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# Longitudinal Joint Specifications and Performance

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# JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION  
AND PURDUE UNIVERSITY



## LONGITUDINAL JOINT SPECIFICATIONS AND PERFORMANCE

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## EXECUTIVE SUMMARY

### LONGITUDINAL JOINT SPECIFICATIONS AND PERFORMANCE

#### Introduction

One of the advantages of asphalt pavements is that they can minimize traffic disruptions by being paved and opened to traffic quickly. Frequently, asphalt paving is performed while traffic is maintained in an adjacent lane. The disadvantage of this type of construction operation, however, is that it leads to paving one lane at a time, which requires construction of a longitudinal joint between the lanes. A weak joint can cause an otherwise sound pavement to deteriorate prematurely.

The joint area can form a weak plane within the pavement. In addition, the mat near the joint may be less dense and more permeable than the interior of the mat. Both of these factors can allow the ingress of water and air into the pavement, potentially leading to moisture damage and accelerated oxidation of the mixture near the joint, respectively. Joint damage typically results in cracking and raveling, which lets in more water and air, accelerating the deterioration. In cold climates, like Indiana's, this water can freeze and expand, increasing the chances for raveling and joint failure.

Because the creation of longitudinal joints is virtually inevitable and because poor joint quality can lead to premature failure of the pavement, guidance is needed on how to ensure that high quality joints are constructed. Ensuring joint quality requires knowledge of successful joint construction techniques, methods for testing joints to measure quality, and specifications to encourage (or require) proper joint construction. Therefore, this report summarizes an extensive review of the pertinent literature, a review of state specifications, and inspection of several trial projects in Indiana related to longitudinal joint construction and performance. Recommendations are given for continuing and possible future efforts to encourage or require the construction of durable longitudinal joints.

The outcome of this study is intended to provide guidance to the Indiana Department of Transportation (INDOT) and contractors on the proper construction techniques for joints and ensuring the performance of longitudinal joints.

#### Findings

Many different methods for compacting longitudinal joints have been used in the past with varying degrees of success. The ability to compact a joint that will be durable and will perform well is heavily mix and site specific, which may help to explain why so much of the research is somewhat contradictory. Therefore, it seems advisable to allow many options that contractors can choose from to suit the particular circumstances at individual jobsites, particularly with regard to roller patterns.

That said, however, some things do seem to be true in most cases. For example, there are decisions made during the design phase of a project that may affect compactability. These include such things as lift thickness, nominal maximum aggregate size, mix type, lane configuration, traffic control requirements, project scheduling and sequencing, and more.

There are also factors that are within the control of the contractor. Since contractors in Indiana design their own mixes, they can opt to use a fine mix, which may prove to be easier to compact. In addition, they can establish their own rolling patterns

to achieve the best density in an efficient manner (with the exception of 402 mixes where the options are limited). The use of notched wedge joints is an option that is available to contractors in Indiana, and they have proven successful in many states, but there is currently little incentive for contractors to use them in Indiana.

Joint sealers and joint adhesives have not been proven to be effective at reducing permeability in all cases but have rarely, if ever, caused construction or performance problems. They are, therefore, considered to be reasonable preventative measures and their use should continue for the time being. The performance and cost effectiveness of these techniques should be examined and a decision to continue or revise the requirements should be made in the future.

A joint quality specification can be an effective way to improve performance. Most specifications are based on establishing minimum joint densities in comparison to either the mat density or the maximum theoretical density of the mix. A density of 90% of the maximum theoretical density is sometimes used as the minimum for 100% pay. Another common requirement is that the joint density be not more than 2% lower than the density near the center of the mat. Indiana may consider the implementation of a longitudinal joint density specification in the future after assessing the success and cost implications of the current recurring special provision.

Visual inspections of nine projects that included special joint treatments, including double tack coats and, mostly, joint adhesives, revealed that these projects are generally performing quite well, although most are relatively recent. The two oldest projects date to about 2003–2004; they are beginning to show some minor joint separation and cracking but the density of the mat surrounding the joints appears to be fairly uniform. These joints should perform for much longer given routine crack sealing. The double tack coat appears to be less effective at bonding the joint. Monitoring of these existing projects should continue to assess their performance and guide future refinements to the specifications for longitudinal joint construction.

#### Implementation

Based on the conclusions reached through a review of the pertinent literature, survey of state practices and current INDOT experience with longitudinal joint construction, the following implementation suggestions are offered.

- Continue the use of joint adhesives and joint sealers, which together may prolong joint life by reducing permeability and improving durability and bonding of the joint.
- Continue to allow the contractors to establish appropriate rolling patterns for 401 mixes.
- Revisit the requirement to pull up adjacent lanes when using a notched wedge joint to once again make this an attractive alternative for contractors to use; the improved productivity associated with not pulling up the adjacent lane would encourage contractors to use this generally successful technique.
- Consider implementation of a PWL (percent within limits) joint density specification in the future as a logical next step after assessing the success and cost implications of the current use of joint adhesives and sealers. A joint density specification would provide a means for assessing whether various joint construction techniques or new materials are truly beneficial.

- Initiate a project to monitor joint performance before the collective memory of what has already been attempted is lost.
- Communicate best practices to promote better longitudinal joint construction to a wide range of audiences.

Through these new and continuing efforts, INDOT and the asphalt paving industry can strive to improve pavement performance by focusing on what is often the “weak link”—the longitudinal joint.

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## 1. INTRODUCTION

One of the advantages of asphalt pavements is that they can minimize traffic disruptions by being paved and opened to traffic quickly. Frequently, asphalt paving is performed while traffic is maintained in an adjacent lane. The disadvantage of this type of construction operation, however, is that it leads to paving one lane at a time. This can be problematic because it requires construction of a longitudinal joint between the lanes. A weak joint can cause an otherwise sound pavement to deteriorate prematurely.

Paving one lane at a time can introduce two conditions that can lead to poor joint quality. One, the first lane paved is unsupported or unconfined along the edges of the lane; the lack of confinement can allow this material to slough off or move laterally under the compaction equipment, resulting in lower density. Two, the material along the edge of the mat cools more quickly than the interior of the mat, which also can result in lower densities, and yields a cold edge to pave against when the adjacent lane is paved. Since the edge of the first paved lane is cold, it tends not to bond well or adhere to the newly placed lane to create a monolithic mat. The joint area, then, forms a weak plane within the pavement that can separate and allow the ingress of water, potentially leading to moisture damage, and air, which can hasten oxidation of the mixture near the joint. Joint damage typically results in cracking and raveling, which lets in more water and air, accelerating the deterioration. In cold climates, like Indiana's, this water can freeze and expand, increasing the chances for raveling and joint failure (1).

The joint typically deteriorates through three stages of distress (2):

1. Development of a separation or crack at the joint,
2. Ingress of water and incompressible foreign matter into the joint area and
3. Deterioration of the joint area through cracking and raveling.

These stages are illustrated in Figures 1.1, 1.2, and 1.3. These photos were taken on different roads in Indiana in July 2012.

Another way to look at the causes of joint deterioration is in terms of durability and permeability. A lack of durability at a joint will allow the faces of the joint to separate, creating a crack that water and air can enter. Permeability of material around the joint can also allow water and air to penetrate and cause deterioration on one or both sides of the joint. So, to perform well, the sides of a joint need to stay bonded together and the material surrounding the joint needs to be relatively impermeable. Ensuring low permeability is usually accomplished through attaining good density.

A great deal of attention has been paid to longitudinal joints over the last five decades. The first report on longitudinal joint issues is apparently a 1964 Highway Research Board publication (3). These authors were the first to document in print that the



**Figure 1.1** Joint deterioration often starts with separation then cracking around the joint.

density in the area of the joint was often low, precipitating the subsequent performance issues. Now the consensus among researchers and experts in asphalt construction is that this low density zone is most commonly created through the scenario above where the cold side of the joint is unconfined and is not adequately compacted. There are other factors that can also lead to lower densities that will be discussed further in this report.

It is also acknowledged that the best way to prevent longitudinal joint distress is not to construct longitudinal joints in the first place (1,4). This can be accomplished by paving in echelon, which means one paver follows a few meters behind another paver, placing adjacent lanes at nearly the same time (1,4,5). In this situation, hot material is placed on both sides of the would-be joint and the material can be compacted into a virtually monolithic layer. Another option is so-called tandem paving, which also uses two pavers, but they



**Figure 1.2** Low density material around the joint can allow for the ingress of water and air.



**Figure 1.3** Joint deterioration continues and extends further into the mat.

are separated a little further apart, which can allow traffic to travel on the first lane paved (4). (These options will be discussed in Chapter 2.)

The need to maintain traffic and access to businesses and homes, however, usually precludes the possibility of closing a roadway to traffic and paving in echelon. Thus, construction of longitudinal joints is a necessity in most cases. Given that need, many people have explored how to construct strong, durable longitudinal joints.

This report summarizes the findings of a detailed literature review, review of state specifications and inspection of several trial installations of different types of joint construction techniques in Indiana.

## 1.1 Problem Statement

Because the creation of longitudinal joints is virtually inevitable and because poor joint quality can lead to premature failure of the pavement, guidance is needed on how to ensure that high quality joints are constructed. Ensuring joint quality requires knowledge of successful joint construction techniques, methods for testing joints to measure quality, and specifications to encourage (or require) proper joint construction.

## 1.2 Objectives

The overall objective of this research project was to provide a review of the current state specifications/guidelines for joint construction and of the available literature on methods available for assessing joint density and joint performance. Studies conducted in other states were also reviewed to provide insight into lessons learnt by other state agencies. The outcome of this study was intended to provide guidance to the Indiana Department of Transportation (INDOT) for the development of a joint specification and to provide guidance to the contractors on the proper construction techniques for joints and verifying the quality of the joint density.

## 2. FINDINGS

This chapter summarizes the findings of a detailed, extensive review of the available literature and an appraisal of state specifications on longitudinal joints in asphalt pavements. In addition, it summarizes a recent field inspection of a number of trial projects constructed in Indiana in 2010–2012 using different joint construction techniques. A synthesis of the literature review is provided in Appendix A for those desiring more details. Photographs from the field inspection are provided in Appendix B.

### 2.1 Literature Review

A detailed literature review was performed as a part of this study. A summary of the most pertinent references is provided in Appendix A. This section is a synthesis of the sometimes conflicting observations and evidence uncovered through the literature review.

#### 2.1.1 Joint Construction Techniques

Many case studies and other research efforts have been directed at identifying the best performing joint types. Techniques investigated have typically included:

- Echelon or tandem paving;
- Various rolling patterns;
- Joint types, specifically butt, tapered and notched wedge;
- Edge restraining or precompaction devices;
- Infrared joint heaters;
- Cutting wheels;
- Joint adhesives and
- Joint sealers.

These options will be discussed further here.

While not the focus of any identified research efforts, full-width paving is obviously preferred where feasible. By paving the full width of the pavement or pavement and shoulders in one pass, no joint is created. This option is limited, however, by practical issues such as the pavement width, size of equipment needed, production capacity of the hot mix plant and paver, and the necessary lack of traffic. Echelon paving with two pavers nearly side by side may sometimes be performed where the pavement is too wide for full-width paving, but also requires no traffic. Tandem paving may be an option where limited traffic has to be maintained. This type of paving is similar to echelon paving, but the two pavers are separated further so that traffic can pass between the pavers and travel on the newly placed mat. Often, a pilot car is used to guide traffic through the work zone. Both echelon and tandem paving involve two pavers, which increases costs and requires high production from the hot mix plant. Tandem paving has increased costs for traffic control and may entail safety considerations. The use of these options is severely limited, mainly because of traffic considerations, and they are rarely used though perform well when feasible. Designers can consider

accommodating this type of paving when preparing contract documents (4).

When cold joints are required, the most common attempts to improve performance involve various rolling patterns. There is a great division of opinion on which rolling pattern is the best. Researchers, contractors and even state specifications offer conflicting direction on this matter. Most seem to agree that an unconfined edge should be rolled with the edge of the roller overhanging the edge of the mat by about 6 in. This directs the energy of the roller downward with little lateral distortion of the edge of the mat (6). A few, however, suggest keeping the roller back about 6 in. from the edge of the mat (7). There is also a difference of opinion regarding rolling a confined edge; there are those who advocate overlapping the joint (5) and those who pinch the joint by keeping the roller entirely on the hot side for the first pass. For example, Kandhal and his various co-authors observed opposite results in Michigan and Colorado (8–10). It has been suggested that pinching the confined joint may result in a ridge that is not fully compacted by the later roller passes (6).

Different shapes of joints have also had varying degrees of success. The vertical or butt joint is the conventional and most commonly used joint type. Evidence shows that this type of joint can be well constructed with attention to detail, but they can also perform poorly if not constructed properly. Because of the sometimes problematic performance of these joints, other joint types have also been explored.

Butt joints may also present safety issues when traffic is maintained during construction of thick lifts (2). As traffic attempts to cross from one lane to another, the edge drop off can cause handling problems. Therefore, many states require that adjacent lanes be paved within a fairly short timeframe when butt joints are used (7,11,12). This requirement affects productivity as time is lost backing the paver up to pull the adjacent lane, so many contractors find alternate joint shapes more attractive.

Tapered and notched wedge joints avoid problems with safety at the edge drop off by creating a small ramp that traffic can more easily traverse. The tapered joint is simply a sloped edge, but tapering down to almost zero can be challenging, especially with coarse or large nominal maximum aggregate size (NMAS) mixes. The notched wedge joint was first used in Michigan in 1985 (1) in an attempt to improve on the tapered joint. The notch at the top, and sometimes the bottom, provides space to accommodate the aggregate in the mix. Notched wedge joints are growing in popularity but can still have issues. For example, if traffic crosses before the adjacent lane is placed, the notch can be distorted or obliterated. There are also sometimes problems with compacting the wedge, which can result in lower densities near the wedge. Coring over the wedge can also be problematic since various percentages of the cold and hot side of the joint can be sampled depending on the exact location of the core.

The FHWA is currently promoting the use of the so-called Safety Edge for the outside edge of lanes where

the shoulders will be aggregate or earthen. Frequently the shoulder material is eroded away or displaced by rain or errant traffic. If the edge of the lane is vertical, the same handling problems as noted with butt joints during construction can be experienced. The inability to control the vehicle or overcompensating when attempting to return to the travel lane has resulted in many accidents and fatalities. The Safety Edge uses a device to form a wedge at the outside edge of pavement that allows vehicles to return to the proper lane more easily. It has been observed that this device may provide some confining pressure at the outside edge of the lane that can result in higher densities (13).

Predating the Safety Edge, there have been several attempts over the years to provide confining pressure at the edge of otherwise unconfined mats. Various brands of edge restraining or precompaction devices have been manufactured commercially or by individual contractors. Some are attached to the paver and others to the roller. Results with these have been mixed, at best (9,10,14–17). It has also been observed that successful use of these devices often requires considerable skill on the part of the operator (14).

Another option to promote good joint performance is the use of infrared heaters to heat the edge of the cold mat before placing hot material beside it (2,9,10,18–20). The goal is to reheat the pavement enough that it will adhere well to the adjacent lane, similar to a hot joint formed during echelon or tandem paving. These devices have achieved some success but there are potential operational and technical issues with their use. From an operational point of view, using heaters towed in front of the paver require additional equipment and manpower, and lengthen the paving train. These devices can also interfere with trucks delivering mix to the paver. Heaters mounted on the side of the paver can be in the way and cause workers to be more exposed to traffic. Heaters can also overheat or scorch the pavement, especially if they fail to turn off automatically when the paver stops. The cost is also higher because of increased needs for equipment, manpower and energy. Nonetheless, because these heaters can help to create more monolithic joints, they are used fairly often in some parts of the country.

Another option is to remove the low density material from an unconfined edge before placing the adjacent lane. This can be done with a cutting wheel or the sharpened edge of a blade or bucket. Again, this has had mixed success (5,8–10,14–16). The concept seems reasonable but the implementation is challenging. The operation requires considerable skill to produce a straight, clean edge (14); if the edge is not straight, it is more difficult to overlap when paving the next lane to provide enough material to form a good joint. It also creates debris that must be removed by brooming or by hand before paving. All of these activities also increase paving costs. The cutting wheel is not commonly used for roadway paving for these reasons.

