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Development of a Joint Density Specification Phase II: Evaluation of 2004 and 2005 Test Sections

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16. Abstract

Hot mixed asphalt (HMA) pavements are normally constructed with multiple passes of the paver. Typically, one lane is laid-down with each pass. Consequently, a longitudinal construction joint is formed between the constructed lanes. A low density at the longitudinal joint would result in water penetrating into the HMA layer and damaging the HMA mix and the supporting layers. The water damage usually causes premature failure of the flexible pavement. One way to avoid such failures is to construct a dense longitudinal joint that would prevent the intrusion of water.

The overall objective of this research was to establish the needed knowledge base for the development and implementation of a longitudinal joint specification for the Nevada Department of Transportation (NDOT). A field-testing program was carried out to evaluate the effectiveness of the various joint geometries and compaction techniques in increasing the joint density and providing improved performance.

In order to meet the objective of this research two field-testing programs were conducted. The field-test projects in the summer 2004 evaluated five joint geometries and two joint rolling techniques. The field-test project in the summer 2005 evaluated the three most promising joint geometries as identified from the summer 2004 program.

Based on the analysis of the data generated from all the field-testing programs, it is recommended that NDOT implements the following joint density specification:

- **The density at the joint should be a maximum of 2% less than the corresponding mat density.**

AND

- **The density at the joint should be a minimum of 90% of the theoretical maximum density (TMD).**

Reviewing the data from the summer 2005 project on the joint densities and the differences between the mat and joint densities leads to the following conclusion: All three joint geometries: natural slope (A), cut edge with rubberized tack coat (C), and tapered joint at 3:1 (E) will meet the recommended joint density specification

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DEVELOPMENT OF A JOINT DENSITY SPECIFICATION
PHASE II: EVALUATION OF 2004 AND 2005 TEST SECTIONS

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EXECUTIVE SUMMARY

Hot mixed asphalt (HMA) pavements are normally constructed with multiple passes of the paver. Typically, one lane is laid-down with each pass. Consequently, a longitudinal construction joint is formed between the constructed lanes. A low density at the longitudinal joint would result in water penetrating into the HMA layer and damaging the HMA mix and the supporting layers. The water damage usually causes premature failure of the flexible pavement. One way to avoid such failures is to construct a dense longitudinal joint that would prevent the intrusion of water.

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INTRODUCTION

Hot mixed asphalt (HMA) pavements are normally constructed with multiple passes of the paver. Typically, one lane is laid-down with each pass. Consequently, a longitudinal construction joint is formed between the constructed lanes. The density of the HMA mix at the longitudinal joint depends on the geometry of the joint and the compaction technique.

The density of the HMA mix at the longitudinal joint is usually lower than the density of the HMA mix throughout the regular mat away from the joint. This low in-place density translates into higher air-voids around the longitudinal joint leading to the penetration of moisture into the HMA mix. As the HMA pavement is subjected to environmental effects and traffic loads, the moisture-saturated mix at the joint becomes an easy target for moisture-related damages such as stripping and raveling.

Further damage of the joint allows moisture to penetrate to the base and subbase layers leading to great reduction in the strength properties of these layers. As a result of this water intrusion, the entire pavement structure weakens and failures occur under the action of repeated traffic loads and environmental factors.

One way to avoid such failures is to construct a dense longitudinal joint that would prevent the intrusion of water. Several joint geometry and compaction techniques have been recommended to optimize the density and performance of the longitudinal joint. A successful joint construction technique would provide a joint with high density and strong bond between the two paved lanes. The high-density requirement can be checked during the construction process while the strong bond assessment requires long-term performance monitoring of the pavement.

Objectives

The overall objective of this research was to establish the needed knowledge base for the development and implementation of a longitudinal joint specification for the Nevada Department of Transportation (NDOT). This objective was met through the conduct of two major phases:

a) Phase I. Review the literature on research efforts and current specifications for longitudinal joint geometries and compaction techniques employed by various highway agencies.

b) Phase II. Conduct a field-testing program to evaluate the effectiveness of the various joint geometries and compaction techniques in increasing the joint density and providing improved performance.

Scope

In order to meet the objective of this research two field-test projects were built in the summer 2004: one project on highway US 395 - Washoe Valley in northern Nevada and one project on highway US 95 - Las Vegas in southern Nevada, and one project was built in the summer 2005: on highway US 395 – Cold Springs in northern Nevada. The summer 2004 field-testing program evaluated five joint geometries and two compaction techniques. The five joint geometries selected were:

- Natural slope
- Edge restraining device
- Cut edge with rubberized asphalt tack coat
- Cut edge without rubberized asphalt tack coat
- Tapered joint at 3:1.

The rolling techniques selected were:

- Rolling from the hot side with 6” overlap on the cold side
- Rolling from the hot side at 6” away from the joint

Nuclear density gauges and field cores were used to evaluate the in-place density of each treatment. The densities were measured at both sides of the joint and at the mid-width of the mats of the two lanes placed on each side of the joint.

Based on the analyses of the density data collected from the two field projects constructed in the summer 2004, three joint geometries were selected for further evaluation: natural slope, cut edge with rubberized tack coat, and tapered joint at 3:1. These three joint geometries were evaluated on a field project constructed in the summer 2005 on highway US 395 Cold Springs. Field cores were used to measure the in-place densities at both sides of the joint and at the mid-width of the mats of the two lanes placed on each side of the joint.

BACKGROUND

Several research studies have been conducted to evaluate the effectiveness of the various joint geometries and compaction techniques. Most studies evaluated the impact of the various techniques on the joint density and its performance. A total of four studies were reviewed and summarized in Reference 1. The review of previous research efforts on joint geometries and compaction techniques led to the following conclusions and findings:

- Numerous longitudinal joint geometries were evaluated through field studies conducted by the National Center for Asphalt Technology. However, the research did not identify an optimal method for joint construction.

- The studies conducted by Quality Engineering Solutions in Nevada and the Texas Transportation Institute in Texas identified the urgent need for specifications on the longitudinal joint density.

- The study conducted by the New Jersey DOT showed that the wedge geometry of the longitudinal joint would provide better performance than the vertical face geometry.

Another task of this research was to review the current specifications on the construction and density requirements for longitudinal joint of Hot Mix Asphalt (HMA) pavements. The specifications from all fifty Departments of Transportation (DOT), the local Regional Transportation Commissions, and the Federal Aviation Administration (FAA) were reviewed. The review covered the following issues:

- Joint density specifications
- Joint geometry recommendations
- Joint rolling patterns
- Joint density measurement techniques
- Joint density incentives and disincentives

The specification reviews were summarized in Reference 1. The review of the specifications led to the following conclusions and findings:

- Ten state highway agencies and the FAA have formal specifications for longitudinal joint density.

- The majority of the current longitudinal joint density specifications call for either a percent of theoretical maximum density or a relative density.

