# CONSTRUCTING HIGH-DENSITY LONGITUDINAL JOINTS TO IMPROVE PAVEMENT LONGEVITY

## Final Report

## PROJECT SPR 842

Oregon Department of Transportation

# CONSTRUCTING HIGH-DENSITY LONGITUDINAL JOINTS TO IMPROVE PAVEMENT LONGEVITY

## FINAL REPORT

## SPR 842

by

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Research Section
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Salem OR 97301

and

Federal Highway Administration
1200 New Jersey Avenue SE
Washington, DC 20590

**February 2024**

Technical Report Documentation Page

| | | |
|---|---|---|
| 1. Report No.<br>FHWA-OR-RD-24-10 | 2. Government Accession No. | 3. Recipient's Catalog No. |

| | |
|---|---|
| 4. Title and Subtitle<br>Constructing High-Density Longitudinal Joints to Improve Pavement Longevity | 5. Report Date<br>August 2024 |
| | 6. Performing Organization Code |
| 16. Author(s)<br>Vipul Chitnis; 0000-0001-7163-157X<br>Mayank Sukhija, PhD; 0000-0002-7062-1406<br>Erdem Coleri, PhD; 0000-0002-1904-878X | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>School of Civil and Construction Engineering<br>Oregon State University<br>101 Kearney Hall, Corvallis, OR 97331 | 10. Work Unit No. (TRAIS) |
| | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address<br>Oregon Dept. of Transportation<br>Research Section and Federal Highway Admin.<br>555 13th Street NE, Suite 1 400 Seventh Street, SW<br>Salem, OR 97301 Washington, DC 20590-0003 | 13. Type of Report and Period Covered<br>Final Research Report |
| | 14. Sponsoring Agency Code |

15. Supplementary Notes

17. Abstract

In Oregon, asphalt cracking is the primary distress mode, necessitating costly rehabilitation and maintenance. Cracking failures around longitudinal joints (especially on roadway sections with centerline rumble strips) have been an important issue in Oregon, affecting the overall long-term performance of the Oregon roadway network. Longitudinal joint construction in asphalt pavements is the most critical phase of the construction process, as it is difficult to achieve a consistently high density of longitudinal joints similar to the mat density. This issue often affects the structural integrity and results in premature failure of the asphalt pavements. The primary objective of this research study was to determine the most effective longitudinal joint construction strategies for Oregon. Based on the findings from all components of this study, high tack coat application (at rates ranging from 0.14gal/yd$^2$ to 0.18gal/yd$^2$) on the longitudinal joint and the hot pinch methods were recommended to be used together to improve the density and the cracking resistance along the longitudinal joints. The proprietary Void Reducer product was also determined to improve the density and cracking resistance of the longitudinal joints. However, the cost of this strategy is higher than that of the other strategies. For this reason, for a limited paving budget, its use can be limited to applications in critical locations such as colder regions, mountainous areas, and critical highways with heavy truck traffic. This strategy is recommended for use in several additional constructions if funding is available.

| | |
|---|---|
| 18. Key Words<br>Longitudinal joints; Density Profiling System; asphalt; tack coat, compaction; joint density; hot pinch; permeability, X-Ray CT, Computed tomography. | 18. Distribution Statement<br>Copies available from NTIS, and online at<br>http://www.oregon.gov/ODOT/TD/TP_RES/ |

| | | | |
|---|---|---|---|
| 19. Security Classification (of this report)<br>Unclassified | 20. Security Classification (of this page)<br>Unclassified | 21. No. of Pages<br>143 | 22. Price |

Technical Report Form DOT F 1700.7 (8-72) Reproduction of completed page authorized Printed on recycled paper

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| APPROXIMATE CONVERSIONS TO SI UNITS | | | | | APPROXIMATE CONVERSIONS FROM SI UNITS | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Symbol | When You Know | Multiply By | To Find | Symbol | Symbol | When You Know | Multiply By | To Find | Symbol |
| | | **LENGTH** | | | | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm | mm | millimeters | 0.039 | inches | in |
| ft | feet | 0.305 | meters | m | m | meters | 3.28 | feet | ft |
| yd | yards | 0.914 | meters | m | m | meters | 1.09 | yards | yd |
| mi | miles | 1.61 | kilometers | km | km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | | | | **AREA** | | |
| in$^2$ | square inches | 645.2 | millimeters squared | mm$^2$ | mm$^2$ | millimeters squared | 0.0016 | square inches | in$^2$ |
| ft$^2$ | square feet | 0.093 | meters squared | m$^2$ | m$^2$ | meters squared | 10.764 | square feet | ft$^2$ |
| yd$^2$ | square yards | 0.836 | meters squared | m$^2$ | m$^2$ | meters squared | 1.196 | square yards | yd$^2$ |
| ac | acres | 0.405 | hectares | ha | ha | hectares | 2.47 | acres | ac |
| mi$^2$ | square miles | 2.59 | kilometers squared | km$^2$ | km$^2$ | kilometers squared | 0.386 | square miles | mi$^2$ |
| | | **VOLUME** | | | | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | ml | ml | milliliters | 0.034 | fluid ounces | fl oz |
| gal | gallons | 3.785 | liters | L | L | liters | 0.264 | gallons | gal |
| ft$^3$ | cubic feet | 0.028 | meters cubed | m$^3$ | m$^3$ | meters cubed | 35.315 | cubic feet | ft$^3$ |
| yd$^3$ | cubic yards | 0.765 | meters cubed | m$^3$ | m$^3$ | meters cubed | 1.308 | cubic yards | yd$^3$ |
| NOTE: Volumes greater than 1000 L shall be shown in m$^3$. | | | | | | | | | |
| | | **MASS** | | | | | **MASS** | | |
| oz | ounces | 28.35 | grams | g | g | grams | 0.035 | ounces | oz |
| lb | pounds | 0.454 | kilograms | kg | kg | kilograms | 2.205 | pounds | lb |
| T | short tons (2000 lb) | 0.907 | megagrams | Mg | Mg | megagrams | 1.102 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact)** | | | | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit | (F-32)/1.8 | Celsius | °C | °C | Celsius | 1.8C+32 | Fahrenheit | °F |

*SI is the symbol for the International System of Measurement

# ACKNOWLEDGEMENTS

The authors would like to thank the Oregon Department of Transportation (ODOT) for providing funding for this research. The authors thank the members of the ODOT Project Technical Advisory Committee and ODOT research for their advice and assistance in the preparation of this report. In particular, Cristhian Galvez, Frank Belleque, Mike Stennett, Chris Duman, Jim Gunter, and Erin Parker participated in the TAC. The authors would also like to thank Cristhian Galvez, Mike Stennett, Tim Earnest, Chris Duman, and Jim Gunter of ODOT, who organized the material sampling and fieldwork components of the research effort. The authors would also like to thank FHWA for providing the Density Profiling System (DPS) for this study. The authors would also like to thank all undergraduate research assistants of the OSU Asphalt Materials and Pavements (AMaP) research group for their help with sample preparation and testing, as well as James Batti for his help in the laboratory.

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# 1.0 INTRODUCTION

Fatigue cracking and rutting are considered the primary mechanisms for the failure of asphalt pavements. These distresses result in continuous maintenance, such as sealing the cracks and constructing thin overlays before the pavement reaches its design life. One of the leading causes of these distresses is improper compaction during construction, which results in lower density and, consequently, higher air voids within the asphalt mixture. In asphalt pavements, longitudinal joints are considered the critical location at which the density is relatively lower than the main mat density (Foster et al. 1964). The longitudinal joints occur in asphalt concrete pavements because it is practically difficult to pave the entire width (comprising multiple lanes) of the pavement in one pass. Hence, the general practice is to pave one lane followed by paving other lanes adjacent to the previously constructed lane.

When hot-mix asphalt (HMA) is placed next to the previously constructed lane (cold mat) during construction, a longitudinal joint occurs between the newly constructed lane and the old one. During compaction, the particles (coarse and medium-sized aggregates) in the HMA are pressed into the cold mat but then retreat from the stiff-cold mat under heavy compactor loads, which increases the chances of improper compaction around the joint and higher voids. This mechanism results in a lower density at the longitudinal joint than the constructed lane. According to a report by the Federal Highway Administration (FHWA) and Asphalt Institute (AI) (Buncher and Rosenberger 2012), paving operations that do not follow any special longitudinal joint construction specifications result in a 2-5% lower density of the joint than the mat density. According to Tran et al. (2016), a 1% increase in density can create a 33.8% to 66.3% improvement in the long-term fatigue cracking and rutting performance of asphalt mixtures, respectively. Thus, 2-5% lower densities along the longitudinal joints are expected to result in premature failures along the roadway networks. For this reason, fatigue cracking occurs around the longitudinal joints before the pavement structure reaches its design life. It is well known that the centerline rumble strips (CLRS) constructed on longitudinal joints with lower density are also more likely to crack in a shorter period (Weaver et al., 2023). Cracking from a longitudinal joint generally propagates to the rest of the mat, resulting in localized failures around the pavement section (Williams et al., 2009).

Since the 1990s, the performance issues related to the longitudinal joints have been assessed in various parts of the United States. Many construction techniques and suggestions have been developed to increase the performance and density along the longitudinal joints (Kandhal et al., 2002). The objective of developing those techniques and suggestions was to improve the uniformity of pavement density and reduce premature cracking and raveling failures at the joints. In general, a proper longitudinal joint construction technique may improve pavement longevity with less maintenance and rehabilitation.

In Oregon, asphalt cracking is the primary distress mode, sometimes necessitating costly rehabilitation and maintenance at intervals of less than the intended design lives. Failures around longitudinal joints (especially on roadway sections with centerline rumble strips) have been an important issue in Oregon, affecting the overall long-term performance of the roadway network. The longitudinal joint construction methods and products evaluated and recommended in this study will help ODOT reduce the pavement cracking originating from longitudinal joints and improve the long-term performance of pavements in Oregon. Improved cracking performance is expected to lead to reduced life cycle costs, increased pavement condition ratings, and reduced roughness for the Oregon roadway network.

## 1.1 ORGANIZATION OF THIS RESEARCH REPORT

The research presented in this report facilitates the implementation of different construction techniques and special products to improve the cracking resistance of longitudinal joints along asphalt-surfaced pavements in Oregon. This research report is organized as follows:

- Chapter 1: This introductory chapter points out the critical need for this research study and outlines the general research methodology followed in this study and the key objectives.

- Chapter 2: A comprehensive literature review on longitudinal joint construction techniques and special products is provided in this chapter.

- Chapter 3: The third chapter of this report is titled *"Survey Results and Analysis"* and focuses on obtaining ODOT and the Oregon paving industry's opinions on current longitudinal joint construction techniques and the potential of new emulsion technologies and their implementation in Oregon. Findings from the ODOT survey and the industry meeting were used to structure the laboratory and field components of this research study.

- Chapter 4: The fourth chapter of this report is titled *"Laboratory Investigation of Longitudinal Joint Performance".* The main objective of this chapter was to evaluate different products (mostly special emulsions and tack coats), construction methods, and technologies to determine their potential for implementation to improve the long-term performance of longitudinal joints.

- Chapter 5: The fifth chapter of this report is titled *"Field Investigation of Longitudinal Joint Performance".* Chapters 2, 3, and 4 provided knowledge on the most promising construction methods and special products to improve the long-term performance of longitudinal joints. The main objective of this chapter was to test the potential of those promising construction methods and special products in actual construction projects.

- Chapter 6: A summary of major findings and conclusions of the research completed in this study are provided in this chapter.

- Finally, Chapter 7: This chapter includes a comprehensive list of references used in this report.

## 1.2 KEY OBJECTIVES OF THIS STUDY

The main objectives of this study are to:

- Determine the factors that control the longitudinal joint density and performance through agency/industry surveys and meetings, laboratory testing, and field evaluations,

- Determine the most appropriate and efficient longitudinal joint construction strategies,

- Recommend a test method and a parameter for more accurate quality control testing of the longitudinal joints, and

- Based on the research project findings, develop a methodology with different special products (emulsions and other technologies and construction processes) for longitudinal joint construction.

# 2.0 LITERATURE REVIEW

In this comprehensive literature review, current strategies and protocols followed for constructing longitudinal joints and their effectiveness were evaluated by checking the past research studies and surveys conducted with state Department of Transportation (DOTs) agencies and asphalt contractors.

## 2.1 THE CURRENT PRACTICE OF LONGITUDINAL JOINT SPECIFICATIONS

### 2.1.1 Density Protocols in Various States

Since the 1960s, several state agencies have been investigating the failure of pavements due to deterioration in the longitudinal joints. In addition, based on the findings from past experiences, the state DOTs have provided suggestions regarding the permissible range of density requirements. The survey conducted by McDaniel et al. (2012) and Williams (2011) provided the range of density for satisfactory performance of longitudinal joints as recommended to several DOTs ranging from 89% - 92%. Figure 2.1 shows states that have density protocols for the construction of longitudinal joints.

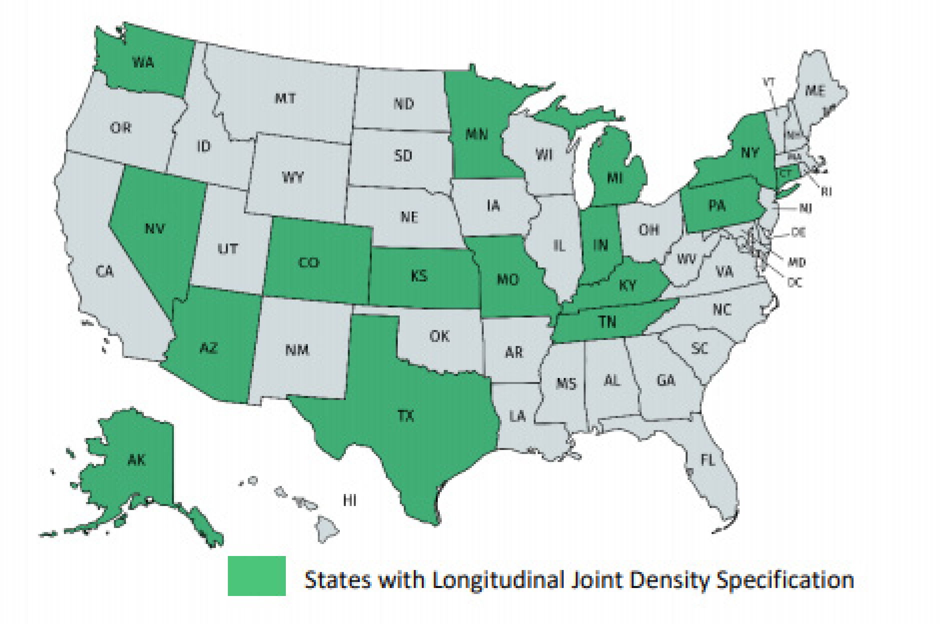


**Figure 2.1: States with longitudinal joint specifications. (Putman and Kim 2018)**

As density plays a vital role in longitudinal joints, various states in the U.S.A. have specified the methodology to be followed to construct longitudinal joints that yield lesser air voids or maximum percentages of density at longitudinal joints. For example, the State of Michigan rewards the contractor if the longitudinal joint section in the pavement has a density greater than or equal to 90.5%. Table 2.1 summarizes the specifications related to densities followed in several states.

**Table 2.1:Longitudinal joint density specification in various states. (Putman and Kim 2018)**

| Joint Density Requirement | | |
|---|---|---|
| **State** | **Percent** | **Requirement** |
| **AK** | > 91 | Of theoretical maximum specific gravity (2011; 2016) |
| **AZ** | - | Same density requirements as mainline paving (2016) |
| **CO** | ≥ 92 | Of theoretical maximum specific gravity (2011), tolerance 4% variation (2016) |
| **CT** | 90-97 | Of theoretical void free density (2011) |
| **IN** | > 91 | of theoretical maximum specific gravity (2012) |
| **KS** | ≥ 90 | Of theoretical maximum specific gravity, or interior density minus joint density less than equal to 2 $lb/ft^3$ (2015) |
| **KY** | 87-97 | Of theoretical maximum specific gravity (2016) |
| **MD** | - | Method specification for longitudinal joints (2012) |
| **MN** | - | Same density requirements as mainline paving (2011) |
| **MI** | ≥ 89 | Of theoretical maximum specific gravity (2012; 2016) |
| **MO** | > 98 | Of the interior density (2011) |
| **NV** | ≥ 90 | Of theoretical maximum specific gravity (2016) |
| **NY** | 90-97 | Of theoretical maximum specific gravity (2016) |
| | 90 | Of theoretical maximum specific gravity (2011) |
| **PA** | 90 | Of theoretical maximum specific gravity (2012) |
| **TN** | 89 | Of theoretical maximum specific gravity (2011) |
| **TX** | > 90 | Of theoretical maximum specific gravity (2011) and no more than 3% less than mat density (2012; 2016) |
| **WA** | > 90 | Of theoretical maximum specific gravity (2012) |
| **FAA** | 93.3 | Of theoretical maximum specific gravity (2011) |

### 2.1.2 Compaction Protocols in Various States

Compaction is an essential factor in determining the performance of the pavement. Different types of rollers, such as steel, rubber, and pneumatic, use different modes; for instance, static and vibratory are used for compaction of pavements. The compaction method for longitudinal joints can be decided on whether the edge of the pavement is unconfined or confined. Confined edges are easier to compact as the asphalt material stays in the constricted area, which helps in achieving the required density. It is difficult to compact the unconfined edges, and placing the roller compactor wheel is important. Placing the roller compactor wheel over the edge of the pavement leads the material to spread out in the unconfined direction. If another lane is constructed adjacent to this, it will lead to a low density at the longitudinal joint and wastage of material. In the field, the general method of placing the wheel of the roller compactor 3-6 inches from the unconfined edge is preferred. The idea behind this is to avoid any lateral roll-down of the asphalt material. If the overhang is less than 3 inches, it causes the edge of the roller wheel to come close to the unconfined edge, which later results in the formation of a crack.

Compaction techniques such as rolling from the mat and going towards the edge, rolling from the hot side/cold side, and then compacting the excess overlayed material are other methods utilized. Some state DOTs have given recommendations on the compactive effort, which helps in getting the required density at the longitudinal joints. Three passes at different angles are considered effective in constructing transverse joints, while no specification exists for the longitudinal joints. In addition to this, there have been cases in the field where compaction of the longitudinal joint has been attempted by placing the wheel exactly on the longitudinal joint. This method leads to the disappearance of the camber, which causes water accumulation at the longitudinal joints, causing premature distress on the pavements. Figure 2.2 shows states that follow compaction specifications.

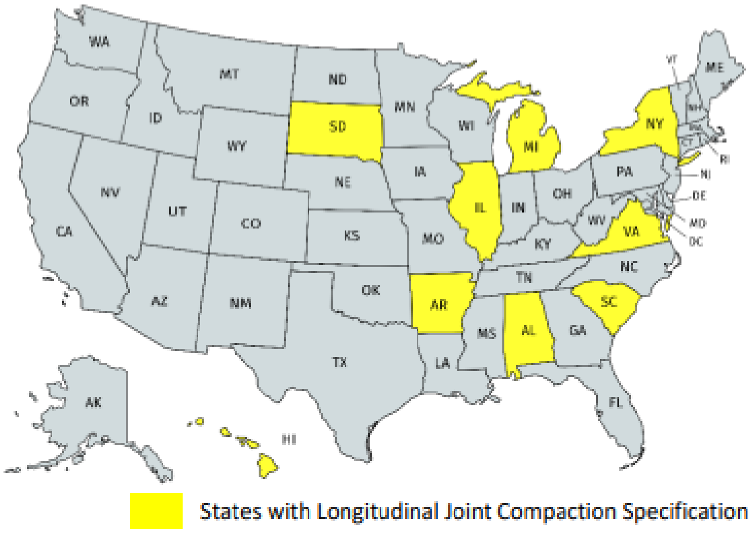


**Figure 2.2: States with methods specifications related to compaction. (Putman and Kim 2018)**

### 2.1.3 Tack Coat Protocols in Various States

In addition to the specified density and compaction requirements, some researchers have also given inputs on the specifications for tack coats to be applied during the construction of longitudinal joints. Several states, such as Kansas, Maryland, and Oklahoma, have been using tack coats to improve longitudinal joint performance (Williams 2011). Tack coats help facilitate the bond between the aggregates, thus reducing the chances of water and air infiltration into the pavement microstructure. This helps in the reduction of stripping and raveling of the aggregates in the longitudinal joints of the pavements. The states that follow guidelines on the longitudinal joint tack coat application are mentioned below. Figure 2.3 shows the states where the tack coat application is considered beneficial for the construction of longitudinal joints, and hence, they encourage the contractors to use it. Several states, such as Georgia, Nebraska, Minnesota, and Wisconsin, require the edges of the first lane to be tacked properly prior to the construction of the second lane (McDaniel et al., 2012).

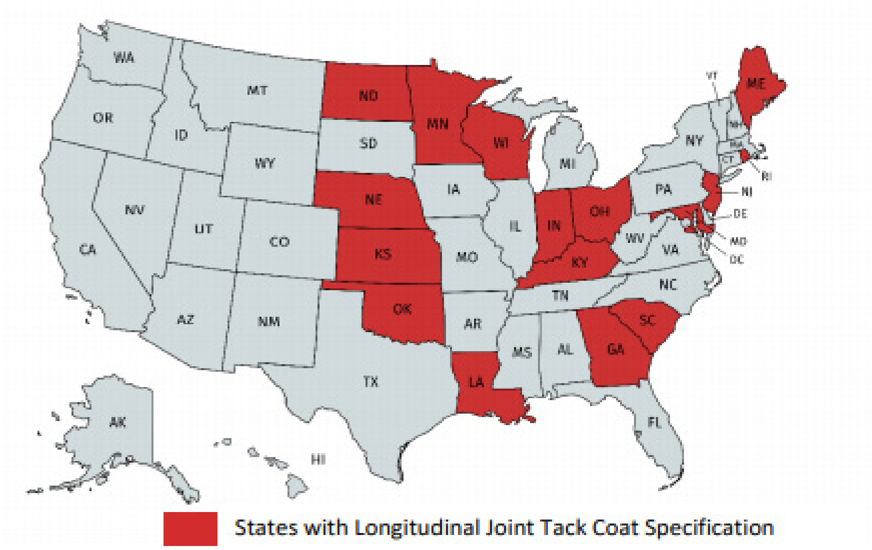


**Figure 2.3: States with tack coat specifications for construction of longitudinal joints. (Putman and Kim 2018)**

## 2.2 CAUSES OF FAILURE IN LONGITUDINAL JOINTS

Traditionally, asphalt concrete pavements are constructed to serve a life of 15-20 years. But due to multiple reasons, such as rutting, cracking, bleeding, etc., their service lives decrease. Longitudinal joints form the weakest section on the pavement. The primary reason is the unconfined edge at the pavement section. The majority of sites have one confined edge. The unconfined edge causes the material to roll out from the pavement, leaving less material at the edge. This issue leads to poor compaction and higher air-void content in the asphalt layer, causing the ingress of water and air. In addition, the cold joint forms a problem by making it difficult for the hot material from the new lane (hot mat) to blend in with the material at the edge (cold mat). At first, small cracks start surfacing at the joints. Later, the water and air ingress into the asphalt layer cause further deterioration by stripping off the weakly bonded aggregate particles from the cracks, further widening the faults. Finally, block crack patterns develop, leading to the deterioration of the joints and premature failure of the pavements. Hence, the failure of longitudinal joints is mainly attributed to the low density at the joints and the high permeability at the location of the joints (Buncher and Rosenberger 2012). According to Linden et al. (1989), for every 1% increase in the air avoid content after 7%, the pavement's service life reduces by 10%. Figure 2.4 and Figure 2.5 show the opening of the joint and cracks starting at the joint.

**Figure 2.4: Opening of longitudinal joint. (Brown 2016)**

**Figure 2.5: Cracking at the longitudinal joint. (Kim 2017)**

For longitudinal joints, the primary reason for failure is the joint density issues originating from the compaction problems along the joints. Not achieving the required density levels results in higher permeability along the joints. Research has shown that the density and permeability parameters are related to the nominal aggregate size used in the construction of the pavements. In addition to this, density also depends on the lift thickness and the amount of compaction achieved in the field (Choubane, B. et al. 1998; Cooley, L. et al. 2002; Mallick, R. et al. 2003).

Based on the research studies conducted by several state DOTs, specifications regarding the density required at the longitudinal joints were developed. Many of the state DOTs have suggested density levels at the longitudinal joints that are less than 2% of the mat density and, in no case, less than 90% of the theoretical maximum density. From the field study conducted by Sargent (1999), joint densities were always more than 2% less than the mat density.

In addition to density, the adhesion level achieved along the longitudinal joints between the cold and hot mats can be accepted to be another important parameter for evaluating long-term joint performance. If a high level of bonding between the two lanes is not achieved during construction, it may not be possible to avoid premature cracking along the joint, even when high-density levels were achieved along the joints. For this reason, density should not be considered as the only parameter controlling the longitudinal joint performance. For this reason, this study used density and adhesion strength parameters to evaluate long-term joint performance.

## 2.2.1 Parameters to Measure the Performance of Longitudinal Joints

The performance of longitudinal joints can be assessed mainly by considering two critical parameters: The density of the compacted material at the joint and the permeability of the longitudinal joint. In addition, indirect tensile strength tests and X-Ray CT imaging technology can be used to investigate various parameters for the joint and relate them to the longevity of the pavement joints.

### *2.2.1.1 Density measurement*

Numerous methods have been devised to evaluate the density of the sections at the longitudinal joints. The most widely used method in the field is the field nuclear density gauge measurement technique. This method involves seating the instrument close to the joint and measuring the density at that location. In addition to this, laboratory techniques like Saturated Surface Dry (SSD), vacuum sealing, parafilm, Core Reader, dimensional analysis, and X-ray tomography methods are used to measure the density of longitudinal joints.

### *2.2.1.2 Permeability measurement*

Darcy's law is used to determine the permeability of the joint, as permeability and infiltration are considered important factors for assessing the quality of longitudinal joints. Falling head field permeameters are used on a large scale for assessing permeability. In addition to this, a longitudinal joint permeameter developed by the University of New Hampshire was used. Moreover, a vacuum permeameter was also used in Kentucky and Arkansas, which produced reliable results in predicting the voids in the samples (Williams, 2011).

Cooley (1999) analyzed four different field permeameters and compared them with laboratory permeability measuring instruments. From this study, the FP3 method of permeability measurement showed results similar to that of the laboratory and was easy to use compared to other methods that were studied. This FP3 technique consisted of 3 tier standpipe and was developed by the National Centre for Asphalt Testing (NCAT).

The falling head permeameter shown in Figure 2.6 was used in the lab to get the time required for 500 ml water to flow through the specimen. Then, Darcy's equation is used to determine the permeability of the sample cores.

$$\boldsymbol{k = \frac{aL}{At} * \ln\frac{h1}{h2} * t} \tag{2-1}$$

Where:

- k = coefficient of permeability of the core
- a = cross-sectional area of the cylinder
- A = area of the specimen
- L = length of the specimen
- h1, h2 = head of water
- t = time

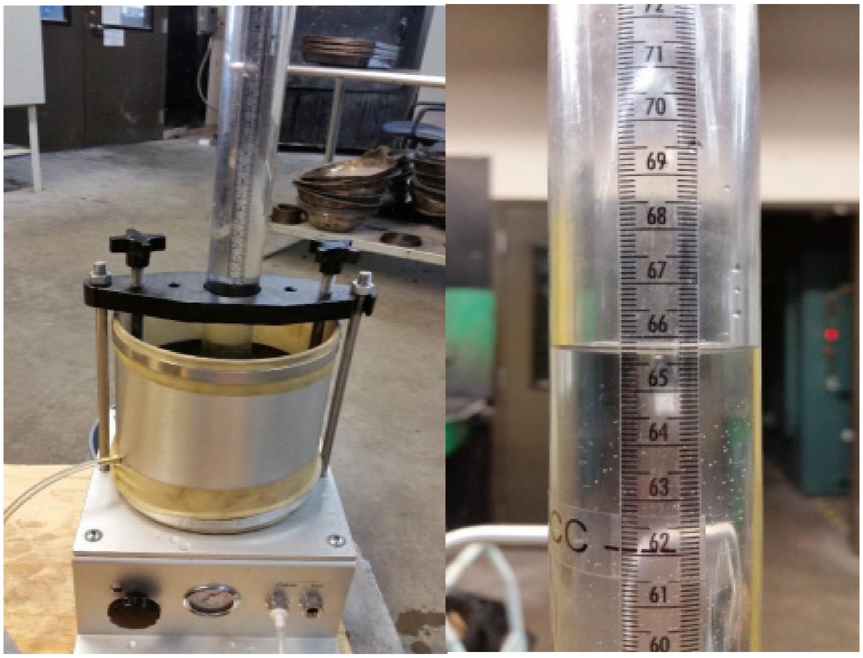


**Figure 2.6: Falling head permeameter. (Kim 2017)**

**Figure 2.7: NCAT Permeameter. (Stephen and Sushanta 2009)**

Coleri et al. (2014) used ASTM and NCAT methods to determine the permeability of porous asphalt pavements. NCAT uses the falling head permeameter equation. Figure 2.7: NCAT Permeameter shows the NCAT permeameter used for field testing. The ASTM C 1701 method was used to determine the infiltration rate of the pavement. The equation used to get the infiltration rate is as follows.

$$\boldsymbol{I = \frac{KM}{D^2 * t}} \tag{2-2}$$

Where:

- I = coefficient of infiltration,
- M = mass of infiltrated water, kg
- D = inner diameter of infiltration ring, mm
- t = time required for a measured amount of water to infiltrate the pavement, s,
- K = constant factor.

A series of permeability tests were conducted at the accelerated pavement test (APT) sections at the Knife River Corvallis Asphalt Plant (Weaver et al., 2023). A total of 22 field infiltration tests were conducted. It was expected that the dense gradation of the asphalt mixture with an acceptable level of compaction (also approved by the ODOT inspector) provided impermeability. As expected, the infiltration tests resulted in little to no water infiltration for most of the locations, with densities ranging from 91% to 94%. Moisture infiltration was observed near the edges of the section (where the air void content was about 4-5% higher than the rest of the test section). The permeability tests conducted on the joints also resulted in zero permeability. Based on the results of this preliminary investigation, using permeability testing to determine a parameter that can provide an indication of the longitudinal joint density and performance is not included in this research study.

#### *2.2.1.3 Indirect tensile strength (IDT)*

This test serves as the method to assess the interaction characteristics between the binder and aggregates. IDT does not measure the exact properties related to the joint performance. However, the measured IDT strengths from the cores removed from the joint can help quantify the bond strength between the cold mat and hot mat (Huang and Shu, 2010). Figure 2.8 shows the alignment of the specimen in the IDT test. This test measures the maximum load that is applied to the specimen. Then, the following equation is used to calculate the strength of the core samples.

$$\textbf{Strength} = \frac{\mathbf{2 * P}}{\boldsymbol{\pi} * \mathbf{D} * \mathbf{H}} \tag{2-3}$$

Where:

- P = maximum load applied
- D = diameter of the specimen
- H = height of the specimen

In this study, strength parameters will be calculated using the IDT test results to quantify the adhesion of the lanes along the joint to evaluate the long-term performance of longitudinal joints. In addition to strength, fracture energy, CT-Index (Zhou et al. 2017), and flexibility index (Ozer et al. 2016) parameters will also be evaluated to determine the best parameter for joint performance quantification. In addition, the IDT test is expected to assist in understanding the improvement of tensile strength by using polymers or Void Reducers in the joints.

**Figure 2.8: Indirect tensile strength. (Kim 2017)**

#### *2.2.1.4 X-ray CT scanning*

Huang and Shu (2010) conducted X-ray scans of the cores removed from joints. Later, these cores were examined using digital image processing technology to determine the distribution of the air voids in the pavement cores. Figure 2.9 shows the process for conducting X-ray CT imaging. The X-ray source transmits the waves of the designated wavelength on the sample. The sample is rotated through 360°. The images from the samples were used to evaluate the properties of the samples. Plessis and Boshoff (2018) used this non-destructive technique to analyze the material properties in the concrete mixes.

Thus, this technology can also be used as a diagnostic tool for measuring the pores and interior crack patterns in the joints. It can serve as a single tool in determining the cores' "ground-truth" density, air voids, and permeability, which can be later checked with the other methods explained previously.

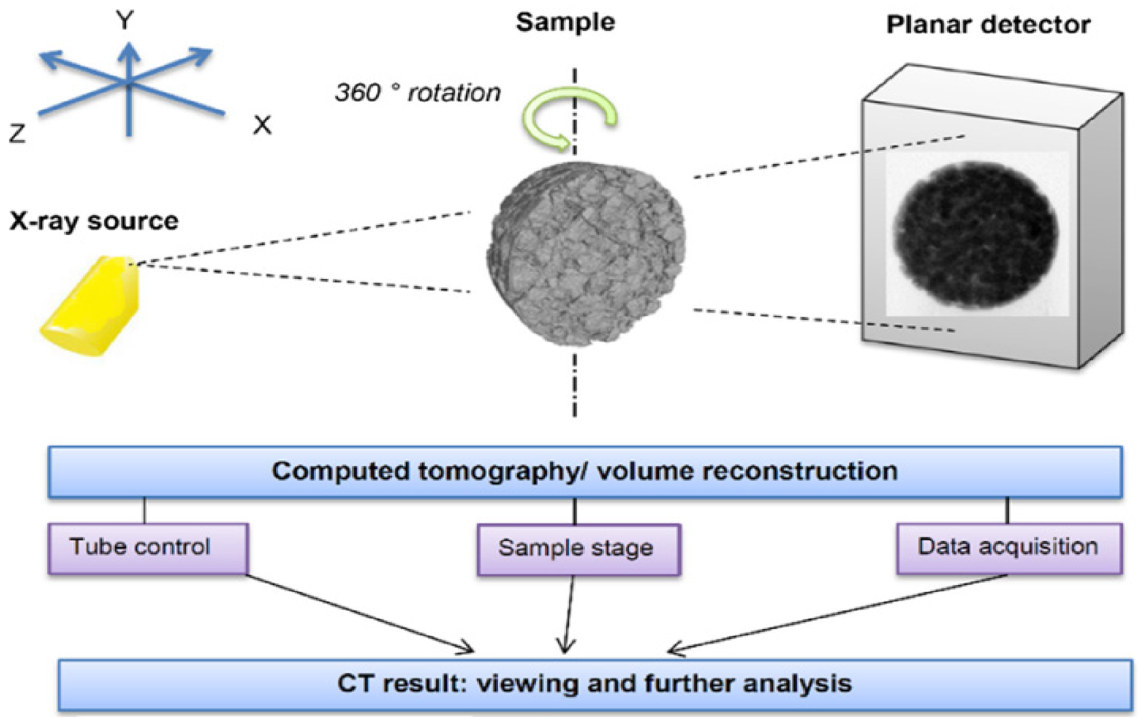


**Figure 2.9: Basics of X-ray CT imaging technique. (Plessis and Boshoff, 2018)**

## 2.3 TECHNIQUES FOR THE CONSTRUCTION OF LONGITUDINAL JOINTS

### 2.3.1 Echelon Paving

As joints in all pavement structures present early failure problems, it is best to avoid them. The traditional method of compacting the first lane and later compacting the adjacent lane after some time causes temperature differences at the edge. The concept of paving adjacent lanes simultaneously, also called echelon paving, was developed to prevent this issue and its effects. Two lanes are constructed simultaneously using two paver machines that are operated independently. The distance between the two pavers is important, and the goal should be to keep the distance as minimal as possible. To obtain the best results, two pavers are placed within a distance of 10 meters from each other, as this will cause the first lane material to be hot and avoid the formation of cold joints (Benson and Scherocman 2006). Figure 2.10 shows the construction of pavement using the echelon paving technique. As the temperature of the material placed in both lanes is constant, the two lanes constructed act like one without any longitudinal joint. This method stops the premature deterioration of the pavement. An overlap of about 1-1.5 inches provides the highest density. The Port Authority of New York and New Jersey constructed pavements using echelon paving. The average air void content was 6.5%. (Bognacki 2006). In addition, the shift from one lane to another is smooth with little or no bump, thus reducing the risk for bike riders.

Simultaneous construction of these lanes is practically complex due to restrictions on the equipment and the operation of several pieces of equipment in conjunction. In addition, it also increases investment, making it uneconomical in some cases.

**Figure 2.10 Echelon paving at GingerMan Raceway South Haven, MI. (https://www.forconstructionpros.com)**

## 2.3.2 Joint Heater/ Infrared Heater

Echelon paving is possible in cases where the construction of both lanes simultaneously does not cause traffic congestion or inconvenience to the public. It is also not always possible to have two pavers available for construction at the same time. Traditionally, the asphalt pavements are constructed with one lane undergoing construction while the other is open to traffic. Thus, keeping this in mind, methods to improve joint performance other than echelon paving were developed.

Pre-heaters are towed ahead of the paver machine, and then an additional paver-mounted infrared heater is used to maintain the compaction temperature just before compacting the asphalt. The unconfined edge of the cold lane is heated to match the temperature of the material to be paved. A mixture of propane and air is injected at high pressures, producing infrared radiations of wavelength that heat the material to match the paving material temperature. As the temperature at the joint reaches 120° C (250° F), the second lane is immediately compacted (Williams 2011). This process helps in proper compaction by not allowing the hot material to bounce back from the cold and stiff asphalt material. This process results in good bonding between the old material and the new material, thus increasing the density at the joints. This technique is practiced in the U.S.A. and Canada and has been significant in providing the characteristics required at the joint for achieving the desired life cycle of the pavements. This method is compared to the echelon paving technique as both methods result in compacting hot material at the joints.

In Alaska, Yakutat airport runways and taxiways were constructed using infrared heaters and echelon paving. The general contractor for this project was Knik Construction and infrared heaters manufactured by Head Design Equipment were employed at work. According to Amanda Gilliland, Knik's project manager, the use of infrared heaters helped eliminate the labor-intensive work of truncating the dropped asphalt at the unconfined edge. This process eliminated approximately 600 $m^3$ (21,000 $ft^3$) of wastage of asphalt material. Thus, making the construction more economical. It was also reported that the use of infrared heaters assisted in meeting the Federal Aviation Administration (FAA) requirements related to density.

According to Daniel J.S. (2006), the use of infrared heaters increased the performance of the longitudinal joints by increasing the density compared to the control section. It also increased the indirect tensile strength of the joint. Research studies in the U.S.A. indicated that joint heaters were effective in increasing the density of the joints and showed better resistance to vehicular loading than cold joints (Fleckenstein et al. 2002). On the other hand, Huang and Shu (2010) had conflicting results. Cores from joints constructed with infrared heaters had more air voids than samples with joint adhesives and joint sealers (discussed later). Still, they showed the highest resistance to permeability and had comparatively higher tensile strength values than other construction methods.

Daniel and Real (2006) researched using an infrared heater to construct the pavements in New Hampshire in 2003-2004. The entire cross-section of the pavement, including the base, binder, and subsurface, was heated. Thermocouples were placed in the pavement layer to measure the level of heating in the pavement. The results demonstrated higher resistance to cracking and failure of pavements constructed using infrared heaters on the longitudinal joint compared to the control sections. It was believed that heating the cold mats to 60°C - 70° C was the best method to achieve the required compaction. Figure 2.11 shows the infrared heater towed and the paver compacting the hot joint with the weight of the screed as a first-pass compaction. The distance between the paver and the towed heater is maintained to construct hot joints and avoid temperature differences to achieve high density at the joints. From Table 2.2, it is evident that the surface layer had a 33% reduction in the air voids, which is expected to result in a significantly better joint performance.

**Figure 2.11: Paving with an Infrared Joint heater. (Daniel and Real, 2006)**

**Table 2.2: Air voids measured from the pavement cores. (Daniel and Real, 2006)**

| Layer | Section | Location | # Specs | Avg. (%) | Std. Dev. (%) | COV (%) |
|---|---|---|---|---|---|---|
| **Base** | **Infrared** | **Joint** | 14 | 10.1 | 0.9 | 8.7 |
| | | **Mat** | 16 | 6.3 | 0.8 | 12.7 |
| | **Control** | **Joint** | 12 | 10.7 | 0.7 | 6.2 |
| | | **Mat** | 17 | 5.3 | 0.7 | 13.8 |
| **Binder** | **Infrared** | **Joint** | 15 | 12.2 | 1.3 | 11.1 |
| | | **Mat** | 16 | 6.3 | 1.0 | 16.1 |
| | **Control** | **Joint** | 14 | 12.1 | 0.6 | 5.2 |
| | | **Mat** | 17 | 6.4 | 0.8 | 13.1 |
| **Surface** | **Infrared** | **Joint** | 14 | 9.6 | 1.3 | 13.5 |
| | | **Mat** | 16 | 7.0 | 1.3 | 18.0 |
| | **Control** | **Joint** | 14 | 12.1 | 0.9 | 7.8 |
| | | **Mat** | 14 | 7.4 | 1.3 | 17.1 |

It is important to determine whether the heating of material for the second time after compacting with infrared heaters affects the properties of the aggregate and the bonding properties of the binder. Adjusting the height of the pre-heating unit is crucial as overheating may affect the binder properties and result in a less ductile asphalt mixture at the joints. Figure 2.12 shows the mounted infrared joint heater by Head Design Equipment.

