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16. Abstract

When placing hot-mix asphalt concrete (HMAC), paving the full width of the pavement in a single pass is usually impossible; therefore, most bituminous pavements contain longitudinal construction joints. These construction joints can often be inferior to the rest of the pavement and can eventually cause an otherwise sound pavement to deteriorate more quickly. The objectives of this project were to (1) assess the density along the longitudinal construction joint of several Texas pavements to determine if a problem exists; (2) document information from the literature; (3) synthesize aviation construction data where a history of a joint density specification exists to determine if such a requirement can be met by paving contractors; and (4) modify current HMAC specifications to require joint density measurements if justification is verified.

Results of this project confirmed what was found in the literature: there is an area of low density in the edge of the lane paved first. Field evaluations conducted on 35 Texas pavements in this project found that the density was always lower at the unconfined edge than in the middle of the lane and this was almost always statistically significant. This difference in density could range from 2 to 12 lbs per cubic ft but the average was about 6 to 7 lbs per cubic ft (or 4 to 5 percentage points).

Aviation data analyzed in this project indicate that contractors are routinely able to meet the joint density requirements as specified in the Federal Aviation Administration (FAA) P-401 specification.

The data in this project provide for a very strong indication that a joint density specification is justified.

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DENSITY EVALUATION OF THE LONGITUDINAL CONSTRUCTION JOINT OF HOT-MIX ASPHALT PAVEMENTS

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of this project was Cindy Estakhri (#77583).

ACKNOWLEDGMENTS

The authors would like to acknowledge the contribution of Mr. Donald Pinchott who traveled extensively across the state to perform the data collection for this project**.** The author would like to thank the TxDOT project director for this study, Dr.Magdy Mikhail of the Houston District, for his participation and assistance. Thanks also go to the district personnel and contractors who provided field assistance during the data collection. The authors would also like to thank TTI's research technicians, Sidney Greer and Rick Canatella, for performing laboratory testing on the field cores.

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CHAPTER 1.0 INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

When placing hot-mix asphalt concrete (HMAC), paving the full width of the pavement in a single pass is usually impossible; therefore most bituminous pavements contain longitudinal construction joints. These construction joints can often be inferior to the rest of the pavement and can eventually cause an otherwise sound pavement to deteriorate more quickly.

The Texas Department of Transportation (TxDOT) specifications do not address compaction in the vicinity of longitudinal construction joints. For this reason, it is presumed that there is poor compaction in the vicinity of the longitudinal construction joints, resulting in increased permeability, decreased density, and decreased performance of HMAC.

The objectives of this research project were to:

- assess the density along the longitudinal construction joint of several Texas pavements to determine if a problem exists;
- document information from the literature, other agencies, and contractors regarding joint density issues of performance and cost;
- synthesize aviation construction data where a history of a joint density specification exists to determine if such a requirement can be met by paving contractors; and
- modify current HMAC specifications to require joint density measurements if justification is verified.

1.2 RESEARCH APPROACH

The objectives of the research project were accomplished through the tasks described below:

Perform Literature Review and Information Survey

In this task, published literature and other sources of information were reviewed to achieve the following:

- Identify results of similar research where joint densities have been documented.

- Identify results of research documenting densities associated with different types of joint construction techniques.

- Identify costs associated with improving construction joint densities.

- Identify states that currently have a joint density specification.

Airfield Data Collection

The objective of this task was to document densities from some airfield construction projects where a joint density specification existed to determine if it was possible to meet such a specification. Since airfield pavements are constructed according to Federal Aviation Administration (FAA) specification Item P-401, joint density determinations are made during construction. TxDOT Aviation Division personnel provided researchers with construction data from several airfield pavements and these data are presented in this report.

Case Studies on Performance

The objective of this task in the project was to document case studies in Texas (from published or printed information) where joint density was an issue associated with performance. Results from three case studies are presented herein.

Design Field Experiment

TxDOT identified the following variables for consideration in the field experiment with regard to the selection of hot-mix projects:

1. Mixture Type
    - Coarse Matrix High Binder (CMHB)
    - Dense Graded, Type D
    - Dense Graded, Type C
    - Superpave (of lesser importance due to the limited number of mixtures planned for construction)

2. Aggregate Type
    - Crushed Limestone
    - Crushed Gravel

    (Note: No CMHB gravel mixes were identified in the field.)

3. Asphalt Layer Thickness (also of lesser importance relative to other variables)
   - Thin (2 inches)
   - Thick (4 inches)
     (Note: No 4-inch thick overlays were identified in the study so all overlay thickness were limited to 1.5 to 2 inches.)

Of primary concern in the experiment design was to select an adequate sample size to identify whether or not there was a difference in density at the construction joint. To determine, statistically, the number of samples needed per cell of the experiment, the following criteria were established by the researchers and the project director (PD).

Criteria 1:

What is the precision of the nuclear density gauge which is the primary measurement technique for density determination?

According to ASTM D 2490, the instrument precision of the nuclear density device is 0.62 lb/ft^3, which corresponds to an air void content of about 0.5 percentage points.

Criteria 2:

What is the acceptable probability of Type I and Type II errors? In other words, for a Type I error, what is the acceptable probability that we will reject the null hypothesis when the null hypothesis is true? The null hypothesis is that the density at the construction joint is the same as the density in the middle of the lane. For a Type II error, what is the acceptable probability that we will fail to reject the null hypothesis when the null hypothesis is false?

Acceptable probability for both a Type I and Type II error was selected to be 5 percent.

Criteria 3:

What is the air void difference (at the joint versus middle of the lane) that we want to be able to detect in this experiment?

This was selected to be 1.0 percentage point (i.e. if there is a difference in air voids by as much as 1.0 percentage point at the joint versus the middle of the lane, we want to be 95 percent sure that we were able to detect it in this experiment).

Using these criteria in a statistical analysis, it was determined that a sample size of eight was needed for each cell of the experiment.

Pavements were selected from ongoing construction projects and all measurements occurred during construction after the final roller pass and while traffic was controlled for construction purposes.

Collection of Field Data on Highway Pavements

Nuclear density measurements were made on each of the field pavements using a thin-lift nuclear gauge. Measurements were made transversely across the paved lane at the joint and/or unconfined edge, 12 inches from the edge, 24 inches from the edge, and in the middle of the lane. These density measurements were at five locations spaced about 200 feet apart.

Through district personnel and/or through researchers, contractors were requested to provide eight 4-inch diameter cores corresponding to density-measurement locations: four cores near the unconfined edge and four cores in the middle of the lane as designated by researchers. Unfortunately, most of the project's contractors did not provide the cores, and research funds were not available to perform coring activities by Texas Transportation Institute (TTI).

Rice specific gravity values were obtained from the field/plant laboratories for the day's production.

Laboratory Testing

Cores were tested in TTI's laboratory. Tests measured bulk specific gravity on each core and permeability on four of the eight cores: two from the unconfined edge and two from the middle of the lane.

CHAPTER 2.0 LITERATURE REVIEW

There were four objectives to the literature review in this study. These included:

- Identify research results where joint densities have been documented.
- Identify research results documenting densities associated with different types of joint construction techniques.
- Identify states that have construction joint density specifications.
- Identify costs associated with improving construction joint densities.

Documentation of joint densities in the literature typically associates the joint density with various construction techniques. Some of these techniques include those which are used in Texas at the present time. Therefore objectives one and two above are combined and summarized in section 2.2. Prior to presenting the literature documentation of joint densities, it is necessary to define many of the construction techniques which are discussed in the literature.

2.1 DESCRIPTION OF JOINT CONSTRUCTION TECHNIQUES

This section of the report contains the description of the different types of techniques identified in the literature that included some documentation of joint densities associated with the techniques. There are certainly other construction techniques not mentioned here, particularly those associated with some of the new equipment to improve joint densities. This report describes techniques limited to those with measured and documented densities.

Foster et al. (1964) defines three types of longitudinal joint construction techniques:

Hot Joint - A hot joint is produced with pavers operating in echelon spaced close enough together so that the lane placed first does not cool significantly before the second lane is placed.

Semi-Hot Joint - A semi-hot joint is produced when there is a restriction on the distance a paver may proceed before setting back and bringing up the adjacent lane to match the first lane. The material in the first lane cools to about 120 to 140 °F before the adjacent lane is placed.

Cold Joint - A cold joint occurs where the first lane has cooled overnight or longer before the next lane is placed or where the first lane is carried so far ahead that the face has cooled to well below 120 °F.

The following subsections describe placement and rolling techniques for the subsequent lane for a semi-hot or cold joint as described by Foster et al. (1964).

Bumped Joint - In placing the subsequent lane, the paver may be operated to either butt the joint or overlap the first lane 2 to 4 inches. The overlapped material may be scooped up with a shovel to a neat line at the joint, swept back on the hot lane, or pushed back with a lute creating a bump. See Figure 1a below. In the latter case, the overlap must be adjusted so that the roller can crowd the bump into the joint. Rolling may be started from the first lane overlapping the subsequent lane by about 4 inches (Figure 1b) or on the subsequent lane pinching the material into the joint (Figure 1c).

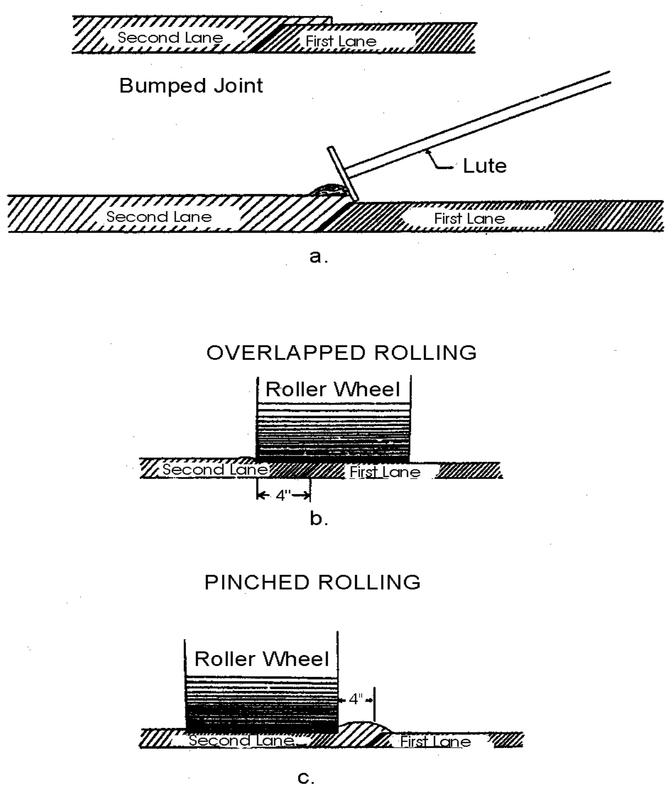


Figure 1. Joint Placement and Rolling Procedures for Bumped Joint with Overlapped or Pinched Rolling. (After Foster et al. 1964)

The wedge joint and notched wedge joint are described below.

Wedge Joint - The longitudinal wedge joint consists of two overlapping wedges. The 3:1 inclined face of the joint is formed in the first bituminous mat placed by a sloping steel plate, which is attached to the inside corner of the paver screed extension. The plate is mounted about 3/8 to ½ inch above the existing pavement.

Notched Wedge Joint - The construction of a notched wedge joint is accomplished using a steel plate attached to the front of the screed. As the plate is pulled through the loose mix, the notched wedge shape is formed. The standard method to compact the wedge portion of the joint is a small static roller cantilevered from the rear of the paver.

The National Center for Asphalt Technology performed a study evaluating several different types of longitudinal joint construction techniques. These are described by Kandhal and Mallick (1997) below.

Rolling from Hot Side - Compaction at the joint is done from the hot side of the lane being constructed wherein a major portion of the roller wheel remains on the hot side with a 6-inch overlap on the cold lane.

Rolling from Cold Side - Rolling is done in the static mode with a major portion of the roller wheel on the cold side with about 6 inches of the roller wheel on the hot side of the joint. This technique is believed to produce a "pinching" effect on the joint. However, timing in this type of rolling is critical. When the roller is operated on the cold side, the hot side undergoes cooling which can make it difficult to achieve the desired compaction level.

Rolling from Hot Side 6 inches Away from Joint - Compaction in this method is started with the edge of the roller about 6 inches from the joint on the hot side. The lateral pushing of the material toward the joint during the first pass of the roller is believed to produce a high density at the joint. This method is particularly recommended by some asphalt paving technologists for tender mix or thick lifts, which have the potential for the mix to be pushed towards the joint.

Tapered Joint (12:1) with 0.5 inch Offset without Tack Coat - In this so-called Michigan wedge joint technique, the joint between the adjacent lanes is constructed as two overlapping wedges. The wedge joint is formed by tapering the edge of the lane paved first. The taper is then overlapped when the subsequent adjacent lane is placed. A taper of 1:12 (vertical/horizontal) is used. The taper is formed by attaching a steel plate to the paver screed. After the initial lane is placed and tapered to the required slope, the lane is compacted with the roller not extending more than 2 inches beyond the top of the unconfined edge. The tapered, unconfined face of the wedge is compacted with a small roller attached to the paver.

Tapered Joint (12:1) with ½ inch Offset with Tack Coat - This technique is similar to the above technique except that a tack coat is applied on the unconfined, tapered face of the cold lane before the overlapping wedge is placed and compacted. The tack coat is generally applied to prevent the ingress of water and to obtain good adhesion between the lanes.

Edge Restraining Device - The restrained edge compaction technique utilizes an edge-compacted device which provides restraint at the edge of the first lane constructed. The restraining device consists of a hydraulically powered wheel which rolls alongside the compactor drum simultaneously pinching the unconfined edge of the first lane towards the drum providing lateral resistance. This technique is believed to increase the density of the unconfined edge. The adjacent lane is then abutted against the initial lane edge.

Cutting Wheel with Tack Coat - The cutting wheel technique involves cutting 1.5 - 2 inches of the unconfined, low-density edge of the initial lane after compaction, while the mix is still plastic. A 10 inch diameter cutting wheel mounted on an intermediate roller is generally used for this purpose. The cutting wheel can also be mounted on a motor grader. A reasonably vertical face at the edge may be obtained by the process which is then tack coated before the placement of the abutting hot-mix asphalt (HMA). Compaction is performed by rolling from the hot side.

Cutting Wheel without Tack Coat - This type of joint is constructed in the same way as the above joint except that no tack coat is applied to the vertical face before placement of the adjacent hot lane.

Joint Maker - This is an automated joint construction technique and a recent innovation in joint-making technology. It consists of a device which is attached to the side of the screed at the corner during construction. The device forces extra material at the joint through an extrusion process prior to the screed. A kicker plate is also furnished which is attached to the side of the paver to lute back the overlapped HMA without the help of a lute man. It is claimed that proper use of the joint maker ensures high density and better interlocking of aggregates at the joint. Rolling of the joint is done from the hot side.

Tapered Joint (3:1) with 1 inch Offset - In this method used in Colorado, the unconfined edge of the 2 inch thick cold lane is constructed with a 1 inch vertical step (offset) at the top of the joint. The remainder of the joint is constructed with a 3:1 taper. The vertical face is not tacked, but the taper surface is tacked before placement of the adjacent hot material. The vertical step (offset) is formed by placing a 2 foot long piece of 2 inch by 2 inch angle iron under the drag device used to form the 3:1 taper. Rolling is done from the hot side.

Rubberized Asphalt Tack Coat - The unconfined edge of the first paved lane adjacent to the joint is not provided with any taper. A rubberized asphalt tack coat (Crafco pavement joint adhesive part number 34524) is applied on the face of the unconfined edge before placing the adjacent lane. The thickness of the tack coat is about 1/8 inch. Rolling of the joint is done from the hot side.

New Jersey Wedge (3:1) - A wedge joint consisting of 3:1 taper is formed during construction of the cold side by using a sloping steel plate attached to the inside corner of the paver screed extension. During the second pass of the paver an infrared heater is used to heat the edge of the previously placed layer to a surface temperature of about 200 °F. During placement of the hot side material, the cold side is overlapped by 2 to 3 inches. The overlapped material is luted back 3 to 4 inches from the edge of the cold mat. Rolling of the joint is done from the hot side.

Densities associated with these various construction techniques are described in the following section.

Joint Trimming - Longitudinal joints may be trimmed to remove uncompacted, low density material and present a clean, firm face for contact with the paving material placed for the adjoining lane. A wheel cut is where the blade is mounted on the pneumatic or steel-wheel roller. A joint can also be cut back with a concrete saw; however, it is not very practical.

Joint Heating - Joint heating was accomplished in Foster's (1964) study through the use of an 8 ft long infrared heating device attached to the side of a paver and maintained at 1.5 inches above the pavement surface. It successfully softened the pavement to a depth of about 0.75 inches. For a width of about 4 inches at the edge of the cold lane.

2.2 RESEARCH RESULTS WHERE JOINT DENSITIES WERE DOCUMENTED

The following is a discussion of several studies which provide some documentation of joint densities.

Foster, Hudson, and Nelson (1964)

A study done by Foster et al. (1964) provides joint density documentation very pertinent to this study. Foster evaluated construction techniques in Maryland and North Carolina. The authors evaluated hot joints, semi-hot joints, and cold joints along with several types of construction methods and the densities associated with each. Table 1 presents the Foster et al. (1964) results from Maryland and Table 2 presents the data from North Carolina.

Foster et al. (1964) noted that an unanticipated finding was the presence of a severe density gradient across the joint in cold-joint construction and in certain types of semi-hot joint construction as illustrated in Figure 2. The area of low density is in the edge of the lane placed first, whereas practically all of the special joint construction procedures, such as bumping or pinching, are concerned with attempts to get a high density at the joint in the lane placed subsequently. Foster et al. (1964) noted that the extent of low- and high-density areas was not determined and the density gradients shown in Figure 2 are based on judgment.

Foster's analysis of the data found that there was no clear-cut superiority to any of the procedures used in cold-joint construction from the standpoint of density in the initial lane. Overlapped rolling produced the highest densities in the initial lane in semi-hot joint construction.

Table 1. Densities of Hot-Mix Asphalt Samples in Maryland. (After Foster et al. 1964)

Sample No.	Type of Joint	Density, pounds per cubic foot (pcf)			
		Adjacent to Joint Unconfined Side	Joint	Adjacent to Joint Confined Side	Lane Sample
	Hot Joints				
A-1	Overlapped Rolling	142.5	142.8	144.1	
A-2	Overlapped Rolling	144.5	144.6	143.0	
A-3	Overlapped Rolling		140.6		
A-4	Lane Sample				137.9
A-5	Lane Sample				142.8
A-6	Lane Sample				147.0
	Semi-Hot Joints				
B-1	Not tacked, Not compacted	138.1	136.4	147.0	
B-2	Not tacked, Compacted, Pinched	139.0	141.6	147.0	
B-3	Not tacked, Compacted, Bumped	137.3	141.9	148.3	
B-4	Not tacked, Compacted, Overlapped	143.2	140.2	148.4	
B-5	Tacked, Not compacted	136.9	136.7	147.2	
B-6	Tacked, Compacted, Pinched	141.1	144.6	146.4	
B-7	Tacked, Compacted, Bumped	138.5	144.5	147.4	
B-8	Tacked, Compacted, Overlapped	143.8	139.7	148.7	
B-15	Not tacked, Compacted, Overlapped	143.8	141.2	141.2	
B-16	Not tacked, Compacted, Overlapped	145.8	146.2	145.3	
B-17	Lane Sample				140.4
B-18	Lane Sample				139.5
B-19	Lane Sample				144.5
B-21	Lane Sample				140.2
	Cold Joints				
C-1	Not tacked, Compacted, Pinched	136.7	134.9	145.9	
C-2	Not tacked, Compacted, Bumped	137.6	137.9	142.0	
C-3	Not tacked, Compacted, Overlapped	136.5	140.4	147.6	
C-4	Tacked, Compacted, Pinched	140.0	140.3	146.9	
C-5	Tacked, Compacted, Bumped	137.1	140.7	145.3	
C-6	Tacked, Compacted, Overlapped	136.3	138.1	143.2	
C-7	Not tacked, Pinched, I-R Heated	137.5	135.8	143.7	
C-8	Not tacked, Bumped, I-R Heated	133.2	138.3	145.1	
C-9	Not tacked, Overlapped, I-R Heated	133.7	136.7	140.4	
C-10	Tacked, Pinched, I-R Heated	137.0	138.7	144.0	
C-11	Tacked, Bumped, I-R Heated	137.3	132.1	142.7	
C-12	Tacked, Overlapped, I-R Heated	136.8	131.8	140.9	
C-13	Tacked, Compacted, Pinched, Sawed	139.4	140.3	145.6	
C-14	Tacked, Compacted, Bumped, Sawed	138.7	142.3	144.8	
C-15	Tacked, Compacted, Overlapped, Sawed	140.2	139.1	145.0	
C-16	Not tacked, Compacted, Pinched, Wheel Cut	138.3	138.1	145.7	
C-17	Not tacked, Compacted, Bumped, Wheel Cut	137.5	141.5	143.9	
C-18	Not tacked, Compacted, Overlapped, Wheel Cut	140.7	140.2	145.3	
C-19	Not tacked, Pinched, Sawed, I-R Heated	140.8	138.7	143.6	
C-20	Not tacked, Bumped, Sawed, I-R Heated	138.2	141.5	147.6	
C-21	Not tacked, Overlapped, Sawed, I-R Heated	140.1	138.7	143.0	
C-22	Not tacked, Pinched, Wheel Cut, I-R Heated	140.3	138.7	142.6	
C-23	Not tacked, Bumped, Wheel Cut, I-R Heated	137.1	142.5	147.0	
C-24	Not tacked, Overlapped, Wheel Cut, I-R Heated	139.5	138.2	144.7	
C-25	Tacked, Compacted, Bumped, Wheel Cut	139.3	135.3	139.3	
C-26	Tacked, Compacted, Overlapped, Wheel Cut	138.0	140.6	147.3	
C-27	Tacked, Compacted, Pinched, Wheel Cut	133.4	137.8	148.0	
C-28	Lane Sample				144.6
C-29	Lane Sample				145.9
C-30	Lane Sample				144.6
C-31	Lane Sample				138.2
C-32	Lane Sample				145.3
C-33	Lane Sample				144.0

Table 2. Densities of Hot-Mix Asphalt Samples in North Carolina. (After Foster et al. 1964)

Sample No.	Type of Joint	Density (pcf)			
		Adjacent to Joint Unconfined Side	Joint	Adjacent to Joint Confined Side	Lane Sample
	Cold Joints				
D-1	Tacked, Overlapped	125.5	125.9	129.5	
D-2	Not tacked, Overlapped, Bumped	126.1	131.2	131.2	
D-3	Not tacked, Overlapped	123.3	125.3	131.5	
D-4	Not tacked, Bumped	124.1	118.9	131.5	
D-5	Not tacked, Overlapped	125.5	127.9	132.0	
D-6	Not tacked, Overlapped, Bumped	122.7	123.7	129.7	
D-7	Not tacked, Overlapped	125.2	120.2	126.5	
D-8	Tacked, Overlapped, Bumped	121.7	121.6	130.5	
D-9	Tacked, Overlapped	122.7	126.1	129.5	
D-10	Tacked, Overlapped, Bumped	122.1	123.5	129.5	
D-11	Tacked, Overlapped	123.5	124.4	128.2	
D-12	Tacked, Bumped, Pinched	123.8	128.2	130.0	
D-14	Tacked, Bumped, Pinched	123.6	131.7	128.0	
D-15	Not tacked, Overlapped	126.5	125.4	131.0	
D-16	Not tacked, Overlapped, I-R Heated	127.9	126.8	130.6	
D-17	Not tacked, Overlapped	126.5	130.6	132.6	
D-18	Not tacked, Overlapped, I-R Heated	126.9	127.5	132.0	
D-19	Not tacked, Overlapped, I-R Heated	124.6	129.7	131.8	
D-20	Not tacked, Overlapped	126.4	132.1	133.5	
D-1c	Lane Sample				124.0
D-7c	Lane Sample				129.2
D-8c	Lane Sample				124.6
D-14c	Lane Sample				125.4

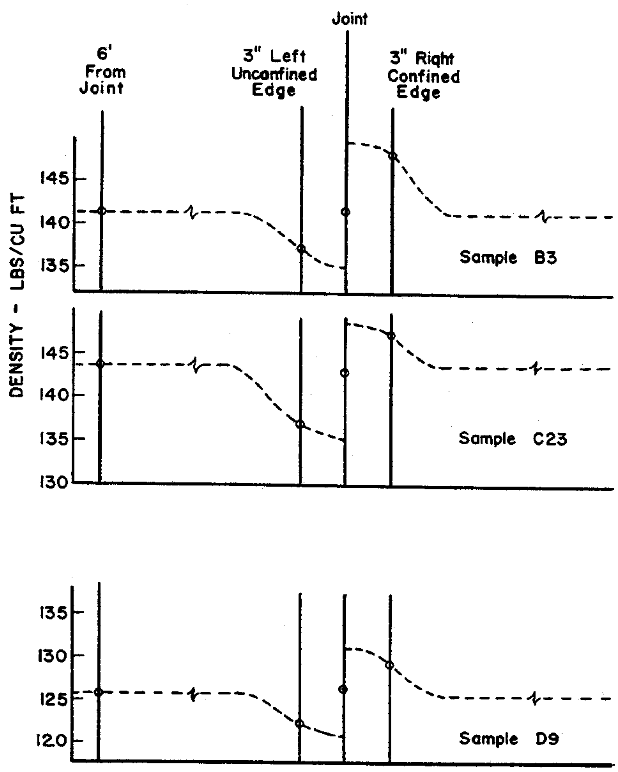


Figure 2. Typical Density Gradients Across a Joint. (After Foster et al. 1964)

Burati and Elzoghbi (1987)

Researchers collected data on field projects to determine current joint density values, to determine correlation between mat and joint density, and to determine differences between the use of in-place density and the use of percent compaction for density acceptance. Two runway projects were evaluated using cores and three different nuclear gauges.

Data were collected from 10 lots on the Morristown project and 18 lots at Rochester. A total of 80 core densities (40 mat and 40 joint) and 384 readings for each of three nuclear gauges (total of 1152 nuclear density values) at Morristown. At Rochester, a total of 144 core densities (72 mat and 72 joint) and 1242 nuclear gauge readings (414 for each of the gauges) were obtained. The t-statistic is used to test the hypothesis that the means of the two data sets are equal. In Table 3, there is essentially no chance (0.0001 or less) that the means of the data sets are equal for any of the sources. Because similar results are displayed in Table 4 for Rochester, Burati and Elzoghbi (1987) assume that the joint densities obtained are statistically significantly different from the mat densities obtained on the projects.

Some of the major fndings of the research effort with respect to joint density included the following:

- "Joint density and percent compaction values were consistently and statistically significantly lower than mat density and percent compaction values for both projects studied. This relation was true for both the nuclear gauge and core results, confirming the previous limited data that were available.

- Joint density values were statistically significantly more variable than the mat density values for the nuclear gauges on both projects. The joint core results were significantly more variable than the mat core results for the Rochester data but not for the Morristown data." (Burati and Elzoghbi, 1987)

Table 3. Results of Hypothesis Tests on Mat and Joint Density Data for the Morristown Project. (After Burati and Elzoghbi, 1987)

Source	No.	Mat Mean (Std. Dev.)	No.	Joint Mean (Std. Dev.)	F-statistic (Prob > F)*	t-statistic (Prob > *t***
Core	40	151.5 (3.3)	40	145.6 (3.9)	1.43 (0.269)	-7.39 (0.0001)
CPN	192	147.1 (4.0)	192	136.5 (5.9)	2.18 (0.0001)	-20.77 (0.0001)
Troxler	191	148.8 (3.9)	191	138.7 (5.7)	2.08 (0.0001)	-19.48 (0.0001)
Seaman	192	149.5 (4.6)	192	138.2 (6.6)	2.09 (0.0001)	-20.19 (0.0001)

* Probability of obtaining an F value as large as the one shown if the variances are actually equal.
** Probability of obtaining a t value as large as the one shown if the means are actually equal.

Table 4. Results of Hypothesis Tests on Mat and Joint Density Data for the Rochester Project. (After Burati and Elzoghbi, 1987)

Source	No.	Mat Mean (Std. Dev.)	No.	Joint Mean (Std. Dev.)	F-statistic (Prob > F)*	t-statistic (Prob > *t***)
Core	72	150.7 (2.1)	72	143.3 (4.3)	4.13 (0.0001)	-13.07 (0.0001)
CPN	207	141.8 (3.7)	207	141.8 (4.4)	1.40 (0.016)	-11.35 (0.0001)
Troxler	207	147.7 (3.2)	207	143.7 (4.1)	1.64 (0.0004)	-11.05 (0.0001)
Seaman	207	150.0 (2.9)	207	144.6 (4.1)	1.99 (0.0001)	-15.26 (0.0001)

* Probability of obtaining an F value as large as the one shown if the variances are actually equal.
** Probability of obtaining a t value as large as the one shown if the means are actually equal.

Baker, Croteau, Quinn, and Hellriegel (1990)

Baker et al. (1990) did a study in New Jersey to evaluate the effectiveness of the wedge joint by measuring the density gradient across the joint. Nuclear density measurements were taken on three projects where both wedge joints and conventional butt joints were used. Measurements were taken as shown in Figure 3. Comparative joint density measurements are shown in Figure 4. New Jersey had a specification at the time placing a 1500 ft limit on the length of the mat that may be placed before bringing the paver back to place the adjacent lane (in an attempt to avoid a cold joint).

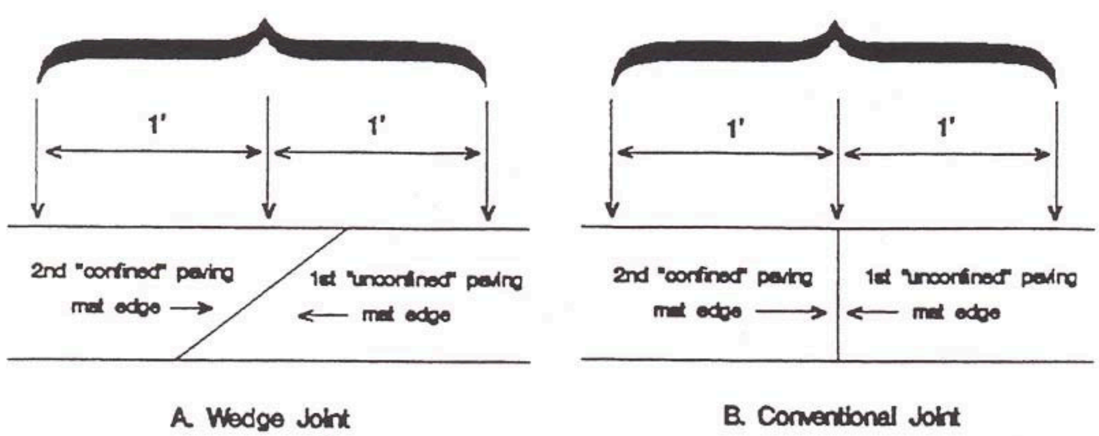


Figure 3. Density Test Layout. (After Baker et al. 1990)

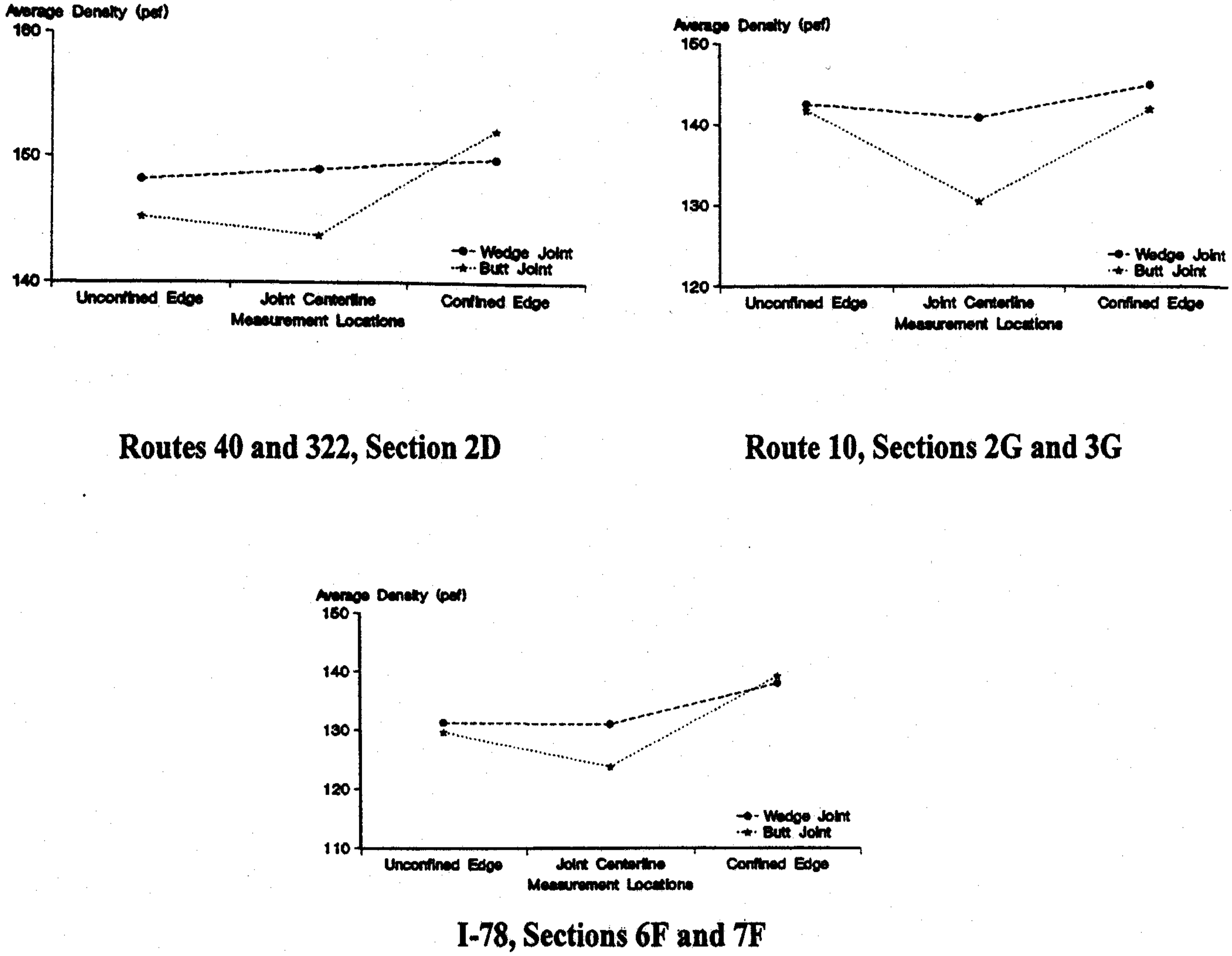
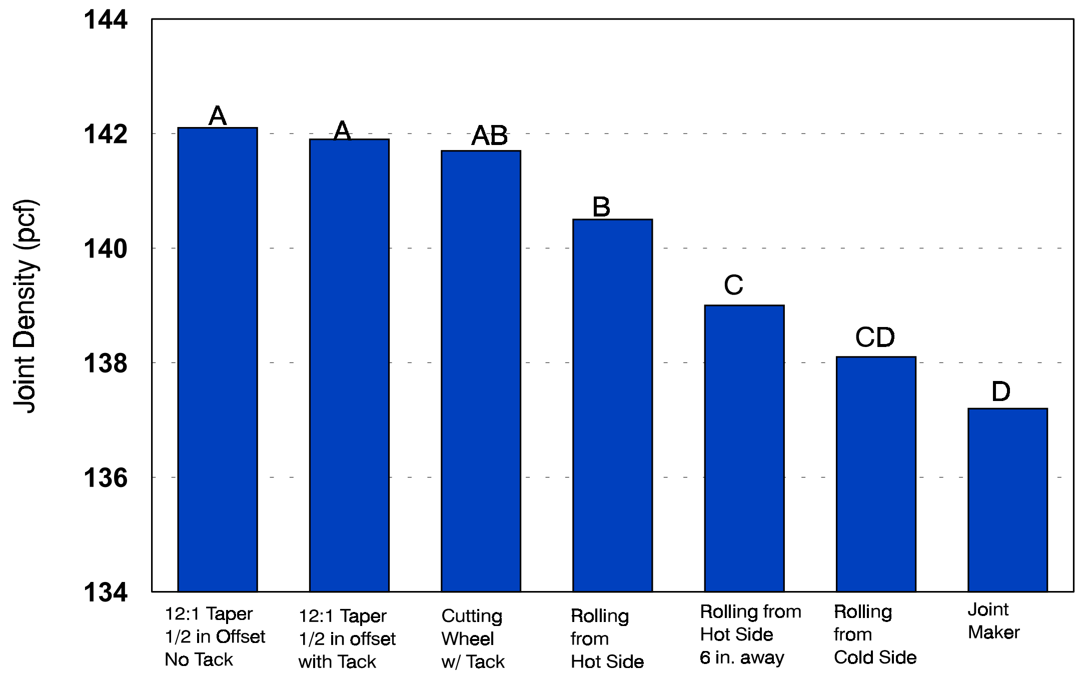


Figure 4. Comparative Joint Density Measurements. (After Baker et al. 1990)

Baker et al. (1990) concluded that the wedge joint technique produces higher, more uniform density than the conventional butt joint technique. They note that the observed improvements in density, combined with the elimination of the vertical shear plane in the conventional butt joint, suggests that the wedge joint procedure will provide a finished joint that is more resistant to opening under the effects of traffic and weathering.

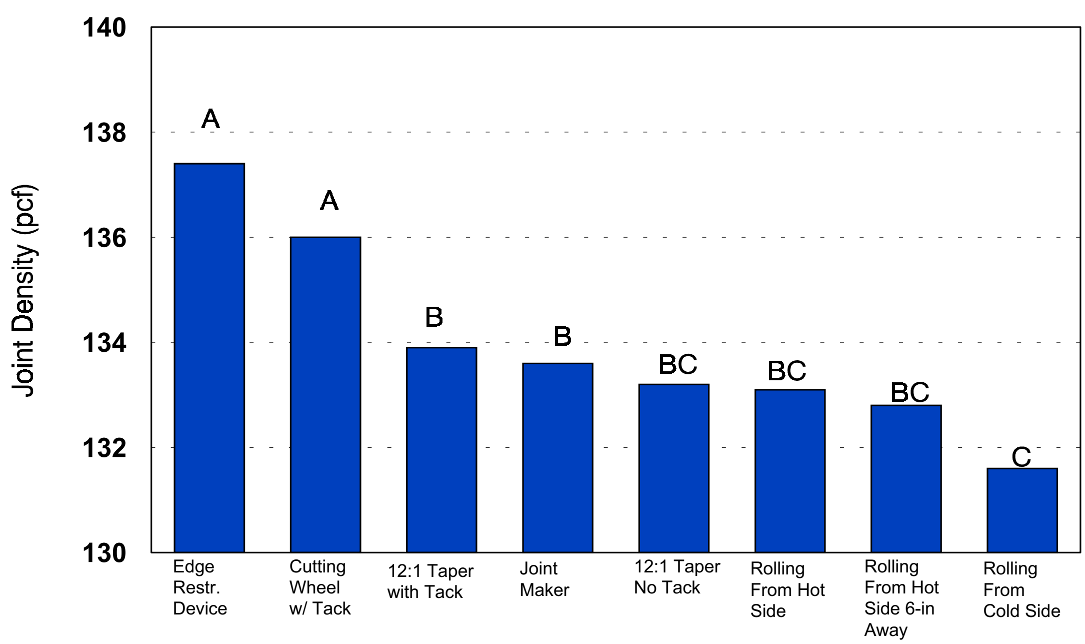
Kandhal and Mallick (1997)

The National Center for Asphalt Technology conducted this study in which 36 HMA test sections were constructed in Michigan (1992), Wisconsin (1992), Colorado (1994), and Pennsylvania (1995) to evaluate the effectiveness of 12 different longitudinal joint construction techniques. The joints with higher densities generally showed better performance than those with relatively low densities. Average joint densities for each of the projects is shown in Figures 5 through 8. The Michigan joint technique (0.5 inch vertical offset and 12:1 taper) appeared to have the best potential of obtaining a satisfactory longitudinal joint. The cutting wheel and the edge restraining device techniques have good potential but were considered to be too much operator dependent to obtain consistent results.



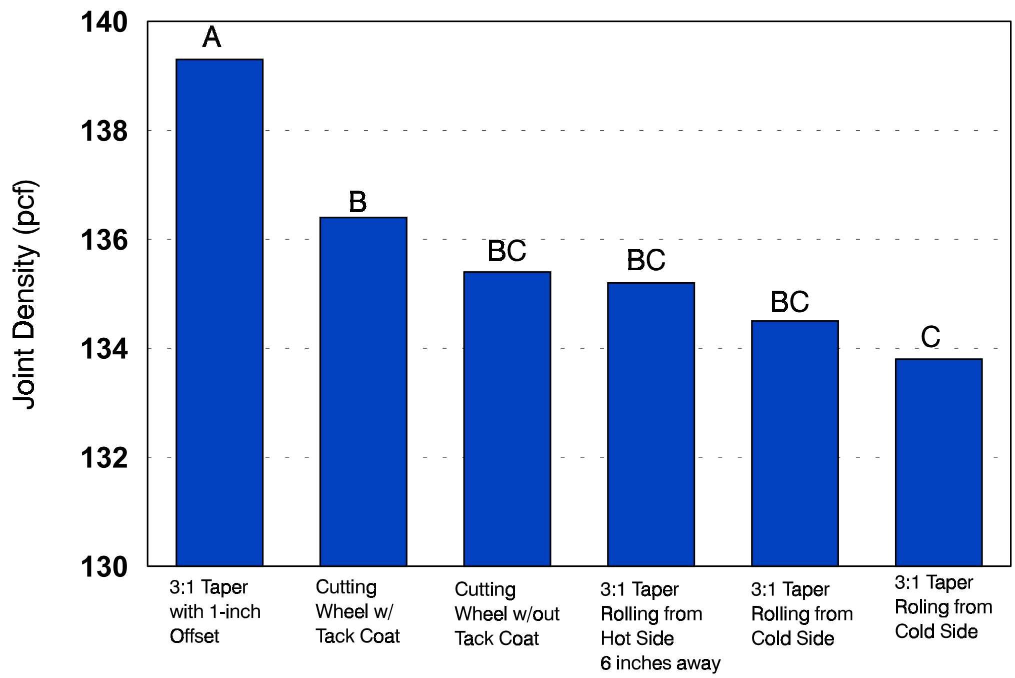
Note: letters indicate ranking of construction technique; means within the same ranking group do not differ at a significance level of % = 0.05

Figure 5. Average Joint Density in Michigan Project.
(After Kandhal and Mallick, 1997; Kandhal and Rao, 1994)



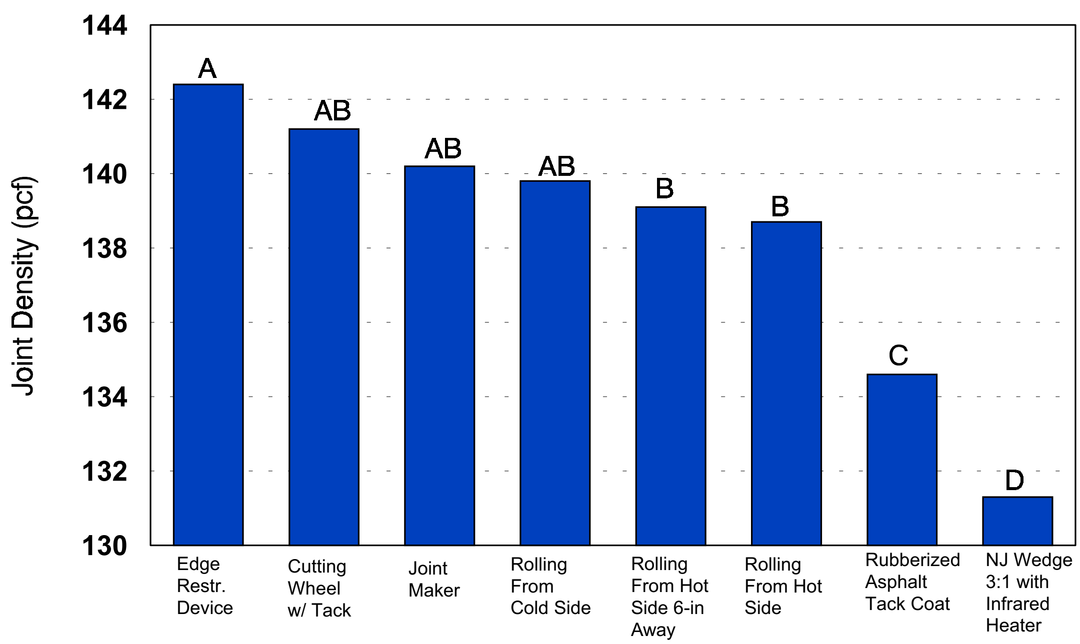
Note: letters indicate ranking of construction technique; means within the same ranking group do not differ at a significance level of % = 0.05.

Figure 6. Average Joint Density in Wisconsin Project.
(After Kandhal and Mallick, 1997; Kandhal and Rao, 1994)



Note: letters indicate ranking of construction technique; means within the same ranking group do not differ at a significance level of % = 0.05

Figure 7. Average Joint Density in Colorado Project.
(After Kandhal and Mallick, 1997; Kandhal and Mallick, 1996)



Note: letters indicate ranking of construction technique; means within the same ranking group do not differ at a significance level of % = 0.05

Figure 8. Average Joint Density in Pennsylvania Project.
(After Kandhal and Mallick, 1997)

Among the three different joint rolling techniques used in all four projects, rolling the joint from the hot side generally gave the best performance followed by rolling from the hot side 6 inches away from the joint.