- Only four highway agencies specify the longitudinal joint geometry.

- Only three highway agencies specify the compaction technique at the longitudinal joint.

- Only three highway agencies apply incentives/disincentives based on the density of the longitudinal joint.

FIELD-TESTING PROGRAMS

The objectives of the field-testing programs were to evaluate the effectiveness of the various joint geometries and compaction techniques in increasing the joint density and providing improved performance. Two field-testing programs were conducted: summer 2004 and summer 2005. The summer 2004 field-testing program evaluated five joint geometries and two compaction techniques. The summer 2005 field-testing program evaluated the three most promising joint geometries. The following presents a description of the techniques recommended for field evaluation. The lane paved first is referred to as the “cold side” and the lane paved second is referred to as the “hot side.”

Project Selection

Some of the requirements established for the project selection were:

- Sufficient length to enable the construction of all the test sections on a continuous and tangent section of the highway.
- Adequate and homogeneous structural behavior over the entire length of the field project.
- Adequate width to allow for proper traffic control, provide safety conditions to the construction crew and researchers as well as to the highway users.
- Allowing adequate time frame to modify the project’s specifications to include the construction procedures required for the test sections.
- Ensure the implementation of this research over the different materials and environmental conditions throughout the state.
- Project characteristics in which the most common or widely used construction methods in Nevada could be applied.

After reviewing all the possible projects that met these requirements, two projects were selected by NDOT personnel as candidates for the summer 2004 program and one project was selected for the summer 2005 program. A detailed description of each of the projects is provided in the appropriate sections.

Joint Geometry

The joint geometry is formed during the construction of the first lane. A total of five joint geometries were recommended for field evaluation in the summer 2004. Each joint geometry was constructed over a minimum of 700 feet long test section. The following represents a description of the recommended joint geometries.

- ***Natural Slope (Geometry A):*** the HMA mix was left on its natural angle of repose as is achieved by the paving process.
- ***Edge Restraining Device (Geometry B):*** this device provides lateral support at the edge of the first paving lane during compaction. It consists of a hydraulically powered wheel that rolls alongside the compactor’s drum simultaneously pinching the unconfined edge of the mix towards the drum and provides lateral support. Previous experience with this technique showed it to provide high joint density.

- ***Cut Edge with Rubberized Asphalt Tack Coat (Geometry C):*** the edge of the first paving lane was cut to a vertical face after the compaction of the mat was completed. In this technique, the vertical cut face was tack coated with rubberized asphalt. Previous experience with this technique provided good joint performance. A technical representative from the rubberized tack coat supplier was present at the site during the construction of the test sections.

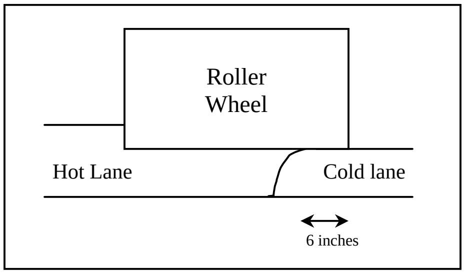
- ***Cut Edge without Rubberized Asphalt Tack Coat (Geometry D):*** the edge of the first paving lane was cut to a vertical face after the compaction of the mat was completed. In this technique, the vertical cut face was not tack coated.

- ***Tapered Joint at 3:1 (Geometry E):*** the edge of the first paving lane was tapered at a 3:1 slope. The taper was achieved through a steel plate connected to the paver. No special compaction effort was placed on the tapered edge. Previous experience with this technique showed good performance.

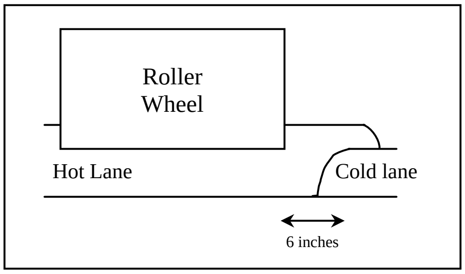
Joint Compaction Technique

The summer 2004 field-testing program evaluated two joint compaction techniques on each of the five joint geometries. The following represents a brief description of the joint compaction techniques that were evaluated.

- ***Pattern I - Rolling from the Hot Side with 6" Overlap on the Cold Side:*** as shown below, compaction started (i.e. first pass) from the hot side of the joint. The major portion of the roller was on the hot side with just an overlap of about 6" on the cold side.



- ***Pattern II – Rolling from the Hot Side at 6" away from the Joint:*** as shown below, compaction started (i.e. first pass) from the hot side of the joint. The roller was kept at 6" away from the joint. This rolling procedure tends to push the loose HMA mix towards the joint.



Compaction of the First-Paved Lane

The first-paved lane included the unsupported edge at the location where it would meet the second-paved lane forming the longitudinal joint. When compacting the first-paved lane, the roller can be placed at three locations: a) inside the unsupported edge; this leads to transverse movement of the mix and the formation of a crack near the joint, b) directly over the unsupported edge: this leads to transverse movement of the mix but no crack will form, and c) extended over the unsupported edge; this situation does not cause any transverse movement of the mix. In this research, the first-paved lane was compacted with the roller having 2-4" hang over the unsupported edge.

SUMMER 2004 FIELD-TESTING PROGRAM

Sections Layout

Figure 1 shows the proposed layout of the test sections on the two field projects constructed in the summer 2004 field-testing program. The total number of sections on each project is: 5 (joint geometries) x 2 (compaction patterns) = 10. The goal was to construct sections with minimum length of 700 feet. Some of the sections on the Las Vegas project were little shorter than 700 feet. Also the layout of the sections differs from the one proposed in Figure 1. The actual sections length and layout for each project will be presented when the specific project is discussed.

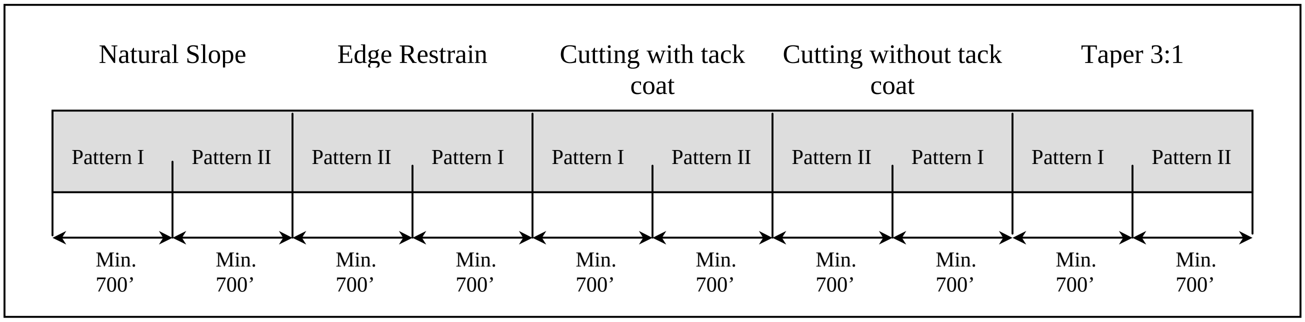


Figure 1 Proposed Layout of Test Sections.