**Figure 2.12: Infrared joint heater by Head Design Equipment, Inc. (Williams 2011)**

### 2.3.3 Butt Joint

Though echelon paving and infrared joint heating techniques create hot joints with the highest densities, they have practical and economic difficulties. Echelon paving can only be used if both lanes are closed to traffic, while the infrared heating technique involves skilled labor and costly equipment. In addition, using propane heaters during construction increases the carbon emissions released and the carbon footprint of the entire process. Excessive infrared heating can also damage the asphalt binder along the joints and result in poor joint performance. For these reasons, other methods to improve longitudinal joint performance should also be considered.

Longitudinal joints can be classified into two types; butt joint and wedge joint. In the former technique, the unconfined edge of the pavement is constructed vertically by using an end gate. The end gate should be steady and strong enough to resist any lateral movement while the material is placed. This method will help in getting a straight, unconfined edge, as shown in Figure 2.13.

**Figure 2.13: Straight vertical butt joint due to end gates down. (https://www.youtube.com/watch?v=6NLURo8IBb4)**

After the first lane has been placed, the compaction is done by having an overhang of 3-6 inches. Changes in the overhang cause the material to bulge out, resulting in the segregation of the material. An overlap of 1-1.5 inches is placed on the cold mat. Differences in the overlap cause problems with matching the joint at the same level, thereby creating a problem for a smooth transition from one lane to another and increasing the safety risks for bike riders. This process increases the human effort of raking the material back to the joint. Raking is the process of pushing the material in excess or sloughed off from the unconfined edge back to the joint. Raking causes the segregation of the material and leads to uneven surface texture, as shown in Figure 2 14 and Figure 2.15. This process also causes difficulty in compacting the second lane and leads to failure at the joints. Figure 2.13 shows the person pushing excess material back over the hot mat. This step is required when the end plate is not strong enough to resist the lateral force from the aggregates, or this can also happen if overlap exceeds the designated limit of 1-1.25 inches over the cold mat. Although this process might make the joint look well compacted with no visible joint line, it may reduce the long-term cracking performance by reducing the material around the joint needed to compact the asphalt layer adjacent to the joint with the rest of the mat.

**Figure 2.14: Raking of material back to the mat.**
**(https://www.youtube.com/watch?v=6NLURo8IBb4)**

**Figure 2.15: Uneven surface texture due to raking.**
**(https://www.youtube.com/watch?v=6NLURo8IBb4)**

Figure 2.15 shows an uneven surface with coarser aggregate due to raking while constructing the right lane, while the left side of the image has a smooth texture and no segregation of material. As a solution to sloughing the material, a cutting wheel is attached to the roller to cut this extra material at the unconfined edge when the material is still in a plastic state. Figure 2.16 shows the roller-mounted cutting wheel used for removing the rolled-off material. Then, the second lane or the hot mat is placed. The compaction, in this case, is done from the hot side of the lane.

Benson and Scherocman (2006) have reported that this technique involves operating the roller for a long time, thus increasing costs. In addition, it also requires the edge to be cut along a straight line, involving precision and dependency on the laborer. If the edge is not along the straight line, it will cause difficulty in constructing the second lane. Longitudinal joints with cutting wheels built on airport roadways have been shown to perform better in terms of density (Brown 2002). In addition, sometimes, a tack coat is applied to the joint after cutting it vertically.

**Figure 2.13: Roller mounted with a cutting wheel. (https://www.equipmentworld.com)**

## 2.3.4 Tapered Joint/ Wedge Joint

The butt joint has a vertical face at the unconfined edge of the pavement, while the wedge joint has the edge in the form of a taper or wedge. In the earlier days, the primary usage of the wedge joint was to facilitate the movement of vehicles from one lane to another during the construction phase of the pavement. This method provides a smooth and safe ride compared to the butt joint.

But later, it was realized that the wedge technique provided a good finish and had better performance than the butt joint, which boosted the research in the construction of wedge joints. Figure 2.17 shows a wedge joint construction.

**Figure 2.14: Notch wedge joint. (https://www.equipmentworld.com)**

A strike-off device is installed at the end of the paver to create the required taper at the joint. This device limits the movement of the material in the transverse direction. While this taper is being constructed, a small roller of approximately 500 pounds is attached to the paver, causing the initial compaction of the asphalt mixture (Fleckenstein et al., 2002). In Kentucky, Fleckenstein et al. (2002) evaluated the performance of four different methods, namely the infrared heater, notch wedge joint, joint maker, and restrained edge. They determined that the notch wedge joint yielded a marginal difference in density compared to the control section but had the least permeability among the four methods. Different taper slopes have been practiced, such as the 3:1, 6:1, and 12:1, by different states in the U.S.A. The taper of 3:1 means for every 1 inch of vertical movement, there will be 3 inches of horizontal laying of the asphalt to create the slope along the joint.

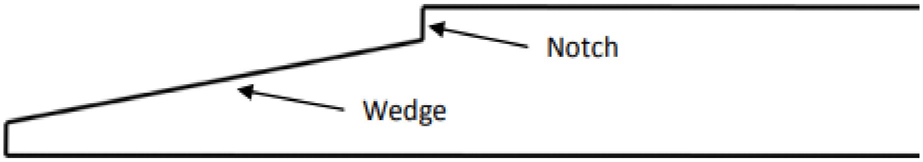


**Figure 2.15: Notch wedge joint. (Williams 2011)**

A simple diagram to understand the wedge is shown in Figure 2.18. The taper of 3:1 is introduced in the cold mat over which the new lane is constructed. Generally, an overlap of about 50 – 75 mm is created on the cold mat. This technique, also called the New Jersey wedge, was reported to perform well in Colorado and New Jersey (Kandhal et al. 1996). The tapered section has less material at the edge of the cold lane, and hence, the overlap from the hot lane causes its high temperature to heat the material in the cold lane. This process leads to good binding between the cold and hot joint, forming a better aggregate interlock along the joint. In addition, a layer of tack coat is generally applied on the tapered edge of the joint before constructing the second lane. This further promotes the connection between the cold and hot lanes.

Kandhal and Rao (1994) researched the construction of longitudinal joints in Michigan and Wisconsin. In Michigan, among the eight methods, *which are Joint maker, Rolling from the hot side, Rolling from the cold side, Rolling from the hot side with 152mm away from the joint, Cutting wheel, Edge restraining method, Rubberized asphalt tack coat, and New Jersey Wedge with a taper of 3:1,* maximum densities were achieved by using the wedge joint without tack coat and with a tack coat. On the other hand, Toepel (2003) also researched the same eight methods of constructing longitudinal joints and reported lower performance for the wedge joints. But later, with improvements in equipment and construction technology, the construction of wedge joints increased in Wisconsin and augmented its performance. Figure 2.19 shows a paver attached with a small compacting roller to compact the joint.

The wedge joint requires more overlap than the butt joint. If the preliminary compaction of the wedge during the construction of the first lane is improper, it may lead to lesser joint density. In addition, compacting with a roller can sometimes lead to the crushing of the aggregate, resulting in a lot of debris at the joint, a significant change in the gradation of the asphalt mix (which leads to poor compaction), and lower density.

**Figure 2.16: Roller attached to a paver for compaction of tapered part in notched wedge joint. (https://www.pavementinteractive.org/)**

## 2.3.5 Longitudinal Joints with Coats (Tack and Adhesives)

### *2.3.5.1 Tack coats*

The technique of applying several surface coats like tack coats, Void Reducer, and other adhesives from different companies has served the purpose of creating durable longitudinal joints. Compaction of the material at the unconfined edge leads to a roll down of 20% of the material (Brown, 2006). The primary reason for the application of these products is to resist this lateral movement of the material.

Tack coat application is spraying the asphaltic emulsion at the joint or between different asphalt layers. Once the lane is constructed and the first pass completed, the entire joint is sprayed with an asphaltic emulsion. This excess binder helps create a strong bond between the cold and hot lane material. It also seals the air voids at the joint, making the joint impermeable. If a wedge joint is constructed with a tapered edge, then a binder is placed over the entire width of the wedge area. After this application, the construction of the second lane begins. The second lane is constructed with a consistent overlap of 1 to 2 inches. An increase in the overlap causes a substantial amount of raking process, leading to segregation of the material at the joint. In any case, raking is generally not the right option to achieve higher density and better longevity.

Williams (2011) conducted a research study on the various methods feasible for constructing longitudinal joints in Arkansas. In this study, techniques involving the notched wedge joint maker, joint heater, joint stabilizer, joint sealants, and varying rolling patterns were studied thoroughly. It was concluded that among various techniques used, joints with tack coats were reported to have the lowest density. Studies from Nevada (Sebaaly et al. 2008) concluded that cutting wheel (application of a roller-mounted cutting blade to remove the sloughed-off material and get a vertical edge at the unconfined edge that is adequately compacted) with a tack served better than the other methods. Based on this study, NDOT was suggested to implement two rules concerning the construction of longitudinal joints. Firstly, the density of the longitudinal joint should be a maximum of 2% less than the mat density. Secondly, the theoretical maximum density at the joint should be greater than 90%.

According to Buncher and Rosenberger (2012), the state of Colorado pays extra to apply the tack coat to the longitudinal joint. The contractor makes sure to have an adequate proportion of tack coat material applied at the joint interface to increase the performance of the longitudinal joints. Among all the methods used to construct sections with a 3:1 taper with a 25-mm (1-inch) offset, tack coat application on the taper was considered the best method to increase joint density.

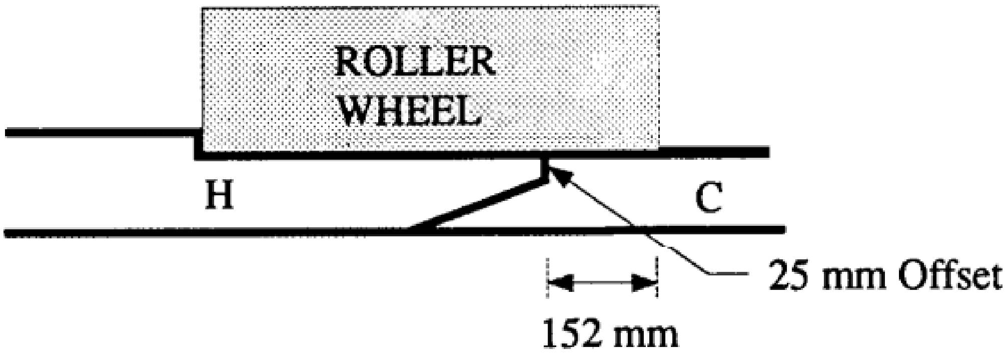


**Figure 2.17: 3:1 taper with 25mm offset. (Kandhal et al., 1996)**

3:1 taper means that for every 1-inch vertical displacement, there are 3 inches of horizontal displacement. This tapering of material at the joint starts 25mm from the top of the surface. Figure 2-20 above shows the details regarding tapered construction.

In addition, Kandhal and Rao (1994) studied eight various longitudinal construction techniques (see Table 2.3) to determine the best method for constructing longitudinal joints in Wisconsin. It was determined that wedge joints with and without tack coat had the highest densities at the joint. The construction of the wedge helped in laying a small portion of asphalt while the first lane was paved, and later, the tack coat helped the hot asphalt from the second mat bond better with the first lane.

Along with this method, another variant, the rubberized tack coat, has also been experimented with to improve cold joints' performance. The study conducted by the Federal Aviation Administration (Kandhal et al., 2007) suggested that a combination of notch wedge joints with rubberized tack coat application is the best.

In 1995, Kandhal et al. (2002) investigated eight different construction techniques of longitudinal joints on State Route 441. The test section in this project was 152 m or 500 feet long. Gradation with 100% aggregates passing the 12.5 mm sieve and a binder content of 6% was used in the study. Joint makers, rolling from the hot side, rolling from the cold side, cutting wheels, edge restraining devices, the New Jersey wedge technique, and rubberized asphalt tack coats were used in the study.

Inspection of the joints constructed in this project was carried out after six years. The effectiveness of every method related to improving the cracking resistance of the longitudinal joints is shown in Table 2-3.

**Table 2.3: Air voids and density measured with different techniques. (Kandhal et al., 2002)**

| Section No. and Joint Type | Density at the Joint (kg/m$^3$) | | Air Voids[1] at the Joint (%) | | Air Voids[1] 305mm (12")_ Away From the Joint on Cold Side | |
|---|---|---|---|---|---|---|
| | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. |
| **1. Joint Maker** | 2252 | 23 | 9.2 | 0.94 | 6.1 | 0.99 |
| **2. Rolling from Hot Side** | 2224 | 36 | 10.3 | 1.49 | 6.2 | 1.10 |
| **3. Rolling from Cold Side** | 2248 | 59 | 9.3 | 2.36 | 4.7 | 1.29 |
| **4. Rolling from Hot Side 152mm Away** | 2233 | 32 | 10.0 | 1.29 | 5.6 | 1.35 |
| **5. Cutting Wheel** | 2264 | 53 | 8.7 | 2.16 | 5.3 | 1.27 |
| **6. Edge Restraining Device** | 2289 | 45 | 7.7 | 1.78 | 5.0 | 1.32 |
| **7. Rubberized Joint Material** | 2160 | 38 | 12.9 | 1.53 | 6.4 | 0.99 |
| **8. New Jersey Wedge 3:1** | 2113 | 54 | 14.8 | 2.15 | 8.4 | 0.84 |

[1] Based on Theoretical Maximum Density (TMD) of 2480kg/m$^3$

**Table 2.4: Evaluation of longitudinal joints after 6 years. (Kandhal et al. 2002)**

| Section No., Sta., Type | Cracking at Joint | | Raveling of Adjacent Mat (Cold Side) Average Rating[b] | | Average Rating | Comments |
|---|---|---|---|---|---|---|
| | % Length | Av. Width (mm) | % Length | Severity[a] | | |
| **1. (169 to 164) Joint Maker** | 85 | 9.5 | 0 | None | 5.50 | Crack is straight. |
| **2. (164+00 to 159+00)** | 99 | 6.25 | 0 | None | 4.75 | Crack is more jagged and appears shallower than Section 1. |
| **3. (159 to 154) Rolling from cold side** | 88 | 9.5 | 0 | None | 4.62 | Crack appears deeper than Sections 1 and 2; longer localized areas of 12.5mm wide crack. |
| **4. (154 to 149) Rolling from hot side 152mm away** | 6 | 3 | 8 | Slight | 8.75 | Joint most visible in most of the section, crack shows up intermittently for short lengths. |
| **5. (149 + 144) Cutting wheel** | 6 | 6.25 | 0 | None | 9.12 | Joint not visible in most of the section, two short lengths of cracking. |
| **6. (144 to 139) Edge restraining device** | 35 | 4.75 | 8 | Slight | 6.75 | Crack is intermittent; slight raveling in between cracks. |
| **7. (139 to 134) Rubberized joint material** | 0 | - | 2 | Slight | 9.88 | Joint not visible except for some spots of joint material. |
| **8. (134 + 129) N.J. Wedge 3:1** | 3 | 2 | 4 | Slight | 7.75 | There is 50-75mm wide raveling on the joint in about 75% of the section, cracking in a few locations only. |

[a] Severity = none, slight, moderate or severe

[b] 0 = unacceptable; 2 = poor; 4 = fair; 6 = good; 8 = very good; 10 = excellent

It is evident from Table 2.3 and Table 2.4 that though rubberized tack coats had higher air voids, their performance after six years was better than the joint maker. This outcome might be due to the issues with joint density measurements with the presence of a rubber material that has a different density and specific gravity than the asphalt binder, or the rubberized tack coat may not have filled the air voids at the joint, but it adequately glued the cold and hot material together. The rubberized material at the joint increased the tensile strength, making it difficult for the joint to break apart; hence, minimal cracking is shown at the surface.

The yearly rankings for the various techniques used in the 4-year span are tabulated in Table 2.4 and Table 2.5. The ranking shows that the application of rubberized tack coat has performed exceptionally well over a span of 6 years.

**Table 2.5: Rankings for the techniques from 1997 to 2001 (Kandhal et al. 2002)**

| 1997 (July) | 1998 (July) | 2000 (October) | 2001 (July) |
|---|---|---|---|
| 1. Rolling hot side (9.8) | 1. Rubberized joint material (9.8) | 1. Cutting wheel (9.0) | 1. Rubberized joint material (9.88) |
| 2. Rolling cold side (8.8) | 2. Cutting wheel (9.4) | 2. Rubberized joint material (7.75) | 2. Cutting wheel (9.12) |
| 3. Rubberized joint material (8.2) | 3. Rolling from hot side (8.8) | 3. N.J. wedge (7.5) | 3. Rolling hot side 152mm (8.75) |
| 4. Joint maker (8.0) | 4. Rolling from hot side 152mm away (8.4) | 4. Rolling from hot side 152mm (7.25) | 4. N.J. wedge (7.75) |
| 5. Cutting wheel (7.8) | 5. Joint maker (7.8) | 5. Edge restraining device (6.5) | 5. Edge restraining device (6.75) |
| 6. Rolling hot side 152mm (7.0) | 6. Edge restraining device (6.4) | 6. Joint maker (4.5) | 6. Joint maker (5.50) |
| 7. Edge restraining device (6.5) | 7. Rolling from cold side (6.0) | 7. Rolling from hot side (4.25) | 7. Rolling from hot side (4.75) |
| 8. N.J. wedge (4.0) | 8. N.J. wedge (5.6) | 8. Rolling from cold side (3.0) | 8. Rolling from cold side (4.62) |

Note: Evaluations were conducted by 4 to 5 evaluators, average ratings are given in parenthesis. Scale of rating: 0 = unacceptable, 2 = poor; 4 = fair; 6 = good; 8 = very good; and 10 = excellent.

#### *2.3.5.2 Joint sealers*

Along with the tack coat types stated in the previous section, other joint sealers, such as the Void Reducer, QuickSeam, etc., were also examined for the construction of longitudinal joints by the Illinois Department of Transportation, New York Department of Transportation, and Tennessee Transportation Department. The permeability in the longitudinal joints at the asphalt surface is ten times more than in the mats of the pavements. To address this issue, joint sealants were used to seal the joints. Joint sealants, such as Void reducer, are placed on the pavement surface before the placement of the first lane of the new asphalt concrete layer. When the asphalt mixture is placed on the roadway section with the sealant material, the joint sealant placed under the new mat melts and starts moving upwards toward the surface of the bituminous pavements. In this way, the air voids around the joint area, causing higher permeability and lower load-carrying capacity, were decreased, resulting in increased tensile strength. In Illinois, the performance of two joint sealants, namely Void Reducer and QuickSeam, was investigated (Winkelman 2004). QuickSeam sealant, available in the form of rolls, was placed on the joint's surface at the center, with the sealant placed equally on either side of the joint. The first lane and second lane were then paved. Similar to this, the Void Reducer is applied at the joint prior to the construction of the joints. However, a Void Reducer is applied in the form of a liquid with varying thicknesses. More research studies are required to be conducted on these sealants to thoroughly understand their influence on joints' longevity.

In New York (Morgan 2009), the effectiveness of three different types of joint adhesives, namely XJB extruded Joint Bond, Crafco Pavement Joint Adhesive, and Deery Cold Joint Adhesive, were studied to reduce cracking issues observed at the joints. All the sealants performed well in terms of compaction. However, more inspection and research are needed to determine the actual effect because it was difficult for the researchers to provide a definitive conclusion as some of the joints with sealants had cracking and raveling issues.

In Tennessee, seven different longitudinal joint construction techniques were studied (Huang and Shu 2010). The techniques involved the use of joint adhesives, joint sealers, and infrared heaters. Laboratory tests were conducted to determine air void content, permeability, water absorption, strength, and internal microstructure (via X-ray CT scanning). From the study, it was observed that the joints with polymer emulsions performed better than all other methods. It was also observed that the joint sealers used in the study had a minute impact on the permeability. The infrared heater was the best among all the techniques evaluated in the study. The volume of air voids at the joints constructed using the infrared heater was the least. The same conclusion was also achieved from the X-ray CT scan images. The air void content, permeability, and indirect tensile strength for various methods analyzed in the research project are given in Figure 2.21, Figure 2.22, and Figure 2.23, respectively.

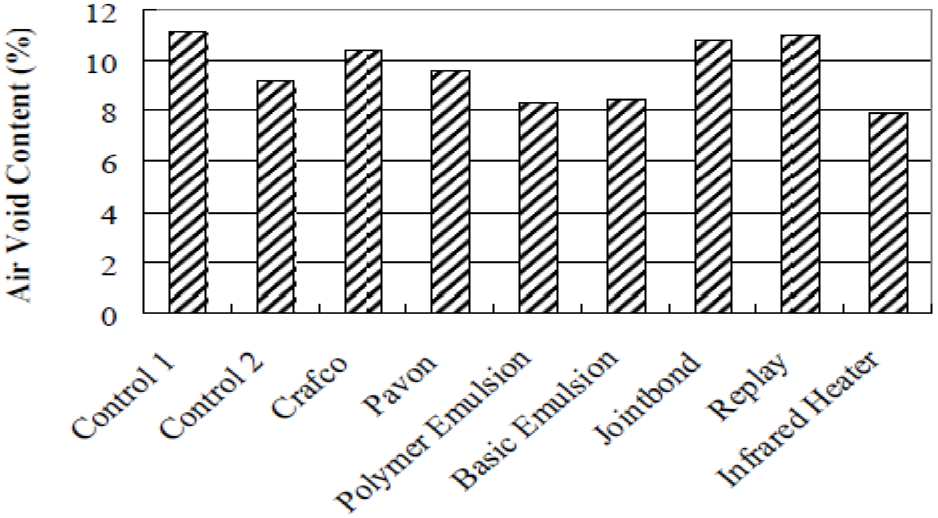


**Figure 2.18: Air void content. (Huang and Shu, 2010)**

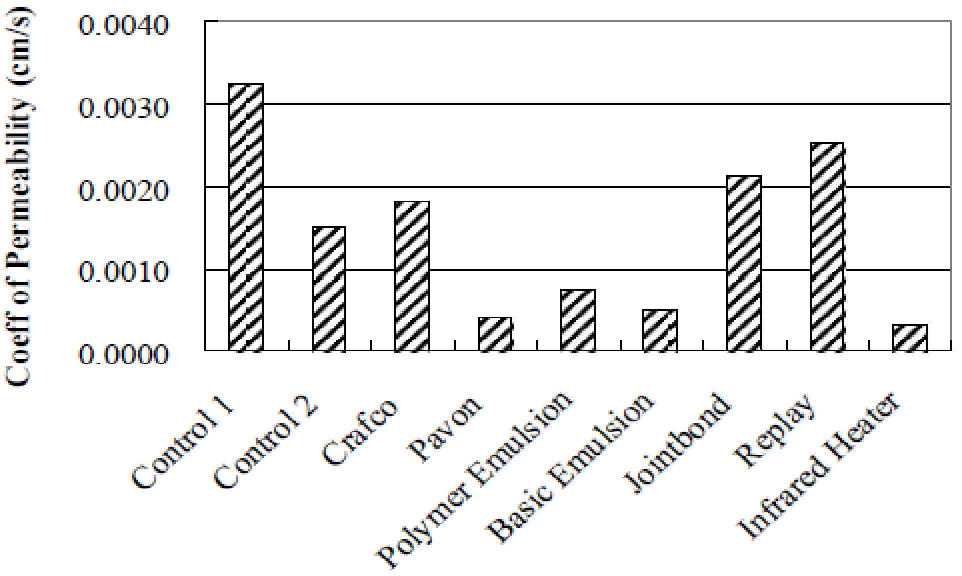


**Figure 2.19: Permeability of the test section. (Huang and Shu, 2010)**

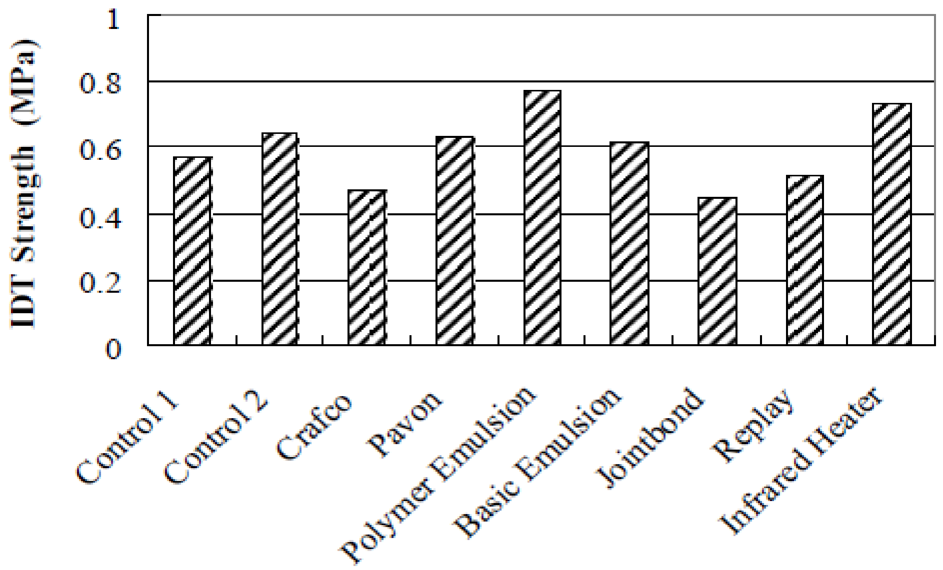


**Figure 2.20: IDT results. (Huang and Shu, 2010)**

#### *2.3.5.3 Joint stabilizers*

In Arkansas, Williams (2011) conducted an experiment using joint stabilizers. A joint stabilizer (Joint Bond) supplied by the company Pavement Technology was used in this study. Stabilizers were applied after the construction of the joints. This chemical penetrates the joint and prohibits joint separation and deterioration by the chemical reaction of the stabilizer and the asphalt material. Joint sealers are generally applied to newly constructed joints. The stabilizers can be applied in a similar way, but the best results are observed when used on the one to two-year older joints. The application of stabilizers reduces the penetration of water in the joints. The density of the cores obtained from the joints constructed using joint stabilizers ranged from 90% to 92%; moreover, the water absorption was also comparatively less (Williams 2011). This material was sprayed from a truck over the joint such that it overlapped 18 inches on both sides of the joint (as shown in Figure 2.24). According to Williams (2011), the cost of applying this on the joint was $0.36 to $0.57 per linear foot.

**Figure 2.21: Application of Joint Bond by Pavement Technology, Inc. (Williams 2011)**

### 2.3.6 Rolling from the Hot Side

In this method, the compaction of the pavement is done from the newly constructed lane. There is an overlap of 152mm (6 inches) on the cold mat, as shown in Figure 2.25. Generally, two passes, a forward pass, and a backward pass, are made for compacting the mat. In both passes, the compaction of the joint is done with steel rollers in vibratory mode. The vibration of the roller increases the compactive energy and reduces the air voids in the pavement, which increases the density of the joint (Kandhal and Mallick, 1997).

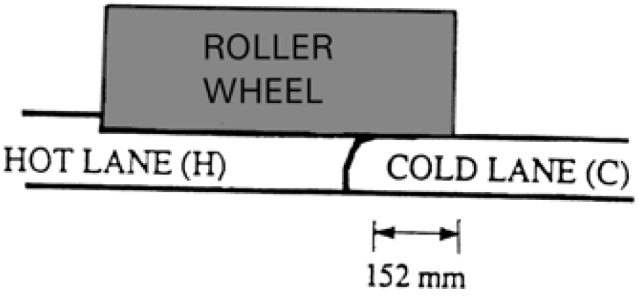


**Figure 2.22: Rolling from the hot side with an overlap of 152 mm. (Kandhal and Mallick, 1997)**

Similarly, if the edge of the roller compactor is placed at a distance of 6 inches from the joint, then it is called the "rolling from the hot side" with 152mm away from the joint (also called the 6 inch pinch in the literature), as shown in Figure 2.26. When the roller moves, it causes lateral displacement of the material in the confined area. As the material is trapped between the compactor and the edge, this increases the density of the asphalt mix at the joint. In Pennsylvania, the first pass was executed by placing the roller wheel 152 mm away from the joint, and the backward pass was made with a 152 mm overlap on the cold joint. Both passes were made in vibratory mode. Several contractors recommended this method for construction (Kandhal and Mallick, 2002).

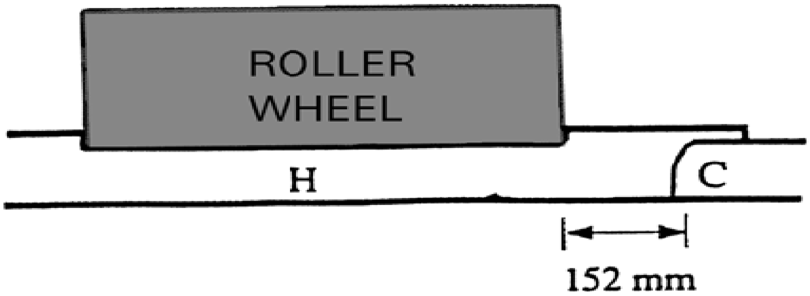


**Figure 2.23: Rolling from the hot side, 152 mm away from the joint. (Kandhal and Mallick, 2002)**

### 2.3.7 Rolling from the Cold Side

Unlike the hot side method, the compaction is done from the cold mat. In this case, there is an overlap of 152 mm (6 inches), but it is on the hot side. According to Kandhal and Mallick (1997), timing plays an important role here. The joint is compacted first in this case. Hence, a proper match between both surfaces can be obtained. The vibratory mode was used during the backward pass in Pennsylvania. Figure 2.27 shows compacting the joint from the cold side with a roller 152 mm on the hot mat.

As the compaction is done from the colder mat, the hot mat starts getting cooler, leading to difficulty in compaction of the pavement layer that can result in uneven surfaces on the mat.

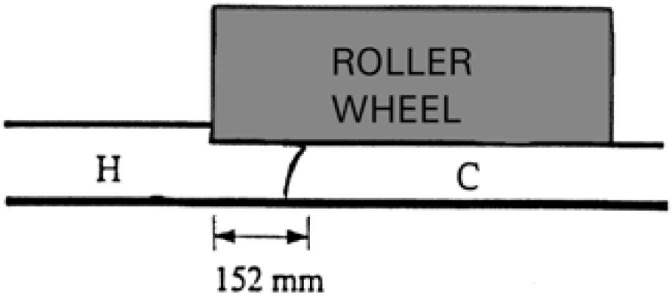


**Figure 2.24: Rolling from the cold side with an overlap of 152 mm. (Kandhal and Mallick, 1997)**

## 2.3.8 Joint Maker

Joint maker is another tool actively used in the construction industry to improve the performance of longitudinal joints. A joint maker is a metal attachment that is mounted on the paving screed that facilitates the pre-compaction of the material at the joint. The rolling in this technology is also done from the hot side of the lane. It helps in providing an adequate amount of material at the joint to match the other lane exactly. Along with this tool, a kicker plate is attached, which helps get a smooth vertical edge. Effective use of the joint maker technique helps increase the density at the joint and develops a better bond between the aggregates at the joint.

In Kentucky, Fleckenstein et al. (2002) evaluated the use of joint maker as a potential tool and concluded that it performed similarly to the control section. The authors stated that more research needs to be done to understand the equipment and its applicability better. In Maine (Marquis 2001), six different methods were used to construct longitudinal joints on the asphalt pavements. Visual inspection was carried out on the experimented sections after one year. Based on the inspection results, it was concluded that the joint maker technique achieved the highest density at the joint after the control section. However, severe cracking was observed on the pavement surface, and it was 15% greater than the control section. In Arkansas (Williams 2011), a notched wedge joint maker was used. This tool provided a wedge at the edge of the joint. The approximate cost of this instrument was $7,500. This technique achieved density levels close to the ones achieved with the joint heater and joint stabilizer. Figure 2-28 shows the joint maker equipment mounted on the paver and compacted wedge at the unconfined edge of the joint.

Figure 2.25: Notched Wedge Joint Maker by TransTech Systems, Inc. (Williams 2011)

### 2.3.9 Edge Restrainers

It is a well-known phenomenon that rolling off of the hot material while compacting at the joint causes problems in the compaction of the longitudinal joint, leading to premature distresses at the interface. To mitigate the impact of this problem on joint performance, an edge restraining device is added at the side of the roller to achieve higher joint densities. A hydraulically operated metal wheel or steel plates are used for this purpose. It helps to confine the material within the joint and compacts the material by continuously pushing it towards the joint. Figure 2.29 shows the side view of the roller mounted with a hydraulic edge restrainer, and Figure 2.30 shows a schematic front view of a hydraulically operated tapered wheel acting as a restrainer.

According to Kandhal et al. (2002), two passes in the static mode at an angle of 45° helped achieve the highest density at the joints and low air voids. A pavement condition survey was conducted to determine the performance of the joint after six years. It was noted that slight raveling and cracking were observed at the sections constructed with this device. Roadway sections constructed with this device consistently had the lowest performance among all the other methods used for joint construction.

In Kentucky, Fleckenstein (2002) used this method in Barren County. The cost of this edge restraining device was about $10,000. According to their evaluations, this device decreased the permeability at the joint. In Wisconsin, the edge restraining method provided the highest densities of all the tested methods but involved dependency on skilled labor (Kandhal and Rao, 1994).

Figure 2.26: Edge restraining device mounted on a roller. (Fleckenstein 2002)

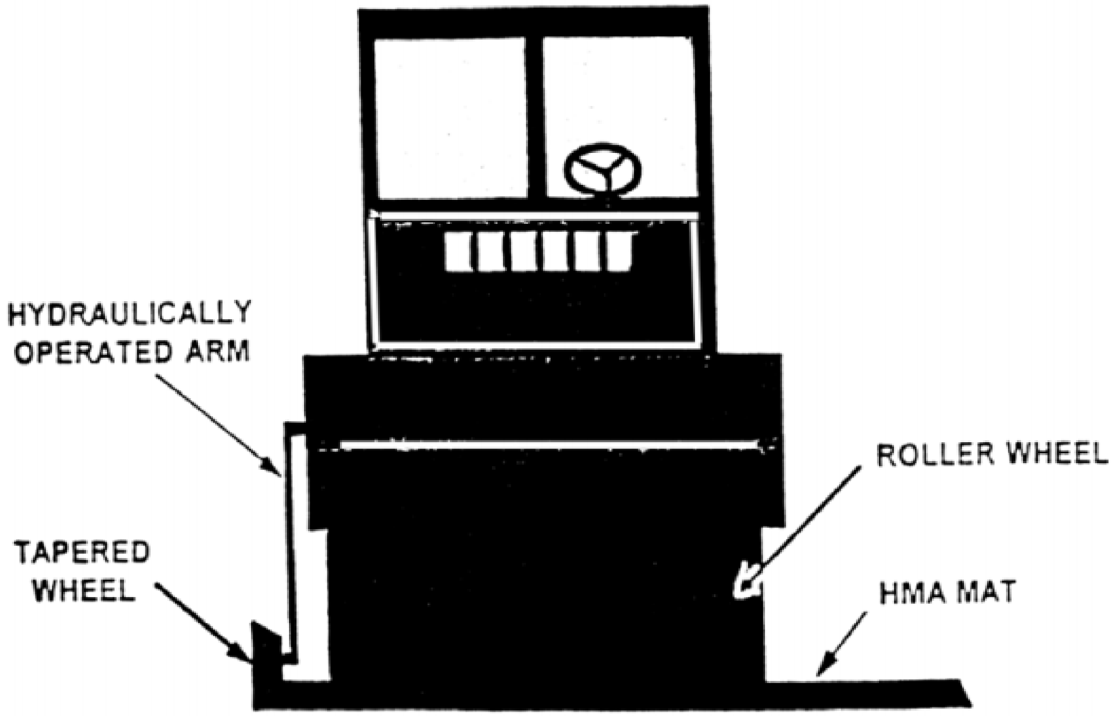


Figure 2.27: Edge restraining device (Kandhal et al. 2002)

## 2.4 SUMMARY

Joints are susceptible to failure in any structure. The best method to avoid or delay failure at joints is to not have joints in the first place. However, preventing longitudinal joints in pavements is challenging while constructing more than one lane at different times. These longitudinal joints form the weakest location on the pavement. The cracks start originating from the joints and propagate over the entire pavement. This issue leads to premature failure of the pavements, leading to significant maintenance and rehabilitation prior to achieving the desired service life.

From the literature, it can be concluded that the primary cause of failure is the low density at the joints. The traditional system of constructing one lane and then paving the second lane induces differences in the material temperature placed at the joint. This difference in temperature causes difficulty in compacting the area at the joint, introducing higher air voids. Density and permeability are the governing parameters for assessing the quality of joints. Hence, some state DOTs have developed protocols specifying minimum density requirements at the joints. Some research studies also used indirect tensile strength and X-ray CT imaging of the cores from the joints to evaluate their long-term performance. Based on the findings from this literature review and the results of this research study, recommendations to improve density and adhesion along the longitudinal joints were provided. Recommended construction and test methods are expected to increase the longevity of the joints and the pavements.

From the literature review, it is understood that an unconfined edge during construction is the real problem. Hence, several methodologies to deal with this issue were studied. Echelon paving and using infrared heaters for constructing longitudinal joints have been shown to achieve high densities but have practical and economic drawbacks. The use of butt joints and notch wedge joints has also been experimented with and seen to perform well in some case studies. However, the construction of a vertical butt joint requires a roller-mounted cutter, or a compacting wheel mounted on the paver or roller. This addition increases the cost and requires dependency on worker skills. Due to drawbacks from the aforementioned techniques, the use of joint sealants, joint adhesives, and joint stabilizers from various industries have been evaluated by many researchers to improve joint performance. It was generally concluded that joints treated with sealants and adhesives performed better by penetrating the asphalt layers and filling the voids. A significant majority of the research studies recommended those special products rather than special construction methods.

Some of the state DOTs in the U.S.A. have developed techniques and specifications to be used for constructing longitudinal joints. The majority of those methods and specifications had to be changed later due to the persistence of the same issues with longitudinal joints. All these research studies were conducted in the field, and no one construction technique has been shown to provide perfect results for achieving higher densities at the joints. In this study, laboratory investigation on simulating various techniques, such as using the infrared heater, vertical edge, notch wedge, and different joint sealers and adhesives, will be studied to develop the best joint construction method and products for Oregon.

Table 2.6 summarizes all the methods that have been experimented in the field to develop better longitudinal joints.