Kandahl and Mallick (1997) recommend that paver manufacturers consider modifying the paver design to obtain a Michigan type, high density unconfined wedge in the lane paved first. They also recommend that highway agencies should specify minimum compaction levels to be achieved at the longitudinal joint. The density at the joint is recommended to be not more than 2 percent lower than the density specified in the lanes away from the joint.

Buchanan (2000)

In this study the notched wedge joint was compared to conventional longitudinal joint construction techniques on projects in five states (Colorado, Indiana, Alabama, Wisconsin, and Maryland). The evaluation consisted of comparing the in-place density obtained through pavement cores at five locations across the longitudinal joint: at the centerline, 6 inches and 18 inches on either side of the centerline.

Project density results and analysis are shown in Table 5. Buchanan noted that the notched wedge joint technique results in an increased centerline density as compared to conventional joint construction for four of the five projects, but the increase was only statistically significant for two of the five projects.

Table 5. Project Density Test Results and Analysis. (After Buchanan 2000)

PROJECT	Density and Statistical Information	450 mm (18 in.) Hot Side		150 mm (6 in.) Hot Side		Centerline		150 mm (6 in.) Cold Side		450 mm (18 in.) Cold Side	
		NWJ	Conv.	NWJ	Conv.	NWJ	Conv.	NWJ	Conv.	NWJ	Conv.
COLORADO	Average Density	93.33[1]	93.30	91.70	92.77	88.40	84.37	88.97	88.33	92.40	90.90
	Standard Deviation	0.91	1.18	0.82	1.14	1.04	0.91	1.42	1.55	1.85	0.85
	NWJ - Conv. ( )	0.03		-1.07		4.03		0.64		1.50	
	t-stat. , P-value	-0.039 , 0.971		1.318 , 0.26		-5.050 , 0.007		-0.522 , 0.629		-1.274 , 0.272	
	Significant ?	NO		NO		YES		NO		NO	
INDIANA	Average Density	94.00	91.57	90.10	92.43	88.13	85.87	93.23	92.70	95.00	93.97
	Standard Deviation	0.30	1.15	1.08	0.67	2.29	2.36	0.95	1.47	0.92	0.97
	NWJ - Conv. ( )	2.43		-2.33		2.26		0.53		1.03	
	t-stat. , P-value	-3.533 , 0.024		3.182 , 0.033		-1.194 , 0.299		-0.528 , 0.626		-1.340 , 0.251	
	Significant ?	YES		YES		NO		NO		NO	
ALABAMA	Average Density	91.53	91.15	90.67	91.35	88.27	86.70	90.57	90.80	92.10	92.40
	Standard Deviation	0.35	2.90	0.75	0.21	0.40	0.71	0.68	1.14	0.92	0.14
	NWJ - Conv. ( )	0.38		-0.68		1.57		-0.23		-0.30	
	t-stat. , P-value	-0.247 , 0.821		1.198 , 0.317		-3.269 , 0.047		0.259 , 0.813		0.437 , 0.692	
	Significant ?	NO		NO		YES		NO		NO	
WISCONSIN	Average Density	90.67	91.83	93.17	92.83	90.33	89.17	90.97	87.97	92.70	92.70
	Standard Deviation	0.07	2.25	0.81	1.72	0.12	0.49	0.31	1.51	0.26	1.51
	NWJ - Conv. ( )	-1.16		0.34		1.16		3.00		0.00	
	t-stat. , P-value	0.852 , 0.442		-0.303 , 0.777		-0.715 , 0.514		-3.363 , 0.028		0.00 , 1.000	
	Significant ?	NO		NO		NO		YES		NO	
MARYLAND	Average Density	91.07	92.63	90.43	92.10	89.97	90.47	91.07	91.03	92.73	93.43
	Standard Deviation	0.60	0.80	0.40	0.53	0.68	0.31	0.72	0.35	0.15	0.80
	NWJ-Conv. ( )	-1.56		-1.67		-0.50		0.04		-0.70	
	t-stat. , P-value	2.704 , 0.0538		4.617 , 0.009		1.161 , 0.310		-0.072 , 0.946		1.485 , 0.212	
	Significant ?	NO		YES		NO		NO		NO	
ALL PROJECTS	Average Density	92.12	92.16	91.21	92.37	89.02	87.36	90.96	90.12	92.99	92.70
	Standard Deviation	1.48	1.56	1.33	1.01	1.39	2.81	1.60	2.20	1.37	1.40
	NWJ-Conv. ( )	-0.04		-1.16		1.66		0.84		0.29	
	t-stat. , P-value	0.065 , 0.948		2.614 , 0.014		-2.042 , 0.0510		-1.180 , 0.248		-0.556 , 0.583	
	Significant ?	NO		NO		NO		NO		NO	

New York DOT

TTI researchers received data from the New York DOT that had been collected regarding the density along the longitudinal construction joint. Data from these construction projects are shown below in Figures 9 through 14.

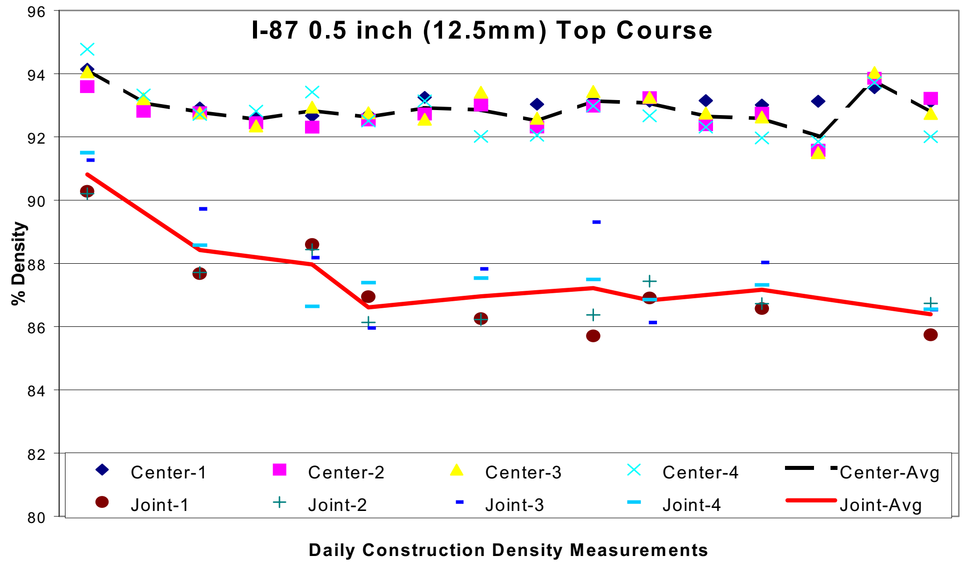


Figure 9. New York DOT Joint Density Data Taken in 1998 on Project I-87, 0.5 inch (12.5 mm) Top Course.

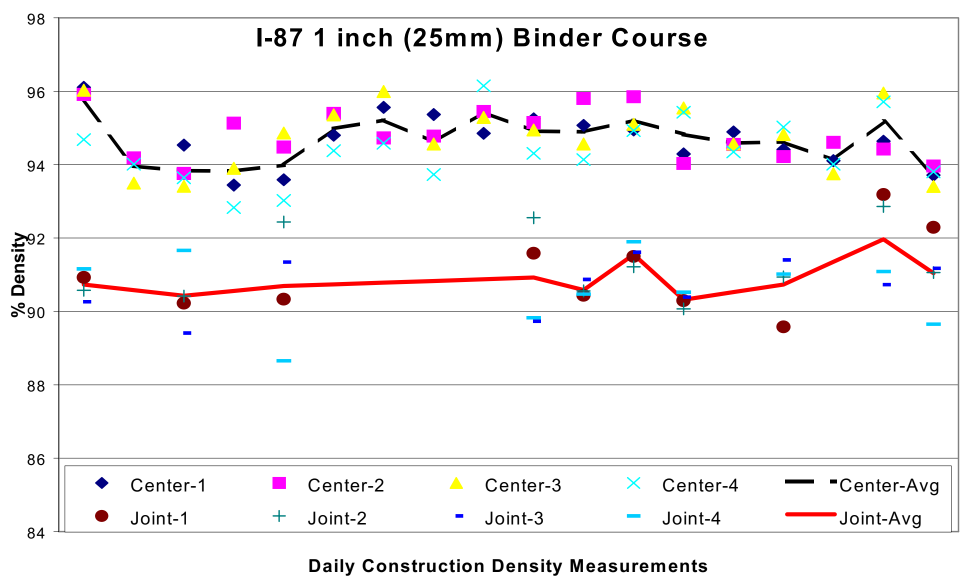


Figure 10. New York DOT Joint Density Data Taken in 1998 on Project I-87, 1 inch (25 mm) Top Course.

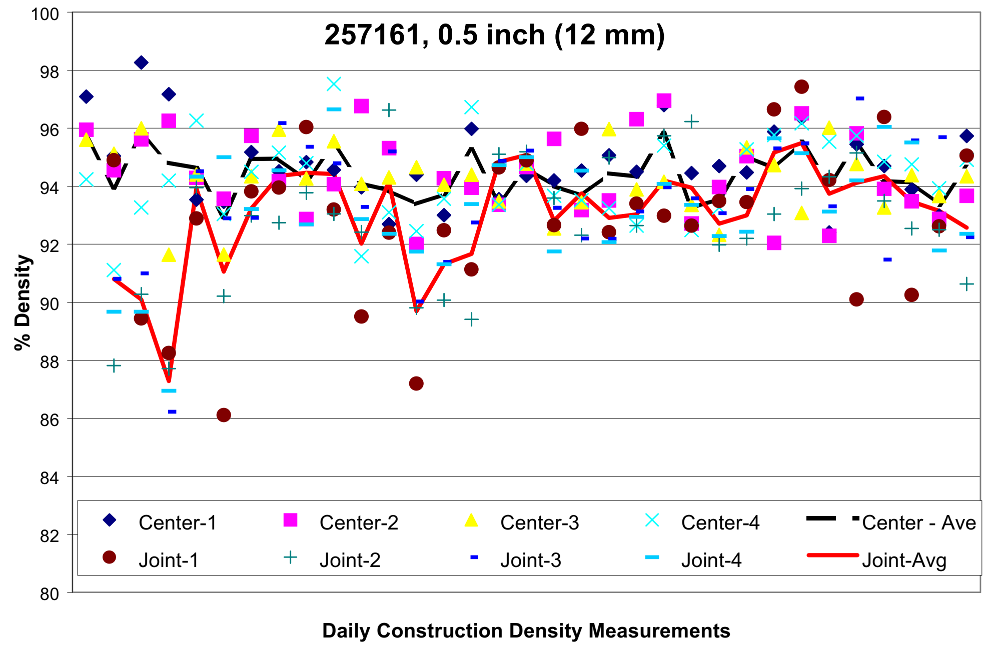


Figure 11. New York DOT Joint Density Data Taken in 1998 on Project 257161, 0.5 inch (12 mm) Course.

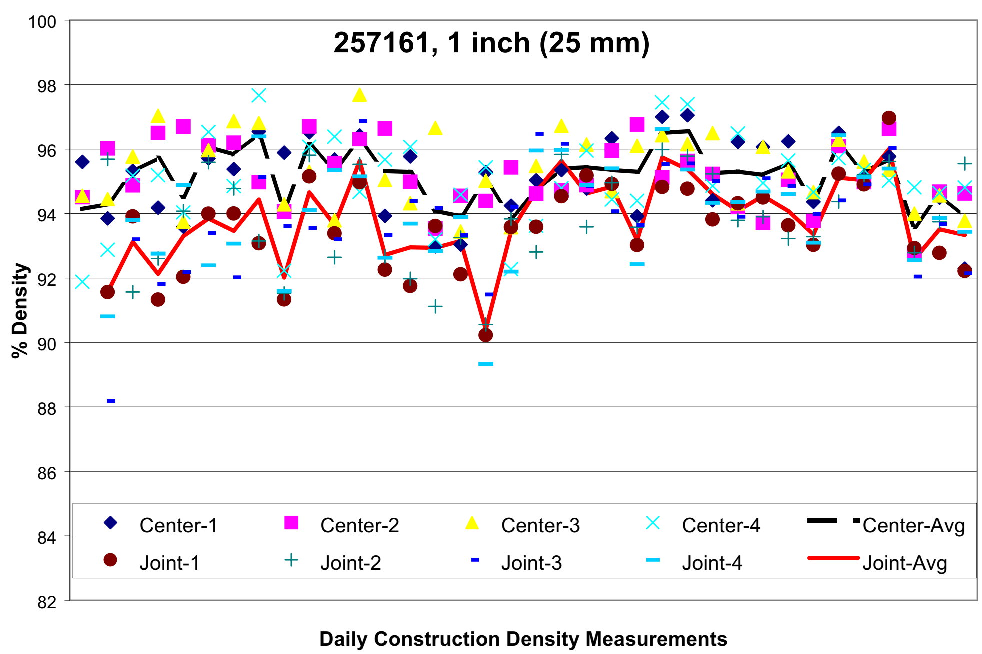


Figure 12. New York DOT Joint Density Data Taken in 1998 on Project 257161, 1 inch (25 mm) Course.

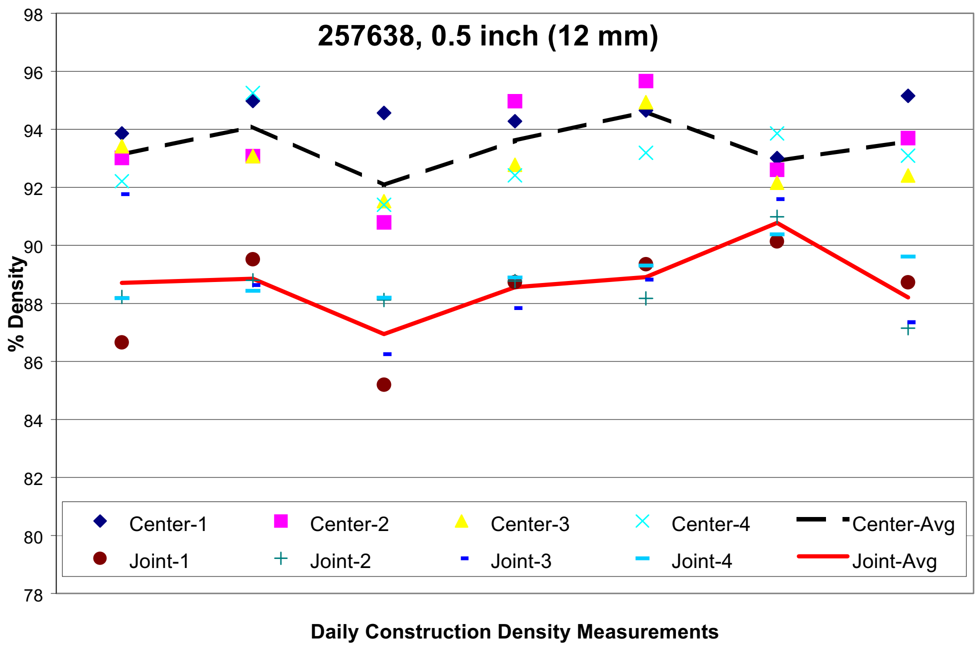


Figure 13. New York DOT Joint Density Data Taken in 1998 on Project 257638, 0.5 inch (12 mm) Course.

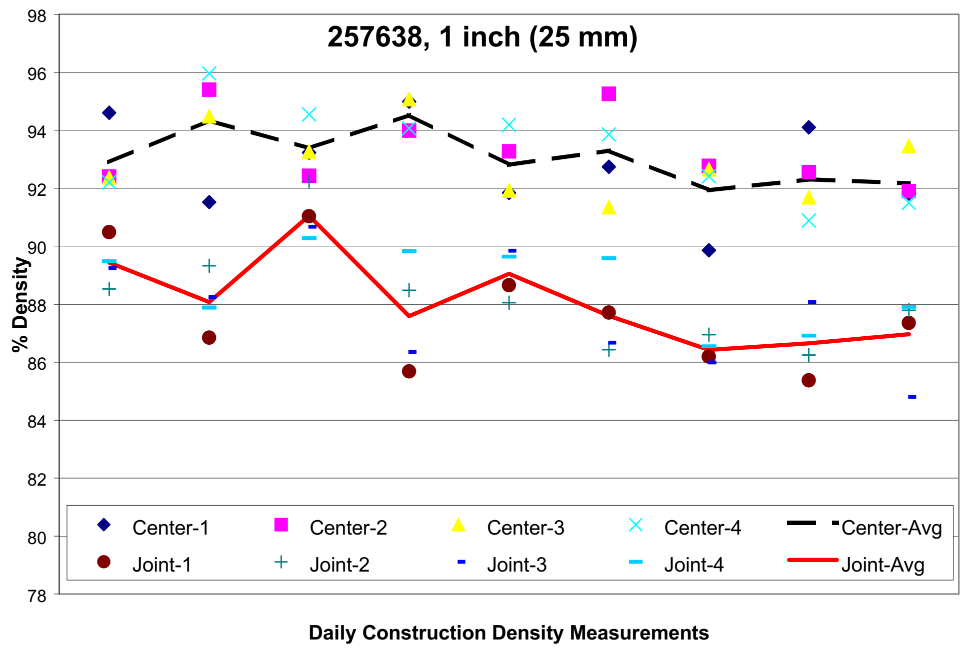


Figure 14. New York DOT Joint Density Data Taken in 1998 on Project 257638, 1 inch (25 mm) Course.

2.3 EXAMPLES OF OTHER STATES' CONSTRUCTION JOINT DENSITY SPECIFICATIONS

New York DOT

The New York Department of Transportation has been addressing the issue of longitudinal joint construction over the past several years and has constructed several projects using pilot specifications. The most current version of that specification (7/7/99) is an end-result specification requiring 90 percent density at the longitudinal joint. It requires that the "Engineer select one pavement core location and one longitudinal joint core location for each sublot." In addition the spec states:

> *Compact the pavement sufficiently to achieve densities, expressed as a percentage of the mixtures average daily maximum theoretical density, in a range of 92% to 97%. Compact the longitudinal joints sufficiently to achieve densities, expressed as a percentage of the mixtures average daily maximum theoretical density, in a range of 90% to 97%.*

Missouri DOT

The Missouri DOT has recently adopted somewhat of a combination method/end-result specification pertaining to the construction of joints in asphalt. The specification requires that the minimum density of all traveled way pavement within 6 inches of a longitudinal joint, including the pavement on the traveled way of the shoulder joint, shall not be less than 2.0 percent below the specified density. This specification is shown below.

> *403.19.1 Longitudinal joints shall be formed by the use of an edging plate fixed on both sides of the finishing machine. These plates shall be adjustable and the outside plate shall be set at an angle of approximately 45 degrees with the surface of the roadbed and in a position that will lightly compact the mixture. The inside plate, or that placing material for the longitudinal joint, shall be normal to the roadbed. When placing the first lane, if the mixture at the longitudinal joint tends to slump, it shall be set up to a vertical edge by light compaction with the back of a rake. Care shall be taken to obtain a well bonded and sealed longitudinal joint by placing the hot mixture in a manner ensuring maximum compaction at this point. If it is deemed necessary by the engineer in properly sealing the longitudinal joint, a light coating of bituminous material shall be applied to the exposed edge before the joint is made. The minimum density of all traveled way pavement within 6 inches (150 mm) of a longitudinal joint, including the pavement on the traveled way side of the shoulder joint, shall not be less than 2.0 percent below the specified density. Once an established procedure has been demonstrated to provide the required density for longitudinal joints, at the engineer's discretion, the procedure may be used in lieu of density tests provided no changes in the material, typical location or temperatures are made. Pay adjustments due to longitudinal density shall apply to the full width of the traveled way pavement and shall be in addition to any other pay adjustments.*

Irregularities in the outside edge alignment shall be corrected by removing or adding mixture before the surface is compacted.

403.19.2 The longitudinal joint in any layer shall offset that in the layer immediately below by approximately 6 inches (150 mm); however, the joints in the completed surfacing shall be at the lane lines of the traveled way or other required placement width outside the travel lane. The placement width shall be adjusted such that pavement marking shall not fall on a longitudinal joint.

Illinois DOT

The Illinois DOT's specification Section 405.13 does not require a specific density at the joint but specifies the following method regarding compaction of the longitudinal joint in bituminous concrete binder and surface course (Class I):

Rolling of the first lane of binder and surface courses shall start longitudinally at the edge having the lower elevation and progress to the other edge, overlapping on successive trips to obtain uniform coverage. The rollers shall not pass over an unprotected edge of the freshly laid bituminous mixture, unless directed by the Engineer. When directed by the Engineer, the edge shall be rolled with a pneumatic tired roller. When laying the bituminous mixture adjacent to a previously placed lane, the first pass of the roller shall be along the longitudinal joint on the fresh mixture with the compression wheel not more than 150 mm (6 inches) from the joint. The second pass of the roller shall overlap the longitudinal joint not more than 300 mm (12 inches) on the previously placed lane after which the rolling shall proceed from the low side of the transverse slope to the high side, overlapping uniformly.

Alaska DOT

The Alaska DOT's Standard Specification for Highway Construction (1998), Section 401-3.14 - Joints requires that the longitudinal joints in asphalt layers be offset by at least 6 inches. It also requires an end-result of 91 percent density at the joint as follows:

Offset the longitudinal joints in one layer from the joint in the layer immediately below by at least 150 mm (6 inches)*. Align the joints of the top layer at the centerline or lane lines. Where preformed marking tape striping is required, offset the longitudinal joint in the top layer not more than 150 mm* (6 inches) *from the edge of the stripe.*

Core the longitudinal joint at the rate of 3 cores per lot. Maintain the joint densities above 91% of maximum specific gravity. Change method of joint construction, if necessary to meet density requirements. The joint densities will

not be included in the price adjustment calculations, but will be a required element of the Contractor's QC plan.

Connecticut DOT

According to the Connecticut DOT's Standard Specifications, Section 4.06, an end result requirement of at least 90 percent density is required at the longitudinal joint stated as follows:

8-b.

In order to obtain tight and well-compacted longitudinal joints, the sequence of the bituminous concrete placing operations for all courses laid shall be subject to the control of the Engineer.

9.

The in-place density of the longitudinal joint(s) of each course of Class 1 or Class 2 placed at a depth of 40 mm (1.5 inches) *or greater shall be compacted to a density of at least 90 percent and no more than 97 percent of the theoretical void-free density.*

11.

On any cold joint, a brush coat of asphaltic material or approved equal shall be used on contact surfaces of transverse and longitudinal joints just before additional mixture is placed against the previously rolled material.

The longitudinal joint in one layer shall offset the previous joint in the layer immediately below by approximately 150 mm (6 inches)*; however, the joint in the top layer shall be at the centerline of the pavement if the roadway comprises two-lane width, or at lane lines if the roadway is more than two lanes in width. In compacting the joint, the steel-wheel roller shall be shifted onto the previously placed lane so that only 25 to 50 mm* (1 to 2 inches) *of the drive weheel extends over the uncompacted material. The steel-wheel roller shall continue to roll along this line and its position shifted gradually across the joint until the joint has been rolled with the entire width of the drive wheel. Rolling with steel-wheel and pneumatic-tired rollers shall be continued until a thoroughly compacted, neat joint is obtained. When the vibratory roller is used for breakdown rolling, compacting the joint shall be accomplished with the roller on the uncompacted material shifted 25 to 50 mm* (1 to 2 inches) *across the joint onto the previously placed lane.*

Adjustment for Density:

The average longitudinal joint density for each lot shall be determined by averaging the densities of ten sublots. The adjustment assigned each lot shall be in accordance with the following:

SCHEDULE OF PAYMENT - JOINT DENSITY

Average Percent Density Class 1 and 2	*Percent Payment (In-Place Price)*
100- 98	*97.5*
97-90	*100.0*
89-87	*97.5*
86-84	*90.0*
83 or less	*70.0*

Utah DOT

In Utah DOT's Standard Specifications for Road and Bridge Construction (1999), Section 02741 - Hot-Mix Asphalt, the following method is noted regarding longitudinal joints:

3.5 Surface Placement

- *Offset longitudinal joints 150 to 300 mm* (6 to 12 inches) *in succeeding courses.*
  - *Place top course joint within 300 mm* (12 inches) *of the centerline or lane line.*
  - *If the previous pass has cooled below 80 °C* (175 °F) *, tack the longitudinal edge before placing the adjacent pass.*

3.9 Density Tests

A.

5. Take a minimum of one core (random numbers table) per sublot from the longitudinal joint for density tests at the joint. The core density will be used for information only.

Pennsylvania DOT

The Pennsylvania DOT has a quite detailed construction method addressing longitudinal joints in their 401.3 specification as follows:

Offset the longitudinal joint in one layer from the joint in the layer immediately below by approximately 6 inches. However, align the joint in the top layer at the approximate paving centerline, if the roadway is two lanes wide; or at approximate lane lines, if the roadway is more than two lanes wide.

Paint the edge of the lane with a very thin coating of bituminous material, Class AET, Class E-6 (AASHTO SS-1 or CSS-1), E-8 (AASHTO SS-1h or CSS-1h), or of the class and type designated for the surface course, prior to placing abutting lanes. If necessary apply AET emulsified asphalt in two applications. When the lane edge is distorted during the day's work, by traffic or other cause, carefully saw the edge of lane to line, as required, prior to painting.

Overlap material in abutting lanes against the vertical face of previously placed lanes. Operate the paver so that, in spreading, the material overlaps the edge of the lane previously placed by approximately 1.5 inches. To assure a true line, closely follow lines or markings placed for this purpose. Keep the depth of the uncompacted mixture being placed adjacent to a previously compacted lane uniformly high to provide for finished grade after compaction. Keep the depth of overlapped material uniform, so rolling will not result in an irregular, rough joint. Immediately after the material has been spread by the paver and before rolling, carefully broom or lute the coarse aggregate in the material overlapping the joint onto the surface of the unrolled lane, leaving behind only the fine portion of the mix. Tightly press this material into the compacted lane when the joint is rolled. Broom or lute immediately after the material has been spread by the paver. Immediately compact fresh mix directly behind the paver at the longitudinal joint.

When compacting the joint, shift the static steel-wheel roller onto the previously placed lane so only 1 or 2 inches of the drive wheel extends over the uncompacted material. Continue to roll along this line, shifting position gradually across the joint until the joint has been rolled with the entire width of the drive wheel. If the vibratory roller is used for breakdown rolling, shift the roller on uncompacted material 1 or 2 inches across the joint onto the previously placed lane. Make the first pass in the vibratory mode. Roll with steel-wheel and pneumatic-tire rollers until a thoroughly compacted neat joint is obtained. Where practical, leave only short lane sections, normally less than 25 feet in length, where the abutting lane is not placed the same day.

2.4 COSTS ASSOCIATED WITH IMPROVING CONSTRUCTION JOINT DENSITIES

There is no information in the literature with regard to cost associated with improving joint densities. A New York DOT engineer stated that they had not observed an appreciable increase in cost associated with the joint density specification: maybe about $1 per ton increase.

The Missouri DOT has not had the specification in place more than one construction season; however, thus far they have noted no increase in cost for hot mix.

3.0 AIRFIELD PAVEMENT STUDIES

3.1 BACKGROUND AND OBJECTIVES

The objective of this task in the project was to document densities from construction data from airfield projects that were constructed according to FAA specification P-401 which states in part the following regarding longitudinal joints:

> *401-4.12 JOINTS.*
> *. . . Longitudinal joints which are irregular, damaged, uncompacted, or otherwise defective shall be cut back to expose a clean, sound surface for the full depth of the course. All contact surfaces shall be given a tack coat of bituminous material prior to placing any fresh mixture against the joint.*
>
> *401-5.1 ACCEPTANCE SAMPLING AND TESTING.*
> *. . . b. Field Placed Material. Material placed in the field shall be tested for mat and joint density on a lot basis.*
> *(1) Mat Density. The lot size shall be the same as that indicated in paragraph 401-5.1a and shall be divided into four equal sublots. One core of finished, compacted materials shall be taken by the Contractor from each sublot. Core locations will be determined by the Engineer on a random basis in accordance with procedures contained in ASTM D 3665. Cores shall not be taken closer than one foot from a transverse or longitudinal joint.*
> *(2) Joint Density. The lot size shall be the total length of longitudinal joints constructed by a lot of material as defined in paragraph 401-5.1a. The lot shall be divided into four equal sublots. One core of finished, compacted materials shall be taken by the Contractor from each sublot. Core locations will be determined by the Engineer on a random basis in accordance with procedures contained in ASTM D 3665.*
>
> *. . .(4) Testing. The bulk specific gravity of each cored sample will be measured by the Engineer in accordance with ASTM D 2726 or ASTM D 1188, whichever is applicable. The percent compaction (density) of each sample will be determined by dividing the bulk specific gravity of each sublot sample by the average bulk specific gravity of all laboratory prepared specimens for the lot, as determined in paragraph 401-5.1a(2). . .*

401-5.2 ACCEPTANCE CRITERIA

. . . .

Table. ACCEPTANCE LIMITS STABILITY, FLOW, AIR VOIDS, DENSITY

Test Property	*Pavements Designed for Aircraft Gross Weights of 60,000 Lbs. Or More or Tire Pressures of 100 lb / sq inch (Psi) or More*		*Pavements Designed for Aircraft Gross Weights Less Than 60,000 Lbs. or Tire Pressures Less Than 100 Psi*	
Number of Blows	*75*		*50*	
	Specification Tolerance Limit		*Specification Tolerance Limit*	
	L	*U*	*L*	*U*
Stability, pounds	*1800*	*---*	*1000*	*---*
Flow, 0.01 in.	*8*	*16*	*8*	*20*
Air Voids Total Mix, percent	*2*	*5*	*2*	*5*
Mat Density, percent	*96.3*	*---*	*96.3*	*---*
Joint Density, percent	*93.3*	*---*	*93.3*	*---*

3.2 CONSTRUCTION DATA FROM TEXAS AIRFIELDS

Personnel from TxDOT's Aviation Division provided data to researchers from recent airfield asphalt paving projects constructed under the FAA P-401 specification which requires a longitudinal joint density. These construction density data in which the mat density is compared with the joint density are shown in Tables 6 through 10.

Based on these data, it is apparent that paving contractors are routinely able to meet the joint density requirements as specified in FAA P-401.

Table 6. Density Data from Paris Airport Asphalt Paving Job (January 2000).

Sample	Mat Density, percent	Joint Density, percent
1/5/00 - Sample 1	97.4	92.6
1/5/00 - Sample 2	99.2	96.2
1/5/00 - Sample 3	98.4	92.5
1/6/00 - Sample 1	99.2	95.3
1/6/00 - Sample 2	99.4	96.2
1/6/00 - Sample 3	98.9	95.2
1/12/00 - Sample 1	97.7	92.3
1/12/00 - Sample 2	96.4	94.9
1/12/00 - Sample 3 retest	97.6	92.3
1/12/00 - Sample 4	97.8	93.1
1/12/00 - Sample 5	98.5	95.0
Average	**98.2**	**94.1**
Standard Deviation	**0.9**	**1.6**
Specification	***96.6 min.***	***93.3 min.***

Table 7. Density Data from Georgetown Municipal Airport Runway, Taxiway, and Apron.

Lot - Sublot	Mat Density, percent	Joint Density, percent
Test Strip 1	99.1	93.9
Test Strip 2	99.0	94.5
Test Strip 3	99.5	93.4
1-1	98.2	95.0
1-2	97.0	94.2
1-3	97.3	94.5
1-4	97.0	96.5
2-1	97.7	96.1
2-2	98.1	94.9
2-3	99.7	95.0
2-4	97.2	96.1
3-1	99.2	94.4
3-2	99.7	98.5
3-3	97.8	95.7
3-4	94.7	99.0
4-1	97.8	96.1
4-2	97.5	97.0
4-3	97.9	96.5
4-4	99.3	96.2
5-1	98.1	95.9
5-2	99.0	96.5
5-3	97.3	97.5
5-4	98.1	95.8
6-1	94.9	93.2
6-2	99.3	96.1
6-3	98.7	94.8
6-4	99.0	92.6
7-1	101.4	96.3
7-2	98.7	93.4
7-3	99.1	95.2
7-4	98.7	94.7
Average	**98.3**	**95.5**
Standard Deviation	**1.2**	**1.5**
Specification	***96.3 min.***	***93.3 min.***

Table 8. Density Data from Mexia Airport Asphalt Paving Job (November 1999).

Lot - Sublot	Mat Density, percent	Joint Density, percent
Test Strip 1-1	94.4	94.0
Test Strip 1-2	95.2	94.7
Test Strip 1-3	96.7	94.6
Test Strip 2-1	99.2	98.2
Test Strip 2-2	98.9	97.1
Test Strip 2-3	100.0	97.1
2-1	98.3	95.0
2-2	98.1	93.5
2-3	99.5	97.8
2-4	98.1	97.2
3-1	97.4	96.4
3-2	99.4	95.7
3-3	98.6	96.7
3-4	100.0	96.9
4-1	99.1	98.6
4-2	99.2	98.2
4-3	99.9	98.6
5-1	98.3	97.1
5-2	98.1	96.1
5-3	99.0	95.8
Average	**98.4**	**96.5**
Standard Deviation	**1.5**	**1.5**
Specification	***96.3 min.***	***93.3 min.***

Table 9. Density Data from Lamesa Airport Asphalt Paving Job (September 1999).

Sample	Mat Density, percent	Joint Density, percent
TS2-1A	98.1	96.0
TS2-1B	99.2	98.2
TS2-1C	99.3	96.1
Lot 2-1	98.1	94.8
Lot 2-2	98.6	94.7
Lot 2-3	98.4	95.6
Lot 2-4	94.7	95.8
Lot 2-5	98.0	95.0
RW-1	98.1	94.8
RW-2	98.6	94.7
RW-3	98.4	95.6
RW-4	97.4	95.8
RW-5	98.0	95.0
Lot 3-1	98.4	95.6
Lot 3-2	97.4	96.1
Lot 3-3	98.7	94.0
Lot 3-4	98.5	95.5
Lot 4-1	98.6	96.2
Lot 4-2	98.0	95.4
Lot 4-3	98.2	95.6
Lot 4-4	97.5	95.6
Lot 5-1	98.2	95.2
Lot 5-2	98.7	95.0
Lot 5-3	98.1	95.4
Lot 5-4	98.6	96.6
Lot 6-1	98.0	95.5
Lot 6-2	98.3	95.0
Lot 6-3	98.6	95.6
Lot 6-4	98.2	95.3
Average	**98.3**	**95.5**
Standard Deviation	**0.5**	**0.8**
Specification	***96.3 min.***	***93.3 min.***

Table 10. Density Data from Lampasas Airport Asphalt Paving Job (December 1999).

Sample	Mat Density, percent	Joint Density, percent
TS-1	97.8	93.8
TS-2	99.0	94.5
TS-1	98.3	96.1
Lot 1-1	99.3	94.6
Lot 1-2	97.4	93.8
Lot 1-3	97.4	96.2
Lot 1-4	99.1	94.8
Lot 2-1	96.4	94.3
Lot 2-2	97.7	95.2
Lot 2-3	97.5	95.9
Lot 2-4	97.7	95.1
Lot 3-1	98.7	95.3
Lot 3-2	98.7	95.2
Lot 3-3	98.6	96.0
Lot 3-4	97.9	96.4
Lot 4-1	98.0	96.2
Lot 4-2	98.7	94.7
Lot 4-3	98.1	96.1
Lot 4-4	97.5	94.5
Lot 5-1	99.5	97.9
Lot 5-2	97.2	97.2
Lot 5-3	98.6	99.7
Lot 5-4	98.4	98.3
Average	**98.2**	**95.7**
Standard Deviation	**0.8**	**1.5**
Specification	***96.3 min.***	***93.3 min.***

4.0 CASE STUDIES ON PERFORMANCE

The objective of this portion of the research effort was to document and/or synthesize some case studies where joint density was an issue which was associated with performance. Three case studies are discussed in this chapter:

- Interstate Highway (IH) 10 Yoakum District;
- United States (US) 277 Loop, Eagle Pass, Laredo District; and
- IH 20, Odessa District.

4.1 FORENSIC INVESTIGATION OF IH 10 IN YOAKUM DISTRICT

The Bituminous Branch of the Construction Division conducted a forensic investigation in the Yoakum district to evaluate the premature failure of an asphalt concrete pavement. These findings were detailed in a letter report to Mr. Wayne Ramert from Maghsoud Tahmoressi dated October 5, 1999. At the time of the investigation, the pavement was exhibiting severe rutting (as much as 1.25 inches) in some locations. In addition, some signs of stripping were observed.

Engineers selected five locations in the westbound lanes for sampling and testing:

- Location 1 in the outside lane (near Mile Marker 684) exhibited the worst rutting (1.25 inches).
- Location 2 (near Mile Marker 685) in the outside lane also exhibited some rutting.
- Locations 3, 4, and 5 were in the inside lane. The pavement was in good condition in these locations with very slight rutting of 1/8 inch.

A trench was cut in the surface layer of location 1 and 12 inch by 12 inch slabs were obtained here as well as cores. In addition to signs of severe stripping in the surface layer, the 4 inch thick underlying asphalt concrete (ACP) layer also showed signs of stripping and disintegration. This underlying ACP layer (limestone) had been in service for about 15 years prior to being overlayed with the gravel ACP mix.

At location 2 the surface layer also showed stripping but not as bad as in location 1. The underlying limestone ACP layer was also in better condition at this location.

Cores taken from locations 2, 3, and 4 showed some stripping of the gravel ACP surface layer. The underlying limestone ACP in these locations was in good condition, with some possible stripping in the bottom 1 inch.

Materials and Tests engineers conducted numerous tests on the field samples including the following:

- extraction and gradation of aggregate;
- binder recovery and asphalt cement properties;
- in-place densities;
- tensile strengths (wet and dry);
- static creep tests;
- Hamburg wheel tracking tests; and
- Georgia loaded wheel tests.

Based on their analysis of all the information, engineers concluded that both the surface ACP (with gravel aggregate) and the underlying limestone ACP layer were both experiencing stripping. It was determined that the surface layer stripping was so severe that it should be removed from the entire project. The underlying 4 inch limestone ACP layer was in various stages of disintegration and stripping and it was recommended that this layer also be removed.

A very important conclusion to the investigation was that the low in-place density at the longitudinal joint was the likely reason for intrusion of water into the pavement. These results are shown in Table 11 below.

Table 11. In-Place Density for Top Layer of IH 10, Yoakum.

Location	Density of Longitudinal Joint, %	Density in Wheel Path, %	Density Between Wheel Paths, %
1	90.5	94.2	93.2
2	90.8	95.6	93.7
3	Not Available	95.2	Not Available
4	Not Available	94.4	Not Available
5	Not Available	95.0	Not Available

4.2 FORENSIC INVESTIGATION OF US 277 LOOP IN EAGLE PASS, LAREDO DISTRICT

In October of 1999, the Bituminous Branch of the Construction Division conducted a forensic investigation of a premature pavement failure on the US 277 Loop in Eagle Pass (TxDOT, 1999). This pavement is a five-lane curb-and-gutter section with a two-way left turn lane in the middle. A full-depth rehabilitation of the pavement was performed about one-year prior to the investigation. The HMAC (Type D) was placed in two 1.5 inch lifts.

Several months after the project's completion, potholes and cracking developed soon after a rain. These were patched by maintenance crews who observed at the time that the base was "dry and hard." The forensic investigation team noticed that there was a pattern in the distress: most of the patches were located along the longitudinal joint. The team took cores at several locations throughout the pavement and performed a laboratory investigation with the following tasks:

- Verify the mixture design.
- Compare density of the ACP near the joint vs. middle of the lane.
- Evaluate moisture susceptibility of the mix.
- Evaluate the rutting susceptibility of the mix.

After the extensive laboratory investigation, the following conclusions were made:

- The plant-produced mix met the mixture design and specification requirements at all locations and for both lifts. However, both asphalt cement (AC) content and percent passing the No. 200 sieve were on the high side, which would make the mix prone to rutting.
- Performance of the mix is marginal with respect to rutting susceptibility.
- Mix failed to meet the minimum Tensile Strength Ratio (TSR) requirement of 0.8 for three out of 6 locations with mild conditioning. Mix does show propensity to strip.
- Low density at the joint most likely caused water to enter the pavement and cause the damage.
- Mixture is susceptible to moisture damage in the long term, even in the locations that do not exhibit any distress at the present time.

The conclusion that the low joint density was a major factor contributing to the pavement damage was based on the following density data shown in Tables 12 and 13.

Table 12. Road Core Densities for Two Lifts Combined - US 277 Loop.

Density, percent Location 1 (Moisture Damage)		Density, percent Location 3 (Moisture Damage)		Density, percent Location 4 (No Distress)	
Joint	Middle	Joint	Middle	Joint	Middle
89.7 89.5 91.1 89.6 88.4	95.5 95.1 90.8 91.3 90.6 91.7 91.7 91.9	89.6 89.8 89.5 89.0 88.7	91.4 91.7 91.5 91.5 91.2	88.7 89.1 89.8 89.2 89.4	92.2 91.9 91.6 91.6 91.4
Avg = 89.7	Avg = 92.3	Avg = 89.3	Avg = 91.5	Avg = 89.2	Avg = 91.7

Table 13. Average Core Density for Top and Bottom Lift - US 277 Loop.

HMAC Lift	Density, percent Location 1		Density, percent Location 3		Density, percent Location 4	
	Joint	Center	Joint	Center	Joint	Center
Top Lift	92.0	89.4	90.0	91.5	90.8	94.0
Bottom Lift	88.9	90.0	89.1	91.7	89.8	90.9

4.3 IH 20 PROJECT NEAR PECOS IN THE ODESSA DISTRICT

Performance problems resulting from poor compaction at the construction joints were experienced in the Odessa district on IH 20 near Pecos. Figure 15 is a photo of the longitudinal construction joint. Note the *lip* along the joint which acts as a dam to hold water. Figure 16 shows alligator cracking which became evident within two days of construction. Moisture entered the pavement through this joint and saturated the base. TTI's forensic team investigated this pavement failure using ground penetrating radar (GPR) and evaluating cores for density and permeability. Core densities indicated that the pavement at the joint had 16.6 percent air voids and the pavement in the main lane had 10 percent air voids. This dense-graded hot mix was placed in winter months when the temperature was about 40 °F which contributed to these density problems.

GPR was also used as a tool to qualitatively examine the densities at the joint. Figure 17 shows a typical GPR trace from a three-layer pavement. Reflection A_1 is from the surface. If A_1 increases, the surface dielectric increases indicating moisture. If A_1 decreases, the dielectric decreases indicating more air in the HMAC. Figure 18 is a trace of the surface dielectric versus distance. For this plot, the GPR was not traveling in a straight line directly over the construction joint but was weaving along both sides of the joint. The *dips* shown on the plot are when the unit crosses the joint. A constant density would give a flat line. Low dielectric indicates higher voids at the joint.

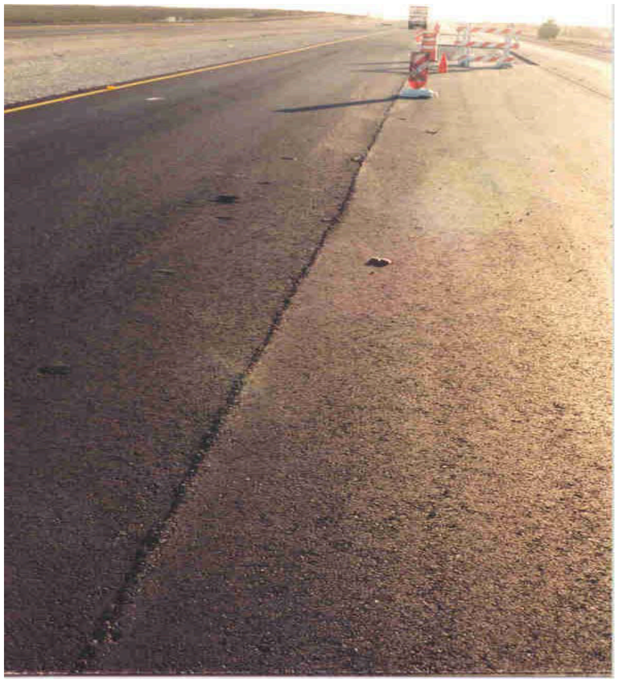


Figure 15. Longitudinal Construction Joint on IH 20, Odessa District.

Figure 16. Alligator Cracking 2 Days after Construction.

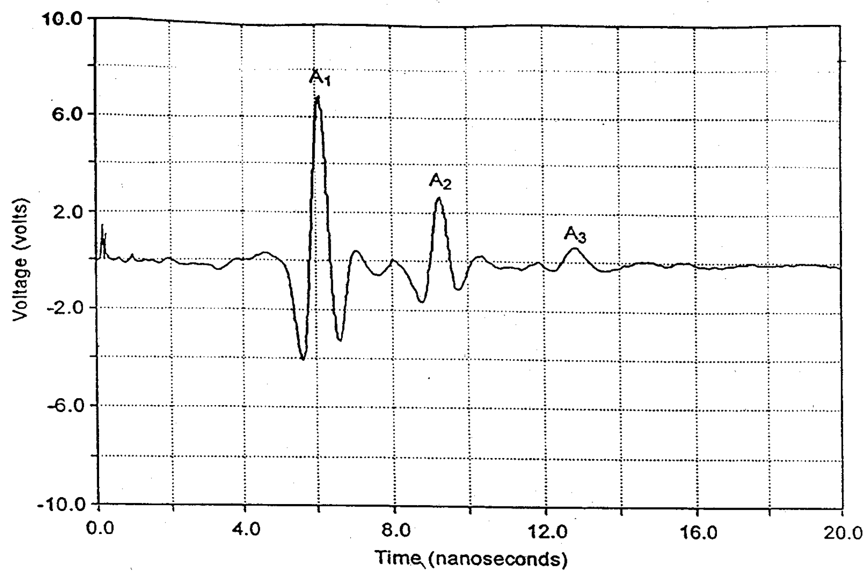


Figure 17. Typical GPR Trace from a Three-Layer Pavement.