On mill and fill projects, an effect similar to that of a cutting wheel can be achieved by milling and filling one lane at a time. In this way, the edges of the lane are

never unconfined. In order to ensure complete removal of the old material, on the second pass, the milling machine should overlap the newly placed lane slightly. So, while this method can avoid compacting an unsupported edge, some new mix is wasted (or rather added to the reclaimed asphalt pavement [RAP] stockpile). There is also a possibility that the material just outside the edge of the milling machine may be damaged (perhaps by microcracking) in the process. Lastly, milling is usually done by a subcontractor, so milling and filling one lane at a time might require the sub to stay on the project longer or return to the project to mill the second lane.

Joint adhesives applied during and joint sealers applied after joint construction have been used extensively (2,5,16,20–24). Joint adhesives are applied either to the underlying lift in the area where the joint will be formed before paving the first lane or are applied to the face of the cold side of the joint after the first lane has been placed and compacted. The heat of the mix placed against the adhesive is intended to mobilize the adhesive to migrate into the mat to some extent and to allow it to bond the hot and cold sides of the joint together. Joint adhesives do not increase the density of the joint necessarily, but rather are supposed to reduce the permeability at the interface by reducing the number of interconnected voids and to bond the sides of the joint together. There have been differences in performance reported with adhesives, as with other techniques. For example, Fleckenstein (15) reported an improvement in permeability when a joint adhesive was used and Williams (24) reported no change in permeability. Although adhesives were not consistently effective at reducing permeability, the only real problem that was apparently caused by the adhesive was one case where it was applied to a concrete pavement, which did not allow the adhesive to penetrate when heated; excess adhesive then migrated upwards into the asphalt layer, creating an area of the mat that cracked at the interface between the over-asphalted and normal areas (25).

Lastly, joint sealers have been evaluated many times (23,25,26). These materials are applied over the top of joints after fabrication in an attempt to seal the top and stop the ingress of water. (The terminology used is sometimes imprecise; some materials (23) are occasionally called sealers but are applied to the face of the joint only, where they act more like adhesives.) Like joint adhesives, the sealants do not necessarily improve the density, but they may reduce the permeability of the mat. Generally these sealants have been relatively easy to apply though their application must be coordinated with installing pavement markings so that the markings are not obscured. Like the adhesives, their performance has not been uniformly effective but they do not appear to have caused any problems.

### 2.1.2 Testing and Specifying Quality Joints

Von Quintus and Rohan evaluated the factors contributing to asphalt pavement distress and demonstrated

that poor joint quality is one of the main causes. Their highest recommendation for improving pavement performance was to implement a longitudinal joint specification (27). An end result specification that allows contractors some flexibility in how they construct a joint is generally preferred over a method specification (6).

Implementing a specification, however, requires some means of testing the joint. The most commonly used method for testing the joint is to measure the density near the joint. Both nuclear and non-nuclear gauges have been used (5,28–31). Results from these studies differ, but overall nuclear density gauges seem to be preferred because they were usually found to have more sensitivity and less variability than non-nuclear gauges. This was not true in every case (31). Believing that permeability is more important than density, many researchers have looked at measuring permeability in the field (32,33). Given the fact that density gauges of some type are usually present on the jobsite any way, however, they are used much more often than permeability meters. Other, more elaborate measurement techniques have also been researched, but have not gained traction (34).

### 2.1.3 Best Practices for Joint Construction

Through the literature review, many best practices for joint construction have been identified. In addition, a report by the Asphalt Institute (35) is nearing publication and includes a number of recommendations. Some of the key recommendations include the following.

Choices made during the design phase of a project can impact the ability of a contractor to avoid constructing joints or to construct good joints, if they are unavoidable. Some of these considerations were detailed by McInnes et al. (4) and include:

- Designers should consider ways to accommodate echelon or tandem paving in contracts. Considerations include:
  - Ensuring paving quantities are large enough to make this type of construction cost effective. There are additional mobilization and operation costs for two pavers and sometimes for additional traffic control. A minimum tonnage of about 10,000 tonnes is suggested as the break point at which these techniques would be feasible. It is also pointed out in this report that the hot mix plant must have sufficient capacity to feed two pavers simultaneously or productivity will suffer.
  - Echelon or tandem paving may not be appropriate if different materials or lift thicknesses are used on adjacent areas, such as mainline and shoulders. Designers should consider whether the cost of using premium materials and deeper lifts on the shoulders can be offset by improved efficiency and requiring fewer mix designs. They should also consider that having higher quality shoulders ultimately may be a benefit when traffic is diverted to the shoulders during rehabilitation and maintenance work or in emergencies.
  - The possibility of closing lanes or diverting traffic to accommodate echelon paving should be considered,

but will depend on traffic volumes and alternate routes. The report advises that it is usually not cost effective to construct median crossovers for paving operations, but there may be cases where it is, especially if the crossovers are needed for other purposes.

- Nighttime lane closures may be feasible because of reduced traffic when daytime closures are not. Requiring nighttime lane closures should be considered during the design period because there are issues that need to be considered, such as noise restrictions near the plant, truck traffic restrictions in some municipalities to reduce noise, the need for supplemental lighting and other concerns.
- Requirements restricting the length of time that milled surfaces can be left open to traffic may need to be reconsidered when echelon paving is discussed for projects involving milling as it can significantly impact the timing and efficiency of paving and the safety of the traveling public.
- The need to provide access to businesses and property may make closing lanes for echelon or tandem paving not feasible.
- Since surface courses are thinner, they can typically be paved more quickly, so it may be possible to pave the surface course in echelon even if underlying layers cannot be paved that way.
- Constructing a good longitudinal joint can be hampered if temporary concrete barriers for traffic control are too close to the edge of the paved area. A minimum offset of 300 mm and desirable offset of 1500 mm are recommended. Barriers could potentially be moved temporarily to allow for paving but there are additional costs associated with that. There may be opportunities, however, to coordinate paving with other work to avoid moving barriers repeatedly. These situations should be noted in the contract documents.
- Scheduling the contract can also affect the ability of the contractor to construct a good joint. If the contract letting and amount of work push paving into colder times of the year, achieving good joint density can be more difficult. Requirements could be included in the contract to defer paving until the spring.
- It may be easier to achieve good joint density with finer mixes. Alternately, smaller NMA mixes might be used (35).

If joints must be constructed, there are some best practices that can help to ensure good performance. The list below represents a synthesis of the various recommendations from an extensive review of the literature (1,2,4-6,8-10,13-22,24-25,35).

- Segregation at the edge of the lane can make the mix more permeable and contribute to joint durability problems, so steps should be taken to control segregation. Operation of the paver can cause edge segregation if the head of material at the augers is not kept consistent or if the augers are operated too fast.
- The placement of joints in different lifts should be planned out before construction to ensure that joints are staggered so that they do not line up one atop the other (a 6 in. offset is typically recommended) and so that the joint on the surface lift is placed at the edge of a travelled lane. If the joints fall in the wheelpath, damage can be

accelerated as traffic forces air, water and incompressibles into the joint.

- The first lane, and subsequent lanes, should be paved to produce a smooth edge line. Paving adjacent to a wandering line is challenging and can lead to a lack of material to compact into the joint.
- When paving adjacent to a compacted edge, the paver should slightly overlap the previous lane (by 1 to 1.5 in.). This material can be compacted into the joint. It should not be broadcast across the lane; i.e., the excess material can be bumped back but should not be luted across the lane. The material is needed at the joint, not halfway into the lane. If there is sufficient overlap, there may be a slight difference in elevation on opposite sides of the joint. A very smooth transverse profile across the joint may be a sign of inadequate material and low density.
- On mill and fill projects, it may be possible to mill and fill one lane at a time so that all edges are confined edges.
- The rolling pattern can be varied to achieve the best density. Overlapping the unconfined edge by about 6 in. and rolling the confined edge from the hot side, overlapping the cold side by about 6 in., are most often recommended.
- Other rolling patterns may also work well depending on a number of variables. The best rolling pattern to use in a given situation may vary depending on lift thickness, underlying layer, mix type, aggregate properties, mix and ambient temperatures, type of compaction equipment available and many more.
- Similarly, the use of specialty equipment for joint construction may work in some cases, but not all. Joint heaters have generally performed well but cost and operational issues must be considered. Edge restraining and precompaction devices have had mixed success. Cutting wheels have been problematic but do work in some cases. The edge restraining devices and cutting wheels seem to be particularly operator dependent.
- Notched wedge joints have been well received in many states, though are not universally accepted.
- Joint sealers and joint adhesives may be useful but have not proven to be consistently effective. Nonetheless, they have rarely (if ever) contributed to real performance problems, so may be a reasonable contingency measure.
- Even if a joint adhesive is used, it is important to take steps to produce acceptable density in the area of the joint to prevent deterioration outside the area of influence of the adhesive.

## 2.2 State Specifications and Other Guidance

A review of state specifications and other directives (general guidance, special provisions, test methods, etc.) was also conducted as a part of this study. A summary of some of the most relevant findings follows, beginning with a review of the current specifications and other materials from Indiana.

### 2.2.1 Indiana

In regards to QC/QA asphalt pavements, the current INDOT specifications (36) state simply in 401.15 that longitudinal joints at the surface shall be located at the lane lines and the joints in underlying courses should be offset by about 6 in. (150 mm). Offsetting the joints

helps to prevent water intrusion by breaking up what could otherwise be a direct path through the pavement, as explained in the INDOT General Instructions to Field Employees, section 13.14 (37). Other details about how longitudinal joints are to be constructed in QC/QA pavements are left up to the contractor. (Longitudinal joints in SMA surfaces are also required to be at the lane lines, as specified in 410.15.)

Density of QC/QA pavements is a significant pay factor, but density cores are to be taken at random locations no closer than 3 in. (75 mm) from confined edges and no closer than 6 in. (150 mm) from unconfined edges. These density cores may pick up some influence of the joint density, as the literature review showed, but they likely will not detect the lowest densities, which typically occur right at the joint. The lower specification limit for density in terms of the  $\%G_{mm}$  is 91.00%; there is no upper limit. (For less than one lot of dense graded mix, densities of 97.0% of  $G_{mm}$  or greater or 88.9% or less are adjudicated as failed material and pay factors vary depending on the  $\% G_{mm}$  above or below that level. For open graded mixes, 100% pay is achieved at 84.0% of  $G_{mm}$ .)

For HMA pavement not covered by QC/QA specifications, i.e., 402 pavements, the same requirement about placing longitudinal joints in the surface at the lane lines and offsetting joints in underlying layers is also required in 402.14. For these mixes, though, the compaction process is specified in detail because density cores are not taken; four options are specified for the roller train and number of roller passes on courses of 440 lb/sq yd (240 kg/m<sup>2</sup>) or less, and two options are available for thicker courses. Section 402.15 specifies that confined edges be pinched, that is the roller is to be held back about 6 in. (150 mm) from the joint on the hot side. Unconfined edges are to be rolled with the roller extending 6 in. (150 mm) beyond the edge of the mat; this conforms to the most commonly recommended practice.

Indiana also has added the Safety Edge to the specifications when the shoulders are aggregate or earth. The Safety Edge device may provide some confinement at the otherwise unsupported edge and may improve the density in that area (13).

In addition to the Standard Specifications and the GIFE, INDOT has some other requirements or options for longitudinal joints. A recent recurring special provision, effective with lettings on or after September 1, 2012, calls for use of a hot poured joint adhesive on longitudinal joints in all surface courses and the top lifts of intermediate mixes. The adhesive is to be applied to the cold face of the joint with a wand applicator at a thickness of 1/8 in. (3 mm). After density cores are pulled, the surface mixes with joint adhesive are to be sealed with an emulsion (38). The adhesive addresses the durability and bonding at the joint while the fog seal addresses permeability surrounding the joint.

INDOT also has on the books a March 2000 construction memorandum encouraging the use of notched wedge longitudinal joints (39). This memo details a 0.5

in. (13 mm) notch and a 12 in. (300 mm) taper. The memo gives contractors the option of using this type of joint, but it is rarely exercised. When originally implemented, if contractors used the notched wedge, they were not required to pull up the adjacent lane the same day, which made use of the notched wedge attractive from a productivity viewpoint. Later pulling up the adjacent lane was required even if the notched wedge joint was used, effectively removing the incentive to construct a notched wedge. The reasons for the change are not widely known. Perhaps with the implementation of the safety edge and its similarity to the notched wedge, this requirement could be revisited.

### 2.2.2 Michigan DOT

The Michigan DOT will be discussed in somewhat more detail than the other states because they have a recent (2012) special provision for Acceptance of Longitudinal Joint Density in HMA Pavements (7). The Pennsylvania DOT's recent specification change will also be discussed in some detail in the next section.

Despite being closely associated with the notched wedge joint, MDOT allows either vertical joints or "tapered overlapping" joints. When vertical joints are used, the contractor must pave the adjacent lane on the same day, which is not a requirement for the tapered joint. The unconfined edge of vertical joints is first compacted with the roller 3 to 6 in. inside the edge of mat, and the second pass is made with the roller overhanging the edge. The confined edge is also pinched in, with the first roller pass 6 to 8 in. inside the joint. The notched wedge joint is formed with a 0.5 to 1 in. notch and a 1:12 taper. The taper is coated with a bond coat before paving the adjacent lane.

The special provision requires that 6 in. cores be taken at random locations centered on the joint between adjacent lifts at the surface. (Mat cores for determining mat density are taken a minimum of 15 in. from the joint.) Cores may be taken at a rate of one per 2000 ft. of joint. The density of the cores is determined relative to the production  $G_{mm}$  and five consecutive cores are averaged. The average joint density must be equal to or greater than 89% of  $G_{mm}$ . Pay adjustments are assessed for values below 89%, incentives are awarded for values above 90% and production is terminated at values below 87%. Dispute resolution procedures are also provided in the special provision.

### 2.2.3 Pennsylvania DOT

The Pennsylvania DOT used a method spec for longitudinal joints until fairly recently and did not measure joint density. In 2006 and 2007, they began measuring joint density to build a baseline for comparison and to explore different construction techniques. They also looked other states' experiences and developed a list of best practices, which they distributed around the state. In 2008 and 2009, densities were again measured to see what impact the best

practices had on joint density. Average joint densities increased about 1% in one year after promoting the best practices (from 87.8% in 2007 to 88.9% in 2008). Since there were still problems with joints, PennDOT worked with industry and FHWA to develop an end result percent within limits (PWL) specification. Density measurements in 2011 showed a further increase in joint density although the average mat density was relatively constant from 2007 on at about 94%. The average joint density in 2011 was 91.1% (40). This increase indicated to PennDOT that the joint density specification was effective at improving joint construction.

The PennDOT PWL specification includes incentives and disincentives. The minimum joint density for full pay is 89% of the  $G_{mm}$ . Incentives up to \$5,000 per lot can be earned for higher densities. The disincentives for low densities can amount to as much as \$12,000 per lot. If the average joint density of a lot is less than 88.0% of  $G_{mm}$ , the contractor is required to apply PG binder over the joint to act as a sealer. Density is measured on one core for every 2500 linear feet of longitudinal joint in surface courses where the mix on each side of the joint was placed under the same contract (40).

Based on the fact that contractors have been able to achieve the target joint density and that bonuses were achieved for 71% of the lots, the minimum joint density requirement will be increased to 90%  $G_{mm}$  in 2013 (40). (In 2011, 18% of the lots received a disincentive and 11% were neutral.)

PennDOT's evaluation of their PWL specification also involved looking at the factors that had a significant effect on joint density. The type of joint—butt vs. notched wedge—was found to have a major impact. The density of the notched wedge joints was 1.5% higher than the butt joints. This large discrepancy may be due to a lack of material in the butt joints. Most of the contractors building notched wedge joints used vibratory plates attached to the paver to compact the wedge. The time of year when the surface was placed also had a significant impact, with most of the low densities occurring from late August through October, when temperatures are lower. The densities of warm mix project were not found to be higher than for hot mix, but contractors reported that the densities were easier to obtain with warm mix. Binder grade (PG 58-22, 64-22 or 76-22) did not have a significant impact (40).

