on a stabilized base. The use of fiber-reinforced concrete may also require earlier joint sawing. Earlier joint sawing may be possible with lighter-weight, early-entry, dry-cut saws.
- Sawing should be performed continuously across or along a joint but should be stopped if more than minor raveling of the joint is taking place (indicating either insufficient concrete strength or a problem with the sawing operation or equipment). When sawing early in the window, sawing deeply through a free edge may cause spalling. This damage can be avoided by stopping the saw a few inches away from the free edge. The remaining concrete can be sawed soon afterwards using a hand-held dry-cut saw.
- Joint sawing must be completed before the pavement stresses due to early-age curl/warp, shrinkage, contraction, restraint and other factors exceed the strength of the concrete. A free software tool called HIPERPAV III® v3.3 is available at https://www.hiperpav.com and can be used to estimate the stress and strength development in concrete pavements (considering the factors described previously) to help identify the sawing window (Ruiz, Garber, and Dick 2015). This software can also be used to assess the impact of proposed mix design changes and changes in weather on the saw cut window and potential for cracking. Concrete maturity estimates based on embedded temperature monitoring systems (i.e., "maturity meters") can provide real-time concrete strength information. In addition, evaporation rates (which indicate the potential for shrinkage-related cracking and the need for timely and effective curing) can be estimated using the nomograph presented in ACI 305R-10 or ACPA's Evaporation Rate Calculator app (http://apps.acpa.org/applibrary/EvaporationRate/).
- Transverse joints are typically sawed sequentially along the length of the pavement placement and are generally sawed ahead of the longitudinal joint(s) when only two or three lanes are placed contiguously. Contractors should have enough saws (and backup saws and replacement parts) to ensure that that saw all required joints before the sawing window closes. Equipment requirements generally increase with smaller panel sizes, as are increasingly common in thinner pavements and many concrete overlays.
- When the sawing window is closing or uncontrolled cracking is imminent (e.g., after the passage of a cold front or other factors), contractors may initially saw every third or fourth joint in a practice sometimes called "skip sawing" to reduce peak early-age stresses. Intermediate joints must still be sawed as soon as possible before stresses at those locations exceed the concrete strength and result in cracking. The joints sawed first often activate before the intermediate joints and exhibit greater widths, but the widths of all joints will generally become relatively uniform over time (ACPA 2010).

v. *Initial Saw Cut Depth and Width*

Saw cut depth is just as important as saw cut timing in the control of concrete pavement cracking. A joint sawed at the proper time but too shallow may not result in a sufficiently weakened plane to prevent a crack from forming at a nearby location.

Recommendations for saw cut depth typically depend on joint design, saw type and assumed bond or friction between the slab and subbase:

- All tied joints are typically sawed to a depth of T/3, regardless of joint orientation or subbase bond/friction, but should not cut the tie bars.
- When using conventional saws, doweled and unreinforced joints are typically sawed to a depth of T/4 when on granular subbase and to a depth of T/3 on stabilized

subbase. The greater saw cut depth on stabilized subbase is due to the higher potential bond or frictional resistance, which requires a greater saw cut depth for reliable crack control. Care must be taken in thinner pavements to not cut the dowels.

- When using early entry saws, a cut depth of T/6 to T/5, with a minimum depth of 1.25 inches, is typically required. If early entry sawing produces dust, it may be too late for shallow cuts to be effective and the conventional saw cut depth requirements should be used. (ACPA 2015).
- When cutting transverse joints in variable thickness sections (e.g., where the concrete layer thickness varies with the crown or super-elevation), maintain a saw cut depth of 1/4 to 1/3 the slab thickness. This may require multiple sawing passes at different saw cut depths in some areas.
- Saw blades wear with use and saw blades may "ride up" over hard aggregate. Monitor blade wear and saw cutting operations to ensure proper saw cut depth.

The narrowest possible cut is all that is necessary to form a weakened plane for concrete pavement crack control. Blades as thin as 1/8 inch may be used if the joint is to remain unfilled or if the joint will later be widened with a second cut to form a joint sealant reservoir. If joint filler material will be used in the initial cut, a single cut 1/4 to 3/8 inches wide may be necessary for filler penetration. If the joint will be sealed, a wider single cut or a second cut (wider and less deep) will be required to establish the proper shape factor for the joint sealant, as described later in this advisory.

**14. How are transverse construction joints (or header joints) designed and constructed?**

Transverse construction joints (also known as "header joints") are built at the end of a section of pavement (typically at the end of each day's paving, at blockouts for intersections or entrances, or when an unplanned interruption in paving takes place) to facilitate continued pavement construction. They are typically constructed perpendicular to the pavement centerline and may be constructed using formwork or by sawing. In either case, there is no aggregate interlock.

An effort should be made to locate construction joints at planned transverse contraction joint locations so that they align with contraction joints in adjacent tied travel lanes or shoulders. This will eliminate the potential for short slabs (prone to longitudinal cracking) and sympathy cracking in adjacent tied pavement.

When the construction joint is closely aligned with a transverse joint in tied adjacent lanes, mechanical load transfer is provided using dowel bars with the same size and spacing as is used on the pavement contraction joints. If the construction joint and adjacent contraction joints are not exactly aligned (e.g., placements due to weather issues, paving equipment failures or other emergencies), isolation material (e.g., 1/4-inch foam board) and no ties should be placed in the longitudinal joint between the two joints.