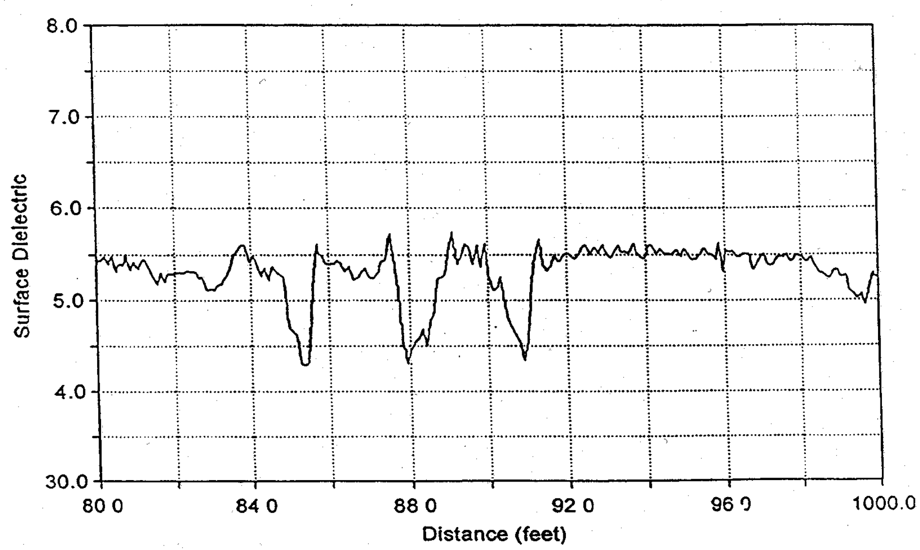


Figure 18. Plot of Surface Dielectric Versus Distance.

CHAPTER 5.0 DENSITY MEASUREMENTS ON FIELD PAVEMENTS

5.1 BACKGROUND AND OBJECTIVES

The objective of the research as presented in this chapter was to assess the density along the longitudinal construction joint of several Texas pavements to determine if a problem exists. Pavements were selected which were representative of those most typically placed in the state. All of the pavement sections were overlays of 1.5 to 2 inches thick. Researchers attempted to find *eight* pavements each of the following types:

- Type C, crushed limestone;
- Type C, crushed gravel;
- Type D, crushed limestone;
- Type D, crushed gravel;
- CMHB, crushed limestone; and
- CMHB, crushed gravel.

In addition, two Superpave pavements were identified and included. Also, three pavement sections which were constructed under a trial *longitudinal joint density* specification were included. These pavements were a stone filled asphalt mix, a stone matrix asphalt (SMA) mix, and a heavy duty SMA mix.

No CMHB mixes constructed with a crushed gravel were identified during this study. Also, due to time constraints of the study and scheduling conflicts, only a limited number of Type D/crushed gravel mixes were included; therefore, all of the Type D pavements (gravel and limestone) are presented together herein.

5.2 FIELD DATA COLLECTION PROCEDURES

Nuclear density measurements were made on each of the field pavements using a thin-lift nuclear gauge in backscatter mode and each measurement was the result of a four minute gauge reading. Measurements occurred during construction after the final roller pass and while traffic was controlled for construction. Measurements were made transversely across the paved lane at the joint and/or unconfined edge, 12 inches from the edge, 24 inches from the edge, and in the middle of the lane. These density measurements were made at *five* locations spaced about 200 ft apart. Figure 19 shows where nuclear densities and cores were taken on a typical pavement cross-section. Note, if only one pass of the laydown machine had occurred at the time of testing and no joint yet existed, measurements were made 6 inches from the unconfined edge of what would become the joint.

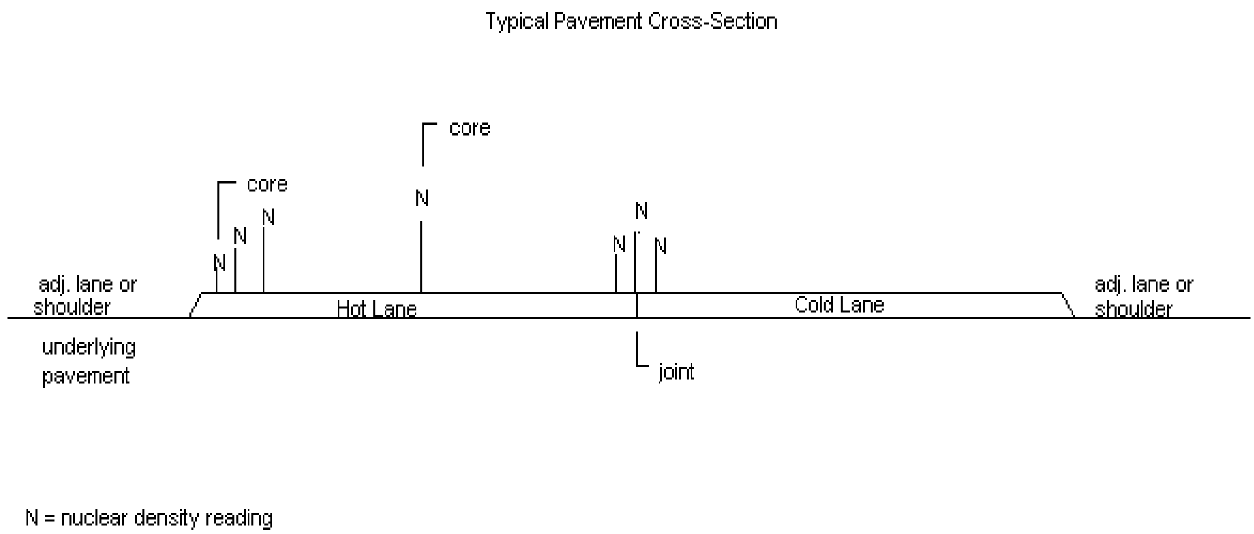


Figure 19. Typical Pavement Cross-Section Showing where Nuclear Measurements and Cores were Located.

Through district personnel and/or through researchers, contractors were requested to provide eight 4 inch diameter cores corresponding to density-measurement locations: four cores near the unconfined edge and four cores in the middle of the lane as designated by researchers. Unfortunately, for most of the projects, contractors did not provide the cores and research funds were not available to perform coring activities by TTI.

Bulk density was measured for all cores to correlate to the nuclear measurements. Permeability measurements were performed on four of the eight cores: two from the unconfined edge and two from the middle of the lane. Photos of core locations and nuclear density testing are shown in Figures 20 and 21.

Rice specific gravity values were obtained from the field/plant laboratories for the day's production.

Figure 20. Typical Pavement Showing Core Locations and Density Testing.

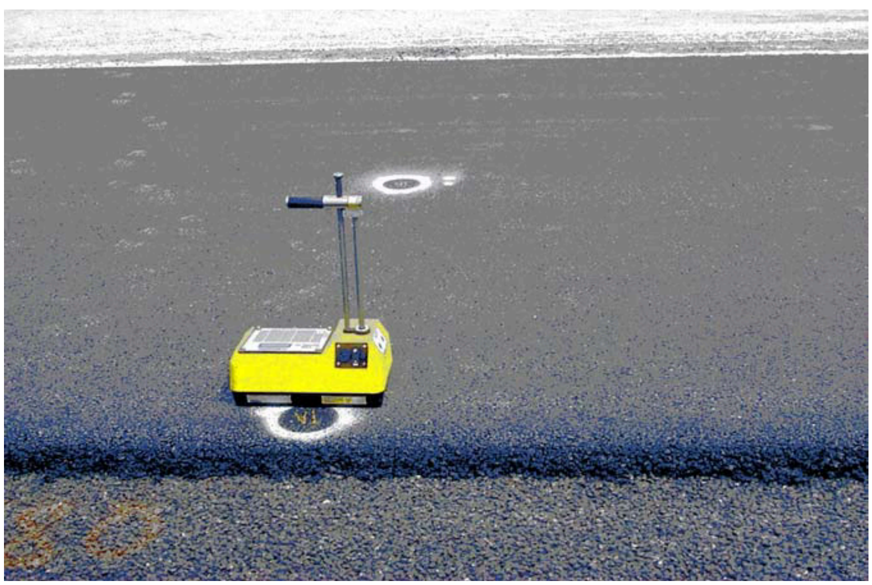


Figure 21. Typical Pavement Showing Core Locations and Density Testing - Side View.

5.3 FIELD DENSITY RESULTS

This section shows density data and analyses for each pavement. For each pavement, the section provides the following exhibits:

- table showing all nuclear density measurements for that pavement (typically 5 sets of readings per pavement), means, and standard deviations;
- figure showing the mean density profile and pavement cross section;
- table showing results of a statistical analysis comparing mean densities at the middle of the lane to other measurement points like the unconfined edge, joint, confined edge, 1 foot from the edge and 2 feet from the edge: this table shows whether the difference in density from the middle of the lane to the unconfined edge, for example, is significant; and
- figure comparing the difference in density (in both pcf and percent) from the middle of the lane to all other measurement points.

Data for each mixture type are shown in the following tables and figures:

- *Type C, Crushed Limestone Pavements* - Tables 14 through 29 and Figures 22 through 37;
- *Type C, Crushed Gravel Pavements* - Tables 30 through 43 and Figures 38 through 51;
- *Type D, Limestone and Gravel Pavements* - Tables 44 through 59 and Figures 52 through 67;
- *CMHB, Crushed Limestone Pavements* - Tables 60 through 73 and Figures 68 through 81;
- *Superpave Pavements* - Tables 74 through 77 and Figures 82 through 85; and
- *Specialty Mixes Built with Joint Density Specification: stone-filled asphalt (SFA), stone-matrix asphalt (SMA), Heavy Duty SMA* - Tables 78 through 83 and Figures 86 through 91.

Type C, Crushed Limestone Pavements

Table 14. Density Data for Farm to Market (FM) 933, Waco, Type C - Limestone Mix.

Station	*A* 0.5 ft from Unconf. Edge	*B* 1ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D* Middle of Lane**	*E* 0.5 ft from Joint on Hot Side	*F* On Top of Joint	*G* 0.5 ft from Joint on Cold Side
1	125.4	129.1	128.2	**128.8**	129.2	127.6	123.5
2	122.9	126.8	128.5	**129.9**	131.7	131.2	127.8
3	124.8	129.3	131.1	**131.9**	127.0	130.6	122.1
4	128.2	131.8	133.3	**135.7**	130.0	132.8	125.5
5	127.0	132.0	133.8	**136.6**	129.0	133.5	128.7
Mean	125.66	129.80	130.98	**132.58**	129.38	131.14	125.52
Std. Dev.	2.04	2.16	2.61	**3.46**	1.70	2.30	2.79

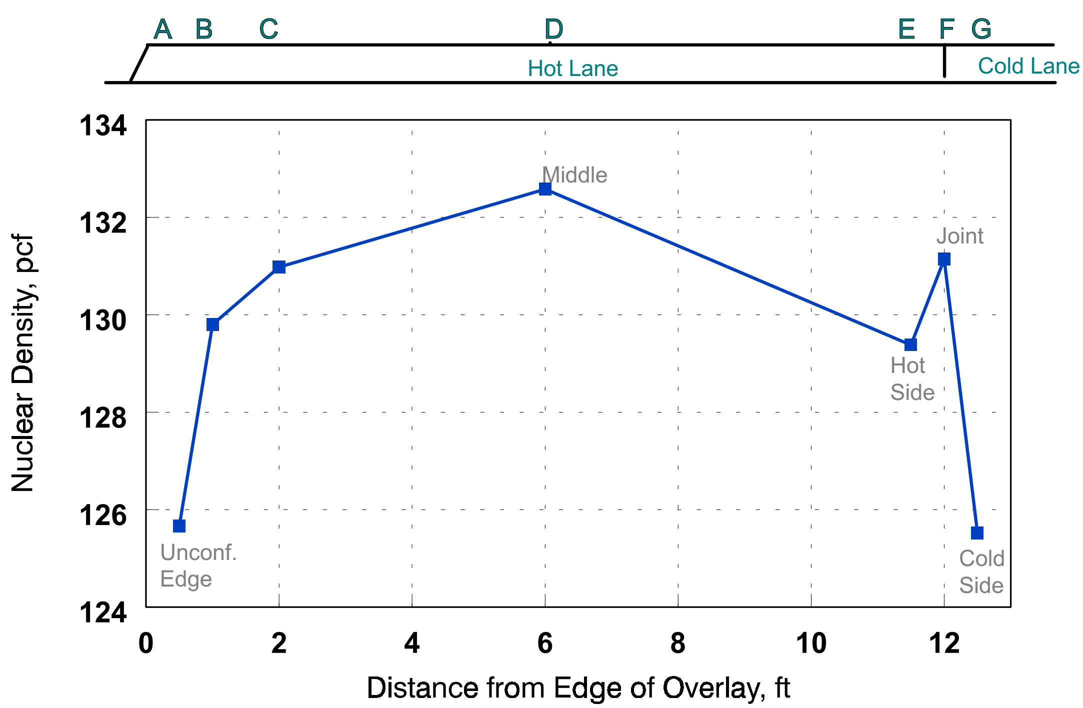


Figure 22. Mean Density Profile for FM 933, Waco, Type C - Limestone Mix.

Table 15. Statistical Comparison of Mean Densities for FM 933, Waco, using Fisher's Planned Least Significant Difference (PLSD) - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-6.92	0.0001	**Yes**
B, D	-2.78	0.0890	-
C, D	-1.60	0.3193	-
E, D	-3.18	0.0536	-
F, D	-1.44	0.3692	-
G, D	-7.06	0.0001	**Yes**

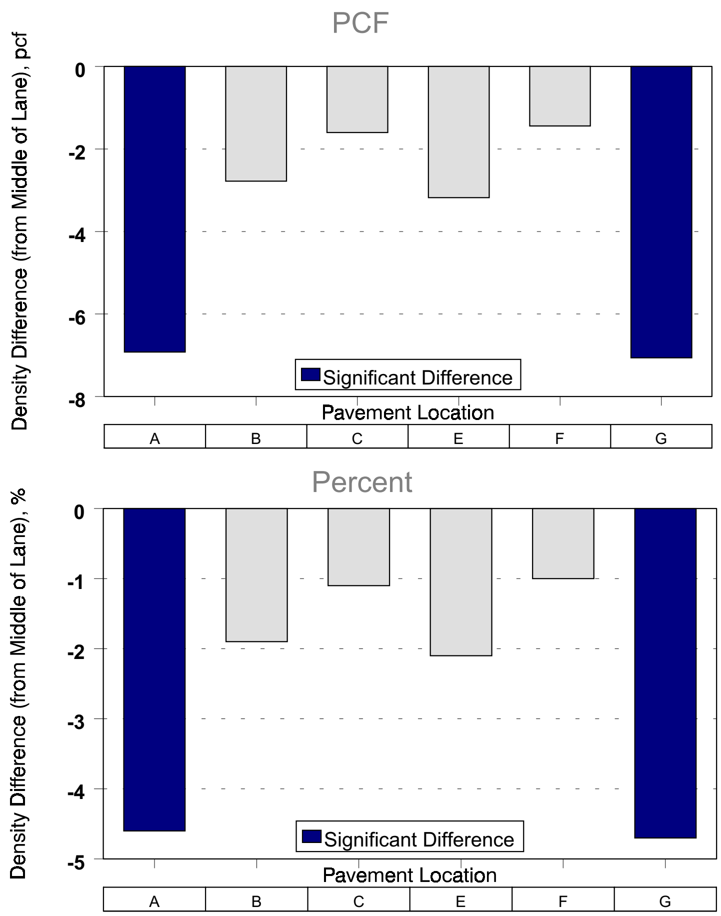


Figure 23. Difference in Density from Middle of Lane for FM 933, Waco, Type C - Limestone Mix.

Table 16. Density Data for IH 10, Beaumont, Type C - Limestone Mix.

Station	*A* 0.5 ft from Unconfined Edge	*B* 1ft from Unconfined Edge	*C* 2 ft from Unconfined Edge	***D* Middle of Lane**
1	123.2	128.2	129.0	**134.4**
2	127.9	123.8	132.2	**131.6**
3	127.4	131.9	135.9	**131.3**
4	123.1	119.3	133.0	**132.0**
5	123.0	127.4	134.2	**136.5**
Mean	124.92	126.12	132.86	**133.16**
Std. Dev.	2.50	4.78	2.57	**2.23**

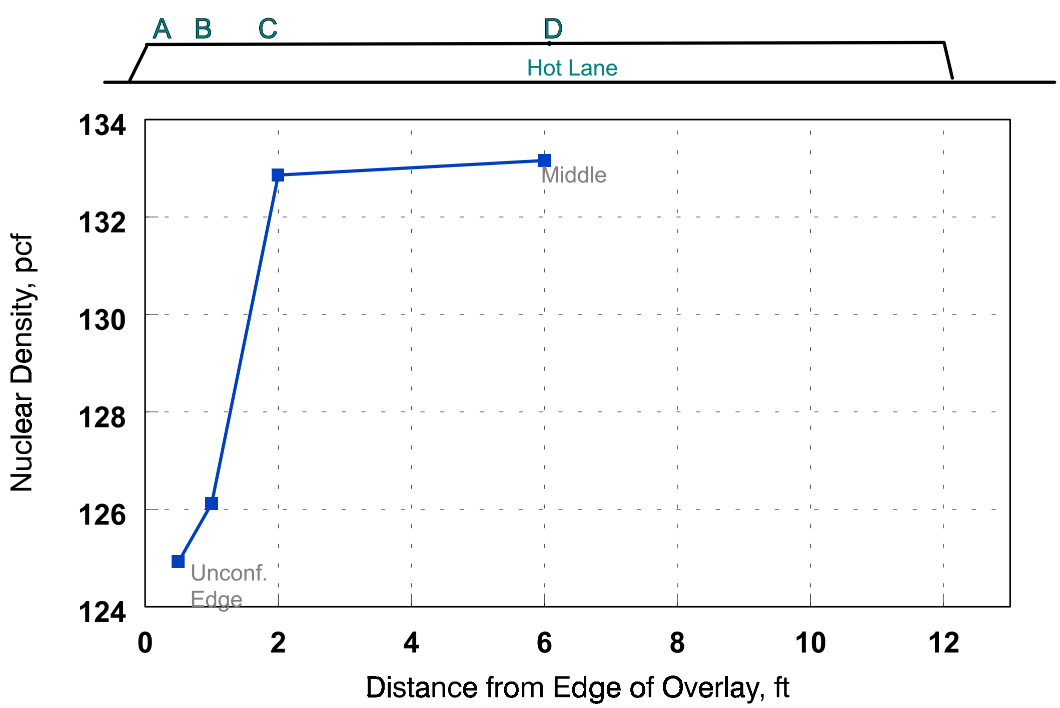


Figure 24. Mean Density Profile for IH 10, Beaumont, Type C - Limestone Mix.

Table 17. Statistical Comparison of Mean Densities for IH 10, Beaumont using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-8.240	0.0063	**Yes**
B, D	-7.040	0.0168	**Yes**
C, D	-0.300	0.9126	-

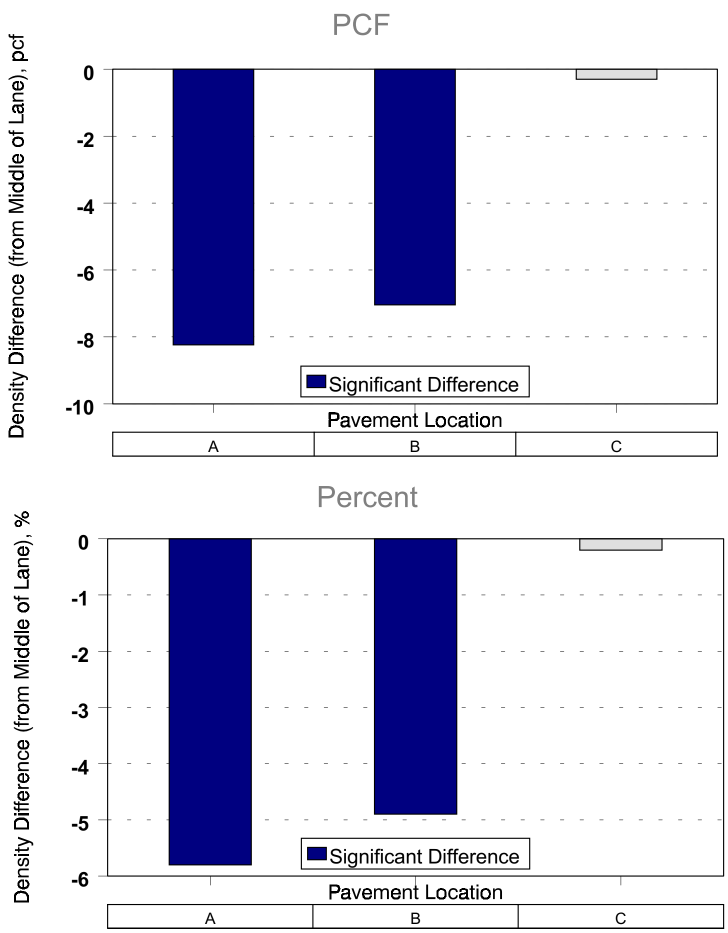


Figure 25. Difference in Density from Middle of Lane for IH 10, Beaumont, Type C - Limestone Mix.

Table 18. Density Data for MoPac, Austin, Type C - Limestone Mix.

Station	***A*** 0.5 ft from Unconf. Edge	***B*** 1ft from Unconf. Edge	***C*** 2 ft from Unconf. Edge	***D*** Middle of Lane	***E*** 0.5 ft from Joint on Hot Side	***F*** On Top of Joint	***G*** 0.5 ft from Joint on Cold Side
1	125.9	131.0	134.4	127.7	126.2	107.3	123.1
2	132.9	133.5	135.1	135.0	125.9	106.2	126.2
3	126.4	118.5	134.7	131.9	121.6	*	*
*	*	*	*	*	*	*	*
Mean	128.40	127.67	134.73	131.53	124.57	106.75	124.65
Std. Dev.	3.91	8.04	0.35	3.66	2.57	0.78	2.19

* Pavement opened to traffic prior to completion of data collection.
Note: Measurements A through E occurred on the shoulder which was being paved at the time of data collection.

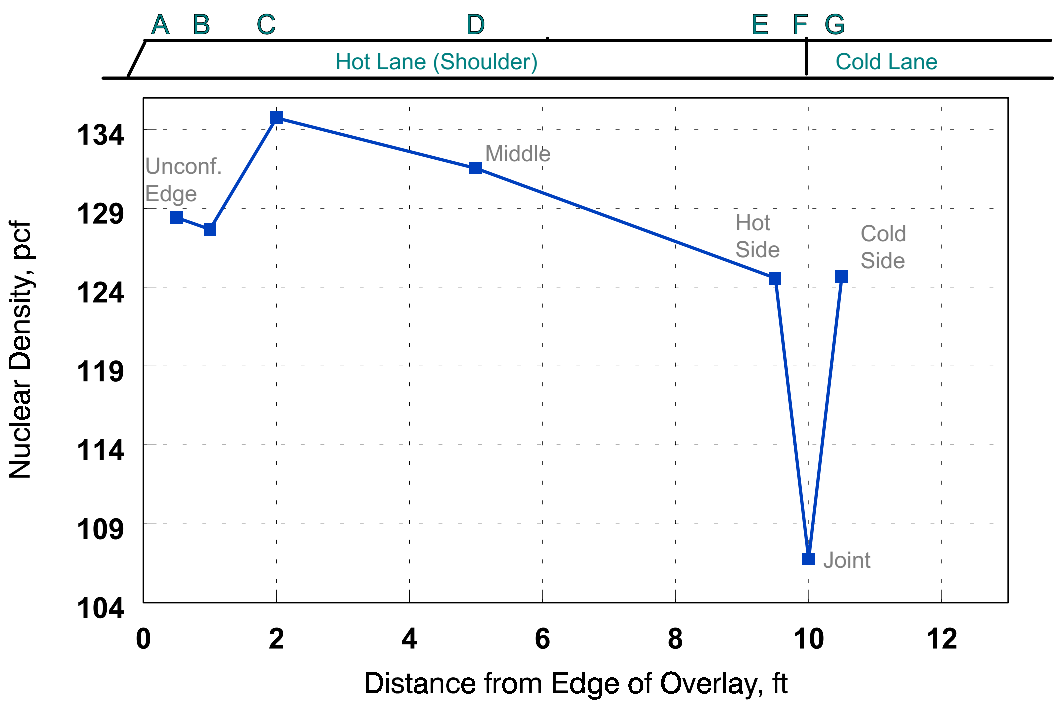


Figure 26. Mean Density Profile for MoPac, Austin, Type C - Limestone Mix.

Table 19. Statistical Comparison of Mean Densities for MoPac, Austin, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-3.133	0.3719	-
B, D	-3.867	0.2747	-
C, D	3.200	0.3622	-
E, D	-6.967	0.0615	-
F, D	-24.783	<0.0001	**Yes**
G, D	-6.883	0.0934	-

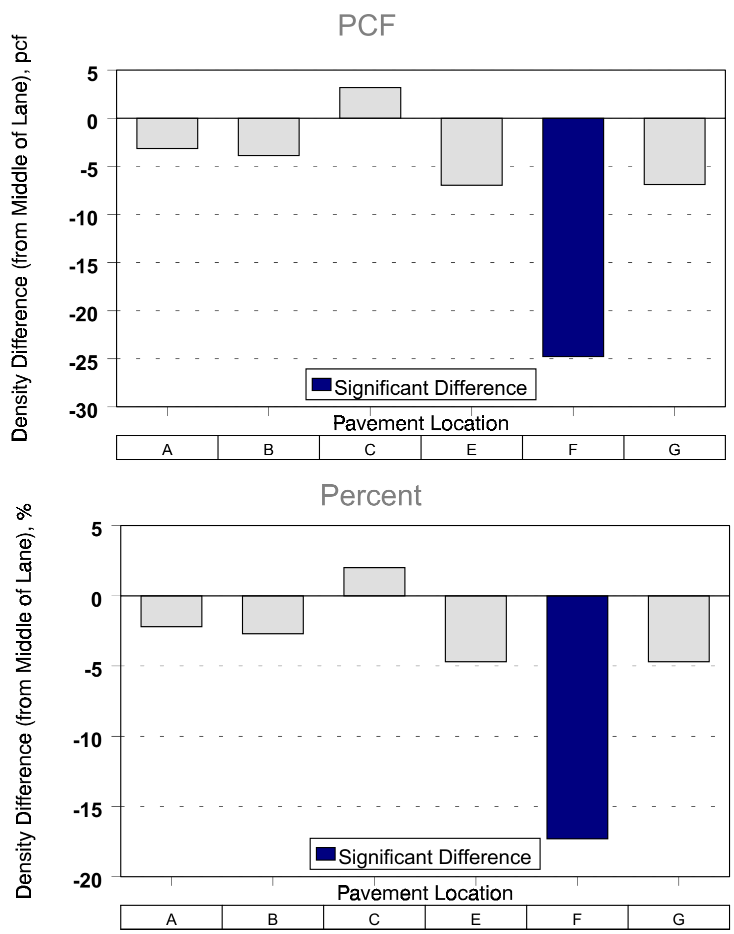


Figure 27. Difference in Density from Middle of Lane for MoPac, Austin, Type C - Limestone Mix.

Table 20. Density Data for FM 51, Ft. Worth, Type C - Limestone Mix.

Station	*A* 0.5 ft from Unconfined Edge	*B* 1ft from Unconfined Edge	*C* 2 ft from Unconfined Edge	***D* Middle of Lane**	*E* 0.5 ft from Unconfined Edge
1	112.1	110.7	114.3	**129.1**	128.8
2	101.5	107.4	107.0	**130.1**	130.9
3	102.6	111.0	115.3	**129.8**	130.4
4	118.2	116.4	115.8	**131.0**	128.6
*	*	*	*	*	*
Mean	108.60	111.38	113.10	**130.00**	129.68
Std. Dev.	8.00	3.73	4.11	**0.79**	1.15

* Pavement opened to traffic prior to completion of data collection.

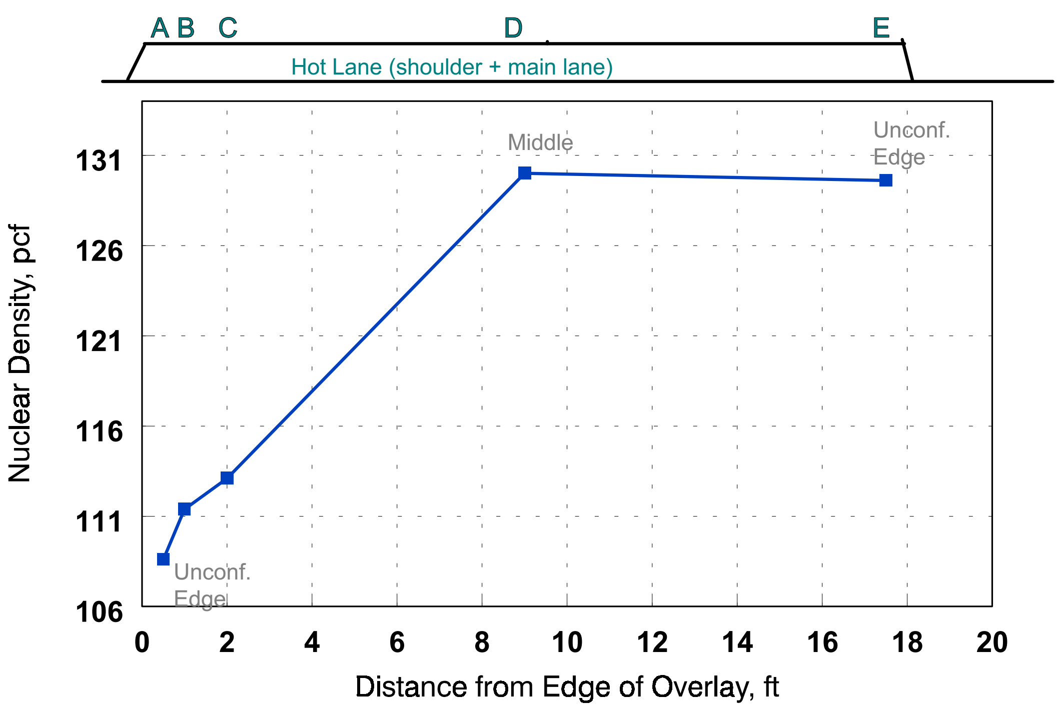


Figure 28. Mean Density Profile for FM 51, Ft. Worth, Type C - Limestone Mix.

Table 21. Statistical Comparison of Mean Densities for FM 51, Ft. Worth, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-21.40	<0.0001	**Yes**
B, D	-18.63	<0.0001	**Yes**
C, D	-16.90	<0.0001	**Yes**
E, D	-0.33	0.9180	-

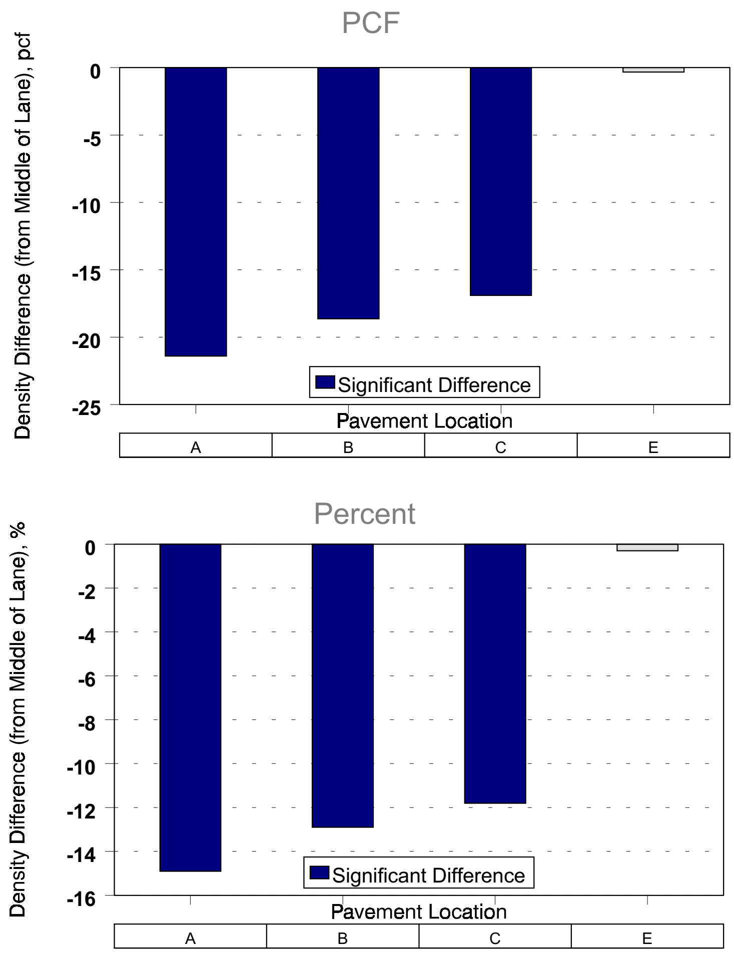


Figure 29. Difference in Density from Middle of Lane for FM 51, Ft. Worth, Type C - Limestone Mix.

Table 22. Density Data for Loop 323, Tyler, Type C - Limestone Mix.

Station	*A* 0.5 ft from Curbed (Confined) Edge	*B* 1ft from Curbed Edge	*C* 2 ft from Curbed Edge	***D* Middle of Lane**	*E* 0.5 ft from Joint on Hot Side	*F* On Top of Joint	*G* 0.5 ft from Joint on Cold Side
1	129.4	132.5	132.7	**138.3**	127.6	108.6	120.8
2	128.1	125.8	125.9	**130.9**	131.4	115.6	128.1
3	131.9	132.4	134.7	**127.9**	126.0	125.9	133.3
4	129.4	134.0	137.0	**135.7**	125.0	126.8	133.6
5	131.8	132.6	131.2	**126.7**	129.5	122.0	131.6
Mean	130.12	131.46	132.3	**131.90**	127.90	119.78	129.48
Std. Dev.	1.67	3.23	4.19	**4.99**	2.59	7.65	5.32

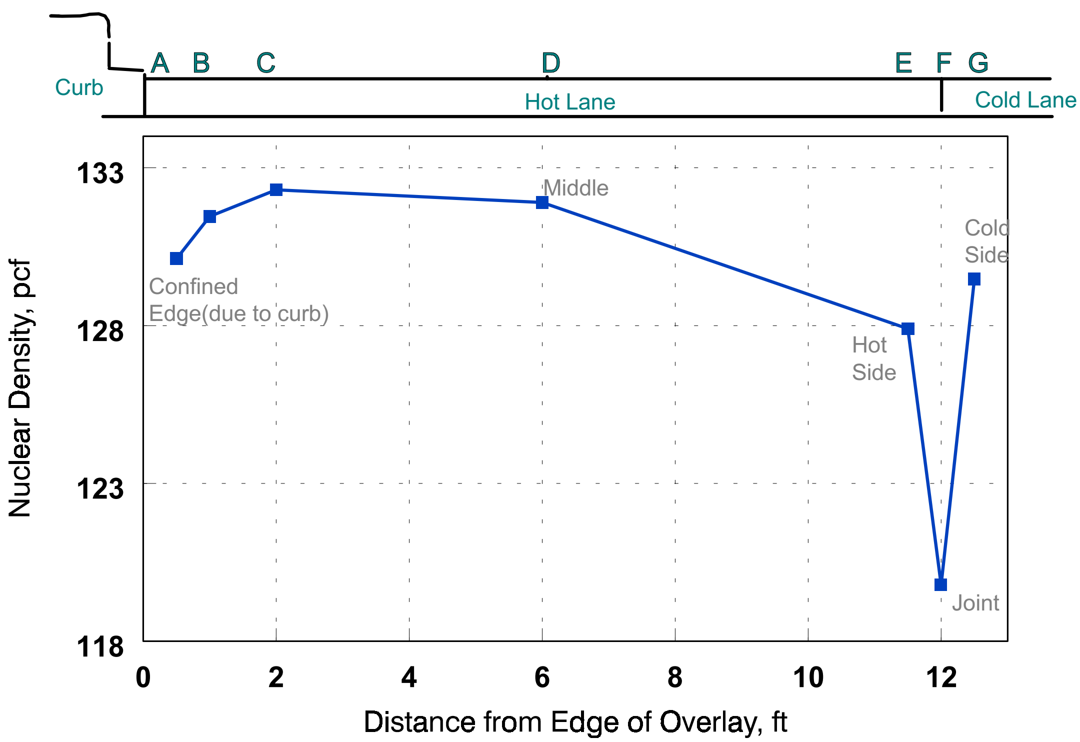
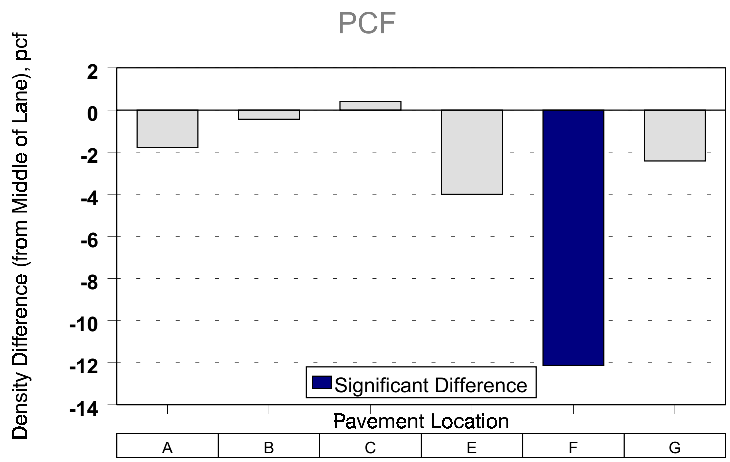


Figure 30. Mean Density Profile for Loop 323, Tyler, Type C - Limestone Mix.

Table 23. Statistical Comparison of Mean Densities for Loop 323, Tyler, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-1.781	0.5470	-
B, D	-0.440	0.8813	-
C, D	0.400	0.8920	-
E, D	-4.00	0.1816	-
F, D	-12.120	0.0003	**Yes**
G, D	-2.420	0.4142	-



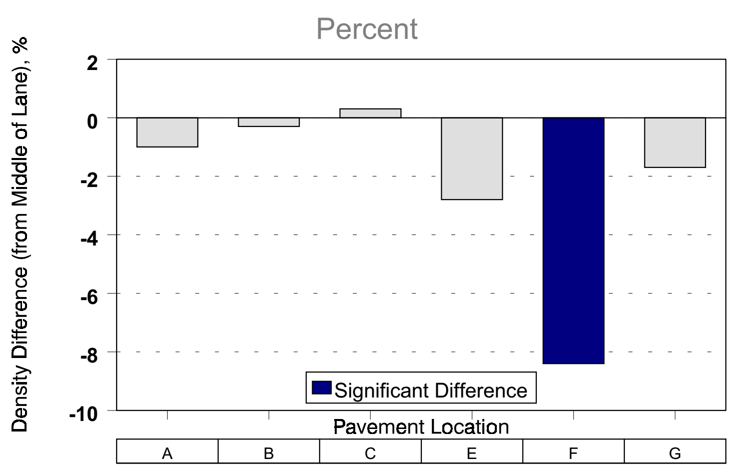


Figure 31. Difference in Density from Middle of Lane for Loop 323, Tyler, Type C - Limestone Mix.

Table 24. Density Data for Dessau Road, Austin, Type C - Limestone Mix.

Station	***D*** **Middle of Lane**	***E*** 0.5 ft from Joint on Hot Side	***F*** On Top of Joint	***G*** 0.5 ft from Joint on Cold Side
1	**134.7**	131.1	109.4	129.2
2	**132.0**	130.2	107.4	126.7
3	**139.8**	132.1	Lip on Joint	129.8
4	**134.5**	129.2	Lip on Joint	124.5
5	**135.2**	133.4	117.0	117.0
Mean	**135.24**	131.20	111.27	125.44
Std. Dev.	**2.83**	1.63	5.06	5.17

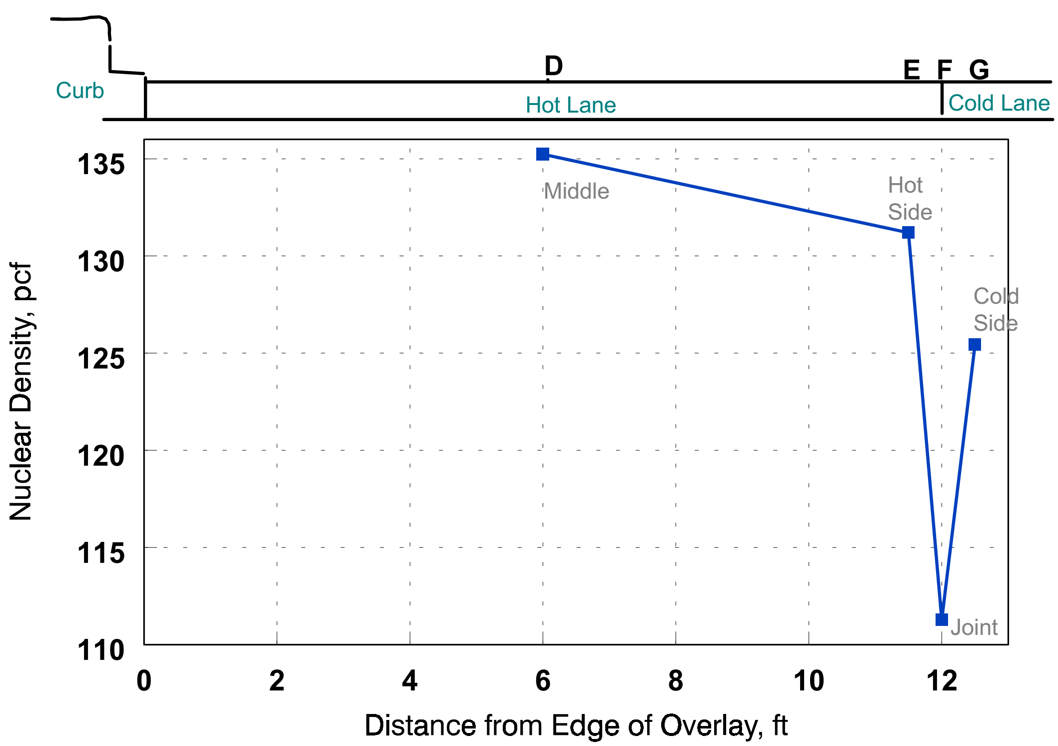


Figure 32. Mean Density Profile for Dessau Road, Austin, Type C - Limestone Mix.

Table 25. Statistical Comparison of Mean Densities for Dessau Road, Austin, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
E, D	-4.040	0.0850	-
F, D	-23.973	<0.0001	**Yes**
G, D	-9.800	4.645	**Yes**

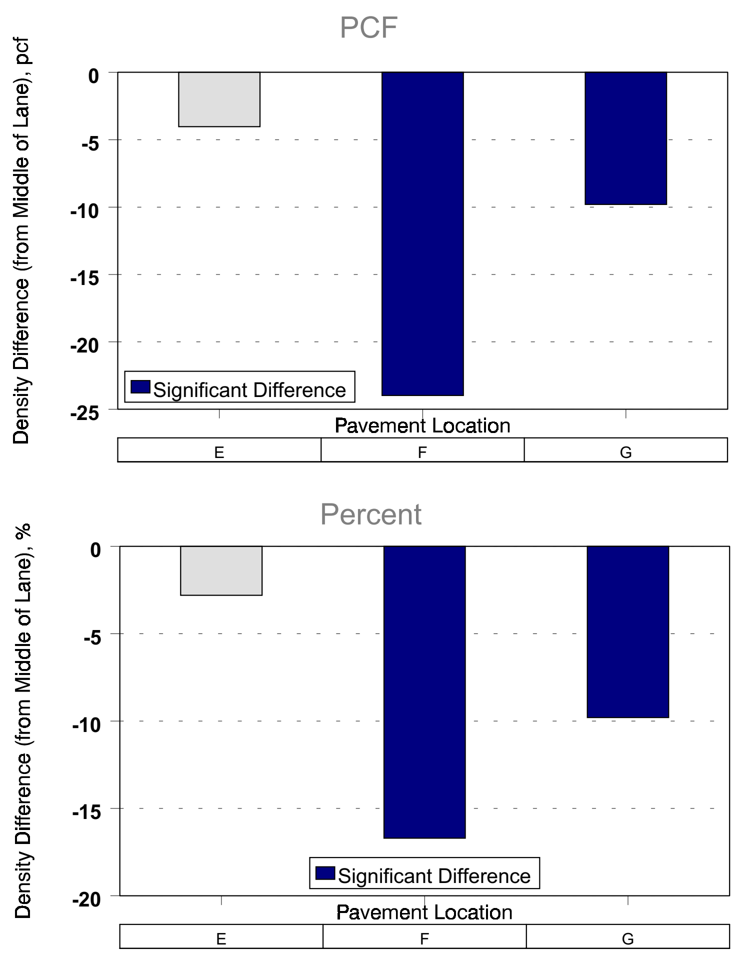


Figure 33. Difference in Density from Middle of Lane for Dessau Road, Austin, Type C - Limestone Mix.