The overall conclusion from PennDOT was that the PWL specification was leading to improved joint construction. The joint density is being improved while mat densities are remaining unchanged, suggesting that it is the increased attention to joint density that is resulting in the improvement. The increase in the required minimum density is expected to further improve joint construction while being achievable.

#### 2.2.4 Other States

Not surprisingly, perhaps, state specifications vary widely in requirements for longitudinal joints, measuring

density and many other factors. This section summarizes some of the practices enforced by other states in the region and some states that are generally recognized as leaders or that are unique in their approaches.

In the 2010 standard specifications, *California* (41), like most other states, requires that longitudinal joints in the surface layers be at the edge of lanes and underlying joints be offset at least 6 in. CalTrans uses density cores taken to represent every 250 tons of HMA. Full pay is obtained for densities between 91 and 97% density for standard construction and between 92 and 96% for QC/QA construction. CalTrans also has a method specification for use in special situations. No specific longitudinal joint density requirements were found in the specifications.

The *Florida* DOT (42) uses five 6 in. (150 mm) diameter cores for density testing in each lot. The minimum density required is 93% of  $G_{mm}$  for coarse mixes and 90% for fine mixes. Florida is somewhat unique in that they require checking the permeability of cores during the initial production subplot if the density is low. Again, no specific joint density requirements were found.

The *Georgia* DOT specifications (43) require tacking the face of longitudinal joints before placing the adjoining mat. The goal is to construct sealed, bonded, smooth joints.

*Illinois* (44) requires a notched wedge joint, with a 1 to 1.5 in. notch at top and bottom and a 9 to 12 in. wide taper, when the difference in elevation between lanes is greater than 2 in. and the roadway is open to traffic. The entire face of the joint is to be coated with prime before placing the adjacent lane. The wedge joint is compacted with a roller attached to the paver weighing 50 lbs per in. of width and with a width equal to the wedge.

The *Iowa* DOT (45) requires that the faces of longitudinal joints be tacked before paving. Joints in underlying layers are to be offset 3 in. or less and sufficient material is to be placed “to secure complete joint closure and full compression of the mixture with a smooth surface and joint after compaction.”

Quality control under the *Kansas* DOT specifications requires the use of a Nuclear Density Gauge. A reading is taken 8 in. (0.2 m) away from the longitudinal joint. Readings are taken from the interior of the mat to find an average interior density. If the interior density minus the joint density is more than 3.0 lbs/cu. ft., the paving is suspended. The joint density is also considered inadequate if it is less than 90% of maximum specific gravity ( $G_{mm}$ ). Paving then continues for 2000 ft. if the density tests have been passed. The longitudinal joints are bonded and sealed with asphalt emulsion or asphalt binder. A sufficient amount of HMA is then deposited to ensure a tight and smooth joint (46).

The *Minnesota* DOT requires an emulsified asphalt tack coat on the face of all longitudinal joints (47).

The *Missouri* Department of Transportation requires that the density of a longitudinal joint must not be



more than 2% less than the interior density of the mat. Density measurements are taken on core samples no later than the day following the placement of HMA. A tack coat may be required on the unconfined edge before the joint is formed, if directed by the engineer. MoDOT uses the common offsets of at least 6 in. with the joint in the surface course being at the edge of the lane (48).

The *Nebraska* Department of Roads requires that a tack coat of emulsified asphalt be applied to a longitudinal joint prior to placement of the adjacent mat. Joints are directed to be parallel and at the edge of major traffic lanes (49).

The *New York* Department of Transportation implements two methods of creating longitudinal joints with HMA. The first method is a butt joint which overlaps the cold mat by 2 to 3 inches. This excess HMA is raked onto the hot mat and then compacted into the longitudinal joint. The second method practiced by NYSDOT is a tapered wedge joint. A step-down greater than 0.5 in. is formed followed by a 1 on 8 slope. The specs direct that the roller should not overhang the step-down during compaction of the first mat. NYSDOT collects data from HMA by utilizing nuclear density gauges, non-nuclear density gauges, core samples, and loose mix samples (50).

The *Ohio* DOT encourages full-width or echelon paving (401.17). When cold joints must be formed, they are to be rolled with a three wheeled roller, then coated and sealed with PG binder or rubberized asphalt emulsion. The adjacent lane must be placed within 24 hours, when under traffic (51).

*Texas* requires that longitudinal joint densities must be no more than 3% less dense than the average mat density. Density measurements are taken through core sampling (52).

The *Virginia* Department of Transportation states that a tack coat should be placed on a longitudinal joint unless the adjacent mat is being placed in echelon to the first. Density measurements are determined using a nuclear density gauge along with core samples taken from the HMA. Virginia does require that the pavement be rolled from the unconfined edge towards the confined edge (53).

The *Washington* State Department of Transportation states that the adjacent lane to a longitudinal joint should be placed no later than the following day after the first mat was placed. Density measurements are taken with a nuclear density gauge along with core samples. Densities must be greater than 90% of the maximum density. If one density reading is below this level, a \$200 price adjustment is applied to that subplot. The notched wedge joint is standard. The notch depth is greater than the maximum aggregate size and less than half the lift thickness. The taper is sloped less than 4:1 and must be “uniformly compacted” (54).

The *Wisconsin* DOT does allow for construction of notched wedge joints or butt joints but if butt joints are used, adjacent lanes on multi-lane roadways must end at the same station. Notched wedge joints are required

for certain lift thicknesses. The joint must have a 0.5 to 1 in. notch at the top and a 12:1 taper. A roller is required for compaction of the wedge and tack coat is applied before paving (55).

## 2.3 Field Evaluations

Prior to implementing the recurring special provisions for joint adhesive, effective September 1, 2012, INDOT had about eight projects using joint sealants or joint adhesives. Most of these projects were let between May 2009 and November 2011. Two, however, were let in 2002 and 2003 in the Vincennes District. The good performance of these projects encouraged wider adoption of the material.

In July 2012, the principal investigator (PI) visited all of these projects to observe their current condition. Brief summaries of the perceived performance of the joints are provided in Table 2.1. Overall, the joints are performing quite well, but some are still very new.

In the oldest two projects, some distress is starting to appear but it is quite minor at this point. There is some minor cracking beginning to appear near the joint and some minor braiding of the crack is beginning in the eastbound lane of I64 just before Exit 4. These were warranty projects, so the contractor chose to use joint adhesive and likely paid more attention to details that could affect performance, such as joint construction.

In order to get some idea of how well the surface was compacted in the vicinity of the joint, water was poured onto the surface, across both sides of the joint, in the westbound lane of I64 near Reference Post 7.0. If areas of the mat were not well compacted, the water would likely be absorbed into the pavement rather quickly (as shown in Figure 1.2). It was assumed that the density would be higher in the wheelpath because of traffic densification, but outside the wheelpaths, the density could be lower. After observing the water for over 15 minutes, the PI saw very little absorption into the pavement. Though informal, this suggests that the mat was fairly uniformly compacted and there was not a severe decrease in density in the area of the joint. Achieving good compaction in the area of the joint will definitely help to promote low permeability. Poor density surrounding the joint may eventually lead to deterioration, though a joint adhesive may delay the problems. It appears the joints on these I64 projects will perform much longer, given routine maintenance. Longer term monitoring of these projects is recommended.

On the newer projects, the joints are generally in good to very good condition, with only small cracks or separation on some projects. These are quite new projects, however, so would be expected to be performing well at this time. The adhesive is visible in some places, showing that it is present near the surface. There are some places where joints are near the wheelpaths, especially near intersections with turn lanes.

Only the US40 project in Richmond had a true control section. Both the westbound lanes with the joint

TABLE 2.1  
Summary of 2012 Observations of Performance of Experimental Projects in Indiana

Contract	Route	Letting Date	Joint Treatment	Condition/Observations/Comments
??	I64	2002 2003	Crafco Joint Adhesive	Generally in very good condition. Some areas of cracking in joint area with minor braiding beginning. Joint adhesive visible in some places. Cracking has initiated but generally has not progressed far. Density appears to be fairly uniform around joint.
R-29560	US40	5/6/09	WB—Joint Adhesive EB—Control	Both directions look very good overall. In some areas joint is virtually invisible; in others visible but tight. Westbound may be slightly better. In some areas, joint is approaching wheelpath.
SRS-30083	SR23	5/20/09	Double Tack Coat	Joints have separated and been sealed. Roadway exhibiting other distresses too, indicating there may have been other problems on this roadway. The separation at the joint suggests a double tack coat is not sufficient to promote good bonding.
R-31907	SR23	9/10/09	Crafco Joint Adhesive	This project includes three sections; one is conventional mill and fill, second has a fiber reinforced asphalt membrane and the third has a stress absorbing membrane interlayer (SAMI). The mill and fill appears to have somewhat more cracking, judging by the amount of crack seal. Joints are similar in the three sections—some separation, little to no deterioration. This road was reportedly in very poor condition prior to the rehabilitation.
RS-32007	SR38	10/6/10	Joint Adhesive & Corrugations	Joint here showed some separation in some areas and virtually none in other areas. There may be some cracking next to joint adhesive.
RS-30769	SR120	3/9/11	Joint Adhesive & Corrugations	Generally the joint looks quite good in this section.
RS-30340	US35	5/11/11	Joint Adhesive & Corrugations	This project includes two different configurations of centerline corrugations. There seemed to be a bigger separation/crack at the joint in test section 2, though it is not known if this could be related to the shape of the corrugations. Joint in test section 1 looks tight. This project was milled and filled one lane at a time. No fog seal was applied.
RS-30917	US231	11/16/11	Joint Adhesive & Corrugations	This section was recently paved so no photographs were taken.

adhesive and the eastbound control section without adhesive are performing well. Monitoring the performance of the joints on this project to compare joints with and without adhesive could help to guide future refinements to the joint construction requirements.



Figure 2.1 Open joint in newly constructed roadway in Indiana, 2012.

The project on US35 was constructed by milling and filling one lane at a time. The performance of this project, then, might help to indicate whether the milling causes any damage in the adjacent material that could cause deterioration. This would help INDOT determine if the practice should be promoted or restricted in the future.

While traveling around the state doing the field inspections, the PI observed many joints that appeared to be performing well. Not all joints were faring as well, however. Some joints seem destined to fail. Figure 2.1 shows a joint on a state roadway shortly after construction in 2011. This joint appears to have been starved of material, either through a lack of overlap by the paver when placing the second lane or not allowing for roll down of the material. Because this joint is so open so early in its life, its durability is questionable.

### 3. CONCLUSIONS AND RECOMMENDATIONS

Based on the information presented in Chapter 2 and in the appendices, a number of conclusions have been reached. In turn, recommendations for implementation have also been developed. Discussion of the conclusions and recommendations follows.

### 3.1 Conclusions

Poor performance at longitudinal joints is frequently a contributing factor reducing the service lives of asphalt pavements. Improving the durability at longitudinal joints could have a great impact on pavement performance.

Many different methods for compacting longitudinal joints have been used in the past with varying degrees of success. The ability to compact a joint that will be durable and will perform well is heavily mix and site specific, which may help to explain why so much of the research is somewhat contradictory. Therefore, it seems advisable to allow many options that contractors can choose between to suit the particular circumstances at individual jobsites. Table 3.1 summarizes the advantages, disadvantages and likelihood of success of the various options.

That said, however, some things do seem to be true in most cases. For example, there are decisions made during the design phase of a project that may impact compactability. These include such things as lift thickness, nominal maximum aggregate size, mix type, lane configuration, traffic control requirements, project scheduling and sequencing, and more.

There are also factors that are within the control of the contractor. Since contractors in Indiana design their own mixes, they can opt to use a fine mix, which may prove to be easier to compact. In addition, they can establish their own rolling patterns to achieve the best density in an efficient manner (with the exception of 402 mixes where the options are limited). The use of notched wedge joints is an option that is available to contractors in Indiana, and they have proven successful in many states, but the incentive to use notched wedge joints to avoid the productivity loss when backing up the paver to pave the adjacent lane is no longer available.

The use of joint sealers and joint adhesives have not been proven to be effective at reducing permeability in all cases but have rarely, if ever, caused construction or performance problems. They are, therefore, reasonable preventative measures.

A joint quality specification can be an effective way to improve performance. Most specifications are based on establishing minimum joint densities in comparison to either the mat density or the maximum theoretical density of the mix. A density of 90% of the maximum theoretical density is sometimes used as the minimum for 100% pay. Another common density requirement is that the joint density be not more than 2% lower than the density near the center of the mat. Managing a joint quality specification is not without issues but is a feasible option to consider in the future.

While permeability may be a more appropriate measure of a joint's resistance to water and air intrusion, density is already being measured as a part of QC/QA activities. So, measuring joint density is a widely accepted and readily implementable practice. When nuclear (or in some places non-nuclear) gauges

are used, they should be calibrated to the specific mix and project characteristics through the use of a test strip and correlation with core densities. Core densities should be determined using either the Corelok or saturated surface dry method, as preferred by the agency. Ultimately, core densities are the preferred measure (such as for dispute resolution). Establishing the appropriate  $G_{mm}$  value to use when the mixes on opposite sides of the joint may differ would need to be addressed; perhaps a conservative  $G_{mm}$  value could be selected and the minimum density specified accordingly.

Seating a nuclear or non-nuclear gauge properly can be problematic at the crown of a pavement. In this case, it may be possible to take density readings on each side of the crown and average the results. With a notched wedge joint, the density should be measured at the center of the wedge, understanding that this represents a combination of the densities of the cold and hot sides of the joint.

#### 3.1.1 Overall Conclusions

Examination of Table 3.1 shows that all of the joint construction techniques considered have advantages and disadvantages. Based on the literature review, survey of state practices, and current INDOT specifications and experiences, some of these techniques can be identified as feasible and likely to succeed and some can be identified as less likely to succeed and not worth pursuing at the present time. The most generally successful and feasible techniques include:

- Variable rolling patterns
- Butt joints
- Notched wedge joints
- Sequential mill and fill (with reservations)
- Joint adhesives
- Joint sealants

How these techniques can be implemented (or their use can be continued) are addressed in the next section.

In addition, full width, echelon and tandem paving can work well where the contract, especially the traffic, can allow their use. Because the majority of contracts must be paved under traffic, however, use of these techniques is likely to be limited at best.

The uses of edge restraining, precompaction and cutting wheel devices are problematic and require highly skilled operators, in addition to other disadvantages. It is not recommended that INDOT promote the use of these devices in the future. If, however, a contractor approaches INDOT and wishes to use one of these devices, INDOT could consider allowing their use, provided good performance can be demonstrated during construction or some sort of performance warranty is offered. If construction issues are noted, the contractor should be required to revert to a more conventional technique.