When the construction joint is placed at least 6 ft away from the next contraction joint, tie bars may be used to hold the construction joint tight, and an aligned contraction joint will be included at the proper location during the next placement. Tie bar size and spacing requirements in this case are similar to what is required for longitudinal joint ties, but it is common to use 18-inch (or longer) #5 or #6 bars (or larger) at 12-inch spacing. An alternate design is to use tie bars with similar diameter to the required dowels (i.e., #8 or #11 bars) concentrated in the wheel paths.

The construction of a formed header typically begins with the placement and anchoring of a header board just beyond the end of the concrete placed by the paver. Dowels (or ties) or dowel hole formers ("false dowels") are inserted in the header board, and concrete is placed and finished by hand to complete the paving from the header to the previously paved concrete. If dowels are used, the protruding ends will be cast into the next pavement section. If false dowels are used, they are removed with the header board and new dowels or ties are anchored in the formed holes before the paving begins. Consolidation of the concrete around the dowel or tie bars is critical to the future performance of formed header joints. Figure 39 shows the construction of a formed header and figure 40 shows the resulting joint.



Figure 39. Construction of a formed transverse header joint (ACPA 2018).



Figure 40. Finished header joint (ACPA 2018).

Sawed headers are constructed by allowing the paver-placed concrete to harden and then sawing the pavement transversely and full depth at a suitable location. The excess concrete is removed and holes are then drilled in the sawed joint face to anchor dowel or tie bars, and new paving beings at that location. This approach is often less labor-intensive than formed headers and typically results in a smoother transition at the header joint (ACPA 2010).

## 15. What should be considered in the design of longitudinal construction joints?

### a. General

Longitudinal construction joints are used between concrete lanes paved in separate passes. Load transfer at longitudinal construction joints may be provided through tie bars, keyway-tie bar systems or (less commonly in highway pavements) dowels. Tie bars also help to prevent the joint from opening; keyways and dowel bars alone do not. Thus, tie bars are generally recommended for use in longitudinal construction joints, even when keyways are used. Tie bars may not be necessary for low-volume roadways, particularly when they are laterally confined by curb and gutter.

### b. Tie Bars

Tie bars can be used alone to hold longitudinal construction joints tight. Longitudinal joints that are not tied may tend to open over time. The amount and rate of opening will be reduced with increased distance to the nearest free edge and with increased restraint at the slab-subbase interface (i.e., with slabs on stabilized subbase layers).

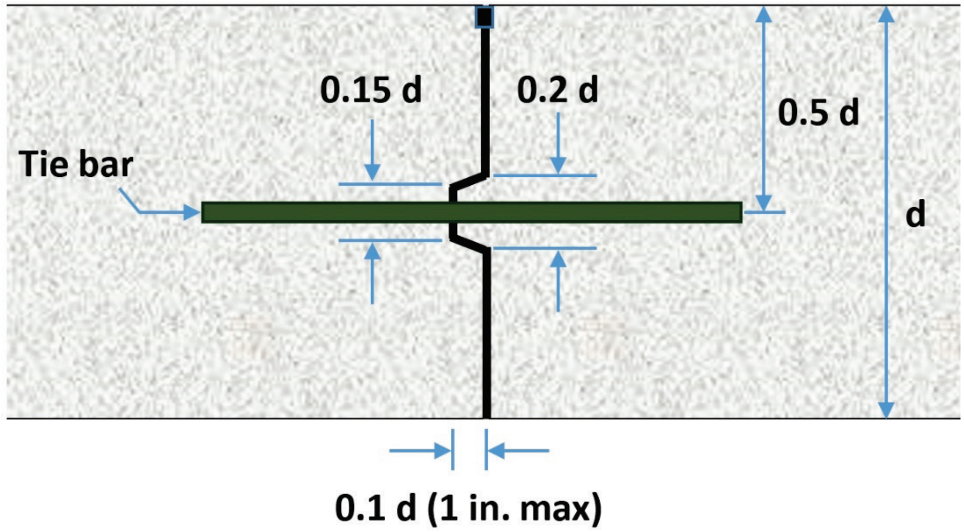
It is commonly recommended that no more than three lanes (including the concrete shoulder) be tied together (ACI 2002). ACPA (1992) recommends limiting the width of tied roadway to about 48 ft based on subgrade drag theory, but notes that there has been good field performance in some instances with up to 70 ft of tied pavement. Mallela et al. (2009) concluded that concrete stresses do not increase significantly when three or more lanes are tied together, and experience in some states suggests that at least four lanes can be tied together without inducing uncontrolled longitudinal cracking. If a very wide section must be placed and local experience with such wide placements is not available, consider using an untied (butt or doweled) contraction joint or construction joint near the center longitudinal joint of roadway sections that exceed 48 ft.

Typical tie bar designs are inadequate for providing load transfer across a flat or “butt” joint. When only tie bars are used and are intended to provide load transfer (rather than just holding the joint tight), they must be sized and spaced to provide adequate load transfer in much the same way that dowel load transfer systems are designed (see Question 7).