Table 26. Density Data for State Highway (SH) 71, Austin, Type C - Limestone Mix.

Station	*A* 0.5 ft from Unconfined Edge	*B* 1ft from Unconfined Edge	*C* 2 ft from Unconfined Edge	***D* Middle of Lane**	*E* 0.5 ft from Unconfined Edge
1	126.1	133.0	132.6	**133.6**	121.5
2	114.0	135.3	134.3	**134.3**	124.2
3	109.8	132.2	131.8	**133.9**	122.7
4	113.4	131.5	130.4	**135.3**	129.1
5	97.93	125.7	128.5	**133.9**	131.1
Mean	112.25	131.54	131.52	**134.2**	125.72
Std. Dev.	10.09	3.56	2.20	**0.66**	4.17

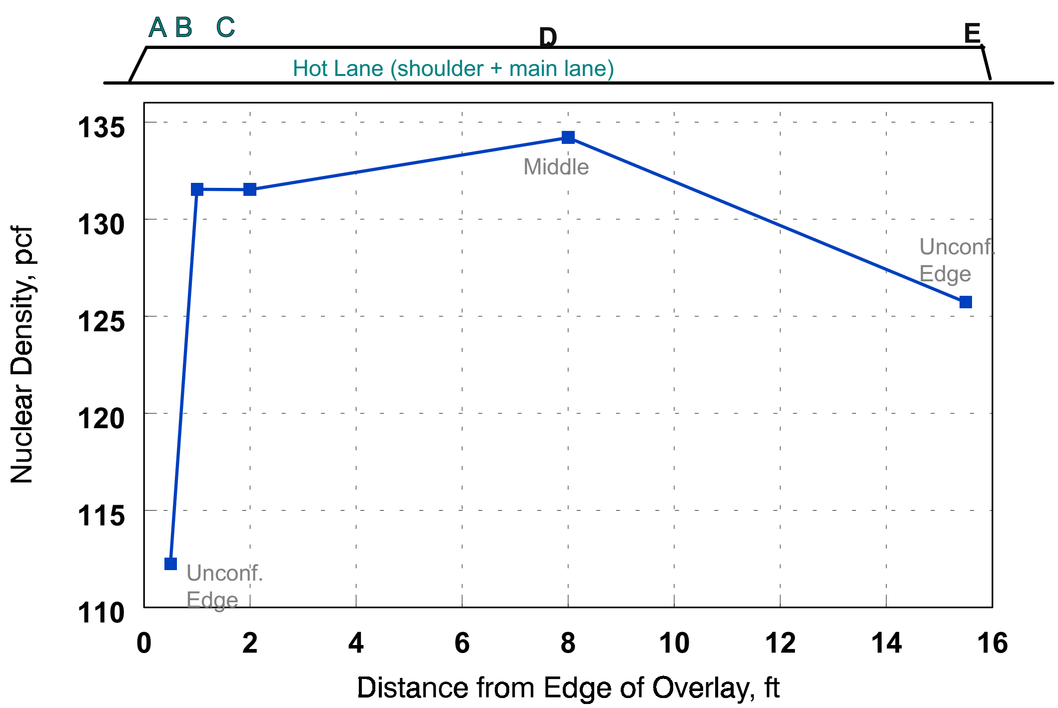


Figure 34. Mean Density Profile for SH 71, Austin, Type C - Limestone Mix.

Table 27. Statistical Comparison of Mean Densities for SH 71, Austin, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-21.954	<0.0001	**Yes**
B, D	-2.660	0.4315	-
C, D	-2.680	0.4281	-
E, D	-8.480	0.0187	**Yes**

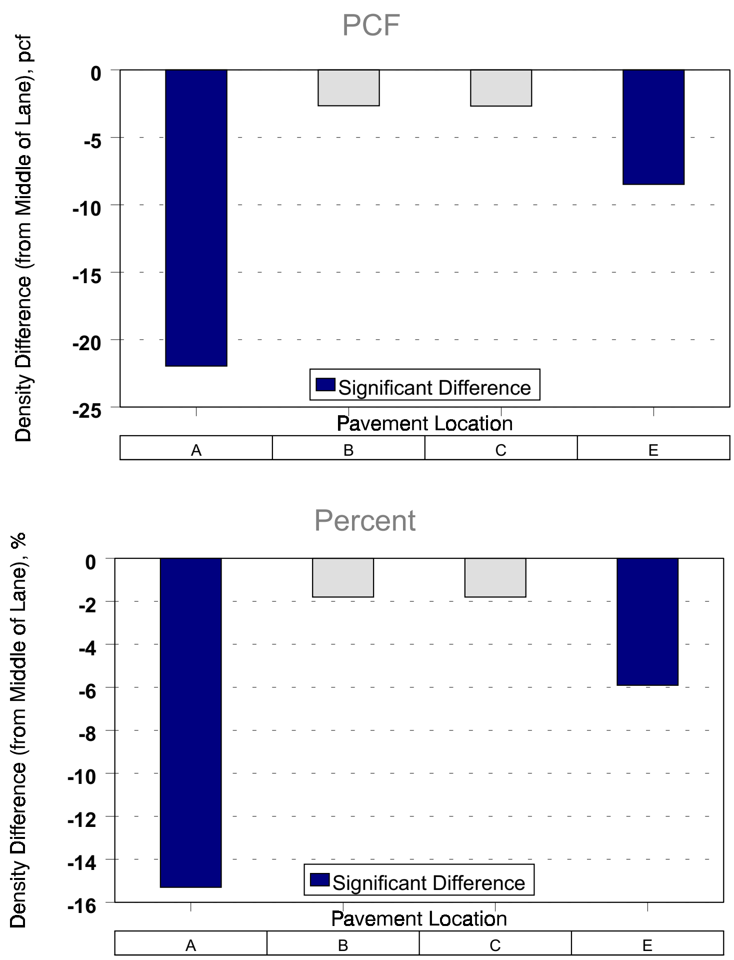


Figure 35. Difference in Density from Middle of Lane for SH 71, Austin, Type C - Limestone Mix.

Table 28. Density Data for US 59, Lufkin, Type C - Limestone Mix.

Station	*A* 0.5 ft from Unconfined Edge	*B* 1ft from Unconfined Edge	*C* 2 ft from Unconfined Edge	***D* Middle of Lane**	*E* 0.5 ft from Joint (Confined Edge)
1	122.3	124.0	129.7	**127.8**	128.8
2	125.3	126.2	128.0	**128.7**	127.9
3	120.6	121.5	125.5	**130.4**	123.0
4	125.9	124.4	127.8	**130.7**	130.7
5	120.7	120.4	126.8	**128.1**	125.1
Mean	122.96	123.3	127.56	**129.14**	127.1
Std. Dev.	2.51	2.33	1.55	**1.33**	3.05

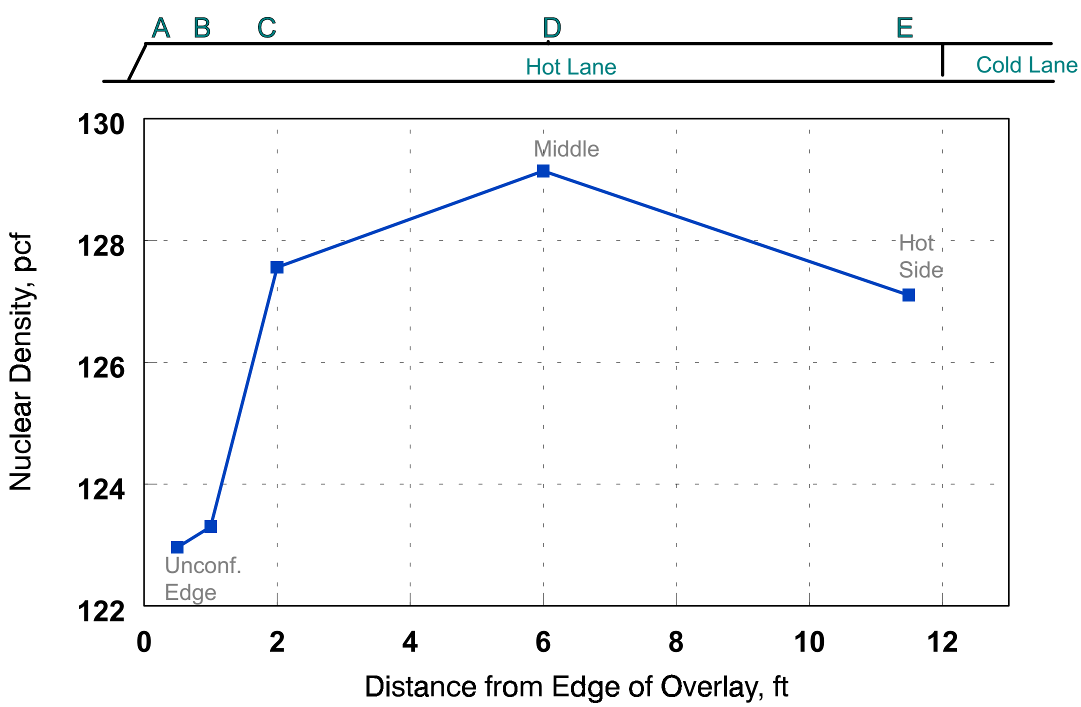


Figure 36. Mean Density Profile for US 59, Lufkin, Type C - Limestone Mix.

Table 29. Statistical Comparison of Mean Densities for US 59, Lufkin, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-6.140	0.0003	**Yes**
B, D	-5.840	0.0006	**Yes**
C, D	-1.580	0.2799	-
E, D	-2.220	0.1344	-

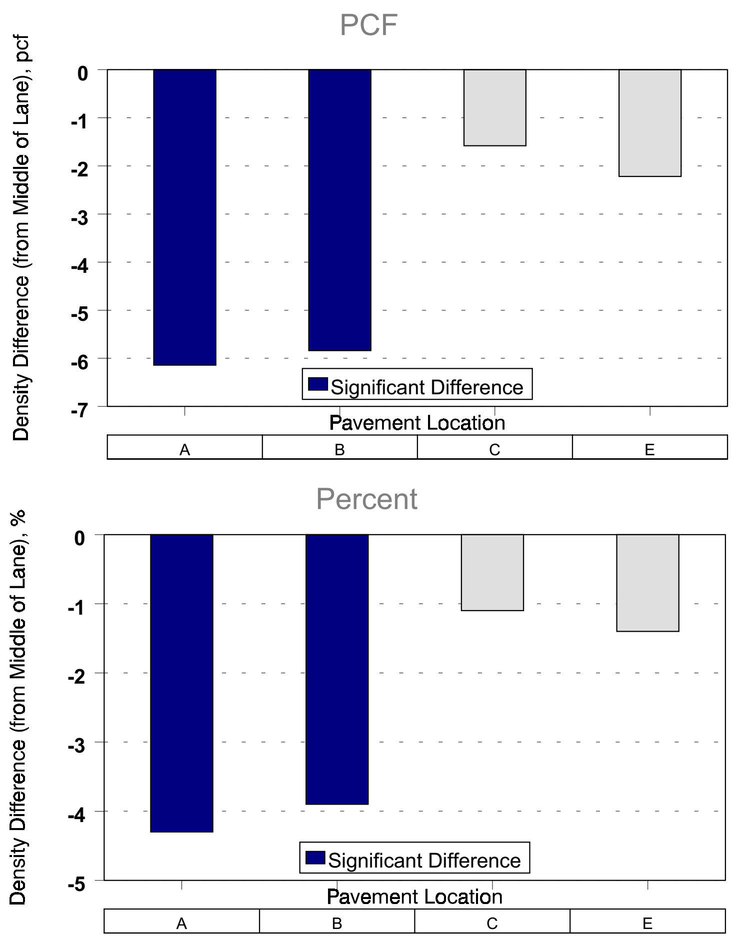


Figure 37. Difference in Density from Middle of Lane for US 59, Lufkin, Type C - Limestone Mix.

Type C, Gravel Pavements

Table 30. Density Data for US 77, Woodsboro - Corpus Christi, Type C - Gravel Mix.

Station	***A*** 0.5 ft from Unconfined Edge	***B*** 1ft from Unconfined Edge	***C*** 2 ft from Unconfined Edge	***D*** **Middle of Lane**	***E*** 0.5 ft from Unconfined Edge
1	131.0	131.7	135.8	**135.4**	131.2
2	133.0	136.1	139.9	**137.9**	128.3
3	128.7	132.6	138.6	**135.2**	130.7
4	130.7	136.0	140.7	**135.7**	133.8
5	127.2	132.3	136.5	**136.5**	130.2
Mean	130.12	133.74	138.30	**136.14**	130.84
Std. Dev.	2.23	2.13	2.12	**1.10**	1.99

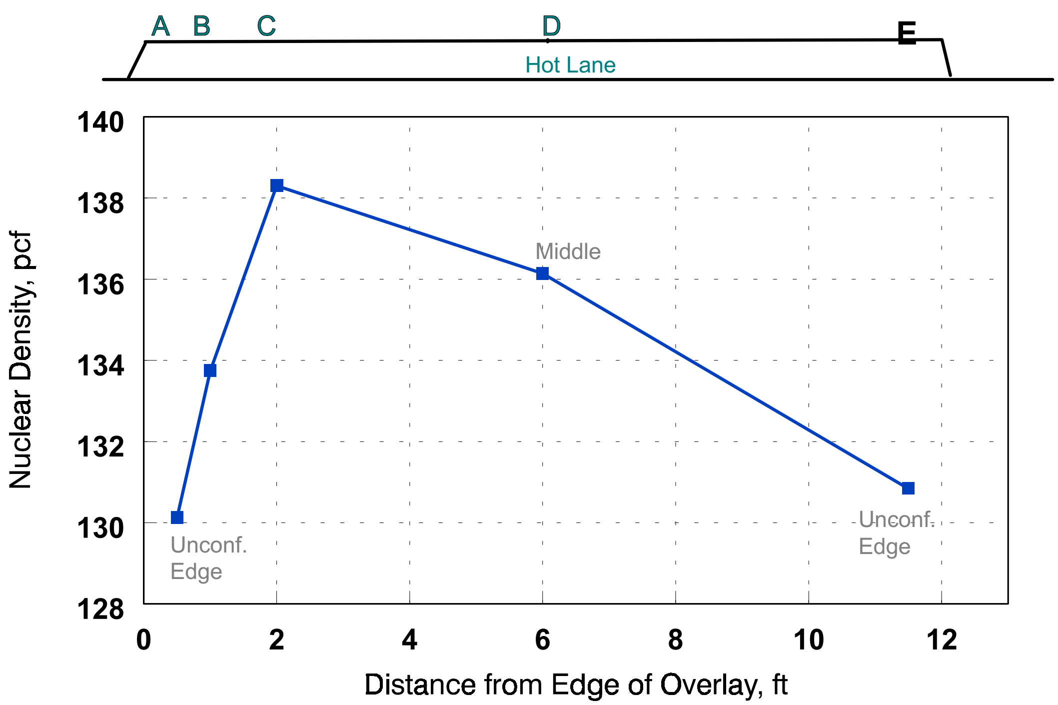


Figure 38. Mean Density Profile for US 77, Woodsboro - Corpus Christi, Type C - Gravel Mix.

Table 31. Statistical Comparison of Mean Densities for US 277, Woodsboro - Corpus Christi using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-6.000	<0.0001	**Yes**
B, D	-2.400	0.0659	-
C, D	2.160	0.0953	-
E, D	-5.300	0.0004	**Yes**

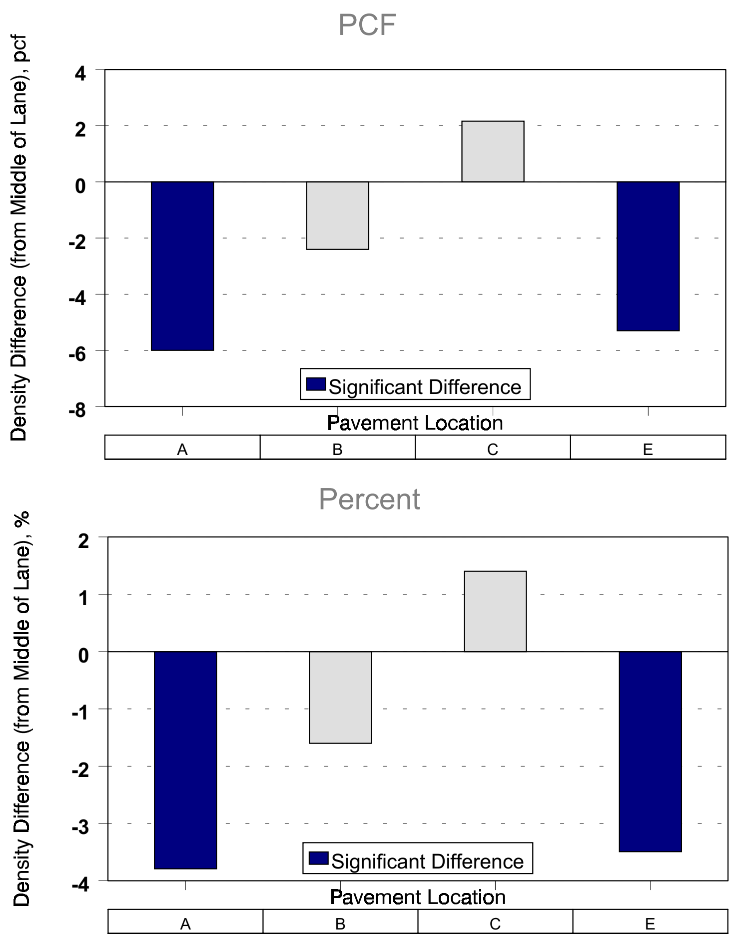


Figure 39. Difference in Density from Middle of Lane for US 77, Woodsboro - Corpus Christi, Type C - Gravel Mix.

Table 32. Density Data for SH 71, Yoakum, Type C - Gravel Mix.

Station	***A*** 0.5 ft. from Unconfined Edge	***B*** 1ft. from Unconfined Edge	***C*** 2 ft from Unconfined Edge	***D*** **Middle of Lane**
1	128.8	132.8	134.6	**129.6**
2	132.7	138.1	136.9	**136.0**
3	128.3	134.4	130.5	**131.8**
4	129.0	133.2	136.2	**137.6**
5	131.1	132.6	131.9	**132.6**
6	131.9	134.6	135.0	**130.4**
7	131.3	135.4	133.3	**133.1**
Mean	130.44	134.44	134.06	**133.01**
Std. Dev.	1.72	1.91	2.30	**2.89**

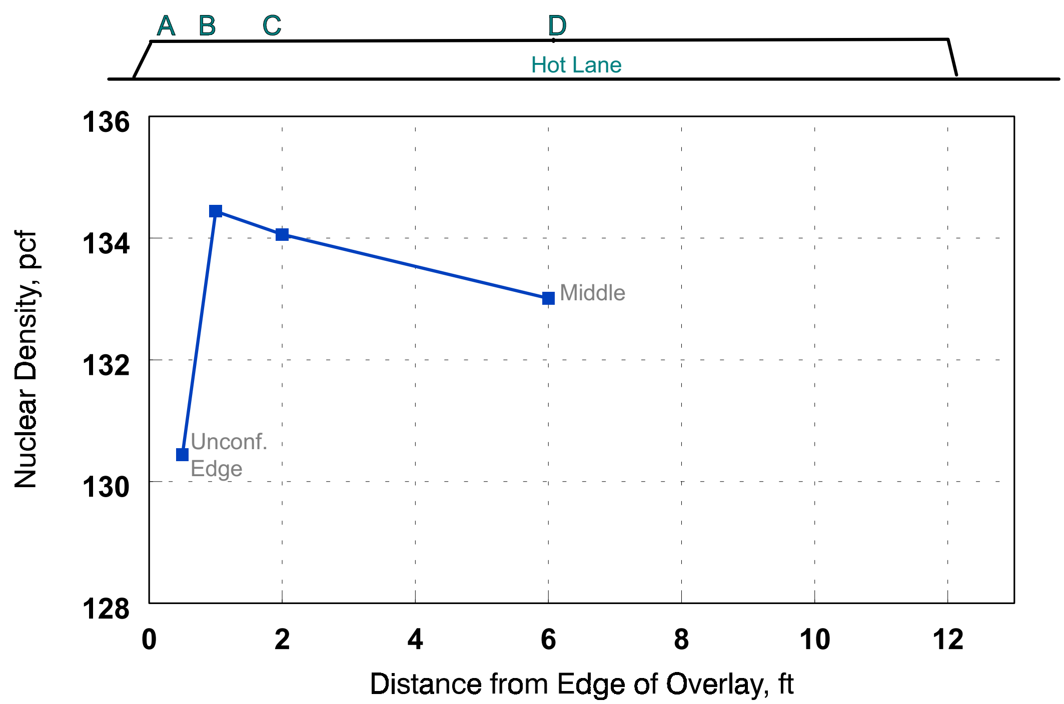


Figure 40. Mean Density Profile for SH 71, Yoakum, Type C - Gravel Mix.

Table 33. Statistical Comparison of Mean Densities for SH 71, Yoakum - Corpus Christi, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-2.571	0.0429	**Yes**
B, D	1.429	0.2466	-
C, D	1.043	0.3945	-

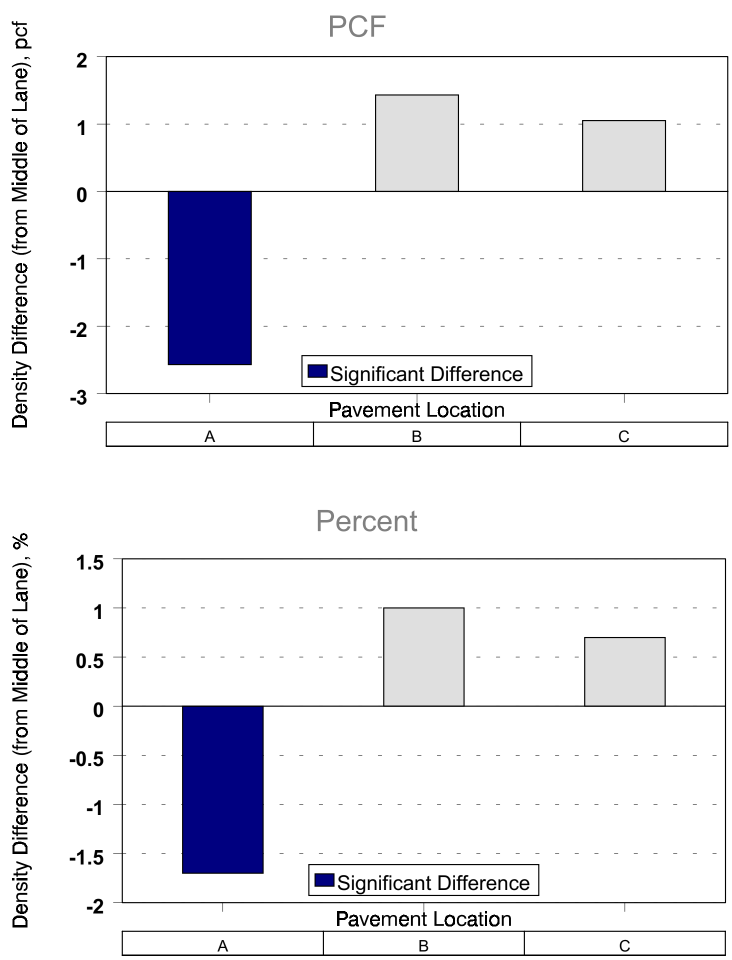


Figure 41. Difference in Density from Middle of Lane for SH 71, Yoakum, Type C - Gravel Mix.

Table 34. Density Data for FM 3129, Atlanta, Type C - Gravel Mix.

Station	*A* 0.5 ft from Unconfined Edge	*B* 1ft from Unconfined Edge	*C* 2 ft from Unconfined Edge	***D* Middle of Lane**	*E* 0.5 ft from Unconfined Edge
1	122.5	129.7	130.2	**133.8**	124.7
2	121.2	127.7	131.8	**133.8**	122.7
3	121.2	131.0	134.0	**134.5**	125.0
4	124.8	131.9	135.5	**136.9**	123.5
5	124.6	135.5	135.8	**139.2**	125.3
Mean	122.86	131.16	133.46	**135.44**	124.24
Std. Dev.	1.76	2.89	2.41	**2.00**	1.10

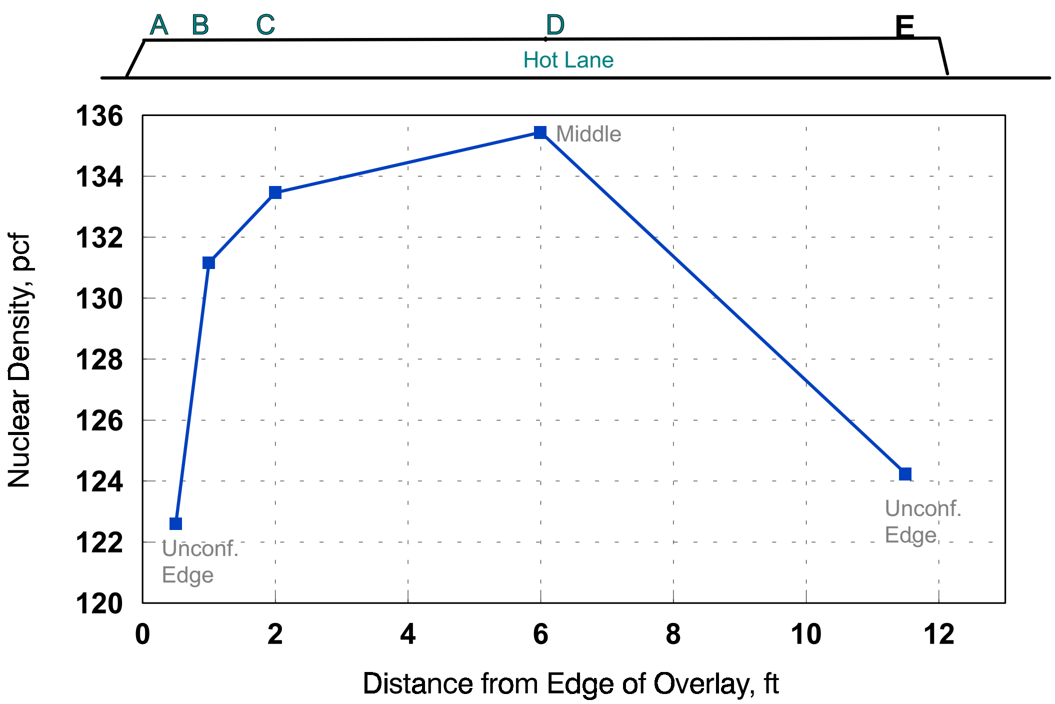


Figure 42. Mean Density Profile for FM 3129, Atlanta, Type C - Gravel Mix.

Table 35. Statistical Comparison of Mean Densities for FM 3129, Atlanta, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	Significance
A, D	-12.58	**Yes**
B, D	-4.28	**Yes**
C, D	-1.98	-
E, D	-11.1	**Yes**

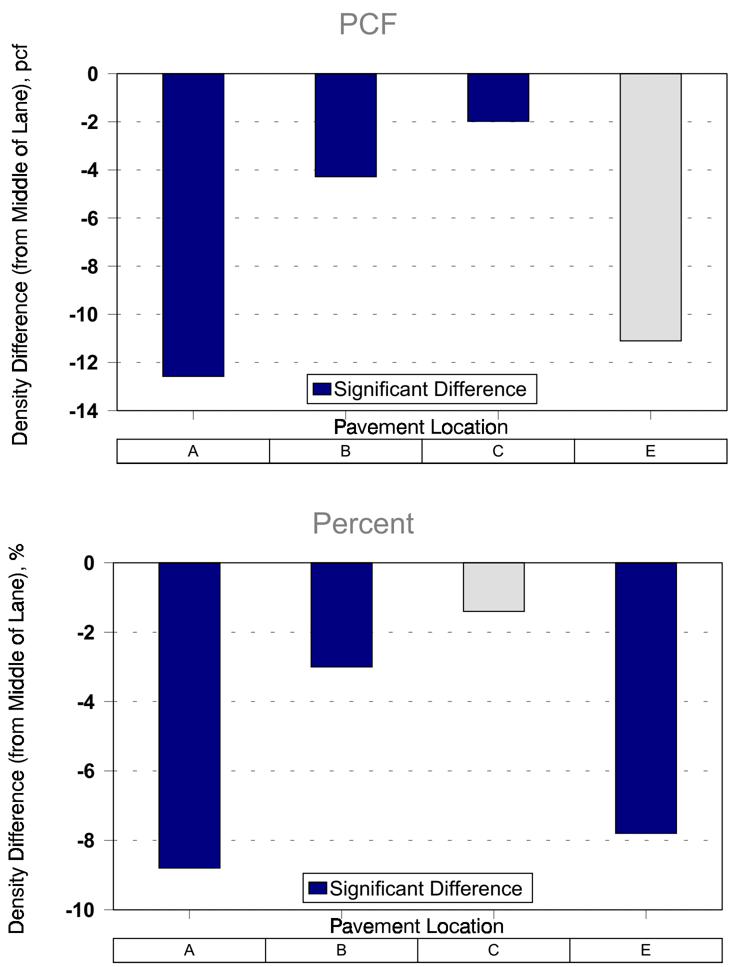


Figure 43. Difference in Density from Middle of Lane for FM 3129, Atlanta, Type C - Gravel Mix.

Table 36. Density Data for US 80, Atlanta, Type C - Gravel Mix.

Station	***A*** 0.5 ft from Unconfined Edge	***B*** 1ft from Unconfined Edge	***C*** 2 ft from Unconfined Edge	***D*** **Middle of Lane**	***E*** 0.5 ft from Unconfined Edge
1	125.6	127.8	129.4	**130.9**	124.8
2	128.8	133.2	132.3	**131.2**	128.0
3	126.8	130.0	132.0	**128.9**	127.2
4	118.8	126.5	128.8	**136.5**	126.5
5	123.5	125.1	130.3	**131.6**	130.8
Mean	124.7	128.52	130.56	**131.82**	127.46
Std. Dev.	3.82	3.18	1.55	**2.82**	2.21

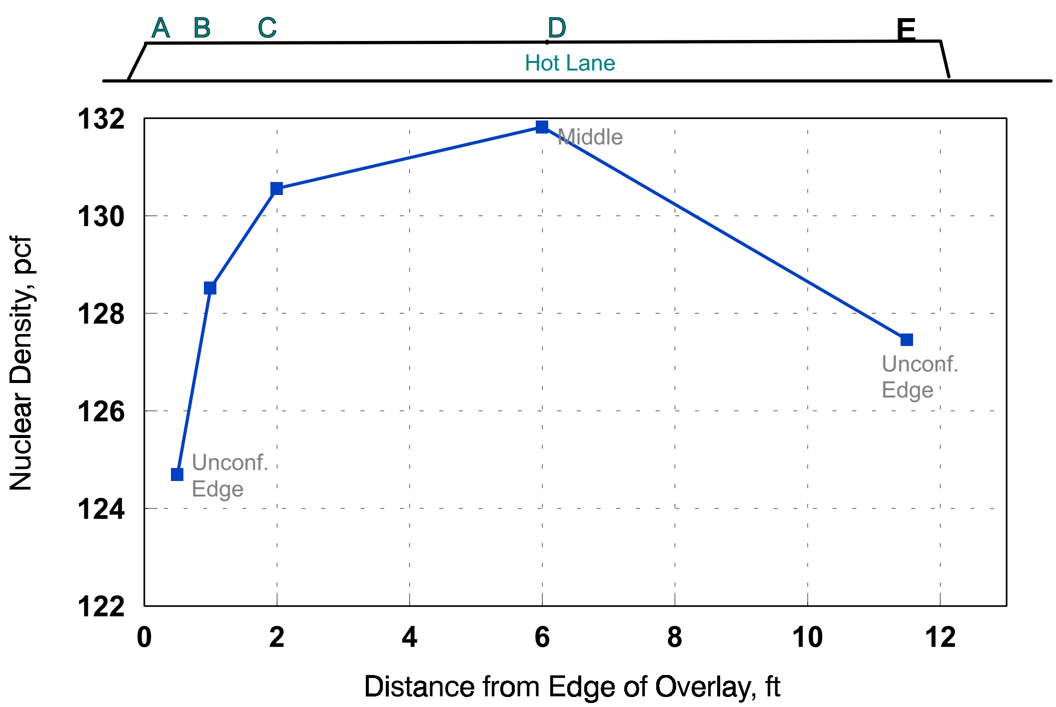


Figure 44. Mean Density Profile for US 80, Atlanta, Type C - Gravel Mix.

Table 37. Statistical Comparison of Mean Densities for US 80, Atlanta, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	Significance
A, D	-7.12	**Yes**
B, D	-3.30	-
C, D	-1.26	-
E, D	-4.36	**Yes**

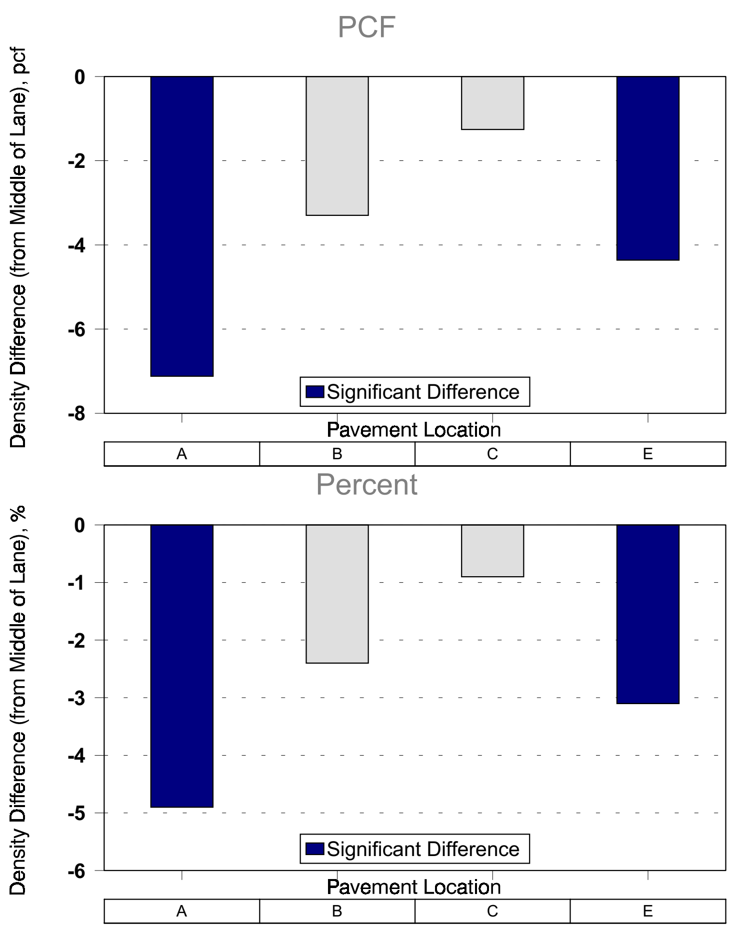


Figure 45. Difference in Density from Middle of Lane for US 80, Atlanta, Type C - Gravel Mix.

Table 38. Density Data for US 57, Laredo, Type C - Gravel Mix.

Station	*A* 0.5 ft from Unconfined Edge	*B* 1ft from Unconfined Edge	*C* 2 ft from Unconfined Edge	***D* Middle of Lane**	*E* 0.5 ft from Unconfined Edge
1	125.9	137.5	132.9	**131.7**	131.3
2	128.4	134.9	134.3	**132.4**	123.9
3	124.8	129.7	130.4	**135.6**	119.3
4	127.4	132.8	132.0	**135.5**	127.7
5	135.5	139.2	137.3	**136.5**	123.0
Mean	128.4	134.82	133.38	**134.34**	125.04
Std. Dev.	4.20	3.76	2.61	**2.14**	4.6

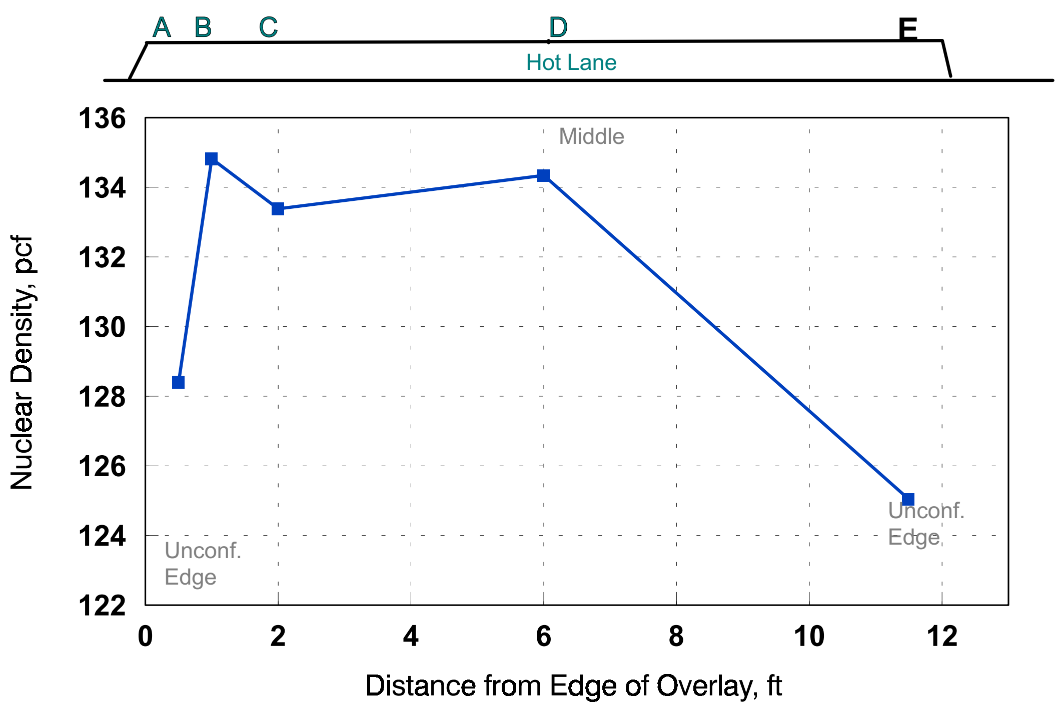


Figure 46. Mean Density Profile for US 57, Laredo, Type C - Gravel Mix.

Table 39. Statistical Comparison of Mean Densities for US 57, Laredo, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-5.940	0.0165	**Yes**
B, D	0.480	0.8346	-
C, D	-0.96	0.6768	-
E, D	-9.30	0.0006	**Yes**

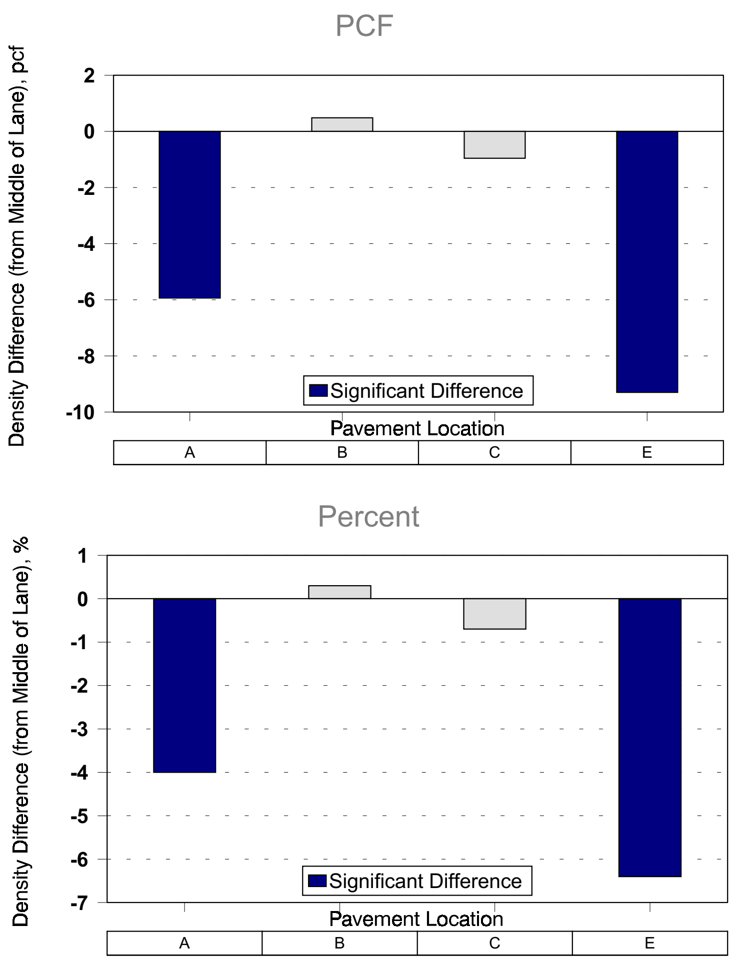


Figure 47. Difference in Density from Middle of Lane for US 57, Laredo, Type C - Gravel Mix.

Table 40. Density Data for FM 1021, Laredo, Type C - Gravel Mix.

Station	*A* 0.5 ft from Curbed (Confined) Edge	*B* 1ft from Curbed Edge	*C* 2 ft from Curbed Edge	***D* Middle of Lane**	*E* 0.5 ft from Joint on Hot Side	*F* On Top of Joint	*G* 0.5 ft from Joint on Cold Side
1	125.4	127.0	132.3	**137.7**	134.7	128.9	135.3
2	128.5	132.5	135.6	**133.9**	135.7	130.2	136.7
3	128.9	132.5	135.7	**132.3**	133.6	112.2	126.6
4	130.7	135.3	137.1	**136.7**	134.8	125.9	124.3
5	130.8	*	*	*	*	*	*
Mean	128.86	131.83	135.18	**135.15**	132.2	124.3	130.73
Std. Dev.	2.19	3.48	2.04	**2.49**	5.07	8.27	6.19

*Opened to traffic prior to completion of data collection.

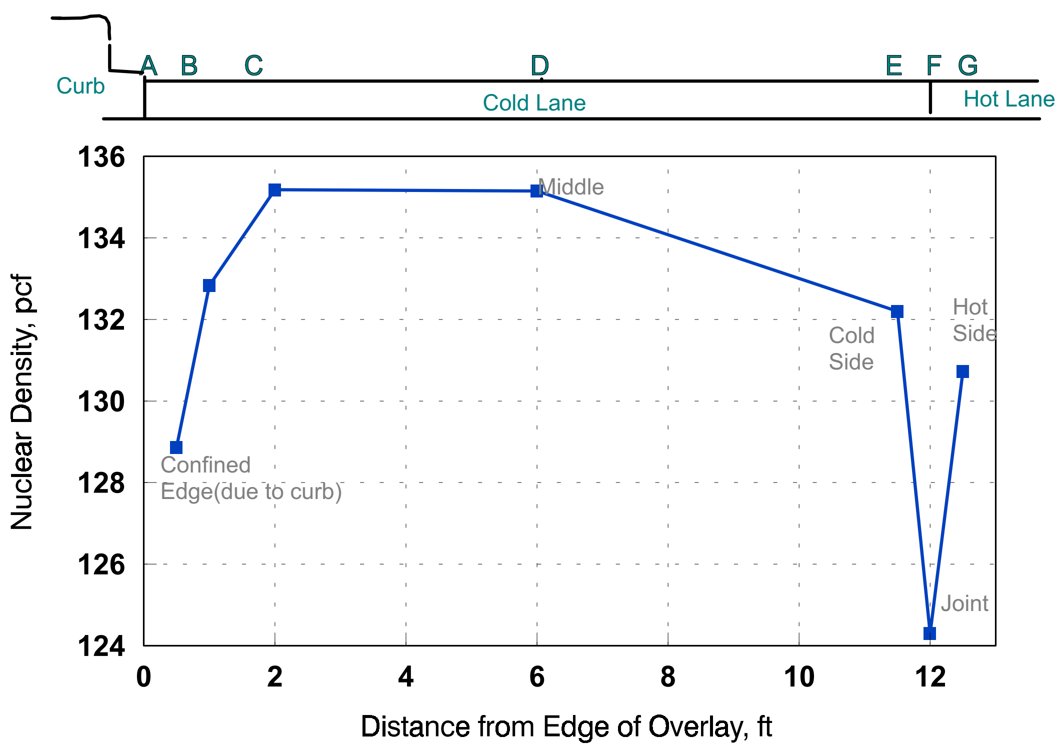


Figure 48. Mean Density Profile for FM 1021, Laredo, Type C - Gravel Mix.