**Table 2.6: Joint Construction Techniques and Issues (McDaniel et al. 2012)**

| Joint Treatment | Advantages | Disadvantages | Likelihood of Success & Acceptance; Recommendation |
|---|---|---|---|
| Full Width, Echelon or Tandem Paving | -Avoids cold joint.<br>-Good performance. | -Only tandem can be done under traffic.<br>-Traffic control/safety issues with tandem.<br>-Echelon and tandem require two pavers and two crews, which increases cost.<br>-Need high-capacity plant. | -Work well when feasible, but rarely feasible mainly because of traffic.<br>-Implement when possible, but will not be routine. |
| Various Rolling Patterns (number and type of rollers, number and location of passes, timing of passes) | -Can change easily when conditions change (Temperature, mix behavior, etc.)<br>-Usually does not require additional equipment or manpower. | -Since there is not one rolling pattern that works in all cases, experience or some tested property is needed to determine what works best in a given situation. | -Changing rolling patterns is easy.<br>-Little to no impact on cost.<br>-Maintain the lack of restrictions for certain mixes. |
| Butt Joint | -Common and familiar.<br>-Can work well when properly constructed, | -Edge drop off requires pulling up adjacent lane (productivity impacts).<br>-Water can penetrate roadway easily if joint separates, especially if joints in underlying layers are not offset. | -Could work well with attention to detail, but experience shows that attention is sometimes lacking.<br>-Continue to require joint adhesive and fog seal. |

**Table 2.6 (continued): Joint Construction Techniques and Issues (McDanieal et al. 2012)**

| Joint Treatment | Advantages | Disadvantages | Likelihood of Success & Acceptance; Recommendation |
|---|---|---|---|
| Tapered or Notched Wedge Joint | -Avoid issue with edge drop off.<br>-Can perform well if properly constructed.<br>-Similar to safety edge, which is becoming more familiar and may provide confinement at the edge of lane. | -Requires compaction of the wedge.<br>-Notch and taper dimensions need to be appropriate for NMAS and layer thickness. | -Can be effective.<br>-Not attractive to contractors if there is a requirement to pull up adjacent lane.<br>-Consider requiring compaction (preferably with vibratory plate attached to paver) for wedge. |
| Edge Restraining or Precompaction Devices. | -Can increase density near joint. | -Requires skillful operator. | -Mixed performance at best.<br>-Not worth promoting. |
| Cutting Wheel | -Removes low density material. | - “Wastes” new mix.<br>-Requires equipment and manpower to cut and to remove debris.<br>-Requires skillful operator. | -Mixed performance at best.<br>-Not worth promoting. |
| Sequential Mill and Fill | -Removes low density material from unsupported edge at center of lane.<br>-Does not require new/more equipment | -May require milling sub to stay on job longer or return later.<br>- “Wastes” new mix.<br>-Milling action might damage adjacent mix in place. | -Expert opinions are mixed.<br>-Maintain contractor option.<br>-Evaluate existing sequential mill and fill projects to decide whether to encourage or restrict in future. |

**Table 2.6 (continued): Joint Construction Techniques and Issues (McDanieal et al. 2012)**

| Joint Treatment | Advantages | Disadvantages | Likelihood of Success & Acceptance; Recommendation |
|---|---|---|---|
| Infrared Joint Heater | -Avoids cold joint.<br>-Increases adhesion at interface.<br>-Works well in some places. | -Requires extra equipment and fuel.<br>-Lengthens paving train.<br>-Interfere with delivery trucks and paving crew.<br>-Safety issues.<br>-Can scorch mix. | -Mixed performance.<br>-Not worth pursuing. |
| Joint Advhesives | -Improve adhesion at the interface.<br>-No negative impacts on performance.<br>-Insurance against poor performance. | -Increase costs.<br>-Require equipment and manpower.<br>-Have not always demonstrated improvement in performance (permeability). | -Cost increases are expected to be low when used routinely; increased performance can easily offset increase in costs.<br>-Continue to require.<br>-Monitor performance to support future decisions. |
| Joint Sealer | -Reduce permeability around the joint.<br>-No additional equipment required.<br>-No negative impacts on performance.<br>-Insurance against poor performance. | -Increase costs.<br>-Have not always demonstrated improvement in performance (permeability).<br>-Must be applied before pavement markings and after coring. | -Cost increases are expected to be low when used routinely; increased performance can easily offset increase in costs.<br>-Continue to require.<br>-Monitor performance to support future decisions. |

# 3.0 SURVEY RESULTS AND ANALYSIS

## 3.1 ODOT SURVEY AND DISCUSSION OF THE RESPONSES

A Qualtrics survey related to longitudinal joint construction was prepared to collect information and gain insights into the various joint construction methods in Oregon. The target groups were the Oregon DOT and the paving industry in Oregon. Moreover, this survey aimed to determine the quality control and assessments that are being followed in Oregon. While ODOT directly responded to the survey, the asphalt paving industry decided that it would be more effective to discuss all joint performance-related issues in a meeting rather than anonymously responding to the questions in the survey. The meeting notes, and the important takeaway points from the industry meeting are also provided in this chapter.

A total of 23 participants responded to this survey from ODOT, and the results are presented in this section. Among the respondents, three people had experience ranging from 2-5 years, while 1 person had experience of more than 5 but less than 10 years. Nine respondents had 10-20 years of experience, and the remaining 10 worked on asphalt pavements for more than 20 years. In other words, the respondents were from diverse experience levels, with the majority (83%) having more than 10 years of experience. Figure 3-1 represents the work experience of different respondents. The majority of the respondents were engineers at the Oregon Department of Transportation (ODOT).

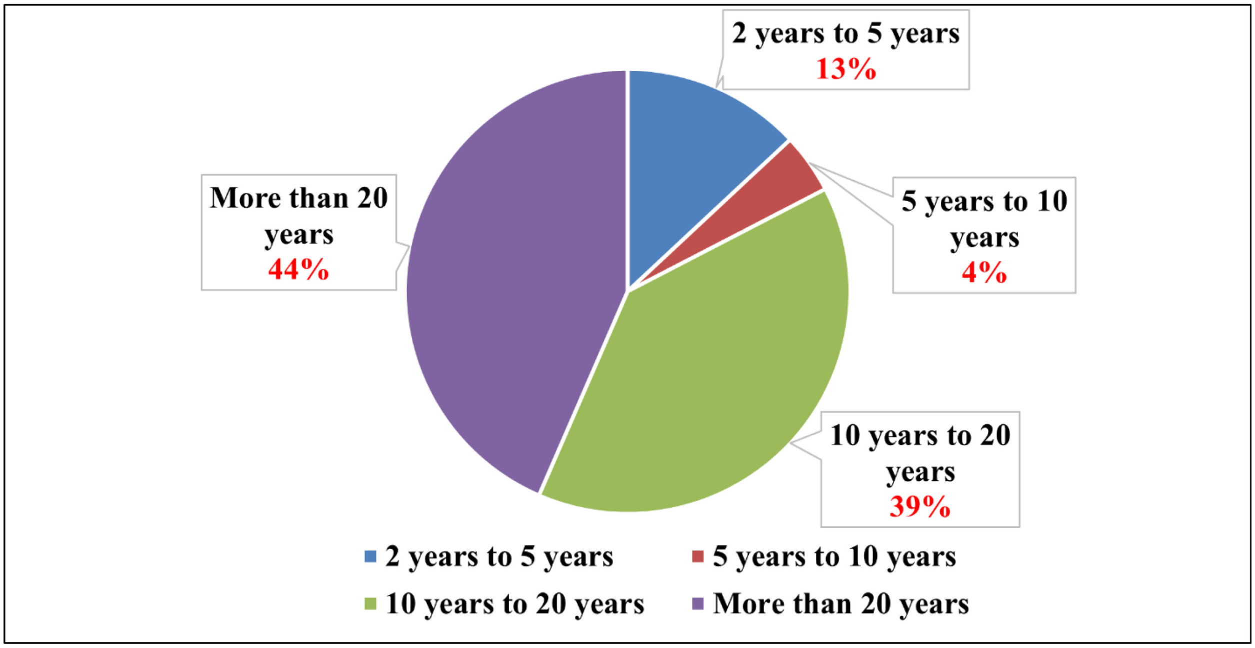


**Figure 3.1: Number of years of experience (Number of Respondents: 23).**

The questionnaire survey designed for the present study is discussed in the subsequent sections.

The first question was framed to understand the importance of longitudinal joints in pavement sustainability.

Figure 3.2 depicts the results from the respondents. As can be seen, 95% of the respondents believed that the quality of longitudinal joints in asphalt pavements is important. This forms the motivation for the present research work.

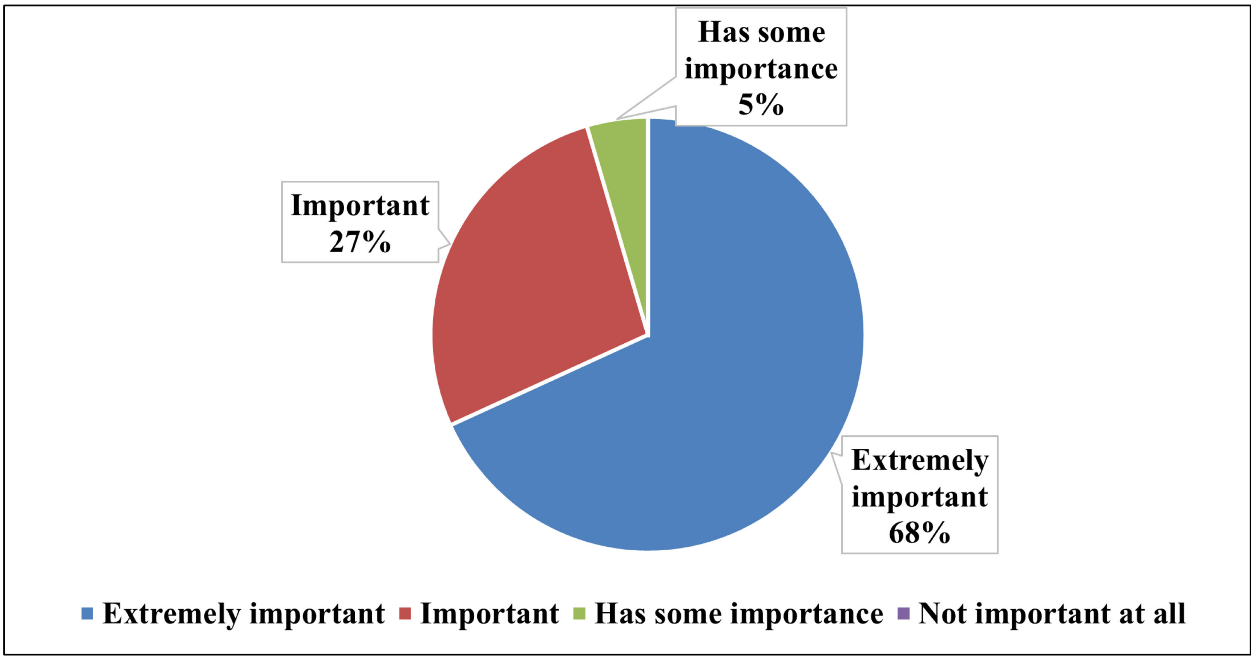


**Figure 3.2: Importance of longitudinal joints.**

To understand whether the pavements in Oregon failed primarily due to longitudinal joints, the survey asked whether longitudinal joints are a major cause of asphalt pavement cracking in Oregon.

Figure 3.3 illustrates the results from the respondents. Evidently, 55% of the respondents believe that longitudinal joints are one of the major causes of cracking failure in Oregon, while 45% think that cracking failure is not related to longitudinal joints.

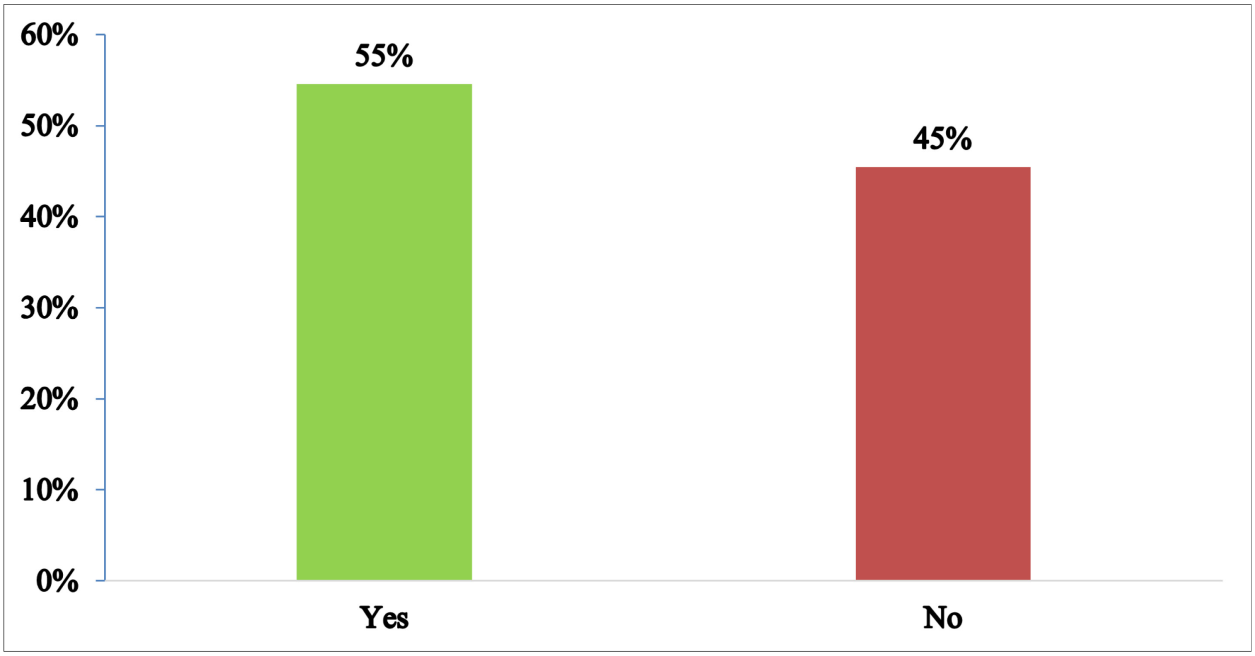


**Figure 3.3: Survey result for the question asking whether longitudinal joints are a major cause of cracking (Number of respondents:22).**

From the literature review, it was observed that density is one of the primary concerns. It was seen that the area along the joint had higher air voids compared to the asphalt mat, which resulted in moisture infiltration and cracking failure. To understand whether density is the suitable method to assess joint construction, the respondents were asked to answer whether density is an effective way of monitoring longitudinal joint performance.

Figure 3.4 presents the results of this particular survey question. More than 70% of the respondents agree that density is an effective way to monitor longitudinal joint performance. On the other hand, 29% of the people contradict.

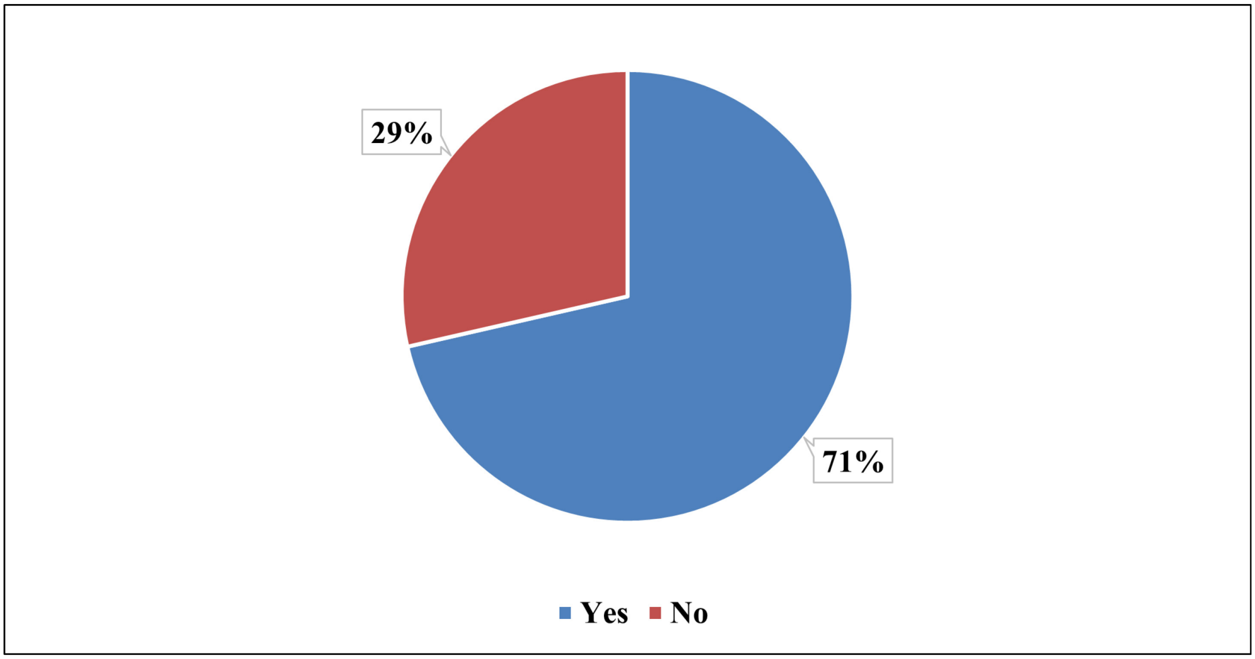


**Figure 3.4: Density as an effective way for monitoring joints (Number of respondents:22).**

The density of the asphalt pavements is monitored either by a nuclear density gauge or by extracting the cores and then conducting the saturated surface dry density test in the laboratory. However, it was essential to know if Oregon follows a specific technique to assess the quality of joints and, if the answer is yes, what specific method is followed for evaluating the longitudinal joint performance.

Figure 3.5 shows the survey results regarding the technique for monitoring longitudinal joint density. According to 86% of the respondents, Oregon currently does not monitor the density along the longitudinal joints, which may be one of the reasons for asphalt pavement failure along longitudinal joints. However, 14% believe that extracting cores and conducting density measurements on these cores in the laboratory is used for density evaluation.

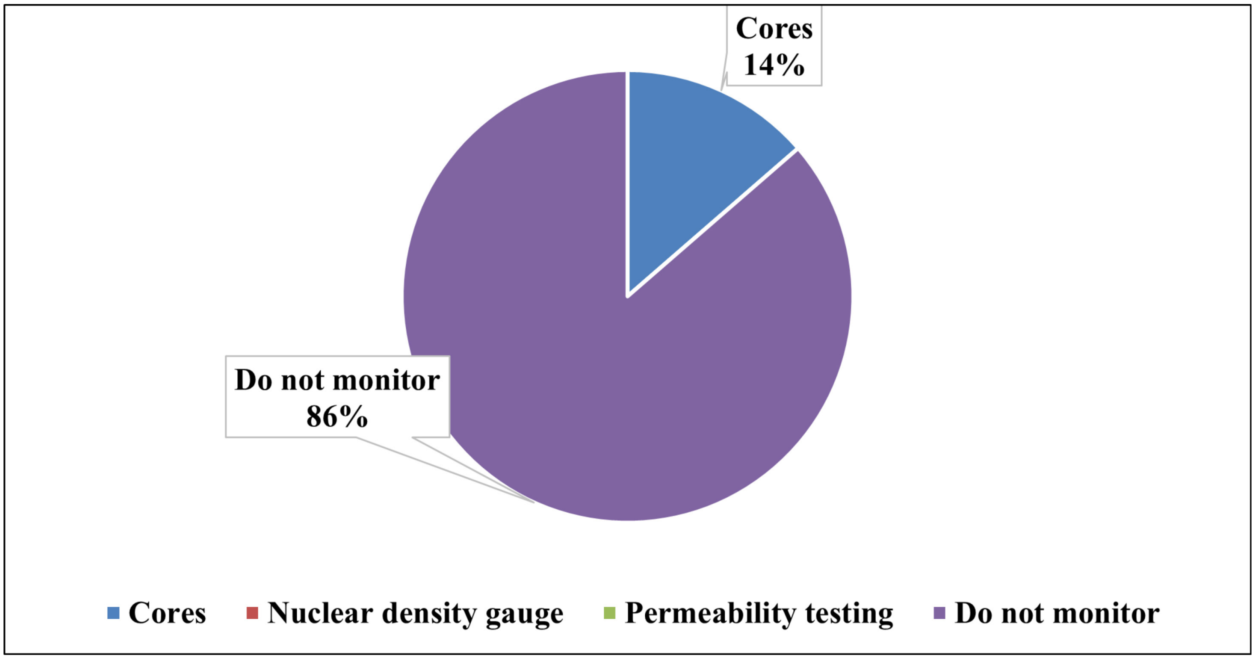


**Figure 3.5: Technique for monitoring longitudinal joint density (Number of respondents: 22).**

As mentioned in Chapter 2.0, according to several past studies, the primary cause of joint failure is expected to be the low density along the joint area due to improper compaction of the new asphalt placed next to the aged asphalt.

Figure 3.6 presents the expected range of densities achieved along the joint in Oregon according to those who responded to the survey at ODOT. Most of the respondents (81%) agree that the density obtained along the joint is less than 90%, which is one of the primary concerns. On the contrary, only 18% of respondents believe that the density along the joint is in the range of 90-92%. This suggests that the density at the joint is comparatively lesser than those obtained in the center of the asphalt pavement.

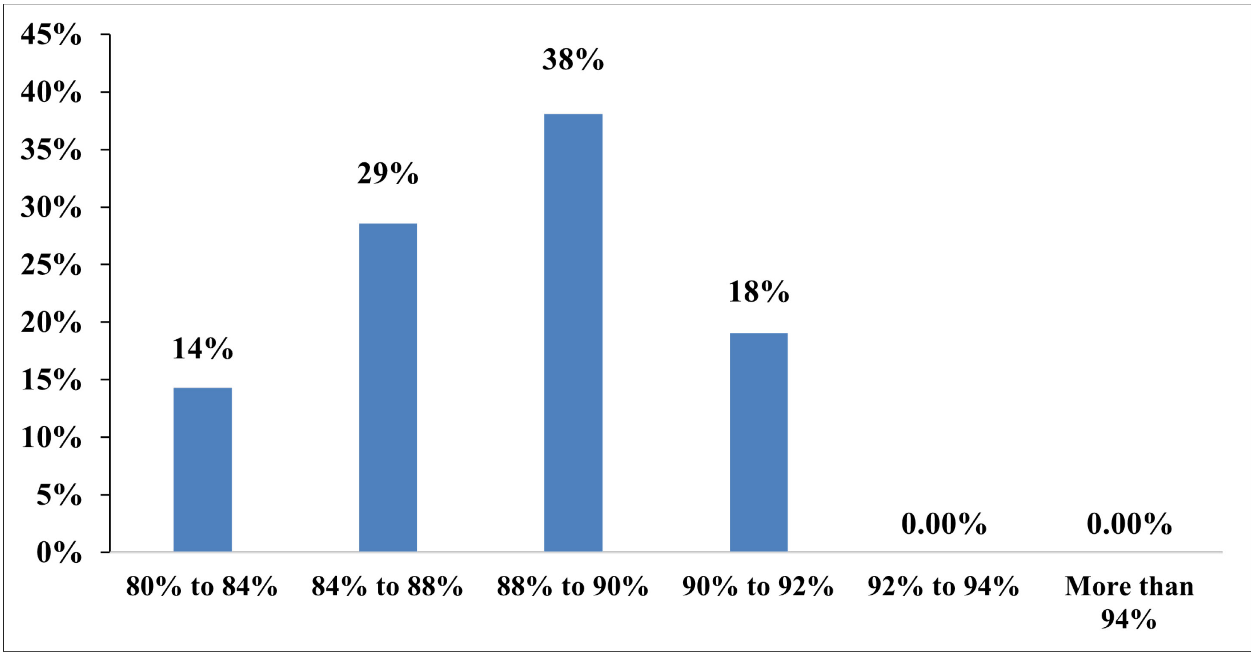


**Figure 3.6: Average expected density achieved along longitudinal joints.**

Typically, three types of rollers are employed during the construction of asphalt pavements: vibratory, non-vibratory, and pneumatic. The survey asked which roller provides the best compaction in the field to understand the effectiveness of different types of rollers used for construction.

Figure 3.7 depicts the results of the particular survey question. As is obvious, the vibratory roller is expected to be effective in providing adequate compaction. This was confirmed by half of the respondents. However, 25% of the respondents believed that the non-vibratory and pneumatic rollers are better for achieving high density in construction.

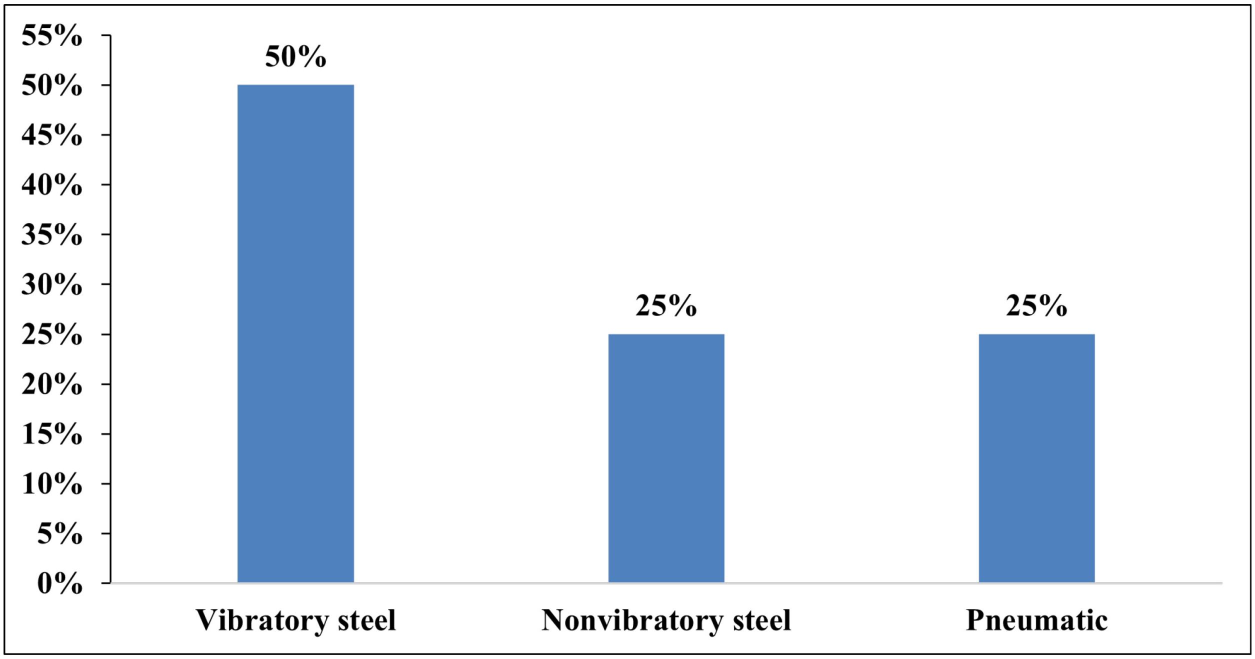


**Figure 3.7: Type of roller for best compaction (number of respondents: 22).**

To improve the density along the longitudinal joints, different joint construction techniques, such as the butt/restrained or wedge, are generally utilized. Different transportation agencies have experimented with these techniques, as summarized in Chapter 2.0. From this perspective, the survey respondents were asked about the joint construction methodology that is generally followed in Oregon. This question provides a relative comparison between the selection of the butt/restrained edge technique and the wedge construction method.

The results for the most prominent joint construction method are shown in Figure 3-8. Around 73% of respondents answered that Butt joint construction is mainly followed for longitudinal joint construction. This result was expected since most of the highway construction in Oregon exhibits mill and fill construction. However, 28% of respondents answered wedge joint is followed for joint construction.

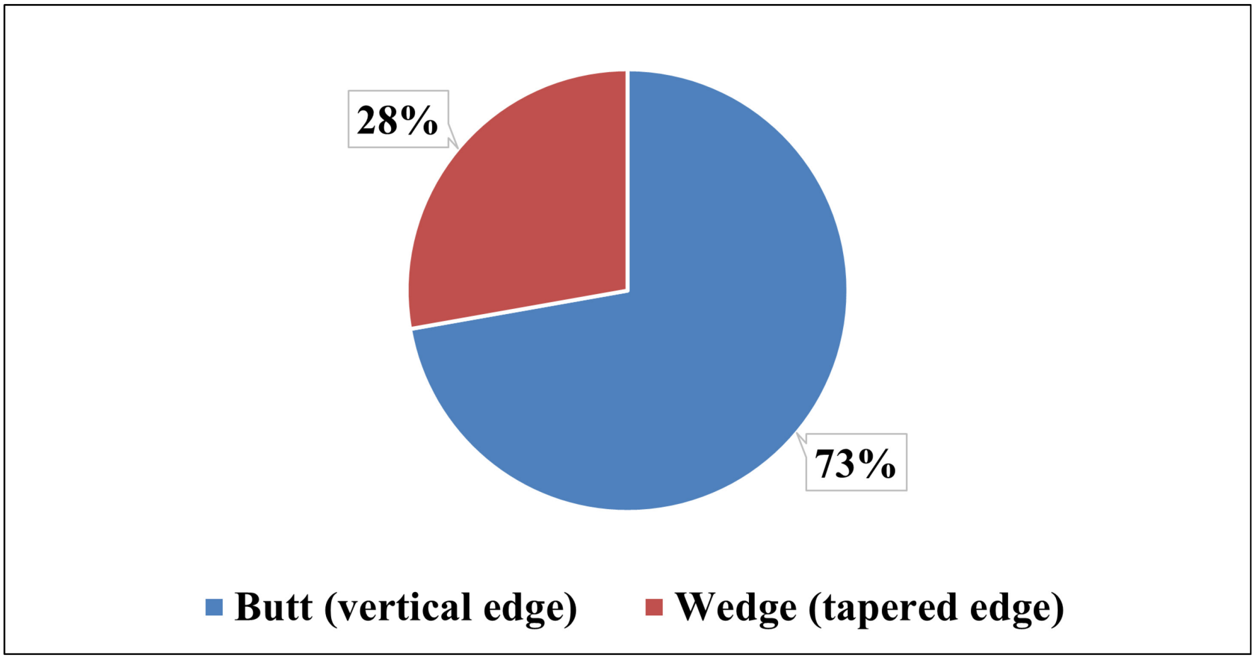


**Figure 3.8: Longitudinal joint construction technique followed in Oregon.**

The method of compaction along the longitudinal joint is important to achieve the required density in that area. Generally, the hot overlap and cold overlap are mostly followed for compaction. In the hot overlap, the roller compactor rolls in such a way that the 6 inches of the roller is placed on the cold mat, while in the cold overlap, the 6 inches of the roller is rolled over the hot asphalt. The respondents were asked about the most followed method for compaction.

Figure 3.9 depicts the results from the pattern generally followed for longitudinal joint construction in Oregon. As can be observed, 94% of the respondents revealed that hot overlap is the most followed technique for longitudinal joint construction.

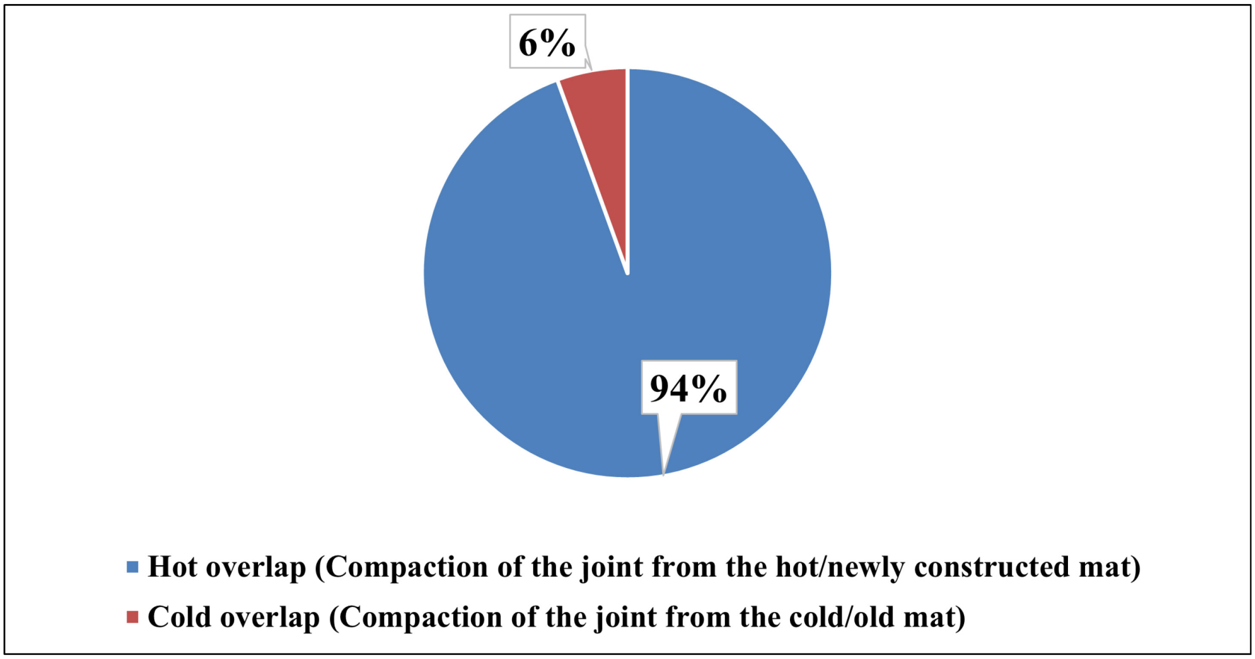


**Figure 3.9: Method for compacting longitudinal joints in Oregon.**

It is well known that compaction along the joint is difficult because of the temperature difference between the hot and the cold mat, which generally results in an area of low density. This results in high air voids, which is the primary reason for the water and air intrusion. This causes the joint to crack due to moisture damage and the excessive aging of the asphalt material along the joints as a result of higher air void content. It is also observed that these joints are sometimes sealed to avoid the intrusion of exterior material into the pavement.

Hence, the respondents were asked if the sealing of joints is the common practice in Oregon after the multilane pavements are constructed.

Figure 3.10 illustrates the results of this survey question. As per the respondents, the joints along the pavement are not sealed right after construction. This can be attributed to the fact that sealing the joints may result in an increase in the cost of construction.

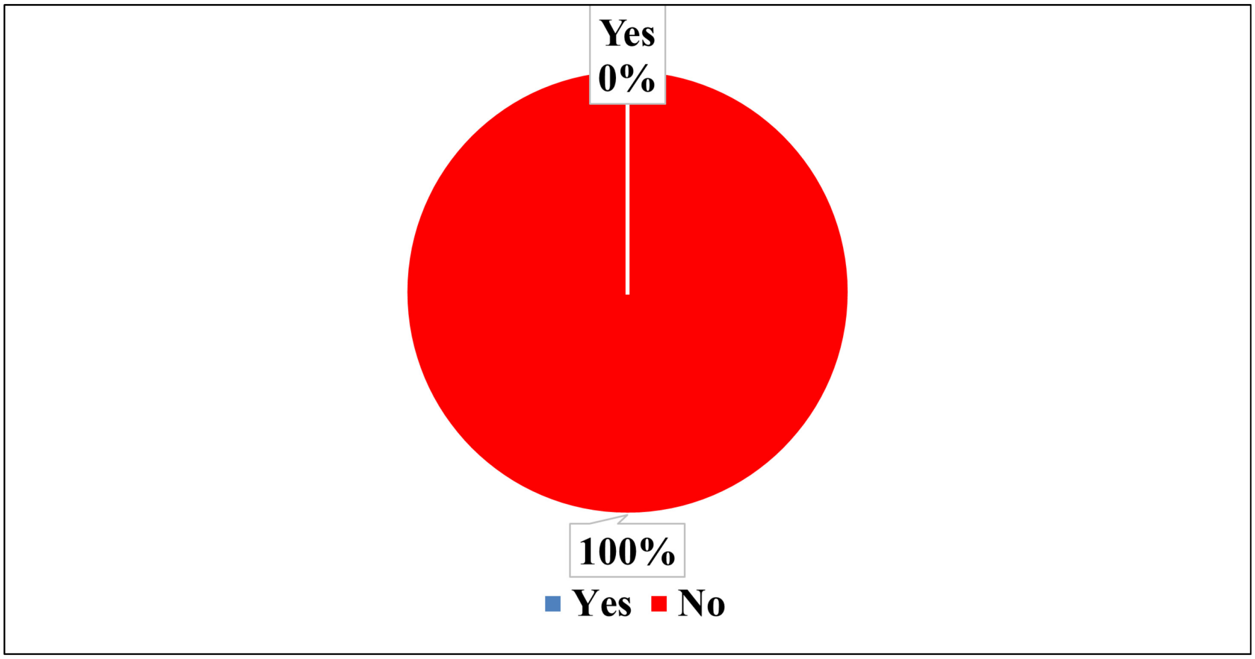


**Figure 3.10: Sealing of entire joint after construction.**

As stated earlier, different longitudinal joint construction methods are practiced to reduce the air voids and boost the cracking performance. These methods involve the use of butt/restrained edge technique, wedge joint construction, use of sealants to improve the bond, the use of infrared heating to increase the temperature of the cold mat, and Echelon paving.

A question was asked in the survey to determine which longitudinal joint construction technique among butt joint, wedge joint, use of adhesives, joint heater, joint maker, and echelon paving is expected to perform the best.

Figure 3.11 shows the opinions of the respondents regarding these techniques in improving joint performance. As per the views of the respondents, the echelon paving that simultaneously uses two pavers to construct multiple lanes in asphalt pavements is expected to lead to the highest performance. The primary reason is the lower temperature difference along the joint, which should result in easy and effective compaction. However, one of the respondents reported that this increases the cost of paving and requires more crew; hence, it is rarely followed in Oregon. In addition, echelon paving requires at least a two-lane traffic closure, which may not be possible in many cases due to mobility concerns. On the other hand, the Butt joint construction is expected to result in fair or better performance, according to the responses. A significant percentage of respondents also stated that tack coats should be applied along the joint on the cold mat to improve the bonding capacity and density between two pavements. Respondents had the least confidence in Wedge joint and joint heater methods.

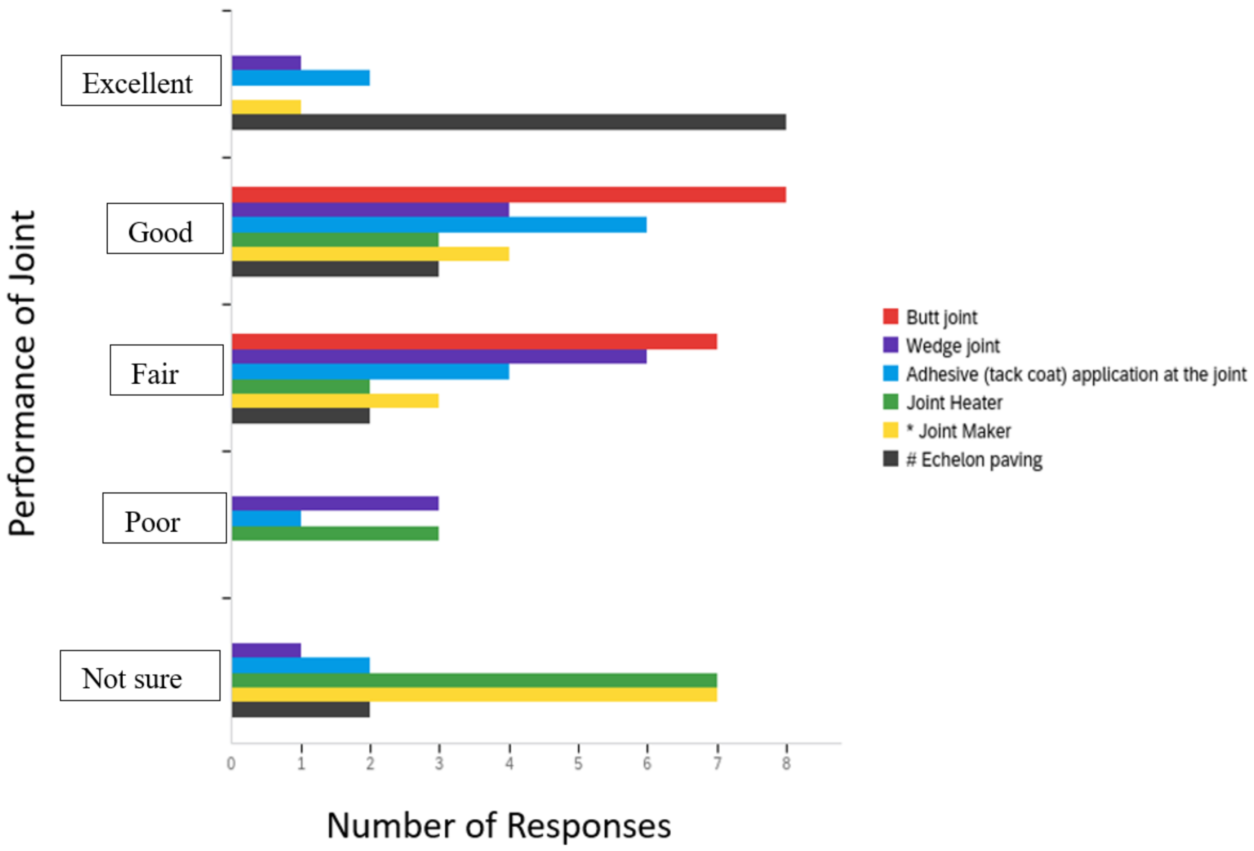


**Figure 3.11: Expected performance of longitudinal joints constructed using different techniques** – (** Joint maker: A special jig attached to the paver to restrain and compact edges better. # Echelon paving: Paving simultaneously using two pavers).*

Centerline rumble strips are an important part of the pavements that help reduce crashes and alert drivers while unintentionally changing lanes. However, these rumble strips are constructed by grinding the top surface of the asphalt pavement. From past research works, it was observed that the installation of rumble strips generates micro-cracks (Weaver et al, 2023 a, b, c). Hence, the survey respondents were asked how important the location of the rumble strip is with respect to the longitudinal joints.

Figure 3.12 shows the results of this question. 96% of the respondents think that the location of the rumble strip with respect to the joint is critical. This is because milling the asphalt along the low-density joint area will increase the chances of cracking failure along the joints.