### c. Keyways

Keyways are tongue-and-groove configurations between abutting slabs that are created using shaped forms during paving. They were originally developed and designed to promote load transfer, help maintain panel alignment, and reduce joint deflections. Keyways are no longer common in U.S. highway construction because of problems associated with difficulty in construction (consolidating concrete within the keyway notch) and performance (shearing of the concrete above, below or through the keyway), resulting in loss of load transfer and cracking or spalling along the keyway (ACPA 2015). Because of these problems, conventional keyways are not recommended, especially for concrete pavement thicknesses less than 10 inches. When keyways are used, tie bars are generally required to hold them tight and they should be dimensioned as shown in figure 41. Consideration should be given to eliminating conventional keyways and increasing the size and/or number of tie bars.

An innovative corrugated keyway design involving several shallow rounded or triangular keys has been developed and implemented successfully in Australia (see figures 42 and 43). While not yet evaluated in the U.S., this design is believed to produce vertical face shapes that are more easily filled with concrete and appears to be less susceptible to shear failure than traditional keyways. If proven useful in the U.S., corrugated keyways (used with tie bars to hold the joint tight and engage the keys) should provide good longitudinal joint load transfer without the problems associated with conventional keyways.




Source: FHWA

Figure 41. Recommended keyway dimensions for highway paving (only for pavements >10 inches thick) (FHWA 1990).

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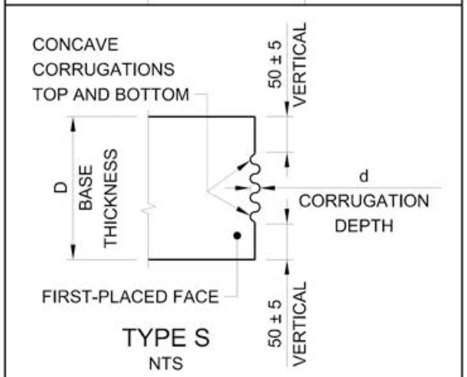
Figure 42. Longitudinal joint with corrugated keyway and tie bars in Australia.

TABLE 10.2: JOINT CORRUGATION DESIGN

| TYPE S: FULL CORRUGATIONS | | |
|---|---|---|
| BASE THICKNESS 'D' (mm) | NUMBER OF CONCAVE CORRUGATIONS | CORRUGATION DEPTH 'd' (mm) |
| < 200 | 3 | 9 ± 3 |
| 200 - 230 | 3 OR | 9 ± 3 |
| | 4 | 8 ± 2 |
| > 230 ≤ 250 | 4 | 8 ± 2 |
| > 250 | 4 | 9 ± 3 |




| TYPE F: CORRUGATIONS LINKED BY FLATS | | | | | |
|---|---|---|---|---|---|
| BASE THICKNESS 'D' (mm) | NUMBER OF CORRUGATIONS | CORRUGATION DEPTH 'd' (mm) | MINIMUM CORRUGATION HEIGHT 'h' (mm) | MINIMUM FLAT 'g' (mm) | MINIMUM VERTICAL 'v' (mm) |
| < 200 | 3 | 9 ± 3 | 20 | 10 | 45 |
| 200 - 240 | 3 or 4 | 10 ± 3 | 25 | 12 | 50 |
| > 240 | 3 or 4 | 12 ± 3 | 30 | 15 | 50 |

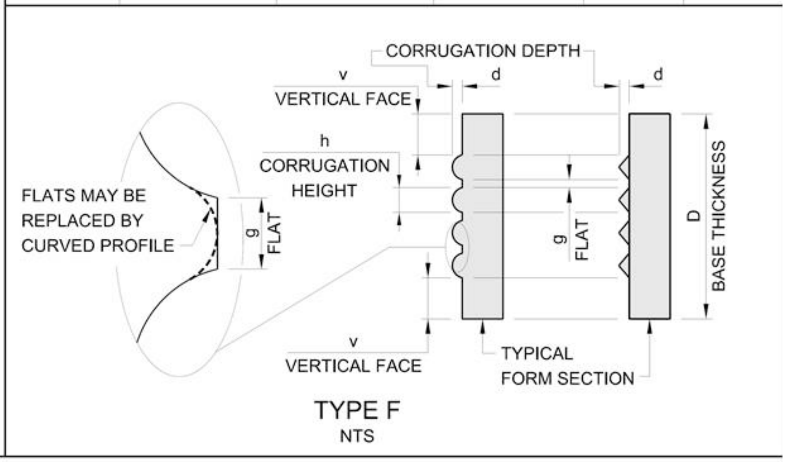



Table 10.2 Notes:

(a) Type S will typically suit slipform paving and type F will suit fixed-form paving.

(b) The top and bottom corrugations must be concave in the first-placed face (that is, convex on the form).



Figure 43. Australian details for corrugated keyway design.

### d. Dowels

Dowels can also be used to provide load transfer (as they are in many airfield pavements) but will not hold the joint tight if they are properly aligned. Dowel systems should be designed using the same criteria described for transverse contraction joints under Question 7.

## 16. What should be considered in the construction of longitudinal construction joints?

### a. General

Longitudinal construction joints can be formed with either conventional fixed forms or using a slipform paver. Tie bars are recommended and should be installed at the time of paving the pilot (first) lane.