The use of joint heaters is also not recommended. Their performance history, in the literature, is too

TABLE 3.1  
Joint Construction Techniques and Issues

Joint Treatment	Advantages	Disadvantages	Likelihood of Success and Acceptance; Recommendation
Full Width, Echelon or Tandem Paving	Avoids cold joint Good performance	Only tandem can be done under traffic Traffic control/safety issues with tandem Echelon and tandem require two pavers and two crews, which increase costs Need high capacity plant	Work well when feasible but rarely feasible, mainly because of traffic Implement when possible but will not be routine
Various Rolling Patterns (number and type of rollers, number and location of passes, timing of passes)	Can change easily when conditions change (temperature, mix behavior, etc.) Usually require no additional equipment or manpower	Since there is not one rolling pattern that works in all cases, experience or some tested property is needed to determine what works best in given situation	Changing rolling patterns is easy Little to no impact on cost Maintain the lack of restrictions for 401 mixes
Butt Joint	Common and familiar Can work well when properly constructed	Edge drop off requires pulling up adjacent lane (productivity impacts) Water can penetrate roadway easily if joint separates, especially if joints in underlying layers are not offset	Could work well with attention to detail but experience shows that attention is sometimes lacking Continue to require joint adhesive and fog seal
Tapered or Notched Wedge Joint	Avoid issue with edge drop off Can perform well if properly constructed Already have a construction memo addressing this Similar to safety edge, which is becoming more familiar and may provide confinement at the edge of lane	Requires compaction of the wedge Notch and taper dimensions need to be appropriate for NMAAS and layer thickness	Can be effective Not attractive to Indiana contractors unless requirement to pull up adjacent lane is lifted Revisit pulling up lane Consider requiring compaction (preferably with =vibratory plate attached to paver) for wedge
Edge Restraining or Precompaction Devices	Can increase density near joint	Requires skillful operator	Mixed performance at best Not worth promoting
Cutting Wheel	Removes low density material	“Wastes” new mix Requires equipment and manpower to cut and to remove debris Requires skillful operator	Mixed performance at best Not worth promoting
Sequential Mill and Fill	Removes low density material from unsupported edge at center of lane Does not require new/more equipment	May require milling sub to stay on job longer or return later “Wastes” new mix Milling action might damage adjacent mix in place	Expert opinions in state are mixed Maintain contractor option for now Evaluate existing sequential mill and fill projects to decide whether to encourage or restrict in future
Infrared Joint Heater	Avoids cold joint Increases adhesion at interface Works well in some places	Requires extra equipment and fuel Lengthens paving train Interfere with delivery trucks and paving crew Safety issues Can scorch mix	Mixed performance Not worth pursuing
Joint Adhesives	Improve adhesion at the interface No negative impacts on performance have recurring special provision Insurance against poor performance	Increase costs Require equipment and manpower Have not always demonstrated improvement in performance (permeability)	Cost increases are expected to be low when used routinely; increased performance can easily offset increase in costs Continue to require Monitor performance to support future decisions
Joint Sealer	Reduce permeability around the joint No additional equipment required No negative impacts on performance Have recurring special provision Insurance against poor performance	Increase costs Have not always demonstrated improvement in performance (permeability) Must be applied before pavement markings and after coring	Cost increases are expected to be low when used routinely; increased performance can easily offset increase in costs Continue to require Monitor performance to support future decisions

mixed. The potential worker safety issues and risks are not favorable.

### 3.2 Recommendations for Implementation

Based on the conclusions reached through a review of the pertinent literature, survey of state practices and current INDOT experience with longitudinal joint construction, the following implementation suggestions are offered.

- Continue the use of joint adhesives and joint sealers.
  - The use of joint adhesives will not likely solve all joint deterioration problems but may contribute to better performance overall by improving the durability of the joint and the bonding between opposite sides of the joint.
  - Joint sealers should continue to be used in conjunction with the joint adhesives and could be used during the service life as a pavement preservation technique to help resist further deterioration if a joint starts to exhibit distress. Some sealers that dry clear are coming on the market and may be useful where pavement markings have already been installed.
  - Performance of at least a sampling of projects with joint adhesives and sealers should be monitored for a number of years after construction to help assess if they are increasing the service life of the pavement and are cost effective. This monitoring should include the early projects on I64, which will give some indication of service life of the adhesives, and the US40 project, which has a control section without the joint treatment.
- Continue to allow the contractors to establish appropriate rolling patterns for 401 mixes.
  - Rolling patterns may need to change to adjust to differing site conditions, temperatures, mix properties, etc.
- Revisit the requirement to pull up adjacent lanes when using a notched wedge joint.
  - Notched wedge joints have been successfully implemented in several states. They should continue to be allowed as an option but their use should be made more attractive, if possible, because currently there is no incentive for contractors to use them.
  - Experience with the safety edge may make these joints more familiar and more attractive to Indiana contractors.
  - The improved productivity associated with avoiding the need to pull up adjacent lanes is of most interest to the contractors but can also ultimately benefit the travelling public (by shortening construction times and improving level of service) and the DOT (by improving joint density, increasing service lives and lowering life cycle costs).
- Consider implementation of a PWL joint density specification in the future.
  - The current requirement for a joint adhesive and joint seal is appropriate and will lead to improvements, but ultimately a joint density specification may lead to even

further improvements by increasing the density and reducing permeability overall.

- Hold this concept in abeyance until the performance of joints with the adhesive and sealer treatments and the cost effectiveness of those treatments can be assessed.
  - A joint density specification would provide a means for assessing whether various joint construction techniques or new materials are truly beneficial.
- Initiate a project to monitor joint performance before the collective memory of what has already been attempted is lost.
    - This project should include monitoring the performance of the earliest uses of joint adhesive on I64 to help determine the service life of the adhesive, comparison of the control and test sections on US40 to assess the effectiveness of the adhesive, and other existing or newly constructed sites to explore geographical, mix type, pavement cross section, joint types and other variables.
  - Communicate best practices to promote better longitudinal joint construction to a wide range of audiences.
    - Designers should be cognizant of the impact that their design decisions may have on construction so that they can avoid creating problems when possible. This could be accomplished by a session during a design workshop.
    - Contractors should be made aware of good practices and the options available to them. The National Asphalt Pavement Association has toolbox talks and other educational materials that can help in this regard. The Federal Highway Administration will be sponsoring workshops with the Asphalt Institute based on their upcoming report; plans are being made to offer one session in Indiana in February 2013. Joint construction has been, and will continue to be, featured at industry conferences, the Transportation Research Board Annual Meeting, user-producer group meetings and other venues. It should also be raised in pre-construction conferences to focus attention on the issue.

Through these new and continuing efforts, INDOT and the asphalt paving industry can strive to improve pavement performance by focusing attention on what is often the “weak link”—the longitudinal joint.

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## APPENDIX A. LITERATURE REVIEW

There has been a great deal of research and a large number of case studies of longitudinal joints for decades. This appendix summarizes, in some detail, many of the most relevant papers on the subject. The summaries are broadly categorized in terms of:

- Longitudinal Joint Construction and Performance,
- Joint Adhesives and Sealers, *and*
- Specifying and Testing Longitudinal Joints.

There is, however, considerable overlap between these categories. For example, many projects comparing different construction techniques for forming the joint also evaluate joint sealers or adhesives.

### LONGITUDINAL JOINT CONSTRUCTION TECHNIQUES AND PERFORMANCE

**Kandhal, P. S., and S. S. Rao. *Evaluation of Longitudinal Joint Construction Techniques for Asphalt Pavements (Michigan and Wisconsin Projects—Interim Report)*. NCAT Report 94-01, January 1994.**

On one project in Michigan and one in Wisconsin, seven to eight different longitudinal joint construction techniques were placed and evaluated. Each technique was placed in a 152 m (500 ft) test section. Only static rolling was performed in these two states. The methods included:

- Rolling from the hot side with a 6 in. overlap on the cold side.
- Rolling from the cold side with a 6 in. overlap on the hot side.
- Rolling from the hot side 6 in away from the joint.
- Notched wedge joint (12:1) without tack coat (compacted with small roller attached to paver in Michigan, not rolled in Wisconsin).
- Notched wedge joint with tack coat.
- Restrained edge compaction (tapered wheel attached to roller) on first lane then rolling from hot side with 6 in. overlap (not used in Michigan).
- Cutting wheel to remove 38–51 mm (1.5–2 in.) of unconfined edge (mounted on motor grader in Michigan but can be on intermediate roller) then rolling from hot side with 6 in. overlap on cold side.
- Joint Maker attached to side of screed.
- Observations made during construction included the following:
- Some segregation at the joint was noted in Michigan, probably due to the gradation of the mix used.
- Some overlap at the joint is needed; if there is no overlap, the paver operator needs to pay close attention to ensure the joint matches. A small deviation without overlap can produce a crack at the joint during construction.
- The edge compactor caused some construction difficulties when used at the edge of the material, as intended, because it caused shoving and tearing of the mat. The edge restraining device could not cover the entire depth of the uncompacted lift. Subsequently, the technique was modified to compact the entire surface first then use the edge restraining device, which could cover the depth of the partially compacted lift, but this essentially results in an unconfined joint.

Cores were taken in the joints and 610 mm (2 ft) into the hot side (5 cores each in each test section). No cores were taken on the cold side. Cores were analyzed to determine the densities and air void contents. Based on the average density at the joint, the Michigan wedge joint, cutting wheel and edge restraining device gave higher densities.

Nuclear gauge readings were taken to supplement the core data about six to seven months after construction. Readings were taken and analyzed at nine locations in each section at the joint and 305 mm (1 ft) away on cold side.

The density results showed that rolling from the hot side with a 6 in. overlap on the cold side was the most consistent; this also provided the highest densities among the rolling techniques. In

Michigan, the joint densities were actually higher than away from the joint, probably because the roller operator paid special attention to the joint; this is not typical. The results from Michigan indicated that the wedge joints, both with and without tack, and the cutting wheel gave the highest densities and were significantly different from the rolling techniques. The Joint Maker gave the lowest density but was not significantly different from rolling from the cold side.

The results were also analyzed in terms of relative density (density at the joint divided by density away from the joint, expressed as a percentage). Since the joint densities were higher than those away from the joint in Michigan, these results are probably not meaningful.

In Wisconsin, the edge restraining device and cutting wheel gave the highest densities followed by the notched wedge joints (with and without tack) and joint maker falling in a group. The three rolling patterns yielded lower densities. Rolling from the hot side with an overlap gave the highest density and lowest variability among the rolling patterns. When analyzed in terms of relative density, the cutting wheel and edge restraint again provided the highest relative densities followed by the joint maker and rolling from the hot side with overlap. It was noted that long term performance may change these rankings.

These results were also published in Transportation Research Record No 1469, Transportation Research Board of the National Academies, Washington, D.C., 1994, pp. 18–25.

**Kandhal, P. S., and R. B. Mallick. *A Study of Longitudinal Joint Construction Techniques in HMA Pavements (Interim Report—Colorado Project)*. NCAT Report 96-03, February 1996.**

This report documents the construction and early performance of seven longitudinal joint construction techniques used on one project in Colorado and two used on a project in Pennsylvania. The techniques were used in 152 m (500 ft) test sections in the wearing courses. The HMA in Colorado was essentially a 19 mm mix with a high percentage of material between the 19 and 12.5 mm sieves, making it prone to segregation. The Pennsylvania mix would be considered a 9.5 mm mix.

The joint construction techniques used in Colorado included:

- 3:1 taper tacked and rolled from hot side with 6 in. overlap. The taper was formed by a steel plate chained to the screed, which produced a fairly rough surface on the taper.
- 3:1 taper tacked and rolled from cold side with 6 in. overlap onto hot side.
- 3:1 taper tacked and rolled 6 in. away on hot side.
- 3:1 taper cut away with cutting wheel after cooling, vertical face tacked and rolled from hot side with overlap.
- 3:1 taper with 25 mm (1 in.) notch rolled from hot side with overlap.
- Unconfined edge coated with rubberized asphalt tack coat (no taper).
- No luting was done on any of these sections. Hot lane was 3 to 5 mm (1/8 to 3/16 in.) higher than cold side after construction.

On the Pennsylvania contract, the project was paved using a New Jersey wedge joint (3:1 taper). This wedge joint was formed by a steel plate attached to the inside corner of the screed extension. An infrared joint heater was used when paving the adjacent lane. A 152 m (500 ft) section using a conventional joint construction technique (unconfined edge tacked, hot lane compacted from hot side with 6 in overlap).

Cores were taken directly over the joints and 305 mm (1 ft) away on the cold side. In Colorado, cores were also taken 1 ft away on the hot side. No cores were taken from the section with rubberized joint sealant. The cores were analyzed to determine the densities and air void contents.

Based on densities, the joints in Colorado ranked as follows: first was the 3:1 taper with 1 in. notch, then the 3:1 taper cut away and face tacked. The joint with the lowest density was the 3:1 taper rolled from the hot side with overlap. The other techniques fell in between and were not significantly different.



In terms of relative density compared to the cold mat, there was no significant difference between any of the techniques except rolling from the hot side with overlap, which gave the lowest density but which was not significantly different from removing the 3:1 taper and not tacking the vertical face (i.e., those two techniques fell in a group and the 3:1 taper also fell in a group with the other four techniques).

The results were somewhat different when comparing the relative density based on the hot mat. In that case, the notched wedge joint produced the highest density and was significantly different from all the other techniques, which all fell in another grouping.

Overall, the authors concluded that the notched wedge joint was the best followed by removing the 3:1 taper with a cutting wheel and tacking the vertical face. When the three rolling patterns are compared, rolling the 3:1 taper from the hot side with overlap produced the lowest density. This is the reverse of what was observed in Michigan and Wisconsin (Kandhal and Rao, 1994).

There were no significant differences between the two methods used in Pennsylvania in terms of density, relative density or densities of the cold and hot halves of the cores over the joints.

After one winter, the joints were examined visually. Only slight to moderate distresses, predominantly raveling, were noted on the sections. There was some scraping, evidently by a snow plow, on the hot side of the joints in Colorado, where the hot side overlapped the cold side slightly.

These results were also published in Transportation Research Record No. 1543, Transportation Research Board of the National Academies, Washington, D.C., 1996, pp. 106–112.

**Kandhal, P. S., and R. Mallick. *Longitudinal Joint Construction Techniques for Asphalt Pavement*. NCAT Report 97-04, August 1997.**

This report expands on the previous two reports (Kandhal and Rao 1994, and Kandhal and Mallick 1996) and presents the longer term performance of the test sections in Michigan, Wisconsin, Colorado and Pennsylvania. In all, 30 test sections incorporating 12 different joint construction techniques were evaluated for periods of one to four years. The density and air void analyses were summarized above, so the discussion here presents the visual examinations. An exception to this is Pennsylvania, where additional test sections had been placed and inspected (in addition to the two discussed in Kandhal and Mallick 1996).

After three years in service, five of the seven test sections in Michigan had developed “a significant amount of cracking.” Only the 12:1 notched wedge joints (with and without tack) had not cracked. All three rolling pattern sections had cracking throughout the entire length. Rolling from the cold side produced the greatest severity of cracking and raveling on the cold side.

The Wisconsin project was inspected after four years in service and cracking, of varying severities, was observed on all eight sections. The performance, from best to worst, was:

- Edge restraining device,
- 12:1 taper with tack coat,
- 12:1 taper without tack coat,
- Joint Maker,
- Cutting wheel with tack coat,
- Rolling from hot side,
- Rolling hot side 152 mm away from joint and
- Rolling from cold side.

The differences between the sections, however, were described as “subtle.” Recall that there was no overlap of the hot mix onto the cold side during construction, which may have contributed to the cracking.

The 3:1 tapered joint that was rolled from the cold side in Colorado demonstrated the worst performance after two years in service; it had a crack of about 6 mm in width throughout 80% of the test section and had slight to moderate raveling throughout. Rolling the tapered joint from the hot side led to cracking throughout about 65% of the length at an average width of 3–6 mm and similar raveling. The other techniques—rolling from the

hot side away from the joint, cutting wheel with and without tack, 3:1 tapered joint with 1 in. notch and rubberized tack coat—all exhibited cracking throughout 10% or less of the length and little to no raveling.

The Pennsylvania section discussed in this report had eight test sections and was constructed in 1995. The edge restraining device produced the highest density, followed by the cutting wheel, joint maker and rolling from the cold side, which were similar. This group was followed by rolling the hot side 152 mm away from the joint and rolling from the cold side. Rubberized tack and a 3:1 wedge with infrared heating produced the lowest densities. After one year, none of the sections was exhibiting cracking and moderate to no raveling was observed at the joint. The joint was visible in most sections, except in the section where it was rolled from the hot side, where the joint was not visible; its performance was rated as a 10 on a scale of 1 to 10. The cutting wheel and rubberized tack sections were also rated as 10s. Rolling from the cold side, the edge restraining device and wedge with heater were rated as 5, 4 and 3 respectively. It was noted that “although the edge restraining device has high average density at the joint, its performance appears to be dependent upon the experience of the roller operator who has to keep the device properly aligned and pressed against the unconfined edge.”

Overall, the joints that were constructed to the highest densities tended to perform the best. Although some of these projects had only been in service for a short time, the following recommendations were made:

- The notched wedge joint appeared to offer the best possibility of good performance.
- The cutting wheel and edge restraining device also appeared to have potential but were noted to be operator dependent.
- The hot material should be placed with an overlap over the cold side.
- The joint should be rolled from the hot side with vibratory compaction while the material is hot.
- Improvements could be made to the paver screed to form a notched wedge or tapered joint, such as attaching a steel plate to form the joint and increasing vibration to compact the taper.
- Minimum compaction levels should be implemented in the specifications; it was recommended that the joint density should be not more than 2% lower than the specified mat density.

