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HMA Longitudinal Joint Evaluation and Construction

Stacy G. Williams

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By

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ABSTRACT

Longitudinal joint quality is essential to the successful performance of asphalt pavements. A number of states have begun to implement longitudinal joint specifications, and most are based on determinations of density. However, distress at the joint is caused by the ability of air and water to enter the pavement structure, which is also related to permeability. Thus, it is necessary to first determine the test method (or methods) that can best ascertain the quality of a longitudinal joint, and to then identify longitudinal joint construction techniques that are most able to create high quality joints.

This project was conducted in two phases. The first phase involved the use of various quality measures (density, permeability, infiltration, and gradation) to describe the quality of longitudinal joints on three projects of varying joint quality. The measures that were able to most accurately identify quality while also adequately discriminating between varying levels of quality were the nuclear density gauge, SSD and vacuum sealing determinations of core density, and infiltration. These methods were then used in Phase 2 to assess a variety of joint construction techniques. Two projects incorporated the use of eight techniques, including the notched wedge joint maker, joint heater, joint stabilizer, joint sealants, and varying rolling patterns. Extensive testing was performed for each test section. The most successful techniques were the joint heater, joint stabilizer, and notched wedge joint maker.

Although permeability more completely captures the fundamental failure mechanisms affecting longitudinal joint quality, density is a routine measure already used in virtually all quality programs. Thus, relationships were sought between permeability and density. Distinct differences in permeability were noted for various levels of density and absorption capacity. As a result, it is believed that measures of density are adequate for limiting the permeability at the longitudinal joint. Based on the results of this study, a minimum joint density of 89 percent is recommended. Although test results do indicate that some joint construction techniques provide superior performance, no specific technology is currently recommended for inclusion in the joint density specification.

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INTRODUCTION

Longitudinal joint quality is critical to the long-term performance of asphalt roadways, and many asphalt pavement failures occur at the longitudinal joint. Because most paving efforts require multiple lane roadways to be paved one lane at a time, the first lane paved is allowed to cool prior to the placement of the second lane. Because the edge of the first lane is unconfined, it cannot be compacted to the same density as the rest of the mat. Additionally, placement of the second lane may not properly bond to the first lane due to the significant temperature differential. This results in an area of the pavement that is susceptible to accelerated damage.

In general, low joint densities have been believed to be primarily responsible for these failures because low densities generally indicate higher levels of permeability, meaning that air and water can enter the joint area and accelerate the potential for deterioration. It is extremely unfortunate when unplanned maintenance is required to rehabilitate an entire lane caused by a failure that is primarily confined to an area that is less than ten percent of the lane width.

To mitigate the common problems associated with longitudinal joints, this study was designed to address two primary objectives. The first was to identify the most appropriate measure of longitudinal joint quality, and the second was to evaluate a number of longitudinal joint construction techniques. Although density has long been considered the primary measure of joint quality, permeability represents the more fundamental basis for typical joint failure mechanisms.

BACKGROUND

Longitudinal joints are typically constructed one lane at a time, such that the first paved lane has cooled prior to placement of the second lane. When the first lane is compacted, the outer edges lack confinement, producing an area of low density. This lane is often termed the "cold" lane. When the second lane is paved, the initial lane offers support, and adequate density is more easily attained. The second lane is typically referred to as the "hot" lane. When the density at the longitudinal joint is low, there is greater potential for the voids to be interconnected, increasing the likelihood of permeability. Permeable areas are then susceptible to invasion by air and water, which lead to the distresses of oxidation, moisture damage, cracking, raveling, and joint separation.

Another problem that may exist in longitudinal joints is the vertical differential that is often present. This differential may be due to poor construction practices or settlement after longitudinal cracking appears. *(1)* Vertical differentials often appear as a depression along the joint, which serves to collect and store water at that location. If the joint is permeable, that water is able to penetrate the pavement structure, accelerating the potential for moisture-related distresses.

In order to maximize longitudinal joint performance, the joint must be both smooth and tight, and good construction practices are essential to these characteristics. There are 3 primary factors that affect longitudinal joint density. The first is the density achieved at the unconfined edge of the cold lane, second is the compaction of the material directly in the joint, and third is the level of compaction of material on the hot side of the joint. *(2)* The compaction of the material in the joint is critically affected by the amount of material in the joint. In general, an asphalt mat will condense to a final compacted lift thickness that is approximately 80 percent of the thickness behind the screed. *(2, 3)* Thus, enough material must be present to fill the joint area to the proper level and at the desired level of compaction.

Compaction of the cold lane can be done in various ways, but should be performed in a manner that minimizes the lateral movement of the mix. A pneumatic tire should not be used to roll the free edge of the cold side of the joint because it pushes the mix transversely, flattening the mat. *(2)* Even though a steel wheel roller may cause some breakdown at the free edge, it minimizes the overall transverse movement of mix. Therefore, only steel wheel rollers should be used, and roller placement is key. If the steel roller is located inside the unsupported edge on the first pass, transverse movement of the mix is likely, and a crack may form near the joint. If the roller edge is placed directly upon the unsupported edge, some transverse movement may occur, but a crack is not likely. If the edge of the roller extends significantly over the unsupported edge, the transverse movement of the mix is minimized and no cracks should form. *(4)* It has been recommended that a steel roller should overhang the unsupported edge by at least 2 feet to achieve greater and more consistent compaction at the joint. *(5)* Applying tack prior to paving the cold lane can also provide some lateral confinement to the cold side of the joint. *(2)*

When the hot lane is placed, there must be some overlap of material onto the cold lane, and 1 to 2 inches is typically recommended. *(6, 7)* If there is not enough overlap, then there will not be enough material in the joint, and there cannot be enough compactive effort to achieve adequate density. In this situation, a depression will develop on the hot side of the joint and collect water during a rain event. If there is too much overlap, then the excess must be removed by raking, or luting, or it will be crushed by the rollers. In either case, joint performance is detrimentally affected.

In general, raking the joint is not good practice. When a mix is raked, the mix that is pushed off of the joint is deposited onto the new asphalt, which changes the texture of the mat from one side of the lane to the other, making the required density virtually impossible to achieve. *(8)* If the excess mix is raked into a hump, then the roller will ride on the ridge, creating high density under the ridge but low density immediately adjacent to the ridge. *(2)* Ensuring the proper quantity of material and proper overlap makes raking unnecessary, and is critical to joint quality.

Proper overlap is a function of the paver and paving process. If paver extensions are used, they may not provide the same amount of initial compaction as the primary screed. Also, if the paver is moving too fast, the auger may not have time to adequately push the material to the outer edges of the screed and there may not be enough material to fill the joint. In some cases, if the auger box is not full enough, coarse aggregate will fall to the outer edges, generating segregation at the joint. *(2)*

By traditional joint construction methods, the cold side of the joint will generally exhibit lower densities than the hot side of the joint, which is reasonable since the cold side lacks confinement and cools without being thoroughly compacted. However, this is not always the case. *(4)*

Joint Construction Techniques

In general, longitudinal joint construction methods can be grouped into several basic categories, including echelon paving, rolling techniques, joint adhesives / sealants, wedge construction, edge restraint devices, cutting wheels, and joint heaters.

<u>Echelon Paving</u>

In echelon paving, multiple lanes are placed at the same time, with the paver in the second lane following closely behind the paver in the first lane. Because both lanes can be rolled before the mat cools, the potential for the density differential at the joint is greatly diminished. Although echelon paving is widely recognized as the most advantageous for producing high-quality longitudinal joints, it is rarely feasible due to traffic considerations and construction sequencing. *(1)*

<u>Rolling Techniques</u>

Rolling techniques can be implemented in several different ways. Most employ a strategy to force the overlapping mix into the joint, creating a consistent density and a smooth joint with minimal vertical differential.

Hot Overlap
In the hot overlap rolling method, compaction is performed such that weight of the roller is primarily located on the hot lane, but the roller drum overlaps the cold side by approximately 6 inches. *(1, 2)* Initial rolling is usually performed with a steel-wheel roller in vibratory mode (i.e., the breakdown roller), generating maximum compaction. By overlapping the cold lane slightly, the vertical differential between lanes is minimized. This method has been traditionally recommended for getting a good bond between the hot and cold lanes. *(2, 3, 6, 7, 9, 10)*

Hot Pinch
In this method, initial joint compaction is performed with the roller in vibratory mode on the hot side of the joint maintaining a distance of approximately 6 inches away from the joint. During this first pass, the material underneath the roller is compressed and moves laterally toward the joint. As a result, the material nearest the joint appears slightly humped. On subsequent passes, this material is then compacted and “pinched” into the joint. Assuming that the proper amount of material is placed, this method has been reported to provide better joint performance than the hot overlap method, especially for a tender mix or when the lift is fairly thick. *(1)* A number of studies have recommended this rolling technique for maximizing joint performance. *(7, 11, 12)* A disadvantage of this method is that during the first pass, some of the material is pushed laterally to form the hump. The steel roller may then ride upon the hump, bridging the neighboring material and leaving low density in the bridged areas. *(2)* Also, secondary cracks may develop along the pinch line. *(13)* Using a pneumatic tire roller can help to compact joints because they can adjust to somewhat counteract the lack of compaction, generate a kneading action rather than bridging effect seen with the steel wheel rollers that provides little or no compaction.

Cold Roll
In the cold roll method, rolling is first performed from the cold side. The roller is placed on the cold side, overlapping the hot side by 6 to 12 inches. To avoid crack development on the cold lane, initial compaction is typically performed in the static mode. This method provides good initial compaction at the joint and helps to eliminate the vertical differential at the joint. There are distinct disadvantages associated with this method in that placing most of the roller on the already compacted mat wastes valuable compaction energy, and compacting in the static mode provides less compaction that vibratory mode. Also, while the joint area is being compacted, the remainder of the mat is allowed to cool, making it more difficult to compact. *(1, 2)* In spite of these disadvantages, experience has proven this method to produce longitudinal joints with minimal cracking. *(14)*

<u>Joint Adhesives and Sealants</u>
Many products have been used to seal longitudinal joints, with the primary intention of preventing the entrance of air and water, thereby reducing joint separation and preserving the integrity of the joint. Although these materials do not typically improve the density at the joint, they have demonstrated good performance after several years in service by limiting the number of interconnected void spaces. *(2, 11, 13, 15, 16)* Most of these products are applied to the face of the joint prior to placing the hot lane,

although some are applied after the both sides of the joint have been compacted. Others are applied to the underlying material prior to overlay placement with the expectation that when the hot asphalt is laid, the heat generated will cause the sealant to migrate upward through the joint, eliminating many of the interconnected void spaces. Although there are many similarities among products, a significant portion of them contain proprietary materials. Some of the products in this category type include: *(17, 18, 19)*

- Rubberized asphalt
- Polymerized emulsion
- Emulsified asphalt
- Acrylic emulsion
- Tack coat
- Joint tapes

Wedge Construction

Longitudinal joints have also been constructed using a wedge at the unsupported edges. This technique employs a paver "shoe" or "boot" that forms the unconfined edge of the mat into a taper. This edge shape is believed to reduce the amount of transverse migration of the cold lane during compaction. It also provides a graduated surface for placing overlapping material that is typically thin enough to absorb the heat from the hot lane, allowing for greater aggregate interlock during joint compaction. A tack coat may also be applied to the wedge face prior to paving the hot lane. An additional advantage of this method is that it provides a safer edge for vehicles to traverse until both sides of the joint are constructed. In the late 1980s, Arizona and New Jersey were the first states to experiment with and implement a wedge joint. *(20)* New Jersey used a steeper wedge slope (3:1) than Arizona (6:1) in an attempt to reduce the potential for raveling that was sometimes noted for the flatter slopes. Wedge forms with 12:1 slopes were implemented by the state of Michigan. Due to the fact that the flatter slopes often experienced segregation and "dragging out" of the larger particles, the wedge design was further refined to include a notch (a vertical face at the top of the wedge). See Figure 1. The notched wedge joint maker is the most commonly used wedge joint, and has been reported to provide an increase of density at the joint. *(2, 6, 12, 21, 22, 23, 24, 25)*

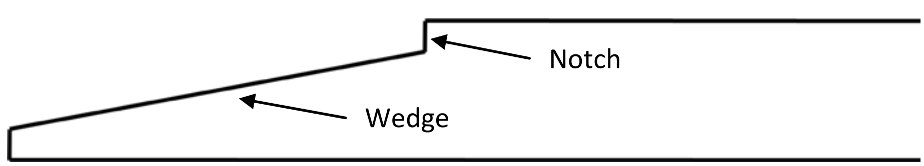


FIGURE 1 Schematic of notched wedge joint.

Compaction of the wedge portion has been treated in a number of ways. In some cases, the initial compaction provided by the boot is felt to be sufficient (provided the auger box stays full enough and the augers properly force material to the outer edges of the screed). In other cases, compaction has been applied to the wedge using truck tires, a steel side roller wheel, a rubber side roller wheel, or a tag-along roller. *(3, 25)* While it is believed that some level of compaction is beneficial for the wedge to perform properly, the amount of compaction generated by the small rollers may not be substantial enough to significantly improve performance. Also, by not compacting the wedge, aggregate particles may maintain a more irregular orientation and generate increased aggregate interlock when the hot side of the joint is placed.

Edge Restraint

The edge restraint method is somewhat similar to the wedge method in that an additional fixture is used at the end of the screed to provide a confining force to the unsupported edge. *(1)* However, the resulting edge is typically much more vertical in nature than the wedge methods. For this method, a tapered wheel is attached by a hydraulic arm to the roller to prevent lateral movement of the mat as the cold lane is compacted. While the edge restraint method is believed to have potential, this method is very operator dependent. *(5, 6, 23)*

Another method for restraining the edge of the unsupported mat is the Joint Maker™ System. The Joint Maker™ is a non-mechanical attachment that is placed on the front side of the screed next to the end gate. The device is set at an angle and serves to pre-compact the mix ahead of the screed. Along with the Joint Maker, a kicker plate is also attached to the end of the screed to automatically rake the excess material back into the joint to help create a more vertical joint face and a smoother joint. Although the concept behind this method is reasonable, it has not clearly demonstrated its ability to generate significant performance improvements. *(1, 23, 26)*

Cutting Wheel

A cutting wheel can be used to create a vertical joint face after the cold lane is paved. Generally, this involves mounting a cutting wheel to an intermediate roller or other motorized equipment, so that the wheel removes the outer portion of material (usually 6 – 8 inches) at the free edge. In this way, the low density material at the edge of the mat is completely removed, and allows for a dense, vertical support against which the hot lane can be paved. Thus, both the cold and hot sides of the joint are denser than joints constructed by traditional methods. The primary advantage of this method is that it has clearly demonstrated the ability generate acceptable performance, and is currently used for airport HMA pavement construction. *(1, 2, 4, 6, 11, 12, 14, 24)* The disadvantages are that the joint quality is highly dependent upon the ability of the operator to cut a straight joint, which critically affects the density of the material on the hot side of the joint. Also, the contractor is forced to "waste" the excess material that is cut from the joint. On large jobs, this amount can be significant. In some cases, the wasted material can be luted back into the joint to generate additional density within the joint, but this can also create segregation at the surface of the joint.

Joint Heater

The basic premise of the longitudinal joint heater is that after the cold lane is placed, the joint area can be pre-heated just prior to placement of the hot lane, allowing for better adhesion between the two sides of the joint, as well as improved consolidation of the entire joint area. This process essentially recreates the circumstances encountered during echelon paving because the "cold" side of the joint is no longer cold. The concept of the joint heater has existed for at least 25 years, and has been used in a number of research projects. *(18, 20, 23, 26, 27)* Recent joint heaters employ propane-powered high efficiency infrared technology to heat the joint area to a relatively soft condition. The heater panels are mounted on a trailer that can be pulled with a small motorized tractor, which travels immediately ahead of the paver. If needed, an additional booster heater panel may be attached to the side of the paver to maintain the desired temperature. In most cases, the joint heater can travel at paver speeds as it increases the pavement temperature to 200 – 250 °F. Although there has been some concern associated with "scorching" the mat, proper heater control should prevent this from happening. The best results occur when consistent heating is maintained, which leads to consistent densities and consistent performance. This technique has been reported to reduce segregation, increase joint density, and provide a very smooth joint. *(18, 20, 23, 27)*

Methods for Assessing Joint Performance

Longitudinal joints were first considered to be a possible root cause of HMA pavement deterioration in the 1960s, when the joint area was determined to be a "low density zone". *(28)* A well-constructed longitudinal joint should have about 1 to 2 percent lower density than the mat, but a poorly constructed joint can have 5 to 10 percent lower density than the mat. *(1, 11, 23, 28, 29)* Because of this, density has been the primary measure of joint quality. However, the fundamental mechanisms of failure are more directly related to the permeability of the joint because the entrance of air and water directly contribute to the distresses of oxidation, moisture damage, cracking, raveling, and joint separation. Thus, measures of permeability should also be considered. Pavement condition surveys also provide valuable insight as to the long-term performance with respect to raveling and cracking at the joint; however, these measures can only be employed after the pavement has been in service for a significant period of time and do not provide performance indications at the time of construction.

<u>Density</u>

Several methods exist for the purpose of measuring density. Those most commonly used are the nuclear density gauge and laboratory measures of density determinations of cores cut from the roadway. Non-nuclear density measures have also been used.

While nuclear and non-nuclear gauges are advantageous because many measurements can be taken quickly and in a non-destructive manner, issues have been cited with the seating of these gauges across the joints, especially at the crown of the roadway cross-section. In fact, a 1 mm air gap in one lane has been shown to underestimate density by 1 to 2 pcf. *(2, 11)* Thus, many "joint densities" measured by the gauges are actually taken with the gauge seated immediately next to the longitudinal joint. Of the available methods, the most accurate measure of joint density is generally believed to be the laboratory-derived density of cores cut from the actual joint. *(11)* However, no specific recommendation has been made regarding the most appropriate laboratory method for joint density determinations. Several procedures are available, including the SSD, vacuum sealing, parafilm, CoreReader, dimensional analysis, and X-ray tomography methods.

In most cases, joint densities are expressed in terms of a percentage of the theoretical maximum density (TMD) for the lot or sublot being measured. In most cases, this is a simple calculation. However, if the core barrel is centered over the visible joint line when cutting the core, the core will actually contain a larger portion of mix from the cold side of the joint because of the shape of the unconfined edge during placement of the cold lane. *(13)* This is especially true if a wedge joint is used. If the hot and cold lanes fall in different lots or sublots, then a provision must be made for the proper method of calculating density (i.e., weighted average, etc.). It is also somewhat common for joint densities to be referred to as a percentage of mat density. (*30*) Because of the varying definitions, it is important that the definition used for a joint density specification be clearly communicated.

Permeability

While density can certainly be an indicator of joint quality, this parameter alone may not be an adequate descriptor in all situations, specifically when joint adhesives and sealants are used. *(15)* Thus, other measures may be more appropriate for indicating the quality of longitudinal joints. Permeability and infiltration have been investigated as possible alternatives, and results appear to be very promising. *(23, 15, 16, 17, 18)* Falling head field permeameters with a tiered standpipe (equivalent or similar to the NCAT permeameter) have been used in most instances. *(31)* Laboratory permeameters have also been used, primarily the Karol-Warner style. A longitudinal joint permeameter was developed by the University of New Hampshire, which was basically a modification of the field permeameter developed at Worcester Polytechnic Institute (WPI). *(15)* The joint permeameter contains 3 standpipes that are not tiered, and are fixed in an assembly so that during the test, the pipes are situated on the longitudinal joint and to either side, such that 3 permeability measurements can be made at the same time. In a Kentucky study, a vacuum permeameter was used *(23)*, and in Arkansas, a vacuum permeameter successfully identified excessive voids at longitudinal joints. *(32)*

Other Methods

In Tennessee, a water absorption method was developed because it was felt that traditional methods of measuring density and permeability were unable to accurately depict the true performance of joints treated with sealants or adhesives. *(18)* In this method, cores from the longitudinal joint were submerged in a water bath for 40 minutes, then dried with a damp cloth and immediately covered with a 150mm diameter paper cloth and gentle pressure applied. The weight of water absorbed into the paper cloth was used to generate a relative comparison of water tightness of the joint cores. *(18)*

In Ontario, Canada, a portable falling weight deflectometer (PFWD) and a multi-channel analysis of surface waves method (MASW) were used to investigate alternative non-destructive methods of describing longitudinal joint quality through measures of elastic modulus. *(33)* The MASW method uses ultrasonic transducers to measure surface waves traveling through the pavement to determine the elastic modulus of the various layers. The MASW method showed promise, but the pavement substructure interfered with measurements produced by the PFWD.

LITERATURE REVIEW

In the 1960s, longitudinal joint research began with a study that demonstrated the density gradient across the longitudinal. *(28)* The researchers hypothesized that this area of low density could be responsible for a number of premature pavement failures and unplanned maintenance activities. In the 1980s, this type of research again gained prominence, and additional studies were performed to investigate the relationship of mat and joint densities, as well as the use of wedge-style joints and the infrared joint heater as methods to improve joint quality. *(3, 20)* In the study, both methods were successful in helping to eliminate the density gradient across the joint, and both were recommended for use. However, further research demonstrated that the wedge joint alone could adequately reduce the density gradient, and the infrared joint heater was no longer included in the recommendation. Since that time, a number of research studies have been conducted to investigate the characteristics of longitudinal joints and to evaluate various techniques for constructing longitudinal joints. A summary of major studies is presented here.

National Center for Asphalt Technology

From 1992 to 2002, a major longitudinal joint study was performed by the National Center for Asphalt Technology (NCAT). The project was carried out in a number of phases, evaluating various joint construction techniques in Michigan, Wisconsin, Colorado, and Pennsylvania.

Michigan and Wisconsin *(1)*

Seven joint construction methods were used in the Michigan project, and 8 techniques were used in the Wisconsin project. All methods were performed on dense-graded HMA overlays, and each was performed for a 500 foot length within the project. The methods were:

- Hot overlap – compaction was performed from the hot side, overlapping the cold side by about 6 inches.
- Cold roll – rolling commenced from the cold side, overlapping the hot side by about 6 inches.
- Hot pinch – compaction began on the hot side, about 6 inches away from the longitudinal joint
- Wedge joint without a tack coat – a small roller was used to compact the unconfined wedge
- Wedge joint with a tack coat – a small roller was used to compact the unconfined wedge
- Restrained edge compaction – a tapered wheel was attached to the roller
- Cutting Wheel – mounted to an intermediate roller to remove low-density material
- Joint Maker – sloping device for added compaction and kicker plate for automatic raking

Conclusions were made based on visual inspection and density measurements at the joint. Comparing the 3 rolling methods, the hot overlap was the most consistent rolling method. On the Michigan project, the wedge joint with and without tack coat, and the cutting wheel provided the highest densities. The cutting wheel displayed the greatest visual quality after one winter season. On the Wisconsin project, the edge restraint and cutting wheel methods provided the highest densities at the joint, followed by the wedge joint and joint maker. Again, after one winter, the cutting wheel method appeared to provide the greatest joint quality.

Colorado *(21)*

In Colorado, 7 methods were used on 500 foot sections of the test project. The techniques used were:

- A 3:1 taper on the cold side with conventional overlapping on the hot side, using the hot overlap rolling method
- A 3:1 taper with the cold roll compaction method
- A 3:1 taper with the hot pinch compaction method
- A 3:1 taper and a cutting wheel to remove the wedge on the following day. Tack was applied to the joint face prior to placement of the hot lane.
- A 3:1 taper and cutting wheel with no tack coat applied to the joint face
- A notched wedge with a 1 inch vertical step and 3:1 slope. The taper face was tacked
- A rubberized tack coat was applied to the joint face after traditional joint construction methods were used to place the cold lane

The best method was determined to be the 3:1 taper with a 1 inch vertical offset with tack applied to the taper. The next best method was the 3:1 taper using a cutting wheel to remove the wedge and applying tack to the vertical joint face. In terms of rolling techniques, the hot pinch method was ranked highest.

Pennsylvania *(6, 21)*

The Pennsylvania trial was performed using the same methods as the Colorado study, but with two additional methods. They were:

- Conventional joint with natural slope using the cold roll compaction method.
- A 3:1 taper formed the cold side of the joint, which was then heated by an infrared joint heater prior to placement of the hot lane. Compaction was performed using the cold roll method.

On this project, the method yielding the best performance was the cutting wheel with rubberized tack applied to the vertical joint face and compacting using the hot pinch method. After a mild winter, it was determined that the 3:1 taper joint was not performing significantly better than the conventional joint.

Summary of NCAT Research Effort *(6, 11)*

Density was the primary measure used to characterize the joints during construction, which was measured at the joint and 12 inches away from the joint on the cold side. Subsequent pavement surveys confirmed that higher densities during construction did, in fact, correlate well with better performance. Thus, density was believed to be an adequate predictor of quality. Overall, the Michigan joint (notched wedge) was chosen as the best technique, and the importance of the vertical offset was emphasized. Although the cutting wheel and edge restraint devices produced good quality joints, they were both operator dependent, which prevented them from producing consistent joints. Good construction practices were emphasized: it was stated that the hot side should always overlap the cold side by 1 to 1-1/2 inches at the joint, and that rolling should be done as soon as possible from the hot side of the joint with a vibratory roller. It was also recommended that pavers should include additional tamping or vibrating features near the edge of the paver screed to provide higher initial densities at the unconfined edge, and that the traditional butt joint should not be used. Agencies were encouraged to implement joint density specifications that required the joint density to be no more than 2 percent lower than the mat density. It was also recommended that joint density measurements be obtained from cores rather than the nuclear gauge because of the seating issues associated with the gauge.

After 6 years, the performance of each test section was evaluated. Based on the 6-year assessment, the rubberized joint material showed the best performance, followed by the cutting wheel. Because all test joints were constructed carefully, good overall performance somewhat masked the effects of the various joint construction techniques. When considering only rolling styles, rolling from the hot side resulted in better performance than rolling from the cold side.

Other Research Efforts

Wisconsin *(25)*

During the NCAT study, the wedge construction method was proven to be a superior performer in Michigan, but did not perform as well in Wisconsin. As a result, further study was undertaken to more thoroughly investigate the wedge joint construction. It was determined that the lack of contractor experience was partially responsible for this phenomenon. Also, the Wisconsin wedge did not contain the ½" vertical notch that was present in the Michigan wedge. Furthermore, the wedge face was not compacted in Wisconsin as it had been in Michigan. Eight techniques were considered, including:

- Conventional method
- Wedge joint method with truck tire rolling
- Wedge joint method without rolling
- Wedge joint method with steel side roller wheel
- Wedge joint method with rubber side roller wheel
- Wedge joint method with tag-along roller
- Cut joint method
- Edge constraint device

Performance results were based on density results and 10-year cracking survey results. Density measurements were taken with the nuclear density gauge and by the SSD method on cores. Poor correlations existed between the core results and gauge results. Thus, the cores were assumed to be most accurate.

The wedge joint with steel side roller and the wedge joint with the tag-along roller were the best performers, and were the only methods that were able to achieve 92 percent density at the joint. Because the construction process was simpler with the steel side roller, it was recommended for use.

Notched Wedge Evaluation *(22)*

During the same time frame, another project was performed to evaluate the wedge joint. The objective of this study was to evaluate the performance of the notched wedge joint as compared to conventional joint construction. Test sections were constructed in 5 different states and random testing was performed on each section. Density was used as the measure of joint quality.

In 4 of the 5 projects, the notched wedge joint technique increased the centerline density over that achieved by the conventional joint construction method, however only 2 of these 4 were statistically significant. For the project that did not benefit from the notched wedge, it was surmised that the large lift thickness was to blame.

In the notched wedge joint sections, it was noted that there was a general decrease in the density of the test locations that were 6 inches from the joint on the hot side. This was likely due to the fact that the wedge was not compacted prior to placement of the hot lane.

One of the primary advantages of the notched wedge joints was the safety benefits associated with the wedge shape. Since there was no significant drop-off, traffic was able to easily traverse the partially constructed joint. This is especially beneficial because a longer stretch of paving can be completed without the eminent need to back up and match elevations before opening the lanes to traffic.

Texas Study *(29)*

As the topic of longitudinal joint quality gained prominence, the Texas Department of Transportation began a project to determine whether or not a significant problem existed in the state with regard to joint quality, and to synthesize information from other sources for the purpose of recommending modifications to the existing HMA specifications. A number of case studies were established, such that density measurements were obtained on 35 pavements at the joint, at 12 inches from the joint, at 24 inches from the joint, and at the interior of the mat. On average, there was a 6 to 7 pcf difference between the unconfined edge and the interior of the mat.

As a result it was recommended that a specification be implemented to require that a joint core density could not be more than 5 pcf less than that of the interior of the mat.

Maine Study *(14)*

In Maine, a study was carried out to evaluate several different joint construction methods. Performance was based on density measurements as well as visual observation. General conclusions are as follows:

- The Joint Maker, control section, hot overlap, and cold roll methods performed well, producing tight joints with good aggregate interlock.
- The cutting wheel exhibited clearly defined joints with little to no aggregate interlock, but densities were high near the joint.
- Based on densities at the centerline joint and 18 inches from the joint, the control section produced the highest densities.
- By visual observation, the cold roll section showed the least severity of cracking.
- The hot overlap, cutting wheel, and joint maker displayed the greatest amount of joint separation, and were not recommended.

Kentucky Study *(23)*

A similar study was performed in Kentucky, in which 5 methods – the notched wedge joint, restrained edge, the Joint Maker, joint heater, and joint adhesive – were used on 12 jobs. In addition to using density (nuclear gauge and cores) as a quality measure, permeability was also determined using a falling head test and a vacuum permeability test. Quality determinations were made at the joint, as well as 6 inches, 18 inches, and 6 feet to either side of the joint.