### b. Installing Tie Bars

It is essential that the tie bars are firmly anchored in the concrete. When using fixed forms, tie bars are easily installed through holes in forms and the plastic concrete can be well consolidated around the tie bars during concrete placement. When using slipform techniques, tie bars should be mechanically inserted into the plastic concrete. Tie bars can be anchored in drilled holes if they cannot be installed in the plastic concrete at the time of paving, but this approach should be avoided, if possible, due to the difficulties associated with anchoring long bars in deep holes.

Construction staging and traffic control sometimes requires minimizing the distance that tie bars extend from the edge of the a given paving lane. One option is to use a two-part threaded tie bar and splice coupler system (see figure 44). Alternatively, the contractor can insert bent tie bars (or can bend straight inserted bars in toward the paved lane after placement) and then bend them out for insertion into the adjacent lane when it is time to pave. Grade 40 bars with flexible epoxy coatings (produced under ASTM A775/A775M) are more tolerant to bending than Grade 60 bars and more brittle epoxy coatings (produced under ASTM A934/934M). The use of smaller bars that are more closely spaced (holding the total area of steel per unit area of concrete joint face constant) may also mitigate bending problems. Potential problems with bent bars may be alleviated by limiting the initial bend to no more than 60 degrees and then not fully straightening the bar for later paving (see figure 45). The partially bent bar will should be left at an angle that provides adequate joint restraint.

If tie bars are bent for any reason, the epoxy or other protective coating at the bend should be inspected and repaired as needed to protect the tie bar from corrosion.

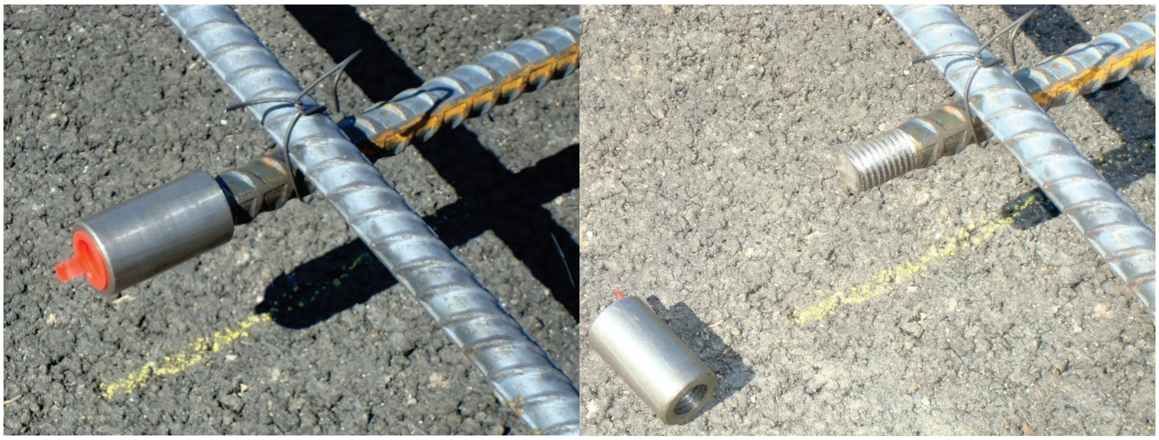


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Figure 44. Typical two-part threaded tie bar and splice coupler system.