Density Measurements

In order to assess the effectiveness of the various techniques in increasing the joint density and providing improved performance, joint and mid-mat densities were measured during the construction of the test sections. The long-term performance of the joint will be used to evaluate the long-term effectiveness of the techniques. This task is not included in this report.

Figure 2 shows a simplified sketch of the density measurement plan. Typically, the elevations at both sides of the joint are not leveled, this leads to an un-leveled nuclear density gauge over the longitudinal joint. Therefore, nuclear density measurements were taken at both sides of the joint and not over the joint. Nuclear density measurements were conducted at the cold side and hot side of the joint at 10 locations within each test section. At each side of the joint, two readings were performed parallel to the joint and 180 degrees apart. Both readings were averaged and recorded as the hot and cold side densities. The nuclear gauge was placed as close to joint as possible, generally between 4 to 6 inches away from the joint. Nuclear density readings were also measured at the mid-width of the cold side and hot side of the mat at the same 10 locations where the joint densities were measured. At each location four readings were taken 90 degrees apart. The average of the four readings was recorded as the density of the cold and hot mid-width mats.

A 4" core was cut at each location where a nuclear density measurement was taken (i.e. at both the joint and the mid-width of the mat). Cutting cores directly over the joint for density measurements was avoided due to the fact that a core obtained over the joint consists of both sides of the joint and will not represent the true impact of the joint geometry. A total of 40 cores were obtained from each section.

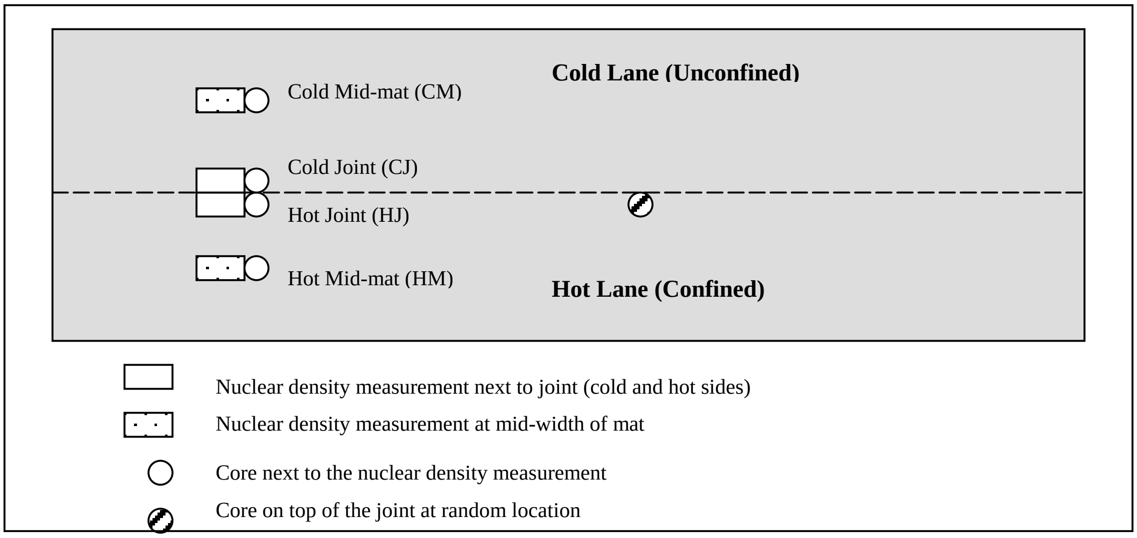


Figure 2 Density Measurements Diagram.

In addition, a 4” core was cut on top of the joint at three random locations within each section. Visual inspections of these cores indicated very uniform and tight structure of the mixtures for all joint geometries and compaction patterns. It was almost impossible to identify the joint through the cores.

US 395 Washoe Valley Project

The first project selected for this study was Contract 3208. It corresponds to a section on highway US 395 in Washoe Valley, from the Carson City/Washoe County Line to Bowers Mansion Road (SR 429). The test sections started at station 111+00 and ended at station 181+00 (10 sections, 700 feet each). The project consisted of a 2” cold milling and the placement of a 2” plantmix bituminous surface and ¾” open-graded wearing course. The constructed longitudinal joint lays between the travel lane and the passing lane in the southbound direction.

Construction of the test sections started on the evening of July 27, 2004 and was completed the morning of July 30, 2004. Nuclear density readings and cores were obtained between July 28 and August 3, 2004. The contractor for the project was Sierra Nevada Construction (SNC) and Frehner Construction Co. was the producer of the HMA mix. The HMA mix used on the project had the following properties:

- Mix design asphalt content of 6.0% by dry weight of aggregates (dwa)
- Binder grade: PG 64-28NV
- Coarse Aggregates were marinated for 48 hours with 1% lime by dwa and the fine aggregates were marinated with 2% lime by dwa.
- The aggregate gradation employed in the project is shown in Table 1.

Table 1 Aggregate Gradation – US 395 Washoe Valley Project.

Sieve Size	% Passing	Job-Mix formula	Specifications
1”	100	100	100
¾”	92	88 - 95	88 - 95
½”	77	70 - 84	70 - 85
3/8”	67	60 - 74	60 - 78
No. 4	50	43 - 57	43 - 60
No. 10	34	30 - 38	30 - 44
No. 40	16	12 - 20	12 - 22
No. 200	5	3 - 7	3 - 8

The project was paved at night between the hours of 8 p.m. and 4:30 a.m. The mix arrived at the site at a temperature between 280° F and 300° F. The ambient temperature during paving ranged from 82°F to 65°F. A Shuttle Bugey ROADTEC SB –2500C was used to load the mix from the windrow into the paver (Ingersoll Rand PF 3200). The breakdown rolling was performed by a steel drum roller (CAT CB634D). The other rollers were a steel drum roller (Ingersoll Rand DD110HF) and a pneumatic roller (CAT PS360B). The breakdown rolling consisted of two passes, forward in static mode and back in vibration mode. The Pneumatic roller applied one pass and the finishing roller applied two passes both ways in the static mode. Figure 3 shows the order in which the test sections were constructed. The rubberized asphalt tack coat was applied by CRAFCO personnel. The temperature of the heating oil was 400°F and the temperature of the tack coat during placement was 359°F.