Table 41. Statistical Comparison of Mean Densities for FM 1021, Laredo, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-6.29	0.058	-
B, D	-3.329	0.3268	-
C, D	0.025	0.9941	-
E, D	-2.950	0.3832	-
F, D	-10.850	0.0035	**Yes**
G, D	-4.425	0.1956	-

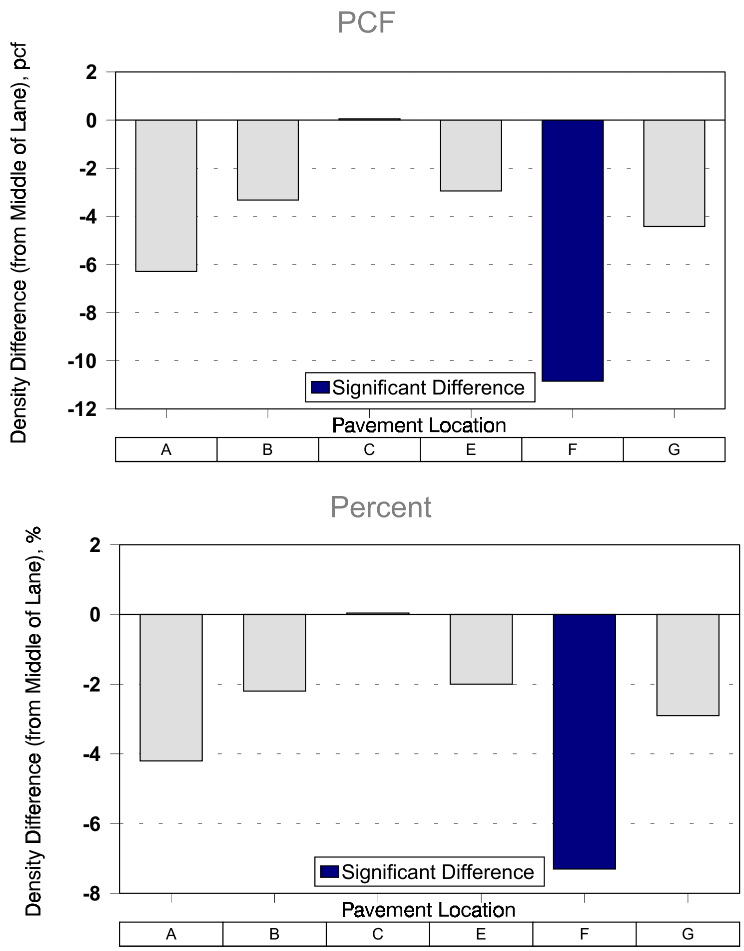


Figure 49. Difference in Density from Middle of Lane for FM 1021, Laredo, Type C - Gravel Mix.

Table 42. Density Data for US 77S, Refugio - Corpus Christi, Type C - Gravel Mix.

Station	***A*** 0.5 ft. from Unconfined Edge	***B*** 1ft. from Unconfined Edge	***C*** 2 ft from Unconfined Edge	***D*** **Middle of Lane**
1	125.8	128.5	135.0	**132.0**
2	127.6	130.7	137.1	**127.0**
3	121.9	129.7	132.4	**134.1**
4	122.7	131.4	134.9	**136.7**
5	112.9	122.9	120.9	**125.9**
Mean	122.18	128.64	132.06	**131.66**
Std. Dev.	5.68	3.39	6.46	**5.14**

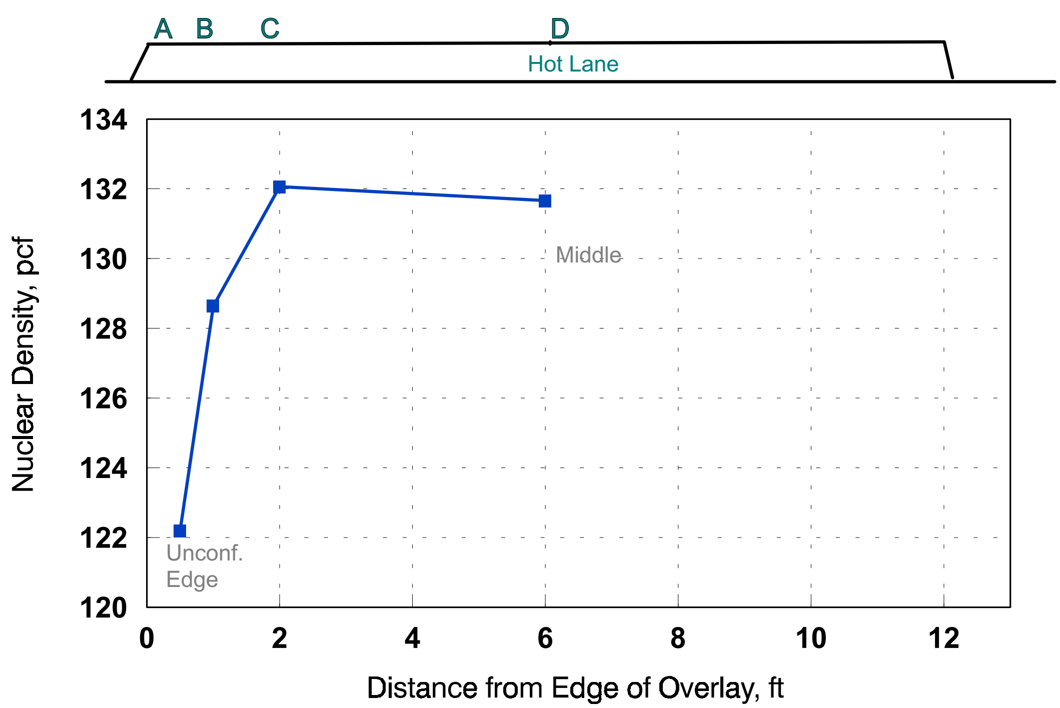


Figure 50. Mean Density Profile for US 77S, Refugio - Corpus Christi, Type C - Gravel Mix.

Table 43. Statistical Comparison of Mean Densities for US 77S, Refugio - Corpus Christi, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-9.48	0.0120	**Yes**
B, D	-3.02	0.3800	-
C, D	0.40	0.9063	-

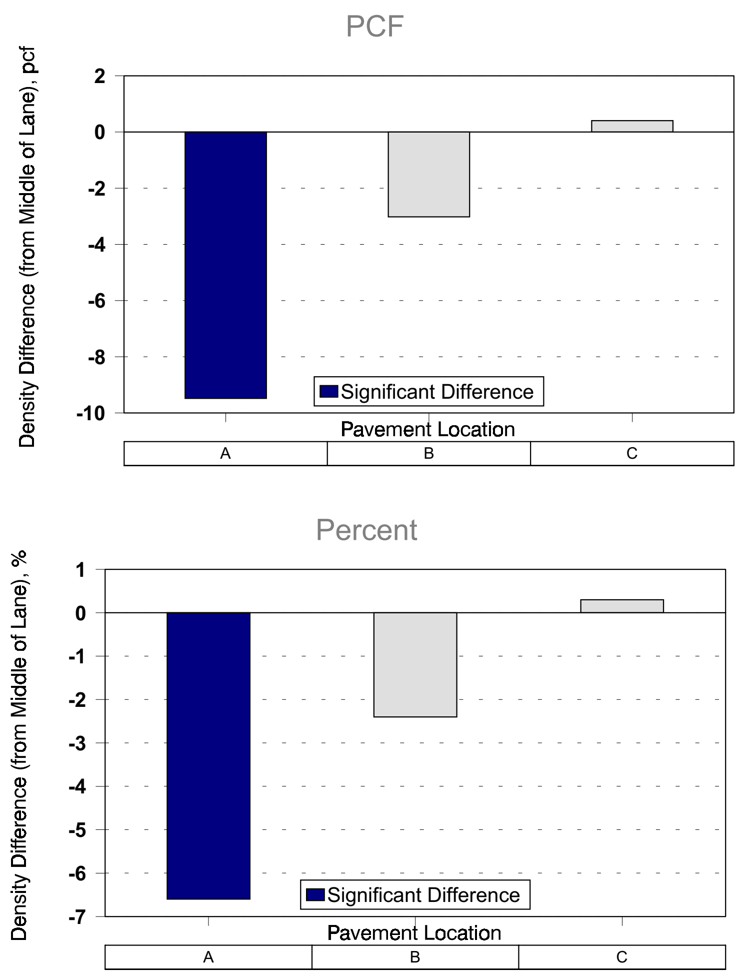


Figure 51. Difference in Density from Middle of Lane for US 77S, Refugio - Corpus Christi, Type C - Gravel Mix.

Type D Pavements

Table 44. Density Data for FM 1176, Brownwood, Type D Mix.

Station	***A*** 0.5 ft from Unconf. Edge	***B*** 1ft from Unconf. Edge	***C*** 2 ft from Unconf. Edge	***D*** **Middle of Lane**	***E*** 0.5 ft from Joint on Hot Side	***F*** On Top of Joint	***G*** 0.5ft from Joint on Cold Side
1	138.3	135.9	140.3	**139.1**	136.7	135.8	130.9
2	139.6	138.9	143.8	**136.9**	137.7	135.5	131.3
3	135.5	137.2	143.8	**137.8**	139.5	136.1	123.7
4	132.1	137.5	146.2	**132.7**	138.8	134.0	122.1
5	131.4	130.1	137.5	**132.1**	137.8	131.7	119.1
Mean	135.38	135.92	142.32	**135.72**	138.1	134.62	125.42
Std. Dev.	3.64	3.42	3.42	**3.14**	1.08	1.82	5.44

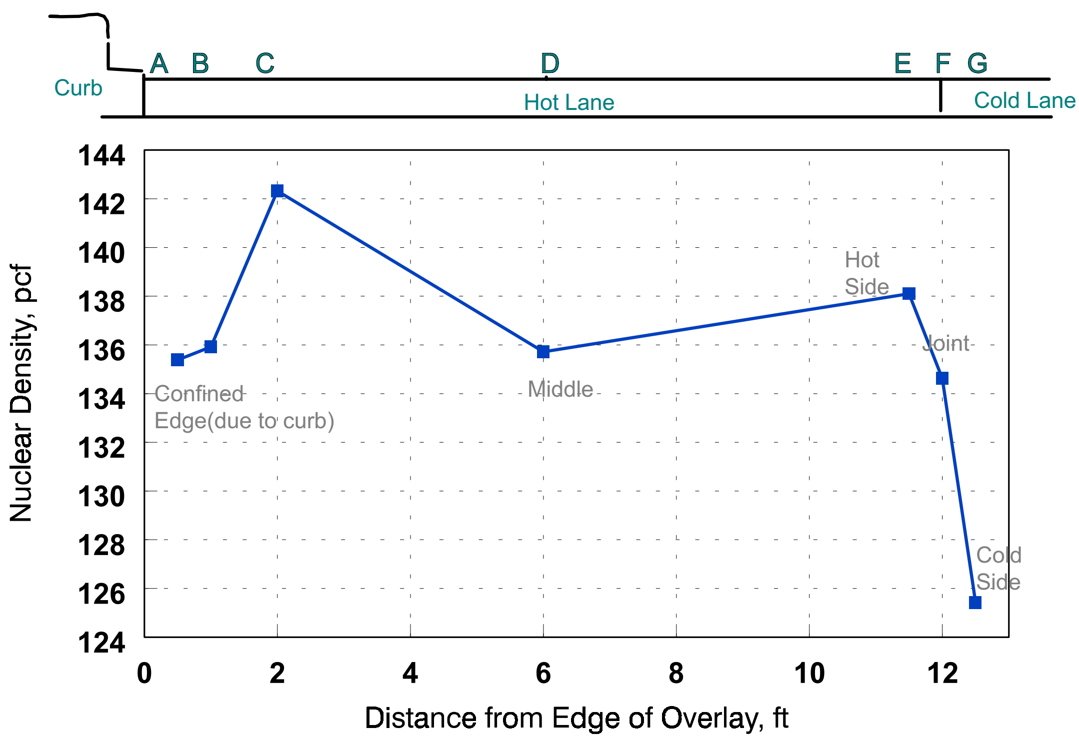
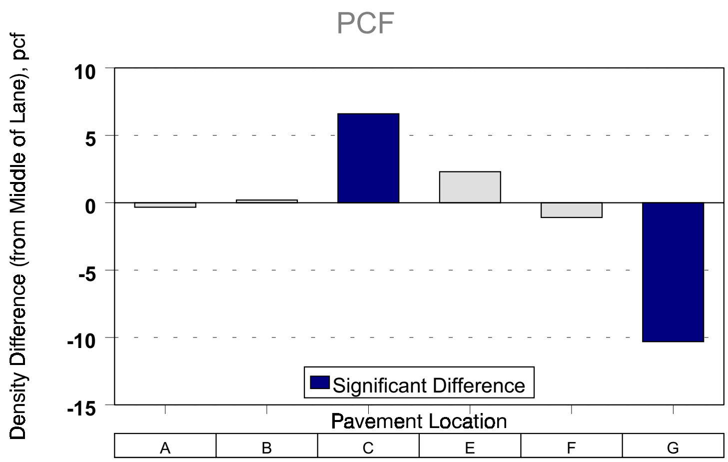


Figure 52. Mean Density Profile for FM 1176, Brownwood, Type D Mix.

Table 45. Statistical Comparison of Mean Densities for FM 1176, Brownwood, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	Significance
A, D	-0.34	-
B, D	0.20	-
C, D	6.60	**Yes**
E, D	2.38	-
F, D	-1.10	-
G, D	-10.30	**Yes**



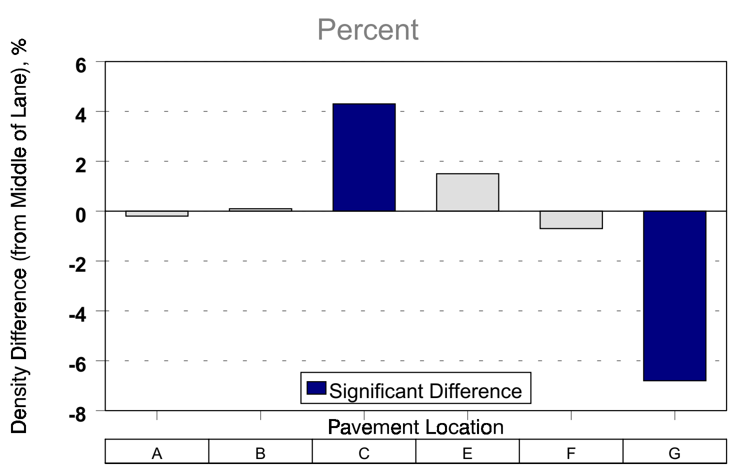


Figure 53. Difference in Density from Middle of Lane for FM 1176, Brownwood, Type D Mix.

Table 46. Density Data for FM 1266, Houston, Type D Mix.

Station	*A* 0.5 ft from Unconfined Edge	*B* 1ft from Unconfined Edge	*C* 2 ft from Unconfined Edge	***D* Middle of Lane**
1	129.5	134.3	139.1	**141.8**
2	132.8	136.8	139.0	**138.5**
3	134.7	137.4	140.1	**141.7**
4	134.8	135.7	137.9	**139.2**
5	136.4	138.4	138.4	**141.2**
Mean	133.64	136.52	138.90	**140.48**
Std. Dev.	2.64	1.58	0.83	**1.52**

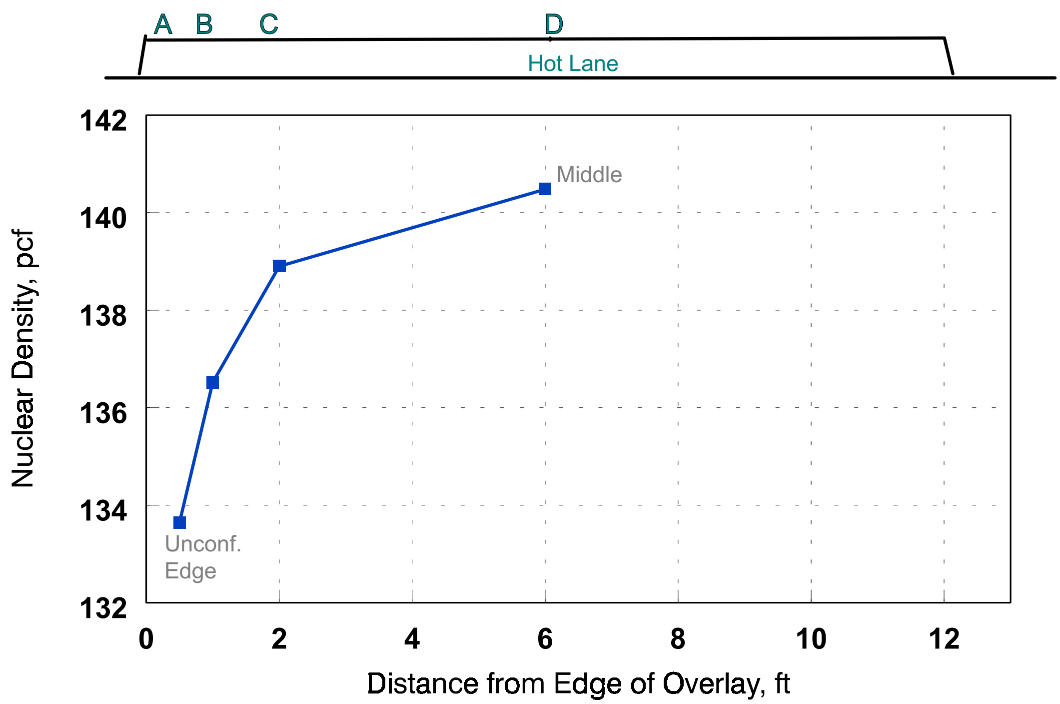


Figure 54. Mean Density Profile for FM 1266, Houston, Type D Mix.

Table 47. Statistical Comparison of Mean Densities for FM 1266, Houston, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	Significance
A, D	-6.84	**Yes**
B, D	-3.96	**Yes**
C, D	-1.58	-

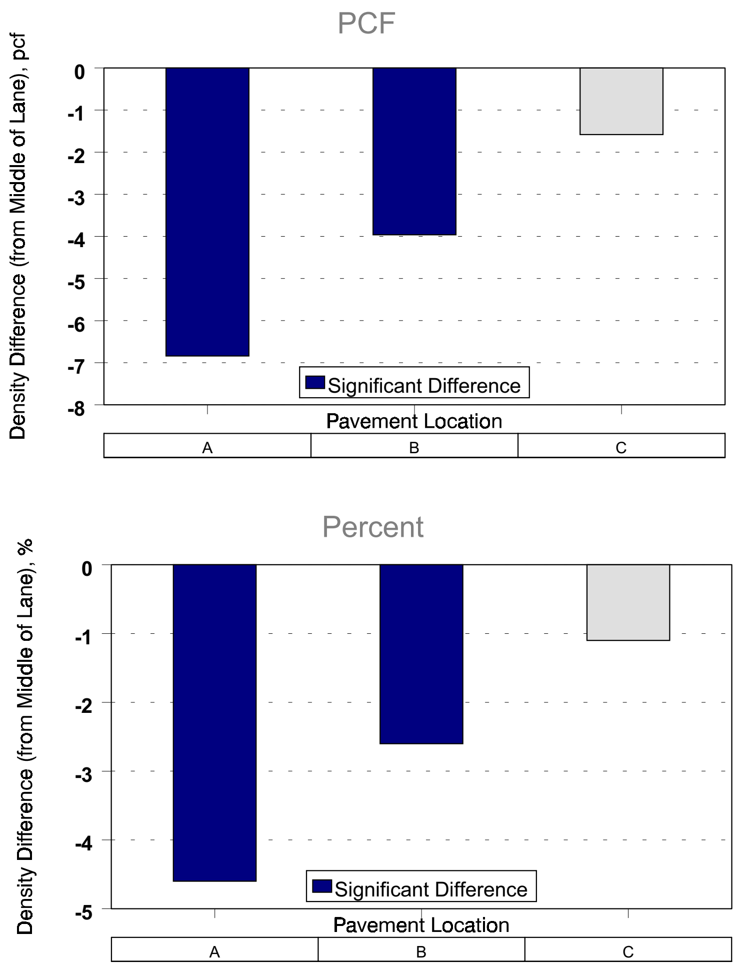


Figure 55. Difference in Density from Middle of Lane for FM 1266, Houston, Type D Mix.

Table 48. Density Data for IH 20, Ft.Worth, Type D Mix.

Station	***A*** 0.5 ft from Unconfined Edge	***B*** 1ft from Unconfined Edge	***C*** 2 ft from Unconfined Edge	***D*** **Middle of Lane**
1	136.1	136.5	135.1	**133.5**
2	120.6	127.0	130.5	**134.6**
3	129.2	133.8	135.2	**136.7**
4	134.8	138.4	141.3	**141.6**
5	128.4	135.9	139.7	**143.0**
Mean	129.82	134.32	136.36	**137.94**
Std. Dev.	6.15	4.41	4.27	**4.15**

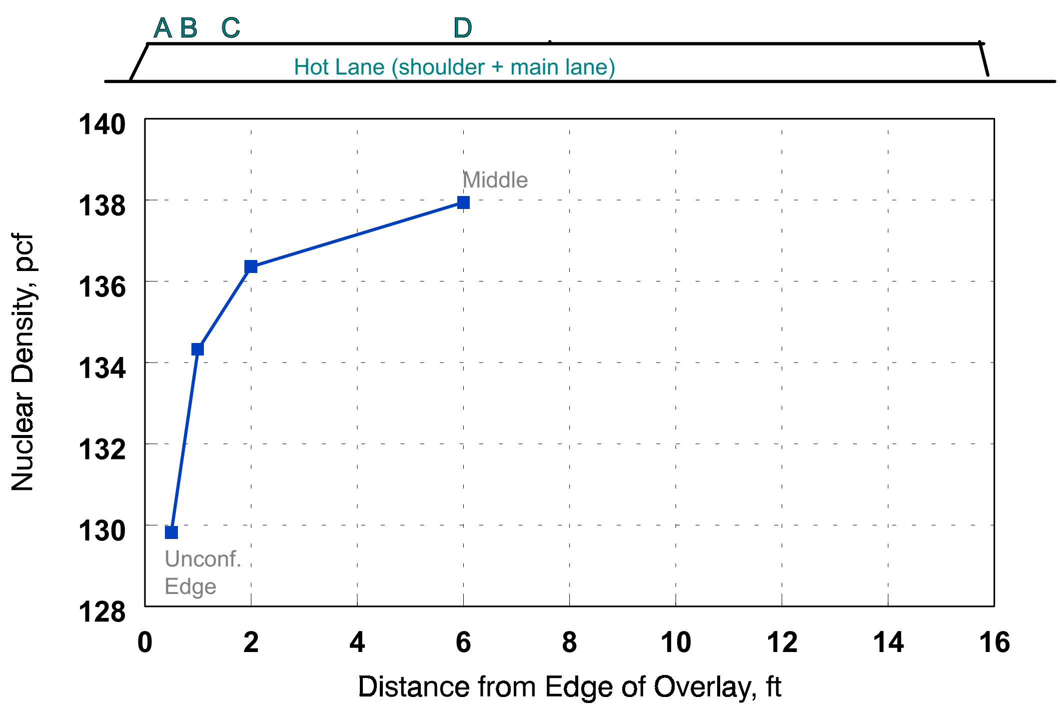
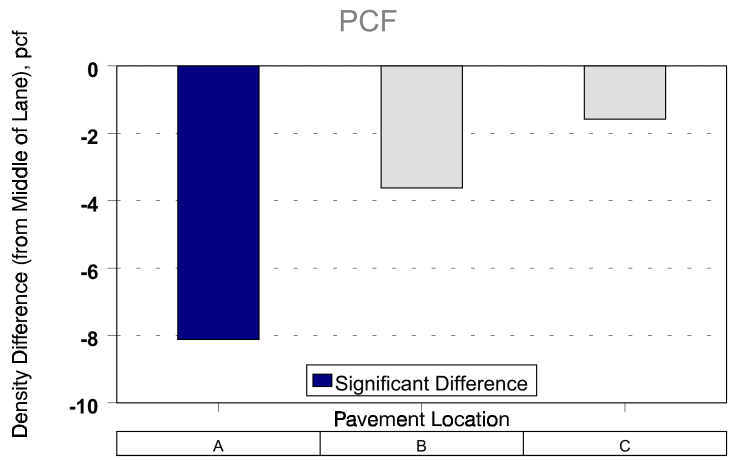


Figure 56. Mean Density Profile for IH 20, Ft. Worth, Type D Mix.

Table 49. Statistical Comparison of Mean Densities for I 20, Ft.Worth, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	Significance
A, D	-8.12	**Yes**
B, D	-3.62	-
C, D	-1.58	-



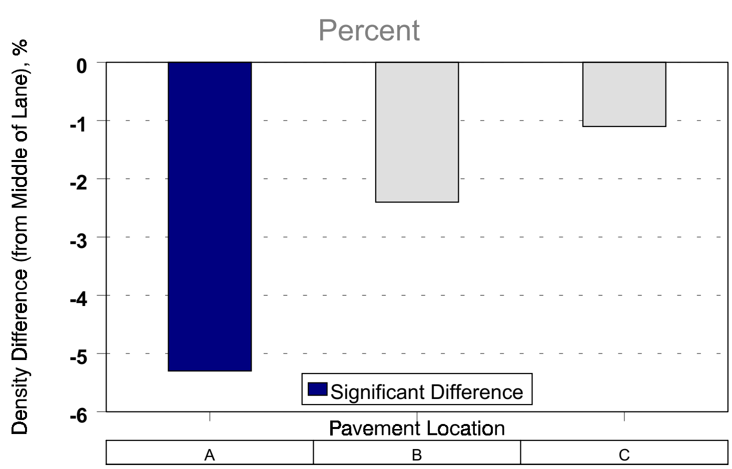


Figure 57. Difference in Density from Middle of Lane for IH 20, Ft. Worth, Type D Mix.

Table 50. Density Data for US 287, Childress, Type D Mix.

Station	*A* 0.5 ft from Unconf. Edge	*B* 1ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D* Middle of Lane**	*E* 0.5 ft from Unconf. Edge
1	134.3	138.9	134.9	**137.4**	133.2
2	137.3	140.6	139.5	**138.7**	137.4
3	136.1	140.4	139.5	**136.8**	137.5
4	134.9	138.9	141.6	**139.0**	136.4
5	137.7	141.2	141.4	**137.5**	133.9
Mean	136.06	140.00	139.38	**137.88**	135.68
Std. Dev.	1.47	1.05	2.70	**0.93**	2.01

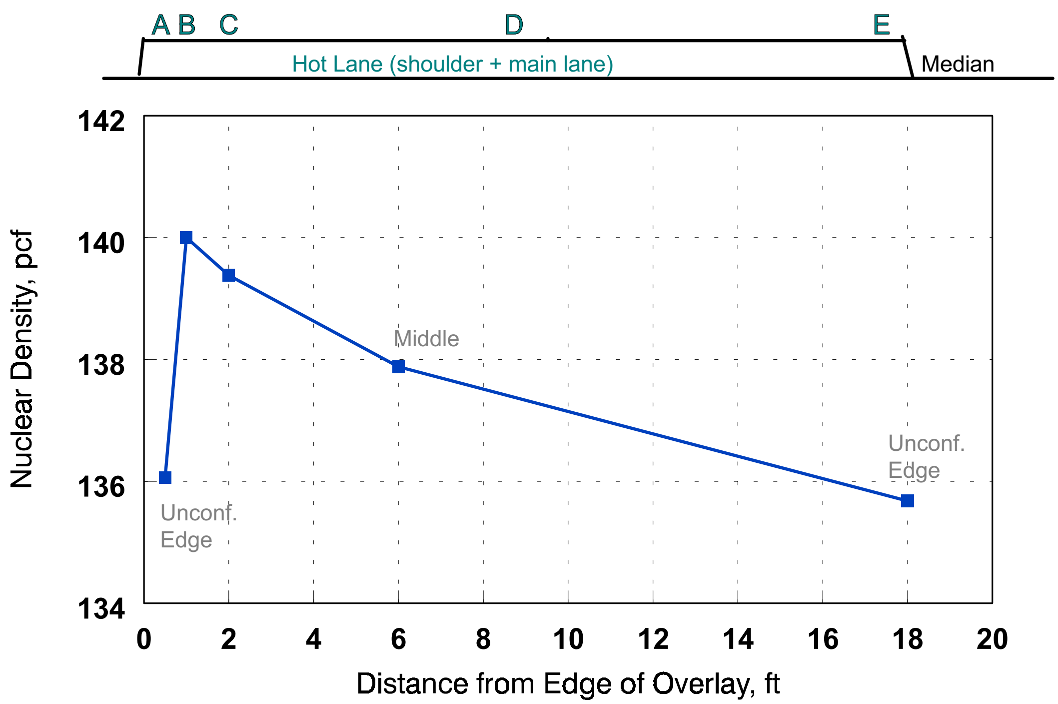


Figure 58. Mean Density Profile for US 287, Childress, Type D Mix.

Table 51. Statistical Comparison of Mean Densities for US 287, Memphis, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-1.82	0.1171	-
B, D	2.12	0.0709	-
C, D	1.50	0.1921	-
E, D	-2.20	0.0616	-

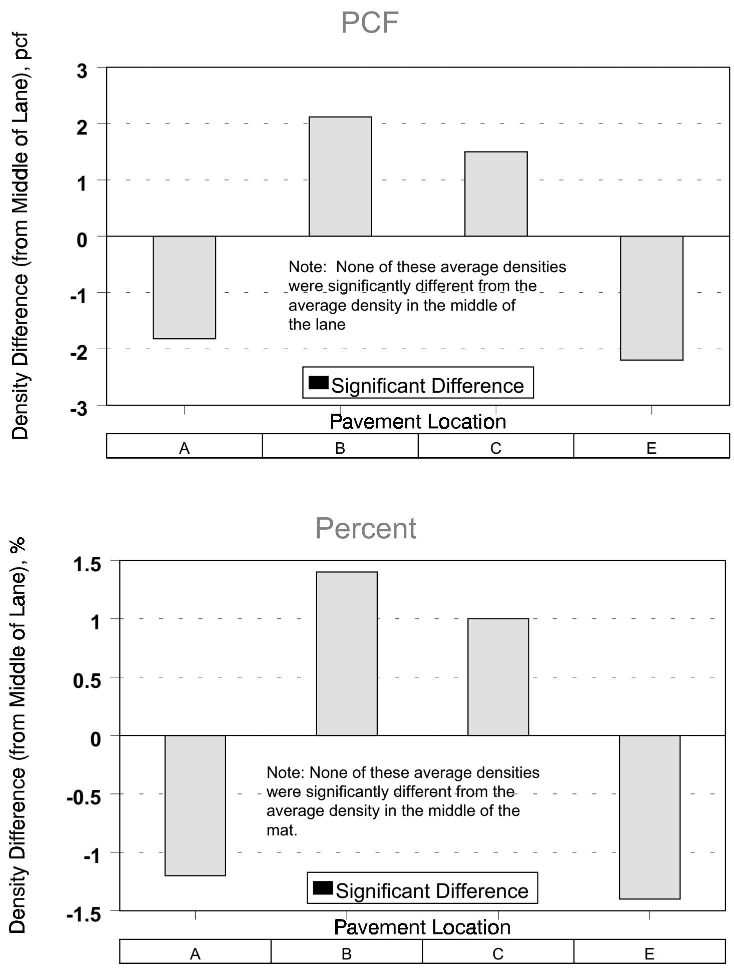


Figure 59. Difference in Density from Middle of Lane for US 287, Childress, Type D Mix.

Table 52. Density Data for SH 114, Wichita Falls, Type D Mix.

Station	*A* 0.5 ft from Unconf. Edge	*B* 1ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D* Middle of Lane**	*E* 0.5 ft from Joint on Hot Side	*F* On Top of Joint	*G* 0.5ft from Joint on Cold Side
1	134.2	136.9	141.1	**141.6**	141.5	121.5	135.2
2	140.5	139.9	141.0	**142.5**	141.5	120.1	130.2
3	133.0	138.4	142.4	**146.5**	137.7	129.2	135.1
4	128.1	135.4	140.1	**141.0**	139.6	120.9	133.2
5	135.4	139.9	142.4	**141.3**	140.1	123.8	138.6
Mean	136.24	138.1	141.4	**142.58**	140.08	123.1	134.46
Std. Dev.	4.47	1.96	0.99	**2.26**	1.58	3.68	3.08

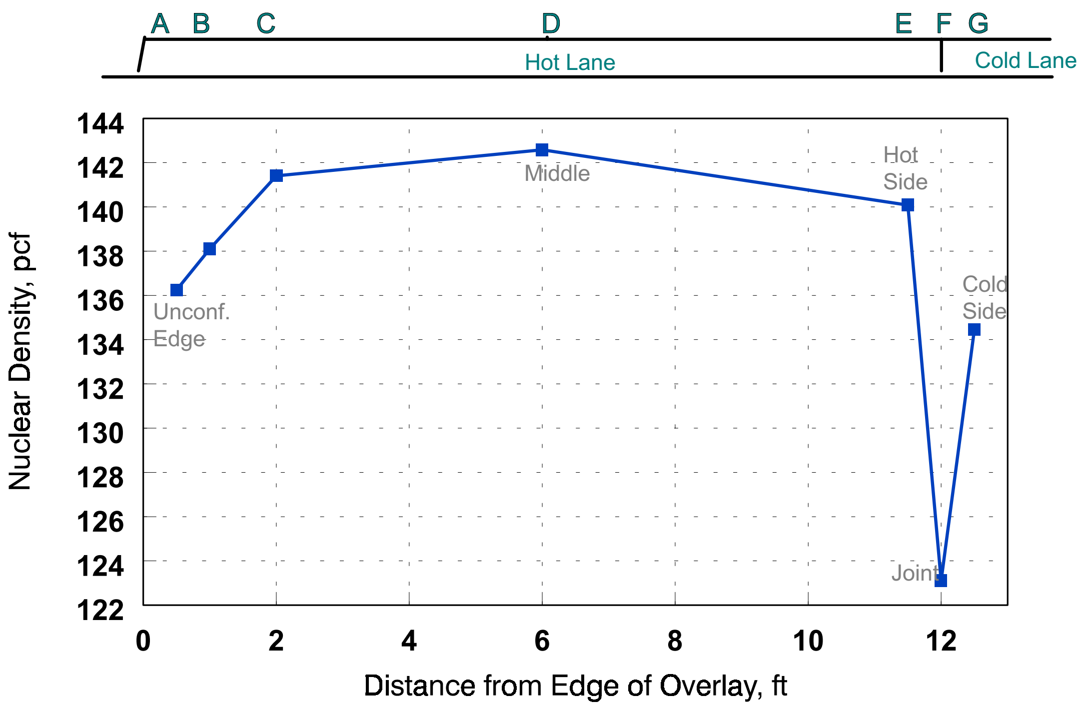


Figure 60. Mean Density Profile for SH 114, Wichita Falls, Type D Mix.

Table 53. Statistical Comparison of Mean Densities for SH 114, Wichita Falls, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-8.34	<0.0001	**Yes**
B, D	-4.48	0.0177	**Yes**
C, D	-1.18	0.5124	-
E, D	-2.50	0.1707	-
F, D	-19.48	<0.0001	**Yes**
G, D	-8.12	<0.0001	**Yes**

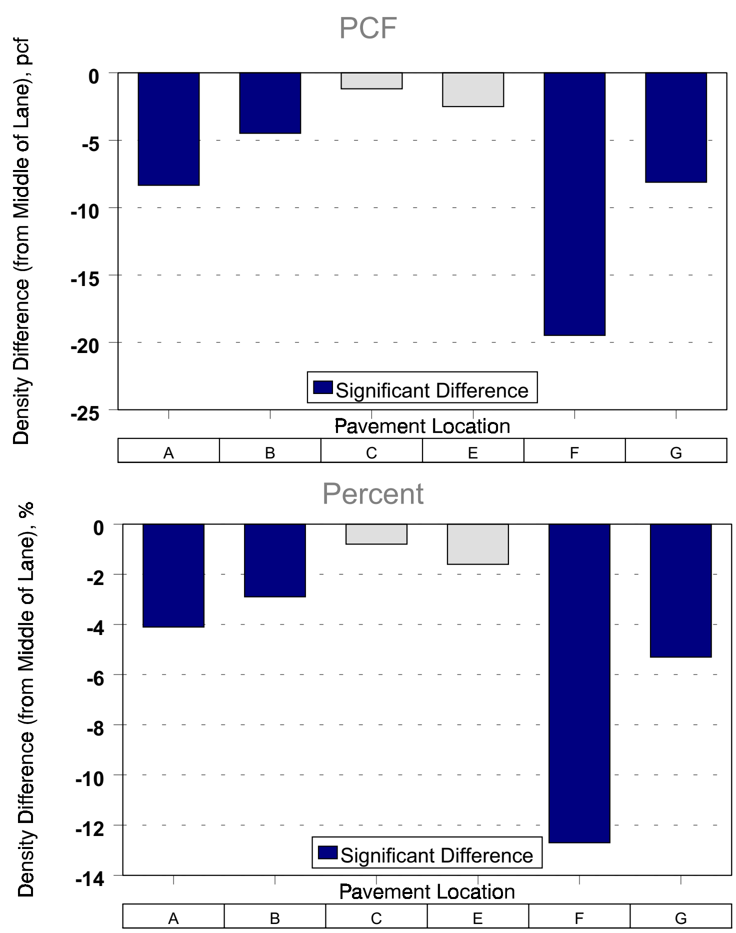


Figure 61. Difference in Density from Middle of Lane for SH 114, Wichita Falls, Type D Mix.

Table 54. Density Data for SH 70, Wichita Falls, Type D Mix.

Station	*A* 0.5 ft. from Unconf. Edge	*B* 1ft. from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D* Middle of Lane**	*E* 0.5 ft from Unconf. Edge
1	133.1	139.6	142.1	**139.3**	133.9
2	133.0	135.0	144.5	**142.4**	132.1
3	132.0	138.2	141.3	**139.1**	132.7
4	131.9	135.5	139.1	**138.8**	133.5
5	134.4	136.1	139.1	**140.6**	134.4
6	137.3	139.1	142.1	**-**	-
Mean	133.62	137.23	141.37	**140.04**	133.32
Std. Dev.	2.02	1.96	2.06	**1.49**	0.92

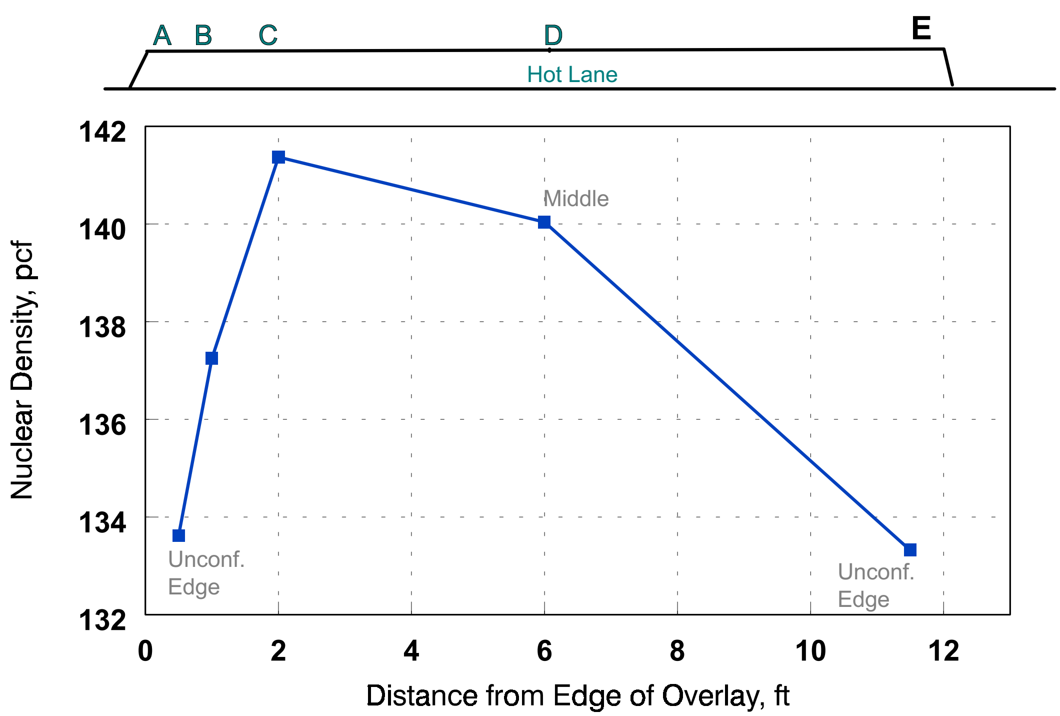


Figure 62. Mean Density Profile for SH 70, Wichita Falls, Type D Mix.

Table 55. Statistical Comparison of Mean Densities for SH 70, Wichita Falls, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-6.42	<0.0001	**Yes**
B, D	-3.16	0.0057	**Yes**
C, D	1.18	0.2612	-
E, D	-6.72	<0.0001	**Yes**

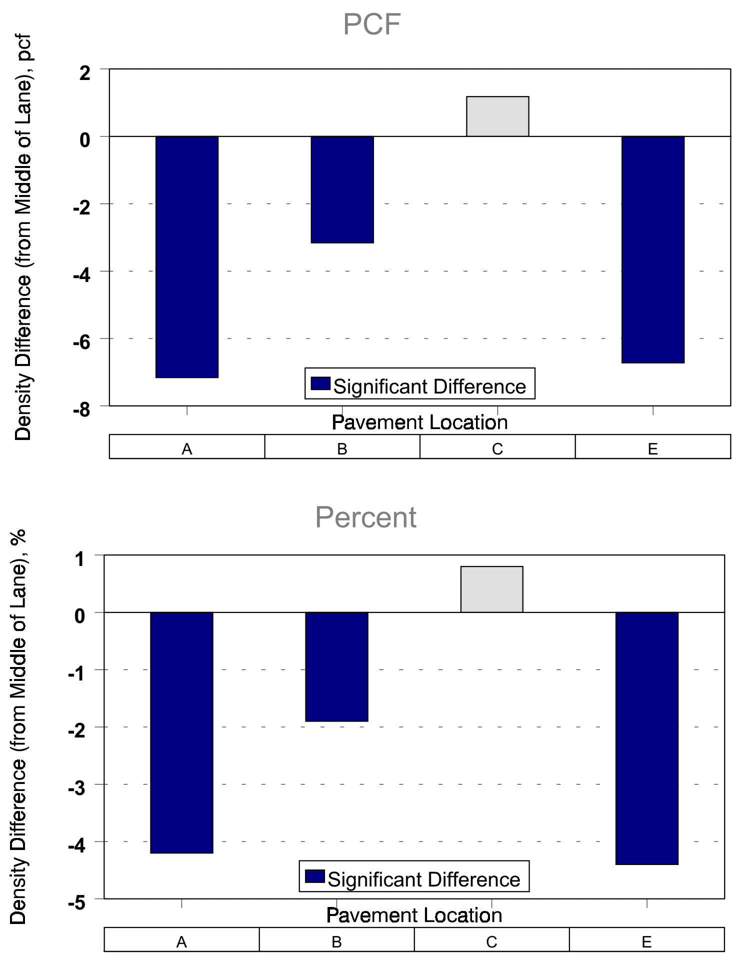


Figure 63. Difference in Density from Middle of Lane for SH 70, Wichita Falls, Type D Mix.

Table 56. Density Data for US 287 - B, Childress, Type D Mix.

Station	*A* 0.5 ft from Unconf. Edge	*B* 1ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D* Middle of Lane**	*E* 0.5 ft from Joint on Hot Side	*F* On Top of Joint	*G* 0.5ft from Joint on Cold Side
1	126.2	130.3	137.4	**139.9**	135.6	133.0	140.5
2	134.1	137.5	139.0	**139.9**	135.6	133.9	138.5
3	132.5	138.7	142.7	**142.3**	134.4	132.2	136.5
4	130.6	135.0	139.0	**138.6**	141.4	137.6	136.8
5	130.4	135.6	138.2	**137.4**	134.8	133.6	137.6
Mean	130.76	135.42	139.26	**139.62**	136.36	134.06	137.98
Std. Dev.	2.96	3.22	2.03	**1.82**	2.86	2.08	1.61

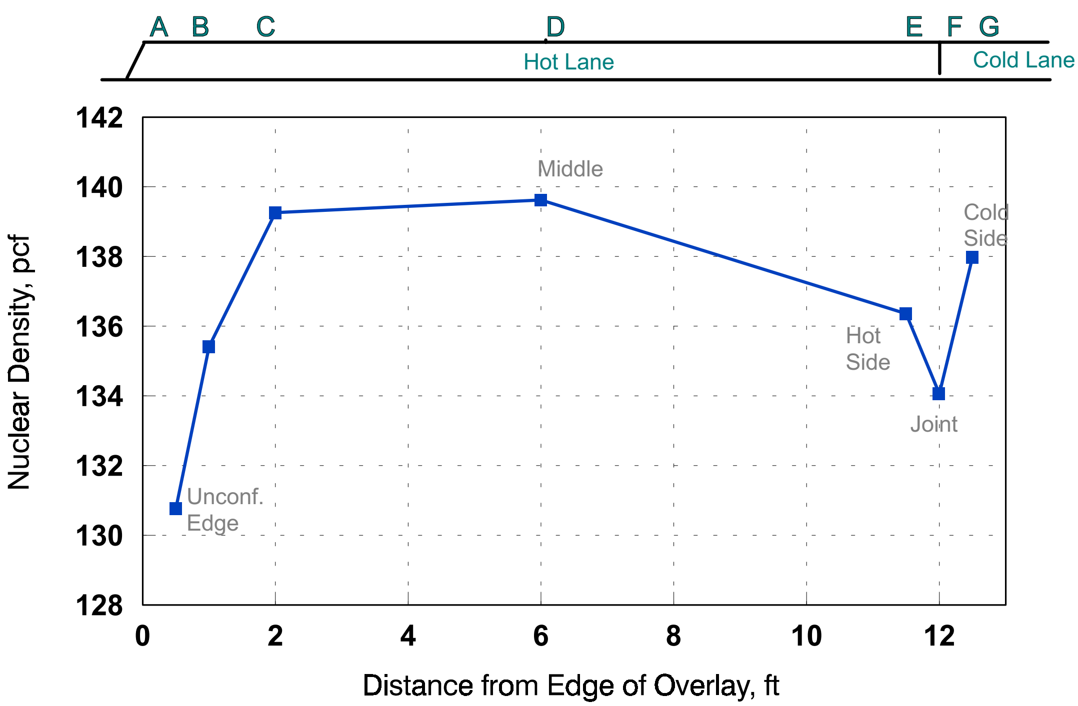


Figure 64. Mean Density Profile for US 287 - B, Childress, Type D Mix.