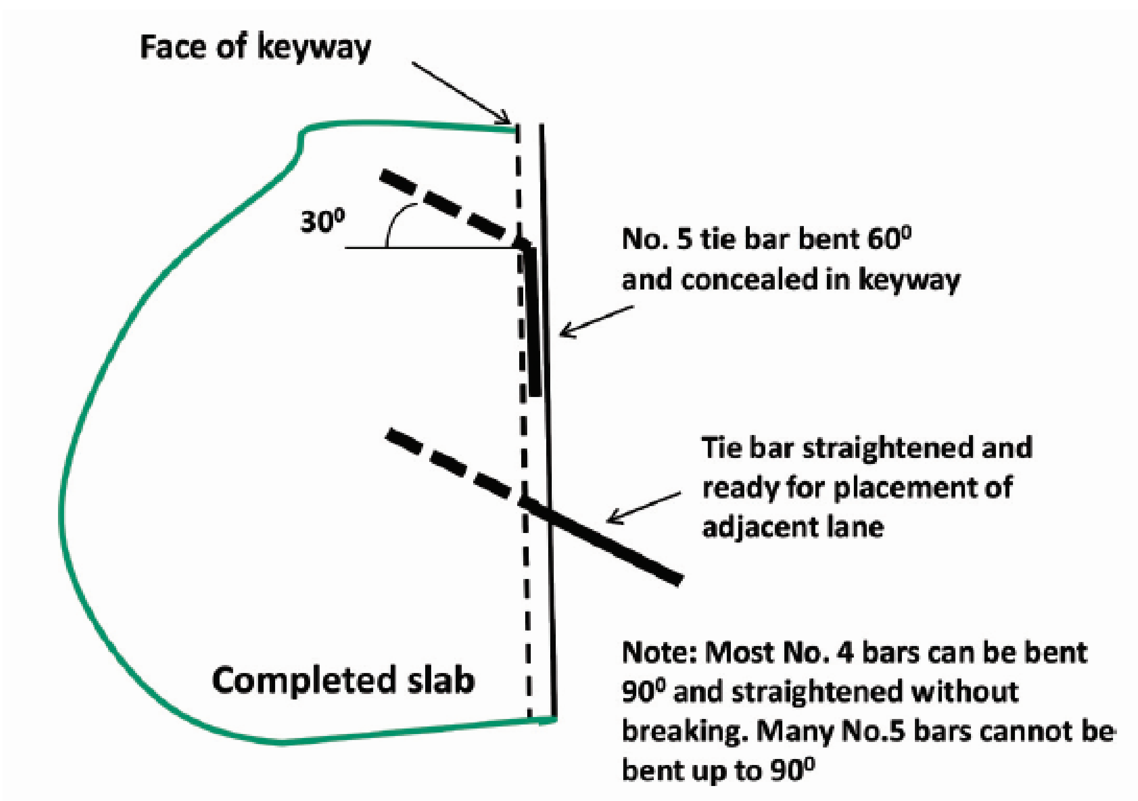


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Figure 45. Schematic for minimizing breakage of tie bars that are bent and then re-straightened (ACI 2015).

### c. Pullout Testing

Adjacent lanes should not be constructed until the pullout resistance of the tie bars has been tested and the results found to be sufficient for holding the construction joint tight. Pullout testing should be done after any bent bars have been straightened. A recommended testing procedure for tie bar pullout testing follows:

- The owner's representative selects 15 tie bars from the first day's placement. After the concrete has attained an average flexural strength of 550 lbf/in$^2$, use a hydraulic jack to apply pullout loads to a maximum load of 12,000 lbs or until the bar slips by 1/32 inch, whichever occurs first. Record the load at test termination. Average of the results of these pullout tests and divide the result by the spacing of the tie bars to determine the average pullout resistance in lbs per linear foot.
- Compare this value with the appropriate value from table 2 for the width of pavement being tied. If the test results for the first day's placement exceed the listed requirements, additional testing will be at the discretion of the owner's representative and will be based on comparisons of the installation methods and spacings of the first day's placement with subsequent placements.

Table 2. Minimum Required Average Pullout Resistance for Tie Bars (FHWA 1990).

| Tied Width of Pavement (Distance from Joint Being Constructed to Nearest Free Edge) | Average Pullout Resistance of Tie Bars, lbs. /L. F. of joint, minimum. |
|---|---|
| 12 ft or less | 2200 |
| Over 12 ft to 17 ft | 3200 |
| Over 17 ft to 24 ft | 4500 |
| Over 24 ft to 28 ft | 5200 |
| Over 28 ft to 36 ft | 6800 |
| Over 36 ft | 9000 |

- If the results of the pullout tests are less than the minimum requirements specified for the width of concrete being tied, the contractor must install additional tie bars to provide the minimum average pullout resistance required, as directed by the owner's representative. Testing of the supplemental tie bars will be at the discretion of the owner's representative.

This procedure will verify that the pullout load capacity is sufficient for design conditions (as established by table 2). For example, if 12,000 lbs of force is successfully applied to each #5 tie bar in a system where the ties are spaced 30 inches apart (a typical design), this corresponds to an average pullout resistance of 12000/2.5 = 4800 lbs per lineal foot of joint. If no more than four 12-ft lanes of pavement will be tied together, the maximum distance from a tied joint to a free edge will be 24 ft. Table 2 requires an average pullout resistance of at least 4500 lbs per lineal foot, so the constructed system is considered to have sufficient pullout capacity. Note that typical pullout criteria when testing to failure would require that the tie bar pullout force is at least 75 percent of the yield strength of the bar (about 13,800 lbs for a Grade 60 #5 deformed bar).

Adjacent paving lanes are generally paved right up against the existing slabs without using a filler, isolation material, or coatings between the lanes. After placement of adjacent lane, a joint sealant or filler reservoir can be sawed to minimize infiltration of water and incompressibles and to minimize potential spalling of the longitudinal construction joint. The dimensions of this reservoir can be the minimum required for the joint sealant or filler being used (see Question 19) because properly designed and constructed joint ties will prevent both vertical and horizontal movements of the joint.

The tying of new concrete pavement to jointed concrete pavement that is older (even by only a few months) may result in the development of cracks in the older pavement (shown previously in figure 31) or crushing of the new concrete if the old pavement joints are open at the time of paving (causing the new pavement to restrain slab expansion in old pavement). Minimize the width of joint opening in the older pavement (e.g., minimize the time between placements or pave during warmer weather) when paving new adjacent tied paving lanes or shoulders.

**17. Is it beneficial and/or cost effective to seal concrete pavement joints?**

The purpose of joint sealant is to minimize the infiltration of surface water, deicing chemicals, and/or incompressibles into the joint. When joint sealing is specified, the selection of sealant is influenced by expected joint movement, traffic type and volume, sealant cost, and desired sealant longevity.

The benefits and cost effectiveness of sealing joints in concrete pavements has been a subject of debate since the mid-1970s when the Wisconsin Department of Transportation (WisDOT) began to construct approximately 50 unsealed test sections in pavements representing a variety of design and traffic conditions over a 15-year period. The debate intensified when WisDOT concluded that pavements with unsealed joints performed comparably to those with sealed joints and, in 1990, adopted a policy eliminating all concrete pavement joint sealing in both new construction and maintenance. Since that time, many other highway agencies have adopted similar policies or have constructed unsealed test sections for study. WisDOT recently modified its policy to require joint sealing on concrete pavements with posted speed limits of less than 45 mph, noting that experience suggests that higher vehicle speeds are needed to prevent incompressibles from lodging in the joints.