**Kandhal, P. S., T. L. Ramirez, and P. M. Ingram. *Evaluation of Eight Longitudinal Joint Construction Techniques for Asphalt Pavements in Pennsylvania*. NCAT Report 02-03, February 2002.**

This report summarizes the performance of test sections in Pennsylvania six years after construction of eight different longitudinal joint techniques. The eight techniques used were:

- Joint maker,
- Rolling from the hot side,
- Rolling from the cold side,
- Rolling from hot side away from the joint,
- Cutting wheel to remove 1–2 in. of unconfined edge,
- Edge restraining device,
- Rubberized tack coat/joint adhesive and
- 3:1 New Jersey wedge and joint heater.

In all cases, the hot mix was placed with the screed overlapping the cold side by 1–2 in. It was intended that the hot mat be bumped back to concentrate mix in the area of the joint but instead the mix was broadcast about 1–1.5 feet out into the mat.

The density results were presented above (Kandhal and Mallick, 1997). The test sections were inspected annually and the rankings changed over time. The performance, as determined through visual inspection, after six years was as follows (from best to worst):

- Rubberized joint material,
- Cutting wheel,
- Rolling 152mm away on hot side,
- New Jersey wedge,

- Edge restraining device,
- Joint maker,
- Rolling from hot side and
- Rolling from cold side.

The performance was generally pretty good, likely because relatively high densities were achieved during construction (air void contents below about 10% except for the sections with rubberized tack and the New Jersey wedge, which were about 13 to 15%). Despite the high air voids, the section with rubberized tack was rated the best performer after six years. On the other hand, the wedge section had substantial raveling along the length of the joint; the New Jersey wedge does not have a notch like the Michigan wedge does, so this may have contributed to the raveling.

It was observed that the use of the cutting wheel did provide good performance but that its success depends on the skill of the roller operator making a straight cut and the paver operator matching that cut when paving the adjacent lane. The edge restraining device also requires considerable skill.

These results were also published by the same authors in Transportation Research Record 1813, Transportation Research Board of the National Academies, Washington, D.C., pp. 87–94.

**Daniel, J. S. Use of an Infrared Joint Heater to Improve Longitudinal Joint Performance in Hot Mix Asphalt Pavements. *Journal of Performance of Constructed Facilities*, Vol. 20, No. 2, May 1, 2006, pp. 167–175.**

The study reported here evaluated a pavement constructed on 193 in New Hampshire using an infrared joint heater on the base and intermediate courses. Thermocouples inserted into each course were used to assess the depth of penetration of the heat, and cores were taken to evaluate any possible changes in the mix properties due to the reheating. The base course consisted of a 25 mm Superpave mix placed 62.5 mm deep, and the 50 mm intermediate layer was constructed using a 19 mm Superpave mix. Two or three preheaters were towed in front of the paver by tractor and another heater was mounted on the side of the paver.

When the first lane was placed, the vibratory breakdown roller made one pass up and back while overhanging the unsupported edge. The adjacent lane was placed without overlapping the screed onto the cold lane. The breakdown roller made the initial pass (up and back) from the hot side while staying about 150 mm away from the joint, then made another pass (up and back) overlapping onto the cold side about 150 mm. The intermediate and finish rollers both made their initial passes from the hot side overlapping about 150 mm onto the cold side. The same roller patterns were used in the test section but the joint was not tacked and the joint heater was used in the test section.

The results showed that the joint heater was able to increase the mat temperature within 25–50 mm of the joint to about 60°C (compared to air temperatures of 16–25°C on different days). Density tests on cores showed higher air voids in the control section than in the heated section. In the control section, most of the cores from the base layer fell apart but those from the test section did not, suggesting that the strength of the base layer joint in the control section was lower than in the test section. The IDT strength tests on the intermediate layer gave higher strengths for the test section than the control, but the difference was not statistically significant. Permeameter testing in the field showed higher permeabilities in the control section than in the test section. Field inspection one year after construction revealed that 93% of the control section joint had cracked while only 17% of the test section joint had cracked. In summary, the results were promising and showed that the joint heater did improve joint properties and performance.

**Daniel, J. S., and W. L. Real. Field Trial of Infrared Joint Heater to Improve Longitudinal Joint Performance in New Hampshire. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1946, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 157–162.**

In a paper related to the study above (Daniel 2006), Daniel and Real discussed construction issues related to the use of joint heaters. Safety was one of the issues noted. The preheaters were towed by a tractor in advance of the paver. This tractor was exposed to traffic in the paved lane and was between the traffic and trucks lined up in front of the paver. The paver heater was mounted on the side of the paver, further restricting space for the workers. Extra traffic control measures, specifically a traffic control officer and additional warning lights, were deemed necessary to avoid accidents.

Cost was another issue. There are costs associated with the purchase or rental of the heaters, propane to power the heaters, additional manpower to operate the heaters and operate the tractor, and there is extra set up time for the equipment. Altogether, the additional cost at the time was \$0.81 per ton at a time when the bid price without the joint heater was about \$33.25 per ton.

There were also operational issues with the use of the preheaters, in particular. The preheaters increase the length of the paving train, which could be an issue on some roadways. Instances where the paver stopped and the heaters did not automatically stop did occur, resulting in burned pavement; this type of malfunction can occur, causing lost time and potential performance problems at the joint.

Conclusions about the air voids, strengths and permeabilities of the base and intermediate courses were as above, but this paper also included results on the surface layer, which was constructed 14 months after the lower layers. The air voids at the joint in the surface layer were 2.5% lower in the test section than in the control section. In addition, the air voids at the joint in the test section surface and base layers were more similar to the mat density than in the control section. The IDT strengths were significantly different as well, with the control cores exhibiting only 75% of the strength of the test section cores. The joint at the surface was hard to distinguish in areas of the test section one year after the surface was placed but was readily apparent in the control section. The performance of the joint in the test section was reportedly significantly better than the control.

**Zinke, S., J. Mahoney, E. Jackson, and G. Shaffer. *Comparison of the Use of Notched Wedge Joints vs. Traditional Butt Joints in Connecticut. Final Report, Report No. CT-2249-F-08-4, Connecticut Advanced Pavement Laboratory, University of Connecticut, November 7, 2008.***

This study reported on three pilot projects placed in Connecticut in 2006 and 2007 comparing the traditional butt joint to a notched wedge joint, focusing on constructability and durability. Ten projects were evaluated including one that used the notched wedge only, two that used both the notched wedge and the butt joint and seven using the butt joint only. Density was measured in the mat and joint areas using both nuclear gauges and by testing cores. Density profiles were developed based on nuclear densities corrected by comparison to the core densities. The data from the different projects was pooled for comparison of density vs. position relative to the joint (1 ft on cold side, 6 in. on cold side, at the joint, 6 in. on hot side and 1 ft on hot side). The mixes on these projects were Superpave mixes of various sizes depending on the layer in the pavement and the project.

On the first project, the wedge was compacted by a vibrating plate compactor affixed to the paver with steel pipe and chains. This vibrating plate was connected to the paver hydraulics so that it started and stopped with the paver. While no density readings were taken on the wedge itself, the technique appeared to work well and the wedge appeared smooth and uniform.

It was determined that the use of the notched wedge joint saved time and avoided the construction of two transverse joints because the paver could construct the entire lane in one pass. Since traffic could traverse the wedge, matching the lanes was not necessary. The wedge held up well to traffic but some large aggregate particles were apparently dislodged by traffic on the wedge. When the second lane was paved the next night, it proved difficult to apply tack coat using a tack truck to the wedge without overspraying onto the finished surface. As a result, only the bottom half of the wedge was usually tacked despite the fact that the specifications called for the entire wedge to be tacked.

Density testing for acceptance on this first project was performed by nuclear gauge testing on the warm side of the joint, which placed this over the wedge. Two 30-sec readings were taken at each location with the gauge rotated 180° between readings. The acceptance test results averaged 92.5% of  $G_{mm}$ .

One project evaluated used a rubberized joint sealant on the butt joint. The joint sealant was used in the top of two 2 in. lifts of 9.5 mm Superpave mix. The sealant was carried in a trailer-mounted melting pot pulled by a pickup truck. The rubberized sealant was reportedly easier to apply in a uniform manner, using a wand, when the lute man tamped the edge of the mat to flatten and smooth out the edge. Nuclear density tests showed the density of the joint with the sealant was 1.7% higher than without (94.8% vs. 93.1%), however, the core densities were comparable to the core densities from other butt joints. The authors concluded that the joint adhesive had little if any effect on the joint density.

The second project was paved over a month later than the first in October 2006. The notched wedge was constructed in the surface only and was compacted by a vibrating plate attached to the paver. Again there were issues with applying the tack on the wedge when paving the second lane. The traffic control set up on this project allowed for closing both lanes in a given direction so that only occasional traffic traversed the wedge. The same nuclear density testing procedure was used as on the first project, and the results were even better, reaching 93.5% of  $G_{mm}$ .

The third project was an interstate project paved in 2007. The notched wedge joint was used in the surface only using the same equipment to form and compact with wedge as in the previous two projects but with some modifications to how the vibratory plate was attached to the paver. This worked well except that in cases where the paver wing needed to be extended in or out, the wedge was not properly shaped for 25 to 50 ft as the position of the vibratory plate was adjusted. Nuclear density results for acceptance testing of the wedge joint ranged from 91 to 97.9% with an average of 93.4%.

Tacking on this third project was better than the previous two. The tack was applied to the wedge by using the outer three nozzles on a distributor truck going in reverse. This resulted in nearly complete coverage of the wedge.

Traffic on the interstate negotiated the wedge without incident despite the higher speeds on this project (posted at 65 mph vs. 50 and 40 mph on the previous two). No spalling or raveling was noted.

Analysis of the core data from this project showed that the density across the wedge joint was much higher than with the butt joint (by about 5% of  $G_{mm}$ ). A comparison of wedge joints left open to traffic vs. one where the second lane was paved the same night showed no detrimental effect of traffic on the joint. In fact, there seemed to be an improvement in the density at the joint of about 2% of  $G_{mm}$ . Being able to leave the joint open to traffic was viewed as beneficial to expedite paving.

This study concluded that there is a statistically significant lower density on the cold side of the joint (6 in.) for both butt and notched wedge joints. The density on the hot side of the joint (6 in.) is significantly higher with both types of joint because of the confinement provided by the existing mat. The densities at the joint and on the cold side of the joint were higher for the notched wedge joint, which showed more uniform density across the joint. The notched wedge joint was found to be constructible with minimal delays and problems. The use of a vibratory plate to compact the wedge was also recommended. The use of rubberized joint sealant did not affect the density at the joint, but long-term monitoring of its performance may show if it is beneficial or not.

The report recommended that Connecticut allow the use of notched wedge joints. It also recommended consideration of a joint density specification using the average of the densities on the hot and cold side of the joint. The then-current specifications required 92% of  $G_{mm}$  on the hot side of the joint; this value was thought to be “unrealistic” for the average of the hot and cold densities.

**Croteau, J. R., J. J. Quinn, R. F. Baker, and E. J. Hellriegel. *Longitudinal Wedge Joint Study, Final Report. Publication FHWA/NJ-89-009. New Jersey Department of Transportation, January 1989.***

This report summarizes a five-year study to develop a technique to construct denser, more uniform joints. New Jersey had attempted to reduce the number of cold joints by limiting the length of a lane that could be paved before pulling up the adjacent lane. This was not successful, as joint deterioration still occurred, and was often inefficient or even impossible in heavy traffic areas. Another concern was the safety of the traveling public when a vertical height differential was created at a butt joint.

In 1982, New Jersey began to explore options for creating more durable longitudinal joints. After looking at wedge joints used in Arizona (with a 6:1 slope), New Jersey decided to try a 3:1 slope to reduce the possibility of raveling and to use a joint heater before placing the second lane. It was expected that the wedge and joint heater would produce a denser, more homogeneous joint.

Nuclear density testing and coring were used to assess the joint densities on one new construction and five resurfacing projects. Three of these projects included a control section with a conventional butt joint.

The wedge was constructed by a steel plate attached to the inside of the paver screed extension. In this case, the wedge was not compacted since it was felt that the uncompacted face would bond better to the adjacent lane, producing a more homogeneous joint. Instead, the roller was allowed to extend no more than 2 in. over the top of the wedge. An infrared heater mounted on the side of the paver was used to heat the unconfined edge immediately prior to placement of the adjacent lane. The second lane was then placed with the paver overlapping the top of the wedge by 2–3 in. and the overlapped material was pushed back across 3–4 ft of the mat with a lute.

Results of nuclear density and core testing on these six projects showed that the density was much more uniform and higher for the wedge joint than the butt joints. On one of the projects without a control section, the infrared heater was not used, and the density was still uniform across the wedge joint. The costs of implementing the wedge joint were reportedly fairly low for the purchase and mounting of the infrared heater, installation of the wedge shaping plate and installing the propane tank. The cost of propane was “insignificant” at the time.

The study concluded by recommending the use of the wedge joint for all lifts on new and reconstruction projects because of the safety advantages. The infrared heater was recommended for use on surface lifts to improve the bond between the adjacent lanes. It was also suggested that the merits of use of infrared heating on underlying layers of the pavement should be evaluated through research.

[NOTE: The 2007 New Jersey Standard Specifications, the most recent version, require the use of wedge joints for longitudinal joints when lift thicknesses are greater than 2 ¼ in. when maintenance of traffic is required. The 3:1 slope is still used but the heater is not required in the standard specifications. They also require a polymerized joint adhesive to be applied over the joint face.]

These results were also summarized in Robert F. Baker, Jack R. Croteau, John J. Quinn and Edgar J. Hellriegel, “Longitudinal Wedge Joint Study,” *Transportation Research Record: Journal of the Transportation Research Board*, No. 1282, Transportation Research Board of the National Academies, Washington, D.C., 1990, pp. 18–26.

**Smith, R. D. *Improvement of Longitudinal Joints in Asphalt Pavement. Iowa Highway Research Board, Project HR-215, January 1987.***

Smith reported on a field evaluation of eight joint construction techniques in Iowa. In 1980, two sections of each of the different techniques were all constructed on one project. The techniques included:

1. Butt joint with 1 in. overlap.
2. Double tack coat on vertical face (first applied at end of day when paving first pass and second applied in the morning before paving second pass).
3. Butt joint with no overlap.
4. No 1:1 slope on edge.
5. Pinching the joint by rolling first pass on second lane with roller 4 in. from longitudinal joint.
6. Trimming 1.5 in. off cold mat before tacking edge and paving second lane and double tacking as above.
7. Trimming edge as in #6 and pinching the joint as in #5.
8. Joint “sealed” by pneumatic tired roller on final pass.

The joints were assessed by pulling cores approximately 3 in. on each side of the joint and one-quarter of the way into the lane. Density testing of the cores proved that the joint densities were lower than the mat density in all cases.

Visual inspections were also performed annually for a total of six years after construction. In the last three years, the percentage of centerline cracking was determined.

Both the density and cracking results showed that the best performance through the first five years came from the fourth technique used, that is eliminating the edge shoe that produced a 1:1 slope at the edge. (Unfortunately, this technique is not well described in the report.) This section had the highest joint density. By the sixth year, however, this section had cracked over 100% of the joint length. Procedures 1, 2 and 3 performed slightly better than the other procedures through six years; the first three techniques had cracking over 90% of the joint length but the others exhibited 100% cracking. The rate of cracking on all of the sections increased markedly after four years.

Smith concluded that none of the techniques were successful in preventing longitudinal cracking at the joint.

**Buchanan, M. S. Evaluation of Notched-Wedge Longitudinal Joint Construction. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1712, Transportation Research Board of the National Academies, Washington, D.C., 2000, pp. 50–57.***

This study also reports on field evaluations of longitudinal joints. In this case, notched wedge joints were compared to conventional joint construction in five states: Alabama, Colorado, Indiana, Maryland and Wisconsin. The density variation across the joints was evaluated by coring at five locations across the mat: at the centerline and 150 mm and 450 mm on each side of the joint. This coring was conducted at three random locations on the conventional joints and three on the notched wedge joints in each state.