In terms of permeability, the notched wedge joint was the best performer, and the infrared joint heater generated the greatest increase in density. The Joint Maker did not improve density at any location, and was not recommended. It was suggested that joint densities should be tested within 3 inches of the joint, and should have a density of no more than 3 percent of that of the central portion of the mat.

Ontario Study *(26)*

In Ontario, Canada, four trials were performed to evaluate the joint heater, the Joint Maker system, and a combination of both the Joint Maker and joint heater. Density was used to compare each of the test sections to a control section. Overall, no single method could be classified as superior. Joint densities were excellent throughout the project, meaning that contractors were able to achieve adequate densities without special devices, equipment, or procedures. A review of contracts that used a temporary specification for longitudinal joints revealed that contractors were able to easily obtain bonus pay without making drastic changes to construction operations.

Illinois Joint Sealant Study *(17)*

In this study, 2 joint sealing products – 1) J-Band ® by Heritage Research Group and 2) QuickSeam ® by Hendy Products, Inc. – were used on 4 projects to assess their abilities to reduce the permeability of the surface along the longitudinal joint. The concept of each product is that it is placed on the old pavement surface and then the overlay is paved. The heat of the new HMA mat reheats the sealant and draws the material upward into the surface layer. If it performs properly, the sealant will migrate into approximately ¾ of the layer thickness, sealing the interconnected voids.

The results of the study were mixed. On 2 of the projects, both products were very successful at reducing permeability; but on the other 2 projects, the products had virtually no effect. In terms of constructability, the JBand was much easier to place than the QuickSeam. Both products had issues with tracking when construction traffic drove over them.

Maine *(16)*

The Maine Department of Transportation has also evaluated several methods for the purpose of improving longitudinal joint performance and plans to consider implementing a joint specification. In one project, three joint sealant products were used – 1) rubberized joint sealer CMC #102 manufactured by Crackfiller Manufacturing Corporation, 2) a joint adhesive from Koch (Koch Product #9005-HV), and 3) an emulsified asphalt grade HFMS-1. The Worster Polytechnic Institute (WPI) permeameter was used to evaluate permeability, and all test sections were watertight. Overall, the 3 sections performed similarly, and there was no distinct advantage noted with respect to joint adhesive type.

New Hampshire Study *(15, 27)*

Permeability and indirect tensile strength were parameters of interest in a New Hampshire longitudinal joint study. In 1999, the infrared joint heater was compared to conventional joint construction methods. The project was successful, and another study was performed. It was determined that overall, the infrared heater sections were the better performers in terms of both permeability and indirect tensile strength. Also, the infrared heated joints showed much less cracking and less segregation than the control sections.

Because permeability was believed to be a key factor in describing longitudinal joint quality, especially when joint sealants were used. Thus, a special permeameter was developed for testing longitudinal joints. The joint permeameter had 3 sections that could test the joint and 1 foot to either side of the joint simultaneously.

New York *(2, 10)*

In 1995, the state of New York formed a task group to study a number of hot mix asphalt issues, including longitudinal joints. They initiated studies using the notched wedge joint as well as joint sealants. While it was believed that good construction practices would solve most of the problems associated with longitudinal joints, the notched wedge was successful in generating slightly higher density values. Because this difference was not significantly greater than for the traditional butt joint, further study of the notched wedge joint maker was not pursued.

The Port Authority of New York and New Jersey (PANYNJ) also investigated longitudinal joint construction and first addressed the issue by requiring a specific type of joint construction. When this was not successful, they changed to an end result type of specification such that a minimum joint is required, however no specific method was required. This approach proved more successful.

Nevada *(4)*

In Nevada, a study sought to establish a knowledge base for aiding in the development of a longitudinal joint specification. Five joint geometries and 2 joint rolling techniques were performed. The most promising techniques from this study were then further evaluated in additional test sections. The 5 joint geometries were:

- Natural slope
- Edge restraining device
- Cutting wheel with a rubberized tack coat
- Cutting wheel without a rubberized tack coat
- 3:1 tapered wedge

The two rolling techniques were the hot overlap and hot pinch methods. Statistically, these two rolling methods were similar. As for joint geometries, most were similar and did not improve the cold side density, but did increase the hot side density. The best performers were the edge restraining device, the cutting wheel with tack coat, and the3:1 tapered wedge.

Tennessee *(18)*

A recent study in Tennessee also investigated several joint construction techniques, which were evaluated based on density, permeability, indirect tensile (IDT), water absorption, and X-ray tomography. Seven techniques were implemented on 3 projects, including joint adhesives, joint sealers, and the infrared joint heater. Performance parameters correlated well in that low densities were consistent with high permeability and low strength values.

Of the joint adhesives, polymer emulsion applied to the joint face was the best performer, and appeared to increase the IDT strength of the joint. Water absorption testing indicated that joint sealers may prevent water from penetrating the joint, but permeability testing did not confirm these results. Overall, the infrared joint heater was the most effective at improving joint quality.

Virginia *(7)*

The state of Virginia took a slightly different approach to the issues associated with longitudinal joints. Rather than implementing a specification or investigating new construction methods, they implemented a field training program and published a longitudinal joint construction memorandum. In order to track the success of the program, joint densities were monitored on state projects and the roller operator had to be notified if measured densities were less than 95% of target densities. This program took place in 2005, and initial results were good. However, in 2006 and 2007, densities began to decline. So the Virginia Department of Transportation and the Virginia Asphalt Alliance again placed increased emphasis on the topic, and joint densities again improved significantly. Thus, the requirement for monitoring is believed to have been an effective measure.

Connecticut *(31)*

In Connecticut, two resurfacing projects incorporated the use of the notched wedge joint, and density measurements were used to compare the performance of the notched wedge to that of the traditional butt joint. Although conclusive evidence has not yet been obtained regarding joint performance, initial observations indicate a smaller density gradient across the joint for the notched wedge. Additionally, paving operations were not slowed by using the wedge, and passenger cars were able to easily traverse the wedge joint during the construction process.

State Specifications

Most state specifications include information regarding the placement of joints with respect to lane lines or relative positioning for joints in multiple lift pavements. The majority of states also provide guidance regarding the rolling patterns to be used in order to provide the best compaction at the longitudinal joint. A few states, such as Michigan and Wisconsin, require particular joint construction techniques for creating quality joints, but do not have density requirements. A growing number of states are implementing joint density specifications, including Texas and Tennessee. For the states with such specifications, the most common requirement is that the joint density must not be less than 90 percent (based on maximum theoretical specific gravity), or that the joint density must not be more than 2 percent less than mat density. The Federal Aviation Administration is the most stringent, requiring a minimum of 93.3 percent density at longitudinal joints. A complete listing of states and corresponding requirements pertaining to longitudinal joints is given in Table 1.

TABLE 1 Summary of State Specifications for Longitudinal Joints

State	Longitudinal Joint Specification
AL	No joint density specification. Joint must be rolled on first pass, layers offset by 6 inches.
AK	> 91% of max specific gravity. Joints of layers must be offset by 6 inches
AZ	None.
AR	No joint density specification. (no density tests taken within 1.5 ft of joint). Joints of layers must be offset by approx. 6 inches. Joint of top layer shall be at lane line. Compact joints first – 1st pass 6" away from joint, 2nd pass overlap cold lane by 6 – 8 inches.
CA	No joint density specification. Joints should be rolled from lower edge to highest portion.
CO	Target joint density = 92% of max theoretical density. Offset joint layers by 6 inches, surface joint should be offset from lane line by 6 – 12 inches.
CT	90% - 97% of theoretical void free density.
DE	No joint density specification.
FL	No longitudinal joint density requirement. Offset joints of layers by 6 – 12 inches.
GA	No joint density specification. Clean and tack vertical face of longitudinal joint. Offset joints of layers by 1 foot.
HI	No joint density specification. Joints should be rolled first, then follow regular rolling procedures.
ID	No joint density specification.
IL	No joint density specification. First roller pass shall be 6 inches away from joint, and 2nd pass shall overlap cold side by 6 inches.
IN	No joint density specification. Offset joints of layers by 6 inches and within 12 inches of lane line
IA	No joint density specification. Regulations for repairing longitudinal joints, but not for constructing new joints.
KS	Difference in mat density and joint density shall not exceed 3.0 pcf, OR be less than 90.0% of max. theoretical specific gravity. Joint face shall be tacked, and joint layers shall be offset by 6 – 12 inches.
KY	No joint density specification. Longitudinal joints should be tacked, offset joints of layers by 6 inches, avoid cold joints when possible.
LA	No joint density specification. Offset joint layers by 3 to 6 inches, use tack, set screed to allow 25% fluff and overlap paver 2 inches on each pass.
ME	No joint density specification. (no testing within 9 inches of joint)

	Joint face shall be tacked.
MD	No joint density specification. Use steel wheel rollers, roll longitudinal joints after transverse joints, offset joint layers 6 inches, use tack coat
MA	No joint density specification
MI	No joint density specification. Longitudinal joints shall be vertical or tapered and coincide with painted lane lines.
MN	Subject to same density requirements as mainline paving.
MS	No joint density specification.
MO	Not less than 2% below specified density within 6 inches of a joint.
MT	No joint density specification.
NE	No joint density specification. All voids shall be filled when constructing longitudinal joints.
NV	No joint density specification. Offset joints of layers by 6 inches, within 12 inches of final traffic lanes, not >1 joint within same traffic lane.
NH	No joint density specification. Surface joint must occur at lane line, joint layers shall be offset by 6 inches. No joints over 1-1/2 inch high left open to traffic unless wedge joint is used, no joint open more than 30 hours.
NJ	No joint density specification. Apply polymerized joint adhesive to joint face for surface courses. Offset joints of layers by 6 inches, and offset surface joint from lane line by 6 inches. Use a wedge joint when maintaining traffic.
NM	No joint density specification.
NY	90% minimum joint density.
NC	No joint density specification.
ND	No joint density specification. Joints must be tacked. Joints of subsequent layers shall not be in the same vertical plane.
OH	No joint density specification. Max slope of 3:1 for wedge joint.
OK	No joint density specification. Joints must be within 1 ft of lane lines, top layer at lane line, use tack coat.
OR	No joint density specification.
PA	No joint density specification. Offset joint layers by 6 in., paint edge of lane with thin coating of bituminous material before placing abutting lanes.
RI	No joint density specification. Joints brush-painted or pressure sprayed with bituminous tack coat, stagger joints by 6 inches.
SC	No joint density specification. Offset joint layers by 6 in. within 12 in. of lane line. Tack joint faces. For confined edges, first roller pass adjacent to edge shall be on hot mat 6 in. from joint. For unconfined edges, compaction shall extend 6 in. beyond edge of mat.
SD	No joint density specification. Offset joint layers by 6 inches, place surface joint at lane line. For confined edges, first roller pass shall be on hot mat, 6" from joint. For unconfined edges, first roller pass shall overlap the mat edge by 6 inches.
TN	89.0% minimum joint density. Offset joints of layers by 1 foot, and place surface joint at lane line. Longitudinal joint heater required for interstate projects in District 4.
TX	Joint density may be no more than 3 pcf less than mat density AND joint density must be at least 90.0% of max theoretical specific gravity.

UT	Test density of at least one core per sublot, used for information only. Offset joint 6 – 12 inches, top course within 12 inches of centerline. If previous pass cooled below 175F, tack edge.
VT	No joint density specification. Provides specific directions on construction of butt or tapered joints.
VA	No joint density specification.
WA	$200 / lot price adjustment for joint density below 90%. Joint layers shall be offset 2 – 6 inches, and surface joint shall be at lane line.
WV	No joint density specification. Offset joint layers by 6 inches, surface joint shall be at lane line.
WI	No joint density specification. Joints constructed using 1:12 wedge with ½" notch and a side roller for taper. Joints are tacked. If cold, joints are heated then tacked. Joint for top layer must be at lane line.
WY	No joint density specification.
FAA	93.3% minimum density required at joint.
Fed. Lands	No joint density specification. Apply asphalt tack coat to the edge of longitudinal joints.

OBJECTIVES

The overall objective of this study was to provide guidance for the improvement of longitudinal joint construction quality for HMA pavements by first assessing methods for measuring joint quality, then evaluating various joint construction methods to determine which were most advantageous.

Because HMA pavement quality is inherently affected by longitudinal joint quality, the integrity of the joints must be preserved in order to maximize the effective life of the pavement. Joint quality is often compromised by the entrance of air and/or water, which are substances that contribute to the premature deterioration of the pavement. Air promotes oxidation and binder hardening, which leads to cracking and raveling. The entrance of water into the joint leads to moisture damage and stripping. In general low densities at longitudinal joints have been blamed for creating highly permeable conditions, making the pavement susceptible to the detrimental effects of air and water. In most cases, density is treated as the primary measure of joint quality. However, density alone may not truly characterize the likelihood of air and water to enter the pavement. Thus, permeability may be a more appropriate measure. Thus, the objective of the first phase of the project was to determine what measure (or measures) could most accurately characterize the quality of the joint, providing a significant link to actual pavement performance, while also providing sufficient discrimination to properly rank joints of known quality.

Next, the best methods were used in the second phase of the study to evaluate the ability of various joint construction techniques to produce good-quality longitudinal joints. Each technique was evaluated with the goal of determining its applicability for incorporation into standard construction practices, while also considering safety and economical feasibility.

The final objective was to compile the results of the research and to provide recommendations for 1) techniques that can be used to improve the quality of longitudinal joints, 2) methods that should be used to quantify joint quality, and 3) proposed construction specification language for enabling AHTD to ensure that acceptable joint quality is achieved in the field.

PHASE 1

In Phase 1 of this study, three projects were selected for evaluation, with the goal of determining the most advantageous method(s) for quantifying longitudinal joint quality. A number of test methods were used to quantify the characteristics of the joint, and these methods were then evaluated based on their abilities 1) to adequately discriminate between varying levels of quality, 2) to accurately rank joints of varying quality, and 3) to easily and economically incorporate into standard quality control / quality assurance (QC/QA) procedures.

Scope

Three field sites were selected for evaluation. The sites were selected in a manner that would produce a range of joint quality both within and between projects. All projects selected had been in service for five years or less, and were 12.5mm Superpave surface mixes designed in accordance with Arkansas specifications. Conventional joint construction methods were used in all cases, and acceptable mat densities were attained at the time of construction. Each site consisted of a five-lane roadway section, and the longitudinal joints tested were those between the lanes of unidirectional traffic. Thus, problems with unevenness at the joint could be attributed solely to the construction of the joint, and not roadway cross-section geometry (i.e., crown). Within each site, four testing stations were chosen such that at each station, testing was performed at the joint (J), 6 inches to the cold side of the joint (6C), 6 inches to the hot side of the joint (6H), 12 inches to the cold side of the joint (12C), and 12 inches to the hot side of the joint (12H). Thus, testing was performed for a total of 60 samples. The testing configuration at each station is illustrated in Figure 2, and site summaries are given in Table 2. Classification ratings for joint quality were given to each project and station based on visual evidence of pavement distresses at the joint, including cracking, raveling, segregation, and vertical offset.

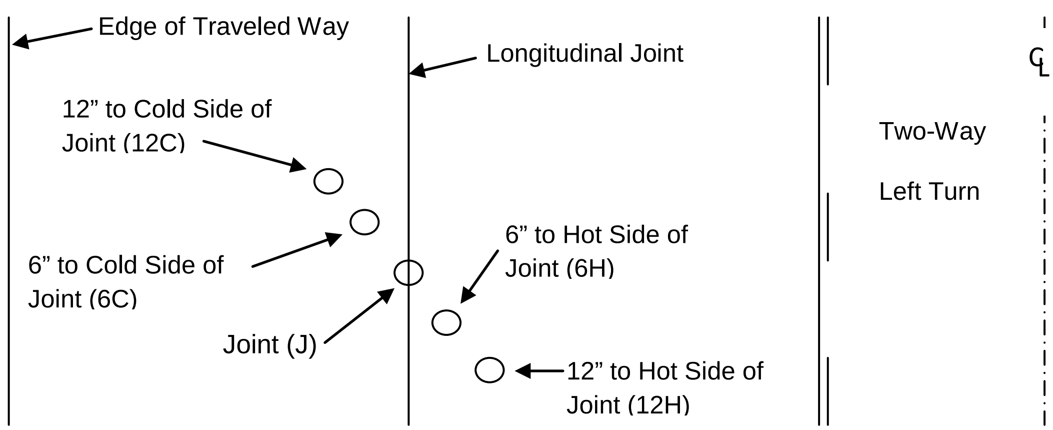


FIGURE 2 Testing configuration at each station (not to scale).

TABLE 2 Site Summaries

Mix Design Property	Site #1	Site #2	Site #3	Arkansas Specifications
NMAS	12.5mm	12.5mm	12.5mm	12.5mm
Binder Grade	PG 64-22	PG 70-22	PG 70-22	
Design Gyrations	75	100	100	
Design Binder Content (%)	6.1	5.4	5.6	
Design Air Voids (%)	4.5	4.5	4.5	4.5
Design VMA (%)	14.6	15.3	15.5	14.0 – 16.0
Max. Theoretical Specific Gravity	2.396	2.439	2.423	
Surface lift thickness (in.)	3	2	2	
Total Asphalt Thickness (in.)	15	11.5	11	
Gradation				
% Pass ¾"	100	100	100	100
% Pass ½"	90	96	100	90 – 100
% Pass $^{3}/_{8}$"	74	87	90	≤90
% Pass #4	40	51	59	
% Pass #8	28	32	41	28 - 58
% Pass #16	16	22	30	
% Pass #30	9	18	24	
% Pass #50	7	15	18	
% Pass #100	5	10	8	
% Pass #200	4.2	5.2	5.7	2 - 10
Date of Construction	Oct 2004	June 2003	Aug 2007	
Visual Joint Quality Rating	Good	Fair/Poor	Fair/Poor	

Site #1 had been in service for approximately 3.5 years, and was rated as having good quality longitudinal joints. Some very slight vertical deviations were present between the two sides of the joint, but no cracking, raveling, or evidence of segregation was noted. A photograph of a typical joint area for Site #1 is shown in Figure 3.

FIGURE 3 Site #1 – Good Condition.

Site #2 had been in service for almost 5 years, and the longitudinal joints were rated as fair to poor. Station 1 exhibited slight cracking, while stations 2, 3, and 4 showed significant cracking and moderate raveling. Figure 4 illustrates the typical distresses noted for Site #2.

Site #3, having been in service for less than one year, displayed no evidence of cracking or raveling. However, segregation was evident at stations 1 and 4, and significant vertical deviations were present across the joints. In fact, vertical deviations of approximately 3/8" were measured at each station tested. This project was rated as fair to poor. Figure 5 shows the typical joint condition at Site #3.

FIGURE 4 Site #2 – Fair/Poor Condition.

FIGURE 5 Site #3 – Fair/Poor Condition.

Test Methods

The fundamental issue at longitudinal joints is the risk for detrimental substances to enter the pavement structure, generating a premature loss of pavement performance. Thus, permeability would seem to be the most appropriate measure of joint quality. However, standard test methods for permeability have not yet been widely accepted for QA measures. Density has been reported to be a significant predictor of joint performance, which is a reasonable expectation because low joint densities are likely to exhibit increased permeability, thereby exacerbating the distresses associated with permeable HMA materials. *(6, 31)* In this way, density measurements often serve as an indirect measure for permeability. Another characteristic that may relate to HMA permeability is segregation. If segregation exists at the longitudinal joint, an increase in permeable voids could exist. Although this parameter is difficult to quantify, measures of gradation may serve as a possible surrogate.

Density, permeability, and gradation were quantified for each test location. Non-destructive field testing was done in place in the field before cores were cut. After the cores were cut, they were transported to the laboratory for further non-destructive testing, as well as destructive testing.

In-place density was determined in the field according to nuclear and non-nuclear methods. Each core location was marked, and then the nuclear gauge (Troxler 3430) was used to measure density according to AHTD Test Method 461. *(34)* Readings were taken on the core location, as well as in four additional equally-spaced locations around the core location, as illustrated in Figure 6. The reported density for each core location was taken as the average of the 5 results. Next, two non-nuclear gauges were used to repeat the measurements. The two non-nuclear gauges used were the Pavement Quality Indicator (PQI) 301 and the Troxler PaveTracker™ Plus Model 2701B. Non-nuclear density testing was performed in accordance with AASHTO TP68, "Test Method for Density of Bituminous Paving Mixtures in Place by the Electromagnetic Surface Contact Methods". *(19)* Again, the reported density at each core location was the average of 5 individual readings. Core offset calibrations were used for all gauge methods, and density values were reported in pounds per cubic foot (pcf). These values were then used to compute density as a percentage of maximum theoretical specific gravity (Gmm) based on the mix design Gmm value.

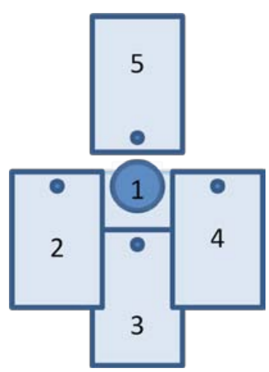


FIGURE 6 Test Point Orientation for Gauges Used to Measure In-Place Density.

Next, permeability was measured in the field at each marked core location using the NCAT field permeameter, and the permeability coefficient was calculated according to Equation 1:

$$k = \left(\frac{aL}{At}\right) \ln\left(\frac{h_1}{h_2}\right) \qquad \text{Equation 1}$$

where:
k = coefficient of permeability, cm/s x 10^{-5}
a = inside cross-sectional area of standpipe, cm^2
L = length of the sample, cm (thickness of the asphalt mat)
A = cross-sectional testing area, cm^2
t = elapsed time between h_1 and h_2, sec
h_1 = initial head, cm
h_2 = final head, cm

Additionally, infiltration rate was calculated according to Equation 2 *(15)*:

$$Inf = \frac{a(h_1 - h_2)}{At} \qquad \text{Equation 2}$$

where:
Inf = infiltration, cm/hr
a = inside cross-sectional area of standpipe, cm^2
A = cross-sectional testing area, cm^2
t = elapsed time between h_1 and h_2, hr
h_1 = initial head, cm
h_2 = final head, cm

The permeability coefficient is a fundamental measure of the water that flows through the pavement. However, it is based on the assumption that water flows only vertically through the layer. In reality, the water can move both vertically and laterally, meaning that the basic assumptions associated with the test are rarely (if ever) truly met. Therefore infiltration, which does not include the thickness of the mat, may be a more realistic measure of the water that enters the pavement's surface as it pertains to the potential for permeability at longitudinal joints.

Next, cores were cut at each location. Laboratory measures of density were determined using the vacuum sealing method (AASHTO T331) and the SSD method (AASHTO T166). *(19)* Density values were reported in pounds per cubic foot (pcf). Paraffin coating, describe in AASHTO T275 was not included in the study.

Upon completion of all density testing, laboratory measures of permeability were determined using the Karol-Warner falling-head permeability device (previously specified in ASTM PS 129-01). Although this test method was withdrawn several years ago, no suitable replacement has superseded it.

Upon completion of the laboratory permeability tests, cores were burned in the ignition oven and washed gradations were performed on the resulting aggregate samples using AASHTO T30. The percent passing each sieve was computed and fineness modulus was determined. In order to provide a fair comparison of gradation results for the different projects, the percents passing each sieve were analyzed based on the difference between the percent passing each sieve and the percent passing the respective sieve on the mix design, expressed as the deviation from the mix design. Positive deviations indicated a greater percent passing a given sieve, revealing a finer gradation than intended for the mix design. Additionally, the sum of gradation deviation was calculated according to Equation 3 as a way to characterize the difference in the sample and the mix design using a single response value.

$$SGD = \left(\sum \left|(\%P_{sample} - \%P_{mix\ design})\right|\right) \qquad \text{Equation 3}$$

where:
SGD = Sum of Gradation Deviation
$\%P_{sample}$ = Percent Passing for Sample
$\%P_{mix\ design}$ = Percent Passing for Mix Design

Although binder content was not an intentional response included in the testing plan, this measure was generated during the ignition process. Thus, the data was collected and compared to the values from the original mixture design binder content, but no correction factors were used. A complete summary of test methods and resulting responses is given in Table 3.

TABLE 3 Summary of Test Methods and Responses

Quality Indicator	Test Methods	Response Parameters
Field Testing (non-destructive)		
Nuclear Density	AHTD 461	Density (pcf) Percent of TMD
Non-nuclear Density (PQI)	AASHTO TP68	Density (pcf) Percent of TMD
Non-nuclear Density (PaveTracker)	AASHTO TP68	Density (pcf) Percent of TMD
Field Permeability	NCAT Permeameter	Coefficient of permeability, *k* (cm/s x 10^{-5}) Infiltration (cm/hr)
Laboratory Testing		
Bulk Specific Gravity by SSD Method	AASHTO T166	Density (pcf) Percent of TMD Absorption (%)
Bulk Specific Gravity by Vacuum Sealing	AASHTO T331	Density (pcf) Percent of TMD
Laboratory Permeability	ASTM PS129 (withdrawn)	Coefficient of permeability, *k* (cm/s x 10^{-5})
Ignition Method	AASHTO T308	Binder Content (%)
Washed Gradation	AASHTO T30	%Passing each sieve size (deviation from mix design) Fineness Modulus Sum of Gradation Deviation (%)

Test Results and Analysis

For each test method and response, the results were first analyzed by graphically considering the change in response with changes in proximity to the joint. Statistical analyses were then employed to determine whether significant differences existed at the various distances from the joints, while also accounting for differences inherent among the projects. Significant practical differences in pavement quality were assumed to exist at and away from the joints. Thus, test methods that were capable of detecting a significant difference in responses at 6 and/or 12 inches to the cold and hot sides of the joint were believed to possess the necessary level of discrimination for assessing joint quality. In other words, if statistically significant differences were evident where practically significant differences were known to exist, the test method would have potential as an adequate measure of quality for HMA longitudinal joints.

Nuclear Density

The nuclear density values, expressed in pcf, for each site are shown in Table 4, and are shown graphically in Figure 7.

TABLE 4 Data Summary – Nuclear Density (pcf)

	Site #1					Site #2					Site #3				
Station	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	141.7	138.9	138.9	140.8	142.9	142.5	138.7	133.6	133.0	133.9	138.4	131.6	124.6	131.2	134.8
2	140.0	137.2	134.1	135.1	137.3	140.6	138.6	133.7	131.6	134.3	140.3	137.5	131.4	136.7	137.7
3	142.6	139.9	138.7	139.4	142.7	142.2	139.0	132.9	136.4	140.7	140.2	134.3	134.0	138.1	138.6
4	143.6	139.6	136.8	138.7	142.8	144.4	139.7	131.2	135.1	140.1	138.4	134.5	130.2	136.5	140.4

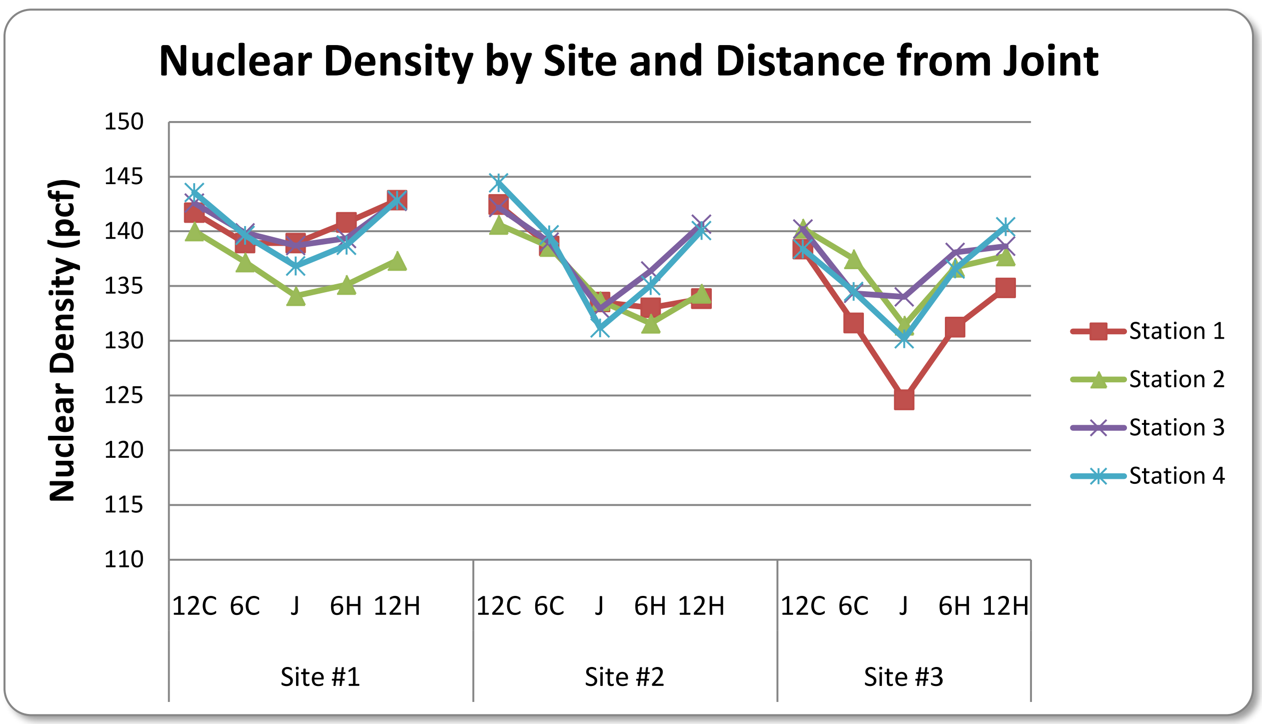


FIGURE 7 Phase 1 Nuclear Density Comparison (pcf).