The debate concerning the need for concrete pavement joint sealing continues today. A national study of the benefits of joint sealing could not conclusively establish that sealing was either warranted or unwarranted in all situations, but few of the pavement sections studied had been in place for longer than 10 years (FHWA 2009). On the other hand, Burnham (2012) reported a significant improvement in the performance of thin bonded concrete overlays of asphalt pavement when the joints are sealed, presumably because the reduced infiltration of water prevented degradation of the bond between the asphalt and concrete. The Seal-No Seal Group, an affiliation of industry stakeholders, maintains a website (https://www.sealnoseal.org) with links to numerous resources concerning joint and crack sealing, including all of those cited herein.

The best answers to the question of the need for concrete pavement joint sealing may be project specific and dependent on the facility type, pavement design (including the drainage, erodibility and frost resistance of the foundation materials), the local environment, the level of heavy truck traffic, required level of service and performance, as well as other factors.

**18. What types of joint sealing materials are available and what factors should be considered in selecting a concrete pavement joint sealant?**

Sealants are generally classified as either liquid (field molded) or pre-formed (compression) types. Liquid sealants include hot- and cold-poured asphalt-based materials, silicone, and other self-leveling or tooled materials that assume the shape of the sealant reservoir at the time of installation and depend on adhesion to the joint faces for successful sealing. Pre-formed sealants are manufactured (typically using neoprene) to specific sizes and with designed internal web structures that permit a range of joint movement while remaining in compression to maintain position within the joint. Table 3 presents a table of commonly used joint sealant materials and applicable material specifications.

Many factors influence sealant selection, including type of joint and expected joint movements, climate (which impacts required extensibility), bond compatibility with substrate materials (e.g., concrete only or concrete and asphalt [lane-shoulder joint]), chemical compatibility with substrate material (e.g., sensitivity of some silicone sealants to limestone aggregate), need for rapid sealant curing, need for resistance to fuel spills or jet blasts, material and installation costs and expected performance life. For highway pavements, silicone and preformed compression seals generally outperform asphalt-based sealants, but often are proportionally more expensive. The use of longer-life sealants should be considered, even with added initial costs, because joint sealant maintenance is often deferred (or ignored).

Table 3. Common Joint Sealants, Applicable Specifications, and Selected Properties (Smith et al. 2014).

| Material Category | Material Type | Specification(s) | Description |
|---|---|---|---|
| Liquid, Hot-Applied Sealants | Polymerized/Rubberized Asphalts | ASTM 0 6690, Type I (AASHTO M324) | Moderate climates, 50% extension at 0°F(·18°C) |
| Liquid, Hot-Applied Sealants | Polymerized/Rubberized Asphalts | ASTM 0 6690, Type II (AASHTO M324) | Most climates,50% extension at 20°F (·29°C) |
| Liquid, Hot-Applied Sealants | Polymerized/Rubberized Asphalts | ASTM 0 6690, Type III (AASHTO M324) | Most climates,50% extension at 20°F ( 29°C} with other special tests |
| Liquid, Hot-Applied Sealants | Polymerized/Rubberized Asphalts | ASTM 0 6690, Type IV (AASHTO M 324) | Very cold climates,200% extension at 20°F ( 29°C) |
| Liquid, Cold/Ambient-Applied Sealants | Single-Component Silicone | ASTM 0 5893, Type NS | Non-sag, toolable, low modulus |
| Liquid, Cold/Ambient-Applied Sealants | Single-Component Silicone | ASTM 0 5893, Type SL | Self-leveling, no tooling, low modulus |
| Liquid, Cold/Ambient-Applied Sealants | Two-Component Elastomeric Polymer (polysulfides,polyurethanes) | Fed Spec SS·S·200E, Type M | Jet-fuel resistant, jet-blast resistant, machine applied fast cure |
| Liquid, Cold/Ambient-Applied Sealants | Two-Component Elastomeric Polymer (polysulfides,polyurethanes) | Fed Spec SS·S·200E, Type H | Jet-fuel resistant, jet-blast resistant, hand-mixed retarded cure |
| Solid, Cold/Ambient-Applied Sealants | Preformed Compression Seals<br>-Polychloroprene Elastomeric (Neoprene)<br>-Lubricant | ASTM 0 2628<br>ASTM 0 2835 | Jet-fuel resistant preformed seal<br>Used in installation of preformed seal |
| Expansion Joint Filler | Preformed Filler Material | ASTM 0 1751 (AASHTO M 213) | Bituminous, non-extruding, resilient |
| Expansion Joint Filler | Preformed Filler Material | ASTM 0 1752, Types HV (AASHTO M 153) | Sponge rubber, cork, and recycled PVC |
| Expansion Joint Filler | Preformed Filler Material | ASTM 0 994 (AASHTO M33) | Bituminous |
| Backer Rod (if used) | - | ASTM 0 5249 | For hot- or cold-applied sealants |

Note 1: ASTM 0 1190 was withdrawn in 2002 and replaced with ASTM 0 6690 (Type I).
Note 2: ASTM 0 3405 was withdrawn in 2002 and replaced with ASTM 0 6690 (Type Ill.
Note 3: The use of preformed compression seals in resealing operations will depend on the condition of the joints.
Note 4: A few agencies no long use backer rods because of concerns that they trap moisture in the joint

## 19. What joint design and construction practices help to ensure achieving the potential benefits of joint sealing?

### a. General

The primary considerations in joint sealant reservoir design are the extensibility (strain) limit and required shape factor for the selected sealant material (or minimum and maximum compression requirements for preformed seals) and the anticipated joint movements. Quality sealant installation requires proper control over joint cleanliness and moisture condition at the time of sealing.