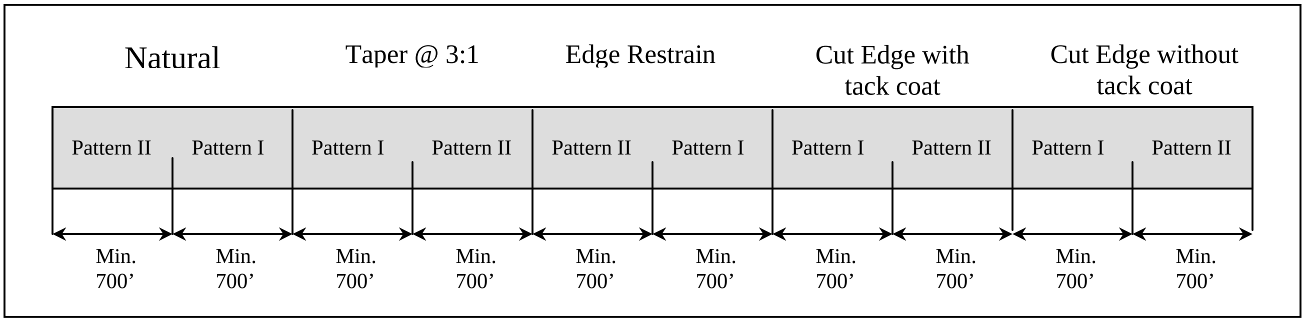


Figure 3 Layout of Test Sections on the US 395 Washoe Valley Project.

US 95 Las Vegas Project

The second project selected for this study was Contract 3192. It consisted of a section on highway US 95 in Clark County from Craig Road (SR 573) to 0.76 miles north of Kyle Canyon Road (SR 157). The test sections started at station 334+59 and ended at station 397+00. The longitudinal joint was constructed between the travel lane and the inside shoulder in the northbound direction. The project consisted of a 2 ¾” cold milling and the placement of a 2” plantmix bituminous surface and ¾” open-graded wearing course.

The Construction of the test sections started on the evening of August 22, 2004 and was completed the morning of August 23, 2004. Nuclear density readings and cores were obtained between August 23 and August 26, 2004. The contractor for the project was Frehner Construction Co. The HMA mix used on the project had the following properties:

- Mix design asphalt content of 4.1% dwa
- Binder grade: PG 76-22NV
- Coarse Aggregates were marinated for 48 hours with a 1% lime by dwa and the fine aggregates were marinated with a 2% lime by dwa.
- The aggregate gradation employed in the project is shown in the Table 2.

The project was paved at night between the hours of 6 p.m. and 4:30 a.m. The mix arrived at the site at a temperature between 319° F and 326° F. The ambient temperature during paving ranged from 96°F to 72°F. A Shuttle Bugey ROADTEC SB –2500B was used to load the mix from the windrow into the paver (CAT AP-1000B). The rolling was performed by two steel drum rollers (CAT CB634D) and a pneumatic roller (CAT

PS360B). The breakdown rolling was performed by the CAT roller and consisted of one pass in vibration mode and back in static, and a second pass in vibration mode both ways. The pneumatic roller applied five passes over the entire lane. And finally the CAT finishing roller applied two passes to each section, the first pass in vibration mode and the last one in static mode. Figure 4 shows the order in which the test sections were constructed. The rubberized asphalt tack coat was applied by personnel from the CRAFCO Corporation. The temperature of the heating oil was 391°F and the temperature of the tack coat during placement was 318°F.

Table 2 Aggregate Gradation – US 95 Las Vegas Project.

Sieve Size	% Passing	Job-Mix formula	Specifications
1”	100	100	100
¾”	92	88 - 95	88 - 95
½”	75	70 - 82	70 - 85
3/8”	65	60 - 72	60 - 78
No. 4	49	43 - 56	43 - 60
No. 10	35	31 - 39	30 - 44
No. 40	18	14 - 22	12 - 22
No. 200	7	5 - 8	3 - 8

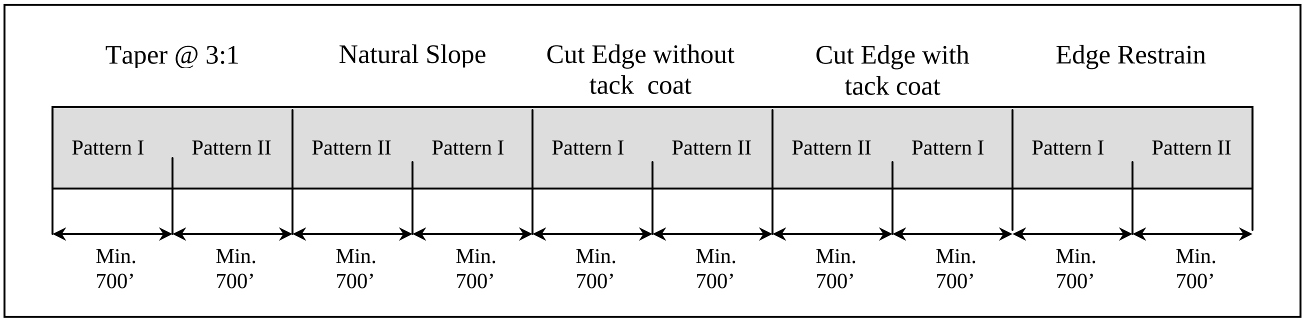


Figure 4 Layout of Test Sections on the US 95 Las Vegas Project.

Collection of Density Data

Field Cores

A total of 40 cores were obtained from each test section resulting in a total of 400 cores from each project (i.e. 800 cores from both projects). The cores were cut at both ends to isolate the layer under study and to provide a smooth surface on the top and bottom of each core. AASHTO Test Procedures T 166-00 Method A, T 209-99, and T 269-97 were used to determine the bulk specific gravity, theoretical maximum specific gravity, and air voids of the samples, respectively (2). Additionla 30 cores per project were taken directly over the joint.

Nuclear Densities

A total of 40 nuclear densities were measured in the field at the predetermined locations for each test section. Correction factors were obtained for each of the nuclear gauges used at both projects by correlating the densities measured by the nuclear gauges and the densities of the cores. Correction factors were applied to each individual reading, according to the nuclear gauge used to conduct the measurements. The objective of the individual correction factors is to reduce the error associated with the nuclear density measurements.

Theoretical Maximum Specific Gravity

The theoretical maximum specific gravity employed in the density calculations was obtained from field samples used for the quality control testing performed by NDOT personnel. Additionally, loose mix samples were collected by the UNR personnel to corroborate the theoretical maximum specific gravity data. Table 3 summarizes the theoretical maximum specific gravities obtained by NDOT and UNR personnel and the AASHTO T209-13 criteria for judging the acceptability of the theoretical maximum specific gravity test results. The data in Table 3 show that all NDOT and UNR results are within the acceptable AASHTO variability ranges.

Table 3 NDOT and UNR Theoretical Maximum Specific Gravities for the Washoe Valley and Las Vegas Projects.