Nuclear density results, expressed as a percentage of the mix design Gmm, are given in Table 5, and illustrated in Figure 8.

TABLE 5 Data Summary – Nuclear Density (%Gmm)

Station	Site #1					Site #2					Site #3				
	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	94.8	92.9	92.9	94.2	95.5	93.6	91.1	87.8	87.4	87.9	91.5	87.1	82.4	86.8	89.2
2	93.7	91.8	89.7	90.4	91.9	92.4	91.1	87.8	86.5	88.3	92.8	90.9	86.9	90.4	91.1
3	95.4	93.5	92.8	93.2	95.5	93.4	91.3	87.3	89.6	92.4	92.7	88.9	88.6	91.3	91.7
4	96.0	93.4	91.5	92.8	95.5	94.9	91.8	86.2	88.7	92.0	91.5	89.0	86.1	90.3	92.9

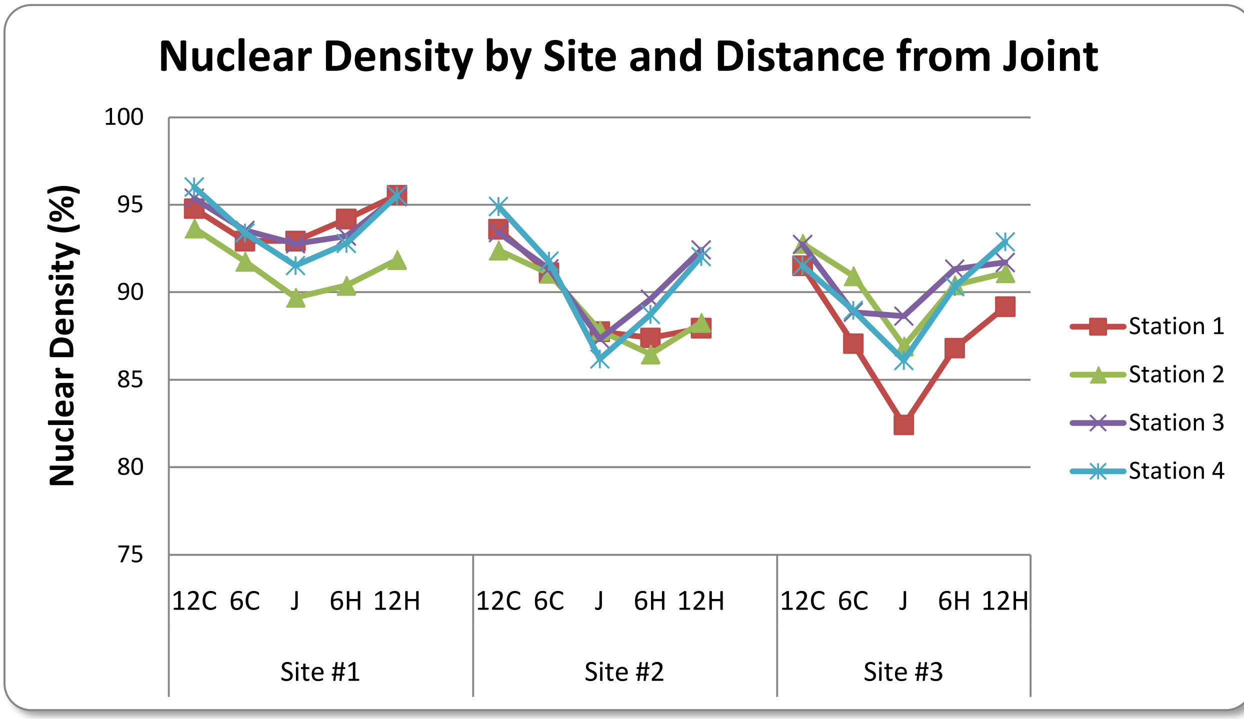


FIGURE 8 Phase 1 Nuclear Density Comparison (%Gmm).

By visual inspection, it is evident that apparent differences in density with proximity to the joint location were detected by the nuclear density gauge. In most cases, the density on the actual joint was lower than the density near the joint. These differences were most pronounced for Site #3, and least evident for Site #1.

Non-Nuclear Density

Non-nuclear testing was performed according to two methods – the Pavement Quality Indicator (PQI™) and the PaveTracker™ 2701B. The density results for the PQI are given in Tables 6 - 7 and Figures 9 - 10, and the PaveTracker results are provided in Tables 8 – 9 and Figures 11 - 12.

TABLE 6 Data Summary – PQI Non-Nuclear Density (pcf)

Station	Site #1					Site #2					Site #3				
	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	137.7	139.0	142.6	139.4	140.3	139.9	133.9	131.1	130.4	132.1	136.0	132.9	132.6	132.3	136.0
2	143.0	136.7	135.0	136.1	138.8	145.4	139.8	134.7	132.8	131.3	137.3	134.9	134.9	135.8	136.9
3	138.1	135.8	138.3	140.5	142.7	146.7	140.6	138.0	141.3	142.0	139.0	135.0	135.1	135.5	136.3
4	144.0	140.7	139.9	138.2	145.3	145.9	136.4	138.0	134.7	139.8	139.2	135.9	135.0	136.0	138.0

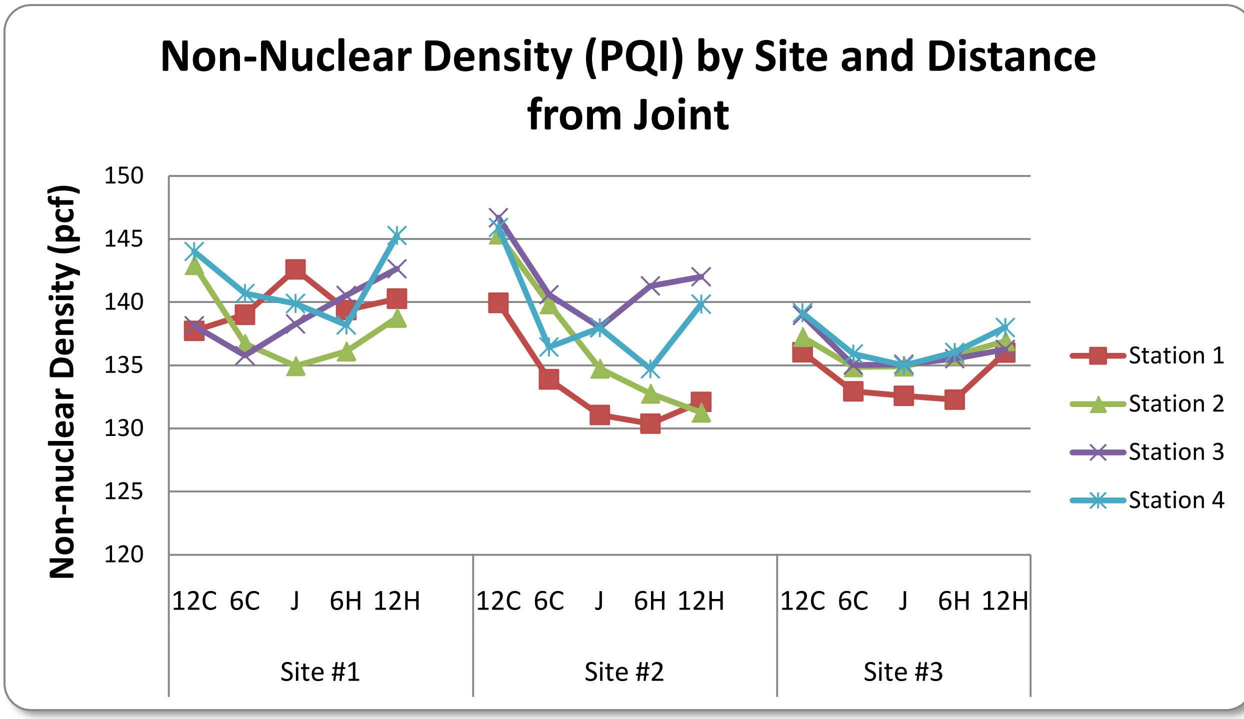


FIGURE 9 Phase 1 PQI Non-Nuclear Density Comparison (pcf).

TABLE 7 Data Summary – PQI Non-Nuclear Density (%Gmm)

Station	Site #1					Site #2					Site #3				
	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	92.1	93.0	95.4	93.2	93.8	92.0	88.0	86.1	85.7	86.8	90.0	87.9	87.7	87.5	90.0
2	95.6	91.4	90.3	91.0	92.8	95.5	91.9	88.5	87.2	86.3	90.8	89.2	89.2	89.8	90.6
3	92.4	90.8	92.5	94.0	95.4	96.4	92.4	90.7	92.8	93.3	91.9	89.3	89.3	89.6	90.1
4	96.3	94.1	93.6	92.4	97.2	95.9	89.7	90.7	88.5	91.9	92.0	89.9	89.3	90.0	91.3

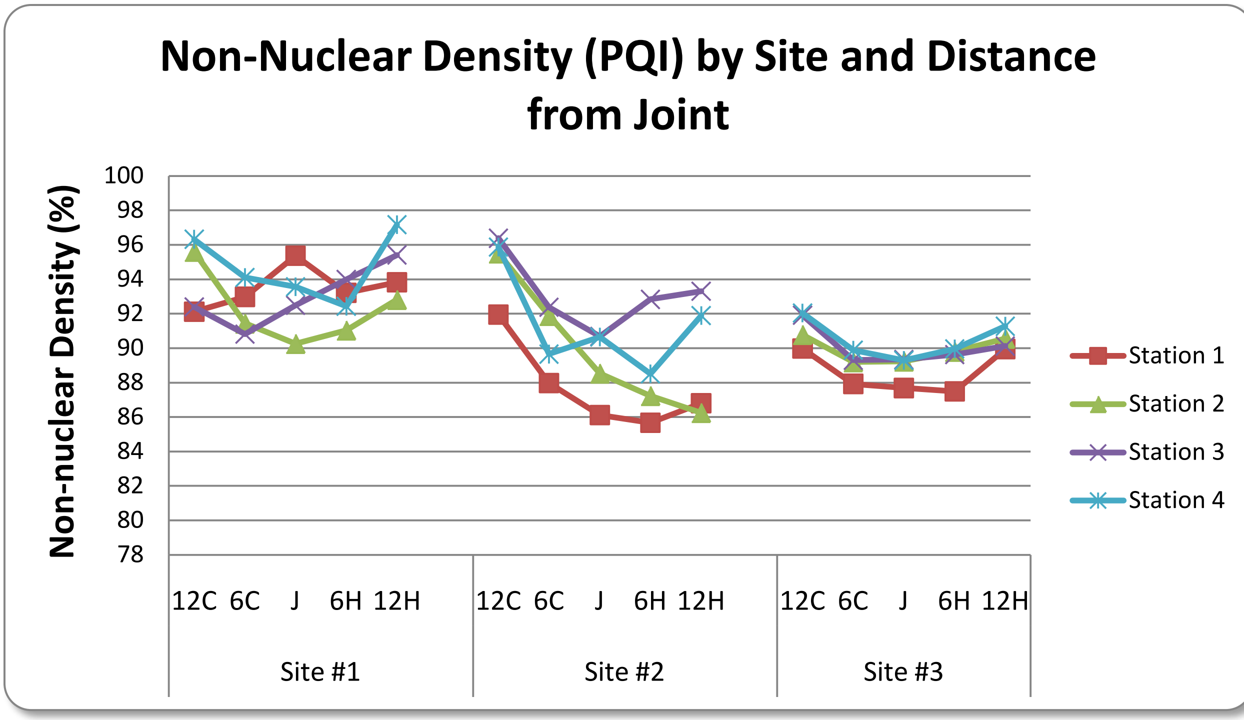


FIGURE 10 Phase 1 PQI Non-Nuclear Density Comparison (%Gmm).

TABLE 8 Data Summary – PaveTracker Non-Nuclear Density (pcf)

Station	Site #1					Site #2					Site #3				
	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	137.1	139.0	143.3	139.6	137.4	139.0	136.5	132.8	133.4	135.5	136.6	131.8	128.9	128.7	132.7
2	143.2	138.0	135.6	134.2	136.7	140.4	137.9	135.3	134.3	135.2	138.9	133.5	134.8	138.3	138.9
3	140.1	139.1	140.7	140.4	142.4	143.6	138.0	137.5	140.2	141.3	139.0	133.9	133.9	137.7	138.5
4	141.0	140.0	141.0	139.5	143.5	145.1	134.5	137.5	134.5	141.7	140.7	134.8	134.1	139.1	138.9

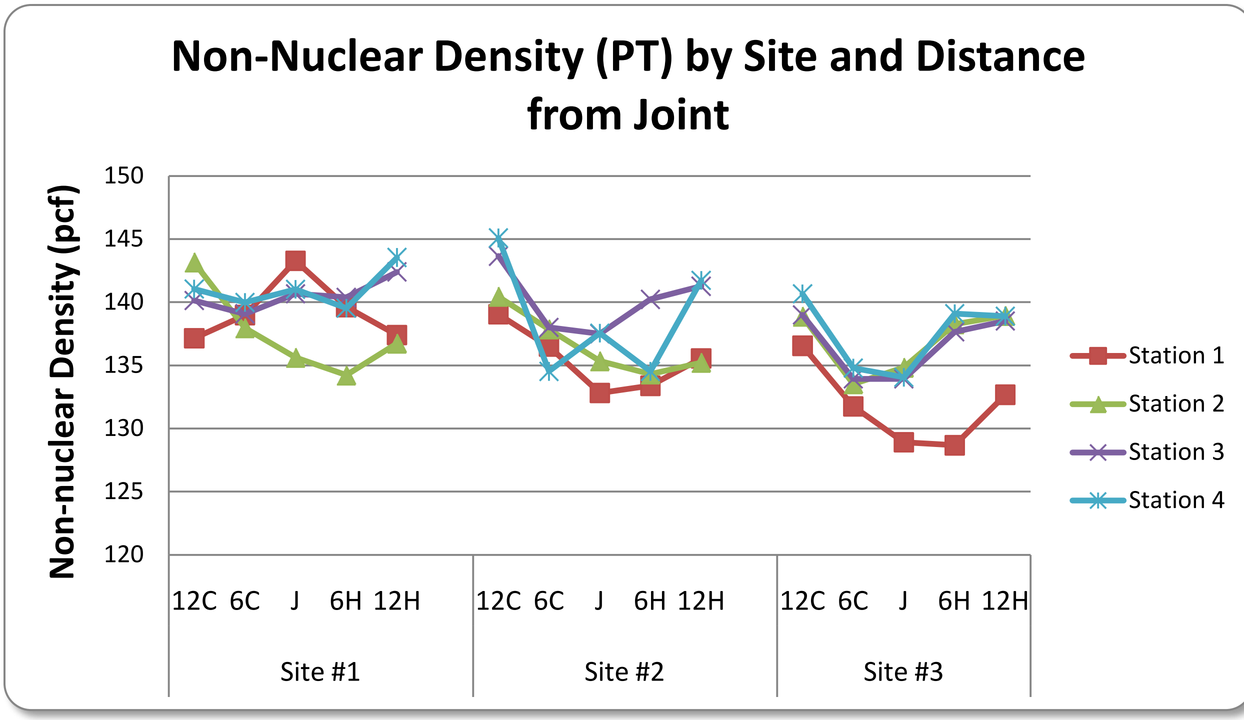


FIGURE 11 Phase 1 PaveTracker Non-Nuclear Density Comparison (pcf).

TABLE 9 Data Summary – PaveTracker Non-Nuclear Density (%Gmm)

	Site #1					Site #2					Site #3				
Station	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	91.7	93.0	95.8	93.4	91.9	91.4	89.7	87.3	87.6	89.1	90.3	87.1	85.3	85.1	87.8
2	95.8	92.3	90.7	89.8	91.5	92.3	90.6	88.9	88.2	88.9	91.9	88.3	89.2	91.5	91.9
3	93.7	93.0	94.1	93.9	95.2	94.4	90.7	90.4	92.1	92.8	91.9	88.6	88.6	91.0	91.6
4	94.3	93.6	94.3	93.3	96.0	95.3	88.4	90.4	88.4	93.1	93.0	89.2	88.7	92.0	91.9

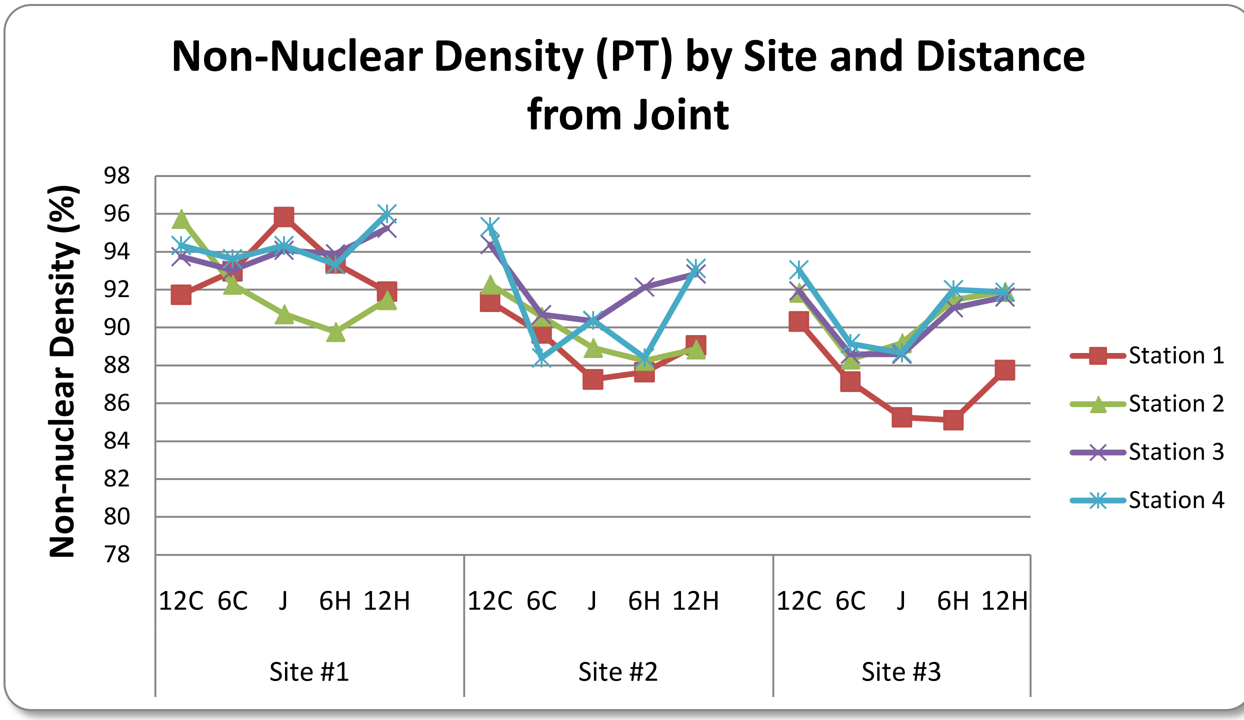


FIGURE 12 Phase 1 PaveTracker Non-Nuclear Density Comparison (%Gmm).

While the non-nuclear testing did detect lower densities at the joint, these trends were much less clearly defined than for the nuclear testing. Also, the differences in density at and away from the joint were smaller. In some instances, the joint density was actually greater than the density near the joint. Overall, the nuclear testing was better able to provide a clearer separation of density values with respect to the distance from the joint.

Field Permeability and Infiltration

In-place field permeability testing was also performed. The results of this non-destructive testing regimen are given in Table 10, and shown graphically in Figure 13.

TABLE 10 Data Summary – Field Permeability, k (cm/s x 10^{-5})

	Site #1					Site #2					Site #3				
Station	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	1.4	0.8	1.9	2.2	1.3	125	47	32	127	24	1305	5911	29861	5313	3804
2	0.7	0.8	4.6	2.3	1.8	4.4	5.2	1357	43	15	440	1677	11281	1182	850
3	0.8	4.0	3.1	1.0	0.9	9.3	3.6	1882	175	35	598	2549	12223	811	446
4	0.9	1.4	3.8	0.4	0.6	1.8	5.1	2782	228	45	1027	3712	12114	964	573

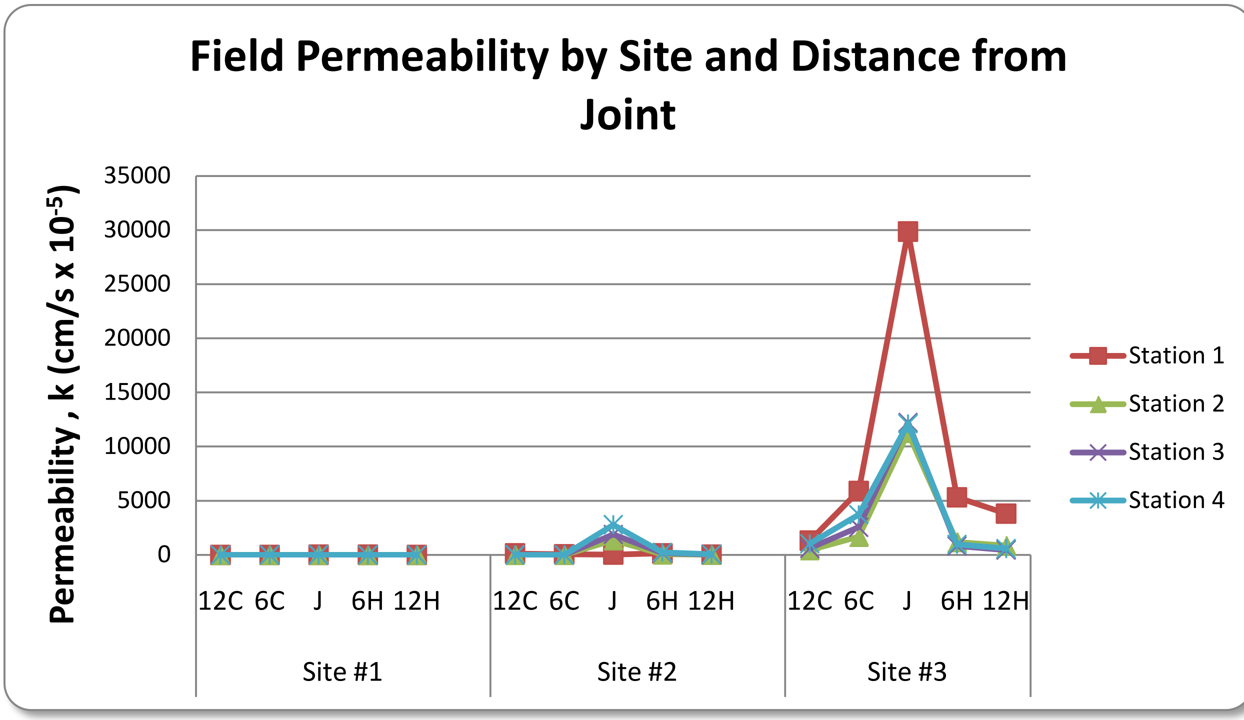


FIGURE 13 Phase 1 Field Permeability Comparison (cm/s x 10^{-5}).

Field permeability measurements were clearly able to detect the high quality joints at Site #1, and the poorer quality joints at Sites #2 and #3. Note that for mainline paving (i.e., center of the mat), permeability values that exceed 125 x 10^{-5} cm/s to 150 x 10^{-5} cm/s are considered excessive. *(35)* The extreme permeability readings at Site #3 somewhat mask the significance of the high permeability levels measured at Site #2.

Infiltration was also calculated from measurements taken during the field permeability testing procedure. Infiltration at each location and site is shown in Table 11 and Figure 14.

TABLE 11 Data Summary – Infiltration (cm/hr)

	Site #1					Site #2					Site #3				
Station	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	0.1	0.0	0.1	0.1	0.1	9.1	3.4	1.8	6.7	1.4	72	195	364	175	124
2	0.0	0.0	0.3	0.1	0.1	0.3	0.4	69	2.4	0.9	24	55	376	40	46
3	0.0	0.2	0.2	0.1	0.1	0.7	0.3	60	9.2	2.0	20	85	154	45	15
4	0.1	0.1	0.2	0.0	0.0	0.1	0.4	87	11	2.4	56	121	396	53	31

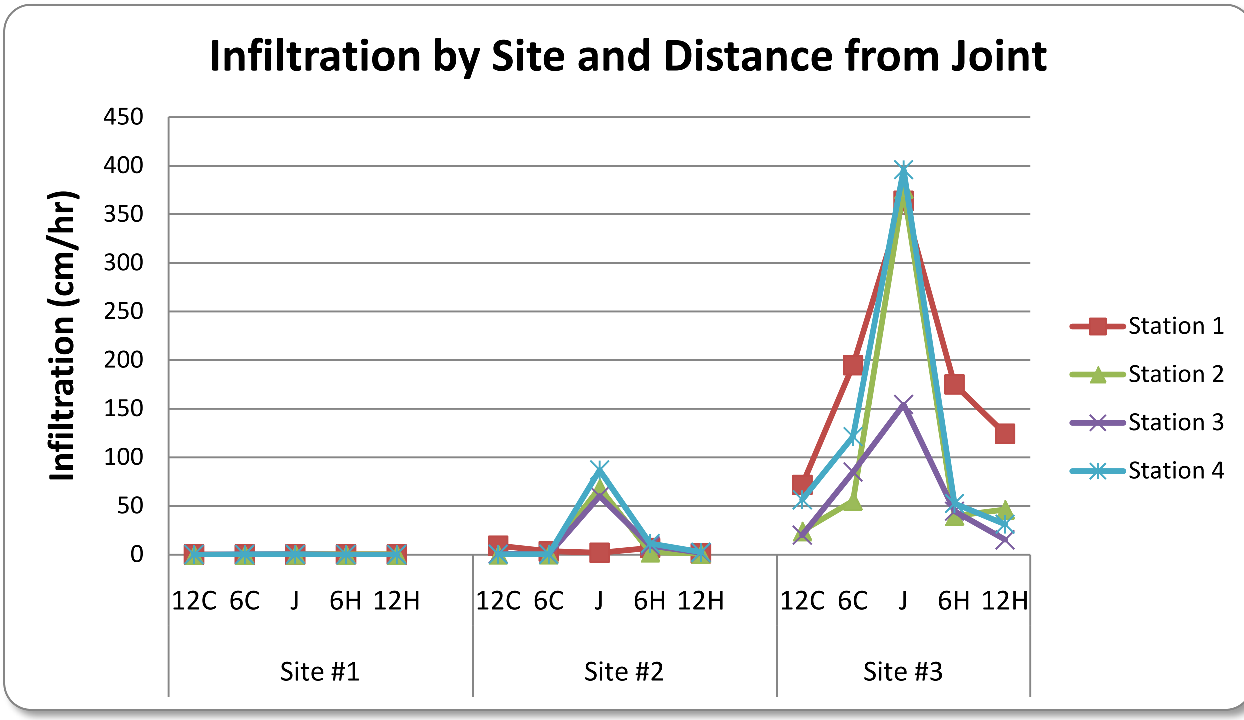


FIGURE 14 Phase 1 Infiltration Comparison (cm/hr).

Infiltration was also able to detect obvious differences among the three sites, as well as significant changes in infiltration at and away from the joint. Site #1 was clearly the best performer, while Site #3 was the worst performer.

<u>Laboratory Density and Absorption</u>

After all non-destructive testing was complete, cores were cut for further laboratory analysis. Laboratory measures of density and permeability were determined, as well as binder content and gradation. Laboratory density was measured by two methods – the SSD and vacuum sealing methods. Vacuum sealing tests were performed according to AASHTO T331 using the CoreLok™ device, marketed by Instrotek, Inc. The results from the SSD testing are given in Tables 12 - 13 and Figures 15 - 16, and the vacuum sealing results are shown in Tables 14 - 15 and Figures 17 - 18. Missing data points exist for cores that could not be extracted from the pavement without significant damage (i.e., complete separation at the joint).