### b. Reservoir Design

#### *i. Estimation of Joint Movement*

The amount of joint movement that a sealant must accommodate is a function of the panel length, friction or restraint between the slab and supporting layer, the shrinkage of the concrete after placement, and the potential movement due to changes in temperature relative to the time the joint was sealed. This value can be estimated using the following equation:

$$\Delta L = CL\,(\alpha \Delta T + \epsilon) \qquad \text{(Eq. 3)}$$

where:

$\Delta L$ = the expected change in slab length (or joint opening), inches;

$C$ = an adjustment factor for slab/foundation restraint due to friction or bond (typically assumed to be 0.65 for stabilized layers, 0.8 for granular layers);

$L$ = panel length, inches.

$\alpha$ = the PCC coefficient of thermal expansion (determined using AASHTO T336 or estimated using typical values; see table 4 for examples based on concrete aggregate type);

$\Delta T$= the difference in temperature from the time the pavement was sealed to the minimum expected ambient temperature at the project site, F-degrees); and

$\epsilon$ = the expected drying shrinkage coefficient of the concrete (see table 5 for typical values). This factor can be omitted for pavement re-sealing projects because it is assumed that all shrinkage has taken place.

Table 4. Typical Values of Concrete Coefficient of Thermal Expansion (AASHTO 1993).

| Type of Coarse Aggregate | PCC Coeff. of Thermal Expansion ($10^{-6}$/°F) |
|---|---|
| Quartz | 6.6 |
| Sandstone | 6.5 |
| Gravel | 6.0 |
| Granite | 5.3 |
| Basalt | 4.8 |
| Limestone | 3.8 |

Table 5. Typical Values of Concrete Coefficient of Shrinkage (AASHTO 1993).

| Indirect Tensile Strength (psi) | PCC Coeff. of Shrinkage (inch/inch) |
|---|---|
| 300 (or less) | 0.0008 |
| 400 | 0.0006 |
| 500 | 0.00045 |
| 600 | 0.0003 |
| 700 (or greater) | 0.0002 |

*ii. Design – Reservoir*

The required sealant reservoir dimensions vary with expected joint movement (described and estimated above) and sealant extensibility (or required range of compression for pre-formed sealants). For example, if the selected sealant strain is limited to 50 percent and the expected joint opening after installation is 1/4 inch, then the initial width of the reservoir must be no less than 1/4 inch / 0.5 = 1/2 inch. If the recommended shape factor (ratio of sealant depth-to-width at the time of installation) is 1.0, the sealant should be installed 1/2 inch wide and 1/2 inch deep. The reservoir cut will need to be deeper to accommodate a backer rod or other means of preventing three-sided adhesion, and to provide 1/4 to 3/8 inch of recess below the pavement surface.

Limitations on liquid sealant strain and shape factor (sealant depth-to-width at the time of installation) vary with material type and source and should be obtained from the manufacturer. Required shape factors vary from 0.5 to 2.0 (ACPA 2010). For example, a shape factor of 1:2 is recommended for typical silicone sealants, while a shape factor of 1:1 is common for hot-poured liquid sealants. Similarly, the working range for any given source and size of pre-formed compression seal is available from the manufacturer. Typical compression seals require joint designs that such that the seal is in 20 to 50 percent compression at all times (FHWA 1989).

Procedures for determining expected joint movement and using it with sealant information to determine required sealant reservoir dimensions for specific sealing materials are typically available from sealant manufacturers. In addition, a “joint and sealant movement estimator” and a “compression seal joint width calculator” are available from ACPA as free online applications at http://apps.acpa.org/applibrary/.

**c. Construction**

Proper joint preparation and sealant installation are essential for good sealant performance. Recommended construction practices are described below.