Project	NDOT Gmm	UNR Gmm	Obtained Range	Acceptable range of two results	Standard Deviation	Acceptable Standard Deviation
US 395 Washoe Valley	2.399	2.403	0.004	0.019	0.0028	0.0064
	2.432	2.429	0.003		0.0021	
	2.402	2.408	0.006		0.0042	
	2.409	2.408	0.001		0.0007	
US 95 Las Vegas	2.643	2.639	0.004		0.0028	
	2.623	2.632	0.009		0.0064	
		2.622	0.001		0.0055	

Analysis of the Density Data

Analysis of Outliers

Due to the large number of density measurements obtained from each test section, an intensive statistical analysis was performed to determine the presence of outliers and to evaluate the variability of the measurements within each section. The following nomenclature was used throughout the analyses: Hot Mat (HM), Hot Joint (HJ), Cold Joint (CJ), and Cold Mat (CM).

Even though the field test sections were constructed as homogeneous as possible by following the same construction procedure, several outliers were determined through a statistical analysis and were discarded. The statistical analysis used to determine the presence of outliers included a studentized residuals analysis and a DFFITS analysis. The studentized residuals analysis checks for the experimental error of each observation as the difference between the value of the observation and the estimate of the treatment mean. The DFFITS analysis checks for influential observations by quantifying how much the standard deviation of a data set is influenced by an observation. Tables 4 and 5 present the number of outliers and their locations. The total number of densities available at each location within each section is 10. The data in Tables 4 and 5 show that there is no specific trend in the formation of the outliers. Once the outliers were identified and excluded from the analysis, average densities were calculated for each test section and for each project.

Table 4 Number of outliers at the Four Locations for each Section employing both density measurement procedures on the US 395 Washoe Valley Project.

Geometry	Rolling Pattern	Cores densities				Nuclear densities			
		HM	HJ	CJ	CM	HM	HJ	CJ	CM
A	I	1	1		1				
	II	1				2			
B	I			3				1	
	II							2	
C	I				1				
	II								
D	I						1		
	II	1				1			
E	I		2					1	
	II								

Table 5 Number of outliers at the Four Locations for each Section employing both density measurement procedures on the US 95 Las Vegas Project.

Geometry	Rolling Pattern	Cores densities				Nuclear densities			
		HM	HJ	CJ	CM	HM	HJ	CJ	CM
A	I	1							
	II						1	1	
B	I					1			2
	II	3	1			3	1		
C	I								
	II								
D	I								
	II	1		2		1		1	
E	I		1	1					
	II			1			1		

Comparative Analyses

The density data collected from field cores and the nuclear gauges were used in two different analyses: a) variability and comparison of densities within each of the sections and b) comparison of densities among test sections and between the two projects.

Variability of the Density Data along the Test Sections

The objective of this analysis was to assess the variability of the density data throughout each test section as measured by both the nuclear density gauge and the cores. Figure 5 shows a typical distribution of the core densities at the four locations throughout one of the test sections on the US 395 Washoe Valley project.

Tables 6 and 7 summarize the nuclear and cores densities distribution at the four locations throughout each section for the two projects. The average, standard deviation, and coefficient of variation (CV) were selected as the statistical parameters employed to assess the variability within each test section for the Washoe Valley and the Las Vegas projects.

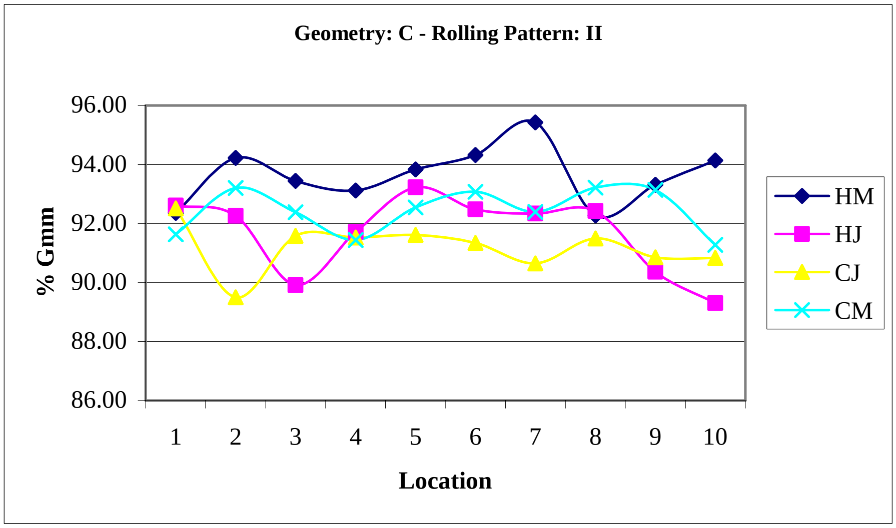


Figure 5 Typical Distribution of Cores Densities for the US 395 Washoe Valley Project.

It should be noted that the data presented in Tables 6 and 7 exclude all outliers that were identified in the previous analysis. The data in Tables 6 and 7 show a very low variability within each test section for the two projects and for both measurement procedures. The highest standard deviation and CV of 3.39 and 3.42, respectively, were found at the cold side joint of section II-B of the Washoe Valley Project and at the hot side mid-mat of section II-B of the Las Vegas project. The relatively low values of the standard deviation and the coefficient of variation prove that an adequate repeatability exists within each test section at the specific location across the pavement.

Table 6 Density Distribution at the Four Locations for each Section on the US 395 Washoe Valley Project.