TABLE 12 Data Summary – Density by SSD Method (pcf)

	Site #1					Site #2					Site #3				
Station	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	143.7	139.9	137.9	141.8	142.5	141.3	139.5	130.5	132.4	133.0	139.8	133.0	125.3	132.3	134.7
2	141.3	137.9	133.2	135.7	138.4	141.5	140.1	-	133.1	135.2	141.2	138.1	127.1	138.7	138.6
3	143.5	140.9	134.3	140.8	142.3	141.5	141.7	-	135.7	139.3	139.1	135.5	125.9	138.4	138.6
4	143.2	139.0	134.3	138.6	142.8	143.8	142.2	-	135.1	138.2	139.9	134.9	-	138.7	139.8

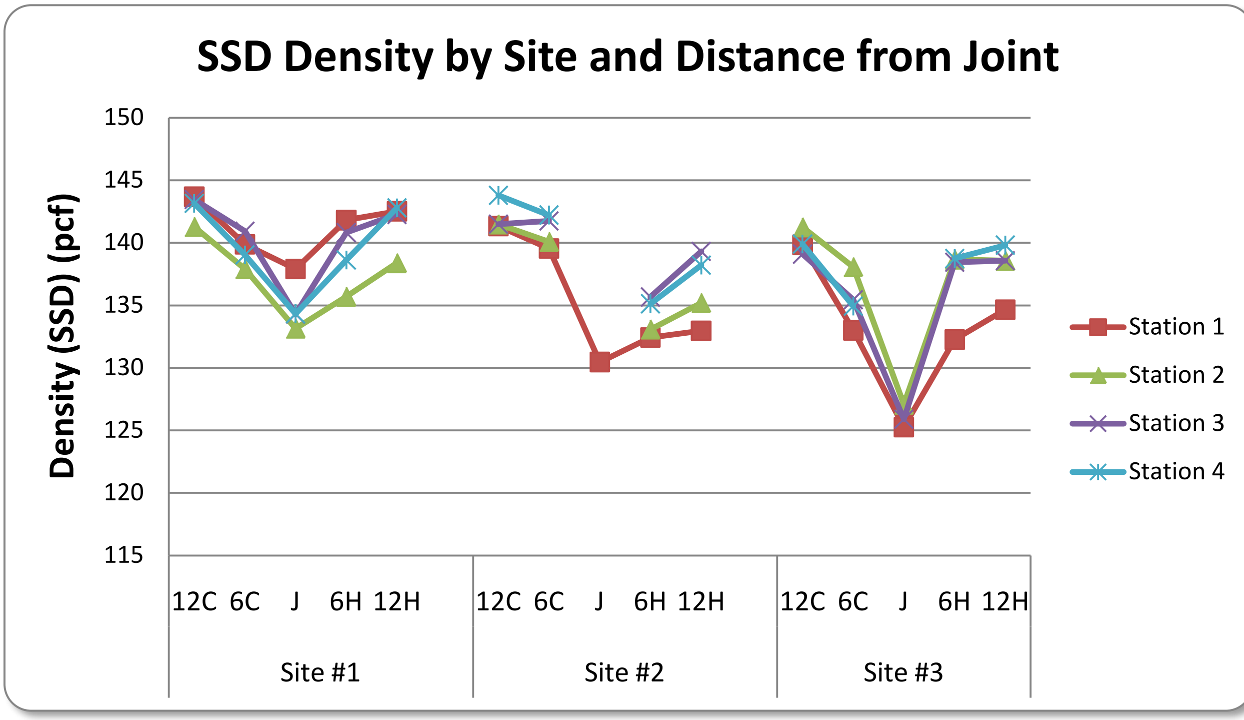


FIGURE 15 Phase 1 SSD Density Comparison (pcf).

TABLE 13 Data Summary – Density by SSD Method (%Gmm)

Station	Site #1					Site #2					Site #3				
	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	96.1	93.6	92.2	94.9	95.3	92.9	91.7	85.7	87.0	87.4	92.5	88.0	82.8	87.5	89.1
2	94.5	92.2	89.1	90.8	92.6	93.0	92.0	-	87.4	88.8	93.4	91.3	84.0	91.7	91.6
3	96.0	94.3	89.8	94.2	95.2	93.0	93.1	-	89.1	91.5	92.0	89.6	83.3	91.6	91.6
4	95.8	93.0	89.8	92.7	95.5	94.5	93.4	-	88.8	90.8	92.5	89.2	-	91.8	92.5

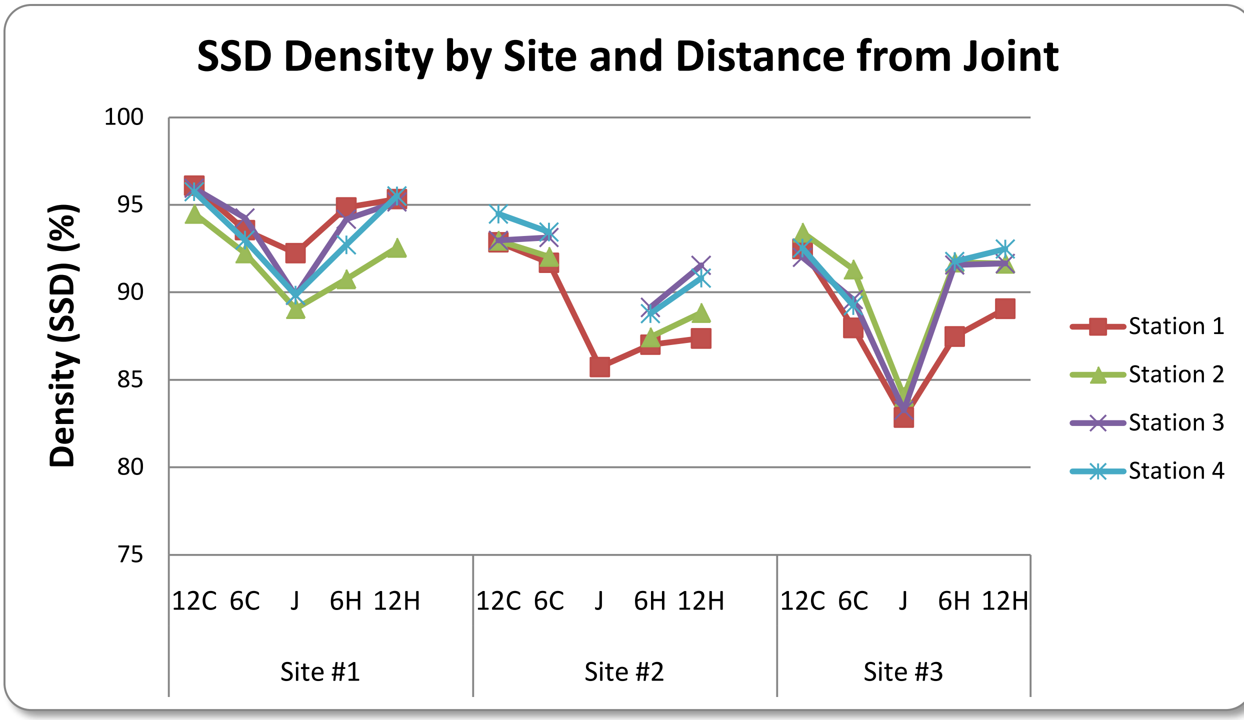


FIGURE 16 Phase 1 SSD Density Comparison (%Gmm).

TABLE 14 Data Summary – Density by Vacuum Sealing Method (pcf)

Station	Site #1					Site #2					Site #3				
	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	140.7	138.2	137.2	141.7	141.8	141.1	139.1	126.8	129.6	131.8	139.1	133.1	119.1	131.9	134.0
2	141.0	136.8	130.1	132.6	137.7	141.0	139.7	-	131.0	132.8	141.3	138.3	123.8	136.9	137.9
3	142.8	139.4	133.2	139.8	142.4	140.7	141.4	-	134.2	138.6	139.1	135.2	124.1	137.8	138.9
4	142.6	136.4	132.0	137.7	141.7	142.7	141.1	-	132.0	141.1	139.9	133.9	-	138.6	139.3

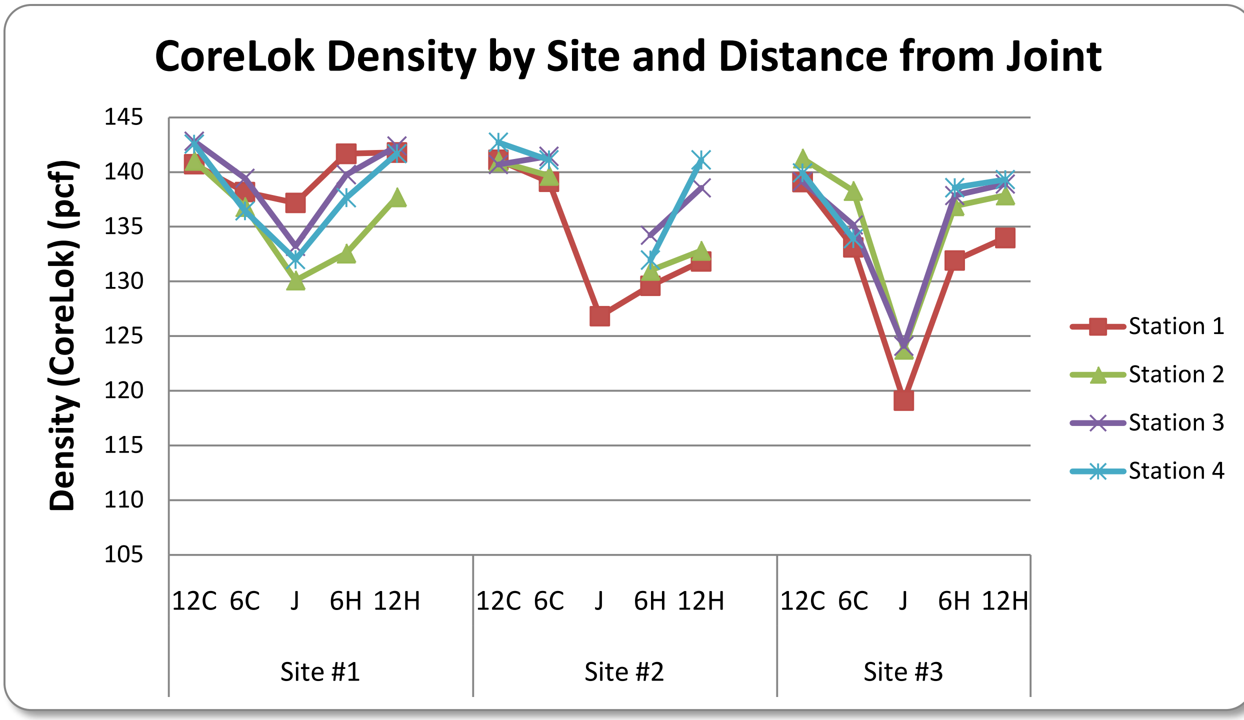


FIGURE 17 Phase 1 Vacuum Sealing Density Comparison (pcf).

TABLE 15 Data Summary – Density by Vacuum Sealing Method (%Gmm)

Station	Site #1					Site #2					Site #3				
	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	94.1	92.4	91.7	94.8	94.8	92.7	91.4	83.3	85.2	86.6	92.0	88.0	78.8	87.2	88.6
2	94.3	91.5	87.0	88.7	92.1	92.6	91.8	-	86.1	87.3	93.4	91.5	81.9	90.5	91.2
3	95.5	93.3	89.1	93.5	95.2	92.4	92.9	-	88.2	91.0	92.0	89.4	82.1	91.2	91.9
4	95.4	91.3	88.3	92.1	94.8	93.8	92.7	-	86.7	92.7	92.5	88.6	-	91.6	92.1

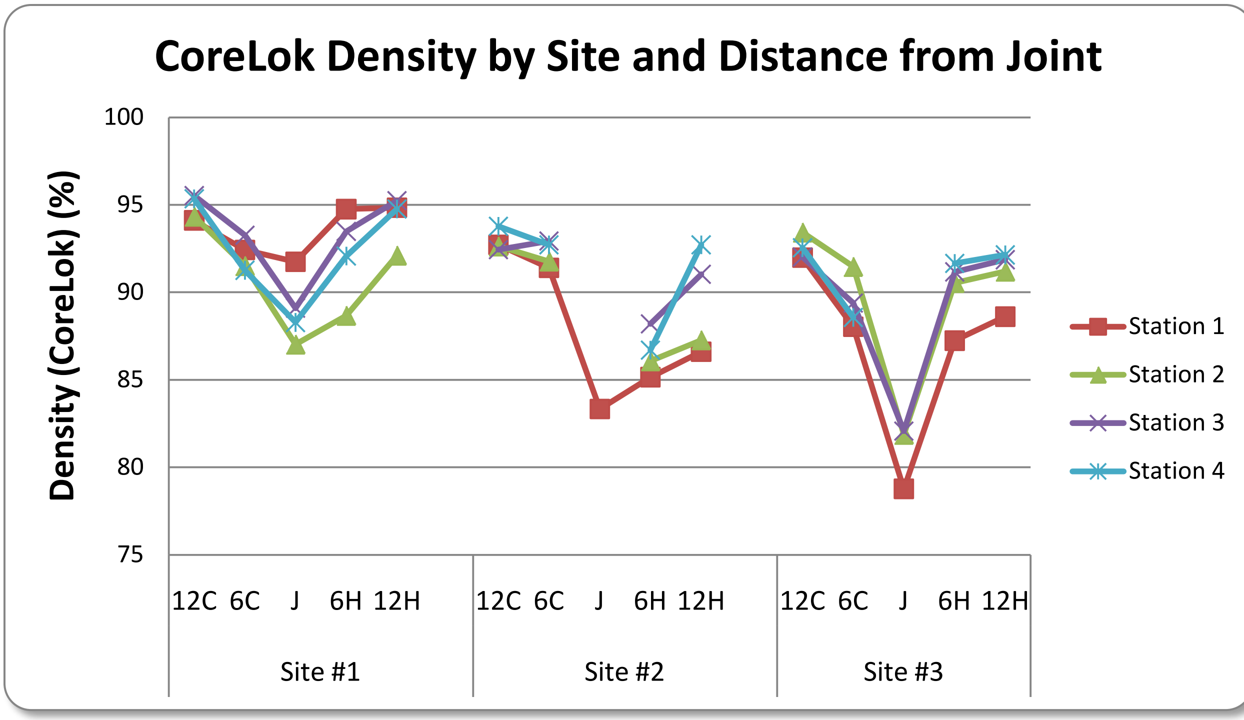


FIGURE 18 Phase 1 Vacuum Sealing Density Comparison (%Gmm).

Both laboratory measures of density demonstrated the ability to detect significant differences in density with proximity to the joint. The laboratory measures captured more distinct differences than the field measures, particularly for Site #1. The vacuum sealing method showed greater differences between density at the joint and near the joint than did the SSD method. It is believed that inherent difficulties in achieving a true saturated surface dry condition during the SSD test are primarily responsible for those differences.

Absorption values were calculated from the data obtained during the SSD test and used to provide a comparison of cores at and near the joint. These results are given in Table 16 and Figure 19.

TABLE 16 Data Summary – Absorption Capacity (%)

	Site #1					Site #2					Site #3				
Station	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	1.2	1.6	2.0	1.2	1.6	2.2	3.0	9.5	7.5	6.8	3.0	6.3	12.2	7.9	5.5
2	0.9	2.0	5.0	3.5	2.5	3.3	2.8	-	7.6	4.6	2.9	4.1	10.2	3.9	3.6
3	1.5	1.3	3.2	1.7	1.8	3.0	2.3	-	5.4	3.3	3.6	5.4	11.2	3.3	2.7
4	1.3	3.0	3.4	2.7	1.6	1.4	2.7	-	6.8	4.3	3.2	5.1	-	3.4	3.0

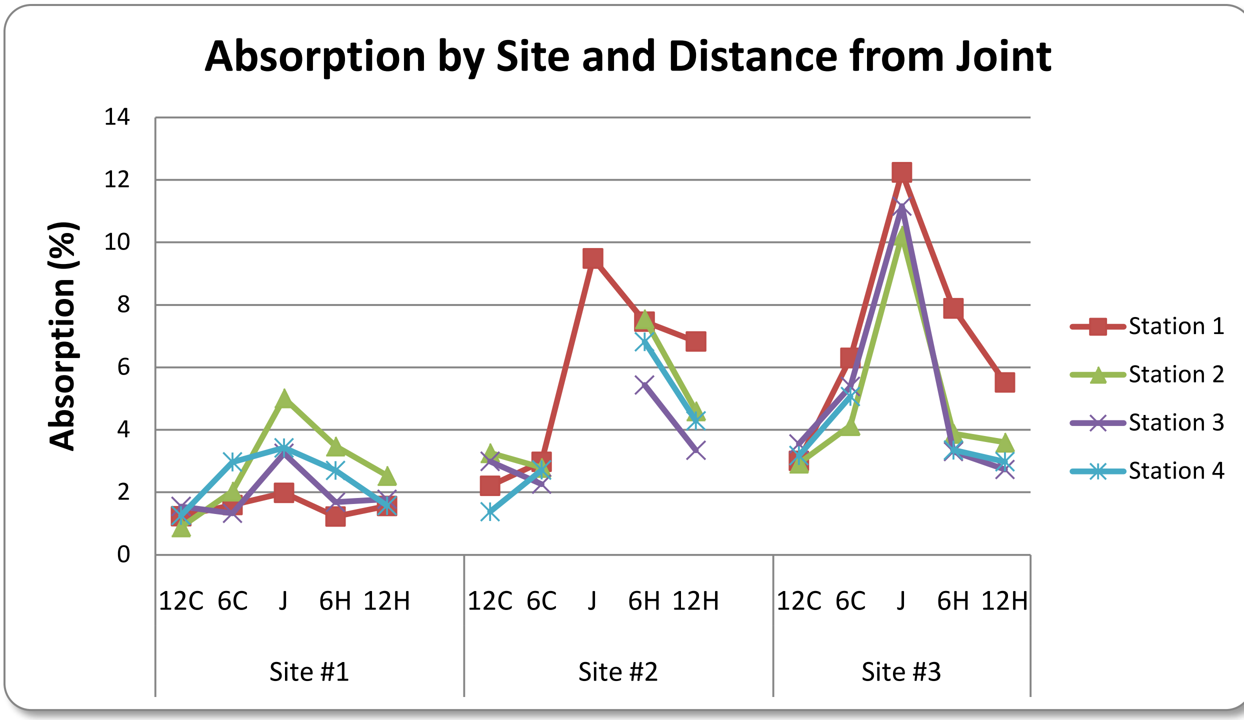


FIGURE 19 Phase 1 Absorption Comparison (%).

Based on the data, absorption capacity appears to be capable of detecting significant changes in absorption capacity at the joint.

<u>Laboratory Permeability</u>

Next, the cores were tested in the laboratory for permeability using the Karol-Warner falling head permeability device. Results are shown in Table 17 and Figure 20.

TABLE 17 Data Summary – Laboratory Permeability (cm/s x 10^{-5})

	Site #1					Site #2					Site #3				
Station	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	2.7	2.6	7.0	0.0	0.0	2.6	3.2	119	41	34	569	1037	1757	1289	758
2	0.0	0.5	103	54	0.4	1.2	3.6	-	17	9.5	68	267	3027	391	180
3	0.0	6.6	1.6	0.0	0.4	2.2	27	-	22	37	258	534	1743	210	172
4	0.0	92	15	0.5	0.8	22	17	-	1	48	267	592	-	316	194

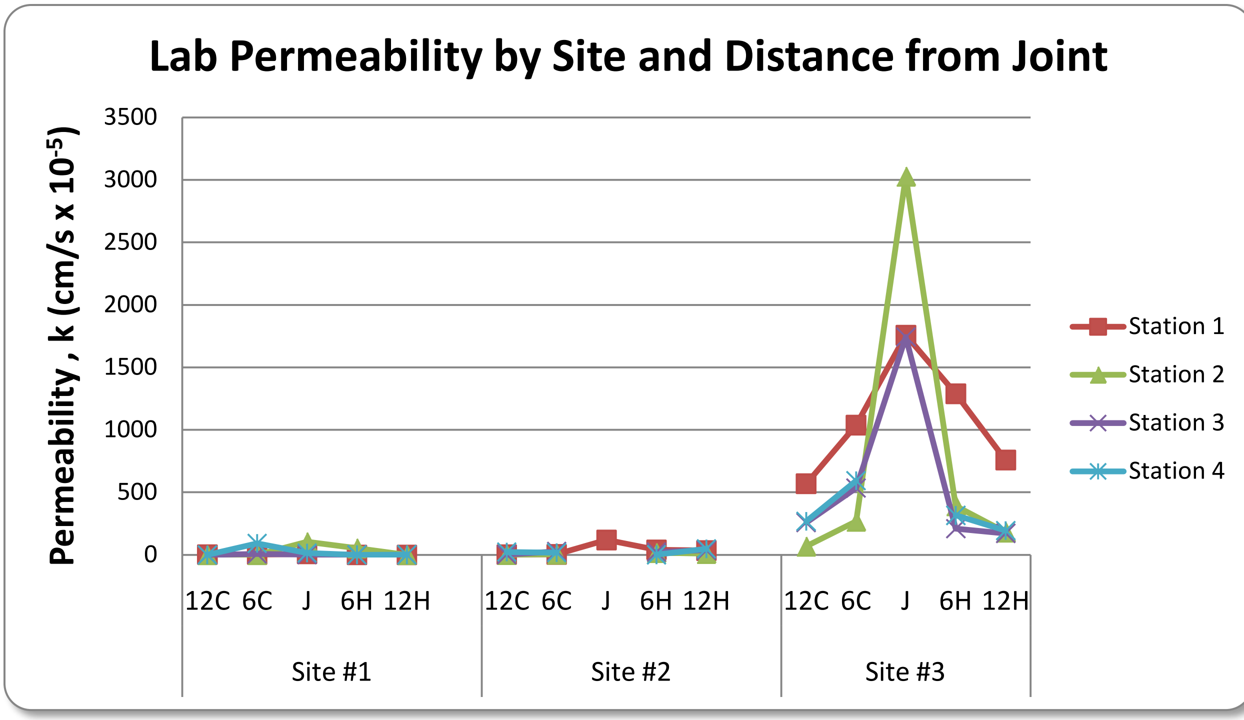


FIGURE 20 Phase 1 Laboratory Permeability Comparison (cm/s x 10^{-5}).

Laboratory permeability results indicated that Site #1 exhibited the best performance and Site #3 showed the poorest performance.

<u>Asphalt Binder Content</u>

Next, the cores were burned in the ignition oven in order to determine binder content, and to ascertain whether any significant changes in binder content exist at or near the joint. Binder content results are given in Table 18 and Figure 21.

TABLE 18 Data Summary – Binder Content by Ignition Oven (%)

	Site #1					Site #2					Site #3				
Station	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	6.6	6.7	5.6	6.9	6.5	6.9	7.0	6.7	7.1	7.1	5.9	5.7	5.8	5.8	6.2
2	6.4	6.8	6.5	6.4	6.4	7.1	7.4	7.0	6.3	7.2	5.3	6.1	3.4	5.5	5.2
3	6.5	6.9	6.5	6.7	6.7	6.9	6.3	7.0	7.8	7.9	5.8	5.9	5.8	6.1	6.2
4	6.7	6.4	7.3	6.5	6.9	6.5	6.8	7.0	7.3	6.9	5.1	5.5	5.8	5.2	5.0

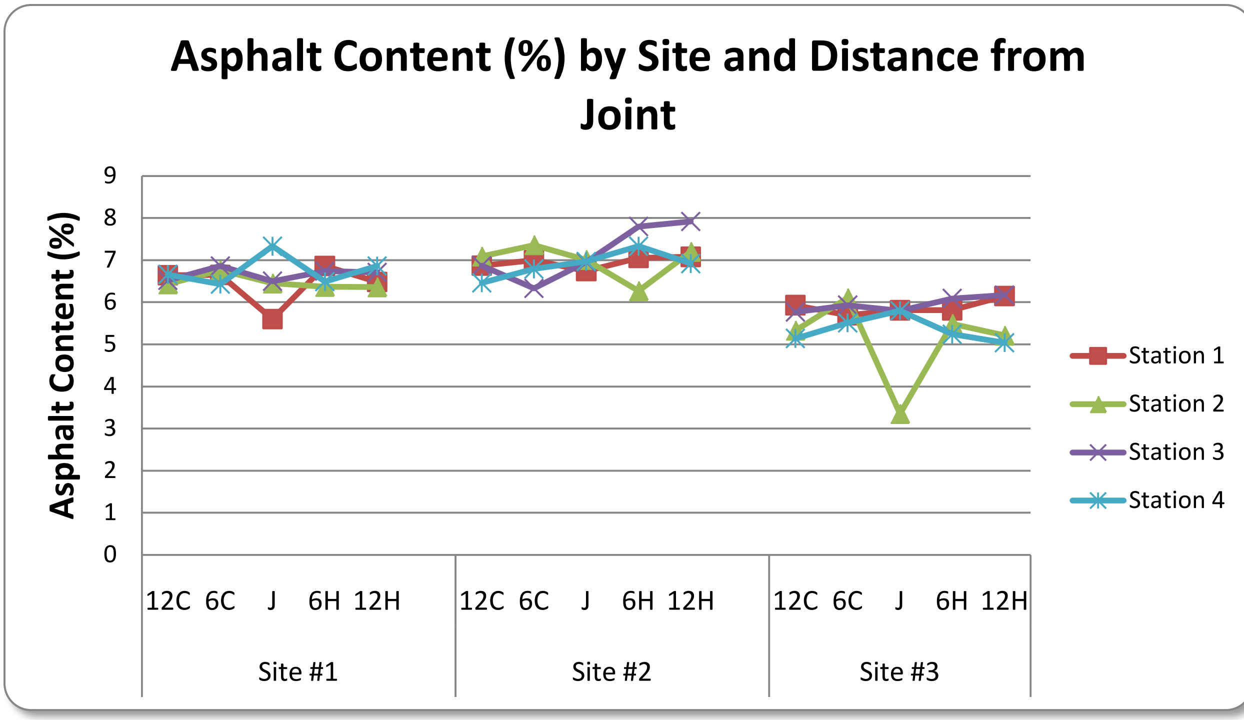


FIGURE 21 Phase 1 Asphalt Content Comparison (%).

Although low binder content was present at the joint for Station 2 of Site #3, binder content comparisons did not generally appear to detect changes across the joint. Binder content was also considered as a function of the difference in measured binder content and design binder content. However, no significant conclusions were added based on this analysis.

Gradation

The bare aggregate resulting from the ignition oven tests was used to determine the gradation of each core. It was suspected that differences in gradation could be an indicator of segregation at the joint, which could help to explain differences in performance at and away from the joints. In order to provide a fair comparison of the various sites, gradation results for each sieve were taken as the difference in the measured value and the design value from the mix design. Then, the absolute values of the differences were summed to provide a total difference in gradation from the design. Test results are shown in Table 19 and Figure 22.

TABLE 19 Data Summary – Sum of Gradation Deviation (%)

	Site #1					Site #2					Site #3				
Station	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	57.5	49.7	54.8	47.7	37.7	19.3	24.6	22.7	7.7	5.8	13.3	9.4	4.5	10.1	50.0
2	52.8	45.5	37.9	32.9	46.3	9.0	32.9	29.6	4.1	13.2	15.0	14.8	17.4	4.0	4.6
3	49.2	52.7	51.7	42.5	46.7	14.2	29.0	70.3	2.4	3.1	3.0	6.2	13.1	20.0	5.1
4	50.7	33.1	41.9	41.0	50.0	21.2	19.9	68.1	9.4	8.0	15.2	5.2	17.3	6.3	2.6

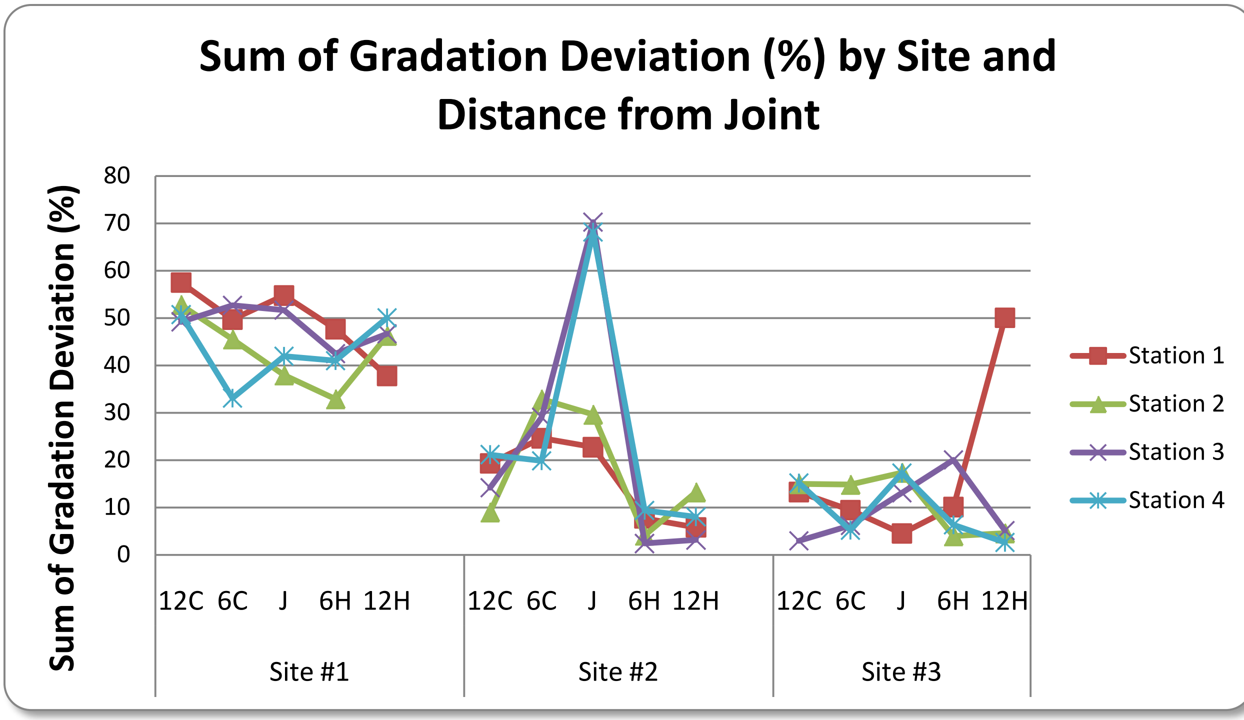


FIGURE 22 Phase 1 Gradation Comparison (%).

In some cases, gradation was a capable indicator of joint performance. In other cases, the results were unclear. Thus, fineness modulus was investigated as an alternative gradation descriptor. Test results are reported as the difference in the measured fineness modulus and the fineness modulus given on the mix design. The results are given in Table 20 and Figure 23.