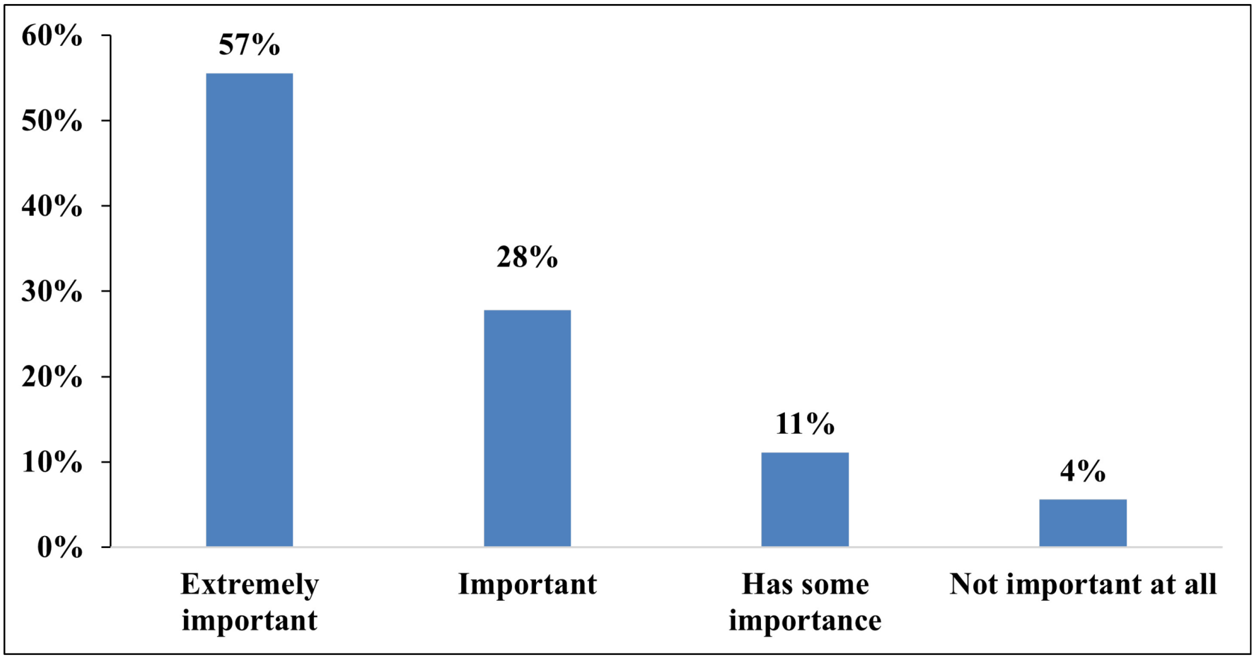


**Figure 3.12: Importance of rumble strip location with respect to longitudinal joints.**

A question regarding the need for method and density specifications for longitudinal joints was also asked in the survey. Results are presented in Figure 3.13. It can be observed that two-thirds of the respondents recommended having both the density and method specs, while 33% think that a minimum density spec would suffice.

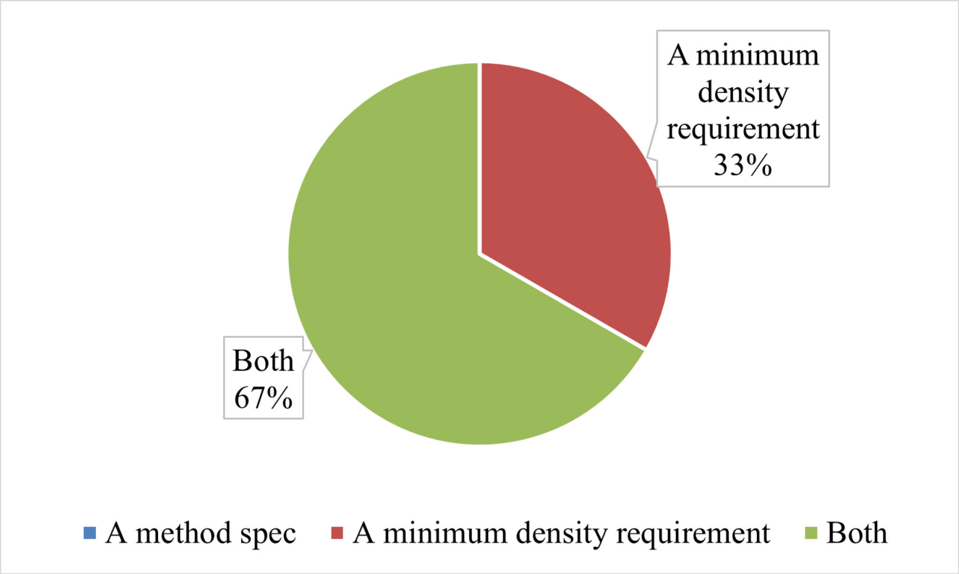


**Figure 3.13: Strategies to achieve the best joint performance.**

An open-ended question was also asked at the end of the survey. The question was, "According to your experience, what would you suggest to improve the performance of the longitudinal joints in Oregon?". 14 people from ODOT responded to the question with important feedback. Those responses are listed here without any modifications:

1. Develop a density requirement with cores. The use of an incentive/disincentive approach should be considered.

2. Use a stratified transverse offset with the longitudinal distance being the random location, but make sure you test one foot off both edges and middle of each half of the lane and center of the lane. Same offsets as the Control Strip.

3. A density spec with enough encouragement to make it in the contractor's best interest to use best practices; I do not know how effective the joint heaters are in practice, but I would like to see a pilot with one and see if they are; same with some of the overbanding post and emulsion or hot asphalt applications at the joint before paving.

4. Density requirements with stiff penalties are needed.

5. Specifications that specifically address the longitudinal joints and a method of enforcement for all.

6. Measure and pay for good densities at the joint and offset the joint for CLRS.

7. Contractor training and improved specifications. Requiring pneumatics would help, too.

8. Add tack to joint installation. It also needs to be done within a few days.

9. If we know the best method to achieve density at the joint, then we should make it a specification and not just a best practice. By specifying the required density at the joint, we could leave it up to the contractor to determine the best method to achieve that result.

10. ODOT longitudinal joint specifications have been the same at least as far back as 1991. We have been partnering with the industry for more than 20 years to try and improve the performance of longitudinal joints, mostly attempting to do so through conference presentations, education, and training for best practices. This has a very limited effect, and the attention to detail is not consistently followed by industry and by Agency inspectors who may have their own opinions about longitudinal joint construction best practices. If we are going to be serious about improving joint performance, then it is time to include a density specification. Until we do so, the use of best practices and joint performance will remain inconsistent at best.

11. Clear specifications on how to construct a longitudinal joint, prescriptive specification. Also, a density requirement on joints. Add the joint density to the ODOT Statistical Analysis, tied to a bonus or penalty.

12. Make a standard on grinding joints. That is where I see the biggest issues coming in. The joint grinding is ridiculously bad and needs work like a spec stating how fast the grinder can go.

13. Having a standard compaction method must be required.

14. Apply tack to the entire joint during construction. Seal any crack that develops with rubber crack seal material at the first opportunity after the development of a crack.

## 3.2 TAKEAWAY POINTS FROM THE INDUSTRY MEETING

A meeting with the paving industry was held on 4/15/2022. The meeting was organized and led by John Hickey, Executive Director of the Asphalt Pavement Association of Oregon (APAO). Dr. Erdem Coleri attended the meeting from OSU to ask some of the survey questions and collect industry feedback. A total of 15 industry members from different companies attended the meeting. A summary of the main takeaway points from the meeting is provided here:

**1.** Some industry members raised some concerns about establishing a density spec for longitudinal joints. Since joint density is mostly affected by material properties, joint density will be highly correlated with main mat density. Since ODOT already has a density spec, implementing a separate joint density spec may not make sense. However, not all the attendees agreed with this statement.

**2.** 6 inches of joint pinch is the standard, but not all contractors are following it. Dealing with the crown can be problematic in some cases.

**3.** All attendees think that complete roadway closures on weekends (52-hour weekend closures) are the most effective way to eliminate longitudinal joint issues (since there will not be any joints). This way, paving can happen much faster, and higher-quality construction can be achieved. Safety issues would also be eliminated in this way.

**4.** Industry members agree that tacking the joint can help improve the joint performance. However, it is not always possible to tack the joint due to traffic flowing on the other side of the road.

**5.** Material placement is one of the most critical components of achieving high-density joints. Need to have some material on the cold mat but not at an excessive level. Raking around the joint is a major problem, resulting in segregation.

**6.** Rolling from the cold side might help improve joint performance. However, crushing rocks on the cold mat would create other issues. In many cases, it is also not possible to compact the pavements from the cold side due to the issues with the traffic closures (not being able to close two lanes at the same time).

**7.** Rolling from the cold side may improve joint density. However, it is expected to increase roadway roughness. They suggested that OSU find a way to measure roughness after construction if rolling from the cold side is going to be evaluated as an option.

8. Saw cutting joint is a method rarely used in Oregon.

9. They were all against the use of pneumatic tire rollers for joint construction. They do not think that these rollers will improve compaction at the joints. They also leave a lot of tire marks and create a rough surface. Maintaining tires is also another issue. However, they suggested using those for chip seal construction (and avoiding roller compactor use) to reduce aggregate damage.

10. No joint sealing has been done on the joints during construction. According to one of the attendees, some cities and counties are sealing joints during construction.

11. **A unified roller compactor training program needs to be established in Oregon**. Every contractor follows a different process, and no uniform training process exists. Superintendent training is also needed to start improving the process from the top.

12. A method spec should be developed. According to the industry members, a strong method spec developed in communication with ODOT and the industry based on the findings from this research project can help improve joint-related issues in the long run.

13. A density spec might also help, according to some industry members. However, density spec may not work when the joint is on a crown. Another concern was related to the cost. According to the attendees, reaching a higher density in paving is almost always more expensive.

## 3.3 SUMMARY

The major takeaway points from the ODOT survey and the industry meeting are summarized in Table 3.1. Both the industry and ODOT think that a method specification is needed for longitudinal joint construction in Oregon. ODOT also strongly supports the development of density specifications. The crown issue for joint density measurement brought up by one of the industry members can be overcome by requiring core or dielectric profiling system (DPS) based density measurement requirements for longitudinal joints. Developing a unified roller compactor operator specification is also suggested by the industry. Rolling from the cold side construction method and using infrared heaters during construction were not supported by both the ODOT and the industry. Both ODOT and the industry supported the idea of trying tack coat applications (and potentially other products) on longitudinal joints as a way to improve performance.

**Table 3.1 Summary of ODOT survey and the industry meeting.**

| ODOT | INDUSTRY |
|---|---|
| A density and a methods spec are both needed in Oregon. | A method spec is needed with an associated **unified roller compactor training program.** A density spec might also help, according to some of the attendees (some were against it). |
| Rolling from the cold side did not receive a high level of support. | Rolling from the cold side might result in surface smoothness issues. |
| 25% of the respondents see pneumatic tire rollers as a potential method to improve joint performance, while 75% do not recommend them. | All are against the use of pneumatic tire rollers for joint construction due to expected smoothness and compaction issues. |
| Supported requiring tack coat application on the cold joint before construction if the research recommends it. | Supported tack coat application on the cold joint before construction. Trying other products to improve joint density was also recommended by one of the attendees. |
| The respondents did not provide significant support for infrared heaters. | The practicality of infrared heaters in a paving process was questioned. The cost was another concern. |

# 4.0 LABORATORY INVESTIGATION OF LONGITUDINAL JOINT PERFORMANCE

## 4.1 INTRODUCTION

Asphalt concrete pavements are designed to withstand heavy and repetitive loads throughout their intended service life of 10-15 years. When hot mix asphalt is placed next to a previously constructed lane or shoulder during construction, a longitudinal joint is formed along the interface. Longitudinal joint construction in asphalt pavements is the most critical phase of the construction process, as it is difficult to achieve a consistently high density of longitudinal joints similar to the mat density. This issue often affects the structural integrity and results in premature failure of the asphalt pavements. Since there are different longitudinal joint construction strategies, finding the most effective strategy/technique is not straightforward. The probable reason for non-uniform density along the pavement is the difficulty in simultaneously paving the entire pavement width. In actual practice, construction agencies use the traditional method of constructing one lane first, followed by the adjacent lane on a different day. However, it raises concerns related to compaction along the interface of the adjacent lanes. In addition, when the new lane is constructed adjoining the previously constructed cold lane, a temperature difference occurs along the interface, leading to a low interfacial bond between the new and old asphalt pavement. This may also be one of the factors that contribute to a lower density of the pavement at the location of longitudinal joints. As per the previous research studies (McDaniel et al. 2012, Williams 2011), the density range for satisfactory performance of longitudinal joints should be around 89% - 92%.

Pavement construction agencies are utilizing different longitudinal joint construction methods to enhance longitudinal joint performance by improving the density. These techniques are categorized into three distinct groups that are mostly based on: (a) compaction methodology or rolling techniques, (b) utilization of longitudinal joint sealants or alternative methods to reduce voids along the longitudinal joint, and (c) creating different longitudinal joint shapes along the pavement edge to enhance the compaction and bond between asphalt pavements (by avoiding the aggregates to be pressed into the cold mat and then retreat from the stiff-cold mat under heavy compactor loads). These techniques are discussed in detail in the literature review section of this report (Chapter 2.0). As determined from the literature review, the primary reason for low density is the temperature difference along the edge of the pavement between two adjacent lanes. Hence, various researchers (Kandhal & Mallick 1996, Toepel 2003, Huang et al. 2010, Nener-Plante 2012) recommended heating the edge of the longitudinal joint before compaction. The edge of the longitudinal joint can be heated using a microwave or infrared heater. It is generally believed that heating improves the compaction along the longitudinal joint and enhances durability by increasing the interlocking between the cold and hot asphalt. However, the excessive heating of binder at the longitudinal joint may cause excessive aging and reduced ductility, leading to premature cracking failure along the interface.

Since there are different longitudinal joint construction strategies and techniques, the performance of the longitudinal joints prepared with these techniques is not consistent. The success of each application is also expected to be a function of the mixture constituents, which are variable across different states. The primary objective of this section was to determine the effective longitudinal joint construction strategies for the pilot section constructions in the field.

## 4.2 MATERIALS AND METHODS

A plant-produced asphalt mixture was obtained from a Level 4 (mixture design level for the highest Equivalent Single Axle Loads (ESAL) highways in Oregon) construction project in Roseburg, Oregon. The mix contained 30% recycled asphalt pavement (RAP) material and 70% virgin aggregates and binder. PG 70-22ER, a polymer-modified asphalt binder, was used to produce the asphalt mix. Figure 4-1 presents the aggregate gradation of the procured asphalt mixture.

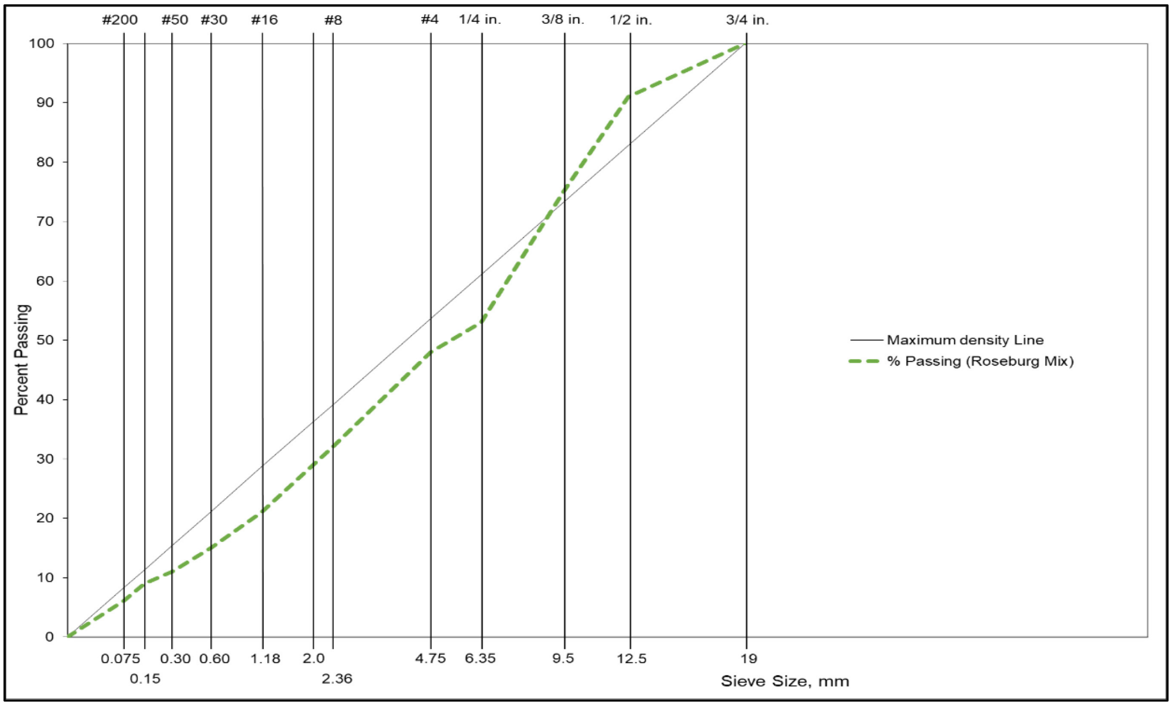


**Figure 4.1: Gradation curve for the sampled asphalt mixture on a 0.45 power chart.**

## 4.3 EXPERIMENTAL PLAN

To assess the impact of various longitudinal joint construction techniques, a total of 8 strategies (plus a control) were selected based on a comprehensive review of existing literature. The study aimed to investigate the effects of different adhesives, namely tack coat (at double application rate along the longitudinal joint) and void-reducing material. The influence of heating the longitudinal joint interface using an infrared heater was also examined. Apart from the application of adhesives and heating effects, the laboratory component of the study evaluated the effects of three distinct edge construction methods: i) restrained edge construction, ii) wedge construction, and iii) loose edge construction.

A series of experiments were conducted in the laboratory to assess the performance of longitudinal joint samples produced by following the methods outlined in the previous paragraph. Experimental design includes density measurement, indirect tensile strength, fracture energy, Hamburg wheel tracking test (HWTT), and determination of tensile strength ratio (TSR) parameter. A hydraulic roller compactor was used to simulate construction and produce the block samples, and subsequently, cylindrical cores of 150 mm in diameter were extracted from these blocks for testing. Table 4.1 outlines the experimental plan for the laboratory testing of both cylindrical and block samples.

**Table 4.1: Experimental plan for longitudinal joint study.**

| Test | Strategies* | Replicates | Total tests | Specimen type |
|---|---|---|---|---|
| **CoreLok Density** | 8 | 4 | 32 | Cores |
| **Indirect Tensile Strength (IDT)** | 8 | 4 | 32 | Cores |
| **Tensile Strength Ratio (TSR)** | 4 | 4 | 16 | Cores |
| **Hamburg Wheel Tracking Test (HWTT)** | 8 | 4 | 32 | Blocks |

*Control specimen
Loose edge technique (LE)
Wedge longitudinal joint
Loose edge with low tack coat (LE Low Tack)
Loose edge with high tack coat (LE High Tack)
Restrained edge with high tack coat (RE High Tack)
Restrained edge – Infrared heating 85°C (RE Low Temp)
Restrained edge – Infrared heating 95°C (RE High Temp)
Void Reducer

## 4.4 SAMPLE PREPARATION METHODOLOGY

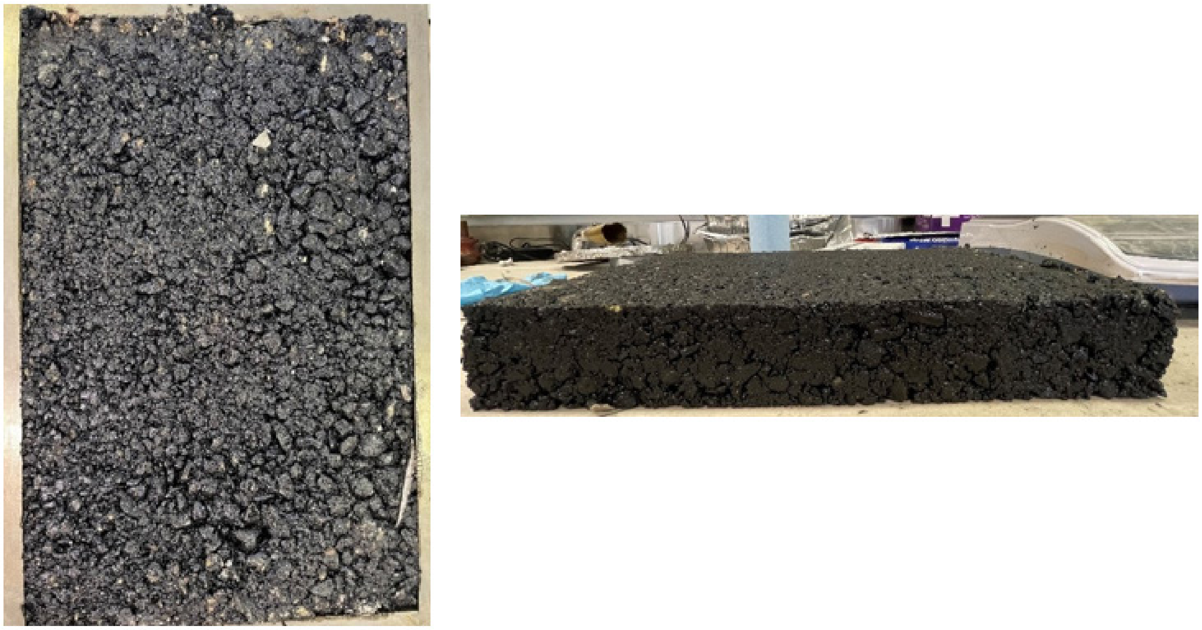
In this study, the plant-produced asphalt mixtures were procured from an asphalt mix plant. The amount of loose mix required for the preparation of samples was determined using the volumetric data (bulk specific gravity and the theoretical maximum specific gravity). The weighed quantities of the loose mix were subsequently placed in an oven at their respective compaction temperature. Following the conditioning process, the loose asphalt mixture was poured into a preheated metal mold to produce a rectangular slab specimen. A hydraulic roller compactor was employed to compact the asphalt mixtures, which allowed the aggregate particles to move relative to one another and orient themselves in their lowest energy positions that emulated in-situ compaction. As stated, the laboratory examination involved the investigation of various strategies and construction techniques. The production details of these strategies and techniques are described in subsequent sections.

### 4.4.1 Control Strategy

The control strategy involved replicating the center portion of an asphalt mat (no joint). This was achieved by compacting the entire asphalt block without any longitudinal joints. Figure 4.2 describes the detailed procedure followed for constructing control specimens. The predefined mass of the production mix was loaded into the compactor molds in two separate lifts, as shown in Figures 4.2a and 4.2b. Each lift comprised half the total mass required to obtain a rectangular slab specimen with 7 ± 0.5% air voids. Through trial and error, it was determined that less than 25 passes of the steel roller were necessary to achieve the desired density. After running the specified number of passes (25 passes to achieve the required air void content), the compacted asphalt block with a height of 60 mm was obtained, as depicted in Figures 4.2c and 4.2d. It is worth noting that the same number of passes were employed to ensure an accurate comparison between different longitudinal joint construction techniques. According to the preliminary assessments, 25 passes were more than enough to reach the 60mm specimen thickness and the target 7 ± 0.5% air voids.

a) Lift 1 with half of the total mass

b) Total material in the mold



c) Control final sample top view

d) Control final sample side view

**Figure 4.2: Specimen preparation of control specimens.**

### 4.4.2 Loose-Edge Compaction Technique

This construction technique simulates the condition in which the pavement edge is constructed without any restraint. This type of technique is commonly followed to build new roads in the United States. In this methodology, the absence of restrictions (confinement) allows the asphalt mixture to flow outward during compaction. Figure 4.3 describes the steps followed for fabricating the specimens using the loose-edge technique. As illustrated in Figure 4.3a, a steel spacer was used to align the material within the mold properly and ensure it remained in place. To replicate this technique, half the mass of the entire block specimen was placed in the preheated molds, as depicted in Figure 4.3b. The spacer was removed before placing the mold under the roller compactor. The passes of the roller compactor caused the material to spread outward, resulting in a slanting edge similar to what occurs during the construction of new pavements on site. In actual practice, this represents the pavement condition after one lane of compaction with the roller compactor in the field without any confinement (no confined edge). Subsequently, the half block with a slanting edge (as presented in Figure 4.3c and Figure 4.3d) was left at room temperature for 7 days to replicate the field compaction scenario where the adjacent pavement lane is constructed after a specific time period. Later, the top and bottom widths of the half asphalt block were measured, and the amount of mix required to fill the mold was calculated. This measured mix was then placed in the mold, and the remaining side of the block sample was compacted. This side of the compacted block specimen represents the second lane of the pavement.

a) Steel spacer b) Sample with the material in the mold

c) final sample after compaction top view d) final sample after compaction side view

**Figure 4.3: Sample preparing technique for longitudinal joint construction without restraint (loose edge construction).**

### 4.4.3 Butt Longitudinal Joint/Restrained Edge

In Oregon, the mill and fill (also called mill and inlay) process is widely employed to construct asphalt pavements. This technique involves removing the worn-out surface layer of asphalt and replacing it with new asphalt material. It is a road resurfacing method that requires the use of heavy machinery, such as a milling machine, to remove the old surface layer to a specific depth. The removed material is then replaced with fresh asphalt, which is compacted to achieve a smooth and robust surface. The process of removing and replacing the old material with new material is referred to as mill and fill, respectively. During the mill and fill process, as only one lane of the pavement surface is removed, a restraint is created at the edge due to the presence of the adjacent pavement surface. To replicate this technique in the laboratory, a rectangular steel spacer was used as a restraining device for the asphalt mix, as shown in Figure 4.3a. Similar to the loose edge technique, half of the total amount of material was loaded into the mold for compaction. The mold, along with the spacer and mix, was subjected to 25 passes of the roller compactor. The restraining device's presence ensured no material movement during the compaction process, forming a vertical edge with a half-block specimen, as depicted in Figure 4-4a. The remaining portion of the block was compacted after a period of 7 days. Figure 4-4b presents the compacted block specimen produced using the butt longitudinal joint/restrained edge technique.

**Figure 4.4: Sample preparation for restrained edge longitudinal joint construction: a) Half specimen after compaction and removal of steel spacer, b) Final specimen.**

### 4.4.4 Wedge Longitudinal Joint Technique

This technique involved the formation of a wedge at the edge of the pavement surface. This wedge was created by introducing a notch at the top and bottom edges, corresponding to the nominal maximum size of the aggregate (NMAS) utilized in the asphalt mix. This study used a 12.5 mm NMAS mix to prepare the test specimen. Accordingly, a spacer with a wedge shape and a 12.5 mm notch at the top and bottom was fabricated to replicate the field construction technique. Figure 4-5 depicts the spacer that was utilized (produced at the OSU machine shop) for constructing the samples. The construction process for this strategy followed a similar approach as the loose-edge longitudinal joint construction method.

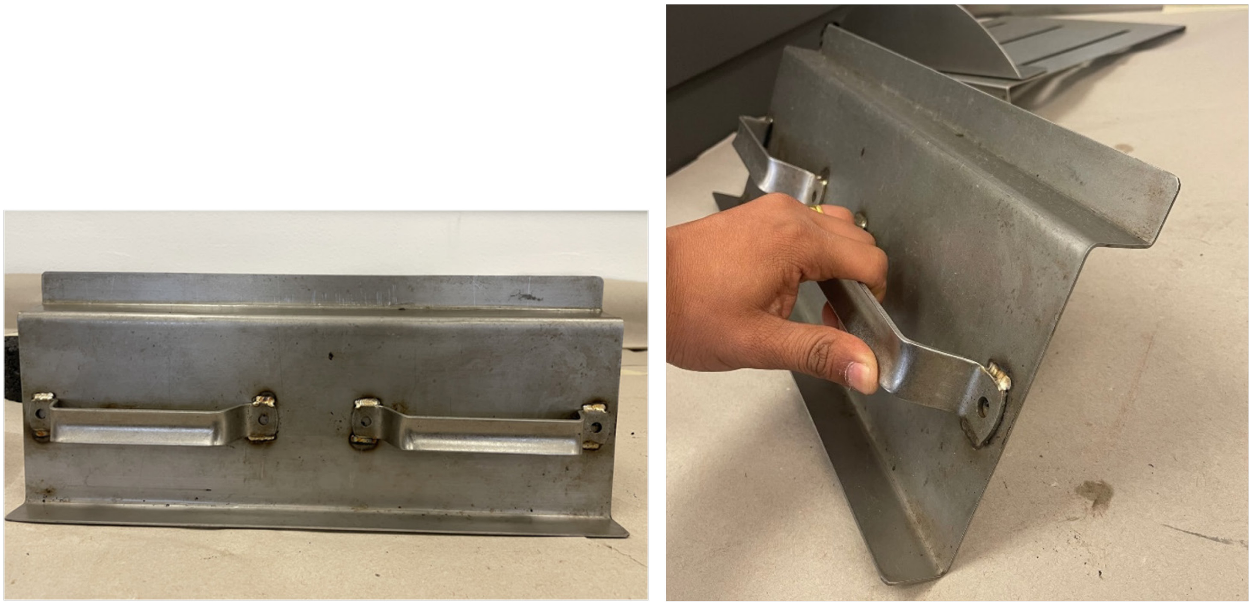


**Figure 4.5: Spacer for wedge construction: a) Front view of wedge spacer, b) Side view of wedge spacer.**

### 4.4.5 High Tack Coat Application

A tack coat is a thin layer of asphalt binder that is applied to an existing pavement surface before overlaying a new asphalt layer. The primary purpose of the tack coat is to establish a strong interfacial bond between the existing and new asphalt pavement layers. Additionally, the application of a tack coat aids in sealing the existing pavement layer to reduce moisture infiltration and lowers the occurrence of delamination and other types of associated distresses, thereby enhancing the durability of the pavement. In the field, a specific amount of tack coat is sprayed along the milled pavement surface and at the longitudinal joint edge using a distributor truck equipped with a spray bar. It should be noted that the application rate of the tack coat at the longitudinal joint edge is typically the same as that on the milled asphalt surface layer.

In this study, an attempt has been made to assess the influence of higher tack coat application rate on the performance of longitudinal joints. A higher tack coat with an emulsion application rate of 0.14 gal/yd$^2$ was used in this study. This application rate is double the amount typically applied to the longitudinal joint during restrained edge construction. The amount of tack coat to be applied was estimated based on the cross-sectional area of the edge of the half-compacted specimen. The first half of the specimen representing one lane was compacted, similar to the restrained and loose edge construction techniques. Later, the predefined amount of tack coat material was filled into a plastic bottle attached to a sponge roller. The roller was rolled smoothly, ensuring a uniform coating thickness of the tack coat over the longitudinal joint edge, as shown in Figure 4.6. The applied tack coat weight was continuously measured using a scale during the application process to achieve the target application rates (for a tack coat with 1/3 water and 2/3 asphalt rate emulsion). After applying the tack coat at the longitudinal joint edge, the remaining portion of the block sample was compacted.

Figure 4.6: Process of applying tack coat at the longitudinal joint edge.

### 4.4.6 Restrained Edge with Infrared Heating

It is well known that the temperature difference between the older pavement and freshly mixed hot asphalt mix results in compatibility issues (see Chapter 2.0). Hence, it is often recommended to heat the longitudinal joint edge to achieve better bonding between the two lanes. Although this technique is not used in Oregon, some state agencies have shown promising longitudinal joint performance results (Kandhal & Mallick 1996, Huang et al.2010, Nener-Plante 2012, Daniel & Real 2006).

In the present study, two different heating temperatures were selected to examine the effect of longitudinal joint edge temperature on the performance of longitudinal joints. These temperatures are 85°C and 95°C. After multiple trials, it was determined that the infrared heater, as shown in Figure 4-7, should be placed at a distance of about 2 inches (5.08 cm) from the sample in order to achieve the required temperature in a specific time. At this particular distance (2 inches, or 5.08cm), the durations required to increase the temperature of the longitudinal joint edge to 85°C and 95°C were estimated to be 3 minutes and 5 minutes, respectively. After achieving these temperatures, the specimens were instantly compacted using a hydraulic roller compactor.

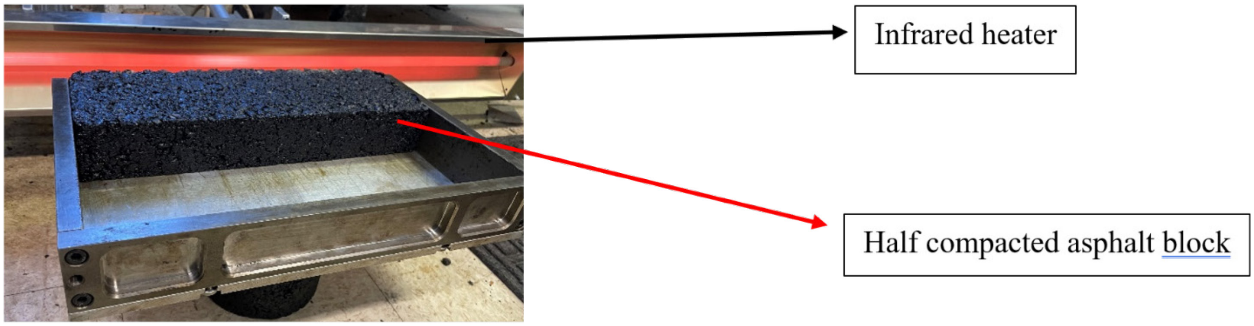


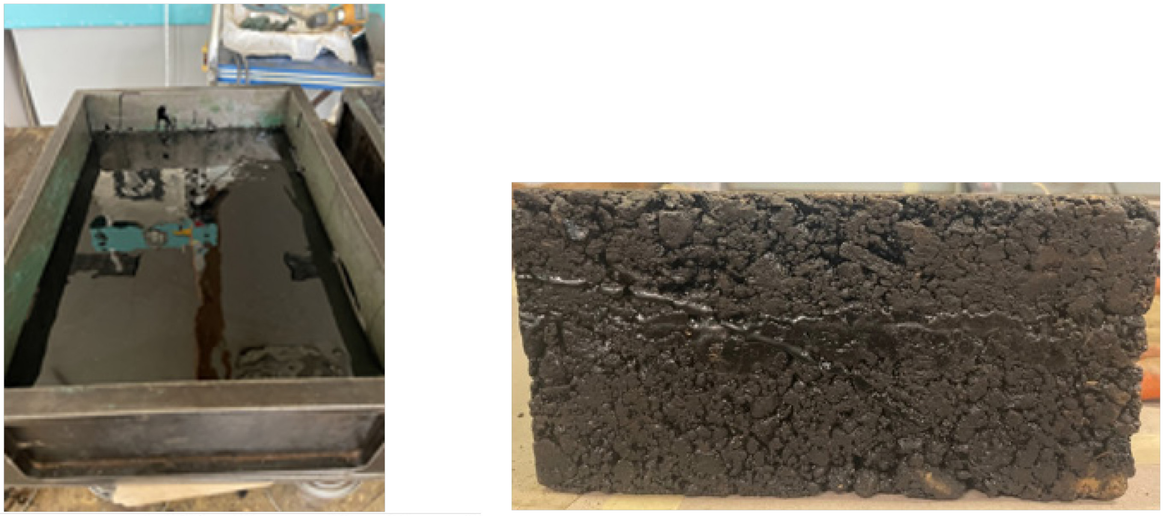
Figure 4.7: Method of heating the longitudinal joint with an infrared heater.

### 4.4.7 Application of Void-Reducing Adhesive

The void-reducing adhesive (called Void Reducer in this report) is used as a proprietary longitudinal joint stabilizer to enhance density and adhesion along the longitudinal joint area. It is applied on the surface using a distributor truck equipped with heating, recirculation, and mixing capabilities. The emulsion is typically sprayed onto a dry and clean area along the longitudinal joint. It exhibits a semi-solid state at room temperature but becomes flowable at elevated temperatures. In this study, laboratory specimens were prepared by following the manufacturer's recommended procedure. In the laboratory, a rectangular slab measuring 260 mm x 400 mm x 35 mm was created with a predetermined mass to achieve 7 ± 0.5% air voids, as depicted in Figure 4.8a. This slab represents the underlying pavement on which the polymeric material will be applied, followed by the construction of the new asphalt pavement. The slab remained in the mold at room temperature for a period of 24 hours. The adhesive material was heated to 160°C for two hours and subsequently poured uniformly on a 35 mm thick slab (Figure 4.8b and 4.8c). Notably, the procedure described for constructing restrained edge specimens was followed to create the 60 mm slab sample, as shown in Figure 4.8d. Considering the influenceable factors, such as overlay thickness, coarse and fine gradation, and the nominal mix aggregate size, the adhesive was applied at a rate of 1.80 lb/ft (for a field application width of 18inches). Figure 4.8 illustrates the process for constructing asphalt specimens with a longitudinal joint and adhesive application.

a) Base for longitudinal joint construction

b) Application of emulsion over the base



c) Base pavement slab after application of emulsion

d) Final specimen with emulsion

**Figure 4.8: Longitudinal joint construction using the Void Reducer emulsion.**

## 4.5 LABORATORY TEST METHODS

This section describes the test methods followed in the laboratory for assessing the performance of longitudinal joint samples constructed using different techniques.

### 4.5.1 Evaluation of Air-Voids

The density of the cylindrical samples cored from the rectangular slabs was determined using the CoreLok instrument. The density of the cylindrical specimens extracted from the rectangular blocks was determined following the ASTM D6752-02 process. This involves vacuum sealing the asphalt samples in a plastic bag and measuring the density by water displacement method. The obtained value of bulk specific gravity and theoretical maximum specific gravity were used to calculate the percent air void content of the samples. Air voids were evaluated to determine whether the longitudinal joint construction process was effective in achieving the desired compaction along the longitudinal joint.

### 4.5.2 Indirect Tensile Strength Test (IDT)

The present study uses the Indirect tensile strength test (IDT) to determine the cracking potential of longitudinal joints. IDT was carried out on all the prepared cylindrical samples following ASTM D6931-17. Cores of 150 mm in diameter and thickness of 60 mm were used for testing. The samples were subjected to a constant loading rate of 50 mm/min, which acts along the vertical diametric planes of the sample. The test was conducted at a temperature of 25°C. The peak load at failure was used to calculate the indirect tensile strength of the specimen. Figure 4.9 presents the setup used for conducting the IDT.

**Figure 4.9: IDT test setup.**

### 4.5.3 Hamburg Wheel Tracking Test (HWTT)

The rutting performance of the longitudinal joint samples was evaluated using the Hamburg wheel tracking test (HWTT) by following the AASHTO T324 specification. The asphalt blocks were placed in the HWTT mold with the following dimensions: 40.01 cm (15.75 in) long, 30.48 cm (12 in) wide, and 10.48 cm (4.125 in) deep. The testing mold was first filled with a steel slab 40.01 cm (15.75 in) long, 30.48 cm (12 in) wide, and 4 cm (1.575 in) deep, as shown in Figure 4-10. After placing the specimen exactly over the steel slab, the longitudinal joint of the slab sample was positioned in such a way that it was under the wheel path of the HWTT device. A 2.54 cm thick layer of plaster was poured into the gaps between the mold and the block to ensure proper operation (no lateral movement under the wheel loads). The plaster's working time was 6-10 minutes (sets in 20-30 minutes), after which the sample was placed in the HWTT system for conditioning. The samples were conditioned in the water for 45 minutes at 50°C prior to the start of the test. The complete sample preparation process is displayed in Figure 4.10.

a) Mold with spacer

b) Control sample on the spacer

c) Loose edge sample with longitudinal joint aligned along the wheel path

d) Plaster applied on the sides

e) Final sample for HWTT test

**Figure 4.10: Preparation of sample for HWTT test.**

### 4.5.4 Moisture Susceptibility

Moisture susceptibility of the asphalt mixtures was assessed using a modified Lottman test as per AASHTO T283. The test involves the evaluation of the Indirect tensile strength (as stated in the preceding section) of the asphalt mixture at 25°C. Unlike IDT, the samples were divided into two sets based on their conditioning. These conditioning states are dry and wet states. In the dry state, the samples were conditioned in the air for 24 hours at ambient temperature, followed by the conditioning in a water bath for 2 hours at 25°C before the test. In a wet state, the samples were first conditioned in a water bath at 60°C for 24 hours, followed by 2 hours of conditioning at 25°C. The ratio of the Indirect tensile strength of wet and dry state samples, popularly known as tensile strength ratio (TSR), is used to determine the moisture susceptibility. A higher value of TSR indicates higher moisture resistance and vice-versa.

## 4.5.5 Statistical Analysis

Fisher's test using the protected least significant difference (LSD) method was conducted to assess the significance of the results compared to the control specimens. The analysis was carried out with a significance level of 95%. Prior to conducting the LSD test, a test for homogeneity of variances was performed to determine the basis of significance among the various longitudinal joint construction techniques (Steel and Torrie, 1980). The mean values from the test results served as the basis for ranking these methods. Equation 1 was employed to calculate the LSD, and the ranking was determined by comparing the LSD with the difference in mean values between the two groups to be ranked. If the absolute difference is greater than the LSD value, the groups are considered significantly different, and different letters are assigned to those.

$$\boldsymbol{LSD = t_{(0.05,Df)} * \sqrt{MSW * \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \qquad \textbf{(4-1)}$$

Where:

- $t_{(0.05,Df)}$ = critical t-value from the degrees of freedom at 95% confidence interval
- MSW = Mean square error within groups
- $n_1$, $n_2$ = represent the number of observations in the group.