Test Section	Statistical Parameter	Cores Densities				Nuclear Densities			
		Location				Location			
		HM	HJ	CJ	CM	HM	HJ	CJ	CM
I-A	Averg	89.7	90.2	90.6	90.8	87.4	87.7	89.7	90.7
	Std Dev	1.42	1.30	0.72	1.08	1.70	1.99	1.43	1.07
	CV	1.58	1.44	0.79	1.19	1.95	2.26	1.59	1.18
II-A	Averg	90.9	90.4	91.1	91.3	92.1	92.7	91.8	93.3
	Std Dev	1.54	0.98	0.55	1.06	2.95	1.24	1.25	1.94
	CV	1.69	1.09	0.61	1.16	3.21	1.34	1.36	2.08
I-B	Averg	93.6	93.3	90.1	91.5	93.3	95.6	90.8	93.0
	Std Dev	0.55	1.74	0.49	1.08	1.26	2.44	1.79	1.27
	CV	0.59	1.86	0.55	1.18	1.35	2.55	1.97	1.37
II-B	Averg	93.1	91.5	92.5	93.9	93.4	90.1	91.2	94.6
	Std Dev	1.09	1.30	1.53	0.48	2.41	1.77	3.09	0.78
	CV	1.17	1.42	1.66	0.52	2.58	1.96	3.39	0.82
I-C	Averg	93.4	92.2	91.3	92.3	92.5	91.3	90.6	91.7
	Std Dev	0.89	1.62	1.06	1.36	2.37	2.38	1.48	1.97
	CV	0.95	1.76	1.16	1.47	2.56	2.61	1.64	2.15
II-C	Averg	93.6	91.7	91.2	92.4	92.8	94.0	92.2	93.7
	Std Dev	0.95	1.32	0.80	0.75	1.36	1.33	2.43	1.50
	CV	1.02	1.44	0.87	0.81	1.46	1.42	2.64	1.60
I-D	Averg	92.1	90.6	91.9	93.3	91.3	91.1	91.5	94.5
	Std Dev	1.20	1.37	0.68	0.74	1.80	1.85	1.62	1.59
	CV	1.31	1.51	0.74	0.79	1.97	2.03	1.77	1.68
II-D	Averg	93.5	91.6	92.0	92.8	93.3	91.2	91.3	93.9
	Std Dev	1.44	1.60	0.69	1.04	2.60	1.91	1.57	1.58
	CV	1.55	1.74	0.75	1.12	2.78	2.09	1.71	1.68
I-E	Averg	90.7	90.9	90.8	91.4	90.4	92.0	92.6	93.4
	Std Dev	1.19	1.32	0.61	1.10	2.86	1.32	1.22	1.68
	CV	1.31	1.45	0.67	1.20	3.16	1.43	1.32	1.80
II-E	Averg	91.7	92.2	90.7	91.4	90.4	93.2	91.3	93.2
	Std Dev	1.20	1.30	0.54	0.68	2.11	1.44	1.00	1.07
	CV	1.30	1.41	0.59	0.74	2.34	1.54	1.09	1.14

Table 7 Density Distribution at the Four Locations for each Section on the US 95 Las Vegas Project.

Test Section	Statistical Parameter	Cores Densities				Nuclear Densities			
		Location				Location			
		HM	HJ	CJ	CM	HM	HJ	CJ	CM
I-A	Averg	92.2	91.2	92.8	95.1	92.3	90.0	92.7	95.6
	Std Dev	1.18	1.09	0.56	0.29	1.81	2.29	2.06	0.98
	CV	1.28	1.19	0.60	0.31	1.96	2.55	2.23	1.03
II-A	Averg	92.8	90.6	92.9	95.4	93.4	88.9	92.5	95.7
	Std Dev	0.58	1.21	0.64	0.69	1.12	1.20	1.99	1.04
	CV	0.62	1.33	0.69	0.72	1.20	1.35	2.15	1.09
I-B	Averg	92.5	92.4	88.7	92.0	92.2	91.9	87.5	91.8
	Std Dev	1.21	1.02	0.71	1.00	1.97	1.31	1.91	2.33
	CV	1.30	1.10	0.80	1.09	2.14	1.43	2.18	2.54
II-B	Averg	93.9	93.1	88.8	91.8	93.4	92.7	88.0	91.7
	Std Dev	2.26	0.97	0.44	0.80	3.20	1.70	1.05	1.54
	CV	2.41	1.05	0.50	0.87	3.42	1.84	1.20	1.68
I-C	Averg	92.2	92.4	92.8	94.9	91.9	92.3	92.0	95.6
	Std Dev	0.73	0.74	1.06	0.94	1.01	1.06	1.67	1.56
	CV	0.80	0.80	1.14	0.99	1.10	1.14	1.81	1.64
II-C	Averg	94.6	92.5	92.8	95.0	95.2	92.3	92.5	95.4
	Std Dev	0.78	0.90	0.72	0.94	1.27	1.61	1.38	1.49
	CV	0.83	0.97	0.77	0.98	1.34	1.74	1.49	1.56
I-D	Averg	92.0	91.2	91.9	94.8	91.7	91.4	91.7	95.6
	Std Dev	1.07	0.79	0.81	0.72	1.03	0.67	1.66	1.30
	CV	1.16	0.86	0.88	0.76	1.12	0.73	1.81	1.36
II-D	Averg	92.9	91.7	92.5	94.9	92.5	91.1	92.5	95.3
	Std Dev	1.22	1.19	0.73	0.69	2.31	1.91	1.39	1.29
	CV	1.32	1.29	0.79	0.72	2.50	2.09	1.50	1.36
I-E	Averg	90.5	90.1	95.2	96.5	90.6	89.3	96.1	97.0
	Std Dev	1.40	1.19	0.37	0.69	1.36	2.08	0.98	1.33
	CV	1.54	1.33	0.39	0.71	1.50	2.32	1.02	1.37
II-E	Averg	91.8	89.8	93.4	95.8	91.5	89.0	93.0	94.9
	Std Dev	1.57	1.29	0.86	0.63	0.94	1.54	1.76	1.68
	CV	1.71	1.43	0.92	0.66	1.03	1.73	1.89	1.77

Comparison of the Nuclear Densities with the Cores Densities

This analysis compared the densities measured by the nuclear gauges and the densities measured on the cores at each of the four locations within each section. A contrast comparison analysis was used to test the significance of the differences between the measurement procedures. This analysis compares the means of the two measurement procedures and determines if the difference is significant at an alpha level of 0.05, meaning that for each comparison reported as being significantly different; there is a 5% chance that this is not true. This analysis was performed using a SAS macro called "Contrast" prepared by Dr. G. Fernandez from the Department of Applied Economics and Statistics at the University of Nevada, Reno.

Tables 8 and 9 summarize the statistical comparisons of the densities on the Washoe Valley and Las Vegas projects, respectively. The labels "SL" and "SH" are employed to indicate that the core density is significantly lower or significantly higher than the nuclear density, respectively. A blank cell indicates a non-significant difference between the two density sets. Tables 8 and 9 show that there is a statistically significant difference between the nuclear densities and the core densities at several locations within the Washoe Valley Project while only one location showed a statistically significant difference within the Las Vegas Project. Within the US 395 Washoe Valley project, the cores densities are typically lower (e.g. 8 out of 11 cases) than the nuclear densities.

This noticeable difference between the density measuring techniques on the two projects can be attributed to the construction process used on each project. All ten sections on the Las Vegas project were constructed in one night leading to a more continuous and homogeneous process; the HMA was continuously supplied to the paver, avoiding the need for stop-and-go situations. The ten sections on the Washoe Valley project were constructed over the period of three nights, and were characterized by numerous interruptions of the placement process.

Table 8 Comparison of Nuclear and Cores Densities on the US 395 Washoe Valley Project.

Geometry	Rolling Pattern	Comparison of Cores to Nuclear Densities			
		HM	HJ	CJ	CM
A	I	SH	SH		
	II		SL		SL
B	I		SL		SL
	II				
C	I				
	II		SL		
D	I				
	II				
E	I			SL	SL
	II	SH			SL

Table 9 Comparison of Nuclear and Cores Densities on the US 95 Las Vegas Project.