TABLE 20 Data Summary – Fineness Modulus (difference from design)

Station	Site #1					Site #2					Site #3				
	12C	6C	J	6H	12H	12C	6C	J	6H	12H	12C	6C	J	6H	12H
1	0.49	0.44	0.49	0.42	0.33	0.16	0.22	0.18	0.06	0.05	0.15	0.11	0.04	-0.10	-0.48
2	0.46	0.41	0.33	0.28	0.40	0.10	0.30	0.23	0.05	0.13	0.15	0.13	0.14	-0.04	-0.03
3	0.43	0.46	0.44	0.36	0.39	0.11	0.25	0.64	0.02	-0.01	-0.01	0.07	-0.13	0.17	-0.05
4	0.46	0.31	0.36	0.36	0.43	0.19	0.18	0.62	0.10	0.09	-0.13	0.05	-0.16	0.05	-0.02

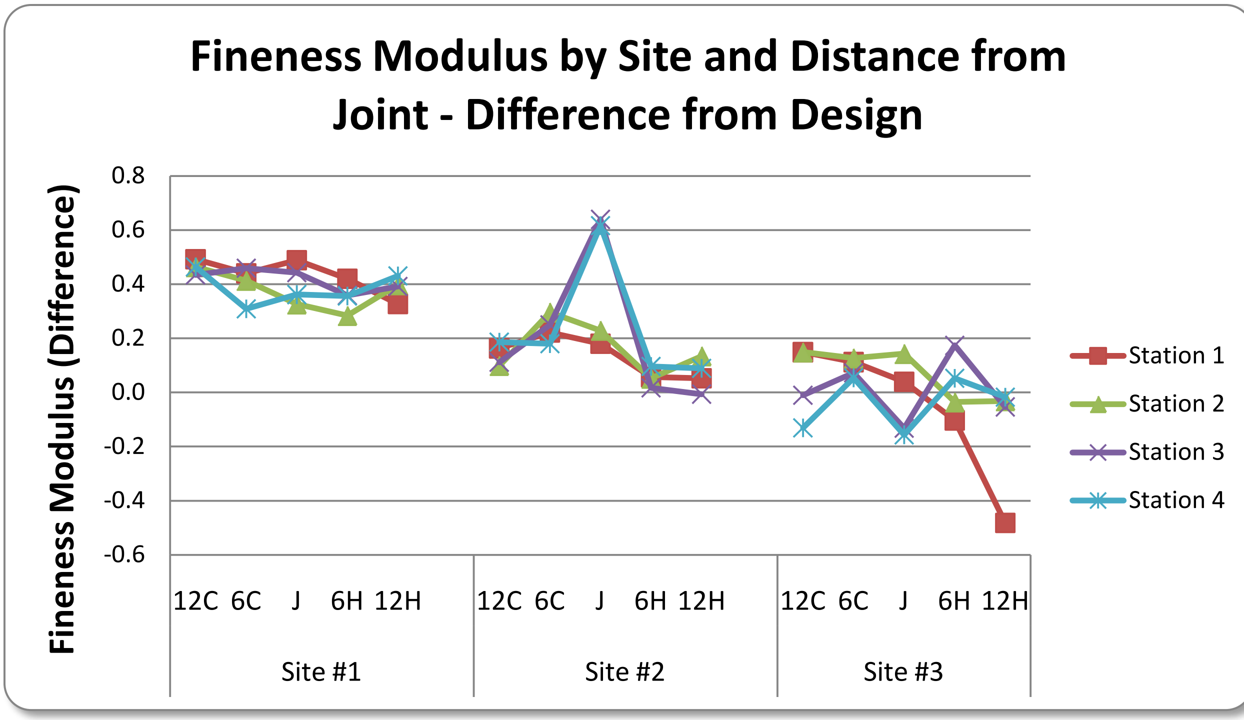


FIGURE 23 Phase 1 Fineness Modulus Comparison (difference from design).

Again, some differences were evident at the joint; however, a consistent trend was not present for all three sites.

Statistical Analysis

Visually, the measures of density, permeability, and infiltration were better able to detect differences at and away from the joint than were gradation and binder content. However, a robust statistical analysis was necessary to determine whether statistically significant differences did, in fact, exist. An analysis of variance (ANOVA) for a complete randomized block design was used to test the significance of distance from the joint, with site serving as a blocking factor. The analysis was completed for each potential measure of quality. Table 21 contains a summary of results for the analysis, as well as notation for the results of the subsequent means tests. A 95 percent level of significance ($\alpha = 0.05$) was used in all cases. In the table, a p-value is given for each measure. For p-values less than α, significant differences were detected between the various distances from the joint, meaning that the measure could successfully detect the presence of the joint. Next, the means test was used to assess which locations were significantly different from one another. The mean value for each location (with respect to the joint – i.e., 12C, 6C, J, 6H, and 12H) is provided, and a solid underline bar indicates that similar locations. Using SSD Core density as an example, the 12C (12 inches to the cold side of the joint) location has the highest density, 93.9%, and the J (joint) has the lowest density, 86.5%. The solid underline bar does not connect the J to any other location, meaning that the joint SSD density is significantly less than at any other location. The solid underline bar does connect the 12H, 6C, and 6H locations, meaning that no significant differences were detected between those locations. The solid underline bar does not connect the 12C to any other location, meaning that the SSD density at 12 inches to the cold side of the joint is significantly greater than any other location.

TABLE 21 Summary of Statistical Analysis for Effect of Distance from Joint

Test Method	ANOVA / Means Test Results					
Nuclear Density (%)	Significant	93.6	92.0	91.1	90.1	88.3
	$p < 0.0001$	12C	12H	6C	6H	J
PQI Density (%)	Significant	93.4	91.7	90.6	90.3	90.1
	$p = 0.0011$	12C	12H	6C	J	6H
PaveTracker Density (%)	Significant	93.0	91.8	90.5	90.4	90.3
	$p = 0.0025$	12C	12H	6H	6C	J
SSD Core Density (%)	Significant	93.9	91.8	91.8	90.6	86.5
	$p < 0.0001$	12C	12H	6C	6H	J
Vacuum Sealing Core Density (%)	Significant	93.4	91.5	91.2	89.7	84.7
	$p < 0.0001$	12C	12H	6C	6H	J
Field Permeability (cm/s x 10^{-5})	significant	293	483	737	1160	5962
	$p = 0.0012$	12C	12H	6H	6C	J
Infiltration (cm/hr)	significant	0.095	0.120	0.150	0.196	0.783
	$p = 0.0002$	12C	12H	6H	6C	J
Lab Permeability	significant	99.37	119.48	215.27	195.05	838.04

(cm/s x 10^{-5})	p = 0.0011	12C	12H	6C	6H	J
Asphalt Content, Difference from Design (%)	not significant p = 0.4642	0.81 12H	0.76 6H	0.75 6C	0.61 12C	0.49 J
%Pass ½", Difference from Design (%)	not significant p = 0.1229	-0.33 12H	-0.29 12C	-0.03 6H	0.49 6C	0.83 J
%Pass 3/8", Difference from Design (%)	not significant p = 0.2987	1.09 6H	1.10 12H	1.95 J	2.33 12C	2.39 6C
%Pass #4, Difference from Design (%)	not significant p = 0.0985	2.51 6H	2.83 12H	4.33 J	4.48 12C	5.27 6C
%Pass #8, Difference from Design (%)	significant p = 0.0266	0.69 12H	1.13 6H	2.59 12C	3.33 6C	3.45 J
%Pass #16, Difference from Design (%)	significant p = 0.0016	1.18 12H	2.11 6H	3.64 12C	4.06 6C	4.63 J
%Pass #30, Difference from Design (%)	significant p = 0.0042	1.65 12H	2.87 6H	3.77 12C	4.20 6C	4.89 J
%Pass #50, Difference from Design (%)	significant p = 0.0160	1.16 12H	2.32 6H	2.51 12C	2.92 6C	3.83 J

%Pass #100, Difference from Design (%)	marginal	1.95	2.38	2.41	2.43	3.50
	p = 0.0655	12H	12C	6H	6C	J
%Pass #200, Difference from Design (%)	not significant	1.83	2.07	2.27	2.29	3.31
	p = 0.0838	12H	6H	12C	6C	J
Sum of Gradation Deviation (%)	significant	23.29	27.91	29.38	31.19	37.49
	p = 0.0417	6H	12H	6C	12C	J
Fineness Modulus, Difference from Design	significant	-0.103	-0.144	-0.214	-0.245	-0.265
	p = 0.0130	12H	6H	12C	6C	J

α = 0.05

Based on the results of the analysis, the following conclusions were made.

- Overall, densities at the joint were less than densities away from the joint.
- In general, the greatest densities were present 12 inches from the joint on the cold lane.
- Significant differences in distance from the joint were detected by all methods of density measurement.
- The nuclear method detected more significant differences than the non-nuclear methods, indicating greater discrimination between the various distances from the joint.
- The SSD and vacuum sealing methods were able to discriminate between the various distances from the joint, and the vacuum sealing method detected a greater number of significant differences.
- Field permeability, infiltration, and laboratory permeability values provided similar discrimination in that the permeability at the joint was significantly greater than that for the other testing locations at each station, especially for projects having joints of a lesser quality rating.
- Infiltration clearly detected significant differences by project.
- Binder content (as measured by difference from design binder content) was not significantly affected by distance from the joint.
- By and large, measured gradations were finer than the mix design gradations.

- For the larger sieves in the gradation (1/2", 3/8", #4, #8), the deviation from the design gradation was not significantly affected by distance from the joint.
- For smaller sieves in the gradation (#16, #30, #50, and #100), significant differences were noted for the various distances from the joint.
- Distance to the longitudinal joint did not significantly affect the percent passing the #200 sieve.
- The sum of gradation deviation was greater at the joint than away from the joint.
- The deviation of gradation from the mix design, as measured by the fineness modulus, was greater at the joint than away from the joint.
- Fineness modulus decreased as the testing location approached the joint, meaning that the gradation was finer at the joint than away from the joint.
- Although significant differences in testing location were detected by gradation and permeability tests, considerable overlap was present, indicating lesser clarity of results.

Overall, the results of the ANOVA indicated that the greatest discrimination in test results was achieved by measures of density – specifically the nuclear density method and the vacuum sealing method for determining bulk specific gravity. Permeability Infiltration clearly indicated differences by project, but provided less discrimination overall among the various distances from the joint. This could mean that although significant differences in density were present at various distances from the joint, differences in permeability and infiltration were not. Alternatively, it could suggest that the permeability and infiltration test methods were simply not able to clearly discriminate between smaller differences. Thus, further analysis was needed to determine which test methods were able to most accurately predict the performance of the joint.

<u>Ranking the Data</u>

In order to assess accuracy, field and laboratory test results were compared to known field performance. Based on visual observation, the 12 joint locations were ranked according to four categories:

- A – good
- B – fair
- C – poor
- D – very poor

Next, the measures of joint quality by various test methods were used to rank the joint locations. For density, data generated by the nuclear density, SSD, and vacuum sealing methods were used. For each method, rankings were produced for densities calculated as a percent of maximum theoretical density, and as a relative percentage of mat density, calculated according to Equation 4. Stations with higher density values received higher rankings.

$$Relative\ Joint\ Density\ (\%) = \left(\frac{Joint\ Density}{Mat\ Density}\right) * 100$$

Equation 4

Construction records were consulted to determine the average mat density at the time of construction. Average mat densities were 94.4, 92.3, and 93.2 percent for Projects 1, 2, and 3, respectively. These densities were similar to those measured at a distance of 12 inches from the longitudinal joint at each station.

Rankings were also generated from the permeability and infiltration data. In addition to the permeability measurements, relative permeability and infiltration percentages were generated using a calculation similar to that for relative joint density. The average permeability at a distance of 12 inches from the joint (hot and cold lanes) was used as the measure of mat permeability. Stations exhibiting lower levels of permeability were assigned higher rankings.

In terms of gradation, rankings were given based on the relative percent passing a given sieve, calculated as the absolute value of the difference in gradation between the joint and mat areas. This was felt to be the most appropriate measure because segregation at the joint should be indicated by a change in the gradation at the joint area. Rankings were also assigned based on differences in fineness modulus, sum of gradation deviation, and relative sum of gradation deviation (i.e., gradation deviation at the joint expressed as a percentage of gradation deviation away from the joint). Stations displaying smaller differences in gradation were assigned higher rankings.

Table 22 provides a summary of the joint rankings. Each testing location is identified by the project and station number; for example, project #2 – station 3 is denoted by 2-3. The visual ranking determined by visual observation of existing distresses is shown, and taken to be the "true" condition of the longitudinal joint. Rankings generated by each joint quality measure as tested in this project are also provided. Matching letter ranks are shown in bold type, indicating an accurate measure of joint quality.

The greatest accuracy was noted for the SSD and vacuum sealing methods, correctly ranking joint quality in 10 of 12 and 11 of 12 cases, respectively. The nuclear density method appeared to correctly identify those joints of good quality, but was unable to consistently rank the joints of poor quality.

In terms of permeability, most measures were able to correctly rank good and poor joints, but were unable to identify joints of marginal quality. Laboratory permeability values and relative infiltration rate (infiltration of the joint expressed as a percentage of the mat infiltration) were both able to correctly rank two-thirds of the joints.

The relative fineness modulus of the joint and the relative sum of gradation deviation (expressed as a percentage of that for the mat) were the gradation parameters that were most able to correctly rank the joints, each being able to correctly assign rankings to two-thirds of the testing stations.

TABLE 22 Joint Quality Rankings for Measures of Density, Permeability, and Gradation

Project - Station	**Visual Ranking**	***Nuclear (%TMD)***	***Nuclear (% Rel.)***	***SSD (% TMD)***	***SSD (% Rel.)***	***Vac.Seal. (% TMD)***	***Vac.Seal. (% Rel.)***
1-1	**A**	**A**	**A**	**A**	**A**	**A**	**A**
1-2	**A**	**A**	**B**	**A**	**A**	**A**	**A**
1-3	**A**	**A**	**A**	**A**	**A**	**A**	**A**
1-4	**A**	**A**	**A**	**A**	**A**	**A**	**A**
2-1	**B**	**B**	**B**	**B**	**B**	**B**	**B**
2-2	**D**	B	B	**D**	**D**	**D**	**D**
2-3	**D**	B	C	**D**	**D**	**D**	**D**
2-4	**D**	C	C	**D**	**D**	**D**	**D**
3-1	**C**	D	D	**C**	**C**	**C**	**C**
3-2	**B**	C	C	**B**	**B**	**B**	**B**
3-3	**B**	**B**	**B**	C	C	**B**	**B**
3-4	**C**	**C**	D	D	D	D	D

Project - Station	**Visual Ranking**	***Field Perm***	***Rel. % Field Perm***	***Lab Perm***	***Rel. % Lab Perm***	***Infiltration***	***Rel. % Infiltration***
1-1	**A**	**A**	**A**	**A**	**A**	**A**	**A**
1-2	**A**	**A**	B	B	C	**A**	**A**
1-3	**A**	**A**	B	**A**	B	**A**	**A**
1-4	**A**	**A**	B	**A**	C	**A**	**A**
2-1	**B**	**B**	A	**B**	A	**B**	A
2-2	**D**	C	**D**	**D**	**D**	C	**D**
2-3	**D**	C	**D**	**D**	**D**	B	**D**
2-4	**D**	C	**D**	**D**	**D**	C	**D**
3-1	**C**	D	**C**	**C**	A	D	B

3-2	**B**	D	C	C	C	D	D
3-3	**B**	D	C	C	**B**	C	C
3-4	**C**	D	**C**	D	D	D	**C**

Project - Station	**Visual Ranking**	***Rel. % Pass #8***	***Rel. % Pass #50***	***Rel. % Pass #200***	***Rel. % FM***	***Sum of Deviation***	***Rel. % Sum of Dev.***
1-1	**A**	B	**A**	**A**	**A**	C	**A**
1-2	**A**	C	B	**A**	B	B	B
1-3	**A**	**A**	**A**	**A**	**A**	C	**A**
1-4	**A**	B	**A**	**A**	**A**	C	**A**
2-1	**B**	A	C	**B**	A	**B**	**B**
2-2	**D**	B	B	B	B	B	C
2-3	**D**	**D**	**D**	**D**	**D**	**D**	**D**
2-4	**D**	**D**	**D**	**D**	**D**	**D**	**D**
3-1	**C**	**C**	**C**	D	**C**	A	**C**
3-2	**B**	A	C	C	**B**	A	**B**
3-3	**B**	**B**	A	A	**B**	A	C
3-4	**C**	A	B	B	A	A	A

Discussion

A test method used to determine the quality of HMA longitudinal joints should demonstrate accuracy, precision, and discrimination. In addition, the chosen test method should also possess practical advantages in order to ensure successful implementation. The following points should be considered.

- Non-destructive measures of density are typically very quick and easy to obtain. However, the ability to properly "seat" the gauges for testing has reportedly been problematic. For the joints tested in this study, no significant issues were encountered. Even when a vertical differential was present at the joint, nuclear gauge results appeared to be within reason. It is noted that all joints used in this study were in an area of consistent cross-slope. Significant difficulties could result if using nuclear or non-nuclear gauges at a crown section.

- Cutting cores and testing bulk specific gravity (Gmb) in the laboratory is typically believed to provide the most accurate measure of density. However, in cases where the cut core does not remain intact throughout the testing process, no data can be obtained. Cores cut at the longitudinal joint must be handled very carefully, especially if the joint is of poor condition.
- The SSD method is generally accepted as the traditional measure of density. However, for samples of low density, the SSD method can be difficult to accurately determine. Since joint samples are likely to exhibit low density, the vacuum sealing method may be able to provide a more consistent result for this parameter.
- Permeability and infiltration values were clearly related to joint quality and provided acceptable discrimination. However, the test methods used to determine these values are not generally accepted by agencies as standard procedures. Thus, the practical aspect of implementing permeability as a measure of joint quality is lacking. In order to justify the use of a non-standard method, the accuracy and discrimination of the method should clearly exceed that of an established method.
- Gradation, as measured by percents passing, fineness modulus, and sum of gradation deviation involve the use of a widely accepted test method. However, the process of generating test results is fairly time-consuming and labor-intensive. In implementing joint quality as a quality control measure, test results need to be available as quickly as possible so that the contractor can make necessary changes in an efficient manner. Again, the accuracy and discrimination of this method as a measure of joint quality would have to be superior to that of other methods in order to justify its use.

Phase 1 Conclusions

When an asphalt pavement fails at the longitudinal joint, the remainder of the mat is more likely to fail prematurely. Distresses, such as cracking and raveling, result when joints are susceptible to the harmful effects of air and water. The focus of Phase 1 of this project was to determine the test method that best describes HMA longitudinal joint quality. A number of methods were investigated, including nuclear density, non-nuclear density, density of field cores by the SSD and vacuum sealing methods, permeability, and gradation.

Of the non-destructive methods investigated in this study, the nuclear gauge was able to provide the greatest level of discrimination. Differences in density at and away from the joint were readily detected by this method. However, the nuclear gauge was not always successful at correctly ranking joints of varying quality. Very good and very poor joints were established, but joints of marginal quality were not adequately identified. While the nuclear gauge may not provide adequate results for QA purposes, this method did demonstrate the capability of detecting actual changes in joint density, making it a viable tool for quality control purposes.

Overall, the procedure providing the greatest accuracy and discrimination for HMA longitudinal joint quality was the vacuum sealing method for measuring bulk specific gravity of field cores. Although it is destructive to the pavement, the vacuum sealing method was able to detect actual differences in density (i.e., provide adequate discrimination), as well as provide an appropriate ranking of joint quality (i.e., accuracy). It is noted that the SSD method also provided a fair representation of joint density. If care is taken to properly perform the method for samples of lower densities, this method could also be used as an acceptable alternative. Therefore, it is recommended that the vacuum sealing method be considered for use in the determination of field core density in the Phase 2 evaluation of longitudinal joint quality, in addition to the SSD and nuclear methods. With respect to permeability, the field permeability measure, as well as infiltration served as a reasonable indicator of joint quality. Thus, these measures are also recommended for use in Phase 2 of the study.

Update of Site #3

Site #3 was originally ranked as being in fair/poor condition. However, this was a somewhat difficult determination to make because Site #3 was relatively new at the time of testing, whereas Site #1 and Site #2 had been in place for 3.5 and 5 years, respectively. Thus, Site #3 was revisited after approximately 2 years in service, where definite signs of joint deterioration were evident, as shown in Figure 24. The visible signs of joint separation and raveling supported the test results generated during the Phase 1 testing regimen.

FIGURE 24 Site #3 Approximately Two Years After Construction.

PHASE 2

The primary objective of Phase 2 of this study was to use a number of joint construction techniques to generate a recommendation for appropriate methods that can be used to improve longitudinal joint quality, which can be easily implemented within an existing quality control/quality assurance (QC/QA) program. Specific objectives were to determine the ability of each technique to affect quality at and near the joint, to determine the most advantageous measure of joint quality for QC/QA purposes, and to explore relationships between joint characteristics that could facilitate the successful implementation of joint quality specifications.

Scope

Two resurfacing projects were chosen for this study, each utilizing a 12.5mm asphalt mixture. The first was a 5-lane section of U.S. Highway 167 near Bald Knob, Arkansas, and the second was a three-lane section (2 lanes plus a climbing lane) of U.S. Highway 65 near Clinton, Arkansas. In each case, the test joint was the joint between unidirectional lanes of traffic, thus eliminating any confounding effects caused by the cross-sectional shape of the roadway. Test sections were situated to avoid areas of difficult geometry or other features that could negatively impact typical construction procedures.

Test Methods

On each project, 8 longitudinal joint construction techniques were used to construct 500-foot sections, described as follows:

Joint Adhesive (CF)

The Crafco Pavement Joint Adhesive, supplied by Southern Star Materials, Inc., was applied to the joint face just prior to placement of the hot lane. This material is a hot-applied polymerized asphalt product that serves to bond the hot and cold lanes together while reducing the permeability at the joint. This product is applied in a 3mm (1/8 inch) band along the cold face of the joint immediately ahead of the paver as the hot lane is placed. The purpose of the Crafco product is to essentially "waterproof" the joint, and to provide improved resistance to thermal expansion and contraction. *(19)* The cost to apply the Crafco joint adhesive to a 2-inch overlay is approximately $0.25 per linear foot. This cost includes all materials, labor, and equipment for a crew to apply the material at a steady rate. Application of the Crafco product is shown in Figure 25.

FIGURE 25 Crafco Product Application.

Joint Heater (JH)

An infrared joint heater, supplied by Heat Design Equipment, Inc., was used construct longitudinal joints by heating the cold lane just prior to placement of the hot lane. The heater trailer uses propane-powered infrared heater panels to raise the surface temperature of the cold lane edge to a range of 212°F to 250°F at standard paving speeds of up to 35 feet per minute. The joint heater marketed by Head Design Equipment, Inc. has been used successfully in Canada and the U.S., and is believed to be the closest approximation of echelon paving in situations where true echelon paving is not feasible. *(36)* The cost of this method is approximately $0.12 per linear foot, which includes the initial cost of equipment (with amortization) and operating costs. For the test projects in this study, the cold lane was heated to a temperature of approximately 230°F. The hot lane was immediately placed and compacted. The joint heater is shown in Figure 26.

FIGURE 26 Joint Heater by Heat Design Equipment, Inc.

Notched Wedge (NW)

The notched wedge joint maker, marketed by TransTech Systems, Inc., was used to form a one-half inch notch and a 1:12 wedge. *(37)* This joint maker is designed to prevent longitudinal joint failure by shaping the mat's edge to increase density and interlock. It is marketed in two forms: the standard wedge and the thin left wedge. The thin lift version is primarily used for overlays that are between 1-¾ and 2 inches thick, while the standard model is used for thicker lifts. The thin lift model was used in this study, as it was most appropriate for the overlay thickness on each project. Although additional compaction devices (i.e., tag-along rollers, etc.) may be used to provide initial compaction to the wedge, no special devices were used for the projects in this study. At the time of purchase for this project, the cost of a pair of thin lift joint maker shoes was approximately $7,550.00. No routine operating costs are associated with this technique. The notched wedge is shown in Figure 27.

FIGURE 27 Notched Wedge Joint Maker by TransTech Systems, Inc.

Joint Stabilizer (JB)

JointBond®, manufactured by D&D Emulsion, Inc., and distributed by Pavement Technology, Inc., is a post-applied polymerized maltene-based emulsion product composed of a petroleum resin oil base and SBR copolymer uniformly emulsified with water. *(38)* This product penetrates the pavement's surface and affects the chemistry of the in-place asphalt binder to help prevent joint deterioration and separation. Typical application rates are 0.07 to 0.25 gallons per square yard. For the projects in this study, JointBond® was sprayed at a rate of 0.11 gallons per square yard onto the joint area after final rolling was completed and the mat had cooled significantly. A spray bar was used to apply a 3-foot wide strip of product to the joint, covering the joint and 18 inches to either side of the joint. The JointBond product was supplied by Pavement Technology, Inc. The cost varies from $0.36 to $0.57 per linear foot, and this variation is primarily due to differences in traffic control needs for a given project. JointBond application is shown in Figure 28.

FIGURE 28 JointBond® by Pavement Technology, Inc.

Tack Coat (TC). A standard tack coat (SS-1) was applied to the cold joint face by aiming the outer nozzle of the spray bar directly at the joint face during tack coat application. This product was included in the study as a potential alternative to the joint adhesive. Application of the tack coat is shown in Figure 29.

FIGURE 29 Tack Coat (SS-1) Applied by Contractor.

Hot Overlap (HO). This method was one of 3 rolling patterns included in the study. In this method, the first pass of the roller was in the vibratory mode with the roller on the hot side, overlapping the cold side of the joint by approximately 6 inches. This method was the control section for each project. A diagram and photo of the hot overlap method are given in Figure 30.

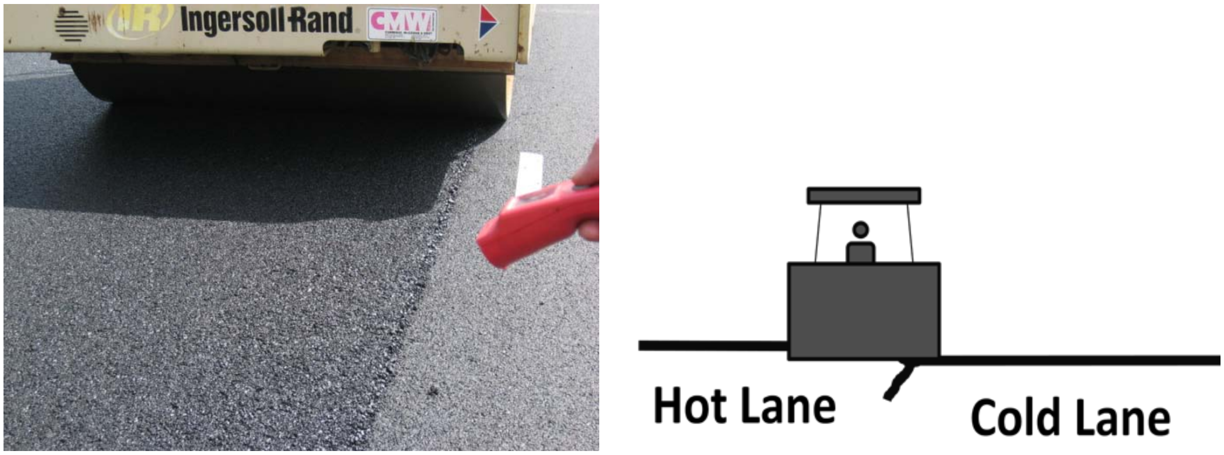


FIGURE 30 Hot Overlap Rolling Pattern.

Hot Pinch (HP). This rolling method required the first pass of the roller to take place in vibratory mode on the hot side, approximately 6 inches away from the joint. During the first pass, the material at the joint formed a hump that was “pinched” into the joint on subsequent passes. This method is currently specified by AHTD. The hot pinch method is illustrated in Figure 31.

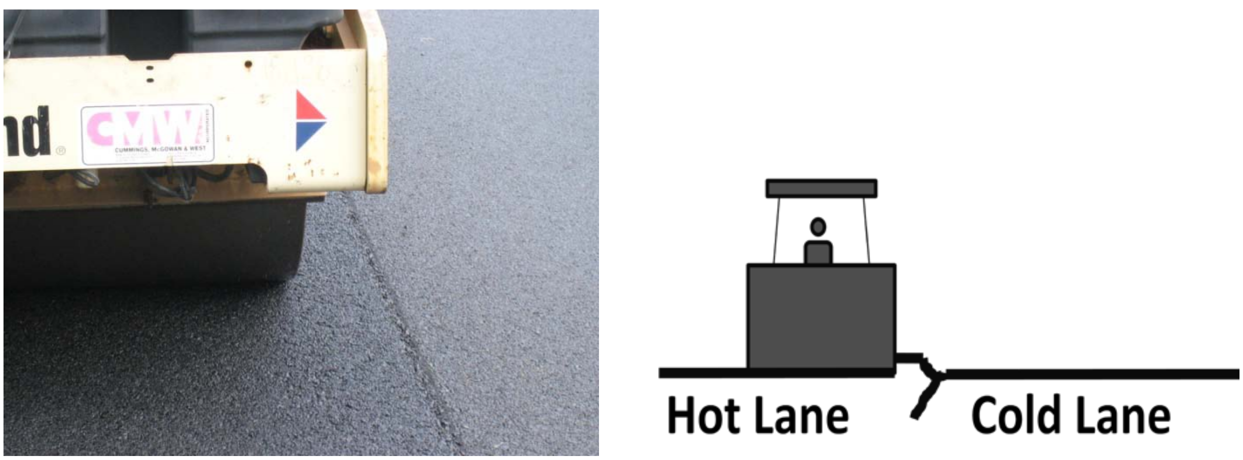


FIGURE 31 Hot Pinch Rolling Pattern.

Cold Roll (CR). In this rolling method, the first pass of the roller was performed in static mode on the cold side of the joint, overlapping the hot side by 6 to 12 inches. The remainder of the mat was compacted on subsequent passes. The cold roll method is shown in Figure 32.