The Colorado project was paved with a fine-graded 19 mm Superpave mix placed in a 50 mm overlay using echelon paving in 1998. The conventional joint in Colorado (at the time) was a 12.5 mm (½ in.) notched with a 3:1 taper. The comparison section was paved using a 25 mm notch and a taper over 300 mm. The taper was compacted with a vibratory plate compactor that was somewhat wider than the taper, resulting in occasional bridging of the wedge. No tack was used at the joint since the paving was in echelon. The cores densities showed that the notched wedge joint resulted in a higher density at the joint (as much as 4% higher). However, there was about a 1% lower density 150 mm from the joint on the hot side, probably caused by the use of the vibratory plate compactor and the bridging that was sometimes observed. This difference was not statistically significant, but is nonetheless of some concern.

The Indiana project was located in Connersville (30<sup>th</sup> St) in October 1998. This project was a 37.5 mm overlay using a fine graded 9.5 mm Superpave mix. The conventional joint here was a butt joint, and the notched wedge joint had a 12.5 mm notch and a 300 mm wide wedge. A small roller weighing about 45 kg and about 300–350 mm wide attached to the rear of the paver was used to compact the wedge. As in Colorado, the density of the notched wedge joint was higher than the butt joint at the joint but was lower 150 mm into the hot side. In this case, however, the only statistically significant differences in densities were on the hot side; the density at 450 mm from the joint was about 2.4% higher with the notched wedge than the butt joint and at 150 mm the density was about 2.3% lower with the wedge than the butt joint. These differences were attributed to inadequate compaction of the wedge.

The Alabama site was a 50 mm thick overlay on US280 using a fine-graded 19 mm Superpave mix placed in November–December 1998. In this case, the contractor elected to pave most of the project with the notched wedge joint to avoid matching the joint each day. This was despite the fact that ALDOT had not previously used notched wedges before and did require lane matching for lift thicknesses of 50 mm or more. The conventional joint, used on about 10% of the project, was a butt joint. A 90 kg roller attached to the back of the paver was used to compact the wedge. The same trend in densities near the notched wedge as seen in Colorado and Indiana was observed in Alabama; that is, the density at the joint is significantly higher for the wedge joint, but the density is lower for

the wedge joint than the butt joint 150 mm on the hot side. The difference at 150 mm, however, is less than in Colorado and Indiana, probably because of the greater weight of the roller.

In Wisconsin, a 9.5 mm Marshall mix was placed in a 25 mm overlay in August 1998. This mix included 15% RAP, whereas the other projects all used virgin mixes. Because of the thickness of the overlay, the notch was only 12.5 mm and the taper was relatively shallow (tapered from 12.5 mm to about 6 mm over 300 mm). Again, a static roller was attached to the back of the paver, as in Indiana and Alabama. A butt joint was used for comparison. In this case, the density with the notched wedge joint was higher than with the butt joint at three of the five locations. The density was significantly higher (by about 3%) 150 mm on the cold side of the joint. The density was slightly higher 150 mm on the hot side, in contrast to the other sites. The density was lower 450 mm from the joint on the hot side, which is surprising since the notch did not extend that far into the mat.

Lastly, the Maryland project involved a 100 mm lift of coarse 25 mm Superpave mix placed in October 1998. A 0.3 m wide vibratory extension on the paver was used to precompact the unconfined edge for both types of joints. When constructing the notched wedge, the vibratory extension compacted the wedge. This extension compacted the wedge to about 70% of the maximum density, but it also tended to decrease the notch depth. On this project, the notched wedge joint actually resulted in about 0.5–1.6% lower densities at all locations except 150 mm on the cold side, where the densities were similar for both joint types. These differences were not statistically significant except at 150 mm on the hot side. The low densities for the wedge joint were attributed to the lift thickness and large nominal maximum aggregate size (NMA) of the mix.

The overall conclusions from this evaluation were that the notched wedge joint resulted in higher centerline densities than the butt joint in four of the five projects and two of those were statistically significant. Increased confinement of the mix in the wedge was credited with causing the increased density. The use of the notched wedge resulted in lower density 150 mm on the hot side of the joint on four projects, probably because of poor compaction of the wedge. Observations of the construction of all five projects suggested that the notched wedge did not cause any construction delays except short ones for contractors who had not used this type of joint before. Production could be increased by not having to back up to match lanes.

**Toepel, A. Evaluation of Techniques for Asphalt Pavement Longitudinal Joint Construction. Report Number WI-08-03. Wisconsin Department of Transportation, November 2003.**

An NCAT report (Kandhal and Rao) revealed that the wedge joints constructed in Michigan achieved the highest densities of eight joint techniques evaluated in Michigan but did not perform well in Wisconsin. In Michigan, a notch was placed at the top of the wedge, but this was not done in Wisconsin. The Wisconsin DOT reviewed these results and concluded that better joint construction techniques were needed in that state, so the referenced project was initiated.

This study again looked at eight joint construction techniques, similar to those used by Kandhal and Rao, placed on US61 in 1993. The joints were evaluated in terms of density and performance (cracking). The specific construction techniques were:

- Conventional butt joint—with tack and pinching of the hot side of the joint (roller 4–6 in. from joint) (Method 1).
- Wedge joint with ½ in. notch and 12:1 taper and tack on the wedge. There were five variations of this type of joint:
  - Rolling wedge with truck tires (Method 2)
  - No rolling with truck tires (Method 3)
  - Steel side roller wheel attached to steel-wheeled roller (Method 4)
  - Rubber side roller wheel attached to rubber-tired roller (Method 5)
  - Rolling with tag-along roller attached to paver (Method 6)

- Cut joint with approximately 2 in. of the unconfined edge cut away with a cutting wheel and vertical face tacked (Method 7).
- Conventional joint with edge restraint device on roller (Method 8).

The contractor on the project, Mathy Construction Company, identified advantages and disadvantages of each method, as summarized in Table A.1. The contractor also commented that the paver modifications needed to form the notched wedge were relatively easy and the wedge was safer for traffic to cross.

Nuclear density readings were taken at seven transverse locations within each test section at the joint, 1 ft on each side and 5 ft on each side. Cores were taken at the joint and 1 ft on each side of the joint at all seven locations. Because of discrepancies between the lab and field densities and between the contractor's and state's nuclear gauges, the core densities were deemed more accurate. All of the joint construction techniques showed a density gradient across the joint but the joints constructed with the tag-along roller and the steel roller attached to the steel wheeled roller (Methods 6 and 4) had the lowest differences across the joint. These two techniques were also the only two that produced joint densities of greater than 92% of the maximum density, the WisDOT standard for surfaces for high volume traffic.

After ten years in service, the joints were inspected. The techniques with the lowest percentage of joint cracking were Methods 6 (21%) and 4 (33%). The others had cracking through 46% (Method 3) to 100% (Method 7) of the test section length.

Masad, E., E. Kassem, and A. Chowdhury. *Application of Imaging Technology to Improve the Laboratory and Field Compaction of HMA*. Texas Transportation Institute, Report No., 0-5261-1, Texas A&M, College Station, Texas, 2009.

As part of a study evaluating the use of X-ray computed tomography (CT) to measure the air void distribution in asphalt mixtures with the goal of improving lab compaction to better match field compaction, Masad et al. also evaluated the air void distribution on several field projects. The field evaluation included

studying the air void distribution near longitudinal joints on projects with different compaction techniques. Nuclear densities and PQI readings were taken and field cores were pulled. This research led to the development of the Compaction Index (CI), which is a function of the number of passes at a point and the position of the point with respect to the width of the roller. Compaction is more effective near the center of the roller than near the edge.

Using the CI, the researchers concluded that the use of a pneumatic breakdown roller improved the uniformity of the air void distribution in the top half of the lift and reduced the total air void content.

Longitudinal joints were evaluated on five projects. The joint types varied between confined and unconfined and vertical vs. tapered. The researchers confirmed that the air voids were higher near the longitudinal joints than in the interior of the mat. They also confirmed that the air voids near confined joints were higher than near unconfined joints. The air void distribution was found to be more uniform near confined joints as well. The difference in compaction at the joints could be explained in terms of the CI since the joints are typically compacted near the outside edge of the roller, which is less effective. To improve the effectiveness of joint compaction, the researchers recommended overhanging the joint by 2 ft. whether the joint is confined or not. No conclusions were offered comparing the tapered and vertical joints.

Johnson, S. K. *Evaluation of TransTech Joint Maker and Precompaction Screed*. Final Report. Report No. FHWA/MS-DOT-PTP-00-002. Mississippi Department of Transportation, Jackson, Mississippi, September 2000.

This study was conducted to determine if the TransTech Joint Maker and Precompaction Screed could lead to improvements in joint and mat density. The problems with joint density, which the Joint Maker is designed to address, have been extensively discussed previously. The Precompaction Screed is intended to provide extra compaction in the wheelpath areas in front of the paver screed to help prevent rutting in the wheelpaths when paving over previously rutting pavements.

TABLE A.1  
Advantages and Disadvantages of Joint Construction Techniques (Toepel)

Joint Type	Advantages	Disadvantages
Conventional Butt	Familiar	Low density Tendency to ravel
Wedge—Truck Rolling	Easy to construct More weight on wedge	Drivers sometimes forgot to roll unless dedicated Tires tended to throw aggregates on new mat Truck tires could scuff edges Inconsistent rolling
Wedge—No Rolling	Well-formed joint No attachments to rollers	Lower densities could result from inadequate compaction
Wedge—Steel Side Roller	Consistent rolling pressure Better formation of notch Easy to attach roller Roller could compact wedge while hot	Additional set up time
Wedge—Rubber Side Roller	Easy for operator to see and align device	Variable compaction pressure from hydraulics
Wedge—Tag-Along Roller on Paver	Applies hydraulic pressure on wedge	Difficult for operator to see and align device Hydraulic pressure could produce too much pressure
Cut Joint	Removes lowest density material	Messy, requires brooming Produces wavy edge More equipment required Slows production
Butt with Edge Restraint	Produces fairly uniform edge	Difficult for operator to see and align device Difficult to maintain position Need to remove excess material from adjacent lane

Both devices were used experimentally on one project in Mississippi. Nuclear density readings were taken at five locations across the mat to compare the densities in test sections with the devices to a control section. Both devices were found to provide higher densities than equivalent locations in the control section. The Joint Maker achieved a 1.6% higher density value (pcf) and 1.4% increase in percent of maximum density (% $G_{mm}$ ) compared to the control when used on the inside edge of the mat (confined). When used on the outside, unconfined edge of the mat, the Joint Maker provided densities 0.9% higher in value and 0.8% higher in terms of percent of  $G_{mm}$ .

## JOINT ADHESIVES AND SEALERS

Several studies have focused on the use of joint adhesives to improve the performance of longitudinal joints by preventing the intrusion of water by sealing the joints. Some of these studies are summarized here. Other techniques were also included in some of these studies but all include adhesives or sealers. Adhesives are applied to the joint before placement and compaction of the adjacent lane, while sealers are applied after the joint has been compacted.

**Huang, B., X. Shu, J. Chen, and M. Woods. Evaluation of Longitudinal Joint Construction Techniques for Asphalt Pavements in Tennessee. *Journal of Materials in Civil Engineering*, ASCE, November 2010, pp. 1112–1121.**

After Tennessee identified longitudinal joint failure as one of the main causes of distresses in asphalt pavements in the state, a study was initiated to evaluate available methods to improve joint performance. This report summarizes the findings of a field study comparing seven different joint techniques, including joint adhesives, joint sealers and infrared heaters. The joint adhesives studied included high-polymer rubber, high-polymer emulsion, anionic emulsion and polymerized emulsion. The sealers comprised polymerized maltene emulsion and polymerized agricultural oil. The seven techniques were used on one resurfacing project constructed in 2008 on State Route 289. The project consisted of a 31.8 mm overlay using a 12.5 mm Marshall mix.

Various tests were used depending on the construction techniques. A total of seven to 11 cores were taken from each project within three days of construction.

The air void contents of the cores from sections with joint adhesives and sealers were similar to those of the control sections. This is, perhaps, not surprising since the materials are intended to improve the bond of the cold and hot sides of the joint or to seal the joint and not to improve the density. Air voids at the joint in these sections were as much as about 5% higher (compared to the hot side) than in the mat 200 mm away. The joint heater, however, was able to improve the density at the joint; air voids at the joint were within about 2% of those on the hot side.

Permeabilities of the different joint techniques followed the same trend as air voids. As the air voids increased, the permeability increased as well. Laboratory permeability testing showed that the two joint sealers did not reduce the permeability of the cores, although this is what they are intended to do. The authors suggest that the sealers do not seal tightly enough to resist the high head of water in the lab test though they may perform well in the field. The use of the joint heater resulted in lower permeability.

To further evaluate the effectiveness of sealers, the authors developed a water absorption test to assess whether the sealers could prevent the intrusion of water. The test was conducted by immersing cores in a water bath for 40 min. The cores were then removed from the bath, surface dried and pressed with a circular paper cloth. The difference in the weight of the cloth before and after pressing against the core surface was a measure of how much water the core had absorbed. Triplicate water absorption tests showed good repeatability and showed that the joint sealers and one of the joint adhesives were effective at preventing water from penetrating the joint area.

The indirect tensile strengths of core specimens from the joints (loaded along the joint) and each side of the joints were

determined. The results showed that the hot side had the highest tensile strength, the cold side was next and the joint itself had the lowest tensile strength in every case. The use of the polymerized emulsion and the joint heater improved the tensile strength at the joint. The sealers did not improve the tensile strength.

The authors concluded that the joint heater was the best technique used since it resulted in lower air voids and permeability and high tensile strength. The polymer emulsion joint adhesive improved the IDT strength but had no influence on air voids or permeability. The joint sealers did not reduce the permeability or density at the joint, but the water absorption test suggests they may still perform acceptably in the field where the head of water is lower than in the laboratory test.

**Morgan, R. L. Centerline (Longitudinal) Joint Adhesive Performance: Two to Three Year Review. Special Report 149. Publication FHWA/NY/SR-09/149. New York State Department of Transportation, November 2009.**

New York State uses the notched wedge joint as the standard but some cracking at the joint is still observed. This study was conducted to evaluate whether joint adhesives could delay or prevent deterioration at the joint. Three different brands of joint adhesives were placed on three overlay projects in 2004 and four projects in 2005. The adhesives were applied in a 2 in. bead and on two projects it was also applied in a 4 in. bead at the top of the wedge. In all but one case, a control section without the adhesive was also placed. On most projects, the adhesive was applied immediately before paving the adjacent lane. On two projects, however, the adhesive was applied the day before and left exposed overnight. When the hot mix was placed against the adhesive, small spots of melted adhesive appeared along the centerline, demonstrating that the adhesive was being melted by the hot mix to create a seal.

Visual inspections were performed at least annually. Cracking and raveling was observed to varying degrees on the different projects and in the different sections. Based on these inspections, the author concluded that the sections with joint adhesives are generally performing as well as or better than the control sections. Two sections with adhesive had more cracking than their control sections, though both sections were performing relatively well. Five sites had no cracking in either the test or control sections. Finally, the author concluded that joint adhesives may be a partial solution to longitudinal cracking. Additional monitoring of these sections would be needed to determine if the adhesives are cost effective and if they prevent or delay longitudinal joint distress long term.

Although this author did not specifically point it out, the data shows that some of the control and test sections showed raveling. So, even if the joint adhesive helped to prevent cracking at the joint and may delay problems, it may not necessarily prevent joint deterioration if the mat near the joint is open and allows water to penetrate.

**Fleckenstein, L. J., D. L. Allen, and D. B. Schultz, Jr. Compaction at the Longitudinal Construction Joint in Asphalt Pavements. Report No. KTC-02-10/SPR208-00-1F. Kentucky Transportation Center, May 2002.**

This study evaluated the use of the notched wedge joint, restrained edge, Joint Maker, reheater and joint adhesive. The use of the cutting wheel was considered but dropped because it did not appear to be implementable on a wide scale. The various joint construction methods were used on 12 construction projects in Kentucky. Each project included a control section. The evaluation techniques used included nuclear density tests, permeability measurements and coring.