Table 57. Statistical Comparison of Mean Densities for US 287 - B, Childress, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-8.86	<0.0001	**Yes**
B, D	-4.20	0.0112	**Yes**
C, D	-0.36	0.8176	-
E, D	-3.30	0.0417	**Yes**
F, D	-5.56	0.0012	**Yes**
G, D	-1.64	0.2979	-

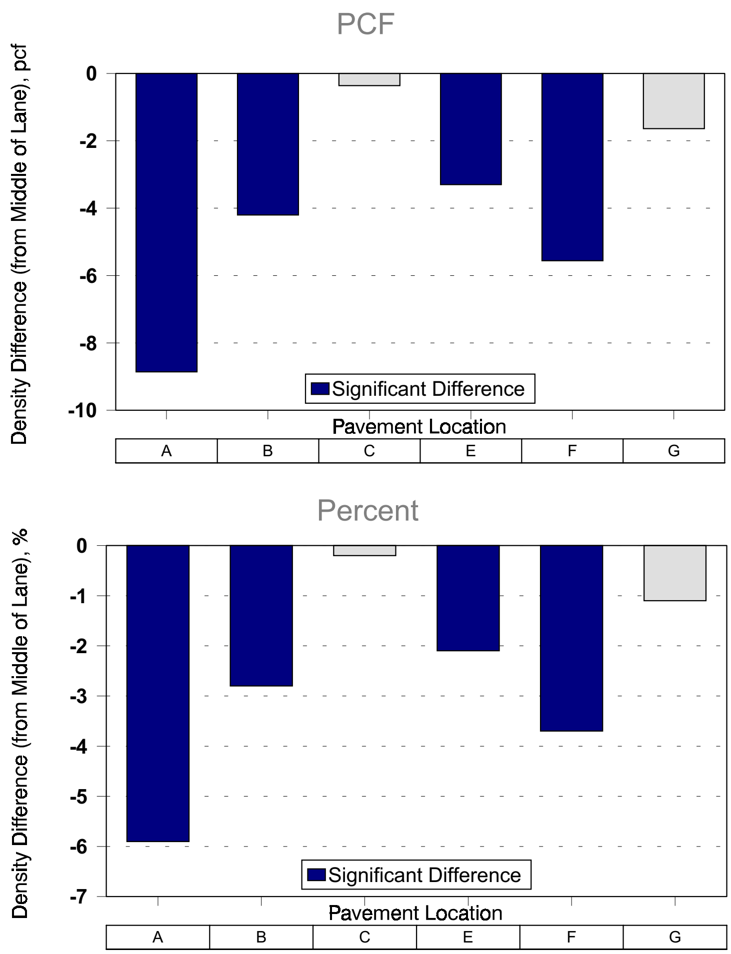


Figure 65. Difference in Density from Middle of Lane for US 287 - B, Childress, Type D Mix.

Table 58. Density Data for US 83, Pharr, Type D Mix.

Station	*A* 0.5 ft from Unconf. Edge	*B* 1ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D* Middle of Lane**	*E* 0.5 ft from Joint on Hot Side	*F* On Top of Joint	*G* 0.5 ft from Joint on Cold Side
0+50	128.3	125.1	131.3	**136.8**	131.4	129.8	135.6
1+00	127.3	128.2	132.0	**137.2**	139.8	127.0	133.5
1+50	124.8	129.2	131.6	**134.0**	135.2	131.0	136.3
2+00	127.1	127.6	133.5	**134.2**	131.5	132.4	137.0
2+50	126.0	134.7	136.5	**137.8**	138.0	129.2	131.4
Mean	126.7	128.96	132.98	**136.0**	135.18	129.88	134.76
Std. Dev.	1.34	3.55	2.14	**1.77**	3.78	2.02	2.29

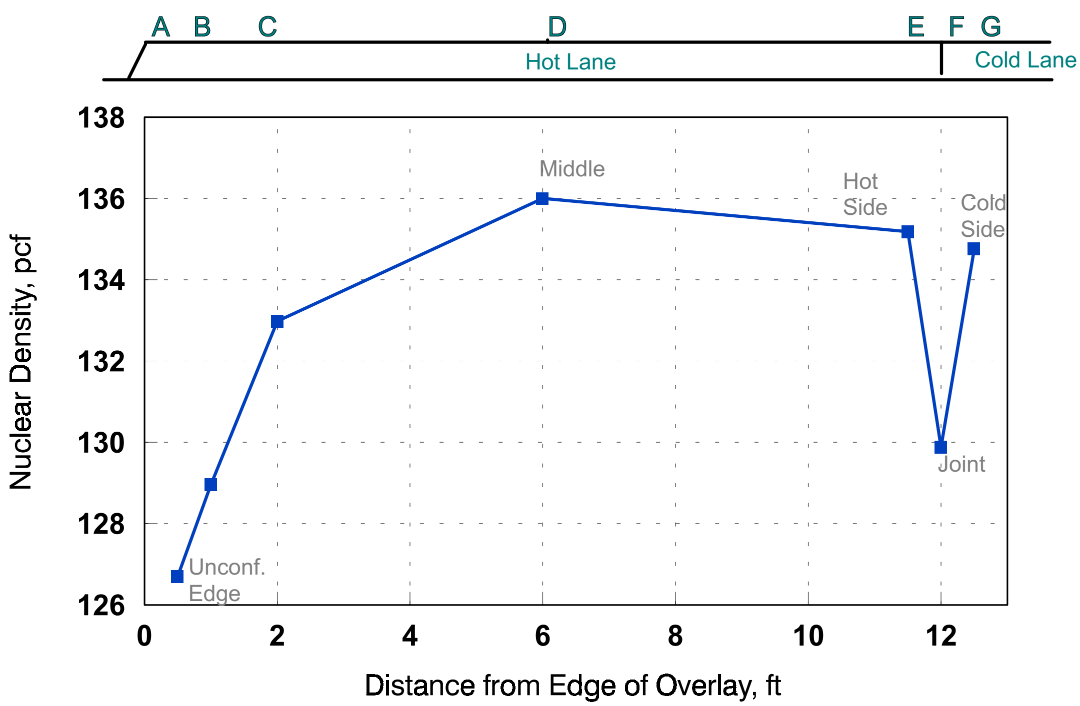


Figure 66. Mean Density Profile for US 83, Pharr, Type D Mix.

Table 59. Statistical Comparison of Mean Densities for US 83, Pharr, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-9.30	<0.0001	**Yes**
B, D	-7.64	0.0001	**Yes**
C, D	-3.02	0.0942	-
E, D	-0.82	0.6417	-
F, D	-6.12	0.0015	**Yes**
G, D	-1.28	0.4688	-

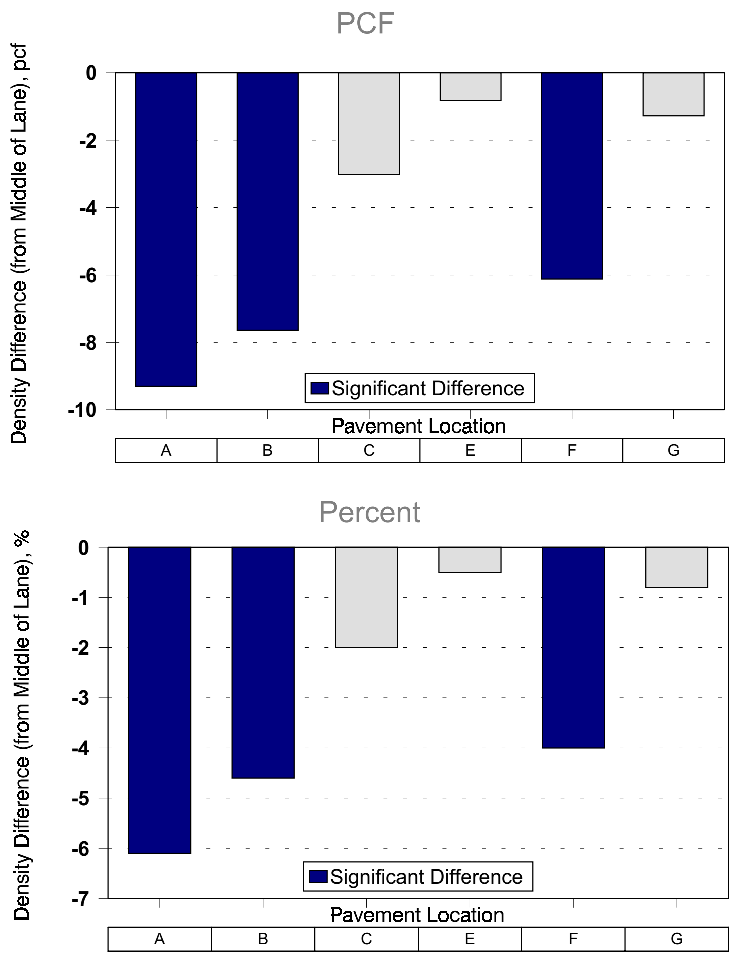


Figure 67. Difference in Density from Middle of Lane for US 83, Pharr, Type D Mix.

Table 60. Density Data for SH 30, Bryan, CMHB Mix.

Station	***A*** 0.5 ft from Unconfined Edge	***B*** 1ft from Unconfined Edge	***C*** 2 ft from Unconfined Edge	***D*** **Middle of Lane**
1	129.7	133.9	136.2	**138.9**
2	130.7	136.8	136.9	**134.7**
3	124.5	128.2	132.3	**138.1**
4	132.2	136.1	134.7	**136.1**
5	129.8	133.4	131.9	**133.8**
Mean	129.38	133.68	134.4	**136.32**
Std. Dev.	2.91	3.38	2.25	**2.17**

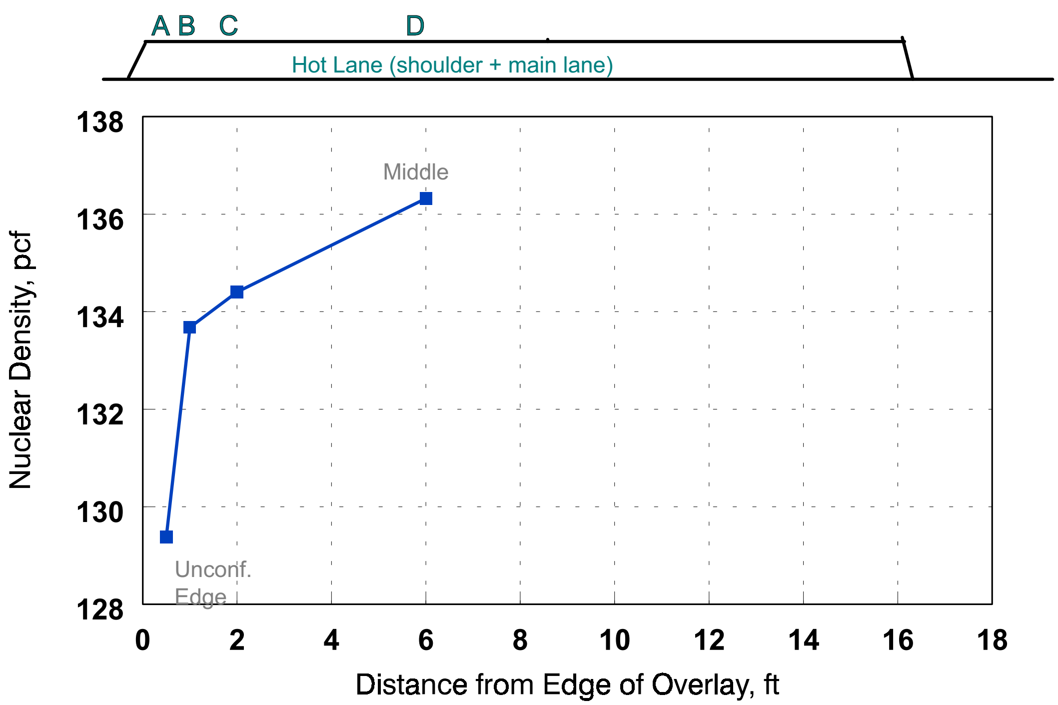
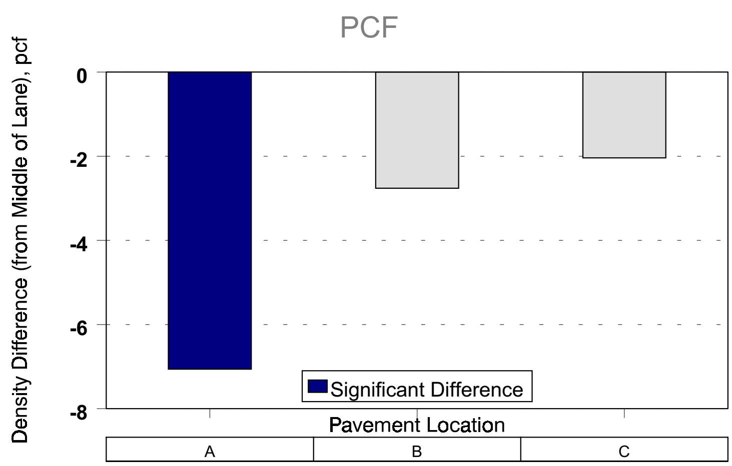


Figure 68. Mean Density Profile for SH 30, Bryan, CMHB Mix.

Table 61. Statistical Comparison of Mean Densities for SH 30, Bryan, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-7.06	0.0008	**Yes**
B, D	-2.76	0.1286	-
C, D	-2.04	0.2535	-



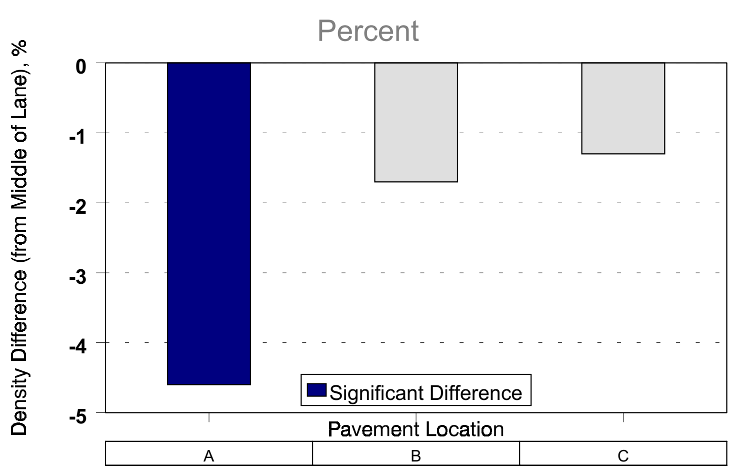


Figure 69. Difference in Density from Middle of Lane for SH 30, Bryan, CMHB Mix.

Table 62. Density Data for SH 6 Business - A, Bryan, CMHB Mix.

Station	*A* 0.5 ft from Unconf. Edge	*B* 1ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D* Middle of Lane**	*E* 0.5 ft from Joint on Hot Side	*F* On Top of Joint	*G* 0.5 ft from Joint on Cold Side
1	120.6	124.5	129.6	**135.0**	130.4	143.1	127.5
2	122.4	125.7	130.4	**133.5**	131.4	141.8	126.4
3	124.7	130.0	130.7	**133.2**	133.4	134.3	130.0
4	123.1	129.7	131.1	**132.1**	132.1	142.3	129.6
5	125.9	131.3	131.3	**128.6**	128.7	127.4	129.6
Mean	123.34	128.24	130.62	**132.48**	131.2	137.78	128.62
Std. Dev.	2.05	2.96	0.67	**2.40**	1.77	6.80	1.58

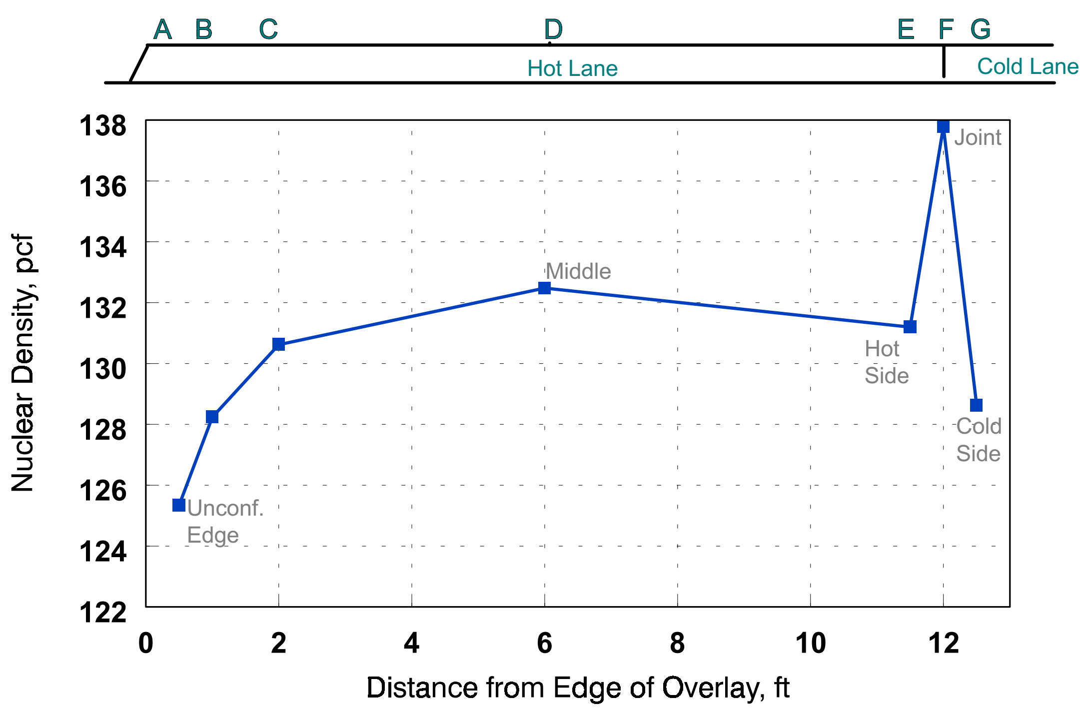


Figure 70. Mean Density Profile for SH 6 Business - A, Bryan, CMHB Mix.

Table 63. Statistical Comparison of Mean Densities for SH 6 Business - A, Bryan, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-9.14	<0.0001	**Yes**
B, D	-4.24	0.0444	**Yes**
C, D	-1.86	0.3638	-
E, D	-1.28	0.5304	-
F, D	5.3	0.0137	**Yes**
G, D	-3.86	0.0656	-

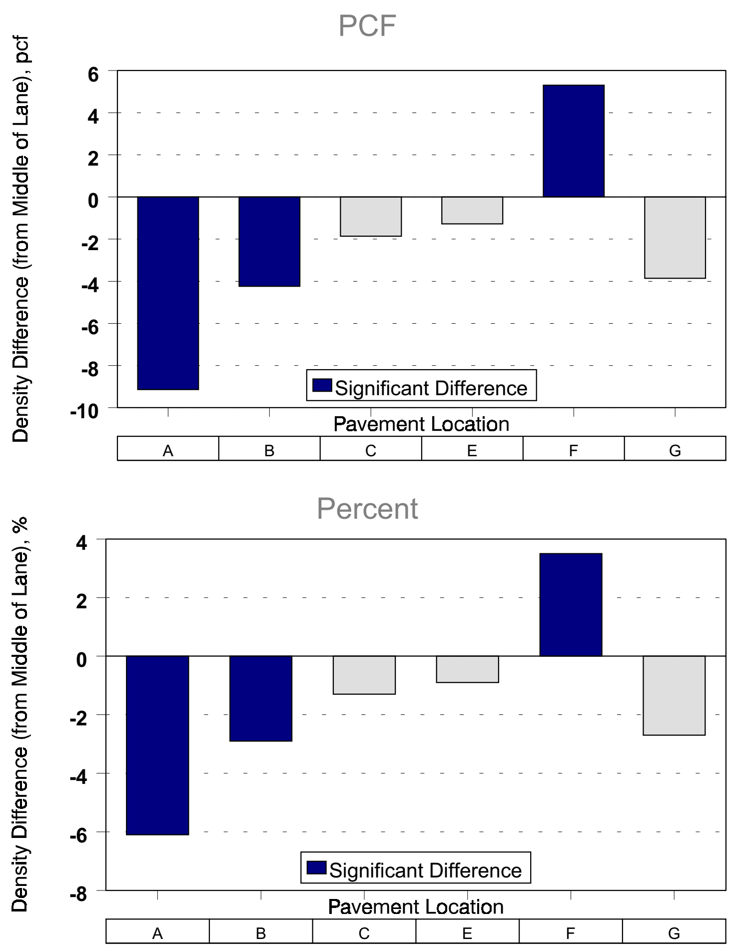


Figure 71. Difference in Density from Middle of Lane for SH 6 Business - A, Bryan, CMHB Mix.

Table 64. Density Data for SH 6 Business - B, Bryan, CMHB.

Station	*A* 0.5 ft. from Unconf. Edge	*B* 1ft. from Unconf. Edge	*C* 2 ft from Unconf. Edge	*D* **Middle of Lane**	*E* 0.5 ft from Joint on Hot Side	*F* On Top of Joint	*G* 0.5ft from Joint on Cold Side
1	130.2	133.8	137.8	**136.6**	141.0	143.6	135.7
2	128.7	129.6	136.0	**136.9**	138.5	140.0	132.4
3	131.3	132.8	137.1	**142.0**	138.1	137.4	127.3
4	132.4	*	*	**139.2**	*	*	*
5	*	*	*	*	*	*	*
Mean	130.65	132.07	136.97	**138.68**	139.2	140.33	131.8
Std. Dev.	1.58	2.19	0.91	**2.50**	1.57	3.11	4.23

* Opened to traffic prior to completion of data collection.

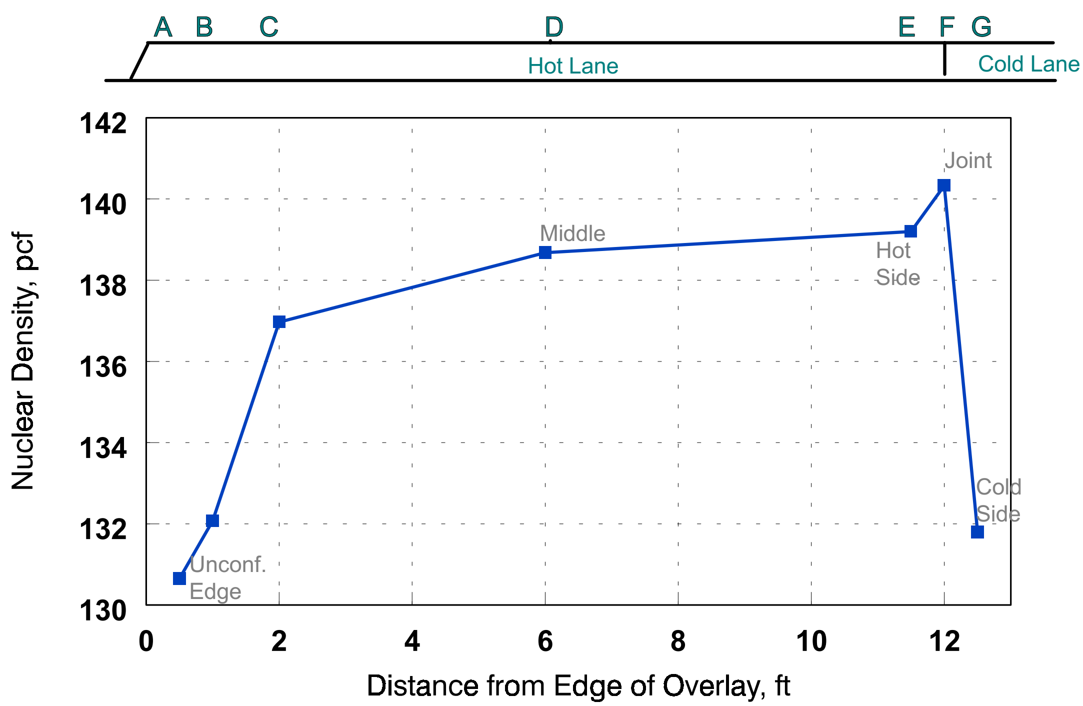


Figure 72. Mean Density Profile for SH 6 Business - B, Bryan, CMHB Mix.

Table 65. Statistical Comparison of Mean Densities for SH 6 Business - B, Bryan, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-8.03	0.0003	**Yes**
B, D	-6.61	0.0030	**Yes**
C, D	-1.71	0.3788	-
E, D	0.52	0.7844	-
F, D	1.65	0.3926	-
G, D	-6.88	0.0022	**Yes**

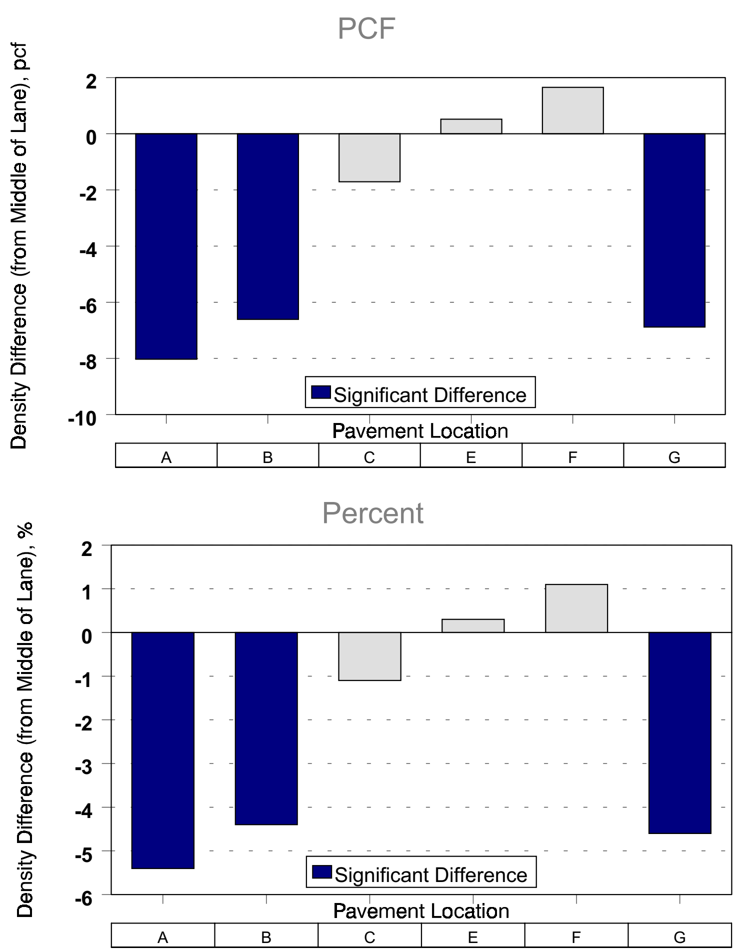


Figure 73. Difference in Density from Middle of Lane for SH 6 Business - B, Bryan, CMHB Mix.

Table 66. Density Data for US 277, San Angelo, CMHB Mix.

Station	*A* 0.5 ft from Unconf. Edge	*B* 1ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D*** **Middle of Lane**	*E* 0.5 ft from Joint on Cold Side	*F* On Top of Joint	*G* 0.5 ft from Joint on Hot Side
1	129.5	135.8	138.3	**130.1**	130.3	128.0	131.9
2	127.4	133.5	138.0	**131.7**	133.6	134.3	129.1
3	126.0	134.0	137.3	**135.8**	134.8	126.0	138.6
4	127.3	135.3	140.9	**131.9**	120.4	114.4	136.8
5	124.9	133.0	136.7	**133.5**	126.6	127.7	134.8
Mean	127.02	134.32	138.24	**132.60**	129.08	126.08	134.24
Std. Dev.	1.73	1.19	1.61	**2.16**	5.82	7.25	3.80

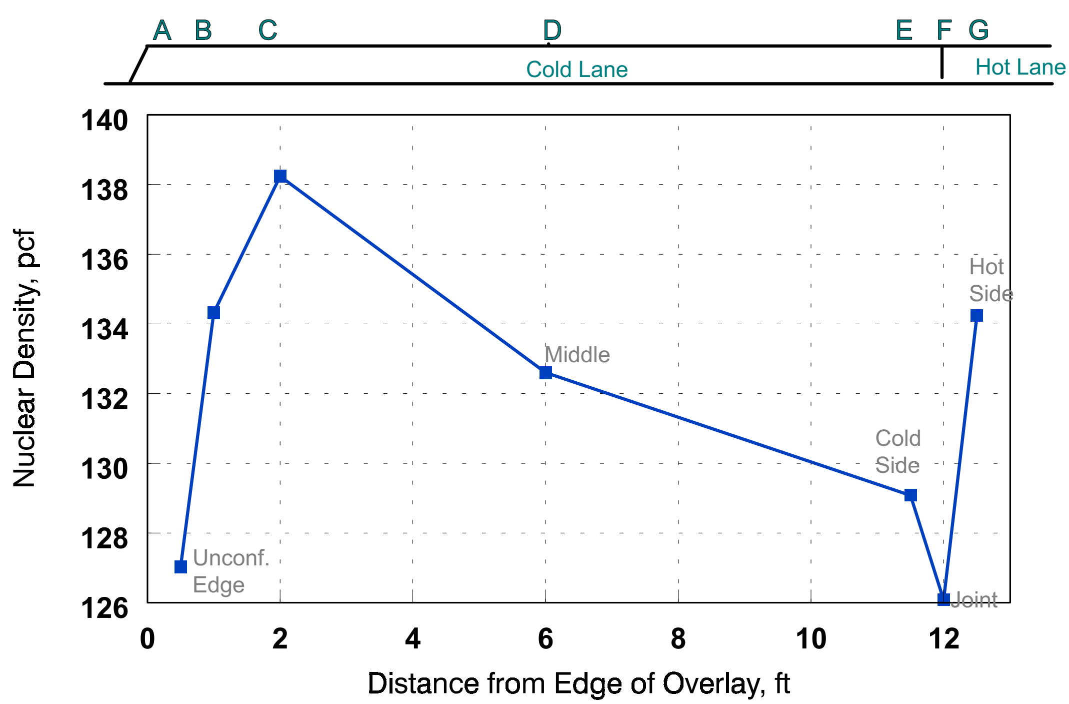


Figure 74. Mean Density Profile for US 277, San Angelo, CMHB Mix.

Table 67. Statistical Comparison of Mean Densities for US 277, San Angelo, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-5.58	0.0361	**Yes**
B, D	1.72	0.5028	**-**
C, D	5.64	0.0343	**Yes**
E, D	-3.52	0.1757	-
F, D	-6.51	0.0158	**Yes**
G, D	1.64	0.5228	**-**

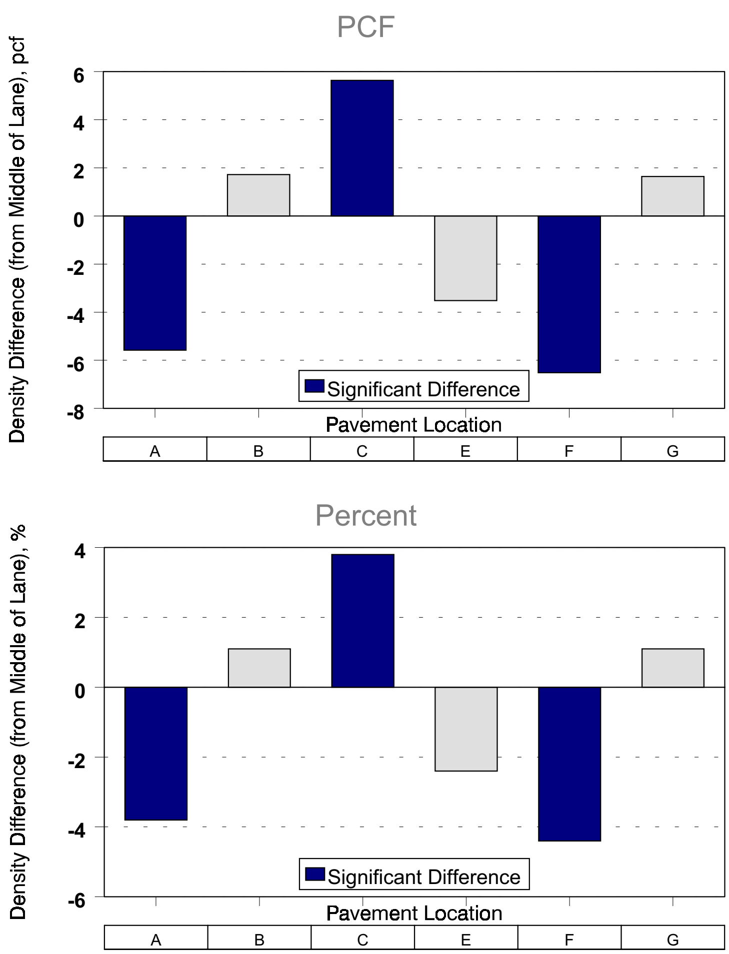


Figure 75. Difference in Density from Middle of Lane for US 277, San Angelo, CMHB Mix.

Table 68. Density Data for US 67, San Angelo, CMHB Mix.

Station	*A* 0.5 ft from Unconf. Edge	*B* 1ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D* Middle of Lane**	*E* 0.5 ft from Unconf. Edge
1	131.3	136.6	131.7	**139.1**	127.6
2	130.8	134.8	138.7	**141.7**	128.4
3	127.8	130.7	131.7	**140.7**	125.0
4	134.2	135.3	138.2	**142.3**	128.0
5	128.5	129.5	131.8	**132.5**	113.6
Mean	130.52	133.38	134.42	**139.26**	125.52
Std. Dev.	2.54	3.10	3.68	**3.96**	6.25

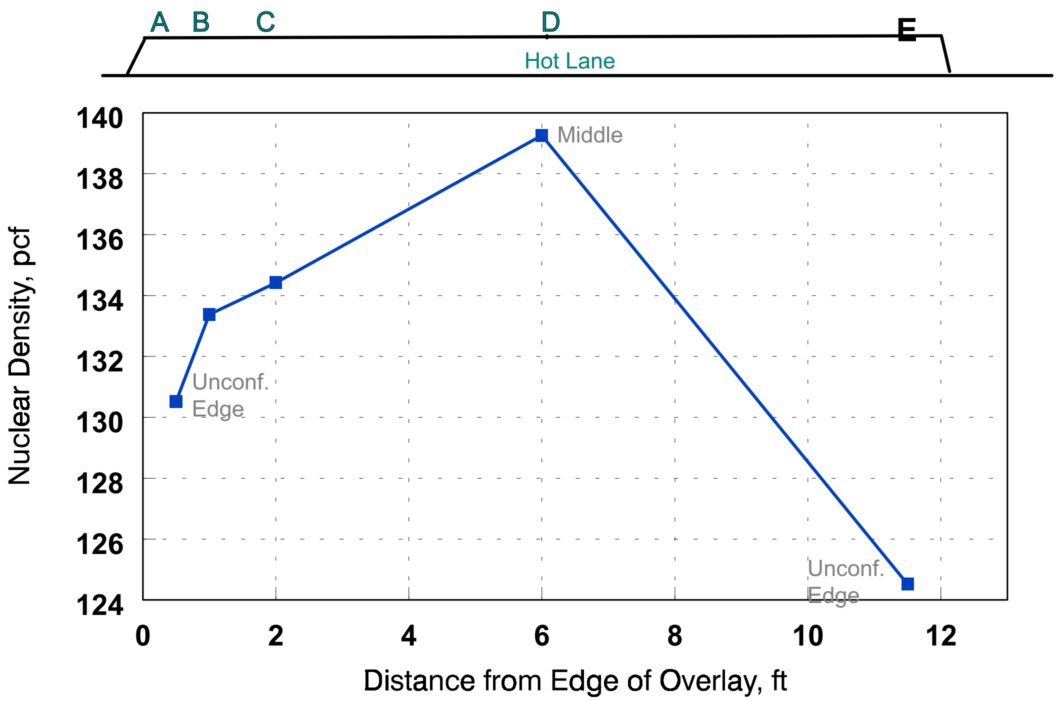


Figure 76. Mean Density Profile for US 67, San Angelo, CMHB Mix.

Table 69. Statistical Comparison of Mean Densities for US 67, San Angelo, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-8.74	0.0031	**Yes**
B, D	-5.88	0.0349	**Yes**
C, D	-4.84	0.0772	-
E, D	-14.74	<0.0001	**Yes**

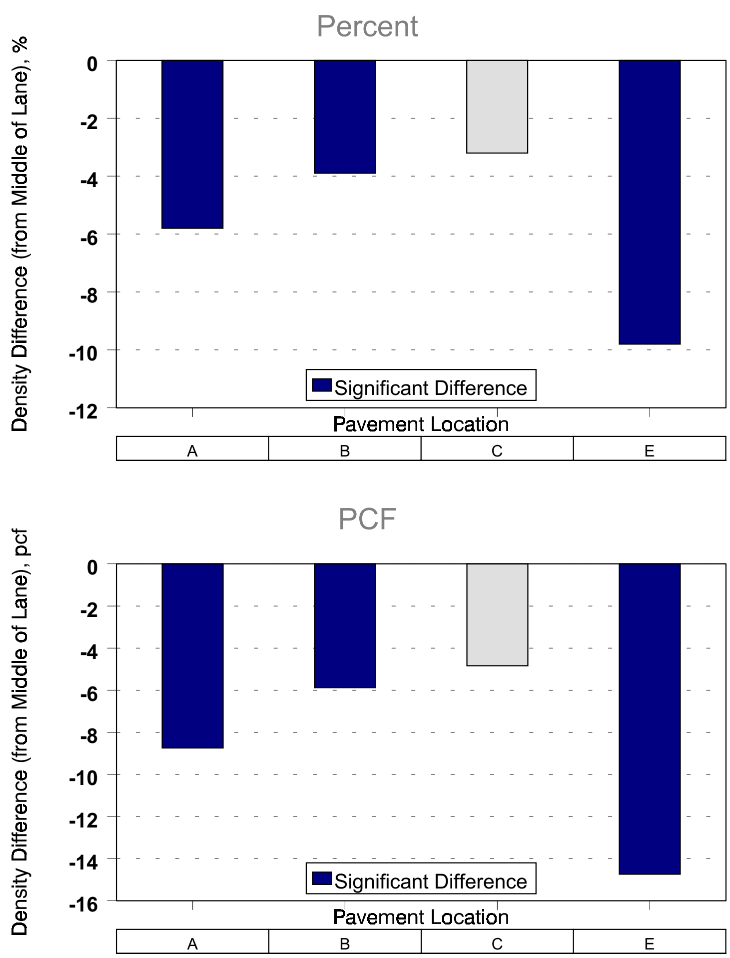


Figure 77. Difference in Density from Middle of Lane for US 67, San Angelo, CMHB Mix.

Table 70. Density Data for Loop 338, Odessa, CMHB Mix.

Station	*A* 0.5 ft from Unconf. Edge	*B* 1ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D* Middle of Lane**	*E* 0.5 ft from Unconf. Edge
1	127.3	131.1	132.6	**130.4**	126.8
2	129.3	130.7	132.3	**131.8**	128.9
3	125.1	127.7	130.0	**130.6**	126.9
4	129.6	133.0	134.9	**135.2**	129.2
5	128.8	130.8	132.6	**131.6**	127.2
Mean	128.02	130.66	132.48	**131.92**	127.8
Std. Dev.	1.86	1.90	1.74	**1.93**	1.16

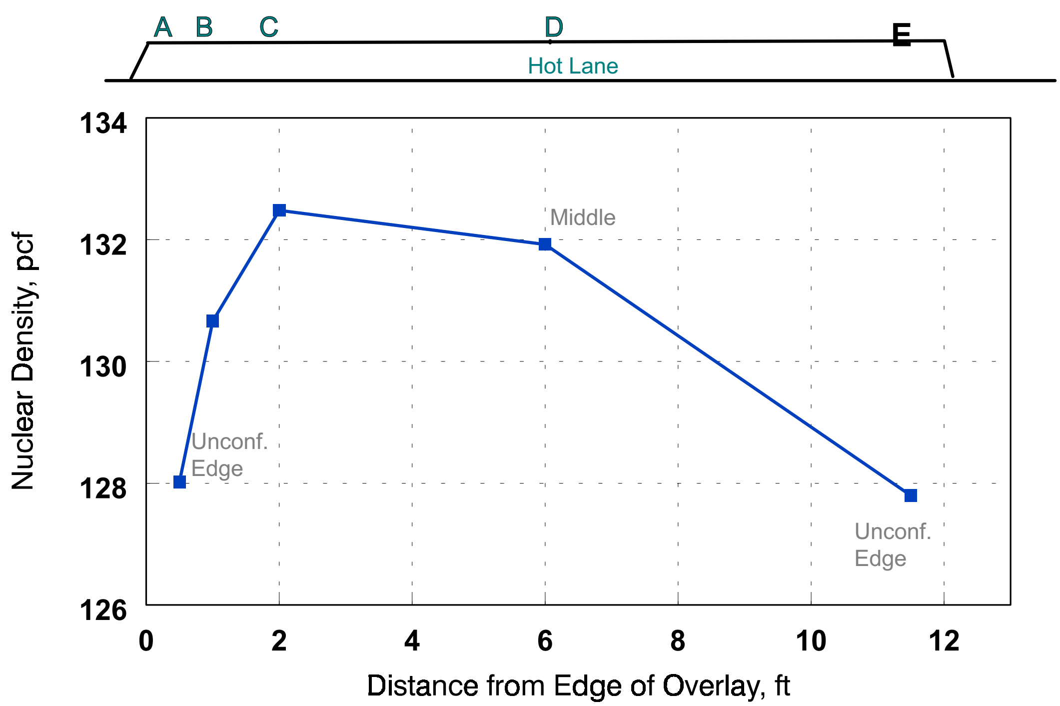
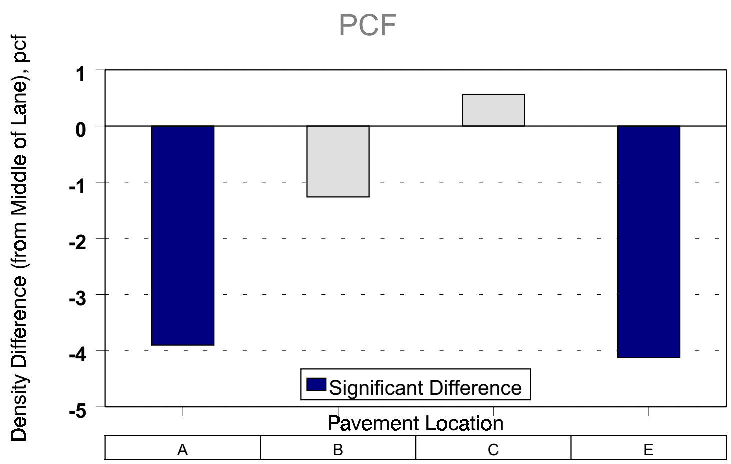


Figure 78. Mean Density Profile for Loop 338, Odessa, CMHB Mix.

Table 71. Statistical Comparison of Mean Densities for Loop 338, Odessa, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-3.9	0.0020	**Yes**
B, D	-1.26	0.2658	-
C, D	0.56	0.6165	-
E, D	-4.12	0.0013	**Yes**



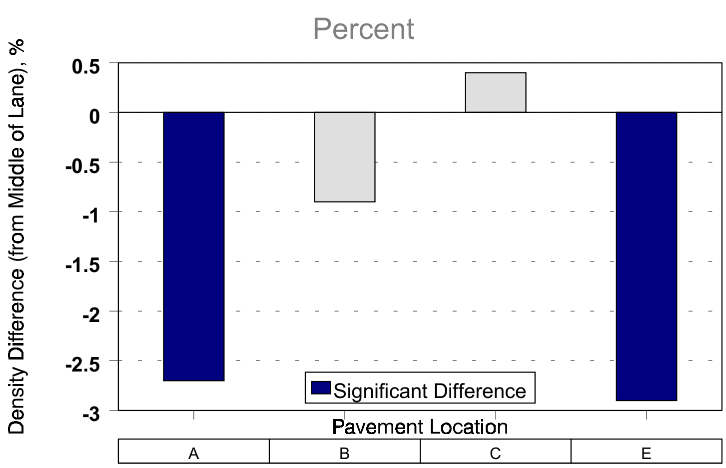


Figure 79. Difference in Density from Middle of Lane for Loop 338, Odessa, CMHB Mix.

Table 72. Density Data for SH 36, Bryan, CMHB Mix.