Geometry	Rolling Pattern	Comparison of Cores to Nuclear Densities			
		HM	HJ	CJ	CM
A	I				
	II			SH	
B	I				
	II				
C	I				
	II				
D	I				
	II				
E	I				
	II				

Comparison of Densities across the Pavement

The objective of this analysis was to compare the densities at the different locations transversely across the pavement. For example, the analysis compares the density at the middle of the hot mat (HM) with the density at the hot joint (HJ). Tables 10 and 11 summarize the comparison of densities across the pavement for the Washoe Valley and Las Vegas projects, respectively. The same contrast comparison analysis previously described for the comparison between measurement procedures was used for the comparison of densities across the pavement.

The data in Tables 10 and 11 show that there are significant differences among densities measured at various locations across the pavement. This indicates that the geometry of the longitudinal joint influences the achieved density at the hot and cold joints and how the densities at the joint compare to the densities at the mid-mat. This analysis, however, did not identify the most effective joint geometry to achieve the best joint density. This objective is tackled in the analysis presented next.

The data in Tables 10 and 11 show that in 21 out of 40 cases, the density of the hot joint is significantly different than the density of the cold joint and in 12 out of the 21 cases the density of the hot joint is lower than the density of the cold joint. This is an unexpected trend since the hot joint is supported during compaction while the cold joint is not, which intuitively leads to a lower density at the cold joint.

The analysis of the density data presented in Tables 10 and 11 shows that the geometry of the joint significantly impacts the densities at the mid-width of the hot and cold mats in 24 out of 40 cases. Table 12 summarizes the actual number of cases where significant differences between the mid-width densities of the hot and cold mats existed. It should be noted that there is a total of four comparisons for each combination of density measuring technique and joint geometry (i.e. 2 projects x 2 rolling patterns). The data in Table 12 show that there is no specific pattern for such impact, i.e. no single joint geometry always impacted or always did not impact the mid-width densities of the hot and cold mats.

Table 10 Comparison of Densities across the Pavement on the US 395 Washoe Valley Project.

Rolling Pattern	Density Meas.	Geometry	Difference Between Locations			
			HM vs HJ	HJ vs CJ	CJ vs CM	HM vs CM
I	Cores	A				SL
		B		SH	SL	SH
		C				SH
		D	SH	SL	SL	SL
		E				
	Nuclear	A		SL		SL
		B	SL	SH	SL	
		C				
		D			SL	SL
		E				SL
II	Cores	A				
		B	SH	SL	SL	
		C	SH		SL	SH
		D	SH			
		E		SH		
	Nuclear	A				
		B	SH		SL	
		C		SH		
		D	SH		SL	
		E	SH	SH	SL	SL

Table 11 Comparison of Densities across the Pavement on the US 95 Las Vegas Project.

Rolling Pattern	Density Meas.	Geometry	Difference Between Locations			
			HM vs HJ	HJ vs CJ	CJ vs CM	HM vs CM
I	Cores	A	SH	SL	SL	SL
		B		SH	SL	
		C			SL	SL
		D			SL	SL
		E		SL	SL	SL
	Nuclear	A	SH	SL	SL	SL
		B		SH	SL	
		C			SL	SL
		D			SL	SL
		E		SL		SL
II	Cores	A	SH	SL	SL	SL
		B		SH	SL	SH
		C	SH		SL	
		D	SH		SL	SL
		E	SH	SL	SL	SL
	Nuclear	A	SH	SL	SL	SL
		B		SH	SL	
		C	SH		SL	
		D		SL	SL	SL
		E	SH	SL	SL	SL

Table 12 Number of Cases where the Mid-Width Densities of the Hot and Cold Mats were Significantly Different and Not-Significantly Different.

Density Measurement	Joint Geometry	Significantly Different	Not-Significantly Different
Cores	A	3	1
	B	2	2
	C	3	1
	D	3	1
	E	2	2
Nuclear	A	3	1
	B	0	4
	C	1	3
	D	3	1
	E	4	0

At this point it is not completely understood as to why the geometry of the longitudinal joint would impact the densities at the mid-width of the hot and cold mats. However, such an impact makes it difficult to clearly define the most effective joint geometry.

Interaction between Joint Geometry and Rolling Pattern

Employing the average of the ten measured locations within each test section, a statistical analysis was conducted to determine the overall behavior of each joint geometry and rolling pattern employed in this research. In addition, the analysis would determine if a specific geometry or a rolling pattern shows a significant difference from the densities obtained on the control section.

The analysis of variance (ANOVA) was used to test the significance of the differences among the five joint geometries and between the two rolling patterns. The statistical analysis was conducted at an alpha level of 0.05, meaning that for each comparison reported as being significantly different; there is a 5% chance that this is not true. The ANOVA is an inferential statistical technique which provides methods for comparing the means of two or more treatments by analyzing the variances of the measurements.

A statistical analysis was conducted to assess the magnitude of the interaction between the joint geometry and the rolling pattern. It was hypothesized that the two rolling patterns used in this research would impact the density at the hot side of the joint. Therefore, the statistical analysis evaluated only the density data at the hot side of the joint.

The entire data set was modeled as a two-factor experiment (joint geometry and rolling pattern), with 5 treatments for the joint geometry and two for the rolling pattern. Each combination of joint geometry and rolling pattern has two sample points (i.e. one sample point from each project). Each sample point represents the average of the ten measurements within each section.

The interaction between rolling patterns and joint geometries was analyzed using ANOVA with a SAS macro called “Fixqlql” prepared by Dr. G. Fernandez from the Department of Applied Economics and Statistics at the University of Nevada, Reno. This macro investigates not only the effects of each joint geometry and rolling pattern over the longitudinal joint density, but also test for the existence of interaction between the two factors evaluated (joint geometry and rolling pattern).

This analysis generated two models: the first model considers that the density at the hot side of the joint is significantly impacted by the interaction between the joint geometry and the rolling pattern and the second model ignores the effect of this interaction. The probability value (P-value) was employed as the parameter used to evaluate the significance level of these models. If the P-value is less than the significance level of 0.05 (i.e. alpha of 5%), then the evaluated factor is significant. Table 13 summarizes the statistical data for the interaction analysis. The data in Table 13 should be viewed in light of the following two criteria:

- The lower the P-value for the model, the more effective the model will be in describing the density data collected in this experiment.

- The lower the P-value for the factor, the more significant the factor will be in influencing the density at the hot joint.

Applying the above two criteria on the statistical data summarized in Table 13, leads to the following conclusions:

- The statistical model without the interaction between joint geometry and rolling pattern is more significant (P-value of 0.01) than the statistical model with the interaction (P-value of 0.089).

- The joint geometry (P-value of 0.005) is highly more significant than the rolling pattern (P-value of 0.869) on influencing the density at the hot joint.