Four projects used the notched wedge with a 12:1 taper and 0.5 in. notch at the top and bottom. A roller of about 400 lbs. or more was towed behind the paver to compact the wedge. The construction issues noted with the notched wedge included difficulty in maintaining the notch during compaction, raveling of the wedge and pick-up of aggregate on the roller, but most of these were termed “controllable.” The nuclear density results indicated better density was achieved with the notched wedge compared to the control on three of the four projects. This

increase in density was observed at the joint and within the mat, apparently due to the edge restraint created by the wedge. Both field and lab permeabilities were reduced for the notched wedge over the control. This type of joint was recommended for use on surface lifts at least 1.5 in. thick.

The restrained edge joint was also constructed on four projects. A beveled wheel, controlled by a hydraulic arm, was attached to a roller and used to provide confining pressure on the edge of the mat during compaction. One project used the wheel on a 1 in. surface course with success. A second project attempted to use the wheel on a 1.5 in lift, but the wheel was not high enough to constrain the uncompacted mat. The wheel could be used after two passes of the breakdown rolled had decreased the mat thickness, but then the mat was compacted in an unrestrained condition, reducing the effectiveness of the wheel. On another project, use of the original wheel was attempted but similar problems were noted, so the bevel was increased to cover the entire face of the uncompacted mat. There were still problems with vertical displacement of the edge of the mat. Densities at the joint were somewhat improved with use of the wheel and permeabilities were generally reduced. Densities were lower, however, on the cold side of the joint and permeabilities were higher, probably because the edge was not adequately restrained. Moving the edge restraining device right up to the edge of the compactor drum was recommended to prevent material from squeezing up between the wheel and the drum.

The Joint Maker, manufactured by TransTech, is a metal device mounted on the front of the screed near the end gate that is intended to provide some compaction to the edge before it passes under the screed. This device was used on three projects. Setting up the device proved to be the biggest difficulty during construction. Some dragging of the mixture was also noted but was improved by heating the Joint Maker. Slight improvements in density were noted on two projects and no change on the third. Lab permeabilities were higher at the joint with the device, but field permeabilities were lower for two projects. Both field and lab permeabilities were substantially lower on the only project with a 1 in. lift thickness. It was determined that the change in densities and permeabilities were not sufficient to support additional testing of the Joint Maker.

The Ray-Tech infrared joint reheater, similar to that used in New Hampshire (Daniel et al.), was used on one project on the Bluegrass Parkway in this study. The project used two preheaters and a third heater affixed to the paver. While the reheaters did bring the cold joint up to paving temperatures, problems were noted during construction. The temperature had to be adjusted manually and the temperatures were too high in some places, causing blistering and scorching. The reheater on the side of the paver prevented the use of skis for smoothness. The production rate was also slowed considerably to allow time for the mat to be heated. Thus, contractors did not like the method. Densities were increased at the joint and permeabilities were decreased. Further testing of this method was recommended because it did appear promising, but refinements were reportedly needed in temperature control and to allow the use of skis.

Joint adhesives were used with various types of joints (notched wedge, conventional and restrained edge). One was a hot poured adhesive by Crafcoc and the other was Tbond Joint Tape. Both adhesives required more labor, with the Tbond being more labor intensive than the Crafcoc. An extrudable type of Tbond would be less labor intensive. Both adhesives also improved the permeability of the joint. The Tbond on the notched wedge joint showed the greatest improvement in permeability and density.

Overall conclusions included the finding that the reheater method yielded the highest densities but was used on only one project. The restrained edge device was next, followed by the notched wedge. The Joint Maker had the lowest density. The notched wedge had the greatest decrease in permeability and the Joint Maker had little to no impact on permeability. The lab and field permeabilities of the reheated section were contradictory.

Field inspections after about two years showed cracking was beginning to appear on several of the projects. The cracking appeared in control sections as well as some produced with the Joint Maker and restrained edge. The sections with joint adhesives

were performing as well as or better than sections without the adhesives.

Based on this study, it was recommended that joint adhesives be used on more projects, the restraining wheel be modified and used again, that these sections be monitored for long term performance and that a specification be written requiring joint density within 3 in. of the joint to be within 3% of the specified lane density.

**Maine Department of Transportation. *Longitudinal Joint Treatment. Technical Report No. 00-18, March 2006.***

Because of problems with longitudinal joint deterioration, the Maine DOT evaluated the use of three different joint sealers and adhesives on one project. One sealer was a rubberized asphalt material from Crackfiller Manufacturing Corporation, and another was a high-float asphalt emulsion. A joint adhesive from Koch Materials Company was also evaluated. The sealers or adhesive were used in both the intermediate and surface courses. The rubberized sealant and the joint sealer were applied with a handheld wand; some gaps were observed in the coverage of the joint face, especially with the rubberized material. The emulsified asphalt was sprayed with a handheld spray bar and covered the top, face and bottom of the joint quite thoroughly.

The rubberized crack sealer began to show separation in the first year after construction, which was attributed to poor construction rather than failure of the sealer. The separation increased over five years but overall the performance was deemed very good. The joint adhesive exhibited similar behavior. The emulsified asphalt sealer was also performing well with little joint separation. There were no significant differences in the performance between these materials after five years.

**Denehy, E. J. *Constructability of Longitudinal Construction Joints in Hot-Mix Asphalt Pavements with Sealers to Retard Future Deterioration. In Roadway Pavement Preservation 2005, Transportation Research Circular Number E-C078, Transportation Research Board, Washington, D.C., October 2005, pp. 16-23.***

The New York State DOT began meeting with industry in 1995 to discuss HMA construction issues, including longitudinal joints. After four years of meetings and review of other states' research and specifications, changes to the specifications allowing use of the notched wedge joint and rolling from the hot side were implemented. In addition, a pilot joint density specification offering a density incentive, but no disincentive, was used on a few projects. NYSDOT also explored use of the TransTech Joint Maker, which it did not find improved joint density. Lastly, they began to investigate the use of joint sealants.

Three different brands of sealants were used with notched wedge joints on three projects in 2004; two were interstate projects and one was on a state highway. No construction problems with the installation were noted, and productivity did not suffer. Additional field trials were planned for 2005 and following.

**Winkelman, T. J. *Experimental Joint Sealants for Hot Mix Asphalt Pavements and Overlays. Report No. I2004-07. Illinois Department of Transportation, October 2004.***

Illinois DOT used two brands of bituminous joint sealants experimentally on four projects in 2003—two on interstates and two on primary state routes. Control sections were included on all four projects. The goal was to explore the constructability and performance of these sealants. This report documents the construction and field permeability testing of the materials. Laboratory permeability testing, examination of the migration of the sealant into the surface course and field inspections were planned future activities (a follow-up report could not be identified).

Winkelman explains that the sealants are intended to reduce the interconnected air voids in the hot mix surface. The sealants are placed in the joint area prior to placement of the surface course. The heat of the surface softens the sealant material and vibratory compaction helps it to migrate up into the surface course, preferably through about 75% of the mat thickness.

To ensure constructability, the sealant materials needed to be easily and rapidly applied. In addition, to ensure good performance, material properties, like dynamic shear and creep stiffness, and application requirements, including thickness and width of the sealant band, were specified.

One sealant, J-Band<sup>®</sup>, was placed in an 18 in. wide strip over the longitudinal joint in the intermediate course. The thickness of the sealant increases from the edge to the center of the band to provide more material in the area of the joint. The other sealant evaluated, QuickSeam<sup>®</sup>, was delivered in 9 in. wide rolls with a wax paper backing on one side and a plastic backing on the other. The material was unrolled onto the intermediate course and was covered by the first lane of surface mix. The wax paper backing was removed prior to placement and the plastic was broomed off before paving. After placement of the first lane, a second strip of the sealant was placed to cover part of the edge of the first lane and extends under the second lane in the area of the longitudinal joint.

The J-Band<sup>®</sup> material was found to be easy to apply and only minimal problems were noted with its installation. Some tracking under traffic was noted and it was found that the adjacent lanes need to be at the same elevation to allow the application equipment to move properly. Lime dust was applied over the J-Band<sup>®</sup> to prevent tracking on one project where there was traffic on the cross streets. About four people were needed for various tasks during installation, but as many as four miles were placed in one day. On one project, significant problems were noted with placement of the surface over the J-Band<sup>®</sup>. Where the sealant was placed directly on concrete, the sealant migrated too far into the HMA surface, causing an excess of asphalt binder in the surface. Then, the action of the rollers created cracks between the rich and normal parts of the mat, creating cracks along the edge of the sealant in both the first and the second lanes.

The QuickSeam<sup>®</sup>, on the other hand, was difficult, labor intensive and time consuming to place. On different projects, between three and eight people were used to place the sealant. Removal of the wax paper and plastic backings was often difficult. The production rate was so slow that sometimes the paver had to stop and wait for the sealant to be placed.

Field permeability testing showed no improvement in permeabilities of the sealed joints versus the control on two projects. On the other two projects, however, the sealants did improve the permeability at the joint, but had no appreciable effect away from the joint (4 and 12 in. away on both sides).

## SPECIFYING AND TESTING LONGITUDINAL JOINTS

**Von Quintus, H. L., and R. Perera. *Extending the Life of Asphalt Pavements*. Report No. RC-1551. Michigan Department of Transportation, May 2011.**

As part of an overall study to identify the features of pavements with good and poor performance in terms of distress index, rutting and smoothness, the authors recommended ways to mitigate the performance problems. Distress data was analyzed to detect whether construction or material issues were contributing to the performance problems. In general, smoothness was quite good (IRI was low), especially on interstates, and rutting was not a problem on most roadways analyzed. Other distresses were the primary causes for the need for maintenance or rehabilitation activities. The main distresses observed were longitudinal cracking at the centerline, in the center of the lane and in wheelpaths; edge; alligator and block cracking; and transverse cracking and tearing.

The key recommendation for mitigating distresses that is of interest here is to implement a longitudinal joint specification to improve the performance of the joints. In fact, this was the highest priority recommendation. A specific specification is not offered but reference is made to a 2009 draft specification developed by Michigan DOT but not implemented at the time of this report.

**Burati, Jr., J. L., and G. B. Elzoghbi. *Correlation of Nuclear Density Results with Core Densities*. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1126,**

**Transportation Research Board of the National Academies, Washington, D.C., 1987, pp. 53–67.**

The study reported in this paper was conducted to determine whether the FAA could use nuclear density gauges to accept asphalt paving projects. Efforts were made to correlate nuclear density readings and core densities on two construction projects. Four cores were taken from the joint area and four from the mat on each project. Three different nuclear gauges were used at the core locations on each project immediately before coring. Nuclear densities were also recorded at random locations across the mat. On one of the projects, joint readings were taken with the gauge perpendicular to the joint with the source and detector on opposite sides of the joint.

Statistical analysis of the data showed that the different types of gauges do not necessarily yield the same results and they had different variability. On both projects, the gauges provided lower densities than the cores. Orienting the gauge perpendicular to the joint resulted in higher densities that were closer to the core density compared to readings taken parallel to the joint. No particular problems were noted regarding using the gauges for measuring joint densities as opposed to measuring mat densities.

The researchers concluded that nuclear gauges cannot simply be used in lieu of core densities for acceptance. If nuclear gauges are to be used for acceptance, test strips should be conducted to calibrate the gauges.

**Williams, S. G., A. Pervis, L. S. Bhupathiraju, and A. Porter. *Methods for Evaluating Longitudinal Joint Quality in Asphalt Pavements*. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2098, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 113–123.**

Williams et al. theorized that density alone may not adequately characterize joint quality, so they evaluated a number of other material properties that could be related to the intrusion of air and water into the pavement. While density is generally easy to measure, there can be issues, such as difficulty seating the gauge at the crown of the pavement. The significance of density may also be questionable when sealers are used.

The parameters considered in this study included: density, permeability and gradation (since gradation might relate to segregation, which would be detrimental to joint performance). Density was determined by nuclear and non-nuclear (PQI and PaveTracker) gauges and by testing cores in the lab. The cores were also used to calibrate the gauges. The cores were tested using AASHTO T 166, the SSD method, and T 275, the vacuum sealing method. Permeability was measured in the lab and field. After testing, the cores were used to determine the gradation and fineness modulus after the ignition oven.

Three projects were tested at four locations each immediately over the joint and 6 and 12 in. on either side of the joint. The projects were all multi-lane roadways so there was no crown at the joint to hinder seating of the gauges. One project had good quality joints, another had fair to poor joints and the third had no cracking but did have some segregation at the joint in some areas. Being able to differentiate between good and poor performance is one of the measures of how appropriate a test method would be. Analysis of variance was used to assess the statistical significance of variations in each test parameter with distance from the joint. When statistically significant differences were noted, Tukey's comparison of means test was used to determine which means were significantly different from the others; considerable overlap in the groupings indicate that the test is not clearly discriminating the differences.

The study concluded that all the methods of density determination were able to detect variations in density, but the nuclear gauge was more discriminating than the non-nuclear methods and the vacuum sealing method was more discriminating than the SSD method. Field and lab permeability tests were also able to detect significant differences between the joints and locations away from the joint, but there was overlap in the groupings of like means. There were some differences in gradation but, again, there was significant overlap, suggesting that this is not discriminating enough.



Overall conclusions from this study included the contention that, while permeability was clearly related to joint quality, there is not a widely accepted standard for the test, making implementation questionable. Nuclear density measurements are quick and easy; in addition they are able to identify good and poor quality joints, though not as good at differentiating marginal qualities. Gradation parameters were related to joint quality in many cases, but measuring the gradation is too time-consuming. The nuclear gauge was deemed to be a practical tool for quality control. Determining the density of cores using the vacuum sealing method was recommended for routine use to determine quality.

**Williams, S. G. Density, Permeability, Infiltration and Absorption Used to Assess Quality of Hot-Mix Asphalt Longitudinal Joints. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2228, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 120–127.**

Williams followed up her 2009 TRB paper with a 2011 paper describing two field projects using eight different techniques to construct joints and a variety of tests to assess their quality. Each project included the following techniques:

- Joint adhesive
- Joint heater
- Notched wedge joint
- Joint stabilizer (polymer emulsion sprayed after joint compaction)
- Tack coat on cold face
- Hot overlap (vibratory roller on hot side overlapping cold side about 6 in.)
- Hot pinch (vibratory roller on hot side about 6 in. away from joint)
- Cold roll (static roller on cold side overlapping onto hot side about 6 to 12 in.)

Each technique was evaluated at three locations on each project using the nuclear gauge, field permeability, infiltration and coring. Infiltration is a measure of how much water flows into the pavement in a given amount of time. The bulk specific gravities and absorption values of the cores were determined by both the vacuum sealing and SSD methods. The cores were also used to calibrate the nuclear densities. In the end, the nuclear density, permeability and infiltration tests were found to differentiate joint quality the best. The notched wedge, joint heater and joint stabilizer were found to provide the best performance in terms of increasing density and reducing absorption, permeability and infiltration. None of the rolling patterns were superior. The joint adhesive did not reduce the permeability at the joint, as it was intended to do; it appeared the adhesive only filled voids at the joint and did not penetrate into the mat to fill voids near the joint.

**Mallick, R. G., and J. S. Daniel. Development and Evaluation of a Field Permeameter as a Longitudinal Joint Quality Indicator. *International Journal of Pavement Engineering*, Vol. 7, No. 1, March 2006, pp. 11–21.**

Permeability is considered a superior measure of joint quality than density because (a) it is more closely related to durability, (b) because of difficulties in measuring density immediately over the joint and (c) because it is non-destructive (vs. coring). Therefore, the authors developed a simple, falling head permeameter with three standpipes that can be used in the field to measure the intrusion of water into the joint and the mat on each side of the joint. The permeameter developed is based on the more familiar NCAT field permeameter and uses a flexible, closed-cell sponge to ensure contact with the surface. Three stand-pipes are used to complete the testing faster and to allow visual comparison of the infiltration of water at different locations.