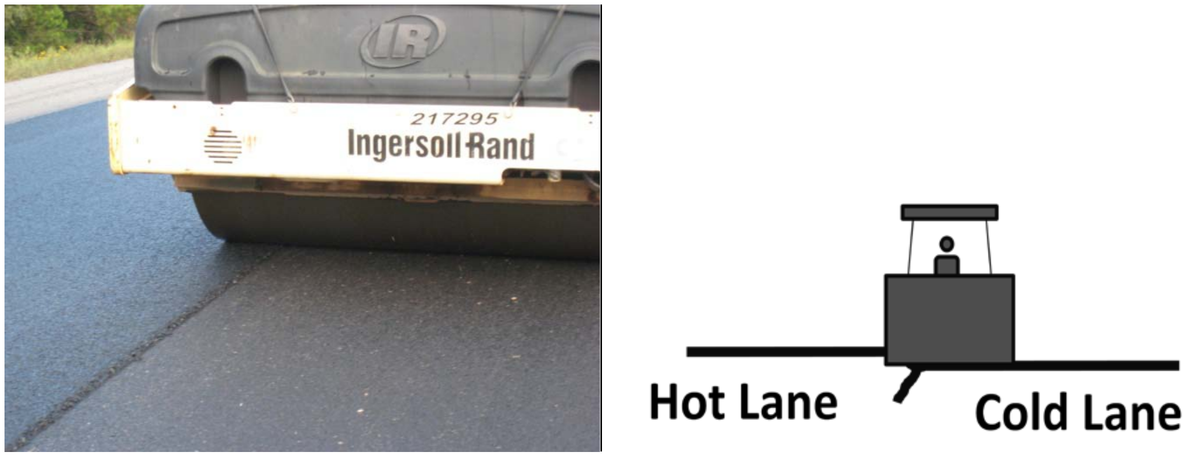
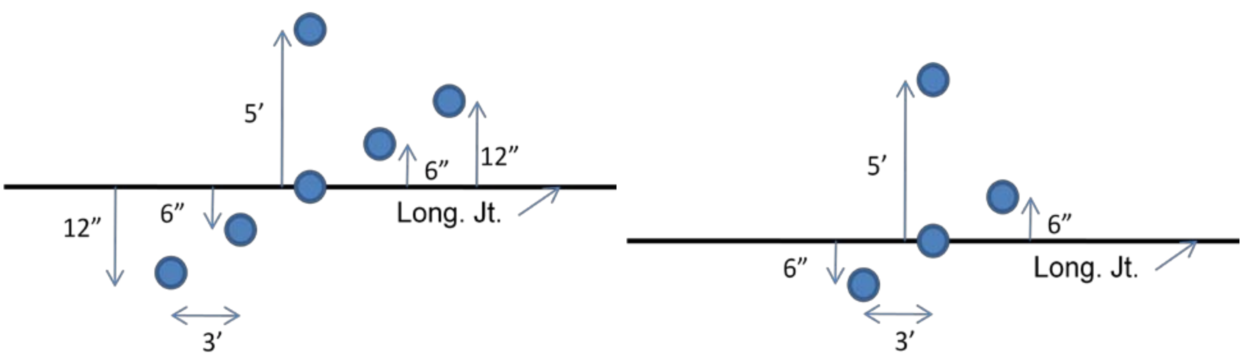


FIGURE 32 Cold Roll Rolling Pattern.

Testing Plan

Within each 500 foot section, 3 testing locations were established, and at each location, core locations were marked at the joint (J), 6 inches to the hot side of the joint (6H), 6 inches to the cold side of the joint (6C), 12 inches to the hot side of the joint (12H), and 12 inches to the cold side of the joint (12C). A mat density location (M) was also established within each section at a distance of 5 feet from the joint. The testing schematic is shown in Figure 33.



(a) (b)

FIGURE 33 Phase 2 Testing Schematic at Each Location for (a) Density and (b) Permeability.

Based on the results of Phase 1, the most advantageous test methods were chosen for assessing joint quality. The methods chosen included both non-destructive (nuclear density) and destructive (SSD and vacuum sealing) density testing, as well as non-destructive permeability and infiltration testing. First, nuclear density testing was performed at all testing points (12C, 6C, J, 6H, 12H, and M) using a Troxler

3430 nuclear gauge. Each reported density was the average of five density readings: one taken directly over the core location, and 4 taken at evenly spaced points around the perimeter of the core location (as performed in Phase 1 – see Figure 6). Density values were reported in pounds per cubic foot (pcf), and percent density was calculated based on the maximum theoretical specific gravity of the mixture as reported on the mix design. A core correction factor was established for each project based on cores tested according to AASHTO T 166.

Next, field permeability tests were conducted using the Gilson AP-1B field permeameter at the 6C, J, 6H, and M core locations. The coefficient of permeability was calculated as previously described in Phase 1. After completion of all non-destructive testing, cores were cut at the 6C, J, 6H, and M locations, resulting in a total of 160 cores. The cores were then transported to the laboratory where they were tested for bulk specific gravity according to the SSD method as described by AASHTO T166 and the vacuum sealing method as outlined in AASHTO T331. Percent density was computed for each specimen as a percentage of theoretical maximum specific gravity as reported on the mix design. In order to provide an additional measurement of the entrance of water into the mixture, percent absorption was calculated for each specimen, according to AASHTO T166.

Test Results and Analysis

Test results were divided into two segments – those describing density and those describing the potential for water to enter the pavement. A complete summary of experimental factors is given in Table 23.

TABLE 23 Summary of Experimental Factors

Projects (2)	**Construction Methods (8)**	**Distance from Joint (6)***	**Responses (6)**
Hwy. 167	Joint Adhesive (CF)	12C	Nuclear Density (NG)
Hwy. 65	Cold Roll (CR)	12H	T166 Density (SSD)
	Hot Overlap (HO)	6C	T331 Density (VS)
	Hot Pinch (HP)	6H	
	Joint Stabilizer (JB)	J	Absorption
	Joint Heater (JH)	M	Permeability
	Notched Wedge (NW)		Infiltration
	Tack Coat (TC)		

*12C and 12H distances used only for nuclear density measurements

Density-Related Responses

The average density values for each project are shown graphically in Figures 34 - 39. In general, densities tend to be lower at the joint and to the cold side of the joint, and density increases on the hot side of the joint. This trend is consistent with traditionally established density variations across a joint. In each figure, a greater vertical difference for a given joint construction method indicates a greater density differential across the joint. The more desirable situation is to have flatter lines, meaning that there is not as great a change in density across the joint.

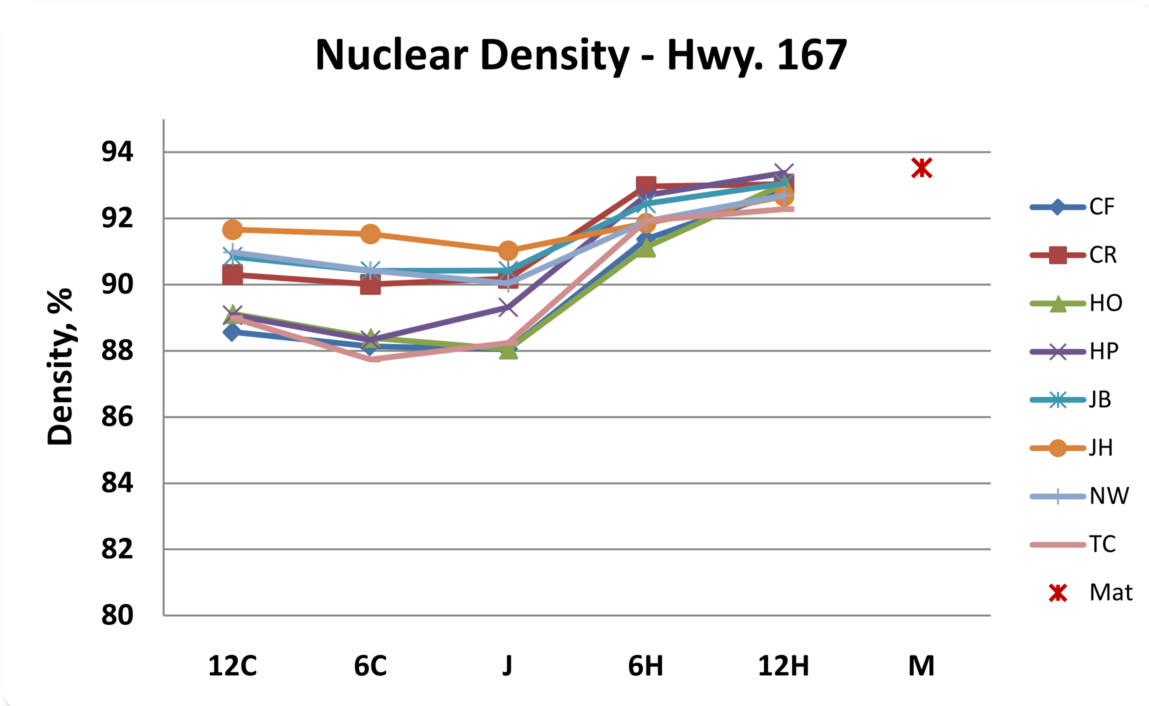


FIGURE 34 Phase 2 Nuclear Density Summary of Results – Hwy. 167.

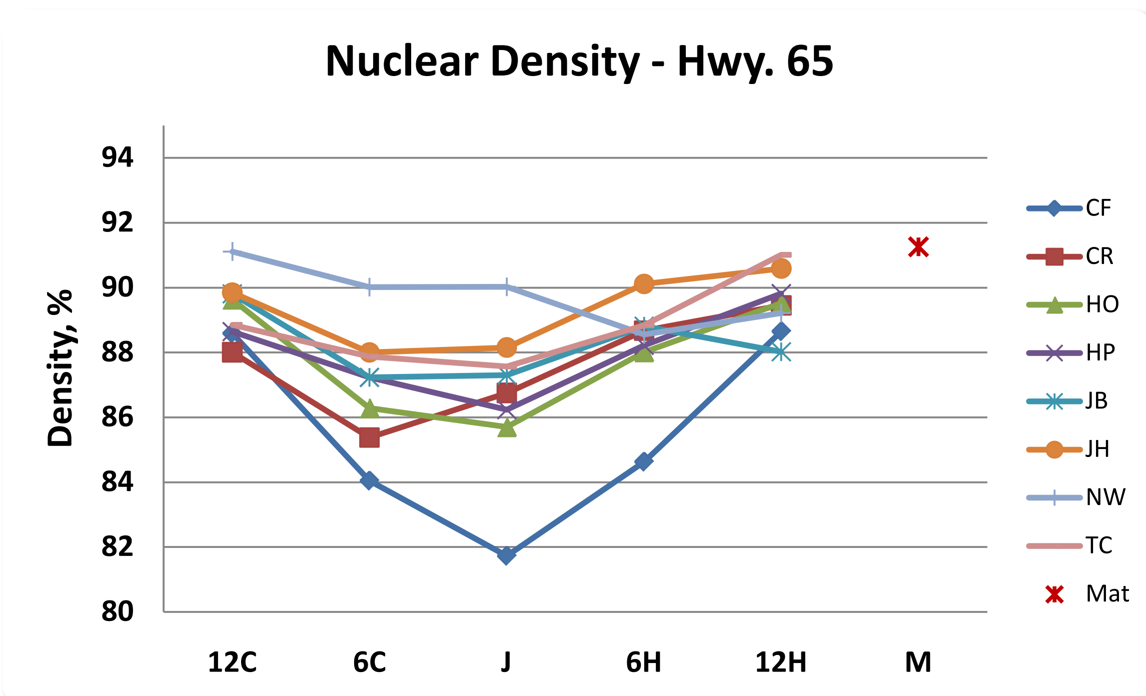


FIGURE 35 Phase 2 Nuclear Density Summary of Results – Hwy. 65.

For nuclear density, the joint stabilizer (JB), joint heater (JH), and notched wedge (NW) methods appear to generate similar densities at and away from the joint, while the joint adhesive (CF), hot overlap (HO), cold roll (CR), hot pinch (HP), and tack coat (TC) methods exhibit practically significant differences at various distances from the joint. In terms of magnitude, the joint heater (JH) and notched wedge (NW) methods generated the highest joint densities, followed by cold roll (CR), joint stabilizer (JB), and tack coat (TC). The lowest joint densities were present in the joint adhesive (CF) section. Note that most density values were less than the minimum specification of 92 percent for mat density. As expected, density values on the hot side of the joint most closely matched the mat density.

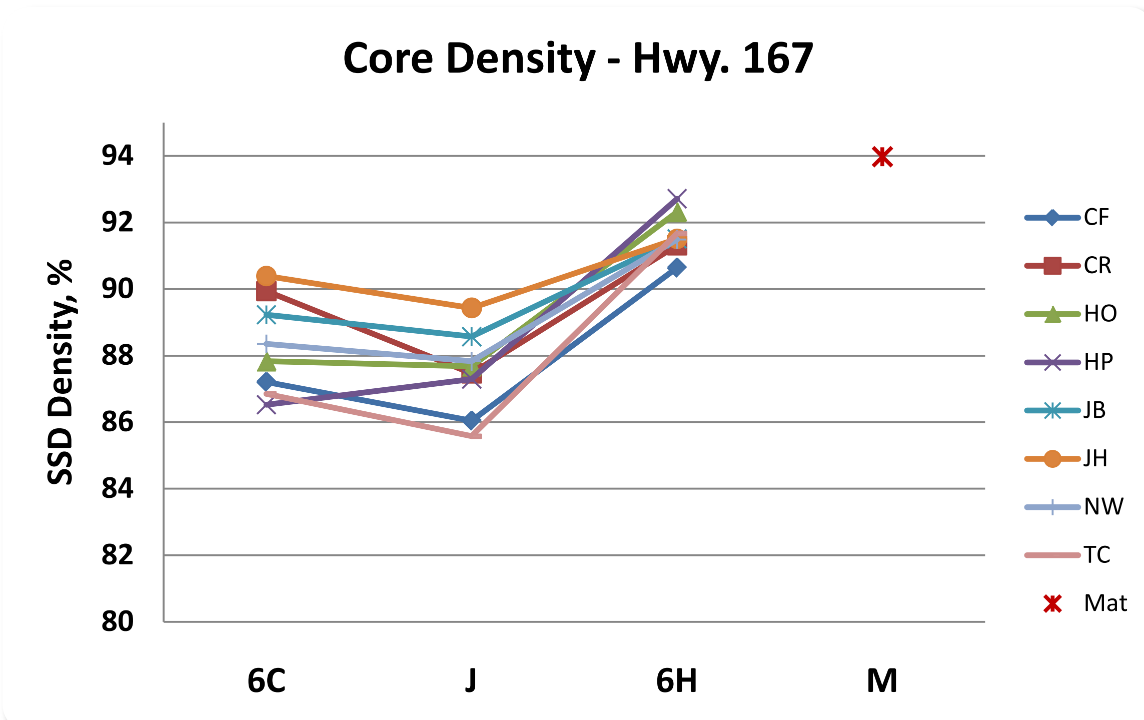


FIGURE 36 Phase 2 SSD Core Density Summary of Results – Hwy. 167.

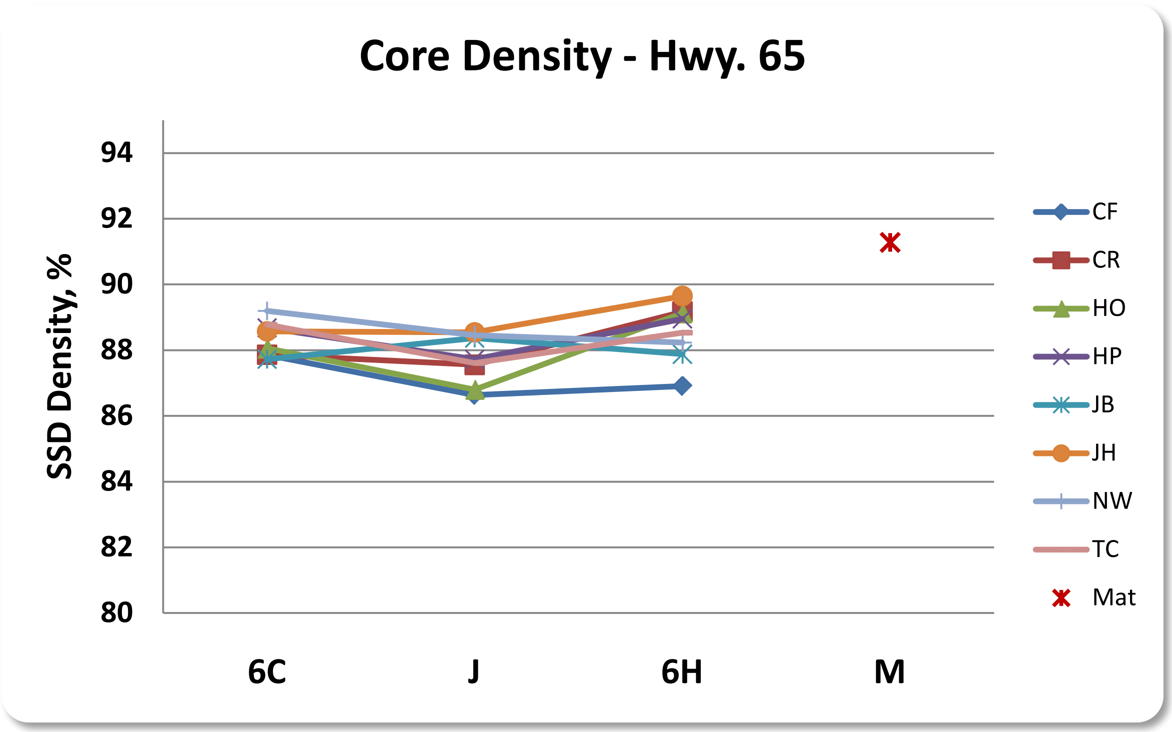


FIGURE 37 Phase 2 SSD Core Density Summary of Results – Hwy. 65.

Core density by AASHTO T166 displayed similar trends, although the variations in density were much less pronounced. The highest joint densities were obtained for the joint heater (JH) and joint stabilizer (JB) methods, while the lowest densities were associated with the joint adhesive (CF) and tack coat (TC) methods. The largest differences between densities at and away from the joint were noted for the hot overlap (HO), hot pinch (HP), and tack coat (TC) methods. Densities on the hot side of the joint were greater than those on the cold side, and more closely approximated the mat density. This trend was more pronounced for Hwy. 167 than for Hwy. 65.

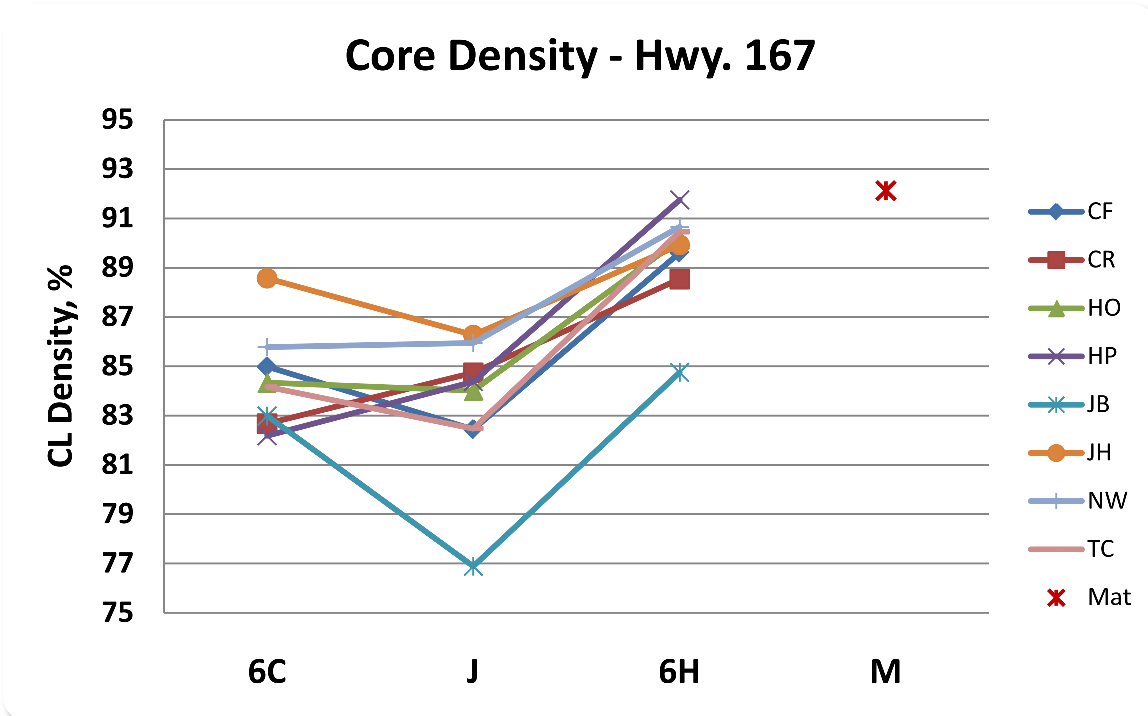


FIGURE 38 Phase 2 Vacuum Sealing Core Density Summary of Results – Hwy. 167.

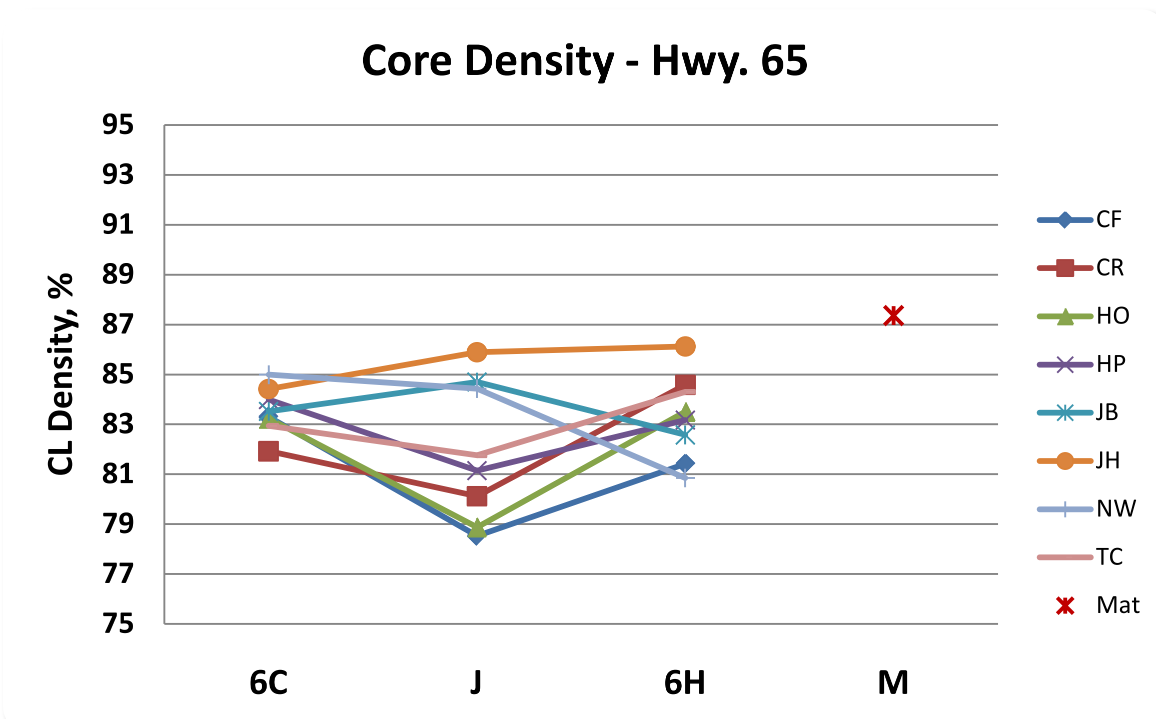


FIGURE 39 Phase 2 Vacuum Sealing Core Density Summary of Results – Hwy. 65.

For the vacuum sealing method, the magnitudes of density were considerably lower than for the other methods. This was not unexpected since the vacuum sealing method tends to result in lower densities than the SSD method, especially for lower density specimens as is typical of joint cores. This is primarily due to the inherent difficulties in obtaining a true saturated-surface-dry specimen condition during testing. Overall, the T331 core density test results showed that the joint heater (JH) and notched wedge (NW) methods were superior at achieving higher densities, while the joint stabilizer (JB) and joint adhesive (CF) methods were not successful. The joint stabilizer (JB) method appeared much more capable when judged by the other measures of density. No suitable explanation was determined for this phenomenon.

Water-Related Responses

Next, the properties describing the entrance of water into the pavement were analyzed. Absorption, permeability, and infiltration results for each project are given in Figures 40 - 45.

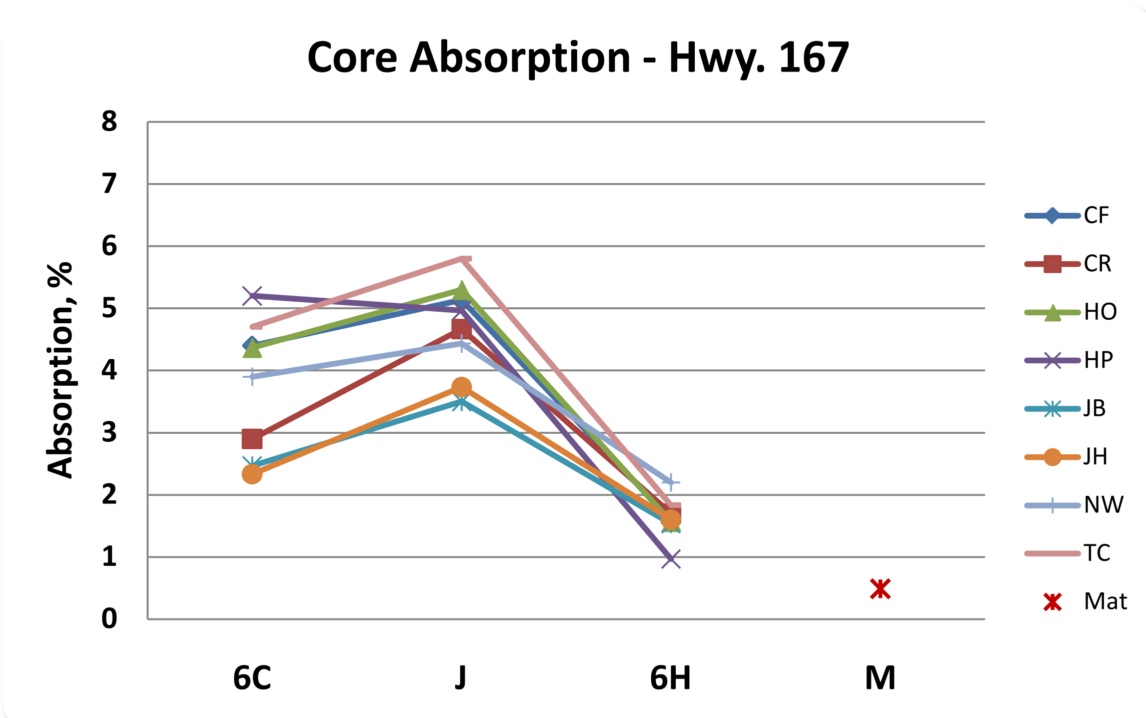


FIGURE 40 Phase 2 Absorption Summary of Results – Hwy. 167.

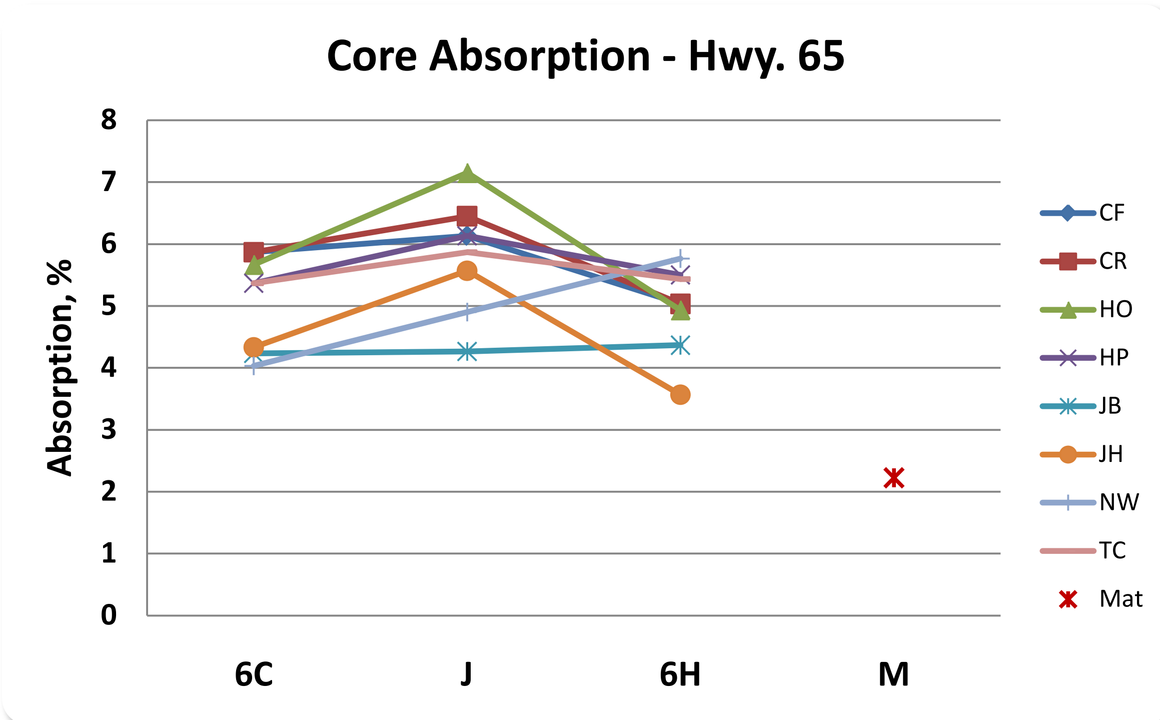


FIGURE 41 Phase 2 Absorption Summary of Results – Hwy. 65.