The results of statistical inferences are shown in letters (such as A, B, C, etc.) throughout the results section. All the longitudinal joint strategies with the same letter have averages that are not statistically different; thus, they were categorized in the same group. Distinct letters indicate that the average value is statistically different from each other. In some cases, overlapping of the groups was observed. Any result with more than one letter signifies that the difference in the average value is not statistically different, and the result could be categorized in either group. It should be noted that the Control specimens received the highest ranking of A as they outperformed all the longitudinal joint construction techniques (as expected since there is no joint in the control specimens). However, some strategies provided results that were not statistically different from the Control specimens and were also labeled as A.

## 4.6 LABORATORY TEST RESULTS AND DISCUSSION

## 4.6.1 Density Using CoreLok

Figure 4-11 shows the average density determined from 4 replicate cores for each longitudinal joint construction strategy. As expected, the control specimen exhibited the highest density among the samples prepared with different longitudinal joint construction strategies. The density along the longitudinal joints constructed with restrained edges was found to be comparable to that of the control sample. It is attributed to the presence of a restraining device or existing pavement, which acts as a constraint and thereby limits the outward movement of the material during compaction. This constraint allows the aggregates to reach their lowest energy positions during compaction and achieve higher densities. Additionally, the vibration from the roller compactor aids in achieving more uniform compaction, resulting in higher density and fewer air voids. Notably, the air voids of samples prepared with these techniques were within the 7 ± 0.5% range. On the other hand, the densities achieved in the samples fabricated with loose edge and wedge longitudinal joint techniques were extremely low. These observations are consistent for both high-tack and low-tack strategies. The outward flow of material without any restrainment during the compaction is the major reason for lower densities in these construction strategies. The air voids in the samples prepared with wedge and loose edge techniques ranged from 17-20% (80-83% density).

Statistical analysis also revealed that there is no significant difference in the density of the control specimen, restrained edge techniques, and the longitudinal joint samples prepared with the application of Void Reducer. Thus, the highest rank was assigned to these longitudinal joint construction strategies i.e., ‘A and A, B’. Conversely, the samples produced with wedge and loose edge techniques (with and without tack coat application) provided significantly lower densities and were found to be statistically different compared to the control specimens. These techniques are grouped in the ‘C’ rank category. It can also be observed that the application of a higher tack coat helps reduce air voids and improve density. The strategy with the high tack coat application rate (0.14gal/yd$^2$) provided density results that were statistically identical to the Control specimens with no joint.

Using the infrared heater at the low temperature (85°C) level did not result in better compaction and higher density. However, keeping it closer to the joint longer to reach 95°C improved the compaction and the density level. This result indicates that reaching the right temperature along the joint is critical. If the joint is overheated, excessive heat can damage the binder, resulting in inferior joint adhesion and lower long-term performance. This level of precision in heating may not be achieved in the field by following a practical method. If the paver is slightly delayed after the infrared heating in the field, the benefits of joint heating would be lost. The issues observed during construction related to the implementation of infrared heaters for joints are discussed in more detail in Chapter 5.0.

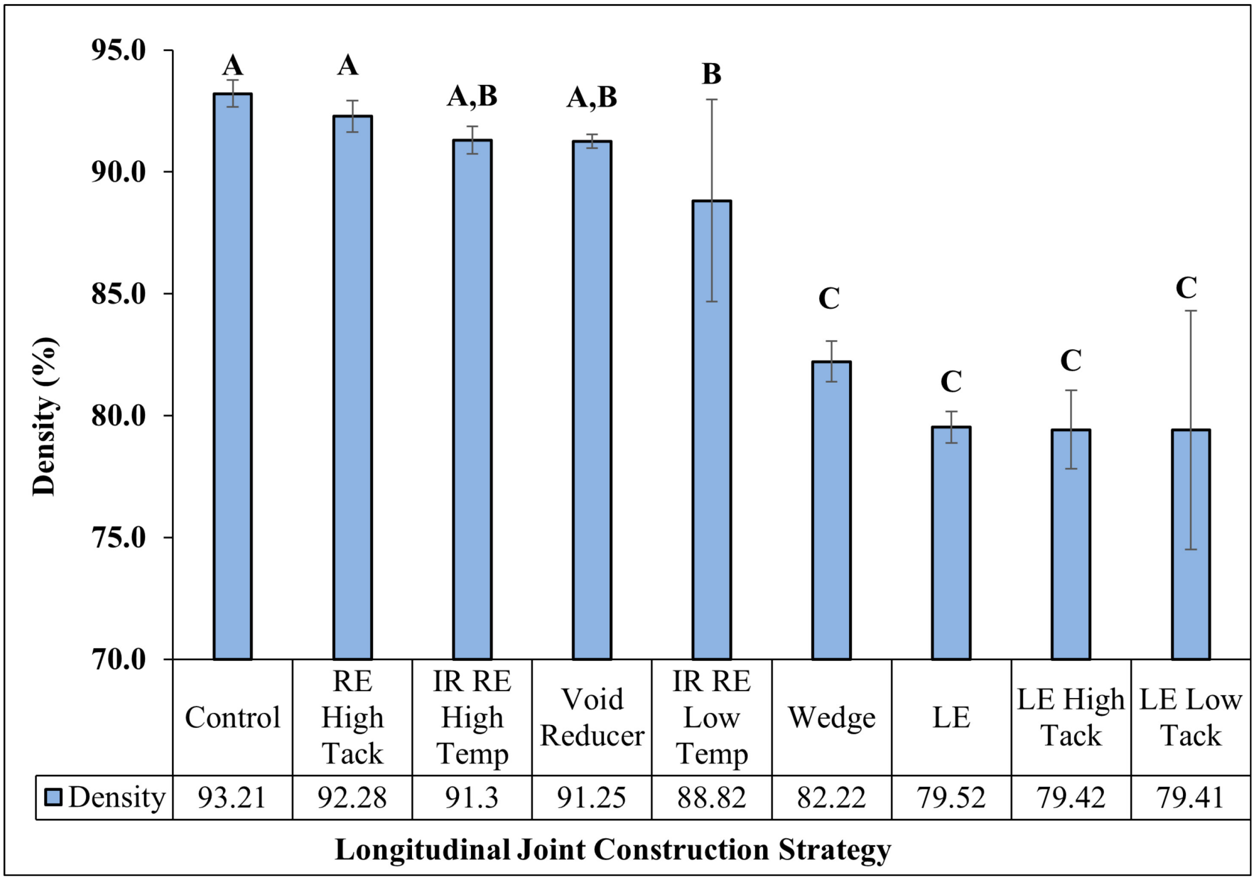


**Figure 4.11: CoreLok density results for different longitudinal joint construction techniques.**

RE - Restrained edge
IR RE - Restrained edge using an infrared heater.
Temp -Temperature
LE - Loose edge

### 4.6.2 Indirect Tensile Strength Test

Figure 4.12 shows the IDT test results of the samples produced with different longitudinal joint construction techniques. The indirect tensile strength of the control specimen (i.e., 0.85 MPa) was higher than all the longitudinal joint construction strategies. It is generally believed that applying a tack coat improves the bond and interlocking at the interface of two pavements. In the present study, it was observed that the restrained edge technique with a high tack coat provided the highest indirect tensile strength (about 0.7 MPa) among different longitudinal joint construction techniques. This result showed that the longitudinal joint construction strategy should be chosen carefully to achieve improved longitudinal joint performance. Nevertheless, it is also essential to ensure uniform tack coat application along the longitudinal joint edge, irrespective of the construction strategy. From the field observations, the tack coat application from the distributor trucks can be inconsistent, leading to variable longitudinal joint performance. For this reason, distributor truck application rate calibration and validation should also be done before the construction. The potential field application of all strategies is discussed in the field evaluation component of this research study and presented in Section 5.0.

The group of all the construction strategies was found to be statistically different from the control specimen (shown with letters different from A for all strategies). It can be observed that the retrained edge with high tack coat and Void Reducer techniques resulted in similar performance and thus are categorized in identical group ‘B’. However, the restrained edge high tack coat option had a higher average strength than all other strategies. Similarly, loose edge techniques (with and without tack coat) exhibited the lowest and almost equivalent indirect tensile strength, therefore clustered in the same group ‘F’. In actual practice, the edges in the loose-edge longitudinal joint construction technique are not confined, which allows the asphalt mix to flow outward, resulting in an increase in air voids and a reduction in strength along the longitudinal joint. It should also be noted that the infrared heating strategy provided the lowest strength out of all the restrained edge techniques.

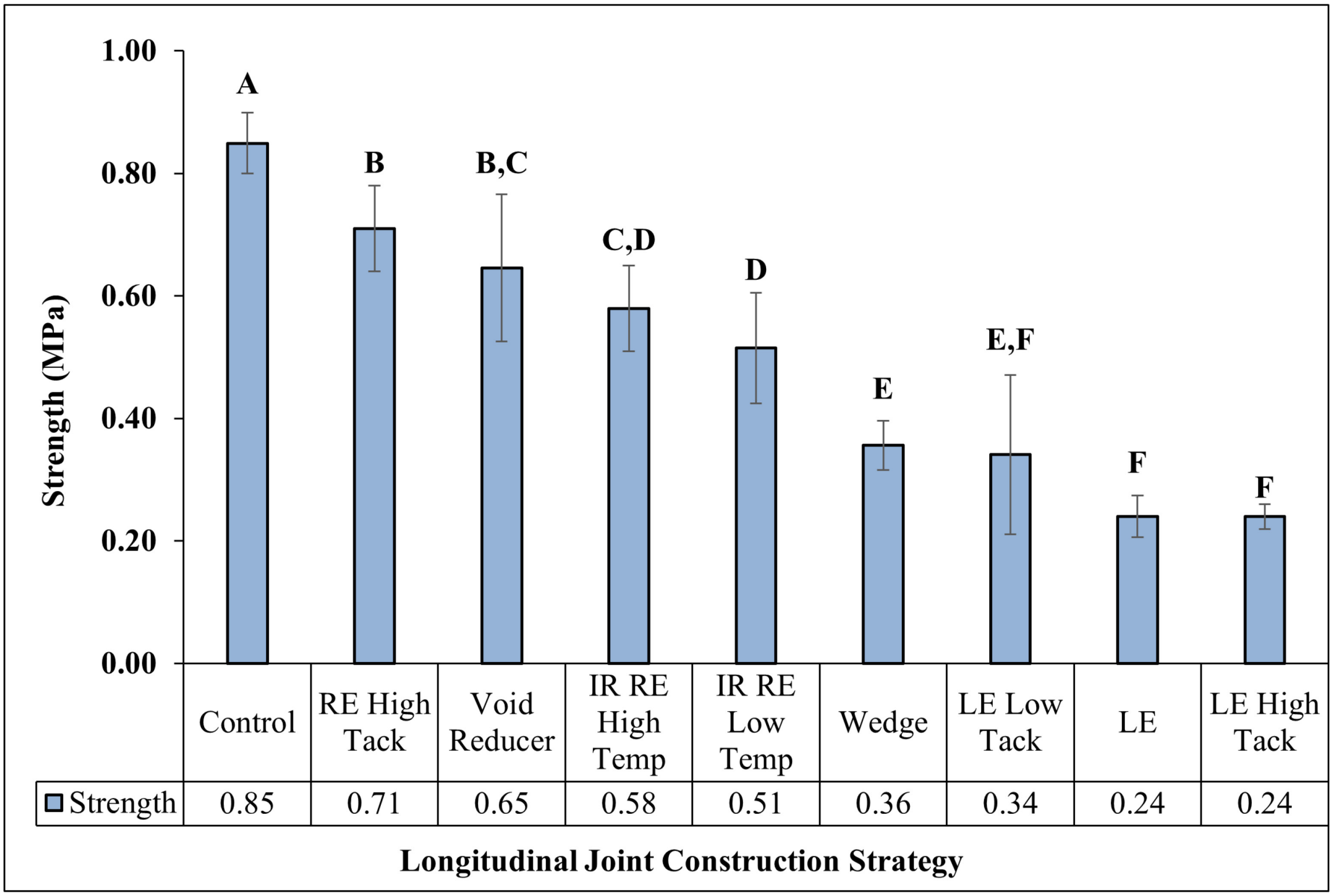


**Figure 4.12: Indirect tensile strength test results for different longitudinal joint construction strategies.**

RE - Restrained edge
IR RE - Restrained edge using an infrared heater.
Temp -Temperature
LE - Loose edge

### 4.6.3 Fracture Energy

Although the indirect tensile strength test is commonly used to assess adhesion along the longitudinal joints due to its simplicity in sample preparation and testing methodology, certain challenges are associated with it. In most of the scenarios, crack path deviations may occur during the test due to the loading platen. The complex stress distribution, coupled with the higher deformation under the loading plate, further complicates the analysis (Huang et al., 2005). To overcome these challenges, fracture energy ($G_f$) was determined to assess resistance against cracking better than the Strength parameter. The fracture energy is determined by using Equation 2 and the load vs displacement output. Unlike indirect tensile strength, the fracture energy allows for a straightforward comparison of cracking resistance among different longitudinal joint construction methods.

$G_f$ is calculated as follows (AASHTO TP 105-13):

$$\boldsymbol{G_f = \frac{W_f}{A_{lig}}} \tag{4-2}$$

Where:

- $G_f$ = fracture energy ($kJ/m^2$),
- $Wf$ = work of fracture (kJ) that is the area under the load vs displacement curve
- $A_{lig}$ = ligament area ($m^2$).

Figure 4.13 depicts the fracture energy of the longitudinal joint samples prepared with different longitudinal joint construction techniques. The Void Reducer technique resulted in higher cracking resistance or fracture energy than other techniques. This result may be attributed to the improved elasticity of the binder due to the presence of a high amount of polymeric material along the joint face. Samples prepared with the restrained edge technique with a high tack coat application rate provided better crack resistance than those prepared with the infrared heating technique, wedge, and loose edge strategies. The probable reason behind lower fracture energy values for wedge and loose edge strategies is the presence of higher air voids (lower density, as shown in Figure 4.11), resulting in reduced bonding and cracking resistance between the constructed lanes.

As per the statistical analysis, there is no significant difference between the control specimens and longitudinal joint specimens constructed with the application of Void Reducer material, and thus, the samples are categorized in the same group. Also, the restrained edge technique involving infrared heating had fracture energy values significantly lower than the Void Reducer and high tack coat strategies. Similar to IDT, the wedge and loose edge techniques were the poorest among the other techniques, resulting in almost half of the fracture energy as those of the control specimen.

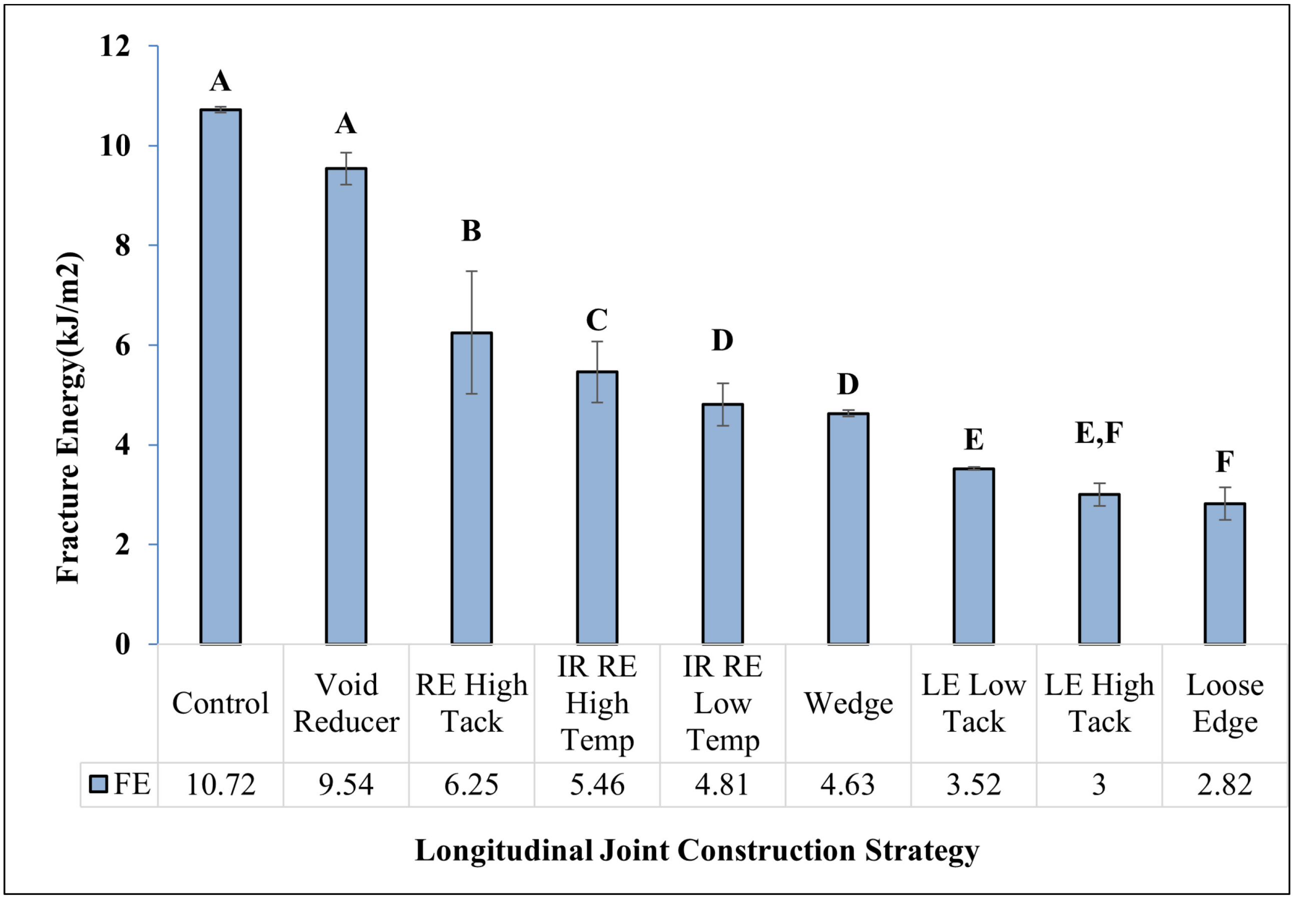


**Figure 4.13: Fracture energy results for longitudinal joint construction techniques.**

RE - Restrained edge
IR RE - Restrained edge using an infrared heater
Temp -Temperature
LE - Loose edge

### 4.6.4 Hamburg Wheel Tracking Test

The slab samples compacted with the roller compactor were directly utilized to conduct the HWTT. In this test, a heavily loaded steel wheel was allowed to pass over the slabs for 20,000 repetitions to accumulate damage. Primarily, longitudinal joints are constructed between the lanes and away from the wheel path. However, in some cases, it was observed that these longitudinal joints appeared around the wheel path, which can be considered a critical scenario. Weaver et al. (2023b) also concluded that the rumble strip installation on longitudinal joints or low-density areas reduces the strength of the pavement and leads to premature failure. Thus, in this part of the study, the impact wheel loading over the longitudinal joint was investigated using the HWTT. For conducting the HWTT test, the joint on the specimen was precisely aligned beneath the center of the wheel to determine its performance. Figure 4.14 illustrates the sample placed in the test equipment with the longitudinal joint aligned along the wheel path.

The variation in the rut depth of the specimens prepared using different techniques is shown in Figure 4.15. It can be observed that the restrained edge technique, coupled with using an infrared heater to heat the longitudinal joint, resulted in the lowest rut depths compared to the other test samples. This reduction can be attributed to the aging of the binder due to the heating at high temperatures, which imparts the stiffening effect and consequently improves the rutting resistance. However, it should be noted that this binder stiffening effect also results in lower cracking resistance, as shown in Figure 4-13. Since cracking is the major mode of failure along the longitudinal joints, using infrared heating may result in early cracking failures. The practical issues related to the use of infrared heaters during construction are also discussed in Chapter 5.0.

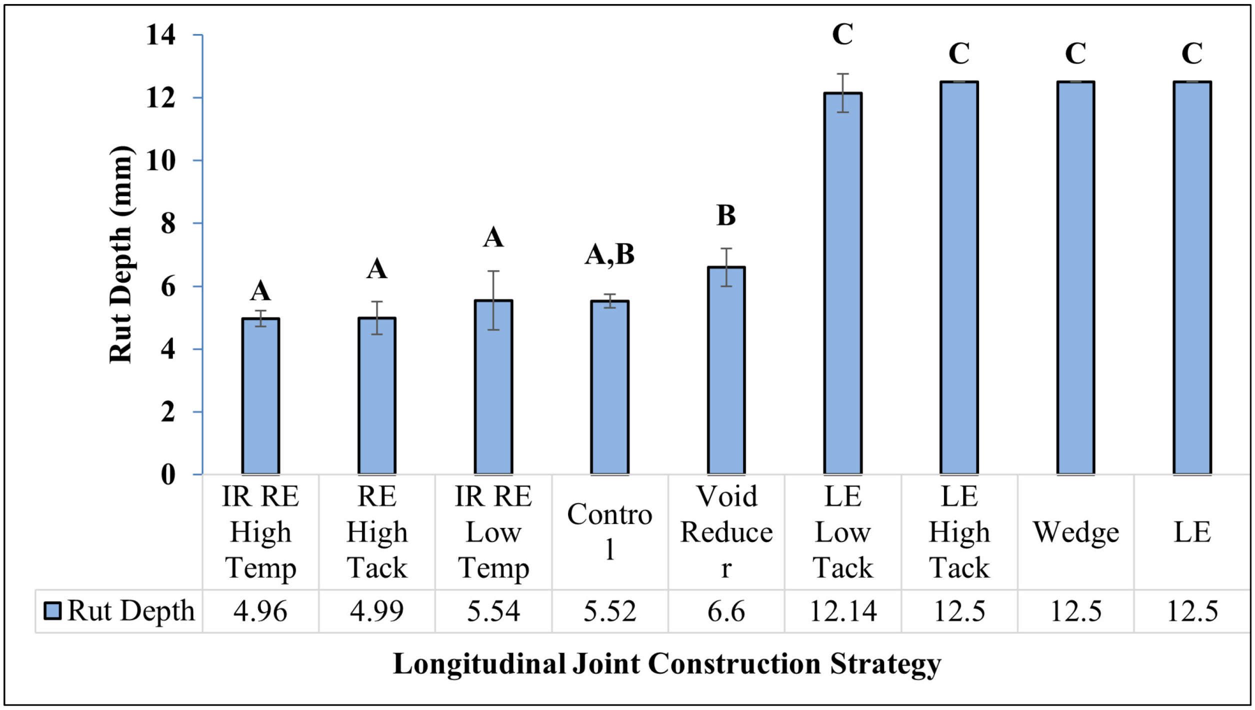
The restrained edge technique with high tack coat application outperformed the control specimen. This improvement can be ascribed to the application of a tack coat with a stiff binder, which enhances interlocking and provides resistance to deformation under a repetitive wheel load. Conversely, the use of loose edge and wedge technique for longitudinal joint construction resulted in a maximum rut depth of 12.5 mm in about 8,000 cycles of the wheel load.

Statistical analysis indicated that the samples produced with the application of an infrared heater and restrained edge technique are statistically the same as those of the control specimen. In addition, the longitudinal joint samples prepared with the Void Reducer resulted in a slightly higher rut depth than the control specimen (as shown in Figure 4.15), but the difference was not found to be statistically significant as compared to the control specimen. Similar to what was observed in other test methods, the loose edge and wedge techniques were statistically different from the control specimen and were found to be the worst-performing among the other longitudinal joint construction techniques.

a) Placement of the longitudinal joint sample in the test equipment

b) Tested sample

**Figure 4.14: HWTT equipment and tested block sample.**



| | IR RE High Temp | RE High Tack | IR RE Low Temp | Contro l | Void Reduce r | LE Low Tack | LE High Tack | Wedge | LE |
|---|---|---|---|---|---|---|---|---|---|
| ■ Rut Depth | 4.96 | 4.99 | 5.54 | 5.52 | 6.6 | 12.14 | 12.5 | 12.5 | 12.5 |

**Figure 4.15 HWTT results for longitudinal joint construction.**

RE - Restrained edge
IR RE - Restrained edge using an infrared heater.
Temp -Temperature
LE - Loose edge

### 4.6.5 Moisture Sensitivity

The general theory of moisture susceptibility-related cracking failures is that moisture/water can easily penetrate the asphalt layer when the joint has a lower density. When truckloads are applied on the saturated asphalt pavement surface, excessive pore pressures internally crack the asphalt, especially around the connection interface between the aggregate and the binder, and result in cracking in the layer. For this reason, moisture sensitivity was also evaluated for the samples prepared with some of the selected (best-performing) longitudinal joint construction techniques/strategies. These techniques were chosen based on the statistical rankings shown in Figures 4.11 through 4.15. The selected techniques were restrained edge with a high tack coat, infrared heating with high temperature, and Void Reducer. Moisture sensitivity was determined using the standard tensile strength ratio (TSR) procedure. The results for the samples prepared with these techniques were compared with the TSR value of the control specimen.

Figure 4.16 presents the TSR value of all the tested samples. As can be seen, all the longitudinal joint specimens exhibited lower TSR values than the control specimen, indicating higher moisture sensitivity. Tack coat application along the joints was determined to improve the bonding ability at the interface and the overall density (as shown in Figure 4.11, Figure 4.12, and Figure 4.13). However, it was found that the application of a tack coat did not result in a TSR value passing the 80% requirement. However, it must be noted that the 80% threshold for moisture susceptibility was developed for asphalt cores without any joints. Having a 74.8% TSR value for a core with a construction joint can be accepted to be reasonable.

Among different techniques, using an infrared heater with a high heating temperature (95°C) and the application of a Void Reducer showed superior resistance against moisture damage. This result may indicate that the heating effect improves the bonding at the longitudinal joint's interface and prevents water ingression. However, excessive heating may cause stiffening of the binder and lead to premature cracking failure, which is undesirable. It is also possible that excessive heating of the joint might have increased the stiffness of the mix and resulted in higher TSR values. Moreover, using a Void Reducer resulted in TSR values passing the minimum requirement, proving that it is efficient in reducing air voids and provides lower susceptibility to moisture than tack coat application.

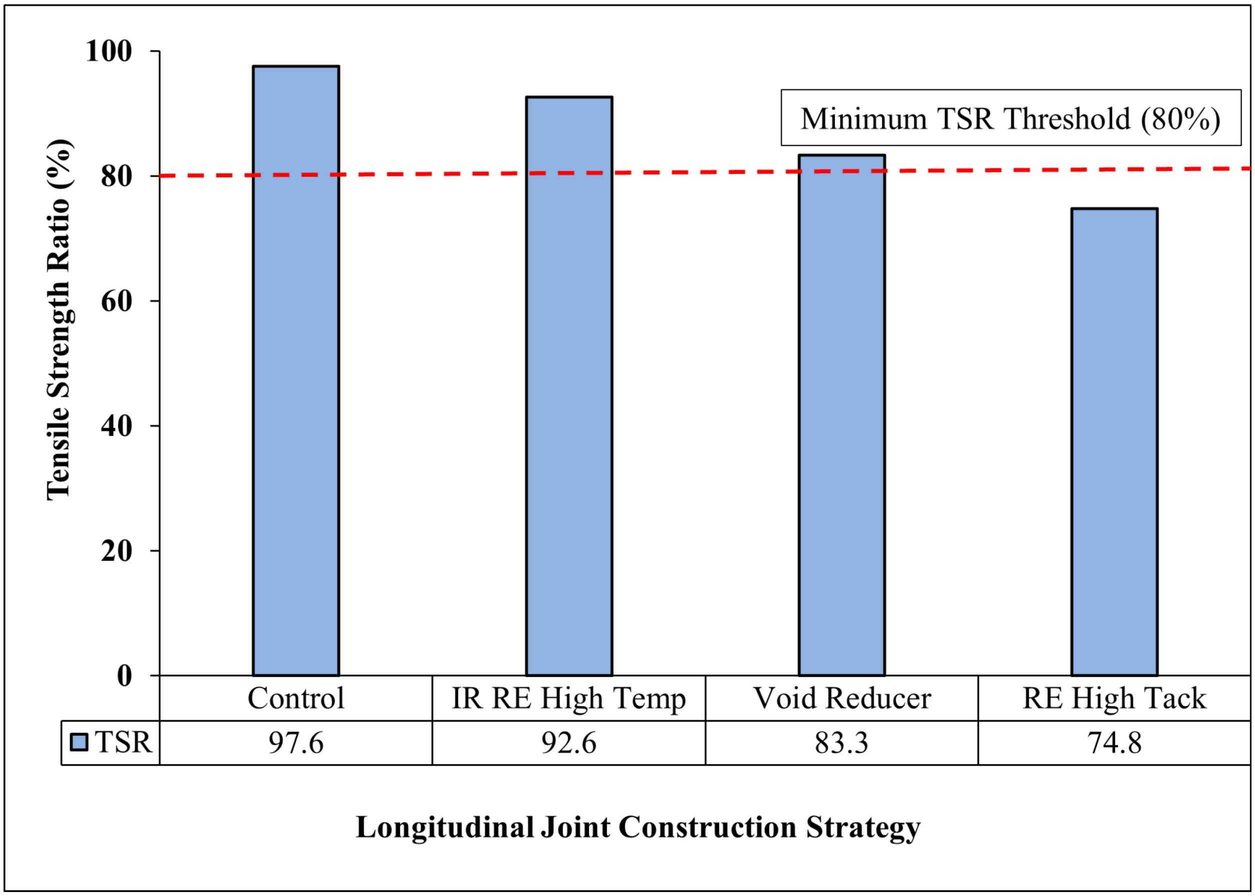


**Figure 4.16: Tensile strength ratio for longitudinal joint construction strategy.**
RE - Restrained edge
IR RE - Restrained edge using an infrared heater.
Temp -Temperature

## 4.7 FINDINGS AND MAJOR CONCLUSIONS

The major conclusions of the laboratory component of this study are:

- Restrained edge construction always provides higher density and cracking resistance. Loose edge construction should be avoided. Since the majority of the constructions in Oregon are mill-and-fill, the cold mat is expected to act as a restrainment and improve joint density. For constructions without mill-and-fill (no confinement), a restraining agent (a jig that can be attached to the roller compactor to increase confinement during compaction) should be used to improve density.

- High tack coat application (0.14gal/yd$^2$) and Void Reducer strategies with restrained edge were determined to be superior to all other strategies.

- The application of a higher tack coat rate helps reduce air voids and improve density. The strategy with the high tack coat application rate (0.14gal/yd$^2$) provided density results that were statistically identical to the Control specimens with no joint.

- The restrained edge technique with high tack coat application outperformed the control specimen in the rutting experiments. This improvement can be ascribed to the application of a tack coat with a stiff binder, which enhances interlocking and provides resistance to deformation under a repetitive wheel load.

- The infrared heating strategy did not provide promising results. Fracture energy values for the infrared heating option were significantly lower than the high tack and Void Reducer strategies. In addition, significantly lower rut depth values for the infrared heated specimens point out excessive aging for this strategy, potentially detrimental to the cracking resistance of the asphalt mixtures. These results suggested that the heating process reduces the cracking resistance along the joint. The practical issues related to the use of infrared heaters during construction are also discussed in Chapter 5.0.

- Using a Void Reducer resulted in TSR values passing the minimum requirement (80% TSR), proving that it is efficient in reducing air voids and provides lower susceptibility to moisture than tack coat application. However, it must be noted that the 80% threshold for moisture susceptibility was developed for asphalt cores without any joints. Regarding the specimens with high tack coat application, having a 74.8% TSR value for cores with construction joints can be accepted to be reasonable.

Based on the results obtained in this Chapter, the following detailed findings were achieved. The major conclusions listed above were developed based on the following more detailed findings:

- The presence of a restraining device or existing pavement, which acts as a constraint and thereby limits the outward movement of the material during compaction, results in significant density and cracking resistance improvements. This constraint allows the aggregates to reach their lowest energy positions during compaction and achieve higher densities.

- The samples produced with wedge and loose edge techniques (with and without tack coat application) provided significantly lower densities than all other evaluated strategies.

- The application of a higher tack coat helps reduce air voids and improve density. The strategy with the high tack coat application rate (0.14gal/yd$^2$) provided density results that were statistically identical to the Control specimens with no joint.

- Using the infrared heater at the low temperature (85°C) level did not result in better compaction and higher density. However, keeping it closer to the joint longer to reach 95°C improved the compaction and the density level.

- The retrained edge with a high tack coat and Void Reducer results in similar cracking resistance. However, the restrained edge high tack coat option had a higher average strength than all other strategies. Similarly, loose edge techniques (with and without tack coat) exhibited the lowest and almost equivalent indirect tensile strength.

- The fracture energy parameter provided slightly different results than the Strength parameter. The Void Reducer technique resulted in higher cracking resistance or fracture energy than other techniques. This result may be attributed to the improved elasticity of the binder due to the presence of a high amount of polymeric material along the joint face. Samples prepared with the restrained edge technique with a high tack coat application rate provided better crack resistance than those prepared with the infrared heating technique, wedge, and loose edge strategies.

- The restrained edge technique, coupled with using an infrared heater to heat the longitudinal joint, resulted in the lowest rut depths compared to the other test samples. This reduction can be attributed to the aging of the binder due to the heating at high temperatures, which imparts the stiffening effect and consequently improves the rutting resistance. However, it should be noted that this binder stiffening effect also results in lower cracking resistance. Since cracking is the major mode of failure along the longitudinal joints, using infrared heating may result in early cracking failures.

- The restrained edge technique with high tack coat application outperformed the control specimen in the rutting experiments. This improvement can be ascribed to the application of a tack coat with a stiff binder, which enhances interlocking and provides resistance to deformation under a repetitive wheel load.

- The longitudinal joint samples prepared with the Void Reducer resulted in a slightly higher rut depth than the control specimen, but the difference was not found to be statistically significant as compared to the control specimen.

- Using an infrared heater with a high heating temperature (95ºC) resulted in superior resistance against moisture damage. This result may indicate that the heating effect improves the bonding at the longitudinal joint's interface and prevents water ingression. However, excessive heating may have caused stiffening of the binder and lead to premature cracking failure, which is undesirable. It is also possible that excessive heating of the joint might have increased the stiffness of the mix and resulted in higher TSR values.

- Tack coat application along the joints was determined to improve the bonding ability at the interface and the overall density. However, it was found that the application of a tack coat did not result in a TSR value passing the 80% requirement. However, it must be noted that the 80% threshold for moisture susceptibility was developed for asphalt cores without any joints. Having a 74.8% TSR value for a core with a construction joint can be accepted to be reasonable.

- Using a Void Reducer resulted in TSR values passing the minimum requirement, proving that it is efficient in reducing air voids and provides lower susceptibility to moisture than tack coat application.

Based on all these major conclusions and the detailed findings listed above, the most promising high tack and Void Reducer strategies were selected for the field trials. In addition, the hot pinch construction method (described in Section 5.3.2), which was not possible to include in the laboratory trials due to the limitations of the laboratory hydraulic roller compactor, was also included in the field trials as a construction strategy. A proprietary topical joint sealer (called "Topical emulsion" in this report) was also included in the field trials (see Section 5.3.3). This joint sealer was not available for the laboratory component of this research project.

# 5.0 FIELD INVESTIGATION OF LONGITUDINAL JOINT PERFORMANCE

## 5.1 INTRODUCTION

The literature review on longitudinal joint construction has systematically identified diverse construction techniques employed within the United States. A predominant factor contributing to the failure of longitudinal joints is improper compaction along the edges of multilane pavements. This phenomenon increases air voids, allowing moisture and air infiltration within the bonded pavement lanes. To monitor the performance of longitudinal joints in asphalt pavements, researchers followed different testing methodologies discussed in the preceding chapters.

In this study, the laboratory investigation of the longitudinal joint performance focused on examining diverse construction techniques and products, which were meticulously examined through construction simulations using a hydraulic roller compactor and following advanced laboratory test protocols. A total of 8 distinct strategies were deliberately selected, and their respective performances were comprehensively assessed and compared by following different testing procedures. The outcomes of the laboratory investigation indicated that applying a high tack coat along the longitudinal joint or incorporating a Void Reducer membrane exhibits higher density and substantially improves the integrity of the longitudinal joint.

In this part of the study, an effort has been made to confirm the real-time effectiveness of these promising longitudinal joint construction techniques (high tack and Void Reducer) by performing a field study. In addition, the hot pinch construction method (described in Section 5.3.2), which was not possible to include in the laboratory trials due to the limitations of the laboratory hydraulic roller compactor, was also included in the field trials as a construction strategy. The field trials also included a proprietary topical joint sealer (see Section 5.3.3). This joint sealer was not available for the laboratory component of this research project.

These field trials would help further gauge the efficacy of the optimal strategies for longitudinal joint construction in practical applications. After implementing various longitudinal joint construction techniques in the field, the collected asphalt samples (cores) underwent a comprehensive evaluation to determine the most effective technique for delivering high-quality longitudinal joints in the field.

## 5.2 FIELD SITE DESCRIPTION

Three distinct field projects were chosen to evaluate the selected longitudinal joint construction methods. The particulars of these projects are detailed in the subsequent sections.

### 5.2.1 Project 1 - I5: Kuebler - Santiam Pass

The first project was situated on Interstate 5 between Kuebler and Santiam Pass exits. Figure 5.1 presents the geographical location of this project. The construction was for a ramp section where the mill-and-fill construction process was followed. The procedural sequence involved the initial milling of the existing wearing course (followed by sweeping) and constructing a new asphalt layer to replace the removed one. The longitudinal joint in this section was established between the freshly constructed wearing course and the shoulder section, which had been in service for more than ten years.

The composition of the wearing course for this section comprised a Level 4 mix prepared using a PG 70-22ER binder. Notably, the asphalt layer exhibited a lift thickness of 2½ inches.

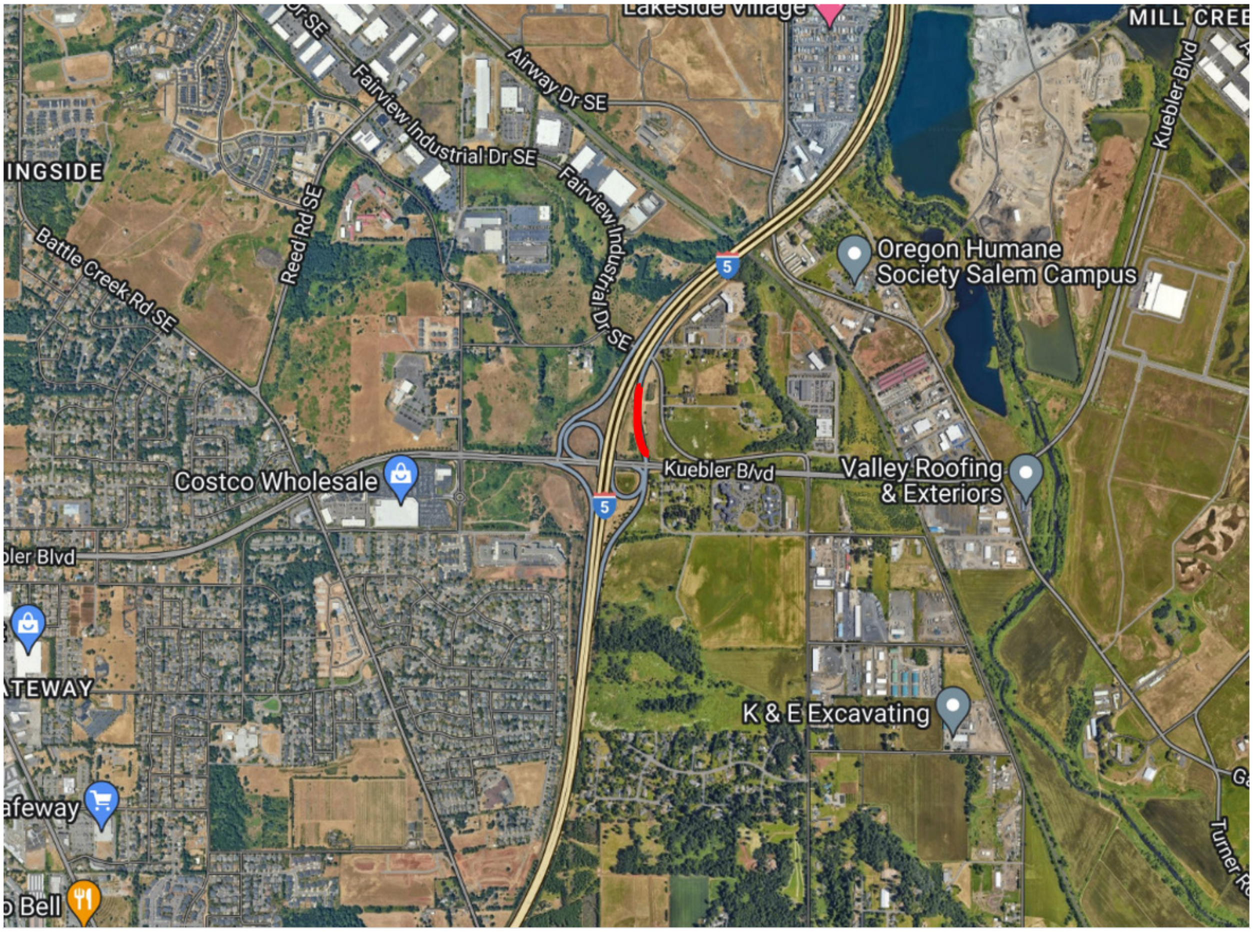


**Figure 5.1: Location for longitudinal joint construction on the I5-Kuebler-Santiam Pass.**

### 5.2.2 Project 2- OR18-McMinnville

The second project was situated on Oregon Route 18 (OR18) at McMinnville. Similar to Project 1 (I5-Kuebler-Santiam Pass), this project also employed the mill and fill construction approach. However, this project had a multilane pavement, and the longitudinal joint was formed between the two recently constructed pavement lanes.