- When a sealant reservoir is required, it is typically constructed using a second saw cut that creates the desired reservoir width. The depth of the reservoir saw cut must be sufficient to accommodate the sealant, the backer rod (if used) and the depth that the sealant will be recessed from the pavement surface (typically 1/4 to 3/8 inch). Tied, non-working joints accommodate no joint movement and may be filled with sealant without a designed sealant reservoir. In this case, the initial joint saw cut should be wide enough to accommodate the installation of joint filler material (typically 1/4 inch, minimum). Figure 46 presents typical reservoir designs and required shape factors for various types of sealant.
- Joints that are to be sealed or filled must be cleaned immediately after saw cutting or joint widening operations and again immediately before sealant installation to remove any sawing residue or incompressibles that might prevent sealant adhesion and/or proper joint function. Effective cleaning techniques may include sand, water, and/or or air blasting.
- Liquid sealants are typically constructed using a compressible backer rod with an uncompressed diameter slightly larger than the joint width at the time of installation. This prevents three-sided sealant adhesion (which might otherwise result in premature sealant failure) and proper vertical placement of the backer rod assists in achieving the proper sealant shape factor. This backer rod is typically a closed-cell polyurethane foam rope having a diameter approximately 25 percent greater than the width of the joint at the time of installation to ensure a tight fit. When using backer rod with hot-applied sealants, use a backer rod product that is suitable for the high sealant temperatures.
- Installation of sealant materials (including techniques for final joint preparation and the use of specialized installation equipment) should be performed in accordance with the sealant manufacturer’s recommendations and agency specifications. Most sealants must be installed in clean, dry joints. The National Concrete Pavement Technology Center (CPTech Center 2004) presents additional details concerning recommended practices for concrete pavement joint sawing, cleaning, and sealing, while FHWA Technical Paper 89-04 (FHWA 1989) provides information specific to the design and installation of preformed compression seals.

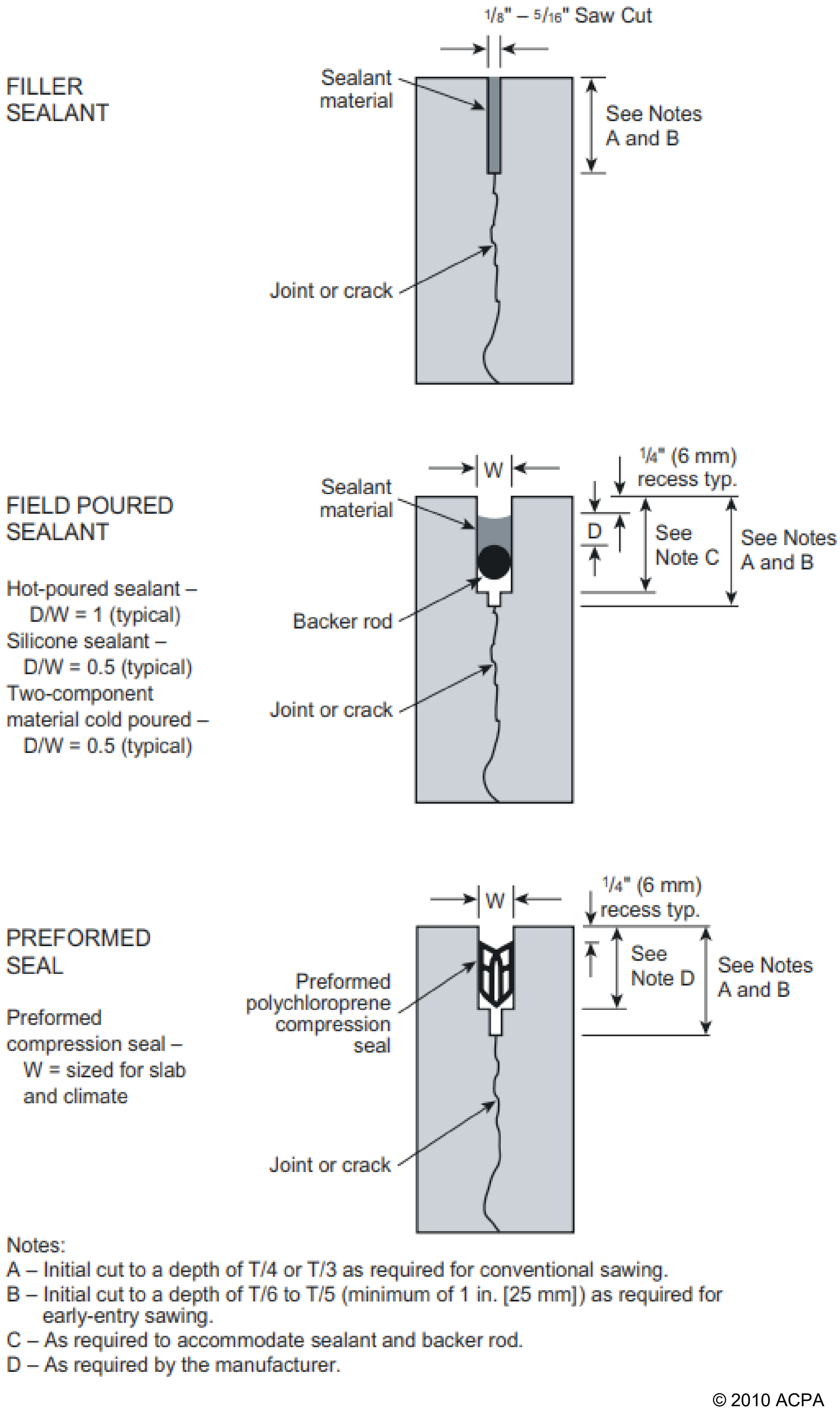


Figure 46. Typical sealant reservoir shape factors and details (ACPA 2010).

### d. Concrete Surface Sealants in Joint Construction

Research concerning the use of concrete surface sealants (e.g., siloxane materials) suggests that they may be effective in improving concrete pavement joint durability in freeze-thaw climates in which deicers are used by limiting the amount water that can penetrate the concrete from the joint (Taylor et al. 2012). Such sealants need to be applied after joint cleaning and before installation of the joint sealant material.

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