For the Hwy. 167 project, absorption computations yielded values of approximately 1.5 percent for most specimens at the 6H distance, but higher values were obtained at the J and 6C distances. The joint stabilizer (JB) and joint heater (JH) methods were most successful at limiting absorption at the joint, while the hot overlap (HO) method was least successful. For the Hwy. 65 project, average absorption values were close to 6 percent at the joint, and approximately 5 percent for tests performed away from the joint. Absorption values were slightly higher on the cold side than the hot side of the joint, and the hot side more nearly matched that of the mat values. The joint stabilizer (JB), joint heater (JH), and notched wedge (NW) were most able to limit absorption at the joint, while the hot overlap (HO) method was unsuccessful.

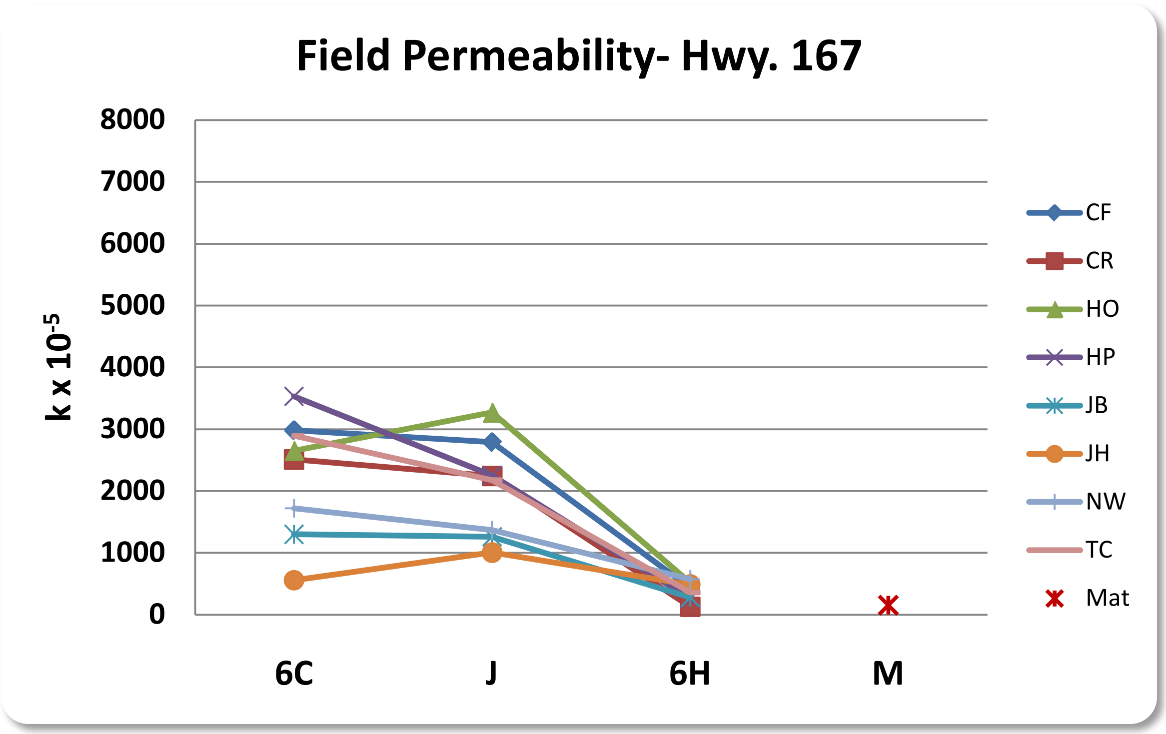


FIGURE 42 Phase 2 Permeability Summary of Results – Hwy. 167.

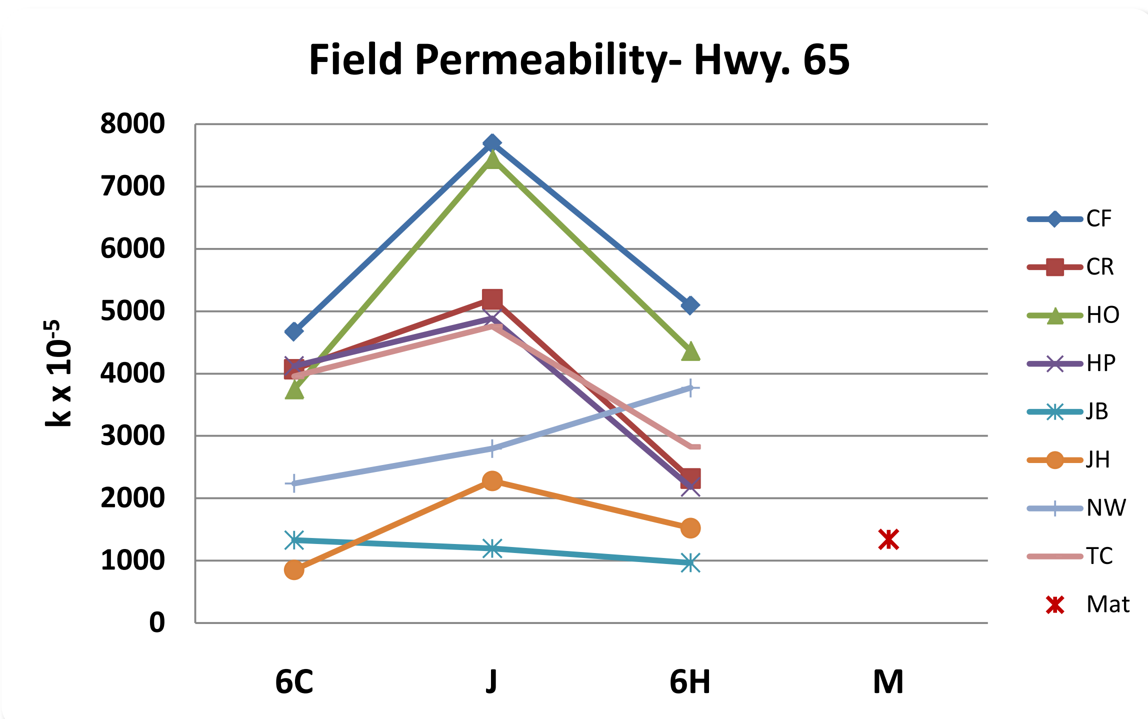


FIGURE 43 Phase 2 Permeability Summary of Results – Hwy. 65.

Field permeability results indicated a more varied performance among the various joint construction methods than most other parameters, especially for the Hwy. 65 project. Permeability values were lower and more consistent for the Hwy. 167 project than the Hwy. 65 project. Overall, the joint stabilizer (JB), joint heater (JH), and notched wedge (NW) methods were the best performers, creating joints with levels of permeability that were fairly similar to that away from the joint. Larger deviations were present for the joint adhesive (CF), cold roll (CR), hot overlap (HO), and hot pinch (HP) methods. Permeability on the hot side of the joint was closer to the mat permeability, particularly for the Hwy. 167 project. For Hwy. 65, the joint stabilizer (JB) and joint heater (JH) methods most nearly approximated the permeability values exhibited for the mat.

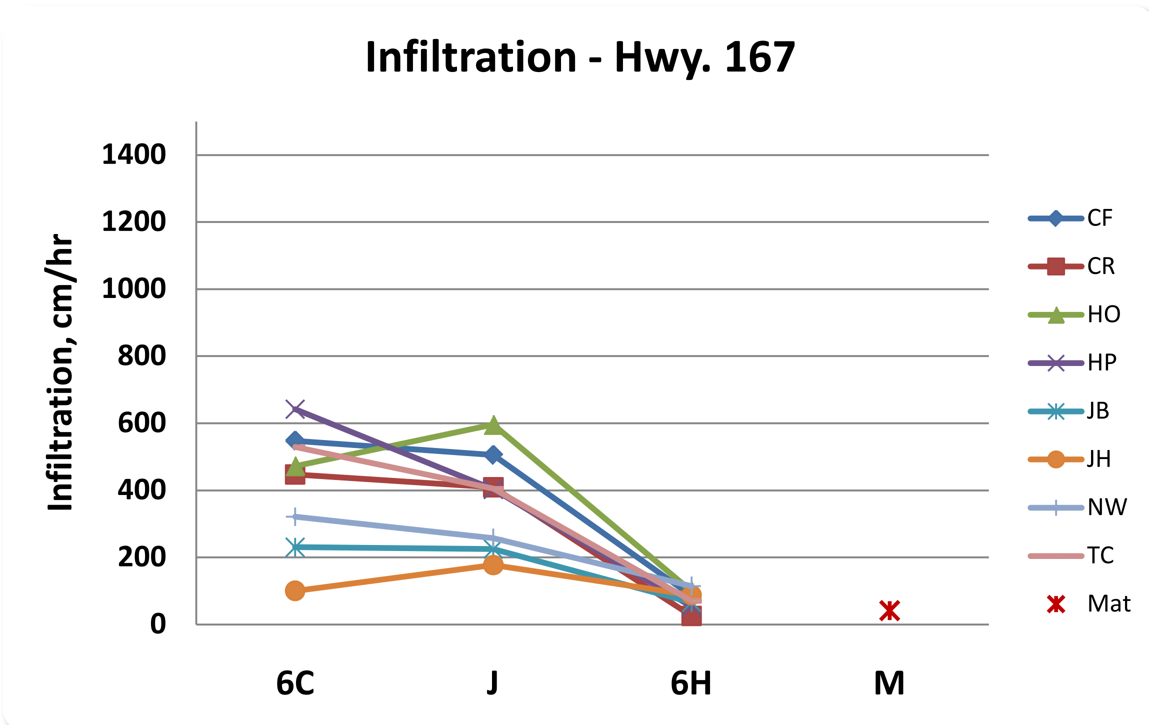


FIGURE 44 Phase 2 Infiltration Summary of Results – Hwy. 167.

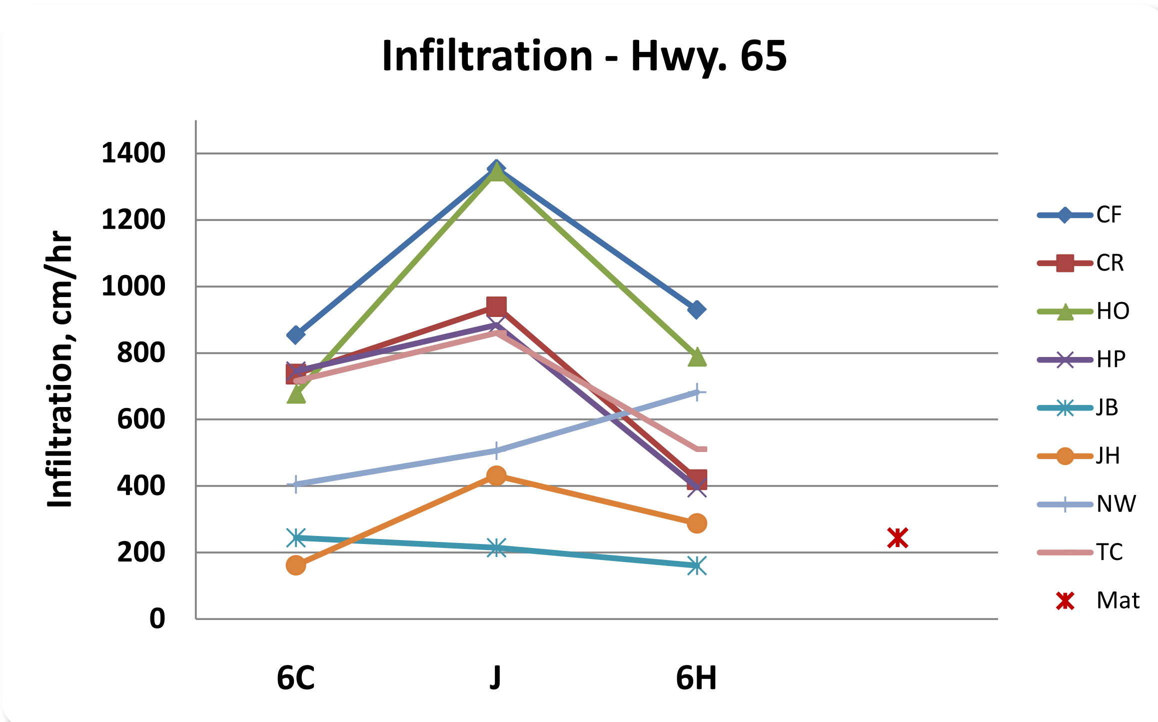


FIGURE 45 Phase 2 Infiltration Summary of Results – Hwy. 65.

Infiltration results were very similar to permeability results, which is reasonable given the fact that infiltration is simply another way to represent the same type of information. Again, the Hwy. 167 project exhibited lower levels of infiltration, especially on the hot side of the joint where values were similar to that of the mat. The joint stabilizer (JB), joint heater (JH), and notched wedge (NW) methods were the better performers, while the joint adhesive (CF) and hot overlap (HO) methods were least successful.

Statistically, the test results were analyzed using analysis of variance (ANOVA) and means tests to determine which test methods were most able to discern significant differences between the various joint construction techniques, as well as differences in properties at the various distances from the joints, while also accounting for differences inherent among the two projects. In selecting a tool for QC/QA purposes, it is important that the test method chosen is capable of detecting differences in properties when differences truly exist. Thus the methods detecting the greatest number of significant differences would be most advantageous in QC/QA efforts. A summary of p-value results from the ANOVA is shown in Table 24. A p-value of less than α indicates significance. In all cases, α was taken to be 0.05.

TABLE 24 Summary of ANOVA for Effects of Construction Technique and Distance from Joint

	p-values describing the significance of factors for each test parameter					
	Nuclear Density	Density by T166	Density by T331	Absorption	Permeability	Infiltration
Method	**<0.0001**	**.0049**	**0.0009**	**0.0001**	**<0.0001**	**<0.0001**
Distance	**<0.0001**	**<.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Method*Dist	0.5698	0.6180	0.6396	0.3300	**0.0338**	**0.0288**

In every case, the method used to construct the joint was found to significantly affect the test results. Also, distance from the joint significantly affected all responses. This means that all test methods were able to discriminate between various levels of each response, and that all methods have merit and warrant further investigation as a QC/QA tool for longitudinal joint quality. For permeability and infiltration, the interaction of method and distance was significant. This interaction showed that for these two responses, method and distance were interrelated. Specifically, the joint stabilizer (JB) and joint heater (JH) methods produced low permeability values at and away from the joint, while the other methods indicated high permeability and infiltration at the joint, but lower values away from the joint.

The next step was to evaluate which of the methods and distances displayed statistical significance. Using a means test, methods and distances were analyzed. Results are displayed in Table 25, indicating the mean and rank for each. Brackets are used to group methods having a lack of statistically significant differences (i.e., similarities) between those methods. In some cases, similarities were the result of mean values that were very close in magnitude. In other cases, the spread of the data (i.e., variation of the parameter) was large enough to mask potential differences. In general, the nuclear density, permeability, and infiltration tests showed the least overlap in groupings, and were most able to differentiate between varying levels of quality. With the exception of the T331 density measure, the joint stabilizer (JB), joint heater (JH), and notched wedge (NW) methods were consistently ranked as superior performers. None of the rolling patterns showed exemplary performance. Therefore, additional measures may be necessary during construction to create high quality joints.

Regarding proximity to the joint, the rankings followed the expected trend with the mat having the best performance (i.e., highest densities and lowest absorption, permeability and infiltration). The joint cores had the weakest performance (i.e., lowest densities and highest absorption, permeability and infiltration). As expected, cores cut from the hot side of the joint were generally better performers than those cut from the cold side. For all response parameters except nuclear density, statistically significant differences were noted for all distances, meaning that proximity to the joint was clearly differentiated. For nuclear density, the 6H and 12C samples were similar, as were the 6C and J samples. Because a significant change in quality existed at distances of just 6 inches from the joint, areas of poor density or permeability may not be detected if a test is performed near the joint rather than on the joint. For this reason, joint quality testing should be performed directly on the joint.

TABLE 25 Summary of Construction Method and Distance Rankings by Response Parameter

Nuclear Density (%)	T166 Density (%)	T331 Density (%)	Absorption (%)	Permeability (cm/s x 10^{-5})	Infiltration (cm/hr)
JH 91.0	JH 90.5	JH 88.2	JB 2.72	JB 815	JB 147
NW 90.8	JB 90.0	NW 86.7	JH 2.84	JH 880	JH 166
JB 90.2	NW 89.8	HO 86.1	NW 3.60	NW 1774	NW 326
CR 89.9	HO 89.7	TC 85.9	CR 3.77	TC 2192	TC 401
HP 89.8	CR 89.6	CR 85.5	CF 3.78	CR 2232	CR 409
TC 89.8	TC 89.4	CF 85.3	HO 3.84	HP 2502	HP 453
HO 89.5	HP 89.2	HP 85.1	TC 3.93	CF 3074	CF 557
CF 88.4	CF 88.9	JB 82.9	HP 4.23	HO 3257	HO 591
M 92.4	M 92.6	M 89.7	M 1.36	M 748	M 143
12H 91.2	6H 90.1	6H 86.4	6H 3.29	6H 1630	6H 299
6H 90.1	6C 88.3	6C 84.0	6C 4.44	6C 2696	6C 490
12C 89.6	J 87.6	J 82.7	J 5.27	J 3288	J 595
6C 88.2					
J 88.1					

CF=Joint Adhesive, CR=Cold Roll, HO=Hot Overlap, HP=Hot Pinch, JB=Joint Stabilizer, JH=Joint Heater, NW=Notched Wedge, TC=Tack Coat

Indirect Tensile Strength

Another measure that was added to the testing matrix was indirect tensile strength. In this procedure, the core sample is loaded in compression in a manner that creates failure in tension. This testing scenario is shown in Figure 46.

(a)

(b)

FIGURE 46 Indirect Tensile Strength (a) during testing and (b) after testing.

Although indirect tensile strength is not necessarily believed to be a fundamental measure of joint performance, the degree to which the hot and cold sides of the joint bond could be an indicator of quality. The results of the indirect tensile tests are given in Figures 47 and 48. Specimens were tested for indirect tensile after being tested for laboratory measures of density. No conditioning procedures or freeze/thaw cycles were used.

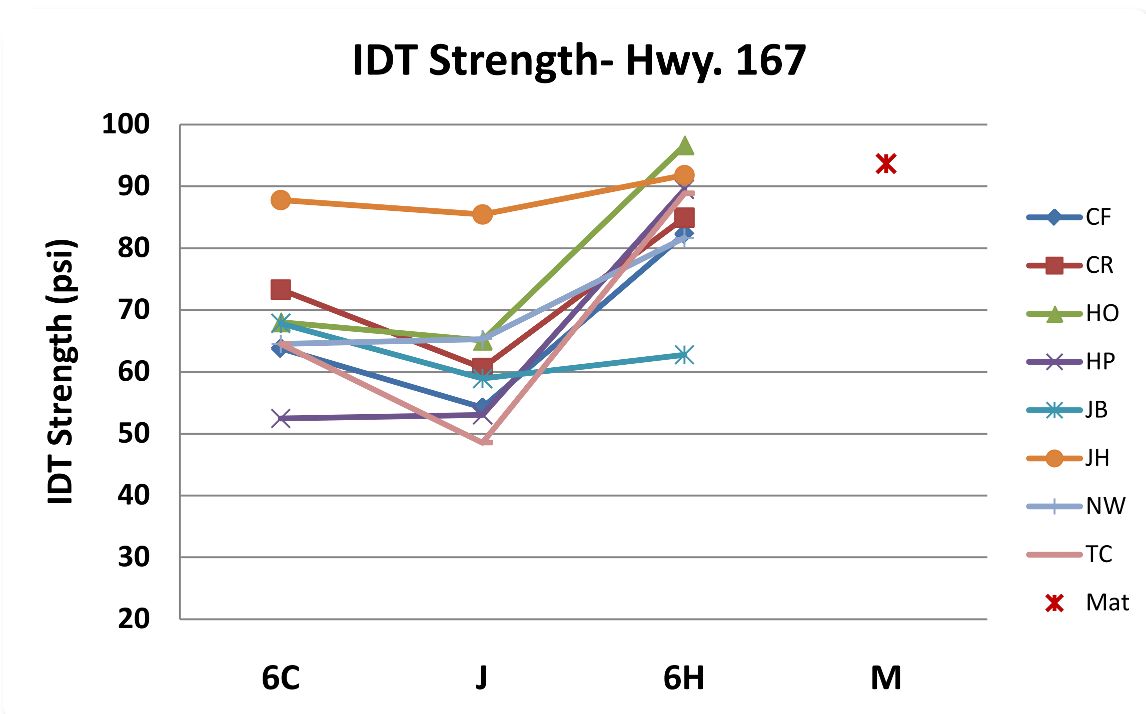


FIGURE 47 Phase 2 Indirect Tensile Strength Summary of Results – Hwy. 167.

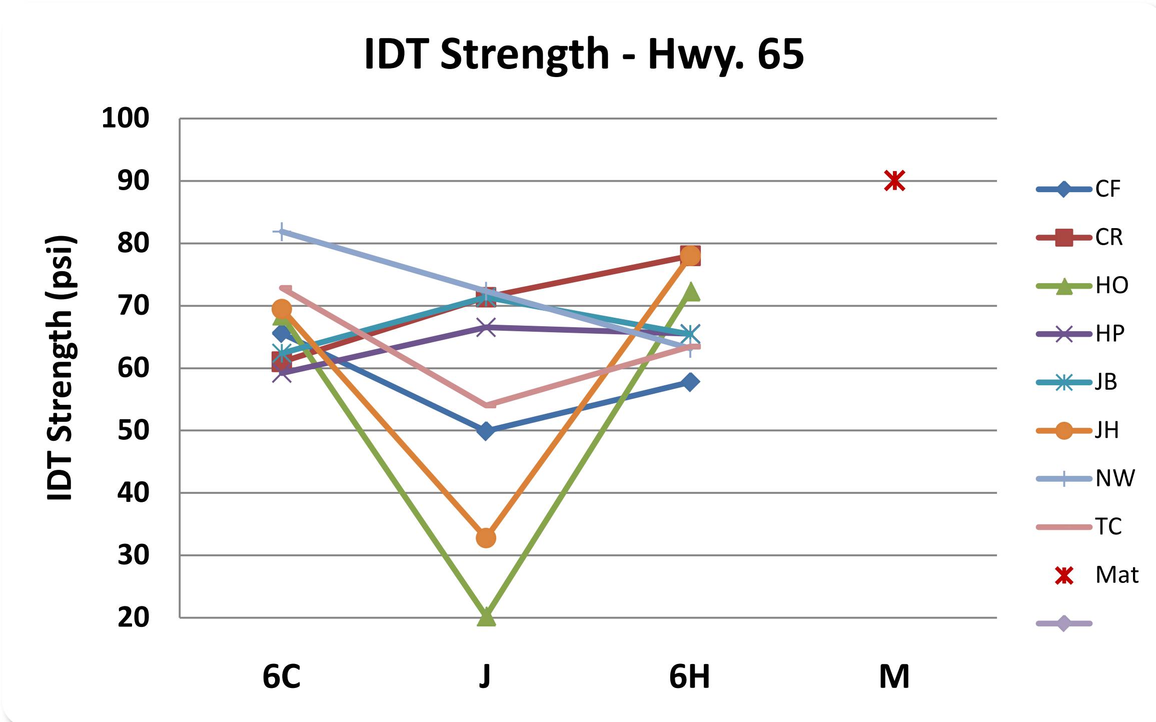


FIGURE 48 Phase 2 Indirect Tensile Strength Summary of Results – Hwy. 65.

In general, the tensile strengths of cores taken at the joint were not as great as for those taken away from the joint where a more homogeneous mixture was present. In general, the strengths of cores taken from the hot side of the joint were greater than that from the cold side of the joint. For the Hwy. 167 project, the joint heater (JH) method was clearly superior to the other methods, while the tack coat (TC) and hot pinch (HP) methods did not perform as well. For the Hwy. 65 project, the notched wedge (NW), cold roll (CR), joint stabilizer (JB), and hot pinch (HP) methods were best, while the joint heater (JH) and hot overlap (HO) methods displayed lesser strengths, particularly at the joint.

Discussion of Construction Techniques

In general, the joint heater (JH), joint stabilizer (JB), and notched wedge (NW) methods were the most successful at limiting the potential for deterioration at the longitudinal joint. This was evident for both the density-related responses and the water-related responses. In terms of density, some of the methods could be reasonably expected to significantly affect density (i.e., joint heater and notched wedge) because the very nature of the techniques involved additional efforts to increase density. Other methods, such as the application of joint adhesives, serve primarily to seal the joint without seeking to affect the actual density. Interestingly, the JointBond® (JB) product appeared to both increase density and decrease permeability, though the method of application did not intuitively cause the anticipation of an increase in density.

According to the 2003 AHTD Construction Specification, the hot pinch (HP) method is specified as the required joint rolling technique. Thus, a comparison of the ability of each technique to affect the responses with respect to that of the traditional, or hot pinch (HP) method, is given in Table 26.

TABLE 26 Average Difference in Responses for Techniques as Compared to Hot Pinch (HP) Method

Method	Nuclear Density (%)	T166 Density (%)	T331 Density (%)	Absorption (%)	Permeability (cm/s x 10^{-5})	Infiltration (cm/hr)
Joint Adhesive (CF)	-2.9	-1.2	-2.3	0.1	1672	286
Cold Roll (CR)	0.7	0.0	0.1	-0.2	147	31
Hot Overlap (HO)	-0.9	-0.2	-0.8	0.5	1789	328
Joint Stabilizer (JB)	1.1	1.0	-2.0	-1.7	-2340	-424
Joint Heater (JH)	1.8	1.5	3.3	-0.9	-1927	-339
Notched Wedge (NW)	2.3	0.6	2.6	-0.9	-1485	-261
Tack Coat (TC)	0.1	-0.9	-0.6	0.3	-103	-11

In terms of nuclear density, all techniques except the joint adhesive (CF) and hot overlap (HO) were effective in increasing in-place density over that of the hot pinch (HP) method, with the greatest average increase of 2.3 percent being achieved by the notched wedge (NW) method. For density of cores tested by AASHTO T166, the joint stabilizer (JB), joint heater (JH), and notched wedge (NW) were able to provide greater densities than the traditional hot pinch (HP) method, with the greatest increase of 1.5 percent being produced by the joint heater (JH). The joint adhesive (CF), hot overlap (HO), and tack coat (TC) methods were not as effective as the hot pinch (HP), while the cold roll (CR) method produced the same average core density. Core densities measured by the vacuum sealing method produced similar results, with the joint heater (JH) generating the highest average density. The exception was that the joint stabilizer (JB) provided lower densities when tested by the vacuum sealing method.

The water-related responses generated similar results, with the joint stabilizer (JB) being the most effective at reducing absorption, permeability, and infiltration levels, followed by the joint heater (JH) and notched wedge (NW) techniques. The joint adhesive (CF) and hot overlap (HO) were least effective, and the cold roll (CR) and tack coat (TC) techniques were similar to the hot pinch (HP).

Overall, the joint adhesive (CF) method, intended to seal the joint, did not perform as well as expected. It was reasonable that density results did not improve over traditional methods, but it was anticipated that permeability would; however, this was not the case. Upon further investigation, it was surmised that the product may have reduced permeability in the finite area of application, but did not positively affect the surrounding material. Density and permeability results from Phases 1 and 2 indicate that decreased density and increased permeability are not limited to the joint, but may also exist near the joint where the Crafco product was not placed. Thus, water could have ‘short-circuited’ the immediate area protected by the joint sealant, as shown in Figure 49. Since the field permeability test involves a six-inch diameter test area and not just the joint face, the joint adhesive (CF) method was unable to demonstrate a decrease in permeability for the entire joint area.

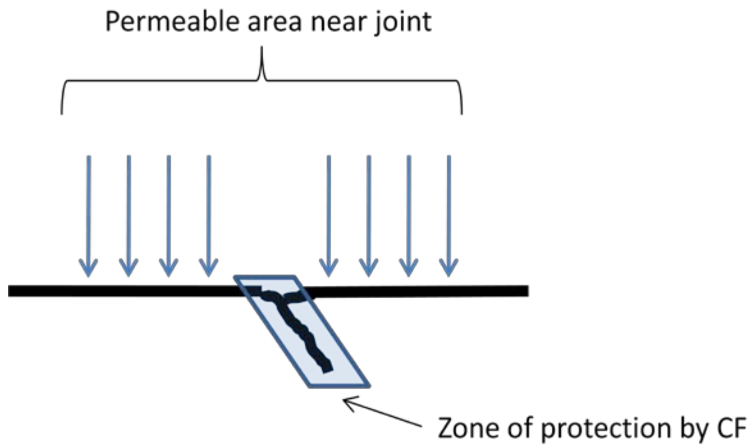


FIGURE 49 Diagram of CF Performance Area and Permeable Area.

Applying tack coat to the joint did not significantly improve joint performance. It is expected that the limited area in which permeability may be affected is subject to the same phenomenon as the joint adhesive (CF) method.

As previously stated, rolling patterns used without additional efforts to improve joint quality were not the best performers in the study. This suggests that when joint quality needs improvement, a simple change in the rolling technique will likely not suffice. Of the rolling techniques investigated, the hot pinch (HP) and cold roll (CR) methods were the better performers, while the hot overlap (HO) method was less effective.