Similar to Project 1, the pavement composition in this project also features a Level 4 mix with a PG 70-22 ER binder. The longitudinal joint construction for this project was bifurcated into two distinct locations. The first section comprised two longitudinal joint construction methods: high tack and hot pinch. Approximately 1 mile north of the preceding section, a proprietary product was applied along the construction joint to penetrate the surface voids and avoid any water intrusion into the joint during the use phase of the roadway. This material is called the “Topical emulsion” in this report. Figure 5.2 depicts the precise location of these sections within the project site.

In this section, the design lift thickness of the wearing course was 2½ inches. It should be noted that the asphalt mixture designs for both field project segments followed the Superpave methods, ensuring a standardized and systematic approach to asphalt mixture design.

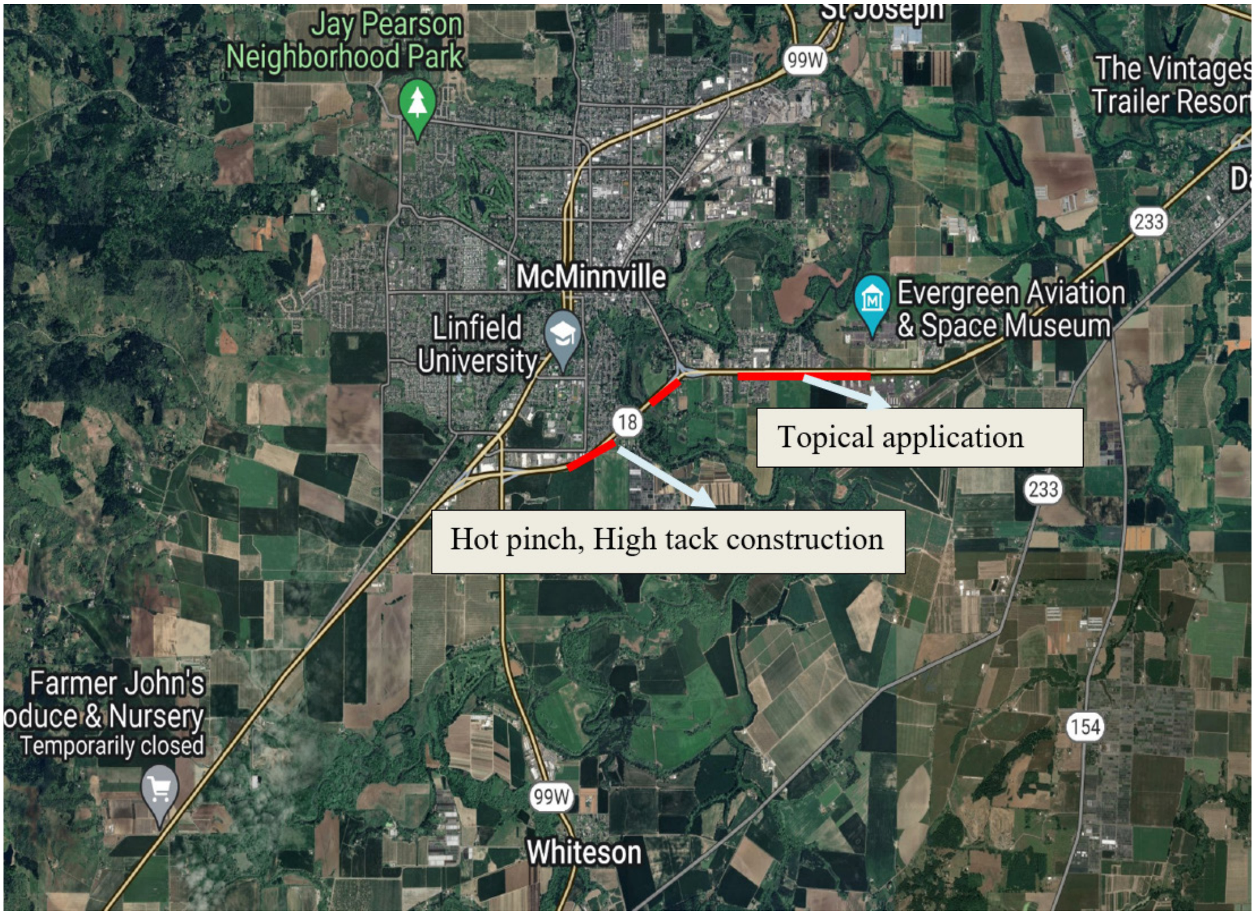


**Figure 5.2: Location for OR18 McMinnville project.**

### 5.2.3 Project 3- Fond du Lac County, Wisconsin

The third project aimed to assess the suitability of a Void Reducer product in developing high-performing longitudinal joints. Due to challenges associated with scheduling the Void Reducer application in Oregon during the designated construction period, a decision was made to obtain the cores from a recently completed project incorporating the Void Reducer application in Fond du Lac County in Wisconsin. The cores used for research were extracted from this construction project. This project concentrated specifically on applying this proprietary product and evaluated its effectiveness in facilitating the creation of high-quality longitudinal joints within asphalt pavements.

This approach allowed for an in-depth exploration of the specific benefits and performance attributes associated with the application of Void Reducer technology in the context of longitudinal joint construction.

## 5.3 DETAILS OF THE FOLLOWED LONGITUDINAL JOINT CONSTRUCTION TECHNIQUES IN THE FIELD

This section presents the procedures followed in the field to construct the longitudinal joints for the above-mentioned projects. It should be noted that various infrared images were captured throughout the construction of these test sections. This was done primarily to check the temperature variations during the compaction of the asphalt mat.

### 5.3.1 High Tack Construction

Most of the construction in Oregon is mill and fill (also known as mill-and-inlay), where the old pavement is milled after its in-service life and later constructed with new asphalt mix. In Oregon, applying a tack coat on the underlying pavement is a general process to improve the integrity between the underlying and the new lift to enhance pavement performance. Although tack coats are also applied to longitudinal joints in some constructions, they are not standard practice.

For the longitudinal joints, the tack coat was applied on the cold edge of the pavement using a spray nozzle attached to a truck. However, for the majority of the construction projects, the application rate along the longitudinal joint was the same as that on the underlying pavement, resulting in incomplete coverage on the exposed longitudinal joint surface. This inadequacy led to lower bonding along the longitudinal joint, potentially causing premature cracking in weak-density areas. Figure 5.3 illustrates the tack coat application on the milled surface before paving and the issues with applying the tack coat on the joint.

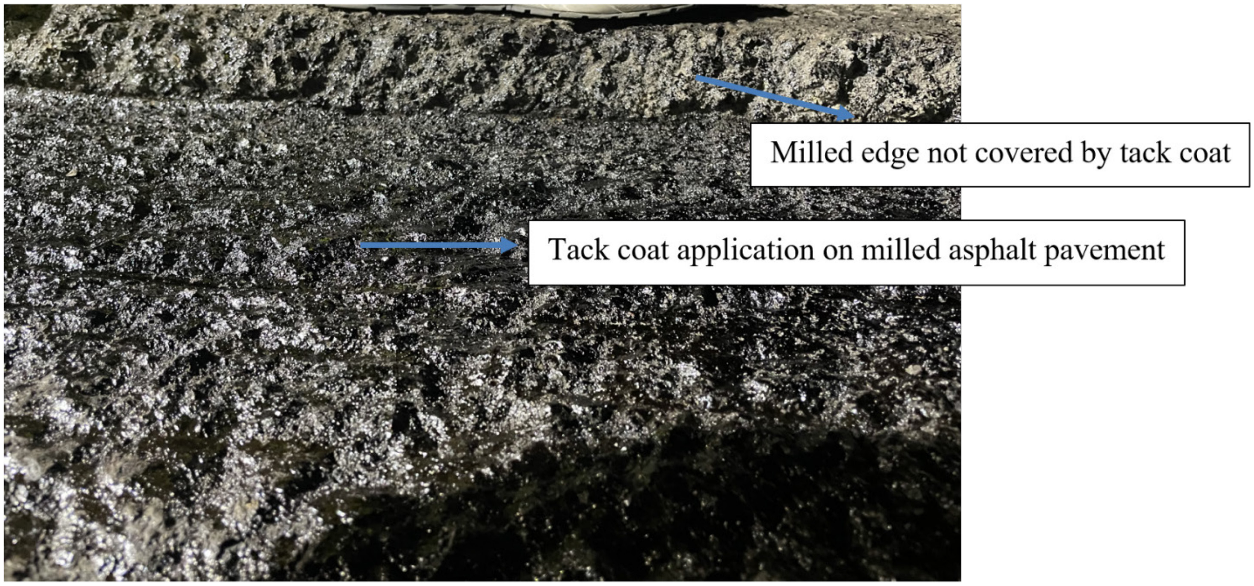


**Figure 5.3: Application of tack coat on milled surface.**

The laboratory investigation (Chapter 4.0) determined that an increased tack coat application rate along the longitudinal joint (0.14gal/yd$^2$) improves density and bonding between two lanes. The heavy tack coat application fills the voids along the longitudinal joints and increases density. In addition, the applied heavy tack coat creates better adhesion between the two mats, resulting in a stronger connection between the two lanes.

For both Project 1 and Project 2, a hand spray pump was employed to apply the tack coat emulsion on the longitudinal joint. The application rate for the tack coat was set at 0.14 gal/yd$^2$, approximately double the rate typically used in mill and fill construction methods. Immediately after applying the tack coat, the asphalt mix was laid using the paver, followed by the compaction. Figure 5.4 shows the pavement edge with the proper tack coat application. The compaction process followed the same technique described for the control strategy in constructing longitudinal joints.

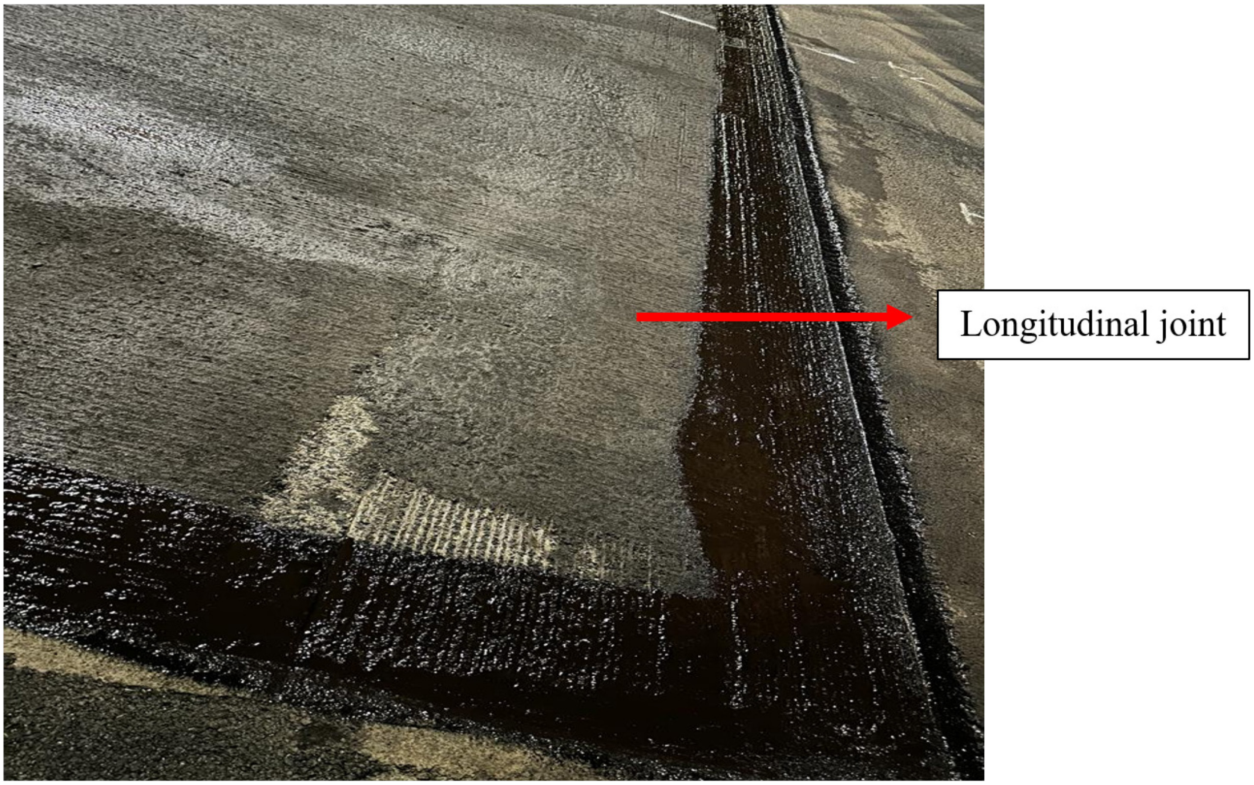


**Figure 5.4: Longitudinal joint with tack coat application.**

## 5.3.2 Hot Pinch Longitudinal Joint Construction

This technique revolves around the compaction process adopted for compacting the longitudinal joints in Oregon with some more detailed specifications. In this technique, after laying the asphalt mix, the first pass of the roller in vibratory mode targeted the center of the pavement, approximately 152 mm away from the cold edge, as shown in Figure 5.5. This initial compaction pushes the mix laterally toward the edge of the cold mat. The second pass of the roller was also subjected to vibratory mode but applied directly over the longitudinal joint. Since one side of the joint is now compacted and the other side is already a cold joint, the hot mix trapped between two stiff mediums can now be compacted to achieve the highest density levels. As per the visual observations during the field construction, the hot pinch longitudinal joint construction technique eliminated the need for raking and luting. The confined mix between the asphalt mix compacted in the first pass and the edge of the cold mat was systematically compacted during the second pass, resulting in enhanced material compaction along the longitudinal joint. The standard compaction process was resumed after the special hot pinch compaction process for the joint.

**Figure 5.5: Hot Pinch construction with roller 152mm away from the longitudinal joint – I5-Kuebler, 08/17/2023.**

### 5.3.3 Longitudinal Joint Sealers – Topical Emulsion

Since the area around the longitudinal joint has less density than the center of the mat, air and water can easily penetrate the joint and result in excessive oxidation (due to the oxygen in the air) and moisture damage during the lifetime of the pavement structure. This results in the dislocation of aggregates along the longitudinal joint and creates a path for further moisture and air infiltration (Williams 2011). Along with different longitudinal joint construction methods, longitudinal joint sealers were used in the current study to evaluate their performance in enhancing the density along the longitudinal joint. In this study, the "Topical emulsion", a proprietary longitudinal joint stabilizer, was applied after pavement construction. The Topical Emulsion is a polymerized emulsion sprayed over the pavement after construction. This is usually applied through a series of nozzles attached to the back of the truck, as shown in Figure 5.6. The typical application rate for this polymerized emulsion is between 0.07gal/yd$^2$ and 0.10 gal/yd$^2$, and it is sprayed at a width of 1.5 feet, centered on the longitudinal joint. Figure 5.7 and Figure 5-8 illustrate the topical application on the pavement construction site at OR18-McMinnville. Since the topical application involves a top-down application process, this technique is expected to improve the density and permeability along the longitudinal joint area. However, the penetration of the emulsion through the joint was unknown and needed to be investigated in this study.

**Figure 5.6: Truck with nozzles on the back for topical emulsion application.**

Figure 5.7: Topical emulsion applied on the I5-Kuebler project.

Figure 5.8: Topical emulsion applied on the OR18-McMinnville project.

### 5.3.4 Void Reducer Application

The application process for Void Reducer involved the following key steps:

1. **Pavement Preparation:** Multiple lanes of the deteriorated pavement were initially milled to remove the old surface. Then, the milled surface was cleaned using sweepers capable of both sweeping and vacuuming.

2. **Void Reducer Application:** The Void Reducer material is applied by spraying it onto the milled surface along the potential location of the longitudinal joint. Similar to topical application, Void Reducer is applied using spray nozzles attached to the rear end of a truck. Void Reducer is sprayed 9 inches on each side of the longitudinal joint, covering the area prone to high air voids. The manufacturer asserts that the sprayed material forms a black strip without any tracking after curing or exposure to the environment. Figure 5.9 shows the Void Reducer application on the pavement surface.

3. **Application Rate:** The application rate of Void Reducer depends on the mix type and the nominal maximum aggregate size (NMAS). The typical application rate for a lift thickness of 2 inches with a 12.5mm NMAS is specified as 1.80 lb/ft (for an 18-inch-wide application).

4. **Hot Mix Asphalt Laying and Compaction:** Following the application of the Void Reducer along the potential location of the longitudinal joint, the hot mix asphalt is laid and compacted following standard construction practices.

**Figure 5.9: Void Reducer applied on the pavement surface (Heritage Inc.).**

According to the manufacturer's specifications, Void Reducer undergoes a phase transition from a solid state to a liquified state when the hot mix is laid and compacted, which was also clearly observed during the laboratory phase of this study. The manufacturer asserts that the liquified Void Reducer can migrate vertically with time, reaching up to 50-70% of the lift thickness from the bottom of the new asphalt layer. As described by the manufacturer, this migration fills the void space along the longitudinal joint in the asphalt pavement, resulting in a higher density. The expected outcome of this process is an enhancement in the performance of longitudinal joints in terms of premature cracking and raveling through the lower permeability and higher adhesion achieved between the two lanes.

## 5.4 FIELD CORING

The two projects undertaken in Oregon were constructed utilizing three distinct longitudinal joint construction techniques. Specifically, the high tack and hot pinch construction strategies comprised sections measuring 100 feet, whereas the section constructed with the topical application product extended to 150 feet. A systematic approach was employed in order to evaluate the performance and adequacy of each longitudinal joint construction technique.

For each project, four cores were extracted from the location of the longitudinal joint. Each half-core on one side of the complete core specimen obtained from the longitudinal joint represented two separate lanes, that is the pavement lane and the cold shoulder. The cores were specifically extracted from the central 60-foot length of the pavement, leaving the initial and final 20 feet on each section of the high tack and hot pinch techniques. Similarly, the initial and final 15 feet were excluded for the section constructed with topical application, and cores from the remaining 120 feet were extracted. To observe the spatial variability along the joints, the cores were strategically extracted from locations spaced at equal intervals within the test section.

In the case of the project located along Oregon Route 18 (OR18), the test section employing topical applications was positioned one mile away from the remaining strategies. Given this separation, three cores were extracted from the longitudinal joint constructed with the Topical Emulsion, and two additional control cores were obtained approximately 50 ft away from this section to assess the product's performance independently.

The diameter of the cores extracted from the field was kept constant at 152.4mm (about 6 inches). Most of these cores, sourced from the I5 and OR18 projects, predominantly comprised underlying layers. Thus, the cores for these projects were precision-cut to a thickness of 65mm using a high-precision saw. Notably, the cores obtained from Wisconsin for the third project underwent sawing to a 40mm thickness, specifically to evaluate the performance of the wearing course in relation to the longitudinal joint. Figure 5.10 shows the coring operation and the core extracted from the pavement. The core locations had been pre-marked, and during the coring operation, a yellow marker was used to make a distinct mark on each core. This mark was made in the direction of the longitudinal joint, ensuring a precise and accurate description of the longitudinal joint location for subsequent analysis and evaluation.

**Figure 5.10: Core extracted from the pavement.**

## 5.5 TEST METHODS

The extracted field cores were tested to assess the effectiveness of various longitudinal joint construction strategies. Each core was cut to precise dimensions in the laboratory before undergoing a series of tests on specimens with a 152.4 mm diameter. Density testing using a CoreLok device was conducted (See Section 4.5.1). This test provided crucial density values, serving as indicators of the success of longitudinal joint construction strategies. Then, X-Ray CT imaging was conducted to quantify the internal void structure of the cores. Then, an indirect tensile strength test (see Section 4.5.2) was carried out to measure the tensile strength and fracture energy of the joint. This test contributed to the assessment of the longitudinal joint's cracking resistance and durability.

### 5.5.1 Density Profiling System (DPS)

The structural performance of asphalt pavements depends on the percentage of air voids in the compacted pavements. It is well-known that the higher air voids lead to increased moisture and air infiltration, which subsequently cause aging, moisture damage, and premature failure of the pavements (Foster et al., 1964). Hence, density measurements are generally carried out after the construction of pavements for quality assurance. The primary methods for conducting density measurements are nuclear density gauge (non-destructive) and saturated surface dry density measurements of the cores extracted from the pavements (William et al., 2009).

Nuclear density gauge involves the passage of gamma radiation in the pavements where neutrons are transmitted and received back after a certain period of time (Dep et al., 2023). As this radiation can be harmful, specialized safety training is required for the person utilizing the device. Moreover, this method allows the operator to select some random locations for density measurement, which can result in misinterpretation of the density over the entire stretch of the pavement. The other alternative to measuring the compaction achieved in the field is by extracting cores from the constructed pavement. This method is classified as destructive as the cores are extracted from a newly constructed pavement. In general, ODOT uses the chevron pattern for extracting cores, which are extracted throughout the entire width of the pavement. However, this method involves extensive staffing and equipment for coring the cores.

Additionally, this method is conducted over a short section of the entire length, which makes this approach inadequate to represent the density achieved over the entire stretch of the pavement.

To address all these problems, the Ground Penetrating Radar (GPR) system was recently developed to determine the relative density of the surface pavement layer (Leiva et al., 2022). The GPR technique is a non-destructive approach that can be effectively used for the entire length of the pavement. In this technique, the GPR transmitter emits electromagnetic waves into the pavement. After changes in the subsurface conditions are noticed, some of the electromagnetic waves are reflected back and captured by the sensor on the system. This is a continuous process wherein the dielectric constant is measured at any instance for any length/section of the pavement. The obtained dielectric constant is further processed and converted to determine the air voids in the pavement, or the percentage compaction density achieved. In the present study, a Dynamic Profiling System (DPS), which works on the principle of GPR, was used to examine the compaction achieved in the field.

DPS was acquired through a loan from the Federal Highway Administration (FHWA) and Mobile Asphalt Testing (MATC). The DPS consists of a wheel-mounted cart with three sensors. These sensors are connected to the tablet computer mounted on the cart, which displays the dielectric constant. Figure 5.11 illustrates the DPS equipment with the sensors and tablet computer connected. The data collection is done by rolling the cart over the pavement twice during the first pass, also called the swerve pattern. This calibration/validation run determines the accuracy of the sensors and provides information on whether the sensors capture the dielectric of the pavement for the designated distance. The second pass consists of the field measurement, where actual measurements are conducted for the section under consideration.

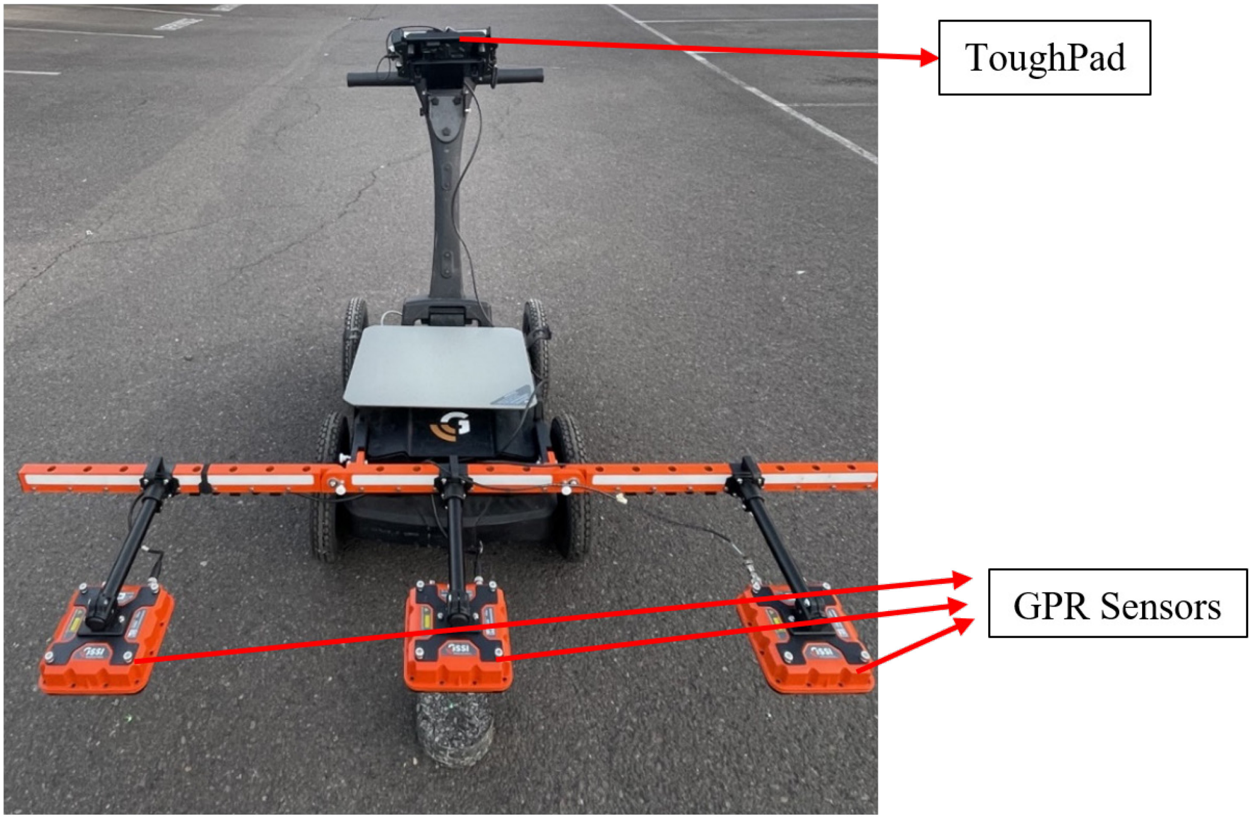


**Figure 5.11: DPS instrument used in this study.**

The current study only used DPS for the I5-Kuebler project due to scheduling and environmental challenges (wet pavement surface due to rain). As mentioned in the earlier sections, the I5-Kuebler project included three different longitudinal joint construction strategies, and each section was 100ft long, except for the topical section (150 ft long). The DPS cart was run on every section after setting up the equipment and calibrating the sensors. Dielectric values were collected after every 0.25 ft in order to get four data points in 1ft length. After that, the mix design calibration was set in the system by using the cores prepared in the laboratory and measuring their air voids. This mix calibration was used to convert the dielectric coefficients to air voids.

The data obtained from these tests collectively provided valuable insights into the structural and material characteristics of the pavement. Overall, the results presented in this study would aid in selecting the best longitudinal joint construction strategies for constructing longitudinal joints in asphalt pavements.

### 5.5.2 X-Ray Computed Tomography (CT) Imaging

X-ray computed tomography (CT) imaging is a valuable technique for analyzing the internal microstructure of any sample/structure. This study used X-ray CT imaging to determine the air void distribution in asphalt specimens constructed using different longitudinal joint construction strategies. The construction methods used for this test comprised high tack application, topical emulsion, Void Reducer, and hot pinch longitudinal joint construction. The test was performed on 6-inch (150mm) diameter cores extracted along the longitudinal joint from the pavement.

In CT imaging, the X-Ray emitted from the source passes through the asphalt core and is captured by the X-Ray detector. The different materials in the asphalt core attenuate to different intensities depending on the density of the material. 2D images were obtained throughout the thickness of the specimen at a sampling distance of 0.5mm. The air-void distribution along the vertical direction of the specimen was obtained by following an image processing technique. The asphalt core samples were scanned at the Oregon State University Veterinary Diagnostic Imaging Center. Figure 5.12 provides a visual representation of the X-Ray scanning process conducted on the asphalt samples.

After scanning, the raw images were obtained in Digital Imaging and Communications in Medicine (DICOM) format. A popular software, namely Dragonfly, was used to process the images. A median filter was applied to all the images to improve their quality. Later, these images were used to segment the air voids from the aggregate and the mastic. Machine learning segmentation was utilized to train some slices where the air voids were differentiated from the other materials in the asphalt sample. These trained slices were further used to segment the air voids in the entire sample. The percentage of air voids evaluated using the X-Ray imaging approach was also compared to the density obtained from the CoreLok device.

**Figure 5.12: Specimens lined up for X-Ray CT Imaging.**

## 5.6 RESULTS AND DISCUSSION

### 5.6.1 Density

CoreLok device was used to determine the density of the field cores extracted from all the test sections. Due to the distinct nature of each project, longitudinal joint construction strategies specific to individual projects were examined independently.

It is critical to note that the I5-Kuebler project had a joint on the shoulder side. The shoulder was constructed more than a decade ago. Since the removed cores had half from the shoulder side, the theoretical maximum specific gravity ($G_{mm}$) determined from the production mix is not expected to provide accurate density values for the field cores. For this reason, X-Ray CT image data is expected to provide more reliable density and air void distribution information for the I5-Kuebler project (provided and discussed in Section 5.6.3). In addition, the cores from Wisconsin with the Void Reducer product had thick polymeric material along the joint area. This material has a specific gravity lower than asphalt concrete. Since it is not possible to determine the theoretical maximum specific gravity ($G_{mm}$) of the asphalt mix with the Void Reducer product, the density values for the cores with this product are expected to be lower than they actually are. To address all these issues with CoreLok density measurements, the research team also included the X-Ray CT imaging component in this study to determine density (see Section 5.6.3). The X-Ray CT imaging process directly identifies the air void distribution based on the image data and does not need any laboratory-measured parameters to calculate the density and air void of the asphalt cores.

Figure 5.13 shows the average values of density obtained for different longitudinal joint construction strategies for the I5-Kuebler project. No statistically significant differences in density were observed in different construction techniques, while there were differences in average values. However, all densities for all three strategies were significantly higher than the acceptable joint density thresholds provided in the literature, which generally range from 90% to 92%. Notably, hot pinch construction showed slightly lower densities, while high tack and topical application densities were higher. The strategy with high tack coat application had the highest density when compared to topical application and hot pinch methods.

In the I5-Kuebler project, the longitudinal joint was formed between the cold shoulder (over 10-year-old asphalt concrete layer) and the new pavement. Having been in service for over a decade, the cold shoulder generally possesses greater density and fewer air voids than the newly constructed pavement, with 7% air voids. In other words, the density values are generally higher than the middle part of the constructed pavement (the mat with no joints). This is a result of the high density of the shoulder that was constructed more than a decade ago. For this reason, the density values presented in Figure 5.13 should only be compared with each other. However, the density data from CoreLok and X-Ray CT images were determined to be close (see Figure 5.21). This result shows that the $G_{mm}$ for the shoulder and the new asphalt mix are not significantly different. When the tack coat with a higher application rate was applied to the edge of the cold mat, it did not infiltrate the cold mat; instead, it filled the voids along the longitudinal joint in the newly constructed asphalt mat, resulting in higher joint density than all other techniques.

Similarly, topical emulsion was applied to both the cold and hot asphalt. After a few minutes of application, it was observed that more emulsion penetrated the newly constructed pavement compared to the cold shoulder since the shoulder had a significantly higher density. Figure 5.14 illustrates the difference in the absorption of the topical product in both the shoulder and the pavement. This differential absorption improved the density along the longitudinal joint. The distinct behavior of the construction techniques in response to the project's specific characteristics highlights the importance of considering project-specific conditions in the evaluation of the effectiveness of the longitudinal joint construction methodologies.

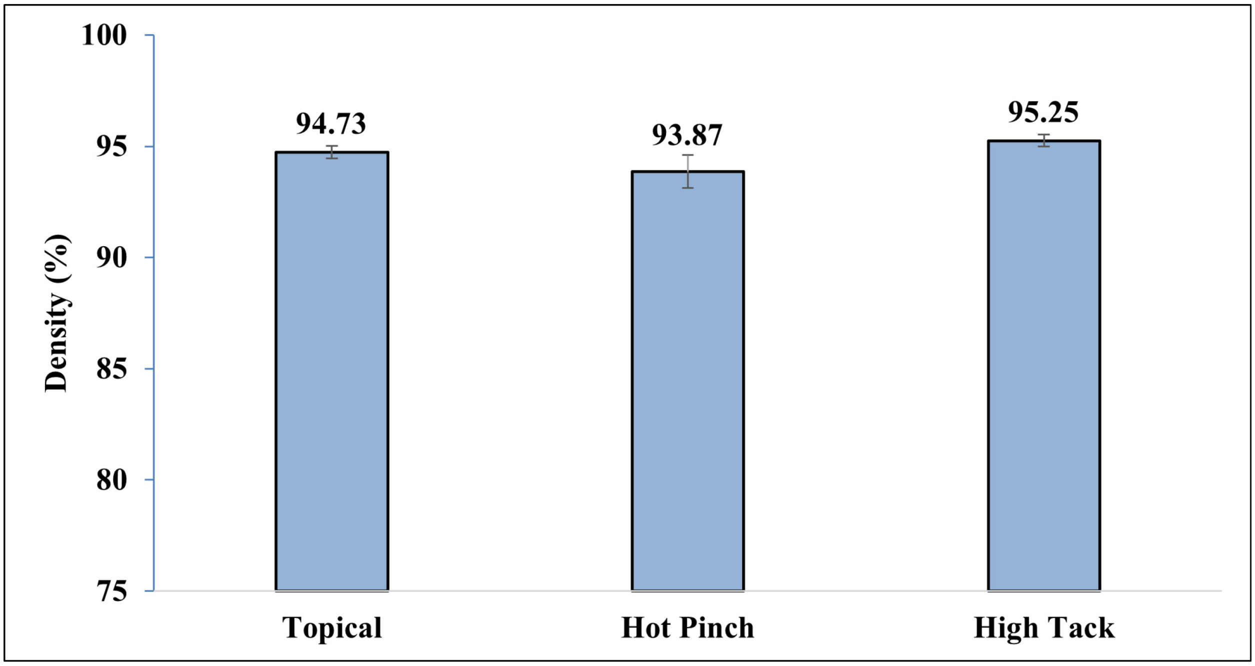


Figure 5.13: Density for different construction techniques on the I5-Kuebler project.

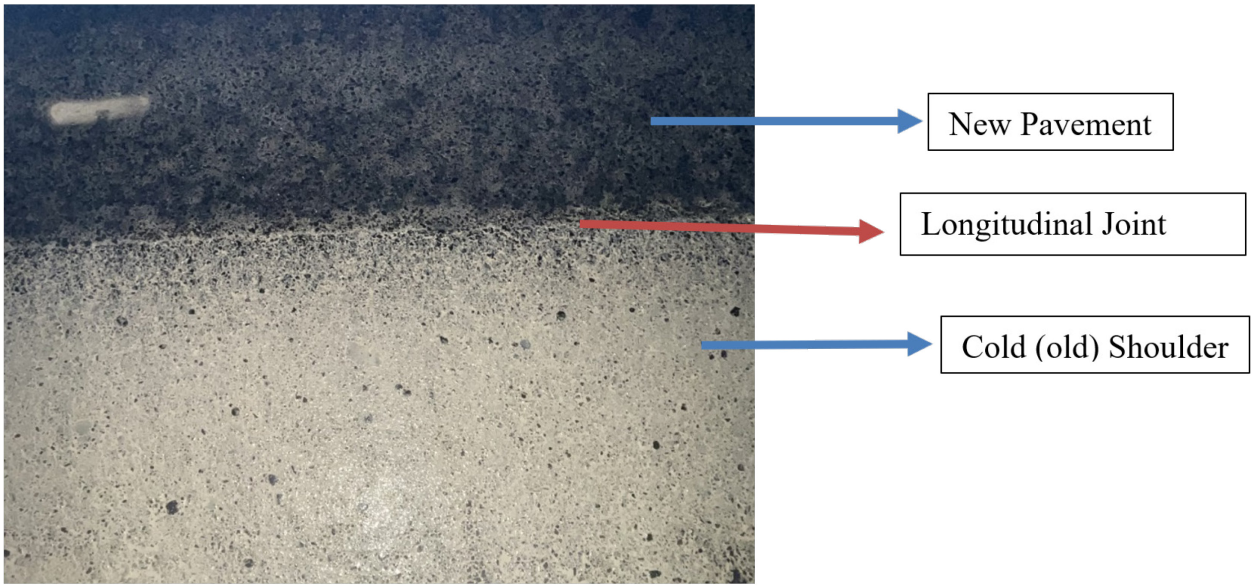


Figure 5.14: Topical emulsion penetration in the new pavement and old shoulder, I5-Kuebler project.

Figure 5.15 describes the densities of the cores obtained from the OR18-McMinnville project. It can be observed that the hot pinch longitudinal joint construction resulted in the highest density. As discussed, both pavement lanes were constructed simultaneously in this project with about a 2–3 day gap between constructions. This technique was effective in compacting both lanes along the longitudinal joint to a higher density level. This resulted in lower air voids along the longitudinal joint.

The high tack coat strategy had slightly lower density values than the hot pinch method. However, it should be noted that the 92% density achieved by using high tack coat application is still high and close to the average density requirements required by ODOT for the middle of the mat. It should also be noted that hot pinch and high tack methods were applied separately for those two sections. Combining those two methods can result in significantly higher longitudinal joint densities.

Unlike the I5-Kuebler project, the topical application was not as effective in filling air voids and improving density along the longitudinal joint in this project. Since this conclusion might be a result of the overall issues with compaction or higher density values at the bottom of the cores, X-Ray imaging results were also analyzed to determine the impact of topical emulsion in sealing the joint surface (see Section 5.6.2).

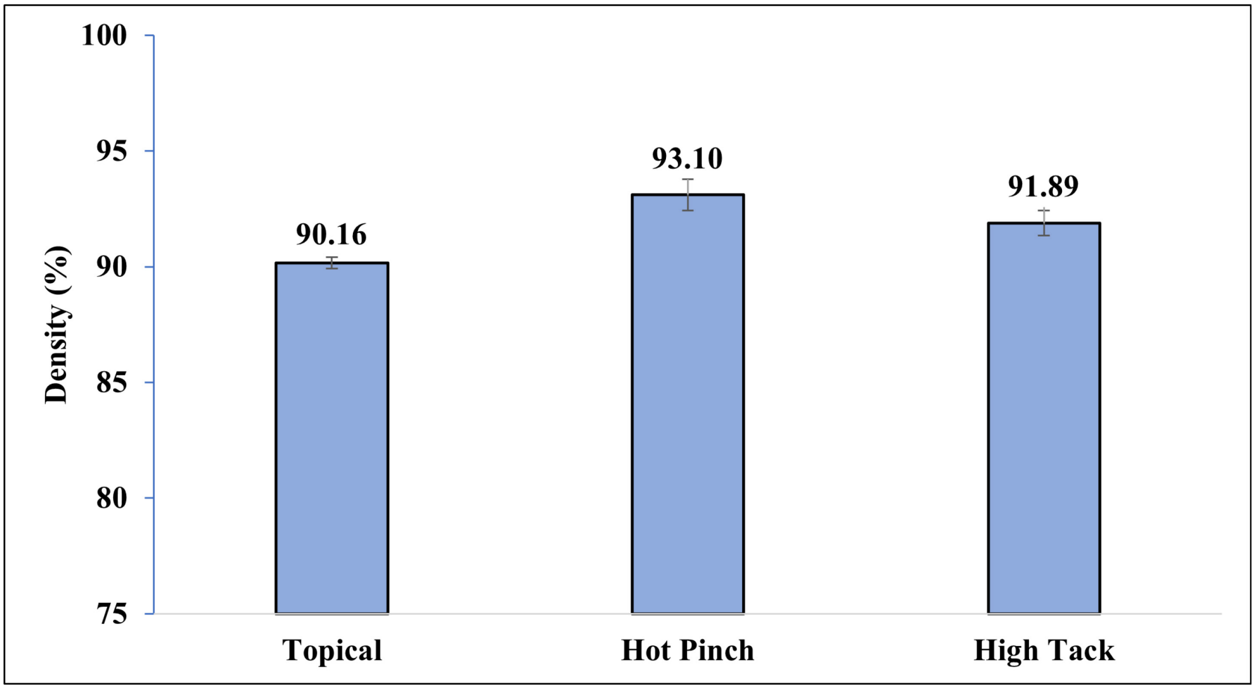


**Figure 5.15: Density for different construction techniques on OR18-McMinnville.**

Figure 5.16 describes the density comparison for the Fond Du Lac County project, where the Void Reducer was applied to improve the density along the longitudinal joint. It was found that the longitudinal joints constructed without the Void Reducer application exhibit higher density than those constructed with the Void Reducer application. However, the difference between the densities was negligible. As the Void Reducer is an emulsion with lower specific gravity than the aggregates, it is expected to lower the combined bulk specific gravity of the core sample. This may be one of the reasons why the density of the Void Reducer sample was slightly lower than the control sample cores. For this reason, the X-Ray CT imaging results presented in Section 5.6.2 should be used to evaluate the effectiveness of the Void Reducer emulsion in reducing the air voids along the joints instead of using the densities measured by the CoreLok method.