Station	*A* 0.5 ft from Unconf. Edge	*B* 1 ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D* Middle of Lane**	*E* 0.5 ft from Confined Edge
1	128.5	132.9	133.0	**134.9**	127.8
2	134.3	136.6	140.9	**141.4**	130.2
3	134.5	140.2	141.1	**139.2**	134.5
4	131.4	134.7	139.3	**140.9**	134.2
5	133.2	138.6	138.2	**138.5**	123.8
Mean	132.38	136.6	138.50	**138.98**	130.10
Std. Dev.	2.49	2.93	3.30	**2.57**	4.50

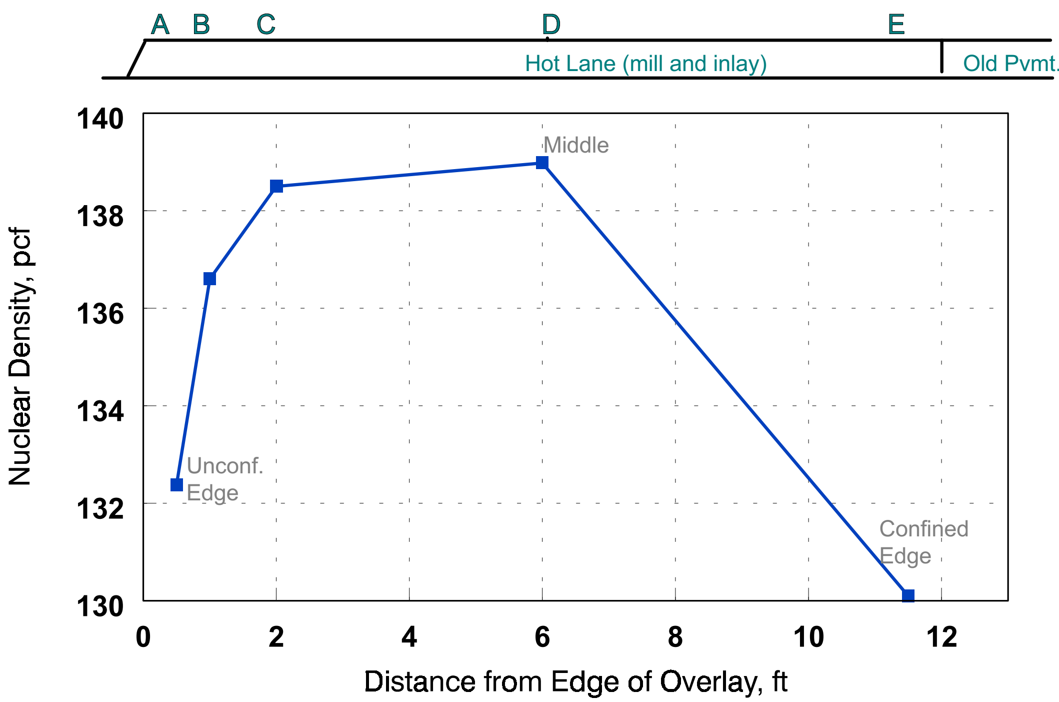


Figure 80. Mean Density Profile for SH 36, Bryan, CMHB Mix.

Table 73. Statistical Comparison of Mean Densities for SH 36, Bryan, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	P-Value	Significance
A, D	-6.60	0.0043	**Yes**
B, D	-2.38	0.2595	-
C, D	-0.48	0.8173	-
E, D	-8.88	0.0003	**Yes**

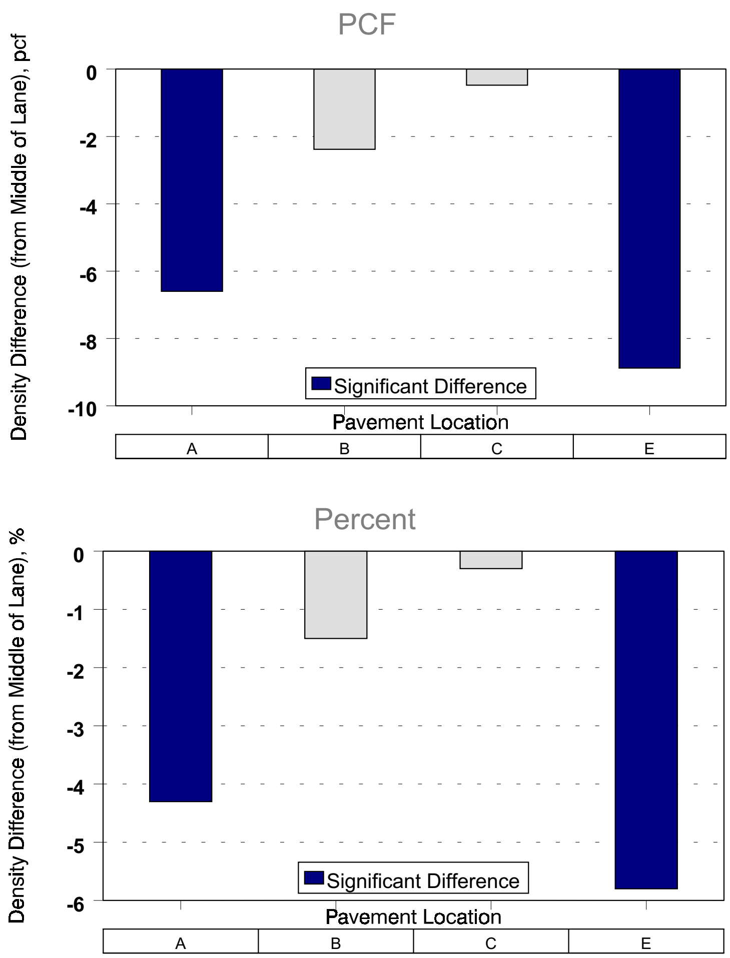


Figure 81. Difference in Density from Middle of Lane for SH 36, Bryan, CMHB Mix.

Table 74. Density Data for SH 6, Waco, Superpave Mix.

Station	***A*** 0.5 ft from Unconf. Edge	***B*** 1ft from Unconf. Edge	***C*** 2 ft from Unconf. Edge	***D*** **Middle of Lane**	***E*** 0.5 ft from Joint on Hot Side	***F*** On Top of Joint	***G*** 0.5 ft from Joint on Cold Side
1	136.0	136.1	137.5	**137.8**	-	134.0	137.8
2	133.3	138.8	140.4	**136.8**	127.3	132.8	134.7
3	132.2	137.7	139.5	**137.7**	124.4	129.4	131.9
4	132.7	138.5	139.5	**139.2**	132.1	128.2	134.2
5	132.9	138.7	143.3	**142.5**	131.0	130.7	136.2
Mean	133.42	137.96	140.04	**138.8**	128.7	131.02	134.96
Std. Dev.	1.50	1.13	2.11	**2.24**	3.53	2.39	2.21

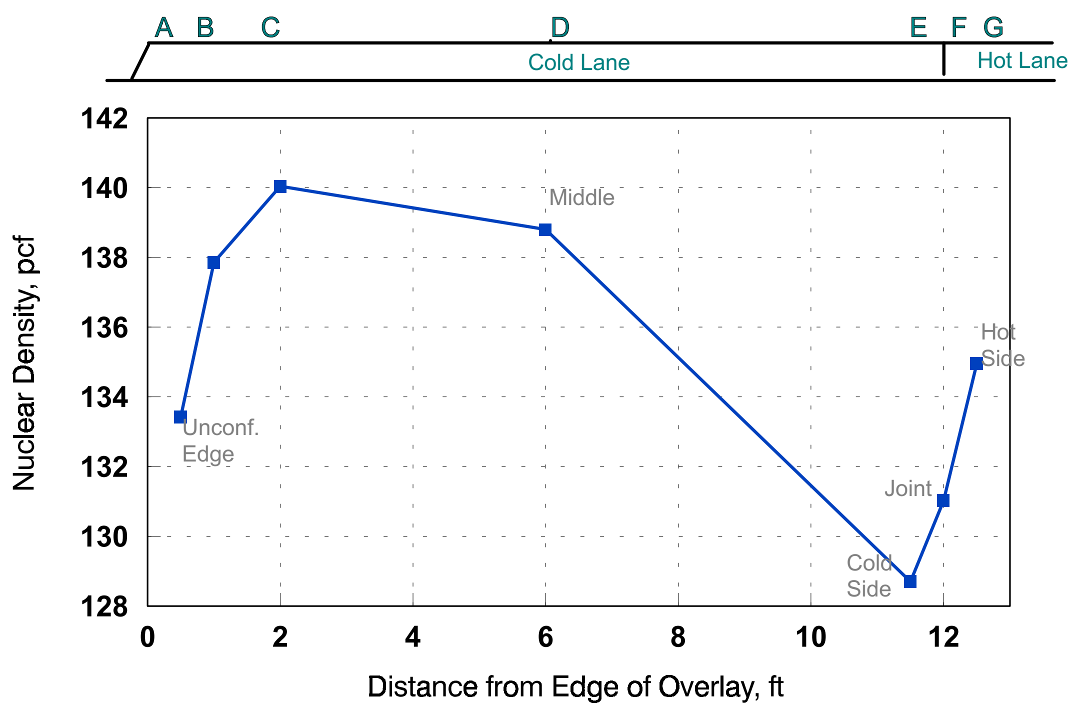


Figure 82. Mean Density Profile for SH 6, Waco, Superpave Mix.

Table 75. Statistical Comparison of Mean Densities for SH 6, Waco, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	p-value	Significance
A, D	-5.38	0.0006	**Yes**
B, D	-.84	0.5523	-
C, D	1.24	0.3822	-
E, D	-10.1	<0.0001	**Yes**
F, D	-7.78	<0.0001	**Yes**
G, D	-3.84	0.0105	**Yes**

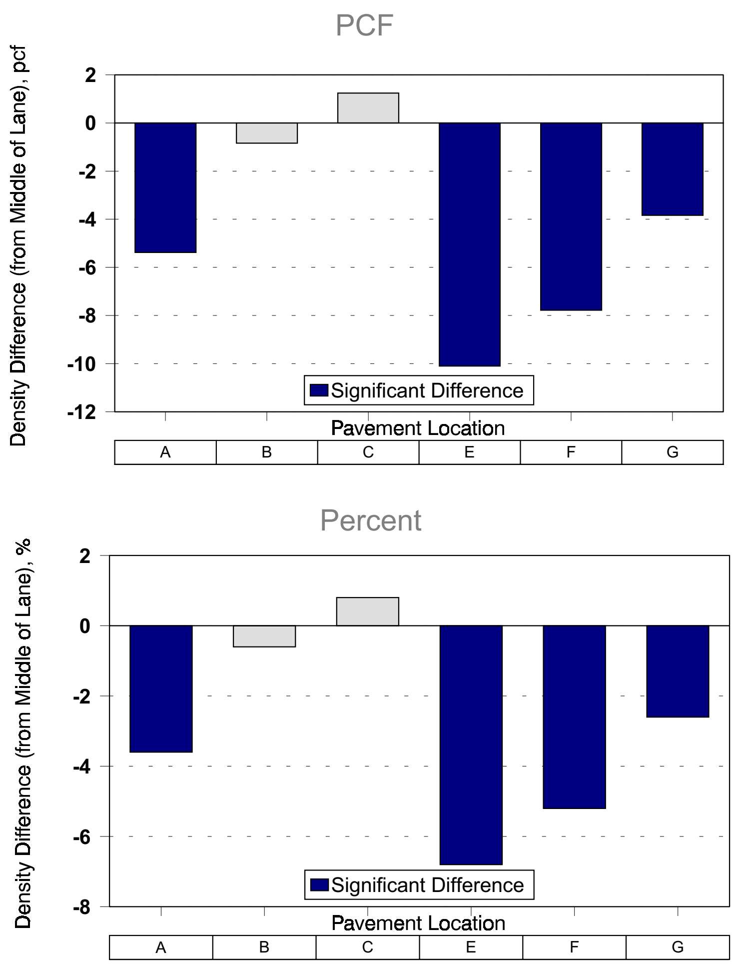


Figure 83. Difference in Density from Middle of Lane for SH 6, Waco, Superpave Mix.

Table 76. Density Data for IH 35, Laredo, Superpave Mix.

Station	*A* 0.5 ft from Unconf. Edge	*B* 1ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	***D*** **Middle of Lane**
1	129.4	136.0	135.6	**136.5**
2	130.3	136.8	138.2	**133.0**
3	133.9	141.4	142.4	**142.3**
4	131.4	136.7	139.1	**138.1**
5	134.3	138.6	140.8	**138.0**
Mean	131.86	137.9	139.22	**137.58**
Std. Dev.	2.17	2.18	2.59	**3.35**

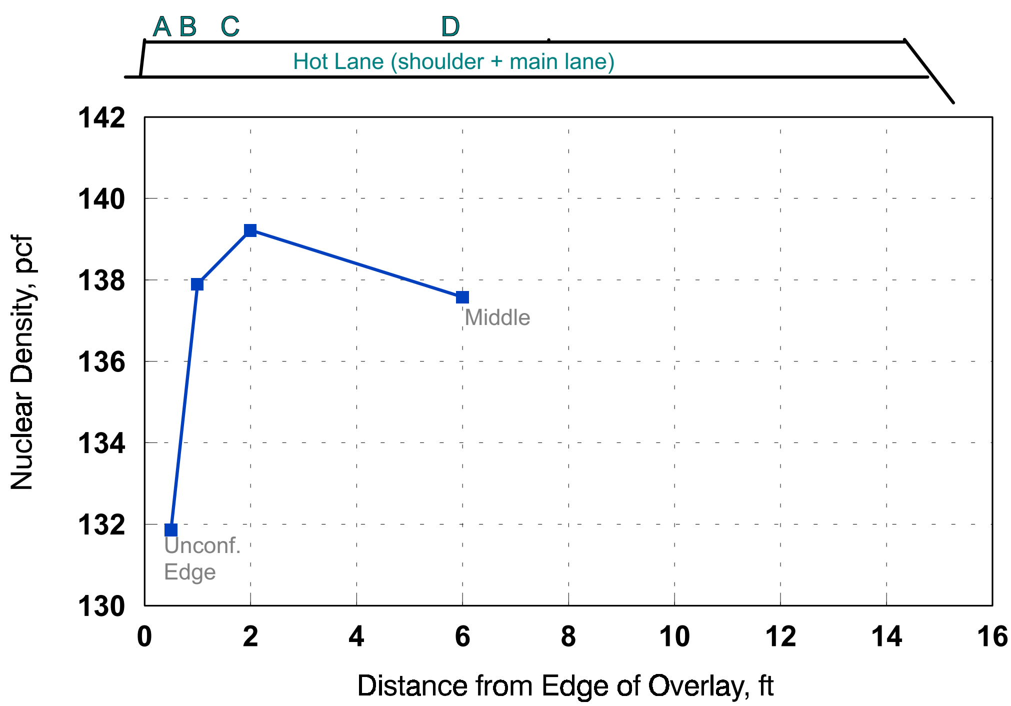


Figure 84. Mean Density Profile for IH 35, Laredo, Superpave Mix.

Table 77. Statistical Comparison of Mean Densities for IH 35, Laredo, using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	Significance
A, D	-5.72	**Yes**
B, D	0.32	-
C, D	1.64	-

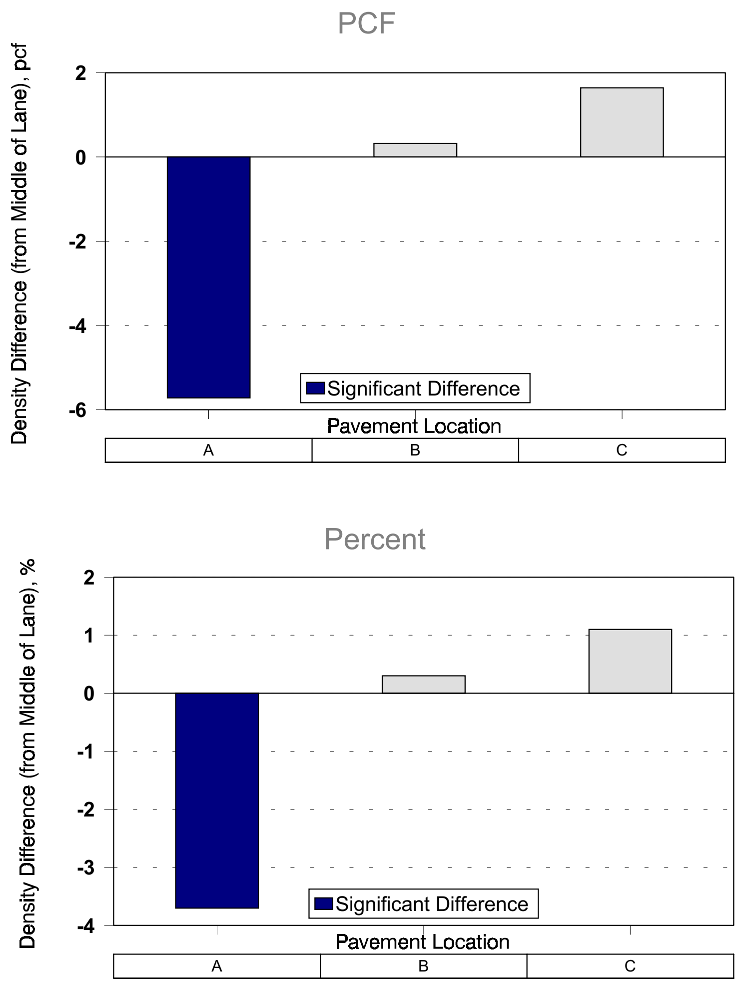


Figure 85. Difference in Density from Middle of Lane for IH 35, Laredo, Superpave Mix.

Table 78. Density Data for US 287, Wichita Falls (Stone Filled).

Station	*A* 0.5 ft from Unconf. Edge	*B* 1ft from Unconf. Edge	*C* 2 ft from Unconf. Edge	*D* Middle of Lane	*F* On Top of Joint	*G* 0.5ft from Joint on Hot Side
1	142.6	146.9	149.3	150.9	134.3	146.6
2	144.7	145.8	148.6	147.4	138.8	144.8
3	139.6	141.0	146.2	147.0	138.2	145.2
4	137.9	139.5	144.1	147.9	137.2	146.3
5	140.1	139.9	147.1	147.9	138.5	145.6
Mean	140.98	142.62	147.06	148.22	137.40	145.7
Std. Dev.	2.89	3.47	2.05	1.54	1.83	0.75

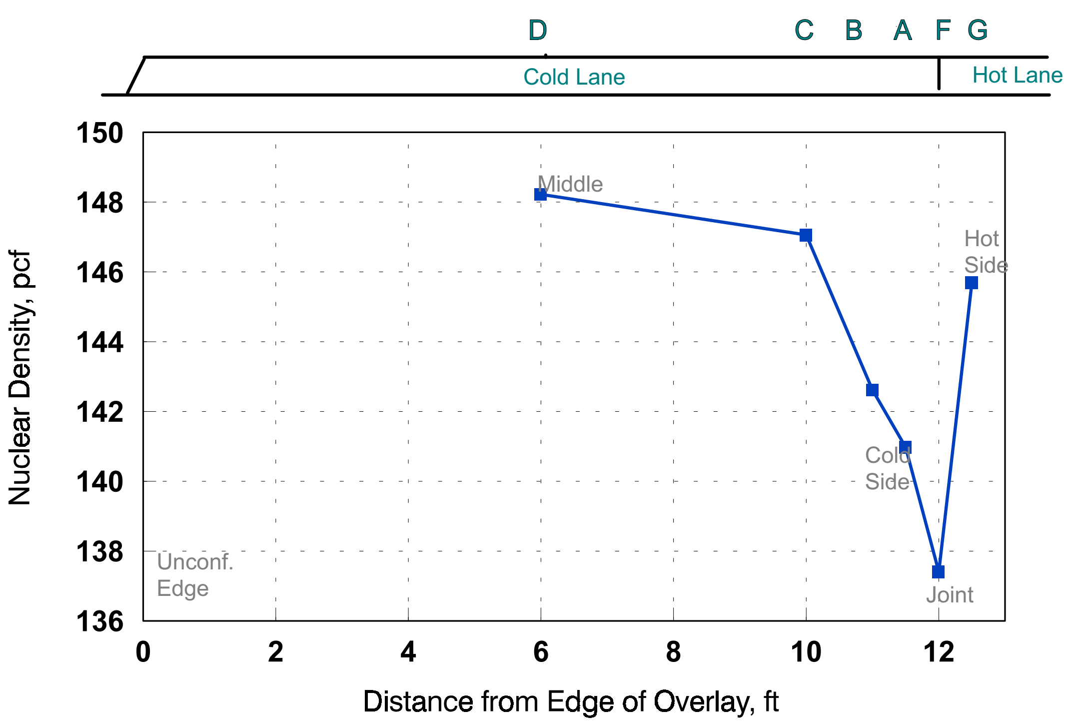


Figure 86. Mean Density Profile for US 287, Wichita Falls (Stone Filled).

Table 79. Statistical Comparison of Mean Densities for US 287, Wichita Falls (Stone Filled), using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	Significance
A, D	-7.24	**Yes**
B, D	-5.60	**Yes**
C, D	-1.16	-
F,D	-10.82	**Yes**
G,D	-2.52	-

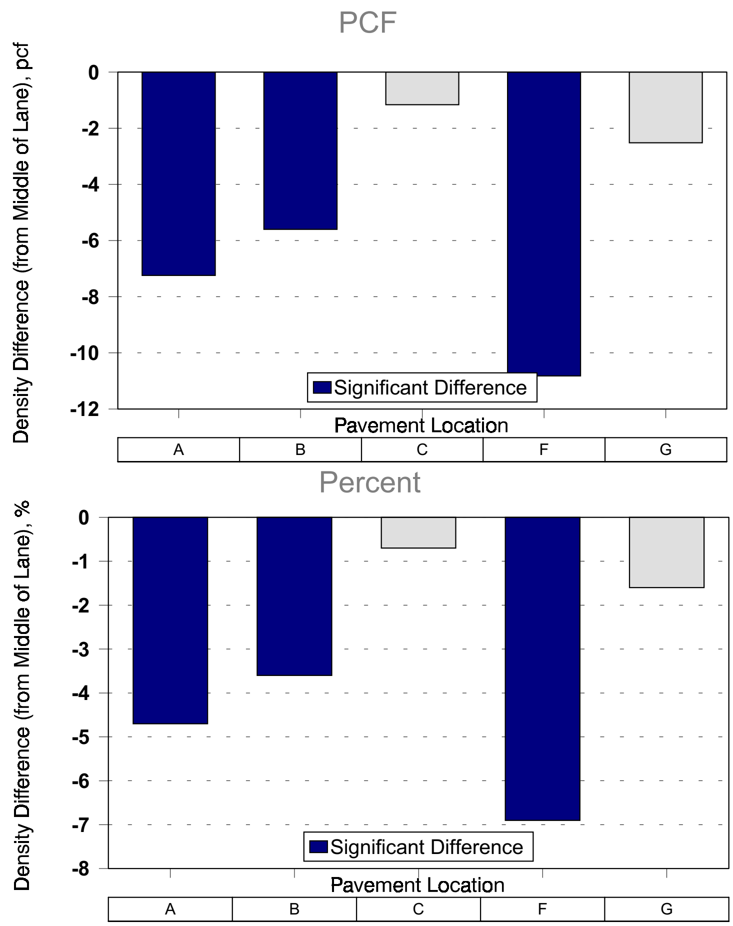


Figure 87. Difference in Density from Middle of Lane for US 287, Wichita Falls (Stone Filled).

Table 80. Density Data for FM 369, Wichita Falls (SMA).

Station	*A* 0.5 ft from Confined. Edge	*B* 1ft from Confined Edge	*C* 2 ft from Unconf. Edge	***D* Middle of Lane**	*F* On Top of Joint	*G* 0.5 ft from Joint on Cold Side
1	145.2	146.1	146.1	**148.9**	132.1	139.6
2	145.6	145.9	145.9	**144.2**	131.7	139.2
3	144.9	145.1	145.1	**143.5**	132.0	140.8
4	147.1	144.9	144.9	**142.9**	138.3	141.8
5	146.1	145.9	145.9	**143.6**	134.1	140.7
Mean	145.78	145.58	145.58	**144.62**	133.64	140.42
Std. Dev.	0.86	0.54	0.54	**2.44**	2.77	1.03

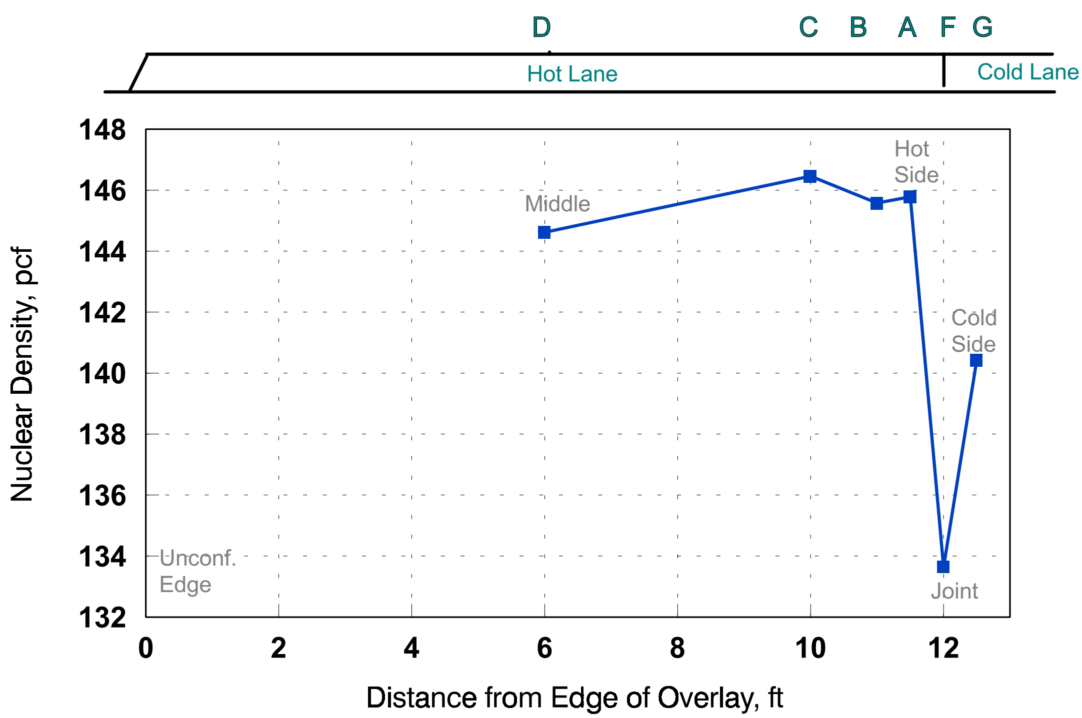
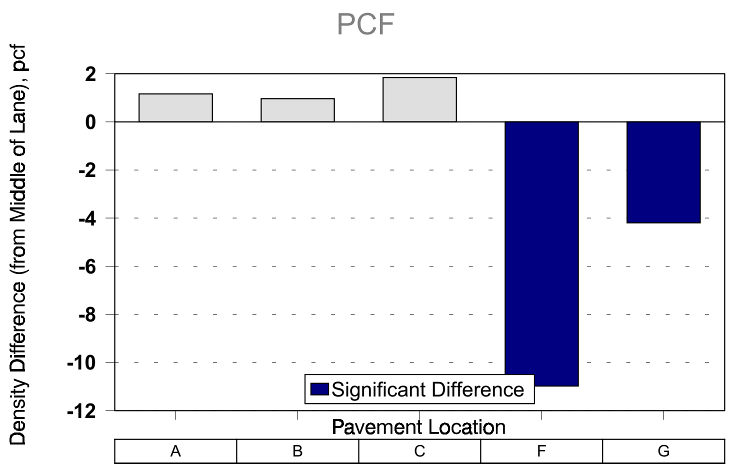


Figure 88. Mean Density Profile for FM 369, Wichita Falls (SMA).

Table 81. Statistical Comparison of Mean Densities for FM 369, Wichita Falls (SMA), using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	Significance
A, D	1.16	-
B, D	0.96	-
C, D	1.84	-
F,D	-10.98	**Yes**
G,D	-4.20	**Yes**



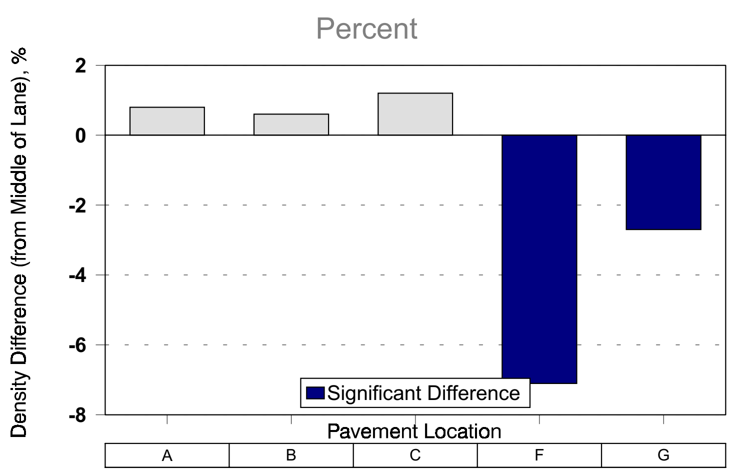


Figure 89. Difference in Density from Middle of Lane for FM 369, Wichita Falls (SMA).

Table 82. Density Data for FM 369, Wichita Falls (Heavy Duty SMA).

Station	***A*** 0.5 ft from Confined. Edge	***B*** 1ft from Confined Edge	***C*** 2 ft from Unconf. Edge	***D*** **Middle of Lane**	***F*** On Top of Joint	***G*** 0.5 ft from Joint on Cold Side
1	143.4	145.7	142.8	**146.5**	138.0	140.5
2	144.1	144.9	144.3	**145.3**	136.1	135.5
3	147.1	146.0	145.2	**145.4**	139.4	138.9
4	144.2	1410	147.5	**147.0**	137.5	139.1
5	145.3	143.6	147.6	**147.8**	136.8	137.7
Mean	144.82	144.24	145.48	**146.4**	137.56	138.34
Std. Dev.	1.44	2.04	2.08	**1.07**	1.25	1.87

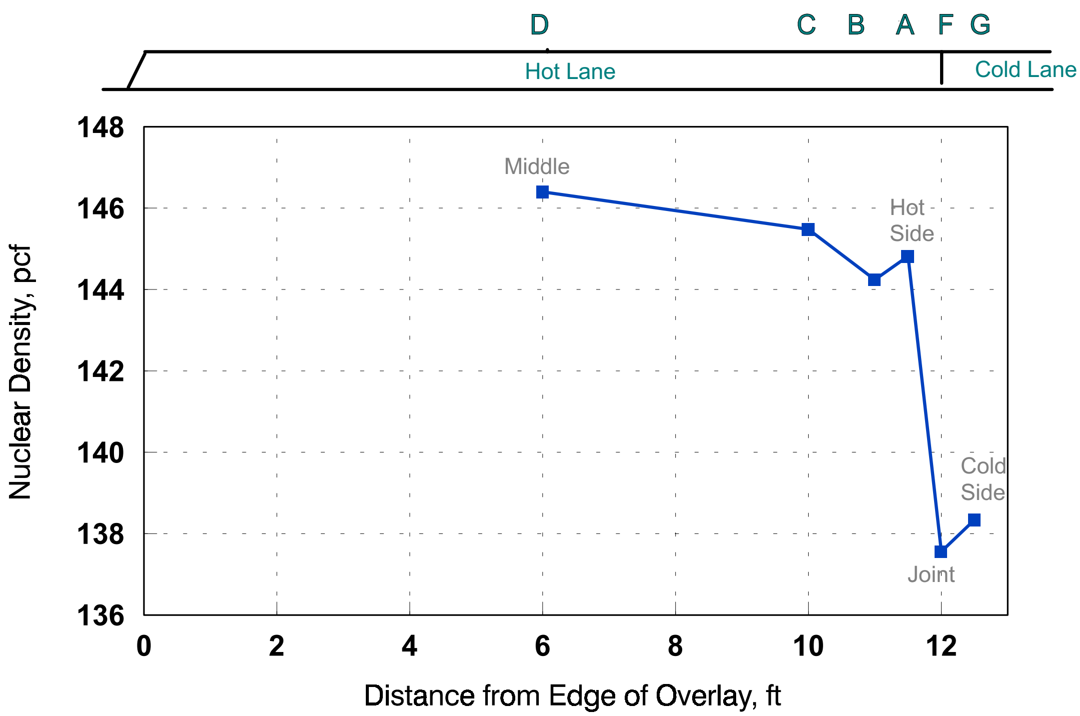


Figure 90. Mean Density Profile for FM 369, Wichita Falls (Heavy Duty SMA).

Table 83. Statistical Comparison of Mean Densities for FM 369, Wichita Falls (SMA), using Fisher's PLSD - Significance Level 5%.

Means Compared	Mean Difference	Significance
A, D	1.58	-
B, D	2.16	-
C, D	0.92	-
F,D	8.84	**Yes**
G,D	8.06	**Yes**

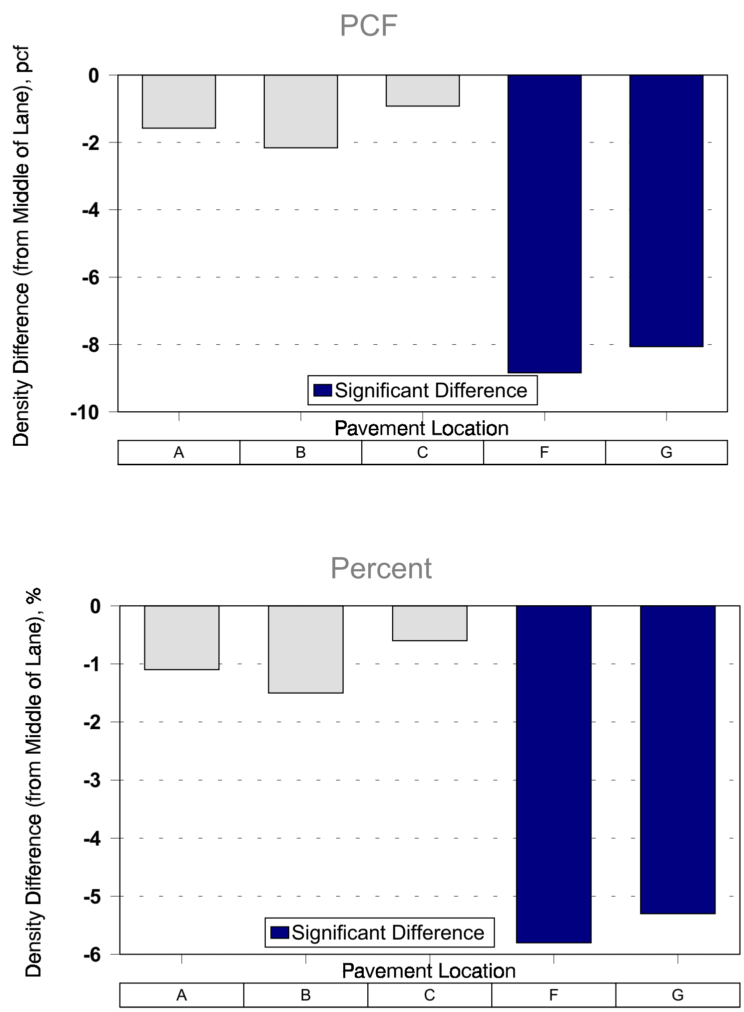


Figure 91. Difference in Density from Middle of Lane for FM 369, Wichita Falls (Heavy Duty SMA).

CHAPTER 6.0 SUMMARY OF DENSITY AND PERMEABILITY DATA

6.1 TYPE C, CRUSHED LIMESTONE PAVEMENTS

All of the density results for the Type C, crushed limestone pavements are shown in Figures 92 through 96. Figure 92 shows the difference in density from the middle of the lane to 6 inches from the unconfined edges. In most cases the unconfined edge had a significantly lower density than in the center of the mat. Densities near the unconfined edge were from 0.4 to almost 10 lbs per cubic ft (0.2 to 7 percentage points) lower than the mat center, averaging about 6 lbs per cubic ft (4 percent).

Density measurements made directly on the joint were also significantly lower than the mat center as shown in Figure 93. Confined edges had much better densities than unconfined edges as shown in Figure 94. While the density near the confined edge was lower than the mat center, it was not usually significant.

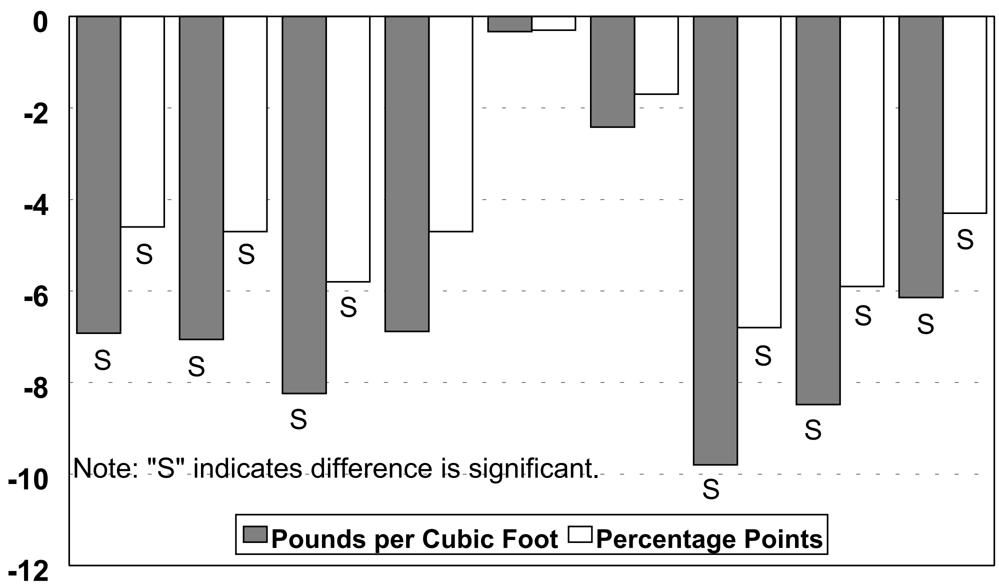


Figure 92. Summary of Mean Density Difference from Middle of Lane to Unconfined Edges of Type C, Limestone Pavements.

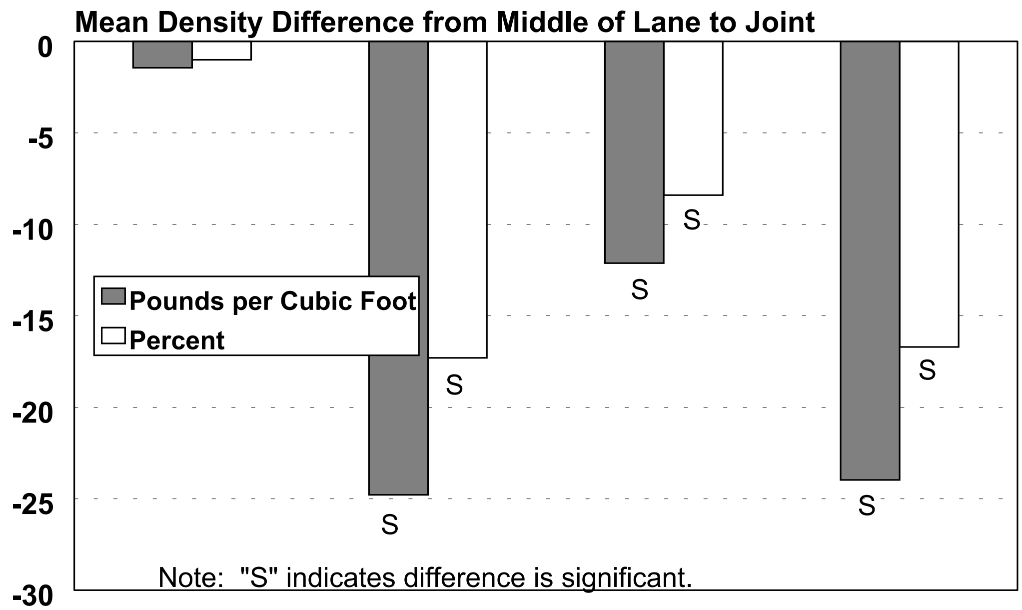


Figure 93. Summary of Mean Density Difference from Middle of Lane to the Joint of Type C, Limestone Pavements.

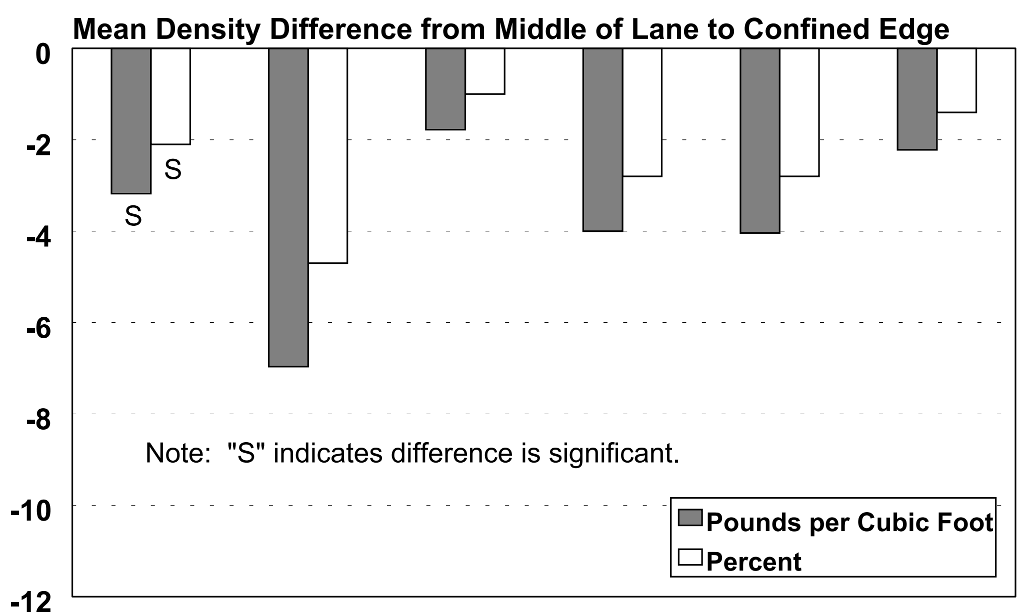


Figure 94. Summary of Mean Density Difference from Middle of Lane to the Confined Edge of Type C, Limestone Pavements.

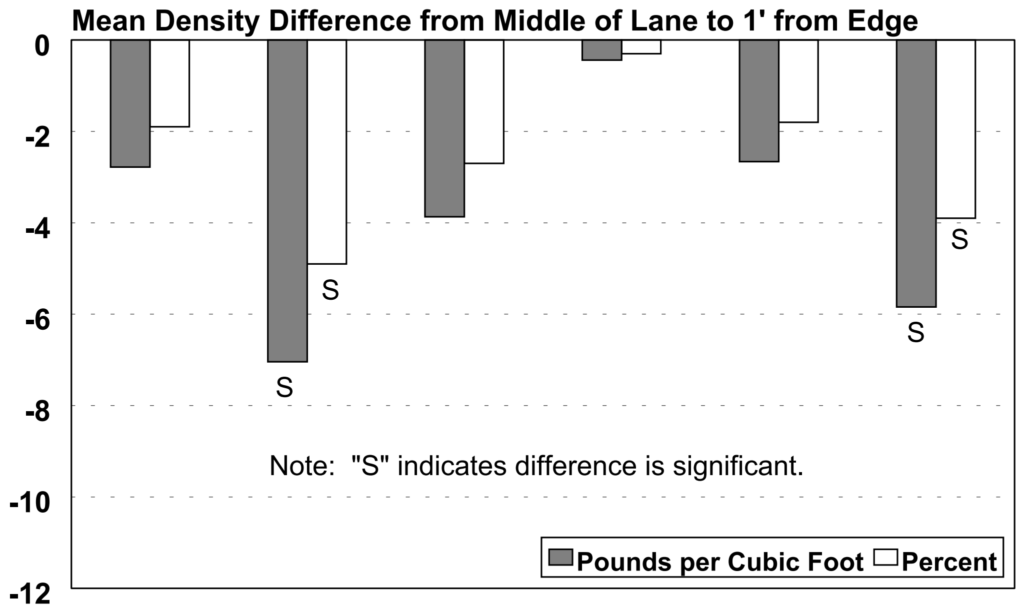


Figure 95. Summary of Mean Density Difference from Middle of Lane to 1 ft from Edge of Type C, Limestone Pavements.

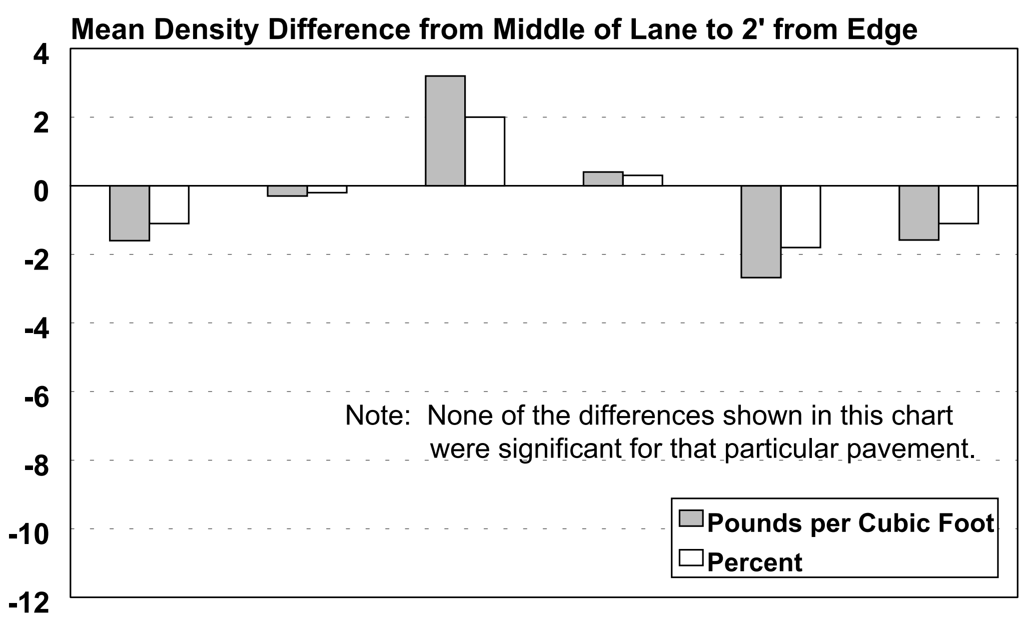


Figure 96. Summary of Mean Density Difference from Middle of Lane to 2 ft from Edge of Type C, Limestone Pavements.