Relationships of Testing Methods

When considering the various methods that can be used to measure the quality of longitudinal joints, each has advantages and disadvantages. The nuclear density method is capable of generating a large number of density measurements in a short time frame and in a non-destructive manner, but the accuracy of the readings is dependent upon the quality of the correction factor. In most cases, the correction factor is determined by a comparison with core density values measured by the T166 method, which carries its own difficulties in accurately measuring specimens with higher void contents. The vacuum sealing method may be able to more accurately detect the lower density values, but is less precise than the SSD method.

As previously stated, density is the most prominent measure of in-place HMA pavement quality, although a measure that describes the ability of water and air to enter the pavement structure provides a more fundamental indication of the potential for typical joint distresses. The data presented in this study suggest that the permeability and infiltration tests do, in fact, provide adequate discrimination for levels of varying quality. The primary disadvantage of these measures are that the test methods are somewhat labor intensive, and are not currently included in most QC/QA programs. Thus, it would be advantageous to determine what commonalities exist between parameters, and whether density could be used to adequately describe absorption, permeability or infiltration. These relationships are presented in Figures 50 - 52.

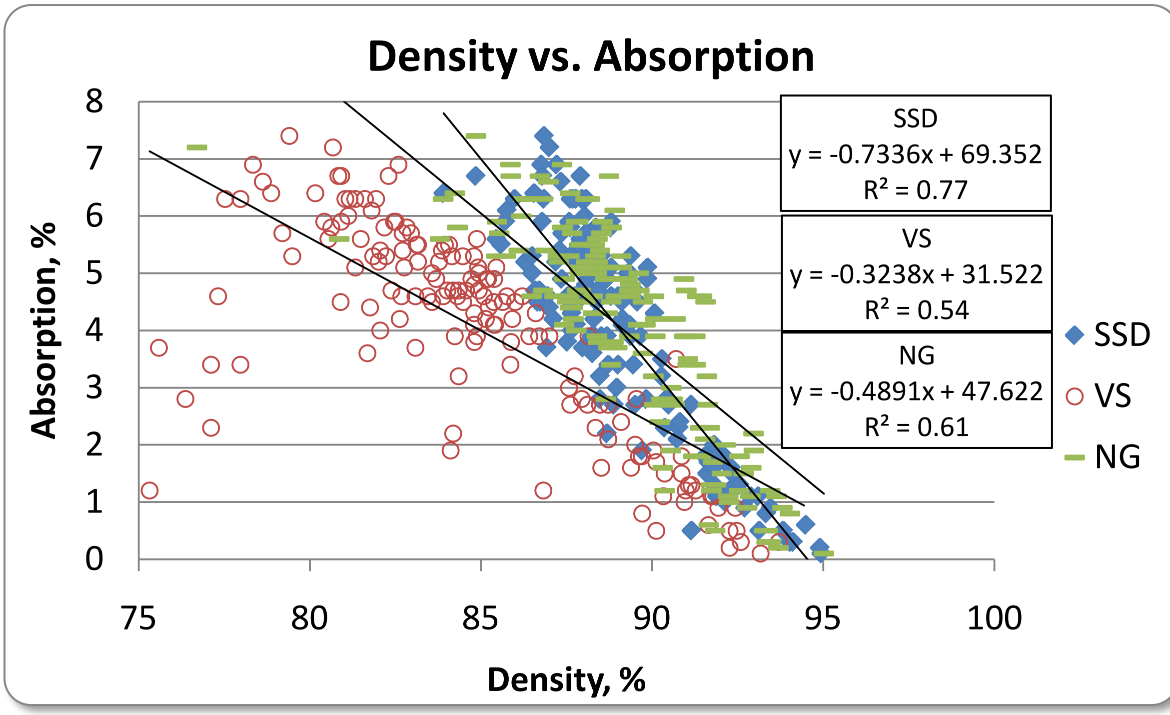


FIGURE 50 Relationship of Density and Absorption for the SSD, Vacuum Sealing, and Nuclear Methods.

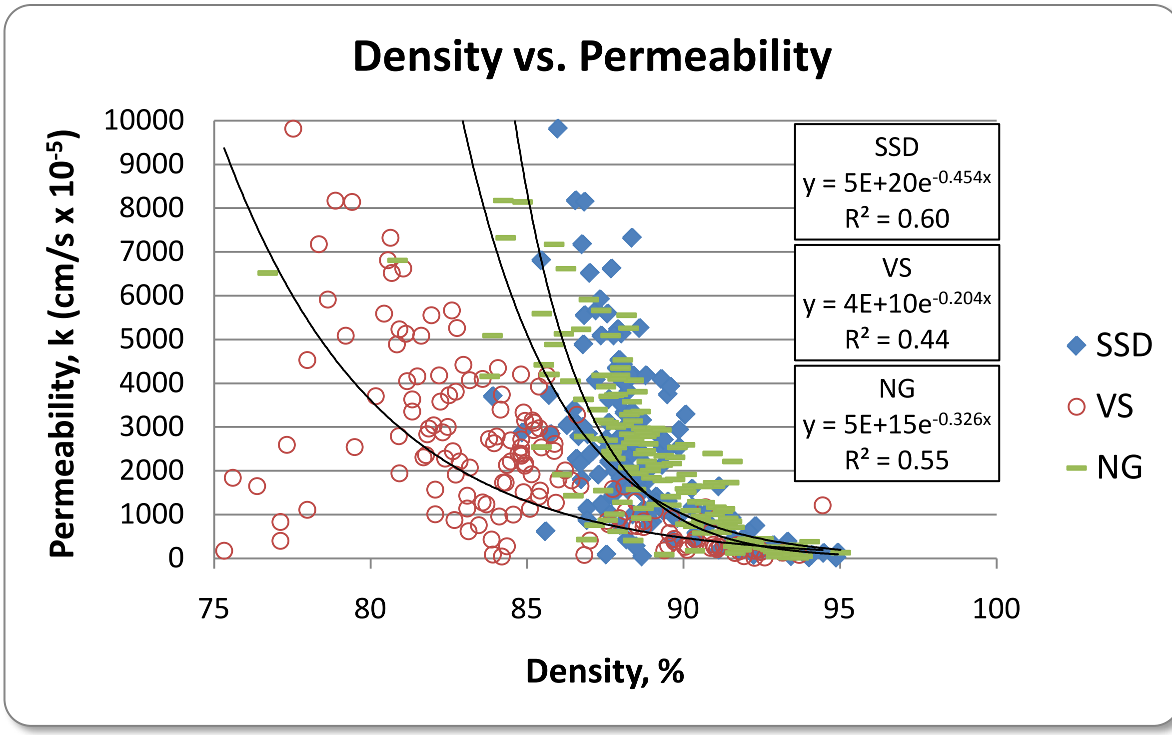


FIGURE 51 Relationship of Density and Permeability for SSD, Vacuum Sealing, and Nuclear Methods.

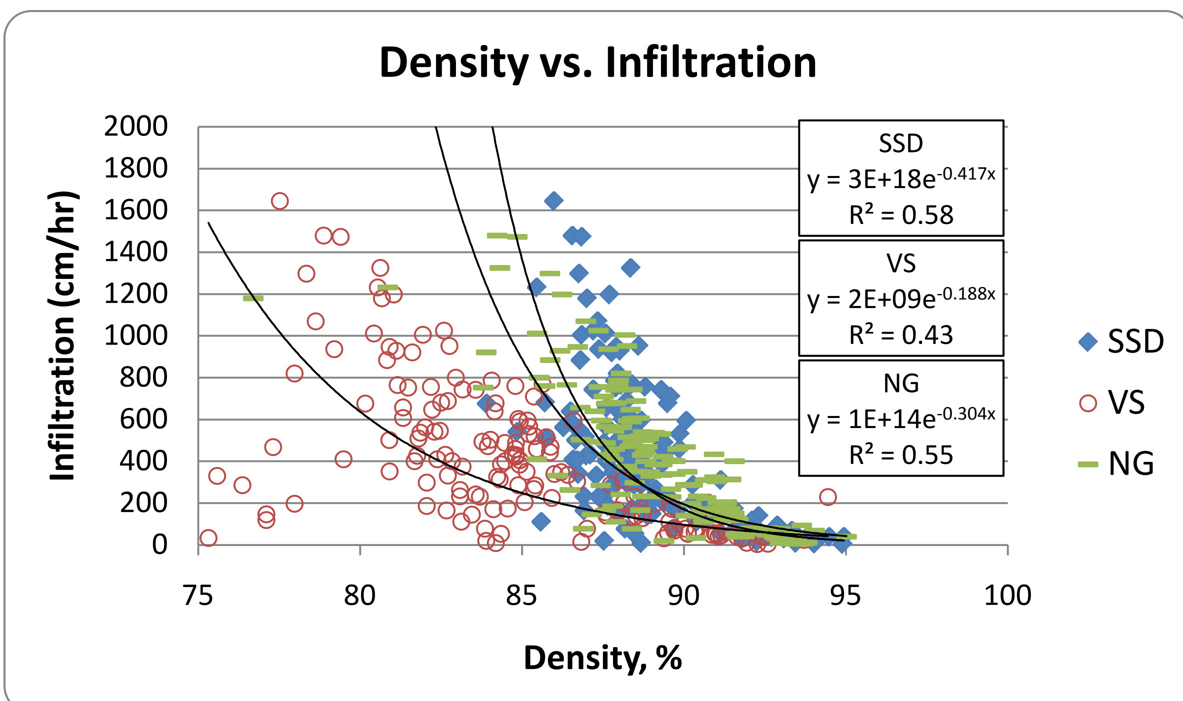


FIGURE 52 Relationship of Density and Infiltration for the SSD, Vacuum Sealing, and Nuclear Methods.

In general, absorption decreased with increasing density, and the relationship was most nearly linear. The relationship of absorption to density by the SSD method provided the strongest relationship (R^2 = 0.77), which is reasonable since absorption values are calculated based on measurements recorded during the SSD test procedure. According to AASHTO T166, the paraffin coating method should be used to more accurately determine density when the absorption values exceed 2 percent. Absorption values of 2 percent related to approximately 91 percent density, and at low absorption levels, there was fair agreement among the various measures of density. As density decreased, the values began to deviate, with a considerable amount of scatter for the vacuum sealing method. Although the relationship between absorption and density by the nuclear gauge was relatively weak (R^2 = 0.61), the practical advantages of this method may outweigh its lack of precision.

The exponential relationships of density and permeability were fairly weak; however, a definite trend of increasing permeability with decreasing density was evident. It was also noted that the lowest values of permeability occurred most consistently at density levels of 92 percent or greater. Similar trends were evident for the relationship of density and infiltration.

Upon further inspection of the density and permeability / infiltration relationships, natural groupings of data appeared to separate the data into three levels of quality. Specifically, the relationship of nuclear density and infiltration is highlighted in Figure 53. Most highway QC/QA specifications require a minimum in-place mat density of 92 percent. For density values greater than 92 percent, the infiltration values are limited to approximately 100 cm/hr. Another natural break in the data occurred at approximately 89 percent density. Coincidentally, for states that currently have a joint density requirement, this value is typically 2 to 3 percent less than that required for the mat (i.e., 89 to 90 percent). This indicates that good mat quality could be described by the corresponding limits of 92 percent minimum density and 100 cm/hr maximum infiltration. Acceptable joint quality could be described as a minimum of 89 percent density and a maximum of 500 cm/hr infiltration. Densities below 89 percent and infiltration values greater than 500 cm/hr would indicate poor quality.

Absorption could also be used as a QC/QA tool, especially in cases where T166 is already routinely used. A density of 92 percent and an infiltration rate of 100 cm/hr corresponded with approximately 2 percent absorption, whereas a density of 89 percent and infiltration rate of 500 cm/hr corresponded with approximately 4 percent absorption when density was measured by the SSD or NG methods. Although it may be desirable in concept to require that joints meet the same requirements as the mat, it is generally accepted that joint quality may be slightly less than that of the mat. Therefore, the limits expressed herein are believed to be reasonable.

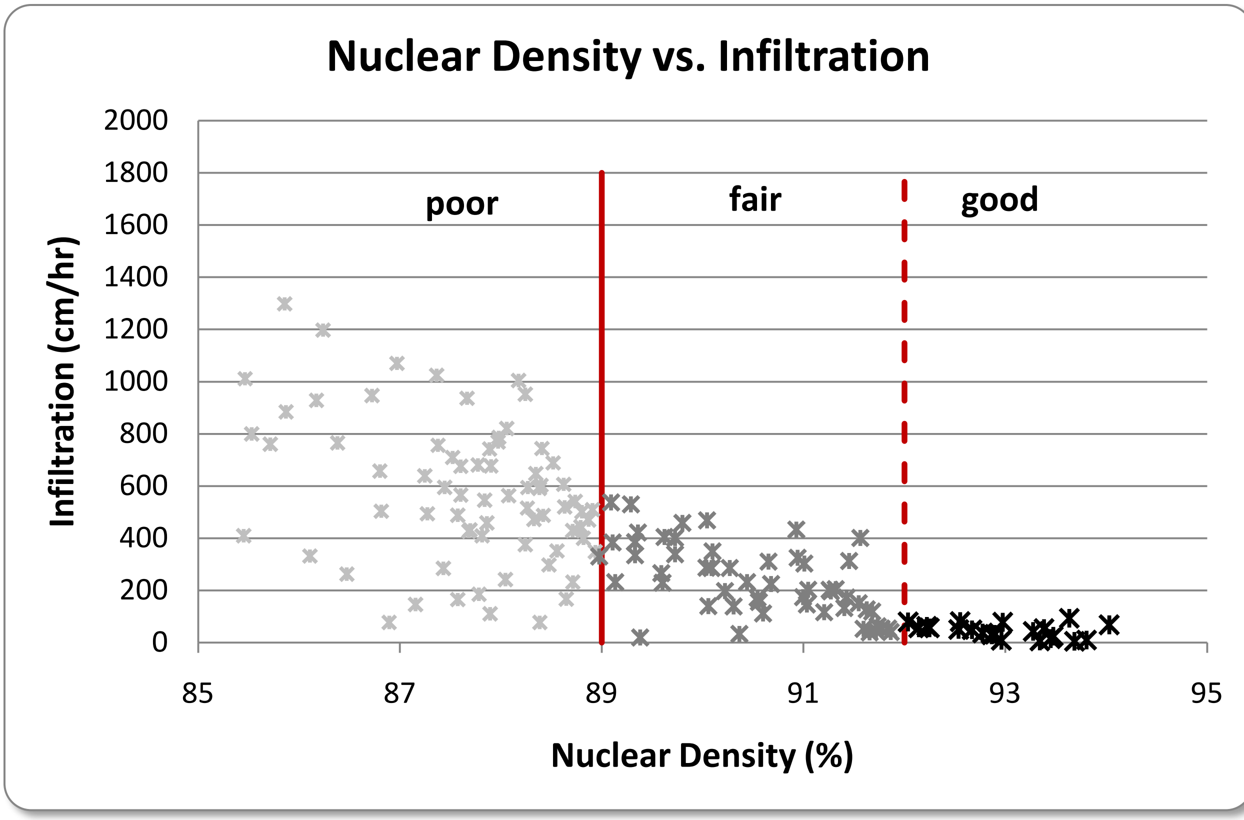


FIGURE 53 Ranges of Quality Based on Nuclear Density and Infiltration.

Phase 2 Conclusions

When implementing an appropriate method for measuring longitudinal joint quality in HMA pavements, the method must be able to distinguish between varying levels of quality, must be related to the potential for applicable pavement distresses, and must be feasible for incorporation into the existing quality system. The data collected in this study was intended to provide a basis for decisions relative to the implementation of a longitudinal joint quality specification.

In Phase 2 of this study, 8 longitudinal joint construction techniques were assessed for two construction projects using performance parameters relating to density and permeability. Testing was performed at the longitudinal joint, on the hot and cold sides of the joint, and in the central portion of the compacted mat. General conclusions include:

- In general, the joint heater (JH), joint stabilizer (JB), and notched wedge (NW) methods consistently demonstrated superior performance as measured by density, absorption, permeability, and infiltration. Traditional rolling techniques and joint adhesives were not as successful in producing similar quality at and away from the joint.
- In terms of distinguishing between varying levels of quality produced by the various joint construction techniques, the nuclear density gauge, permeability, and infiltration parameters

(tested in the field) were better able to discriminate than absorption or core density by the SSD and vacuum sealing methods (tested in the laboratory).

- All testing methods were capable of discerning significant differences in quality relating to proximity to the joint. Significant differences in quality were consistently identified at a distance of only 6 inches from the joint.
- Fairly strong relationships were developed between the various quality measures. Of the three density measures, the SSD method consistently provided the strongest relationship to absorption, permeability, and infiltration.
- For the relationship of density and permeability / infiltration, natural groupings of infiltration data were segmented at 92 and 89 percent density, suggesting that these minimum density values are appropriate specification limits. These values also correlate with 2 percent and 4 percent absorption, respectively.

Although permeability and infiltration provide a more fundamental description of the potential for the distresses typical of a longitudinal joint, density measurements are already commonly used for QC/QA purposes. Because the relationships of density, absorption, permeability, and infiltration are consistently and adequately defined, it is recommended that longitudinal joints possess a minimum of 89 percent density measured by the nuclear gauge or AASHTO T166, and no more than 4 percent absorption as measured by T166. If T331 is used, provisions must be made to account for the differences in measured density. These values correspond with permeability and infiltration values that are consistent and appropriate for producing quality longitudinal joints.

No specific recommendation is made regarding a mechanism for specifying the particular construction technique that should be used to form longitudinal joints. In many cases, good construction practices may be sufficient to produce quality joints. However, if additional steps are desired to improve quality, the methods that provided the greatest benefit in this study were the joint heater, the joint stabilizer, and the notched wedge.

Recommendation for Specification

Based on the results of this study, it is recommended that a joint density specification be included in the AHTD Construction Specification, and that applicable sections be edited to include the following language. Until the Specification is implemented, it would be beneficial to implement these procedures as a Special Provision (SP) on upcoming overlay projects for information only. Thus, any unanticipated problems with the procedures could be addressed prior to inclusion in the Standard Specification.

404.04 Quality Control of Asphalt Mixtures. The Contractor shall perform all applicable quality control sampling and testing of the asphalt mixtures used on the project.

. . . . .

Sampling shall be performed according to AASHTO T 168 and AHTD 465, except that the number and locations for sampling shall be as specified in this subsection and in Subsection 410.09. Test methods shall be as shown below:

Property	**Test Method(s)** (NOTE 1)
Aggregate Gradation	AASHTO T 30, AHTD 460, or AASHTO T 308 1 per 750 metric tons (750 tons) minimum
Asphalt Binder Content (NOTE 4)	AHTD 449/449A or AASHTO T 308
Stability	AASHTO T 245
Air Voids (AV) (NOTE 2)	AASHTO T 269
Voids in Mineral Aggregate (VMA)	AHTD 464
Density – Maximum Theoretical	AASHTO T 209
Density (Field)	AASHTO T 166 or AHTD 461
Density of Longitudinal Joints (Field)	AASHTO T 166 or AHTD 461
Water Sensitivity (NOTE 3)	AHTD 455A
Wheel Tracking Test	AHTD 480

. . . . .

405.05 Construction Requirements and Acceptance. Construction requirements and acceptance shall conform to the requirements of Section 410. The required mat density shall be 92% to 96% of the maximum theoretical density. The required joint density (measured directly on, and centered over, the joint) shall be 89% to 96% of the maximum theoretical density. The required density for ACHM Base Course placed in trench areas less than 6' (1.8 m) in width at levels below the existing pavement surface shall be 90% to 96%.

406.04 Construction Requirements and Acceptance. Construction requirements and acceptance shall conform to the provisions of Section 410. Joint densities shall be measured directly on, and centered over, the joint. When Binder is placed on the shoulders constructed under Section 216 or on reconstructed base course under Section 216 or on reconstructed base course under Section 305, the minimum density shall be 90% of the maximum theoretical density. The required density for ACHM Binder Course placed in trench areas less than 6' (1.8 m) in width at levels below the existing pavement surface shall be 90% to 96%.

407.04 Construction Requirements and Acceptance. Construction requirements and acceptance shall conform to the provisions of Section 410. Joint densities shall be measured directly on, and centered over, the joint. When Surface is placed on the shoulders constructed under Section 216 or on reconstructed base course under Section 216 or on reconstructed base course under Section 305, the minimum density shall be 90% of the maximum theoretical density. The required density for ACHM Surface Course placed in trench areas less than 6' (1.8 m) in width at levels below the existing pavement surface shall be 90% to 96%.

410.07 Spreading and Finishing. The mixture from all types of plants shall be delivered to the paver at no more than 25°F (14°C) above the mixing temperature shown on the approved mix design. In no case shall binder or surface course be placed at a temperature less than 250°F (125°C).

The mixture shall be placed on an approved surface, spread, and struck off to the line, grade, and elevation established. The mixture shall be placed only on a base that shows no evidence of free moisture, and only when weather conditions are suitable. The Engineer may, however, permit work of this character to continue when overtaken by sudden rains to utilize materials that may be in transit from the plant at the time, provided the mixture is within the temperature limits specified and provided the finished pavement otherwise meets specification requirements. Water shall not be applied to the ACHM courses to speed cooling of the mat.

The longitudinal joint in one layer shall offset that in the layer immediately below by approximately 6" (150 mm), however, in general, the joint in the top layer shall be at the centerline of the pavement if the roadway comprises two lanes in width, or at lane lines if the roadway is more than two lanes in width. On roadways with a center turn lane, the Contractor may, at his option, elect to place a joint at the crown (i.e., middle of the center turn lane) of the roadway and eliminate the joints on the lane lines of that lane. The slight excess of asphalt at a longitudinal joint, generated by overlapping during placement of an adjacent mat to a previous mat shall not be scattered across the mat. This material shall be stacked over the joint. ~~The first pass of the steel wheel roller shall be entirely on the new mat, with the edge of the drum 6" (150 mm) away from the longitudinal joint. The second pass of the steel wheel roller shall be made with 6" to 8" (150 mm to 200 mm) of the drum overhanging onto the older mat.~~

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410.08 Rolling and Density Requirements and Joints. At the beginning of placement of each mix design, the Contractor shall establish an optimum rolling pattern for the mix being placed. A strip of approximately 500' (150 m) of the mat being placed shall be used to establish the rolling pattern. A sufficient number of coverages of the entire mat by the rollers proposed to be used by the Contractor during production paving operations shall be made to achieve the maximum density possible. The Engineer will observe the Contractor's use of a nuclear density gauge to verify that the maximum densities possible are obtained.

The established rolling pattern shall be used for compacting all mix placed. If a change in the accepted mix design occurs, or if the compaction method or equipment is changed, or if unacceptable results are obtained, a new optimum rolling pattern shall be established.

If for any reason a rolling pattern cannot be established to produce the specified density, a new mix design will be required. The Contractor shall establish an optimum rolling pattern that will produce the maximum density using the new mix design. Continuous production of the mix shall not begin until an optimum rolling pattern that produces the specified density within the allowable range has been established.

Rolling shall start longitudinally at the low edge and proceed toward the higher portion of the mat. When paving in echelon or abutting a previously placed lane, the longitudinal joint shall be rolled first followed by the ~~regular~~ established rolling procedure. Alternate passes of the roller shall be terminated at least 3' (1 m) from any preceding stop. Rolling on superelevated curves shall progress from the low side. Rollers shall not be stopped perpendicular to the centerline of the traveled way.

The speed of the roller shall be slow enough to avoid displacement of the hot mixture, and shall in no case be more than 3 mph (5 km/h). The roller shall be operated in such a manner that no displacement of the mat will occur. Rolling shall proceed continuously until all roller marks are eliminated and the required density attained. To prevent adhesion of the asphalt mixture to the rollers, the rollers shall be kept moist for the full width of the rollers, but an excess of water will not be permitted.

Upon completion of the rolling operations, the surface shall be smooth and of uniform texture.

If the asphalt binder content varies from the value used to calculate the specific gravity, the maximum theoretical density will be adjusted accordingly. If the Contractor elects to verify the specific gravity or to establish a different specific gravity, he shall perform the test under AASHTO T 209 on production mix and furnish the results to the Engineer. The Contractor and the Engineer will use the specific gravity that best represents the material that is being sampled for acceptance of the pavement. If either quality control or acceptance density tests indicate that the established maximum theoretical density may be in error, the Engineer may require that the specific gravity be redetermined from the production mix. If production has been interrupted for 90 calendar days or the mix design has changed a new maximum theoretical density shall be established. When the material forming the two sides of a longitudinal joint comes from two different sublots, the theoretical maximum density used as a basis for density calculations shall be the average of the theoretical maximum density for the two sublots.

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410.09 Acceptance of the Pavement and Adjustments in Payment. (a) General. The accepted mix design shall be verified by the Contractor at the start of mix production for that design or after an interruption of more than 90 calendar days.

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Acceptance and adjustment in payment will be by lot. The standard lot size for acceptance and adjustment in payment will be 3000 tons (3000 metric tons), with each standard lot divided into four sublots of 750 tons (750 metric tons) each. For longitudinal joint density testing, the standard lot size for acceptance and adjustment in payment will be 12,000 linear feet (3600 meters), with each standard lot divided into four sublots of 3000 linear feet (900 meters) each. These lengths will apply only to areas in which both sides of the longitudinal joint have been formed. The Engineer may establish a partial lot at any time. The Engineer will determine the size of any partial lots established and the number and size(s) of the sublots, if any. Although there are no specified limits for the size of such partial lots, they normally will be not less than 300 tons (300 metric tons) nor more than 3300 tons (3300 metric tons). For longitudinal joint density tests, partial lots normally will be not less than 1200 linear feet (360 meters) nor more than 13,200 linear feet (4000 meters). Field density test shall be performed on the compacted mat on the roadway as soon as possible, preferably not later than the day after placement. Field density tests on longitudinal joints shall be performed directly on the joint as soon as possible after placement of the hot lane, preferably not later than the day after placement.

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TABLE 410-1 (applicable portions only)

Property	Compliance Limits	Price Reduction Limits	Lot Rejection Limits	Sublot Rejection Limits
Density (% of theoretical) BASES, BINDER, AND SURFACES	92.0% to 96.0%	91.0% to 91.9% 96.1% to 97.0%	90.9% or less 97.1% or more	89.9% or less** 98.1% or more
Density (% of theoretical) for ACHM Courses where minimum specified is 90.0%	90.0% to 96.0%	89.0% to 89.9% 96.1% to 97.0%	88.9% or less 97.1% or more	87.9% or less** 98.1% or more
Density (% of theoretical) for longitudinal joints of BASES, BINDER, AND SURFACES	89.0% to 96.0%	88.0% to 88.9% 96.1% to 97.0%	87.9% or less 97.1% or more	86.9% or less** 98.1% or more

**Subject to further evaluation, see text.

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410.10 Incentives. It is the intent of this specification to produce a pavement that is durable and consistently exceeds the minimum test values established in these specifications. To that end, incentives will be included in the pay schedule for ACHM Binder Course and/or ACHM Surface Course. Incentive pay will be according to the following guidelines.

When the entire quantity of either the ACHM Binder Course or ACHM Surface Course meets the following criteria, and incentive of the percentage designated will be applied to the dollar amount for all the components of the designated mix. For the purpose of incentives, the only tests to be considered shall be the average test results for each lot. Incentive pavements will be accomplished by Change Order and will be shown on the final estimate as a separate item increase. An accumulated maximum 6.0% incentive payment is available as follows:

(a) An incentive payment of 3.0% will be added if:

- the asphalt binder content is within ±0.2 percentage points of the mix design value, and
- the total variation, low to high, in air voids is no more than 0.6%, with none outside of the compliance limits, and
- all mat densities fall between 92.0%* and 96.0%, and
- all joint densities fall between 89.0% and 96.0%, and

- there are no areas of segregation outside of the compliance limits as verified by testing according to Subsection 410.09(b)(3)

  *When the minimum specification density is 90.0%, this value is changed to 90.0%

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CONCLUSIONS

The quality of longitudinal joints is critical to the long-term performance of an asphalt pavement. Thus, this parameter should be considered as a part of a quality control/quality assurance program for asphalt pavements. This study was conducted in two phases. Phase 1 included an assessment of the most appropriate measures for determining quality, including density, permeability, infiltration, and gradation. The most effective measures for determining quality included the nuclear density method, the SSD and vacuum sealing methods for determining core densities, and field permeability/infiltration. These testing methods were then used in Phase 2, which involved an evaluation of various construction techniques for forming longitudinal joints, including various rolling patterns, a notched wedge joint maker, an infrared joint heater, joint sealants, and a joint stabilizer. Of the techniques used, the joint heater, joint stabilizer and the notched wedge were most adept at increasing densities and decreasing permeability. Although the various rolling methods often lacked the ability to produce acceptable quality, the hot pinch and cold roll methods exhibited better performance than the hot overlap method. The joint sealants were limited in performance due to the narrow area of effectiveness for each.

Relationships were sought among the various testing methods, and clear delineations in permeability were noted for density categories of less than 89%, 89 to 92%, and greater than 92%. These categories also corresponded with absorption values of greater than 4%, 2 to 4%, and less than 2%, respectively. Thus, measures of density, which are commonly used in QC/QA programs, can be used to effectively limit permeability at the longitudinal joint.

Based on the results of this study, it is recommended that a joint density specification be implemented such that the density of the joint (tested directly on the joint), expressed as a percentage of theoretical maximum density, shall not be less than 89%. No specific recommendation is given regarding a requirement for the methods used to obtain density at the joint, although the data contained in this report suggests that higher densities are most likely to be achieved by using the joint heater, joint stabilizer, and notched wedge methods.

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