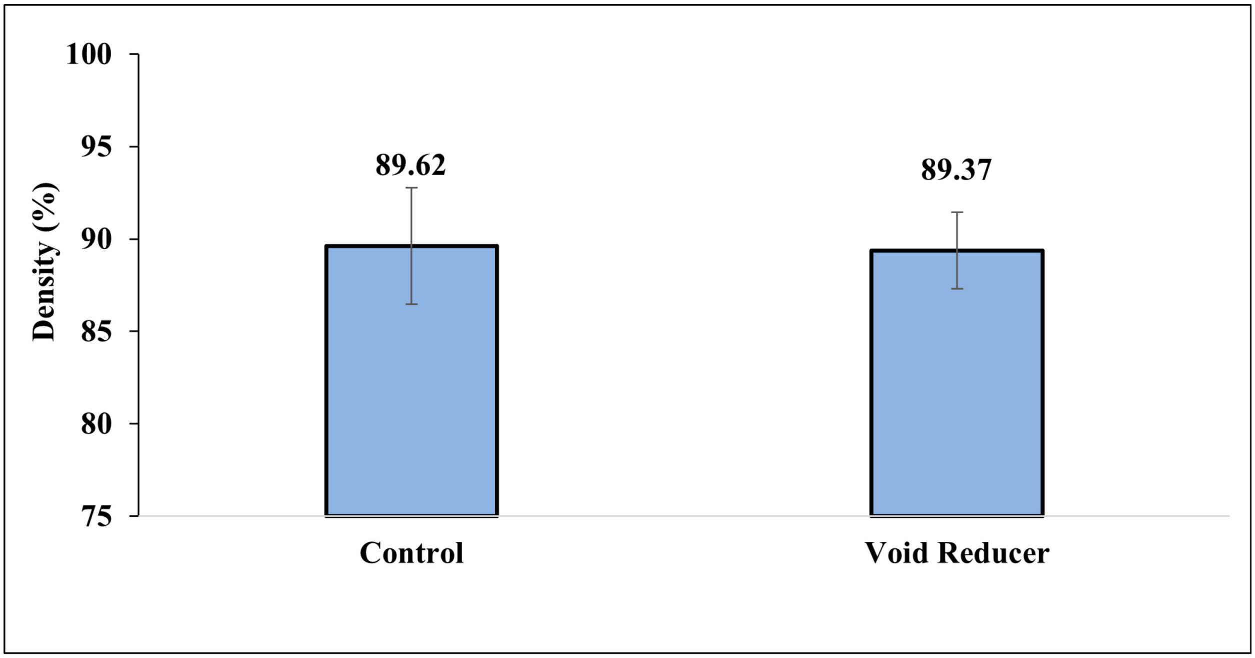


**Figure 5.16: Density for control and Void Reducer longitudinal joint core samples in Fond Du Lac County.**

### 5.6.2 X-Ray CT Imaging

The X-Ray Computed Tomography (CT) Imaging was used in this study to determine the distribution of air voids in the asphalt specimen along the longitudinal joint. In this imaging technique, a beam of X-rays is aimed at the core specimen, generating the signals that are further processed to provide the output in the form of cross-sectional images or "slices". Figure 5.17 illustrates one of the slices from the stack of images for one of the core specimens.

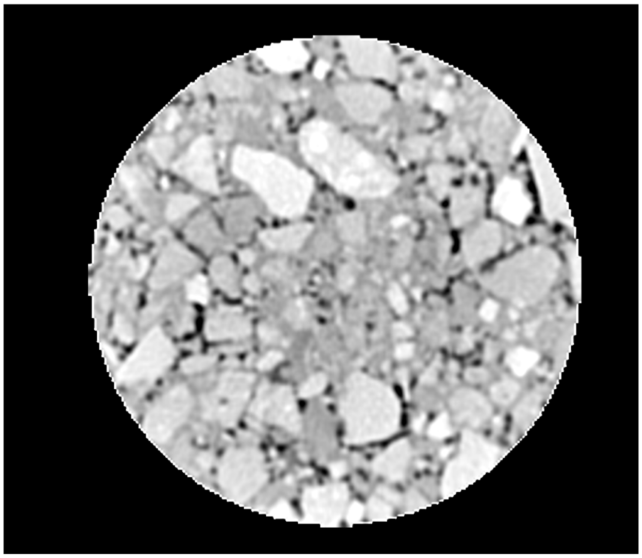


**Figure 5.17: A 2D image slice obtained from the X-Ray scan.**

An attempt has been made to segment the air voids in order to clearly understand their distribution and volume within the compacted asphalt mixture. Therefore, the entire stack of images was segmented and processed using the machine learning segmentation algorithm in Dragonfly® software. Figure 5.18 illustrates the top view (2D image) of the air voids segmented from the other materials (binder mastic and aggregates) in the asphalt mix. Similarly, other images were segmented and used for training through the machine learning segmentation algorithm. It should be noted that the longitudinal joint in the specimen was clearly observed after processing the image. In addition, it was found that the air voids were concentrated along the longitudinal joint, as shown using the red color mark.

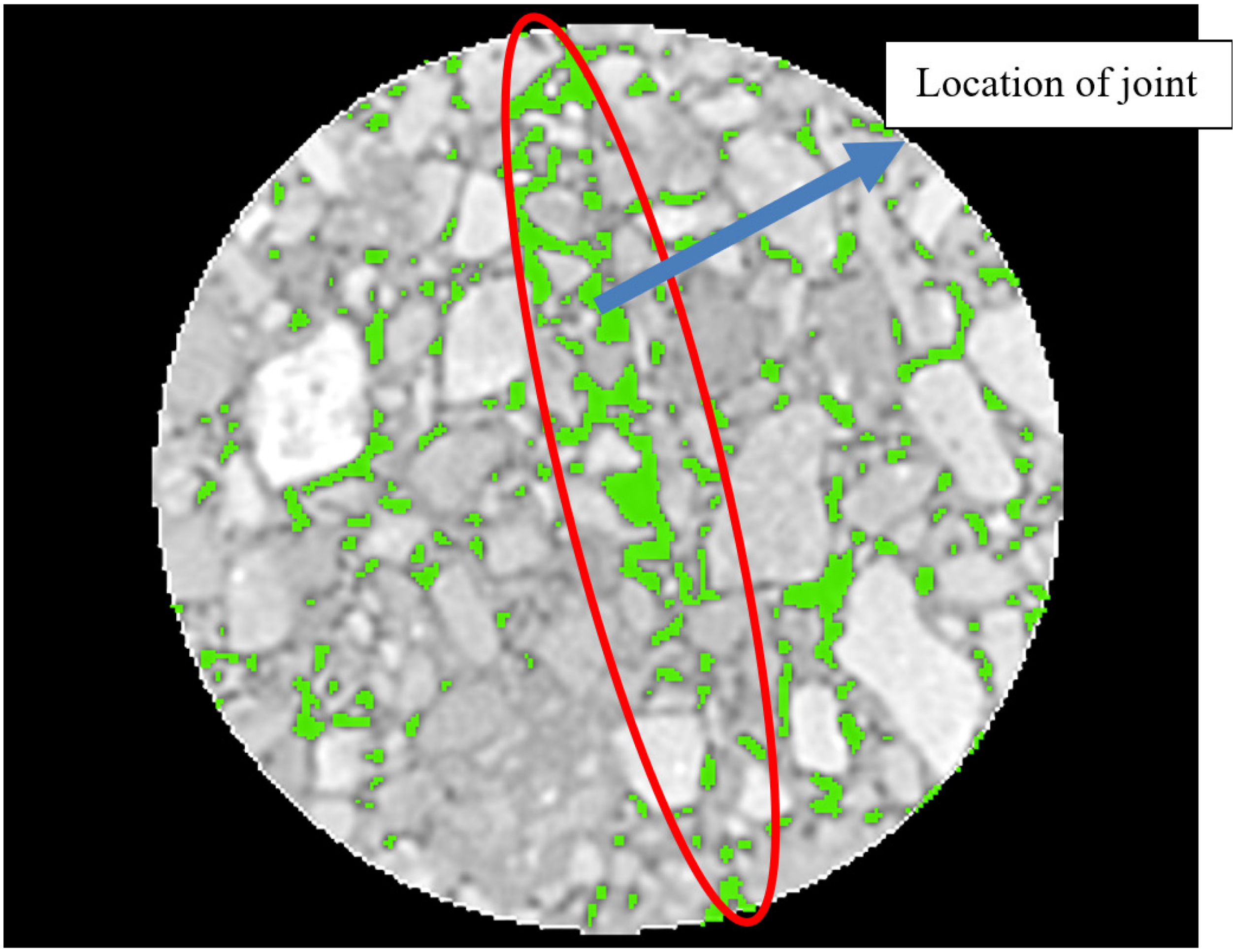


**Figure 5.18: Slice for training the machine learning algorithm.**

Like the top view of the specimen, the distribution of air voids along the thickness of the asphalt mixture was also evaluated, as depicted in Figure 5.19. As can be seen, the air voids are clearly separated from the aggregates and the mastic. After segmentation, the area of the voids was calculated through the software and exported to a CSV file. Similarly, the area of the entire 2D image, consisting of aggregates, mastic, and air voids, was analyzed. The data was further used to find the air void distribution on every slice.

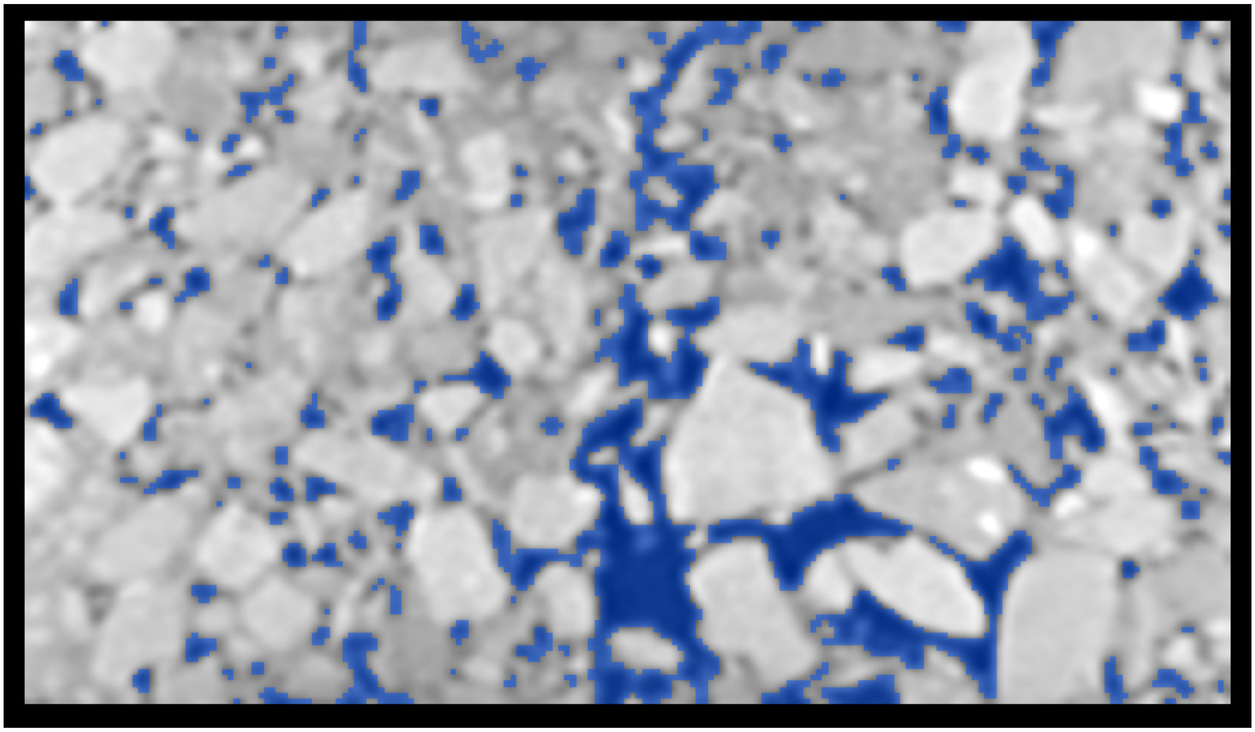


**Figure 5.19: 2D image of the voids separated along the thickness of the asphalt.**

After cutting the samples to an appropriate thickness and before conducting the destructive tests, all the cores were also scanned to understand the distribution of air voids along the entire specimen thickness. Moreover, the effects of applying a high tack coat rate, topical emulsion, and Void Reducer were investigated.

Figure 5.20 shows the average air void distribution from the top of the wearing course to the bottom of the lift for all the specimens for the I5-Kuebler project. It was evident from the X-ray CT image data that techniques such as high tack and topical applications effectively reduced the air voids in the top part of the specimens. In addition to filling the voids at the top of the surface layer, the high tack application effectively also reduced the air voids in the bottom part of the layer. On the contrary, the hot pinch construction resulted in a dense structure in the center of the surface pavement layer but exhibited higher air voids at the top and bottom of the pavement. This result shows that compacting the top portion of the pavement adjacent to the extremely dense shoulder is difficult compared to the center of the mat. For this reason, special products or heavy-tack coat applications are needed to increase the density along those types of longitudinal joints.

The potential issues with using CoreLok® for some of the strategies for density measurements were discussed in Section 5.6.1. The average density values obtained from X-Ray CT images are provided with the CoreLok® densities in Figure 5.21. It can be observed that the densities from the CoreLok® process are always lower than the densities from the X-Ray CT images. However, the results were not significantly different from each other. This result further confirms that all three strategies performed well and resulted in densities that were significantly higher than the acceptable joint density thresholds provided in the literature, which generally range from 90% to 92%.

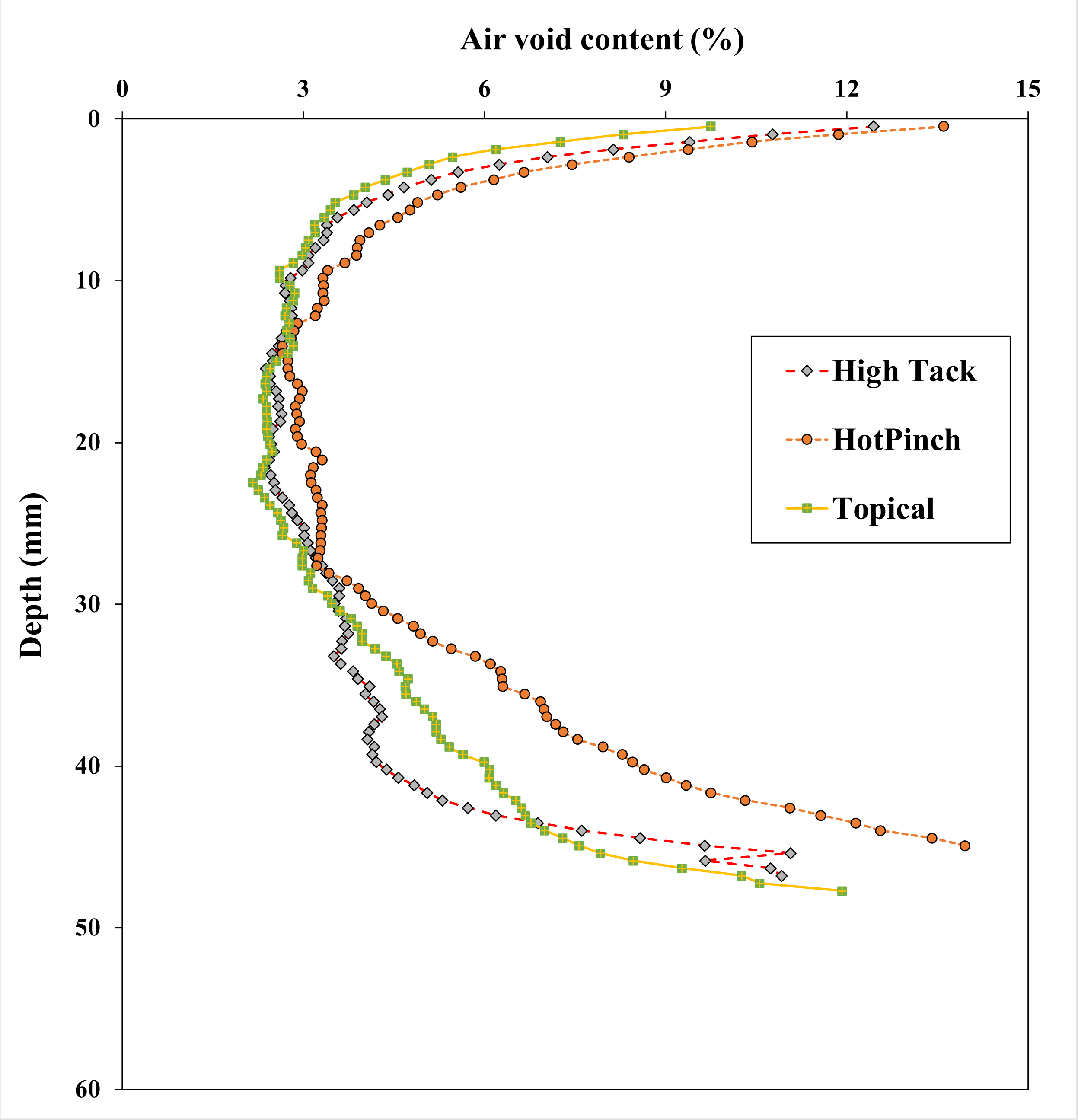


**Figure 5.20: Air void distribution for the I5-Kuebler project.**

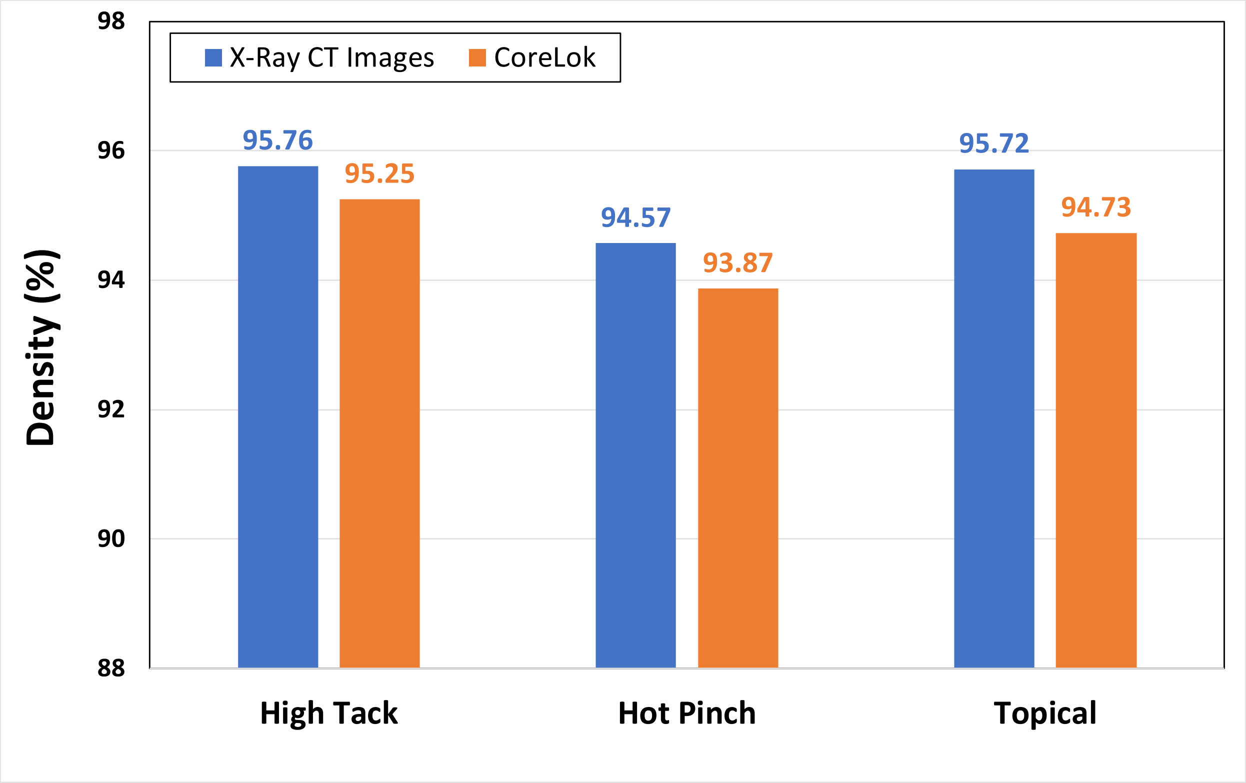


**Figure 5.21:CoreLok and X-Ray CT image-based densities for the I5-Kuebler project.**

Figure 5.22 illustrates the air void distribution in the core samples extracted from the OR18-McMinnville project. As can be seen, similar to the I5-Kuebler project, the high tack coat application along the longitudinal joint improved the density (i.e., filling the air voids) in the top portion of the pavement layer (till around 10 mm). Beyond 10 mm depth, the density/air void differences between the high tack, topical application, and hot pinch construction were generally insignificant. Since both the pavements were recently constructed, hot pinch construction resulted in relatively better packing of the aggregate matrix, resulting in lower air voids. The application of the tack coat was effective in maintaining the air voids below 8% in the top 45 mm of the specimen and thus proves that the higher application of the tack coat along the longitudinal joint is beneficial in filling the air voids. On comparing all the longitudinal joint construction strategies, it was found that the topical application was effective in filling the air voids around the top 10 mm to 15 mm thickness and thus resulted in higher densities throughout the top part of the pavement, which is critical for reducing permeability.

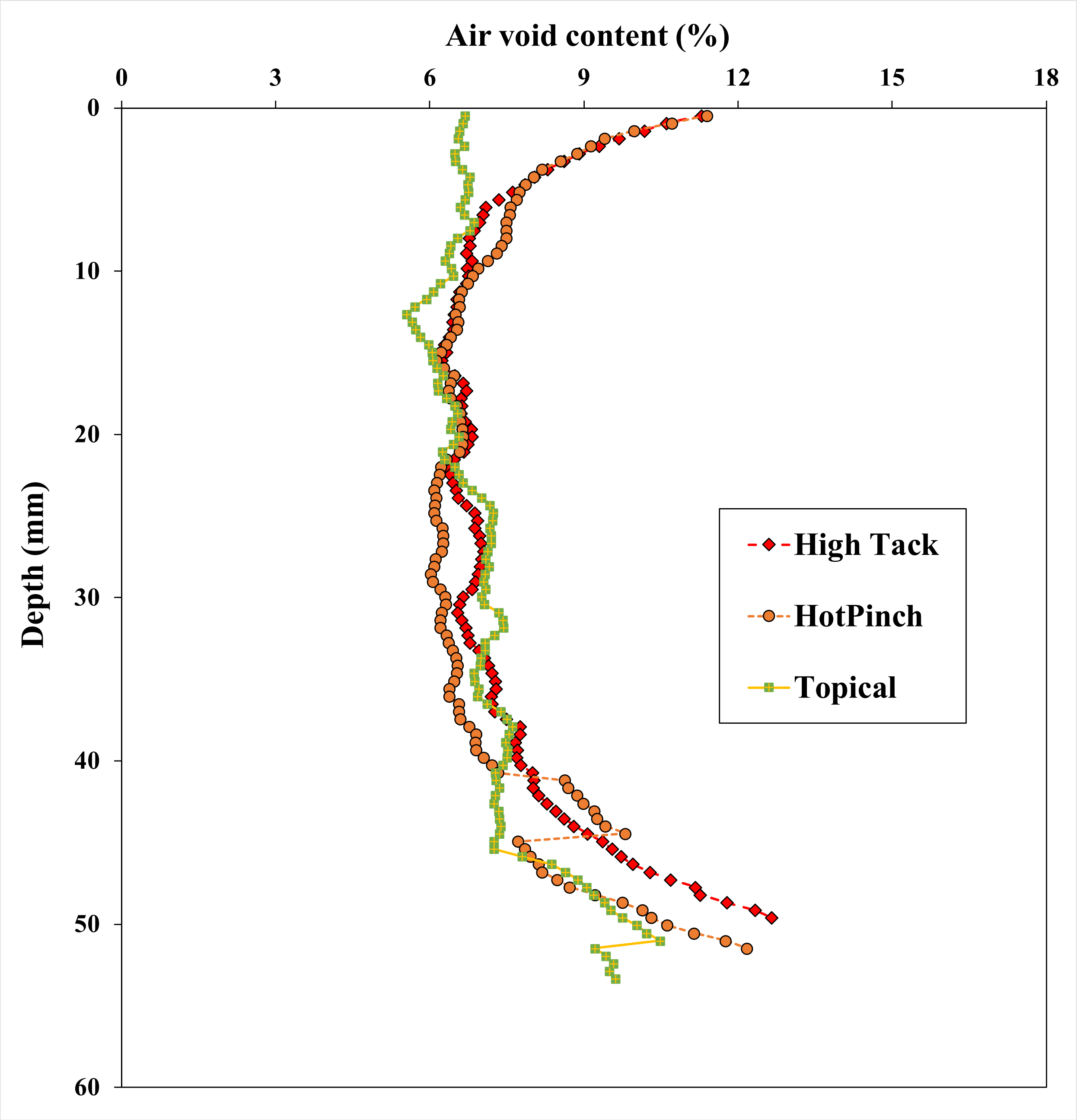


**Figure 5.22: Air void distribution for the OR18-McMinnville project.**

For the OR18-McMinnville project, the average core densities measured using the X-Ray CT images are provided in Figure 5.23, along with the density values measured using the CoreLok® method. It can be observed that the densities measured by both methods are close to each other for the High Tack and the Hot Pinch methods, while the CoreLok® density for the Topical emulsion is significantly lower than the X-Ray CT method. This result is probably due to the different densities of the topical emulsion used when compared to the asphalt mixture. The emulsion is expected to reduce the $G_{mm}$ of the overall mixture, which was not possible to measure in the laboratory. For this reason, X-Ray CT image results can be expected to be the more accurate values for the Topical emulsion strategy. Overall, the X-Ray CT image and CoreLok®-based densities show that all three strategies provided densities that are comparable to the main mat densities expected in Oregon. This result suggested that using one of those strategies or combining some of them can significantly improve joint densities and long-term pavement performance in Oregon.

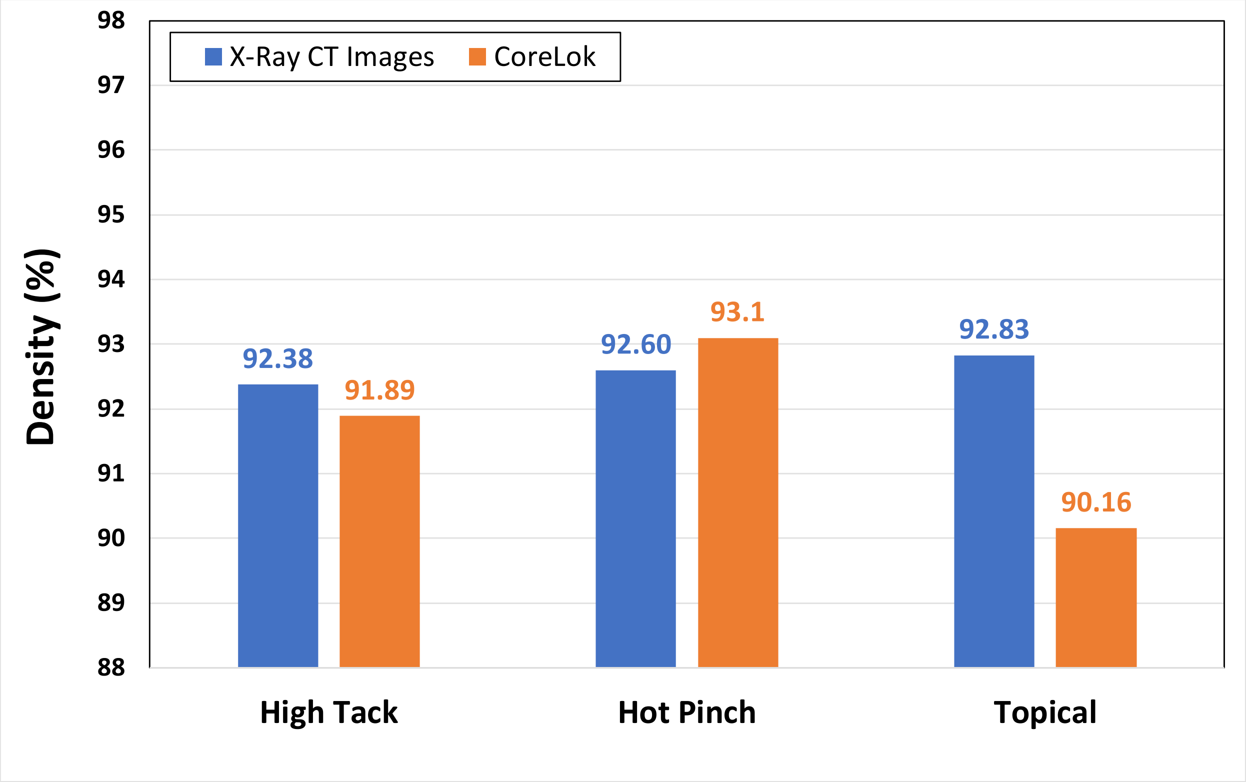


**Figure 5.23: CoreLok and X-Ray CT image-based densities for the OR18-McMinnville project.**

Figure 5.24 describes the air void distribution of the cores extracted from Fond Du Lac County in Wisconsin. The results revealed that the samples extracted from the pavement constructed by applying Void Reducer effectively reduced the air voids compared to the control specimen. The product reduces the voids to less than 3% until the top 7.5mm of the sample. The Void Reducer effectively migrated from the bottom to the top 2.5mm of the sample, which is more than 80% of the thickness of the pavement. Nevertheless, further investigation is necessary to understand the emulsion migration in pavements with a lift thickness of more than 50mm, which is the typical wearing course thickness in the mill and fill construction in Oregon. Moreover, the Void Reducer does not move to the top surface of the asphalt layer, which may pose chances of deterioration due to the infiltration of moisture and air from the top of the surface layer. A similar observation was also noted by Rahaman et al. (2023).

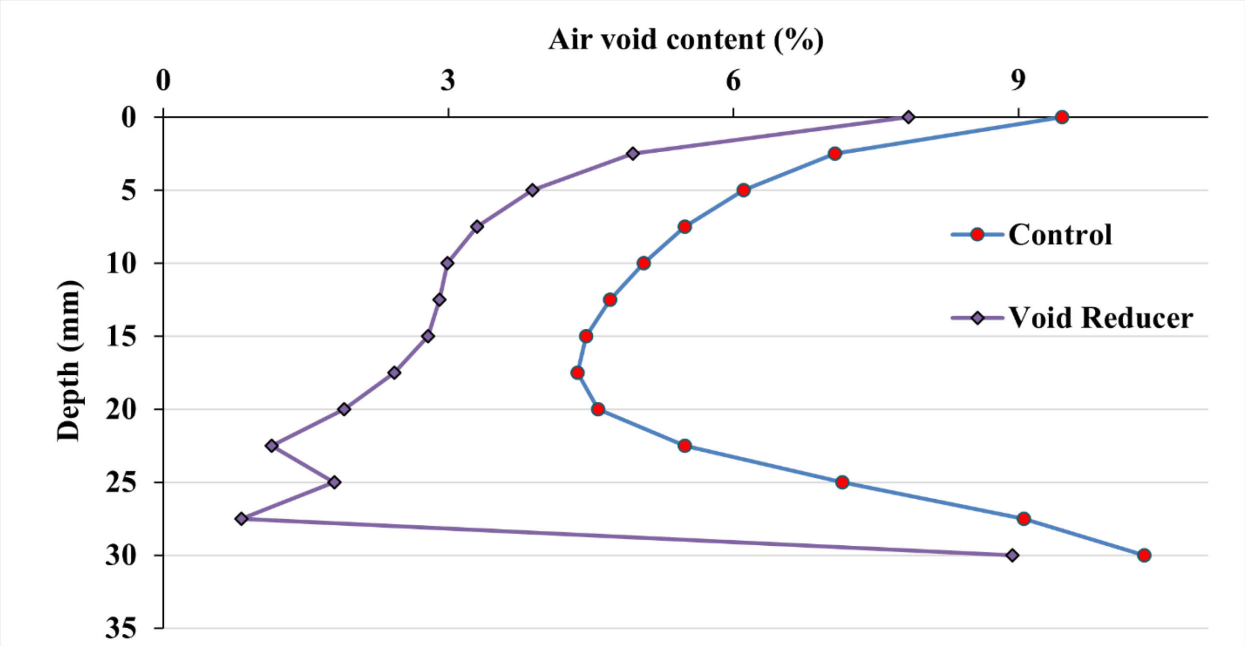


**Figure 5.24: Air void distribution for the Fond Du Lac County-Wisconsin project.**

### 5.6.3 Indirect Tensile Strength (IDT)

Figure 5.25 presents the Indirect tensile strength of the cores extracted from the I5-Kuebler project. It can be observed that all the longitudinal joint construction techniques demonstrate comparable tensile strengths. The application of a high tack coat presents a slightly superior tensile strength when compared with the topical and hot pinch construction methods. Although the tack coat application significantly enhanced the density along the longitudinal joint, it resulted in only a slightly higher tensile strength than the topical emulsion and hot-pinch strategies. This implies that particle orientation of the compacted mix plays an important role, and higher density does not necessarily mean that the sample would yield higher tensile strength.

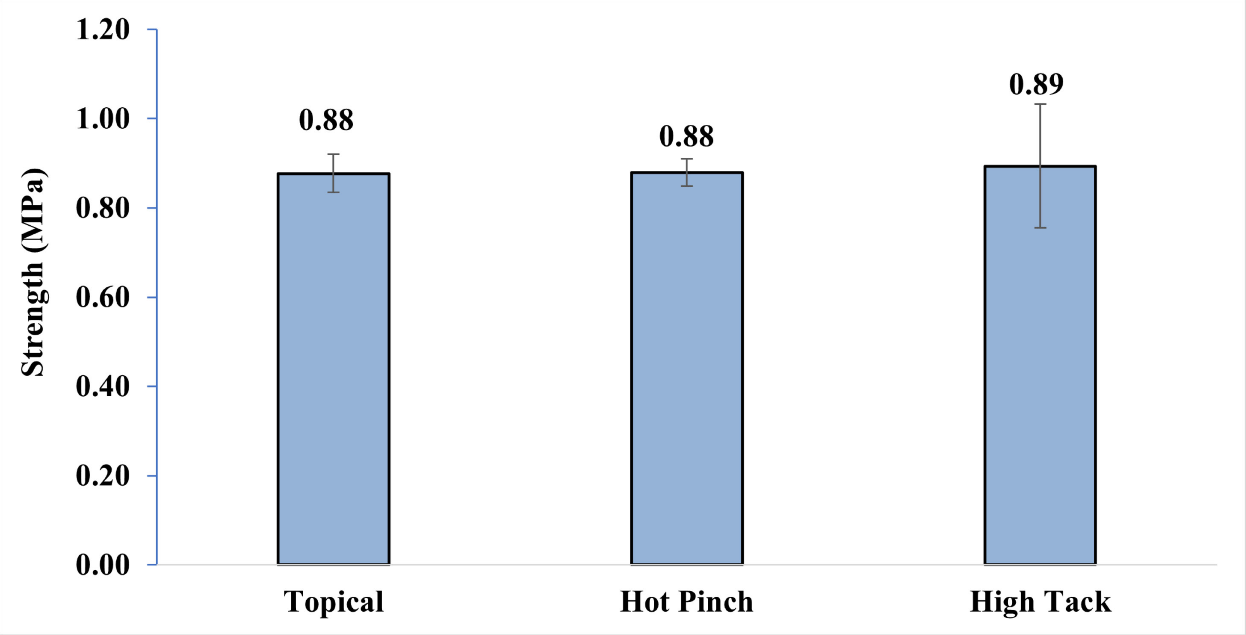


**Figure 5.25 IDT results for the I5-Kuebler project.**

Figure 5.26 depicts the indirect tensile strength of the cylindrical cores extracted from the OR18-McMinnville project. As can be seen, the hot pinch and high tack cases had higher strength values than the topical application. These results suggest that the topical application is ineffective in enhancing strength along the longitudinal joint. This conclusion might be a result of the limited penetration of the topical emulsion into the pavement, limiting its effectiveness in improving the adhesion between the two lanes along the joint line. This result was expected since the major purpose of the topical emulsion was to improve surface density and reduce water and air infiltration, which are generally detrimental to long-term pavement performance. The critical research question here is the penetration level of the topical emulsion. It is expected that the topical emulsion will only penetrate 1 to 1.5 inches into the pavement. However, the effect of this penetration can only be observed in the X-Ray CT imaging results presented in Section 5.6.2.

The samples extracted from the tack coat applied section had slightly higher air voids than the hot pinch method but still yielded slightly higher tensile strengths, suggesting that the tack coat improves the bonding between the two pavements by improving lane-to-lane adhesion along the joint line.

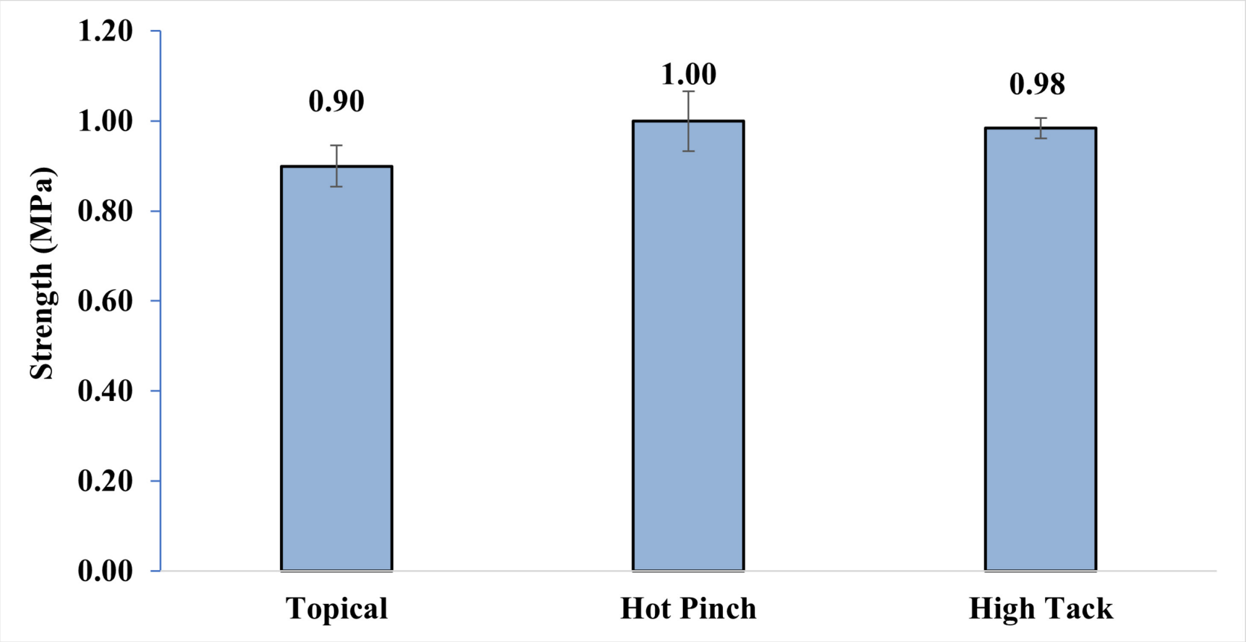


Figure 5.26: IDT results for the OR18-McMinnville project.

Figure 5.27 describes the indirect tensile strength of the Fond Du Lac County specimens. The control section had a slightly higher strength than the samples constructed with the Void Reducer application. However, the results can be considered to be statistically identical by considering the variability of the test results. At intermediate temperatures, the Void Reducer polymer increases its elasticity, thereby reducing its strength. Moreover, the failure in the longitudinal joint cores was ductile due to high plastic deformation (Rahaman et al., 2023).