6.2 TYPE C, CRUSHED GRAVEL PAVEMENTS

Density results for the Type C, crushed gravel mixes are shown in Figures 97 through 101. Density measurements made 6 inches from the unconfined edge (Figure 97) ranged from 2 to 12 lbs per cubic ft (1.8 to 9 percent) lower than in the center of the mat with an average of about 7 lbs per cubic ft (5 percent).

Only one of the pavements tested had a joint constructed at the time of testing, as shown in Figure 98. Density at this joint is significantly lower than in the middle of the lane. Figure 99 shows the measurements made on pavements at a confined edge also showing a lower density than in the middle of the mat; however, the difference is not significant.

Figures 100 and 101 show the mean density difference from the middle of the lane to 1 and 2 ft, respectively, from the edge. As expected, density generally improves as the measurements progress away from the edge.

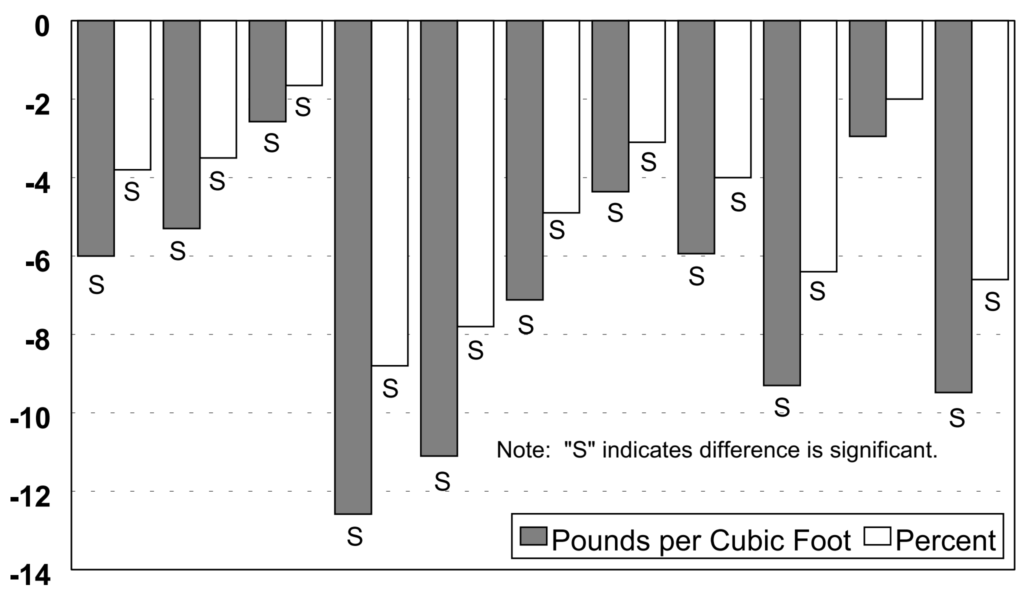


Figure 97. Summary of Mean Density Difference from Middle of Lane to the Unconfined Edge of Type C, Gravel Pavements.

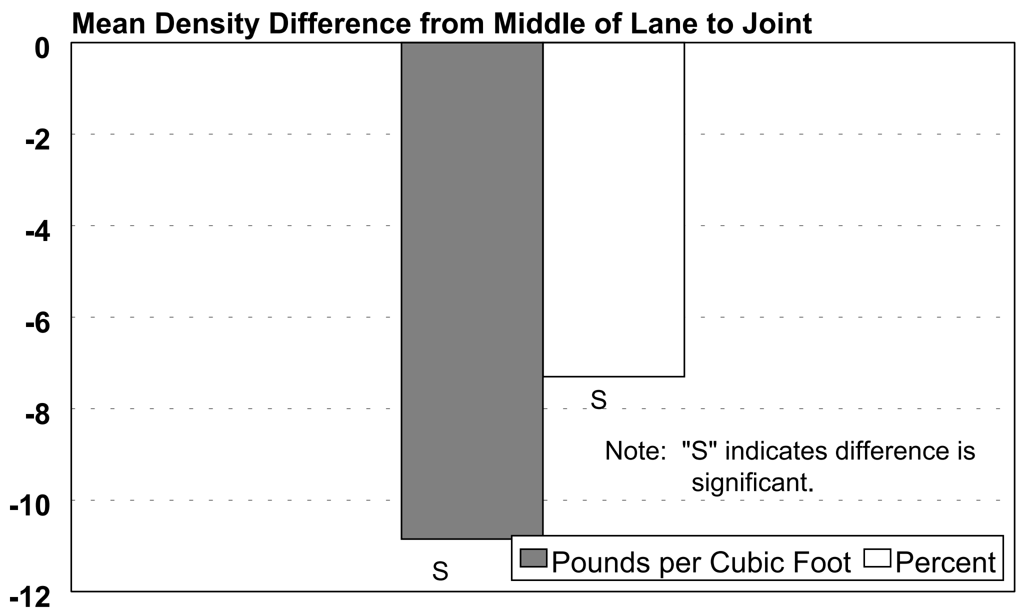


Figure 98. Summary of Mean Density Difference from Middle of Lane to the Joint of Type C, Gravel Pavements.

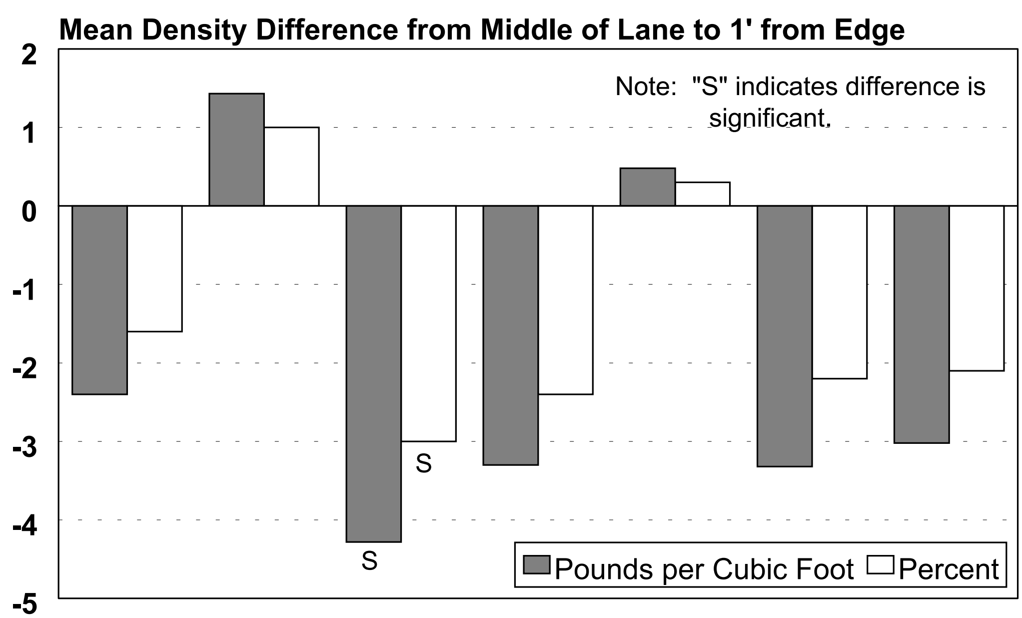


Figure 99. Summary of Mean Density Difference from Middle of Lane to the Confined Edge of Type C, Gravel Pavements.

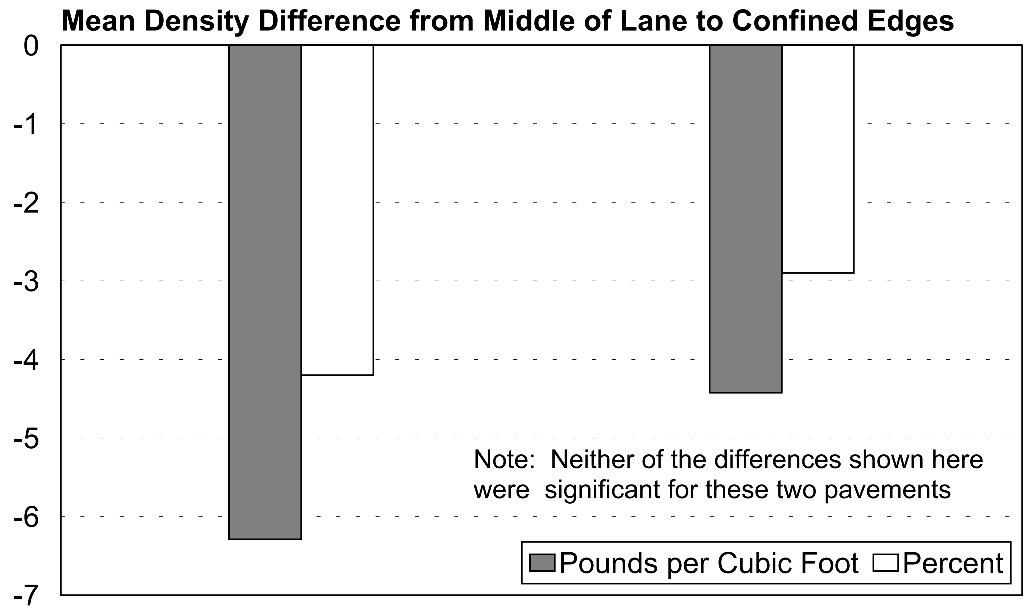


Figure 100. Summary of Mean Density Difference from Middle of Lane to 1 ft from Edge of Type C, Gravel Pavements.

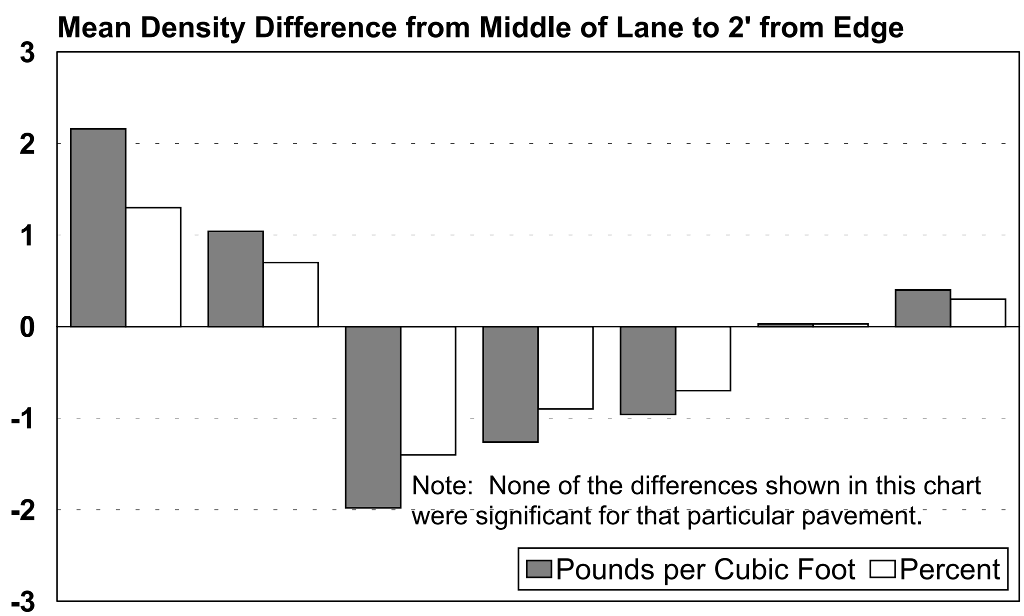


Figure 101. Summary of Mean Density Difference from Middle of Lane to 2 ft from Edge of Type C, Gravel Pavements.

6.3 TYPE D PAVEMENTS

Density results for the Type D, both gravel and limestone mixes, are shown in Figures 102 through 106. Data for the Type D mixes are comparable with what was shown for the Type C mixtures. Density measurements made 6 inches from the unconfined edge (Figure 102) ranged from about 1 to 10 lbs per cubic ft (0.5 to 7 percent) lower than in the center of the mat with an average of about 6 lbs per cubic ft (4 percent).

Four of the pavements tested had a joint constructed at the time of testing as shown in Figure 103. Densities for three of these pavements were significantly lower than in the middle of the lane. Figure 104 shows the measurements made on pavements at a confined edge. Four out of five pavements had lower densities than at the middle of the lane, though not significant.

Figures 105 and 106 show the mean density difference from the middle of the lane to 1 and 2 ft, respectively, from the edge. Several of the pavements had a significantly lower density 1 ft from the edge (Figure 105) but not at 2 ft from the edge (Figure 106).

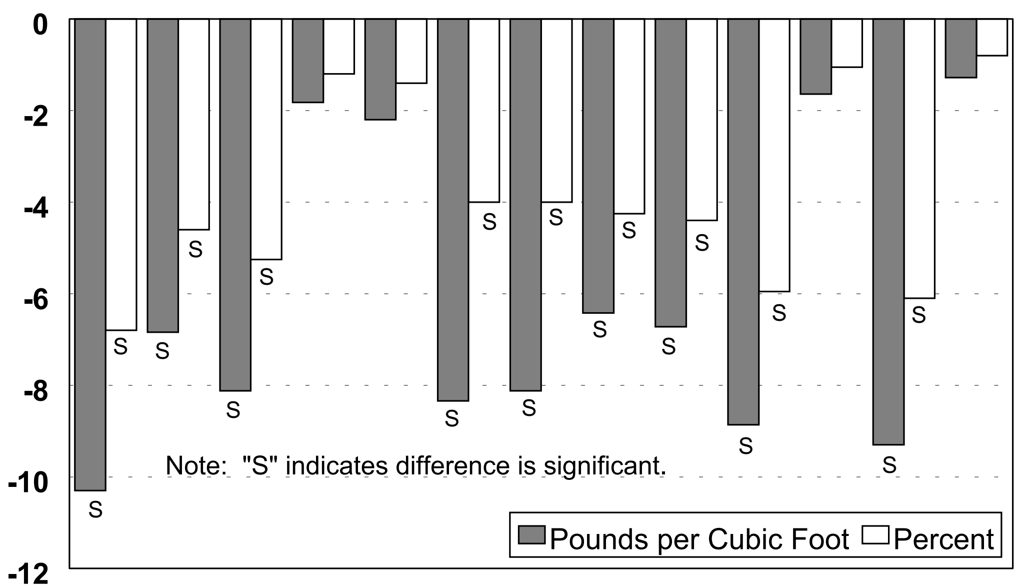


Figure 102. Summary of Mean Density Difference from Middle of Lane to Unconfined Edges of Type D Pavements.

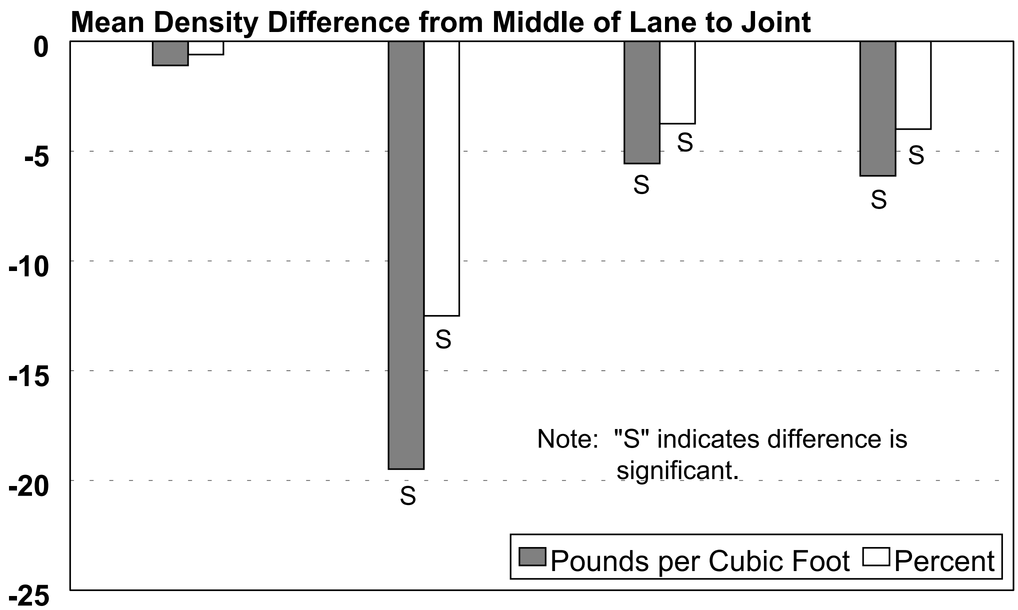


Figure 103. Summary of Mean Density Difference from Middle of Lane to the Joint of Type D Pavements.

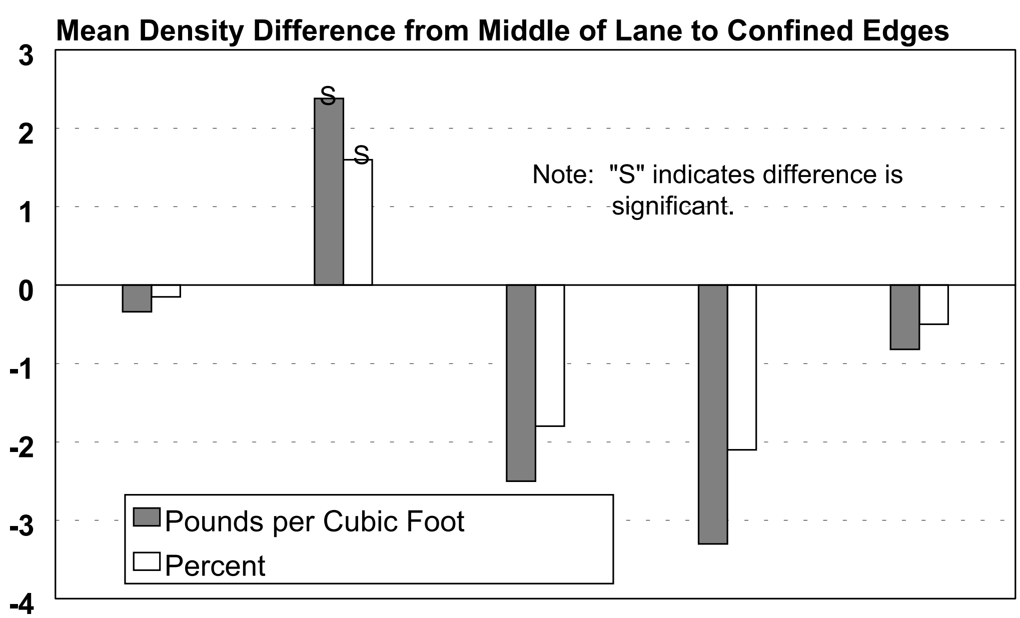


Figure 104. Summary of Mean Density Difference from Middle of Lane to the Confined Edge of Type D Pavements.

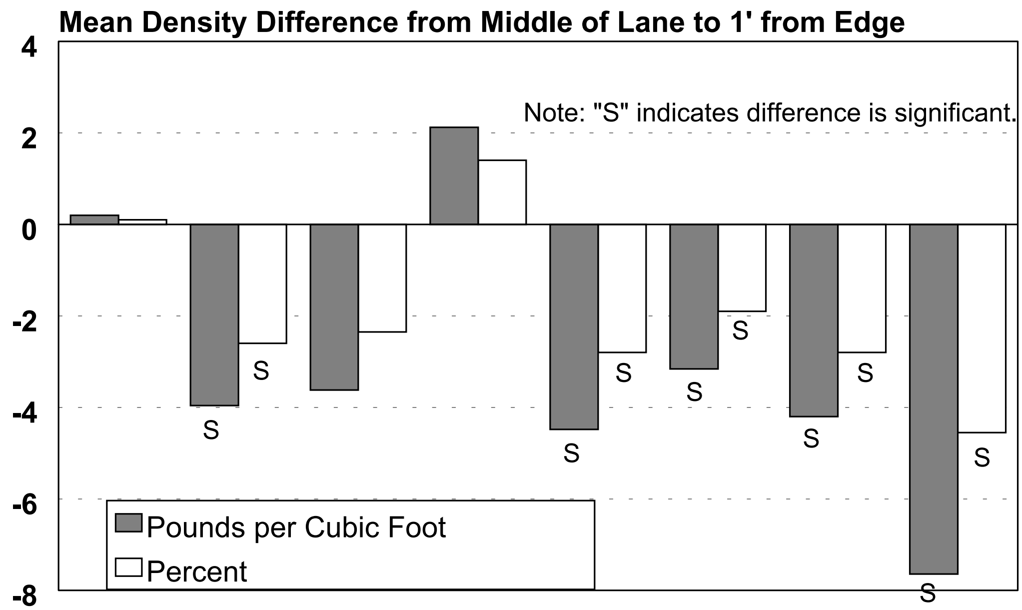


Figure 105. Summary of Mean Density Difference from Middle of Lane to 1 ft from Edge of Type D Pavements.

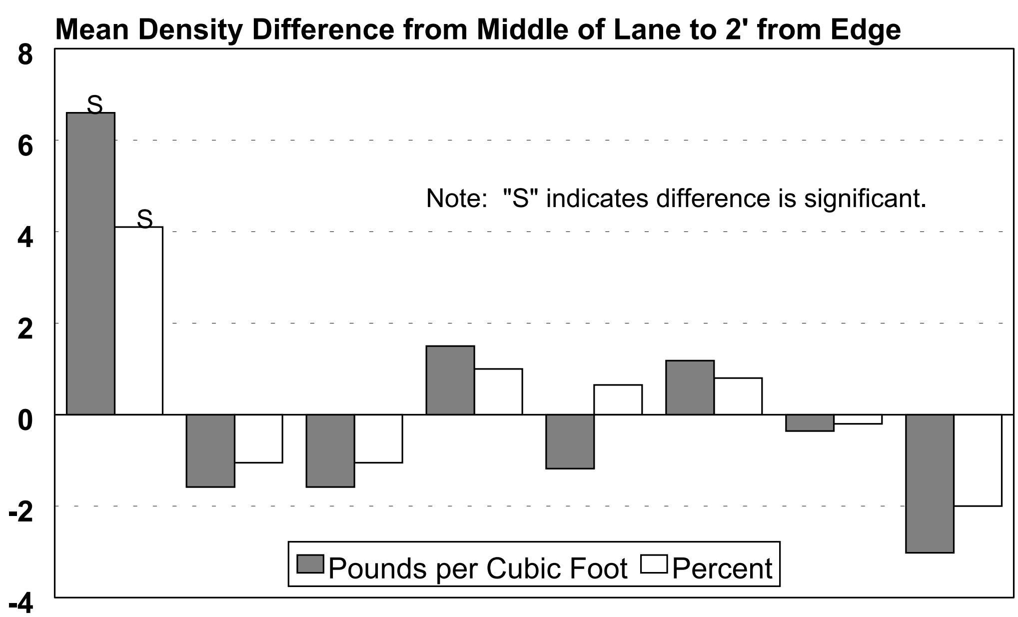


Figure 106. Summary of Mean Density Difference from Middle of Lane to 2 ft from Edge of Type D Pavements.

6.4 CMHB PAVEMENTS

Density results for the CMHB pavements are shown in Figures 107 through 111. Again, data for the CMHB mixtures are similar to both the Type C and Type D mixtures. Density measurements made 6 inches from the unconfined edge (Figure 107) ranged from about 4 to 14 lbs per cubic ft (2 to 10 percent) lower than in the center of the mat with an average of about 7 lbs per cubic ft (5 percent).

Three of the pavements tested had a joint constructed at the time of testing as shown in Figure 108. Densities for one of these pavements were significantly lower than in the middle of the lane. Figure 109 shows the measurements made on pavements at a confined edge. Only one of the four pavements had a significantly lower density than in the middle of the lane.

Figures 110 and 111 show the mean density difference from the middle of the lane to 1 and 2 ft, respectively, from the edge. Several of the pavements had a significantly lower density 1 ft from the edge (Figure 110) but not at 2 ft from the edge (Figure 111).

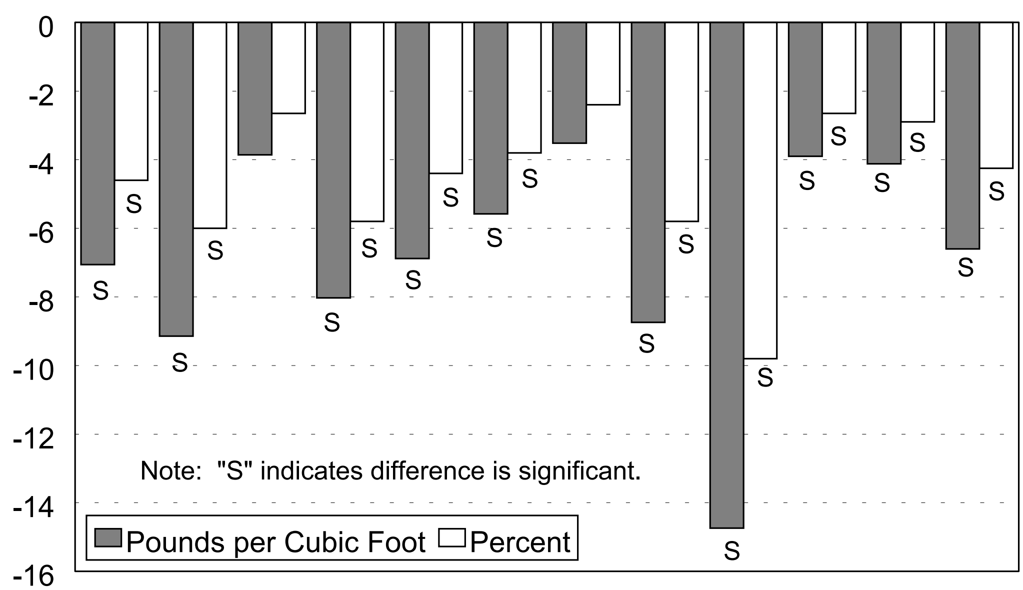


Figure 107. Summary of Mean Density Difference from Middle of Lane to Unconfined Edges of CMHB Pavements.

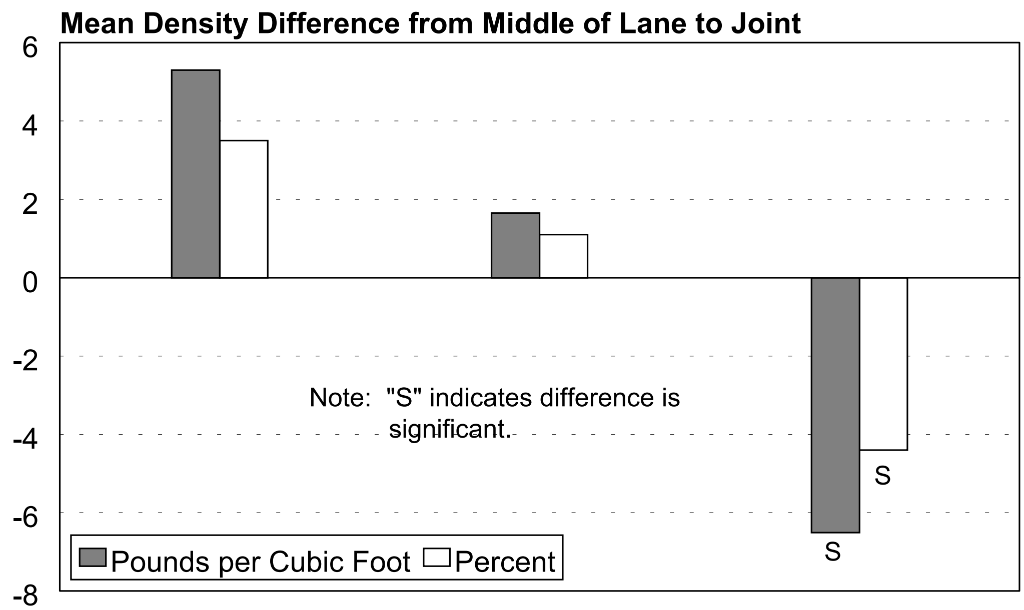


Figure 108. Summary of Mean Density Difference from Middle of Lane to the Joint of CMHB Pavements.

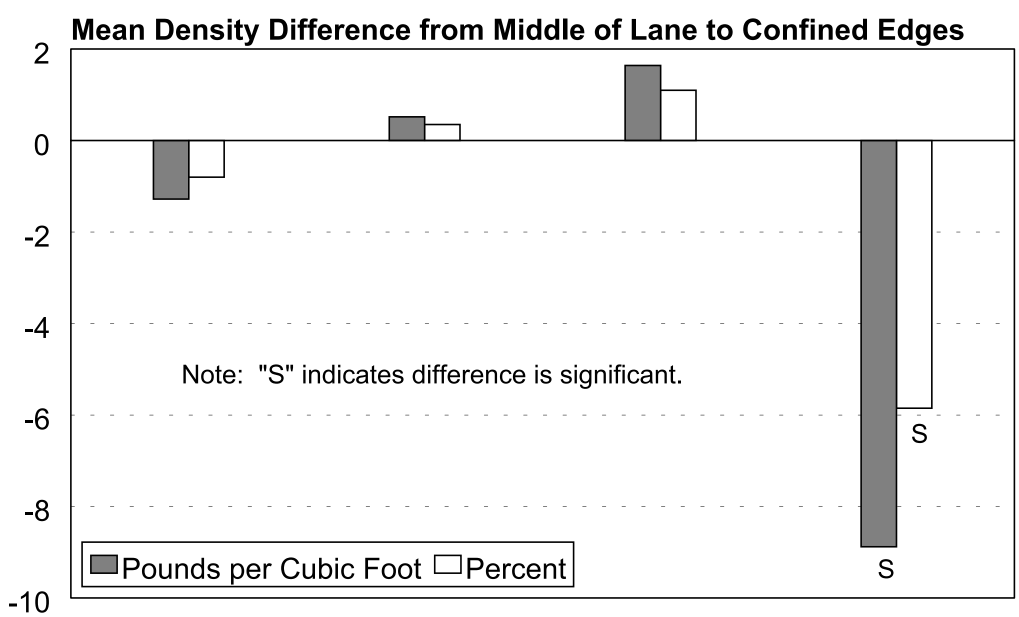


Figure 109. Summary of Mean Density from Middle of Lane to the Confined Edge of CMHB Pavements.

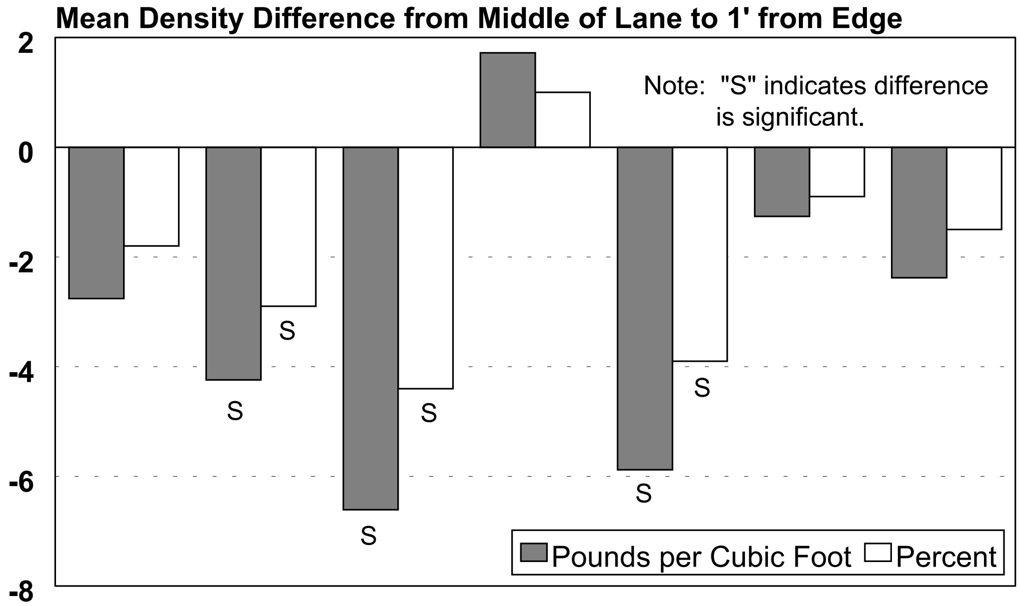


Figure 110. Summary of Mean Density Difference from Middle of Lane to 1 ft from Edge of CMHB Pavements.

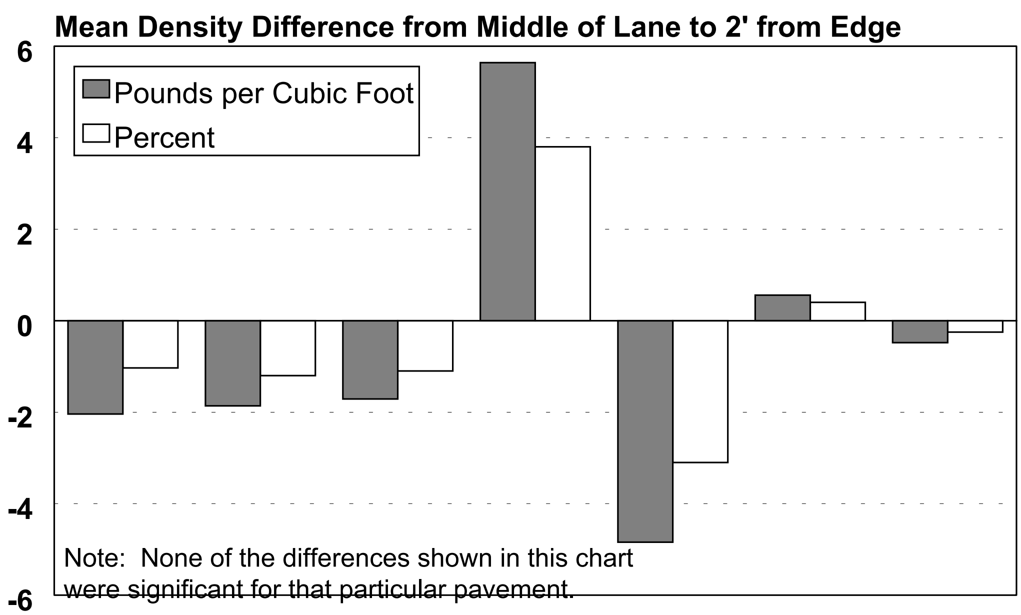


Figure 111. Summary of Mean Density Difference from Middle of Lane to 2 ft from Edge of CMHB Pavements.

6.5 PERMEABILITY OF FIELD CORES

Permeability tests were performed on the field cores and these data are presented in Figures 112 and 113. Dense grade mixtures, Type C and D, are grouped together in Figure 112. There is a trend in the data showing an expected increase in permeability as density decreases. This also corresponds to a higher permeability near the joint versus the center of the mat.

Permeability data for the CMHB cores are shown in Figure 113. Here there is no apparent trend of any kind.

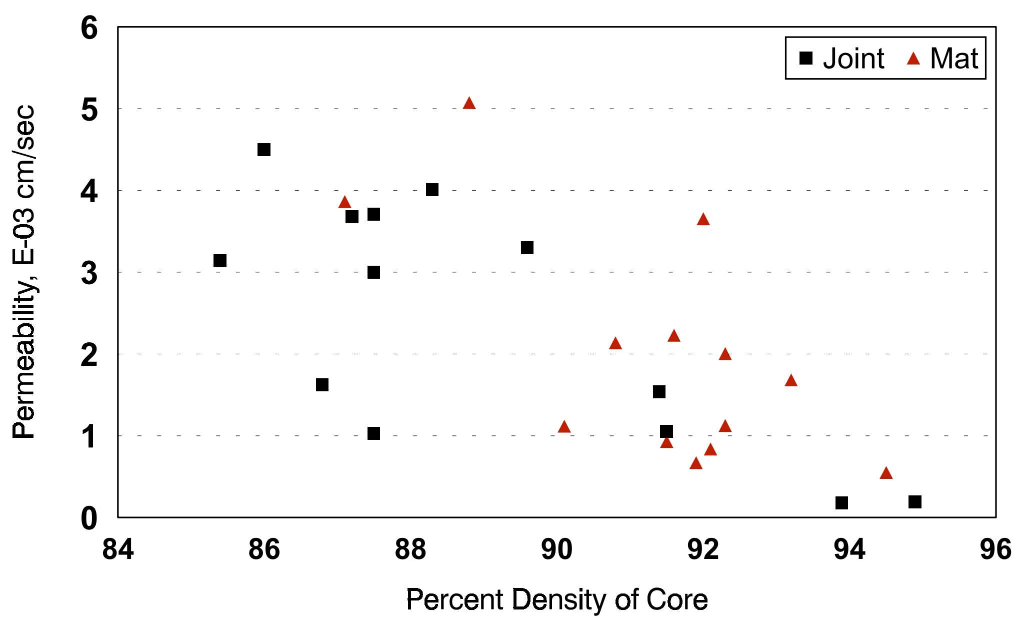


Figure 112. Permeability Data for Type D and Type C Pavement Cores.

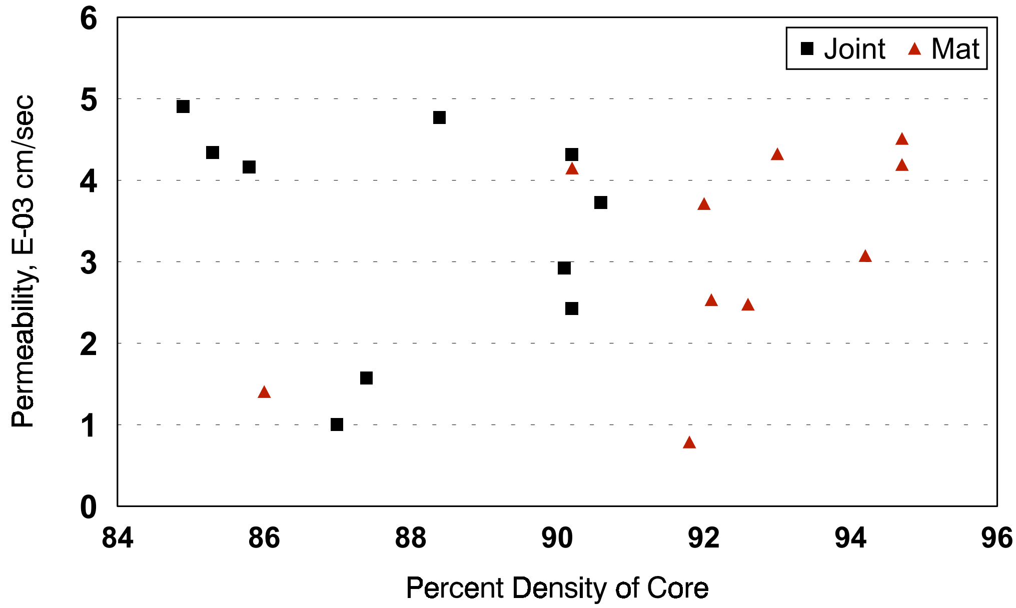


Figure 113. Permeability Data for CMHB Field Cores.

CHAPTER 7.0 FINDINGS AND RECOMMENDATIONS

7.1 FINDINGS FROM LITERATURE REVIEW

- In research studies done as early as 1964, the presence of a severe density gradient across the joint was observed. The area of low density was found to be in the edge of the lane placed first, whereas practically all of the special joint construction procedures are concerned with attempts to get a high density in the lane placed subsequently.

- Many different joint construction techniques were described in this report along with associated densities. In one of the more recent and extensive studies, the notched wedge joint construction technique was found to produce an increased centerline density as compared to conventional techniques.

- Specifications from several states that address density along the longitudinal construction joint are presented in the report and include both performance and method specifications. The New York DOT requires that the density at the joint be at least 90 percent of theoretical maximum compared to the mat density which must be 92 percent. The Missouri DOT requires that the joint density not be less than 2.0 percentage points below the specified density. Several other state specifications are found in Chapter 2.0.

- Very little information was available concerning costs associated with improving joint densities. Generally, it appears no appreciable cost increase will be expected with the implementation of a joint density specification.

7.2 FINDINGS FROM AIRFIELD PAVEMENT STUDIES

- Several projects were analyzed from recent Texas airfield asphalt paving projects constructed under the FAA P-401 specification which requires a longitudinal joint density. Based on these data, it is apparent that contractors are routinely able to meet the joint density requirements as specified in the FAA P-401 specification.

7.3 CASE STUDIES ON PERFORMANCE

- Three case studies were documented in this report wherein forensic investigations were performed to identify causes of premature pavement failures. In these three cases, the pavement failures were attributed largely to inadequate density at the longitudinal construction joint which allowed for excessive intrusion of water into the pavement structure.

7.4 FINDINGS FROM THE FIELD STUDY OF LONGITUDINAL JOINT DENSITIES

- The primary objective of this research project was to assess the density along the longitudinal construction joint of several Texas pavements to determine if a problem exists. Based on the field data presented in this report, researchers conclude there is a strong indication a problem exists and that a joint density specification for HMAC pavement construction is justified.

- Researchers collected density data on 35 pavements, primarily on Type C, Type D, and CMHB pavements. A few other pavements were included: Superpave, stone-filled asphalt, SMA, and heavy-duty SMA mixtures. Measurements were made transversely across the paved lane at the joint and/or unconfined edge, 12 inches from the edge, 24 inches from the edge and then compared to measurements in the middle of the lane. The field data confirmed what was discovered in the literature: the area of consistently low density was found to be in the edge of the lane paved first (or the unconfined edge).

- Almost all of the pavements showed a significantly lower density at the unconfined edge. This difference averaged about 6 to 7 lbs per cubic ft (or 4 to 5 percent) lower than the mat density. While this was an average, the range was from 2 to 12 lbs per cubic ft.

- Permeability tests on field cores showed that for the dense-graded Type D and C mixes, permeability was higher for the cores taken near the unconfined edge compared to those from the middle of the lane. There was no clear trend in the permeability data for the CMHB mixes.

7.5 SPECIFICATION RECOMMENDATIONS

During this research project, TxDOT developed a special provision to Special Specification Item 3146, Quality Control/Quality Assurance of Hot Mix Asphalt. This specification is shown below.

Article 3146.7 Construction Methods is supplemented by the following:

> (9) Longitudinal Joint Density: The Contractor shall perform a joint density verification for each sublot at the random sample locations selected for in-place air void testing. At each location the Contractor shall perform a nuclear density gauge reading within two foot of a mat edge that will become a longitudinal joint. This reading will be compared to a nuclear density gauge reading taken on the interior of the mat more than two foot from the mat edge. When the density within two foot of the mat edge is more than 5.0 lbs./c.f. below the interior mat density, the verification fails and the contractor shall investigate the cause and take corrective actions during production to improve the joint density.
>
> Production of the hot mix asphalt shall cease when two consecutive verifications fail unless otherwise approved by the Engineer. The Contractor shall make changes to the hot mix or the placement process before production is resumed. The Contractor may produce enough mixture to place approximately 2,000

linear feet of pavement one paver width wide. Two joint density verifications shall be performed within these 2,000 linear feet of production and if both verifications are acceptable, the Contractor may resume normal operations. However, if one or both of the joint density verifications fail, the Contractor shall make additional changes as approved by the Engineer and an additional 2,000 linear feet of pavement shall be laid and evaluated as before. This procedure of placing and evaluating 2,000 linear feet sections will be continued until both joint density evaluations pass.

The Engineer may require the Contractor to provide special joint making equipment or implement different joint construction methods to improve joint density. Normal production and joint density verification will resume when both joint density verifications pass. Although it is the Contractor's responsibility to perform joint density verifications, the Engineer may make as many independent joint density verifications as deemed necessary. The Engineer's results will be used to determine joint density when available.

The data presented in this report support the criteria in this specification. The specification addresses the problem area identified in this project: the low density near the edge of the mat laid first. The specification density difference of 5.0 lbs per cubic ft is slightly lower than the 6 to 7 lbs per cubic ft average difference observed in this project yet would provide for a significant increase in density.

REFERENCES

Baker, R.F., J. R. Croteau, J.J. Quinn, and E. J. Hellriegel, 1990. "Longitudinal Wedge Joint Study," *Transportation Research Record 1282,* Transportation Research Board, National Research Council, Washington, D.C.

Buchanan, S.M., 2000. "Evaluation of Notched-Wedge longitudinal Joint Construction." *Transportation Research Record 1712*, Transportation Research Board, National Research Council, Washington, D.C.

Burati, J.L. and G. B. Elzoghbi, 1987. "Study of Joint Densities in Bituminous Airport Pavements." *Transportation Research Record 1126,* Transportation Research Board, National Research Council, Washington, D.C.

Foster, C.R., S.B. Hudson and R.S. Nelson, 1964. "Constructing Longitudinal Joints in Hot-Mix Asphalt Pavements," *Highway Research Record No. 51,* Highway Research Board, National Research Council, Washington, D.C.

Kandhal, P.S. and R. B. Mallick, 1997. *A Study of Longitudinal Joint Construction Techniques in HMA Pavements (Interim Report - Colorado Project).* NCAT Report No. 96-3, National Center for Asphalt Technology, Auburn University, Alabama.

Kahdhal, P.S. and S. S. Rao, 1994. *Evaluation of Longitudinal Joint Construction Techniques for Asphalt Pavements (Michigan and Wisconsin Projects - Interim Report),* NCAT Report 94-1, National Center for Asphalt Technology, Auburn University, Alabama.