The permeameter was to test several construction projects in three states, New Hampshire, Maine and Connecticut. Based on this testing, the following conclusions were reached:

- The field permeameter was practical, fairly quick (10 min), inexpensive, portable and can be operated by one person.

- The test results are reasonable and repeatable.
- Joint sealers and use of a joint heater can reduce the permeability of the joint significantly.
- Joints with sealants and low voids have performed well for three years after construction.
- Adequate density is also required to ensure good performance.
- Additional research is needed to set limiting criteria for joint permeabilities before the device can be used for QC/QA.

**Kvasnak, A. N., R. C. Williams, H. Ceylan, and K. Gopalakrishnan. *Investigation of Electromagnetic Gauges for Determining In-Place HMA Density*. Report No. IHRB Project TR-547. Iowa Department of Transportation, Ames, Iowa, May 2007.**

As part of a study to evaluate the feasibility of using non-nuclear, electromagnetic gauges to assess HMA density, these researchers also used the gauges at longitudinal joints. Two non-nuclear devices, the PaveTracker and PQI, were used. Both were found to be able to detect changes in density with increased roller passes, but the gauge readings and core densities differed. Both gauges were able to detect density differences between the mat and joint areas. The PaveTracker generally yielded lower densities than the cores or the PQI. PQI readings, however, were more variable than the PaveTracker or cores. Implementation of either of these gauges would require a test strip to develop mix and project specific adjustment factors to correct the density readings.

**Apeageyi, A. K., and B. K. Diefenderfer. *An Evaluation of the Potential Use of Non-Nuclear Density Gauges for Asphalt Concrete Acceptance*. Report No. VCTIR 11-R15. Virginia Center for Transportation Innovation and Research, Charlottesville, Virginia, February 2011.**

The Virginia DOT also evaluated the use of non-nuclear density gauges by comparing the PaveTracker and PQI gauges to core and nuclear gauge densities. The non-nuclear gauges were of interest because they are faster to use than coring and avoid the safety issues associated with nuclear gauges. The methods were compared in both the lab and the field. The study found that the non-nuclear gauges were less sensitive to changes in density than the nuclear gauges and were not well correlated the core densities. Therefore, the study did not recommend implementation of non-nuclear gauges for acceptance testing in Virginia.

**Killingsworth, B. M. Quality Characteristics for Use with Performance-Related Specifications for Hot Mix Asphalt. In *Research Results Digest, National Cooperative Highway Research Program Project 9-15, Transportation Research Board of the National Academies, Washington, D.C., August 2004.***

Contrary to the above studies, NCHRP 9-15 found the variability of the PQI, nuclear density gauge and core testing to be the same, statistically, although the average densities may be different. In addition, it was concluded that all three would be acceptable for use in a percent within limits (PWL) specification. The PQI gauge was used on field projects in this study and proposed specification criteria were developed. The in-place density would be considered good if it was 93.2 to 95.8% of the maximum theoretical density and poor if below 92% or above 97%.

The PQI was also used to assess longitudinal joint density. The density would be considered good if the relative density (joint density/mat density x 100%) were greater than 97%, fair if the relative density were 93 to 97% and poor if the relative density were less than 93%. On the four projects evaluated as part of this study, the standard deviation of relative density measurements with the PQI (1.15%) was lower than that of the nuclear gauge (3.97%) and of cores (2.31%).

**du Tertre, A., G. Cascante, and S. L. Tighe. Combining Portable Falling Weight Deflectometer and Surface Wave Measurements for Evaluation of Longitudinal Joints in Asphalt Pavements. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2152, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 28–36.**

These researchers attempted to use nondestructive testing of the pavement to assess the quality of the joints. The Portable Falling Weight Deflectometer (PFWD) is used to measure the deflection of a pavement under an impact load, which can be related to the modulus of the pavement materials. Multichannel analysis of surface waves (MASW) uses seismic waves to determine the stiffness profile of the pavement by measuring the velocity of seismic waves through the pavement. It was hypothesized that use of these two measures together could relate to the condition of the joint.

The PFWD was used to measure the deflection at the joint and 1 m on each side of the joint, and the MASW was used to measure across the joint with a transmitter placed on each side of the joint and an array of receivers spanning across the joint. Measurements were conducted on a test track in Waterloo, Ontario, Canada.

It was found that the PFWD was not precise enough to determine the quality of the joint; the deflection measurements are affected by the stiffness of deeper layers of the pavement, not just of the surface course of asphalt. Some ways to improve the results were suggested. Problems were noted with use of the MASW, mostly related to coupling of the transducers to the pavement surface. More work would be needed to implement either method, or a combination of these methods, for assessing joint quality.

**Estakhri, C. K. Support for the Implementation of a Longitudinal Joint Density Specification for Hot-Mix Asphalt Concrete. Report No. FHWA/TX-06/5-1757-01-1. Texas Department of Transportation, Austin, Texas, May 2006.**

An earlier research project had identified poor joint density as a contributing factor to pavement problems in Texas and recommended implementation of a joint density specification. This project was conducted to identify construction techniques to improve joint density, provide training, procure non-nuclear density gauges for testing joint and assess the joint density criteria.

The TxDOT specification requires performing tests when establish the roller pattern to verify that the joint density is no more than 3.0 pcf lower than the density near the center of the mat. Then, during regular paving, densities are measured in each subplot. If the joint density is more than 3.0 pcf lower than the mat density, it is a failing test. Corrective actions are needed when failing joint densities are measured, and paving is suspended if two successive failures occur.

The promising construction techniques were identified through literature review and talking to experts in the field. The methods identified were notched wedge joints, tapered joints, cutting wheel, joint adhesives and echelon paving. This effort also identified four keys to compacting a good joint:

1. Compacting the unsupported edge by extending the steel drum over the edge by about 6 in. to avoid lateral displacement of the mix.
2. Overlapping the mix about 1 to 1.5 in. onto the cold lane when placing mix in the hot lane to provide material and avoid starving the joint.
3. Not raking the excess material provided in step 2 back away from joint.
4. Overlapping a steel wheel roller about 6 in. onto the cold lane with the majority of the roller weight on the hot side or placing the center of the outside tire on a pneumatic roller directly over the joint.

Few projects had been conducted with the new specifications at the time of this study, but on those when the specification had been in force, contractors were generally able to meet the requirements after gaining a little experience with it. In one district a contractor had two projects with the requirements; he had some difficulty meeting the specification on the first project but was much more successful on the second project using the same mix; this seems to demonstrate the importance of experience with the specification. Based on this study, not changes in the specification were recommended.

**Steven McInnis, Pamela Marks, and Kai Tam. Construction of Longitudinal Joints in Flexible Pavements—Design Guidelines.**

**Report No. MERO-033. Ontario Ministry of Transportation, Downsview, Ontario, Canada, November 2008.**

This report acknowledges that proper joint construction is important for achieving high quality joints and building durable pavements, but also points out planning and design considerations that can also affect joint quality. These issues came to light during meetings of the Ministry and industry in 2007, and the report was prepared to focus attention of designers on the issues.

Paving in echelon and tandem paving (with more separation between the pavers resulting in a warm, rather than hot, joint) are desirable but can be difficult to implement in many cases. They may be feasible techniques when paving new alignments or multilane, limited access roadways where traffic and access to adjoining properties are not issues. Tandem paving can sometimes be accommodated by using a pilot vehicle to guide traffic through the work zone on the newly placed mat (at a controlled low speed). Designers are urged to consider ways to accommodate this type of paving in contracts. Considerations include:

- Ensuring paving quantities are large enough to make this type of construction cost effective. There are additional mobilization and operation costs for two pavers and sometimes for additional traffic control. A minimum tonnage of about 10,000 tonnes is suggested as the break point at which these techniques would be feasible. (It is also pointed out in this report that the hot mix plant must have sufficient capacity to feed two pavers simultaneously or productivity would suffer.)
- Echelon or tandem paving may not be appropriate if different materials or lift thicknesses are used on adjacent areas, such as mainline and shoulders. Designers should consider whether the cost of using premium materials and deeper lifts on the shoulders can be offset by improved efficiency and requiring fewer mix designs. They should also consider that having higher quality shoulders ultimately may be a benefit when traffic is diverted to the shoulders during rehabilitation and maintenance work or in emergencies.
- The possibility of closing lanes or diverting traffic to accommodate echelon paving should be considered, but will depend on traffic volumes and alternate routes. The report advises that it is usually not cost effective to construct median crossovers for paving operations, but there may be cases where it is, especially if the cross overs are needed for other purposes.
- Night lane closures may be feasible when daytime closures are not because of reduced traffic. Requiring night time lane closures should be considered during the design period because there are issues that need to be considered, such as noise restrictions near the plant, truck traffic restrictions in some municipalities to reduce noise, the need to supplemental lighting and other concerns.
- Ontario typically restricts the length of time that milled surfaces can be left open to traffic. This needs to be considered when echelon paving is discussed for projects involving milling as it can significantly impact the timing and efficiency of paving and the safety of the traveling public.
- The need to provide access to businesses and property may make closing lanes for echelon or tandem paving not feasible.
- Since surface courses are thinner, they can typically be paved more quickly, so it may be possible to pave the surface course in echelon even if underlying layers cannot be paved that way.

The report goes on to suggest ways to design and build high quality joints when echelon or tandem paving is not possible. One primary consideration is staggering the joints in multiple lifts. Joints in the surface lift should be at the edge of the travelled lane and not near the wheelpaths.

Constructing a good longitudinal joint can be hampered if temporary concrete barriers for traffic control are too close to the edge of the paved area. A minimum offset of 300 mm and desirable offset of 1500 mm are recommended. Barriers could potentially be moved temporarily to allow for paving but there are additional costs

associated with that. There may be opportunities, however, to coordinate paving with other work to avoid moving barriers repeatedly. These situations should be noted in the contract documents.

Scheduling the contract can also affect the ability of the contractor to construct a good joint. If the contract letting and amount of work push paving into colder times of the year, achieving good joint density can be more difficult. Requirements could be included in the contract to defer paving until the spring.

It may be easier to achieve good joint density with finer mixes. Agencies that specify fine mixes may find it advisable to specify them in some cases. (Alternately, smaller NMAS mixes might be used.)

The report also notes new technologies that may improve joint density which could be required in contracts. These include joint heaters, joint tape or joint bond materials, warm mix asphalt (which may be easier to compact) and hot in place recycling to avoid cold joints. Designers should consider the increased costs associated with these technologies vs. the benefits of improved joints.

Lastly, the report discusses options for maintaining or repairing deteriorated joints. These include routing and sealing joints, patching and micro-surfacing.

## OTHER SYNTHESSES

Anyone wishing more information or for different interpretations of some of the references above may want to read other's literature reviews. Some other available syntheses include:

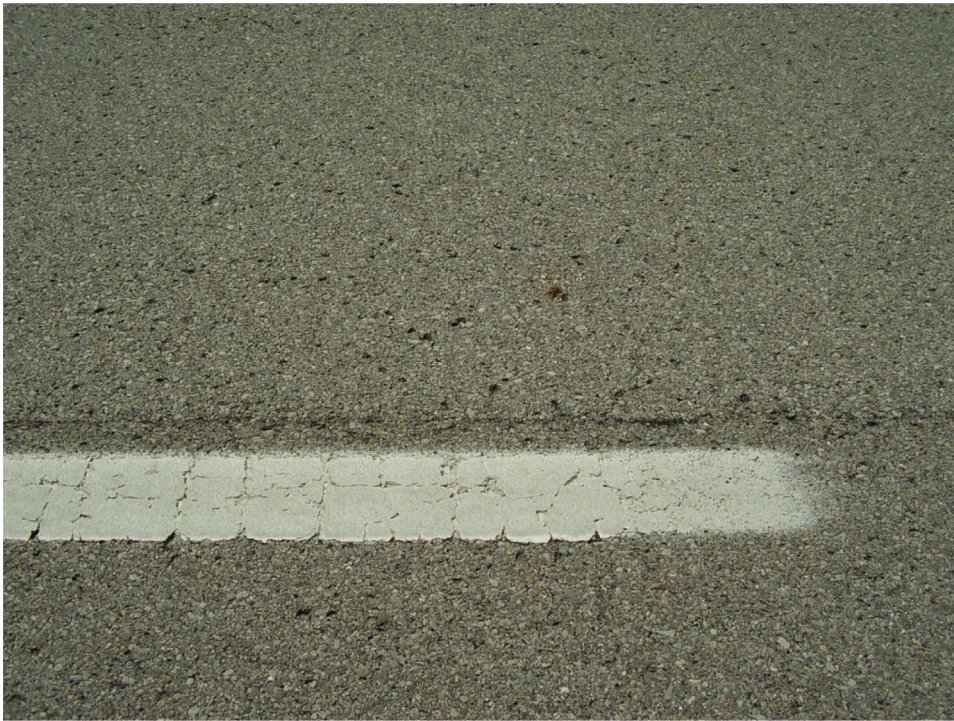
Buncher, M. E., and C. Rosenberger, Asphalt Institute. *Best Practices for Constructing and Specifying HMA Longitudinal Joints*. Draft report dated September 2011. Publication by Federal Highway Administration, Washington, D.C., is pending.

Akpinar, M. V., and M. Hossain. *Longitudinal Joint Construction for Hot Mix Asphalt Pavements*. Report No. K-TRAN: KSU-98-4. Kansas Department of Transportation, March 2004.

Wisconsin Highway Research Program. *Improved Life for Longitudinal Joints in Asphalt Pavements*. Transportation Synthesis Report, May 1, 2008.

Wisconsin Highway Research Program. *Pavement Joint Adhesive Evaluation*. Transportation Synthesis Report, November 30, 2004.

APPENDIX B. PHOTOGRAPHS OF TRIAL PROJECTS IN INDIANA JULY 14-17, 2012



**Figure B.1** I64 eastbound.



**Figure B.2** Joint adhesive visible on surface, I64 westbound.



**Figure B.3** Some joint separation, I64.



**Figure B.4** Cracking and braiding on I64 westbound centerline.



**Figure B.5** Cracking at shoulder joint, I64 westbound.



**Figure B.6** Water not penetrating surface after 15 minutes, I64 westbound.



**Figure B.7** US231 south of Crawfordsville showing water absorption near centerline joint.



**Figure B.8** One of the worst cracks observed, I64 westbound.



**Figure B.9** US40 eastbound—can you see the joint?





**Figure B.10** US40 westbound lanes (looking east).



**Figure B.11** US40 eastbound lanes (looking west).



**Figure B.12** US40 eastbound—note location of joint approaching wheelpath.



**Figure B.13** Deterioration at and beyond joint, US41.



**Figure B.14** SR23 double tack—separation at joint.



**Figure B.15** SR23 double tack.



**Figure B.16** General condition of SR23, test section 1 (conventional mill and fill).



**Figure B.17** SR23 joint adhesive (test section 1)—has been sealed.



**Figure B.18** General condition, test section 2 (fiber membrane).



**Figure B.19** Joint in test section 2 (fiber membrane), SR23.



**Figure B.20** Condition of test section 3 (SAMI), SR23.



**Figure B.21** Area with unsealed joint in test section 3, SR23.



**Figure B.22** Joint on SR38 showing slight separation.



**Figure B.23** Slight cracking at joint, SR38.



**Figure B.24** Close up of SR38 showing what appears to be crack next to adhesive.





**Figure B.25** Another site on SR38 with tighter joint.



**Figure B.26** Joint on SR38, adhesive visible in corrugation.



**Figure B.27** Joint seal and corrugations, SR120.



**Figure B.28** Joint adhesive and corrugations, SR120—adhesive visible near bottom of photo.



**Figure B.29** General condition of SR120.



**Figure B.30** Condition of SR120 east of test section—separated joint has been sealed.



**Figure B.31** Another location on SR120 east of test section—joint has not been sealed, staining suggests water intrusion.



**Figure B.32** Tight joint on US35 (test section 1).



Figure B.33 View of SR35 (test section 1).



Figure B.34 Another part of SR35 showing joint separation (test section 2).



**Figure B.35** SR9 in LaGrange showing poor joint placement.



**Figure B.36** Photo illustrating edge sloughing (although this roadway has been sealed, this shows what sloughing looks like), SR39.