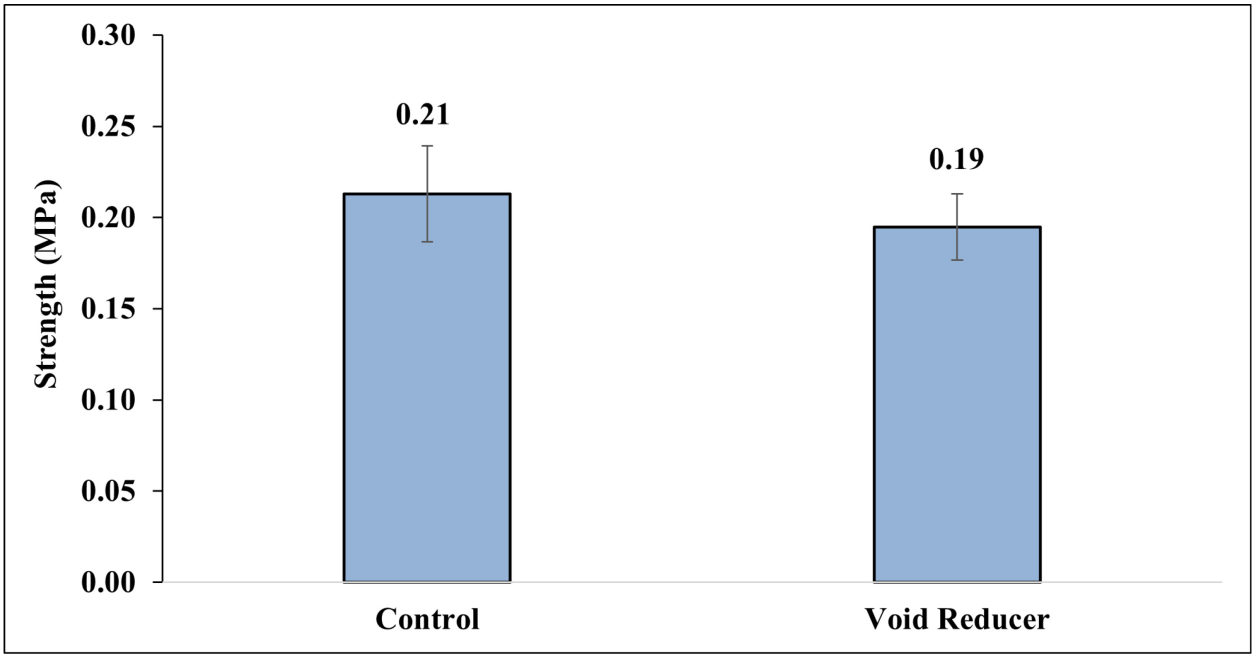


Figure 5.27: IDT results for the Fond Du Lac County project.

### 5.6.4 Fracture Energy

It is generally accepted that the tensile strength of the asphalt mixture alone does not fully capture the long-term cracking resistance of the asphalt mixtures (Saha and Biligiri, 2016). Thus, after conducting the indirect tensile strength test of the samples, the load and deflection data were processed through a MATLAB software to determine the fracture energy of the specimens. Fracture energy measures the material's ability to absorb energy and deform before reaching a point of fracture or failure. It can be used as an indicator of crack resistance. In general, higher fracture energy indicates higher resistance to cracking (Saha and Biligiri, 2016).

Figure 5.28 represents the fracture energy for the specimens obtained from the I5-Kuebler project. It can be observed that the hot pinch longitudinal joint construction strategy resulted in the highest fracture energy. The application of a higher tack coat resulted in slightly lesser fracture energy. This suggests that the hot pinch construction and high tack application along the longitudinal joint effectively resist crack initiation and propagation. The improved cracking resistance for the high tack strategy is due to enhanced bonding between the two pavements with the application tack coat, resulting in one uniform structure instead of two pavements. Additionally, the hot pinch construction compacts the hot mix asphalt constrained between the compacted mat and the edge of the cold pavement. This does not cause the aggregate in the mix to be pressed into the cold mat and then retreat from the stiff-cold mat under heavy compactor loads (Kandhal et al., 2002). On the other hand, the topical application had the lowest performance regarding the fracture energy and proves that it is unsuitable for adding any strength or resistance to cracking along the joints.

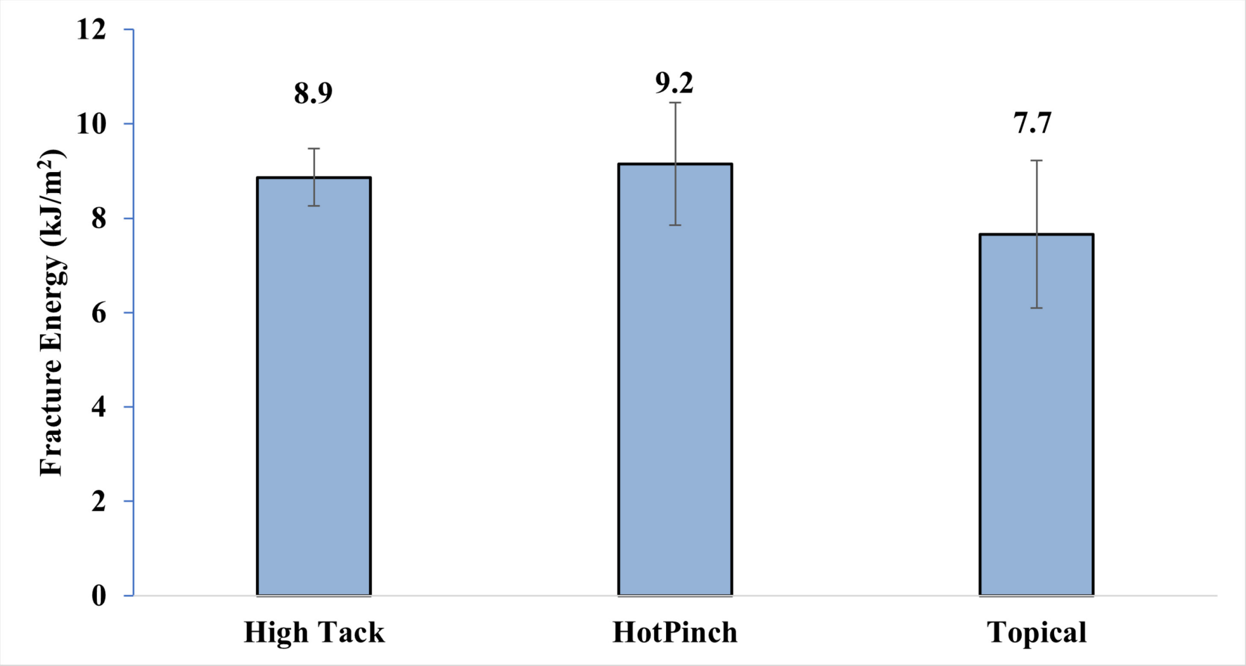


**Figure 5.28: Fracture energy results for the I5-Kuebler project.**

The indirect tensile strength values for all the longitudinal joint construction methods for OR18 were similar, as shown in Figure 5.26. However, the fracture energy results (Figure 5.29) from the OR18 pilot section constructed with different longitudinal joint strategies were quite different. This shows the inadequacy of indirect tensile strength in identifying the most effective construction method for constructing longitudinal joints.

The samples constructed using higher tack coat application resulted in the highest fracture energy among all the longitudinal joint construction strategies implemented in the field. This result suggests that applying a higher tack coat enhances the bonding between 2 lanes and increases resistance to cracking along the longitudinal joint. Moreover, the hot pinch construction technique had a slightly lower fracture energy than the section constructed using a high tack coat application. Therefore, the application of a higher tack coat along the joint in conjunction with the hot pinch compaction technique would result in enhanced density and cracking resistance along the joint. This would reduce the susceptibility of the longitudinal joint to premature cracking and improve the life of the pavement. Like the I5 Kuebler project results, the topical application had the lowest fracture energy among all the longitudinal joint construction strategies. This suggests that the topical application does not contribute to increased cracking resistance. This result was expected since the major purpose of the topical emulsion was to improve surface density and reduce water and air infiltration, which are generally detrimental to long-term pavement performance.

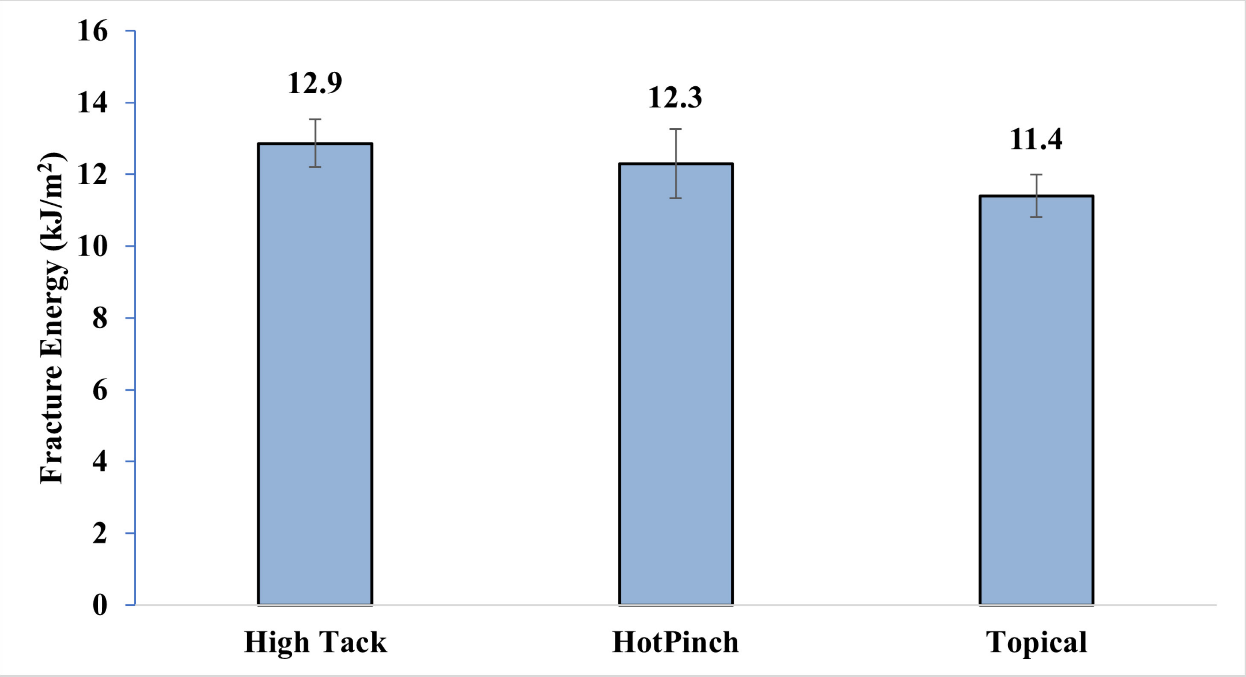


**Figure 5.29: Fracture energy results for the OR18 McMinnville project.**

Figure 5.30 illustrates the fracture energy results for the core specimens extracted from Fond Du Lac County in Wisconsin. It can be observed that the Void Reducer application for longitudinal joint construction indicated 25% higher fracture energy than the control section. After the asphalt mix is laid adjacent to the cold edge of the pavement, the void reducer starts migrating through the voids and improves the bonding along the edge of the asphalt pavement. This suggests that the Void Reducer is effective in resisting crack formation and propagation along the longitudinal joint, which may lead to long-lasting asphalt pavements.

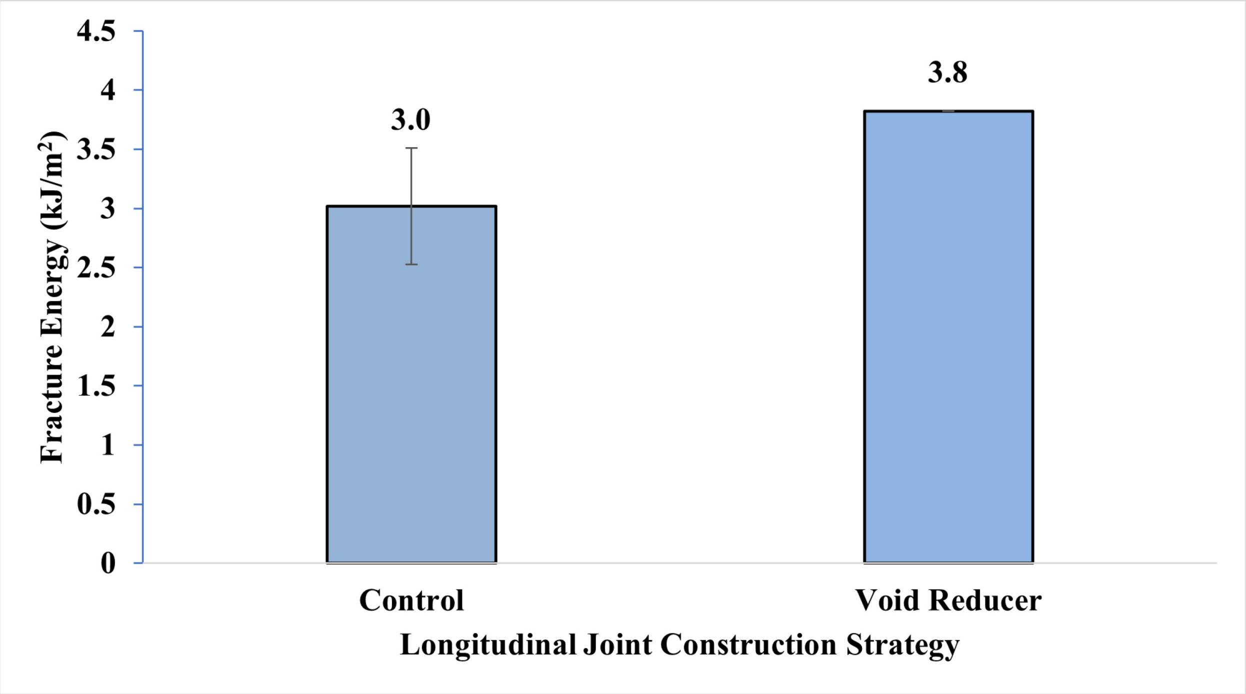


**Figure 5.30: Fracture energy results for the Fond Du Lac County project.**

### 5.6.5 Density Profiling System (DPS)

The density profiling system was used to measure the density along longitudinal joints, which were constructed using different techniques. The dielectric constants measured were converted to actual air void content using the laboratory-prepared cores.

Initially, the data were recorded with one sensor directed over the longitudinal joints and the other two on the cold and new pavement. These sensors were placed at a 4ft distance from one another. Figure 5.31 illustrates the air void distribution on the pavement at three locations (cold pavement, new pavement, and longitudinal joint). As obvious, air voids measured along the longitudinal joint were higher compared to the shoulder lane and new pavement. In addition, the air voids along the longitudinal joint are inconsistent throughout the section, ranging between 6% and 8%. The cold shoulder pavement has been in service for more than a decade and is expected to be denser than the newly constructed asphalt pavement. Similar results were obtained from the DPS, which depicts that the air voids for the cold shoulder were lesser and ranged from 5.5 to 6.4%. The vehicles do not pass over the shoulders often, so the air voids were higher when compared to the mat that would have been in service for ten years. The air voids for the newly constructed pavement were found to be 5.4-6.5%, of which most of the data points were lying above the 6% mark. In Oregon, the newly constructed pavements are expected to have air voids below 8%. Based on these results, it can be stated that DPS equipped with GPR technology effectively differentiates the different asphalt pavement surfaces in terms of air voids/density.

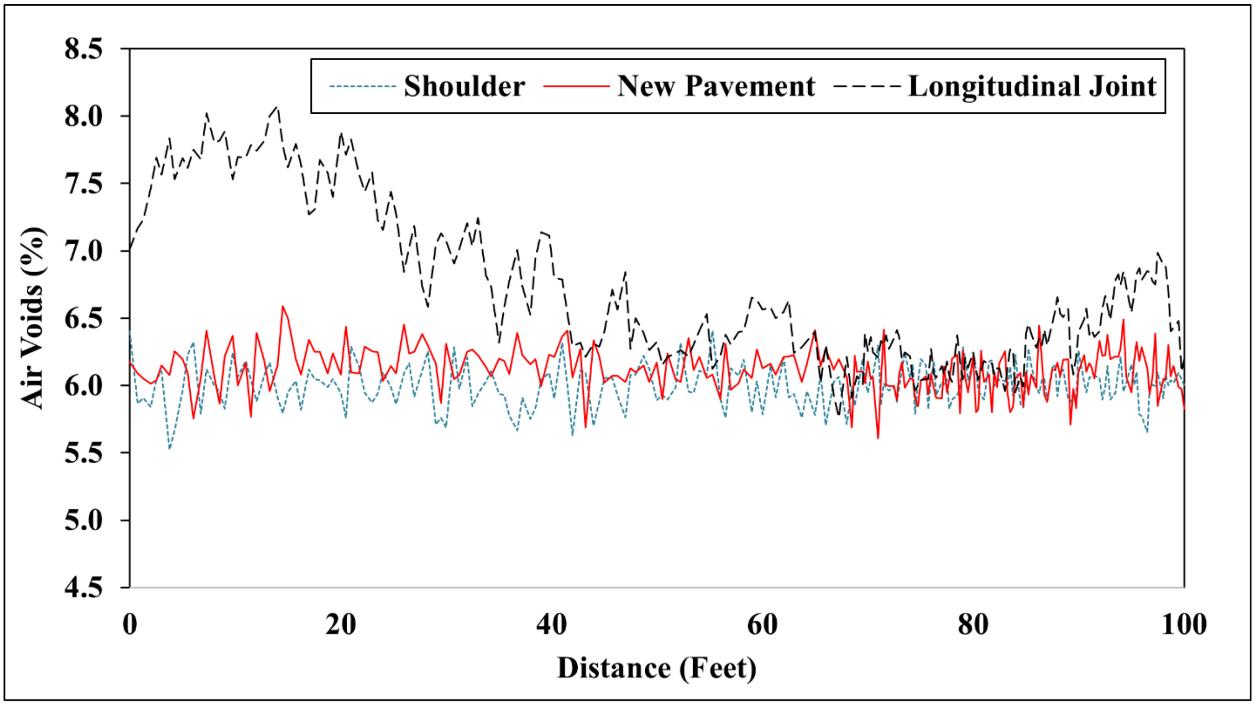


**Figure 5.31: Air void distribution on the I5-Kuebler section.**

After confirming the applicability of DPS in differentiating the pavement surfaces, the same technique was used to run on the longitudinal joint sections of the pilot construction prepared using different longitudinal joint construction techniques. It should be noted that only one sensor was placed over the longitudinal joint, and dielectric constants were measured at every 0.25 ft distance. The air void distribution for different longitudinal joint sections is shown in Figure 5.32**.**

The conventional method of compacting longitudinal joints (indicated as the control) results in inconsistent air void distribution, as depicted in Figure 5.32. Notably, the percentage of air voids was even more than 8%. This may be due to the difference in the temperature along the longitudinal joint, which results in the aggregates being pressed into the cold mat and then retreating from the stiff-cold mat under heavy compactor loads, resulting in higher air voids.

As shown in Figure 5.32, the other longitudinal joint construction strategies, namely the application of a higher tack coat, topical emulsion, and hot pinch rolling technique, resulted in relatively consistent air voids. The hot pinch strategy resulted in the most consistent air voids among all the longitudinal joint construction techniques utilized in the pilot section. The air voids fell between the 5.5-6% range, which is considered the adequate compaction required for enhanced performance of longitudinal joints. The hot pinch construction resulted in compaction of the asphalt mix confined between the cold shoulder and the new pavement, which resulted in lesser bouncing of the material from the cold shoulder. This improved the density along the longitudinal joint, as also observed from the DPS data. Similar to hot pinch, the topical application also resulted in air voids ranging from 5.3 to 6.6%. This may be due to the infiltration of topical application products within the asphalt mat, which lowers the air voids.

On the other hand, tack coat application resulted in air void distribution close to 6% except for a 20 ft segment (between 50 feet and 70 feet), where the air voids jumped to more than 6.5%. The primary reason for this can be the non-uniform application of tack coat over the edge of the shoulder lane. The tack coat was applied using a handheld spraying tool, which may not be accurately and uniformly applying the tack coat. This suggests that improving the tack coat application process on the pavements is important, and thus, necessary modifications should be made in this direction to enhance the performance of longitudinal joints. Additional suggestions regarding the most suitable joint application methods for tack coats are discussed in Chapter 6.0.

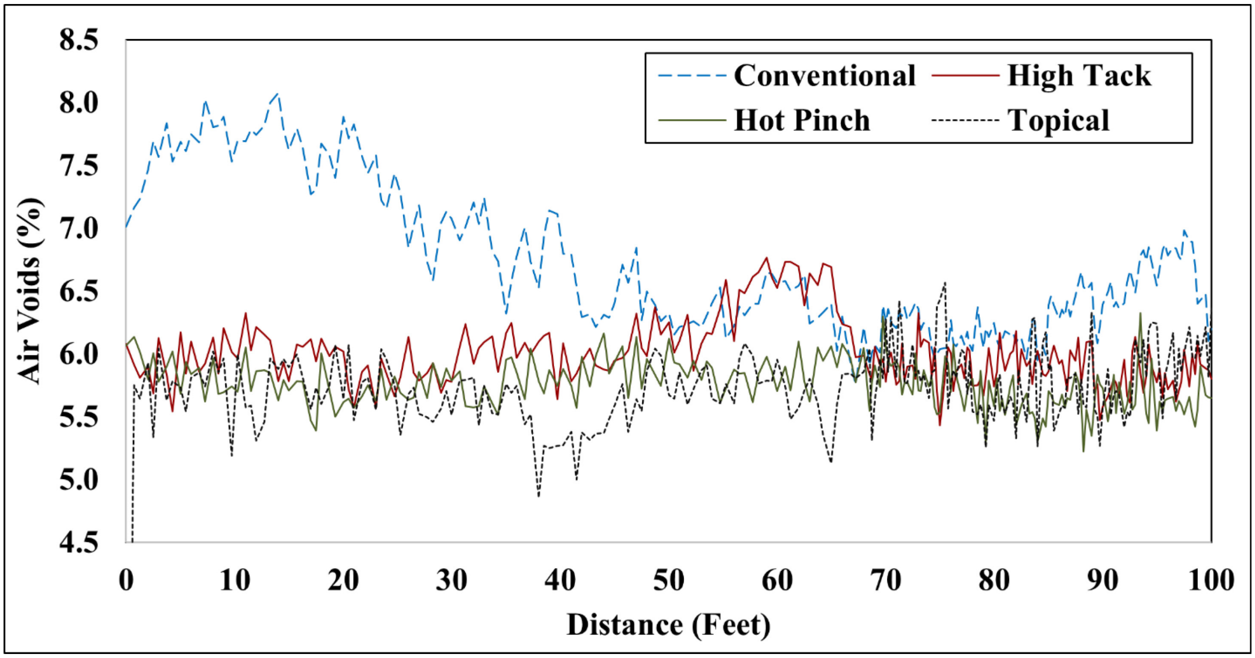


**Figure 5.32: Air void distribution for different longitudinal joint strategies.**

## 5.7 FINDINGS AND MAJOR CONCLUSIONS

The major conclusions of the field component of this study are:

- All four tested strategies improved the density of the longitudinal joints. All densities for all four strategies were significantly higher than the acceptable joint density thresholds provided in the literature, which generally range from 90% to 92%.

- Hot pinch, high tack, and Void Reducer strategies resulted in high cracking resistance values. On the other hand, the topical application had the lowest performance regarding the fracture energy and proves that it is unsuitable for adding any strength or resistance to cracking along the joints. This result was expected since the major purpose of the topical emulsion was to improve surface density and reduce water and air infiltration, which are generally detrimental to long-term pavement performance.

- The samples extracted from the pavement constructed by applying Void Reducer effectively reduced the air voids compared to the control specimens. Nevertheless, further investigation is necessary to understand the emulsion migration in pavements with a lift thickness of more than 50mm, which is the typical wearing course thickness in the mill and fill construction in Oregon. Moreover, the Void Reducer does not move to the top surface of the asphalt layer, which may pose chances of deterioration due to the infiltration of moisture and air from the top of the surface layer. A similar observation was also noted by Rahaman et al. (2023).

- Field test results showed that nonuniform tack coat application may result in reduced density and cracking resistance along the joints. Improving the tack coat application process on the pavements is important, and thus, necessary modifications should be made in this direction to enhance the performance of longitudinal joints.

- Compaction of the asphalt mix by incorporating the hot pinch rolling technique resulted in consistent air voids along the test sections and can be one of the alternative methods to improve the performance of the longitudinal joints.

- This study did not evaluate a combination of different strategies due to the time and coring limitations of the construction projects. However, different combinations of all four strategies have the potential to improve the density and long-term cracking performance of longitudinal joints. Those potential implementation strategies are discussed in more detail in the next Chapter.

Based on the results obtained in this Chapter, the following detailed findings were achieved. The major conclusions listed above were developed based on the following more detailed findings:

- For the I5-Kuebler project, all densities for all three strategies were significantly higher than the acceptable joint density thresholds provided in the literature, which generally range from 90% to 92%. Notably, hot pinch construction showed slightly lower densities, while high tack and topical application densities were higher. The strategy with high tack coat application had the highest density when compared to topical application and hot pinch methods.
- For the OR18-McMinnville project, the high tack coat strategy had slightly lower density values than the hot pinch method. However, it should be noted that the 92% density achieved by using high tack coat application is still high and close to the average density requirements required by ODOT for the middle of the mat. It should also be noted that hot pinch and high tack methods were applied separately for those two sections. Combining those two methods can result in significantly higher longitudinal joint densities.

- For the I5-Kuebler project, the hot pinch longitudinal joint construction strategy resulted in the highest fracture energy. The application of a higher tack coat resulted in slightly lesser fracture energy. This suggests that the hot pinch construction and high tack application along the longitudinal joint effectively resist crack initiation and propagation. The improved cracking resistance for the high tack strategy is due to enhanced bonding between the two pavements with the application tack coat, resulting in one uniform structure instead of two pavements. On the other hand, the topical application had the lowest performance regarding the fracture energy and proves that it is unsuitable for adding any strength or resistance to cracking along the joints.

- For the OR18-McMinnville project, the samples constructed using higher tack coat application resulted in the highest fracture energy among all the longitudinal joint construction strategies implemented in the field. This result suggests that applying a higher tack coat enhances the bonding between 2 lanes and increases resistance to cracking along the longitudinal joint. Moreover, the hot pinch construction technique had a slightly lower fracture energy than the section constructed using a high tack coat application. Therefore, the application of a higher tack coat along the joint in conjunction with the hot pinch compaction technique would result in enhanced density and cracking resistance along the joint. This would reduce the susceptibility of the longitudinal joint to premature cracking and improve the life of the pavement. Like the I5-Kuebler project results, the topical application had the lowest fracture energy among all the longitudinal joint construction strategies. This suggests that the topical application does not contribute to increased cracking resistance. This result was expected since the major purpose of the topical emulsion was to improve surface density and reduce water and air infiltration, which are generally detrimental to long-term pavement performance.

- The Void Reducer application for longitudinal joint construction indicated 25% higher fracture energy than the control section. After the asphalt mix is laid adjacent to the cold edge of the pavement, the void reducer starts migrating through the voids and improves the bonding along the edge of the asphalt pavement. This suggests that the Void Reducer is effective in resisting crack formation and propagation along the longitudinal joint, which may lead to long-lasting asphalt pavements.

- The samples extracted from the pavement constructed by applying Void Reducer effectively reduced the air voids compared to the control specimen. The product reduces the voids to less than 3% until the top 7.5mm of the sample. The Void Reducer effectively migrated from the bottom to the top 2.5mm of the sample, which is more than 80% of the thickness of the pavement. Nevertheless, further investigation is necessary to understand the emulsion migration in pavements with a lift thickness of more than 50mm, which is the typical wearing course thickness in the mill and fill construction in Oregon. Moreover, the Void Reducer does not move to the top surface of the asphalt layer, which may pose chances of deterioration due to the infiltration of moisture and air from the top of the surface layer. A similar observation was also noted by Rahaman et al. (2023).

- According to the DPS results, tack coat application resulted in air void distribution close to 6% except for a 20 ft segment (between 50 feet and 70 feet), where the air voids jumped to more than 6.5%. The primary reason for this can be the non-uniform application of tack coat over the edge of the shoulder lane. The tack coat was applied using a handheld spraying tool, which may not be accurately and uniformly applying the tack coat. This suggests that improving the tack coat application process on the pavements is important, and thus, necessary modifications should be made in this direction to enhance the performance of longitudinal joints.

# 6.0 SUMMARY, MAJOR CONCLUSIONS, AND RECOMMENDATIONS

The high performance of longitudinal joints is crucial to achieving the long-term durability of asphalt pavements. The current study identified the potential factors for the failure of longitudinal joints in asphalt pavements. The primary goal of this research was to determine the most effective longitudinal joint construction strategies for developing high-quality longitudinal joints.

The literature review, the ODOT survey, and the industry meeting results helped the research team identify different longitudinal joint construction strategies practiced in Oregon and all over the United States to develop high-performing longitudinal joints. Moreover, the benefits and drawbacks of using various techniques from the field perspective were studied. The testing methodologies for determining the quality and performance of longitudinal joints were evaluated and summarized in this report.

Once the test methods and the research process were determined based on the literature review, ODOT survey, and the industry meeting, the laboratory component of the research study started.

Laboratory testing procedures were developed to extract the performance of longitudinal joints constructed by following different practices. Nine different longitudinal joint construction techniques, including the control (with no joint), were assessed by simulating the construction of longitudinal joints in the laboratory using a hydraulic roller compactor. These techniques involved different edge geometries, such as the restrained edge wedge technique. Moreover, the effect of increasing the tack coat application rate from 0.07gal/yd$^2$ (typically used for mill and fill construction) to 0.14gal/yd$^2$ was also studied. The use of Void Reducer, a void-reducing asphalt membrane emulsion, was investigated in the laboratory to determine its effectiveness in filling the air voids and increasing the adhesion between the joints. The samples prepared using different techniques were tested following different standard protocols to evaluate their impact on the performance of longitudinal joints. The laboratory test methods utilized to analyze the performance of various longitudinal joint construction techniques include: i) Air void measurement using CoreLok®, ii) Indirect Tensile (IDT) strength, iii) Fracture energy, iv) Hamburg Wheel Tracking Test (HWTT), and v) Tensile Strength Ratio (TSR).

**The major conclusions of the laboratory component of this study are listed in Section 4.7.** The first conclusion of this study was that the restrained edge technique for longitudinal joint construction resulted in higher density levels than the loose edge technique. Table 6.1 presents the laboratory performance rankings for various joint construction strategies for different tests. The rankings in the table show that applying a higher tack coat along the longitudinal joint improved the bonding between the two lanes and improved density. The fracture energy of the specimens constructed with Void Reducer was similar to that of the control specimen, which represented the center of the mat. Although rutting is not one of the primary mechanisms of failure along longitudinal joints, it was observed that sometimes the longitudinal joint falls along the wheel path. The conducted laboratory rutting test (Hamburg wheel tracking test) provided information regarding the impact of different strategies on the stiffness of the joint. Hence, block specimens were tested to determine the effect of different longitudinal joint construction techniques on rutting performance. The use of an infrared heater to heat the cold edge of the asphalt mat increased the rut resistance due to the excessive aging of the asphalt binder along the joint. Since the majority of the longitudinal joints fail from cracking, this stiffening effect is expected to result in premature cracking along the longitudinal joint. On average, statistical inferences revealed that the restrained edge technique with higher tack coat application can be a better alternative for constructing longitudinal joint samples. However, if severe cracking is a primary concern, then Void Reducer can provide adequate resistance to cracking. The eight strategies assessed in the laboratory investigation identified the use of high tack coat application, and specimens constructed using the Void Reducer application resulted in the highest quality longitudinal joints.

**Table 6.1: Ranking for longitudinal joint construction strategies evaluated in the laboratory.**

| Sr. No. | Strategy | Laboratory Tests | | | | |
|---|---|---|---|---|---|---|
| | | Density | IDT | Fracture Energy | HWTT | TSR |
| **1** | RE High Tack | 1 | 1 | 2 | 2 | 3 |
| **2** | Void Reducer | 3 | 2 | 1 | 4 | 2 |
| **3** | IR RE Low Temp | 4 | 4 | 4 | 3 | NA |
| **4** | IR RE High Temp | 2 | 3 | 3 | 1 | 1 |
| **5** | Loose Edge | 6 | 7 | 8 | 8 | NA |
| **6** | Loose Edge Low Tack | 8 | 6 | 6 | 5 | NA |
| **7** | Loose Edge High Tack | 7 | 8 | 7 | 6 | NA |
| **8** | Wedge | 5 | 5 | 5 | 7 | NA |

Note:
RE – Restrained edge
IR – Infrared heater
IDT – Indirect tensile strength
HWTT – Hamburg Wheel Tracking Test (rut depth)
TSR – Tensile strength ratio
NA – Not available

Based on all the major conclusions from the laboratory component of this study, the most promising strategies, high tack, and Void Reducer, were selected for the field trials. In addition, the hot pinch construction method (described in Section 5.3.2), which was not possible to include in the laboratory trials due to the limitations of the laboratory hydraulic roller compactor, was also included in the field trials as a construction strategy. A proprietary topical joint sealer (called “Topical emulsion” in this report) was also included in the field trials (see Section 5.3.3). This joint sealer was not available for the laboratory component of this research project. **The major conclusions of the field component of this study are listed in Section 5.7.**

Following the laboratory investigation, pilot sections incorporating different longitudinal joint construction strategies were constructed. These projects were deliberately chosen to assess their performance in different field conditions. The first project was located on I5 between Kuebler and Santiam Pass exits. In this project, the longitudinal joint appeared between the newly constructed asphalt pavement and the cold shoulder, which had been in service for over a decade.

The second project was located on OR18 at McMinnville, and the longitudinal joint was located between the two newly constructed pavement lanes. Both projects investigated three different longitudinal joint construction techniques, including applying a high tack coat, using the hot pinch rolling technique, and the application of a topical emulsion. Cores extracted from a project in Fond Du Lac County in Wisconsin were used to determine the performance of longitudinal joints constructed with the Void Reducer asphalt membrane.

Due to limitations in the number of cores obtained from these projects, these specimens were tested for three tests, which included: i) Air void measurement (CoreLok®); ii) Indirect Tensile Strength (IDT) and fracture energy for cracking resistance evaluation; iii) X-Ray CT imaging. DPS data was also collected along the longitudinal joint for the I5-Kuebler project to determine the impact of different tested strategies on surface density.

The most significant conclusion from the field component of the research was that all four tested strategies improved the density of the longitudinal joints. All densities for all four strategies were significantly higher than the acceptable joint density thresholds provided in the literature, which generally range from 90% to 92%. Another major conclusion was the superior performance of applying a higher tack coat on the joint. It was seen that the tack coat application improved the density along the longitudinal joint and resulted in uniform distribution of the air voids in the entire lift thickness. In addition, following the hot pinch construction technique resulted in high density and cracking resistance values. These two conclusions were important since both the high tack and hot pinch strategies were low-cost options and could easily be implemented without increasing the cost of paving or requiring any special jigs or equipment. The hot pinch method may require some operator training, but it is expected to take a short time to learn the process due to its simplicity.

CoreLok® density results revealed that samples with Void Reducer had higher air voids compared to the control specimens; however, from X-Ray CT imaging, it was determined that the specimens with Void Reducer application delivered air voids lesser than 3% in more than 70% thickness of the specimen. In addition, the topical application improved the joint density in the upper portion of the pavement; however, it failed to penetrate into the lower part of the surface layer. In addition to this, it did not enhance the strength characteristics of the longitudinal joint. Although these two strategies have the potential to improve the long-term performance of longitudinal joints, they also increase the upfront cost of paving. Void Reducer costs around $3.5 to $5 per linear foot, while the topical emulsion's cost ranges from $0.36 to $0.57 per linear foot. The manufacturer of the Void Reducer quantified the long-term cost impact of using their product for construction and concluded that it has the potential to save $3 to $4 for every dollar invested. For this reason, both products were recommended for use to improve joint performance if funding is available. In addition, they can be used in areas with significant joint cracking issues (colder regions, mountainous areas, and critical highways with heavy truck traffic). However, network-level analysis should be conducted in a future research study to determine the overall cost and performance impact of using these strategies. In a limited budget scenario, increasing the paving cost always reduces the length of the maintained or rehabilitated roadways, resulting in faster failure, reduced user comfort, and increased user costs (through increased fuel use and tire wear) in many regions.

While all implemented longitudinal joint construction strategies in the field provided densities within acceptable limits (mostly higher than 92%), relying on a single method alone would not suffice in significantly enhancing the performance of longitudinal joints. Thus, integrating multiple construction techniques is critical for boosting long-term durability. One approach involves applying an increased amount of tack coat combined with surface treatments to enhance the durability of longitudinal joints. Alternatively, applying a higher tack coat along the longitudinal edge, followed by the hot pinch construction technique for compacting the new asphalt pavement, proves effective. This method not only confines the material towards the edge and improves density but also uses the tack coat to improve the bond and density between adjacent lanes. Detailed recommendations regarding the potential implementation processes are discussed in the next section.

## 6.1 CONSTRUCTION RECOMMENDATIONS

The following construction recommendations were provided based on the findings of this research study:

- A density specification for longitudinal joints can be implemented in the future. However, using different products to improve joint performance makes the core and nuclear density gauge-based density measurements inaccurate. For this reason, this study mainly relied on the X-Ray CT image-based density measurements. In addition, if the density measurements from the joint were collected from the shoulder joint with an old shoulder, the density results may not reflect the actual density along the joint due to the different asphalt materials on both sides of the core. However, if both sides of the joint were constructed using the new asphalt mixture, density measurements could be accepted as reliable and used for quality assurance. In that case, a minimum density of 90% should be targeted. If the density is lower, the contractor can be penalized through the pay factor process, or a topical emulsion application (the proprietary product or an asphaltic emulsion) may be required to be applied. However, it should be noted that density measurements with a nuclear density gauge may not be reliable when the joint is on a crown. Coring or dielectric methods should be followed in those cases.

- This research study recommends applying a high amount of tack coat on the joints with rates ranging from 0.14 to 0.18gal/yd$^2$ (actual application, not the residual rate). The application should not be made directly with a conventional tack coat distributor truck. Those trucks spray the asphaltic emulsion vertically onto the pavement surface, and it is not possible to get complete coverage on the vertical joint wall. For this reason, a handheld pump system should be used for the application. The unit needs to be calibrated before spraying to make sure that it is applying the target amount ranging from 0.14 to 0.18gal/yd$^2$. Another application option would be to install a small jig around the edge nozzle of the distributor truck to divert the vertical emulsion flow onto the joint wall.

- The hot pinch method was effective in increasing joint density and cracking resistance. However, it is crucial to recognize that the success of the hot pinch compaction method depends on the construction crew's proficiency with this technique, highlighting the need for thorough training in its application and execution. A program should be started to train roller compactor operators on this joint construction method. According to the research team's discussions with the operators in the field during the summer of 2023, about half of them are familiar with the method and call it the “airport joint method” since this type of joint compaction was required for airport pavement construction in many places. For this reason and because of the simplicity of the process, it is expected to take a short time to learn the process due to its simplicity.

- The findings indicate that achieving high-quality longitudinal joints necessitates more than a singular construction approach. The hot pinch method generally improved the density around the mid-height of the new pavement lift, while the high tack increased the density of the entire joint thickness. In addition, both methods improved the cracking resistance of the joint. Since both methods are easy and low-cost to implement, this research study recommends combining both methods for longitudinal joint construction.

- The proprietary Void Reducer product has the potential to significantly improve the density and cracking resistance of the longitudinal joints. However, the cost of this strategy is higher than that of the other strategies. For this reason, for a limited paving budget, its use can be limited to applications in critical locations such as colder regions, mountainous areas, and critical highways with heavy truck traffic. This strategy is recommended for use in several additional paving projects if funding is available. However, network-level analysis should be conducted in a future research study to determine these strategies' overall cost and performance impact. In a limited budget scenario, increasing the paving cost always reduces the length of the maintained or rehabilitated roadways, resulting in faster failure for some sections, reduced user comfort, and increased user costs (through increased fuel use and tire wear) in many regions. For this reason, the decision to use the Void Reducer must be carefully made based on detailed cost and life cycle cost analysis.

- The topical emulsion was determined to improve the surface density by penetrating into the surface void network and sealing the surface part of the joint. If a joint is visible after construction and high permeability is expected to be an issue, the proprietary topical emulsion tested in this study or an asphaltic emulsion may be required to be applied to reduce joint permeability and improve long-term performance via reduced moisture penetration and oxidative aging.

## 6.2 POTENTIAL FUTURE WORK

- Long-term performance monitoring of the pilot sections constructed using different longitudinal joint construction techniques should be performed.

- Recommended strategies should also be tested in a full-scale accelerated pavement test section to determine their impact on long-term joint performance. Based on the collected performance data, life cycle cost analysis should be conducted to determine the most economical method of enhancing the longitudinal joint performance.

- The methods recommended in this research study should be implemented in various construction projects across Oregon. In those implementations, part of the sections should be constructed with the conventional methods to identify the impact of those suggested strategies on long-term joint cracking performance.

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