Table 13 Statistical Models for the Density at the Hot Joint.

Model		**P-value**
Model with interaction		0.089
Factors	Joint Geometry	0.018
	Rolling Pattern	0.879
	Interacion	0.747
Model without interacion		0.010
Factors	Joint Geometry	0.005
	Rolling Pattern	0.869

The final recommendation of this analysis was that these rolling patterns do not have a significant impact on the joint density. These two rolling patterns will provide a very similar joint density, but the use of other rolling procedures (i.e. rolling from the cold side) can result in a detrimental impact on the joint density. Therefore it is recommended that NDOT specifies these two rolling patterns and leaves it up to the contractor to select the pattern that best fit the project.

Impact of Joint Geometry

The objective of this analysis was to identify the impact of the joint geometry on the density that can be achieved at the hot and cold sides of the longitudinal joint. This comparison evaluated the average densities obtained from the different geometries at the four measuring points located transversally across the pavement. The density at each location was calculated as the average of the 20 measurements performed on each section while combining the data from the two rolling patterns.

It should be recognized that the most effective joint geometry is the one that leads to the highest densities at the cold and hot sides of the joint and the lowest difference between the densities at the joint and the mid-mat. However, due to the unexpected influence of joint geometry on the densities at the mid-width of the hot and cold mats (i.e. Table 12), the second property may not be effectively assessed. Tables 14 – 17 summarize the densities for the various sections as measured by the cores and the nuclear gauges for both the Washoe Valley and Las Vegas projects that will be used in this analysis.

An ANOVA was conducted to compare the various joint geometries. The ANOVA takes into consideration the variability within each section and its impact on the comparison of the various sections (i.e. joint geometries).

The joint geometry is expected to highly influence the cold side joint density value. It is supposed to promote a better density of the unrestrained edge of the cold mat and may also influence the density of the hot side of the joint. However, no influence was expected to be observed from the joint geometry on the density at the mid-width locations of the hot and cold mats.

Table 14 Core Densities on the US 395 Washoe Valley Project.

Joint Geometry	Location				Difference between Mid-mat and joint	
	HM	HJ	CJ	CM	Hot Side	Cold Side
A	90.30	90.30	90.86	91.04	0.00	0.20
B	93.36	92.36	91.30	92.69	1.07	1.50
C	93.51	91.93	91.26	92.35	1.69	1.18
D	92.78	91.11	91.99	93.03	1.80	1.13
E	91.22	91.55	90.79	91.41	-0.36	0.68

Table 15 Nuclear Densities on the US 395 Washoe Valley Project.

Joint Geometry	Location				Difference between Mid-mat and joint	
	HM	HJ	CJ	CM	Hot Side	Cold Side
A	89.72	90.18	90.72	92.00	-0.51	1.39
B	93.38	92.83	91.00	93.78	0.58	2.97
C	92.67	92.63	91.43	92.66	0.05	1.33
D	92.30	91.14	91.43	94.22	1.26	2.96
E	90.40	92.62	91.96	93.28	-2.45	1.41

Table 16 Core Densities on the US 95 Las Vegas Project.

Joint Geometry	Location				Difference between Mid-mat and joint	
	HM	HJ	CJ	CM	Hot Side	Cold Side
A	92.54	90.93	92.82	95.24	1.74	2.55
B	93.23	92.80	88.74	91.94	0.47	3.48
C	93.38	92.46	92.82	94.95	0.99	2.25
D	92.42	91.45	92.21	94.86	1.05	2.80
E	91.13	89.94	94.30	96.15	1.30	1.93

Table 17 Nuclear Densities on the US 95 Las Vegas Project.

Joint Geometry	Location				Difference between Mid-mat and joint	
	HM	HJ	CJ	CM	Hot Side	Cold Side
A	92.86	89.47	92.60	95.62	3.66	3.16
B	92.81	92.28	87.77	91.76	0.57	4.35
C	93.56	92.31	92.22	95.50	1.33	3.43
D	92.10	91.28	92.11	95.44	0.89	3.49
E	91.07	89.16	94.51	95.91	2.10	1.46

Analysis of Individual Projects

This analysis evaluated the impact of joint geometry on the densities of the cold and hot joints of each project independently. The analysis combined the two rolling patterns resulting in a total of 20 density measurements for each joint geometry. Figures 6 – 13 present the results of the statistical analyses. Each figure presents the average densities along with the upper and lower limits of the 95% confidence limit. In simple terms, any two joint geometries having significant overlap in their confidence limit ranges would not be significantly different.

Using the results of the ANOVA, the figures also identify the significant differences for each case. For example, Figure 6 shows that geometries A and D resulted in significantly different cores densities at the cold joint while Figure 7 shows that all joint geometries resulted in similar nuclear densities at the cold joint. Looking at the data presented in Figures 6-13, the following conclusions can be drawn.

- Densities based from both cores and nuclear gauges lead to similar comparisons among the various joint geometries.

- The impact of joint geometry on the densities at the cold and hot joints differs between the two projects. The impact of joint geometry differs between the two sides of the joint: cold and hot.

- The following sections did not achieve the desired density level of 92% of TMG at the mid-width of the mats: sections A and E on US 395 and sections E (hot mat only) and B (cold mat only) on US 95. The fact that these sections did not achieve the desired densities on the mats, would greatly jeopardize the quality of the joint density data obtained from these sections as will be discussed later.

- On the US 395 Washoe Valley project, none of the joint geometries improved nor reduced the density at the cold joint as compared to the natural slope except the cut edge without tack coat (D), which only marginally improved the cores density. On the hot side of the joint, the edge restrain (B), the cut edge with tack coat (C), and the taper (E) improved the density relative to the natural slope (A).

- On the US 95 Las Vegas project, the data showed that some of the joint geometries reduced the density at the joint relative to the natural slope. However, this observation should be very carefully assessed in conjunction with the density at the mid-with of the mat. At the cold joint, the edge restraining device showed a significant reduction in the density that coincided with a significant reduction in the mid-width density of the cold mat (Tables 16 and 17). At the hot joint, the taper joint showed a reduction in the density that again coincided with a reduction in the mid-width of the hot mat. Based on this data, it can be concluded that if the contractor cannot achieve a good density level at the mid-width of the mat, it is highly unlikely that an improved density at the joint would be achieved.

- In summary, when analyzing the individual projects data and taking into consideration the achieved densities at the mid-width of the mat, the following conclusions can be made:
    - At the cold joint, the taper joint geometry improved the density relative to the natural slope. This improvement was not clear on the US 395 project because of the unachieved density at the mid-width of the mat.

    - At the hot joint, the restrain edge, the cut edge, and the taper edge all improved the density relative to the natural slope. The increase in the joint density achieved by the taper joint geometry on the US 95 project was overshadowed by the significantly reduced density at the mid-width of the hot mat.

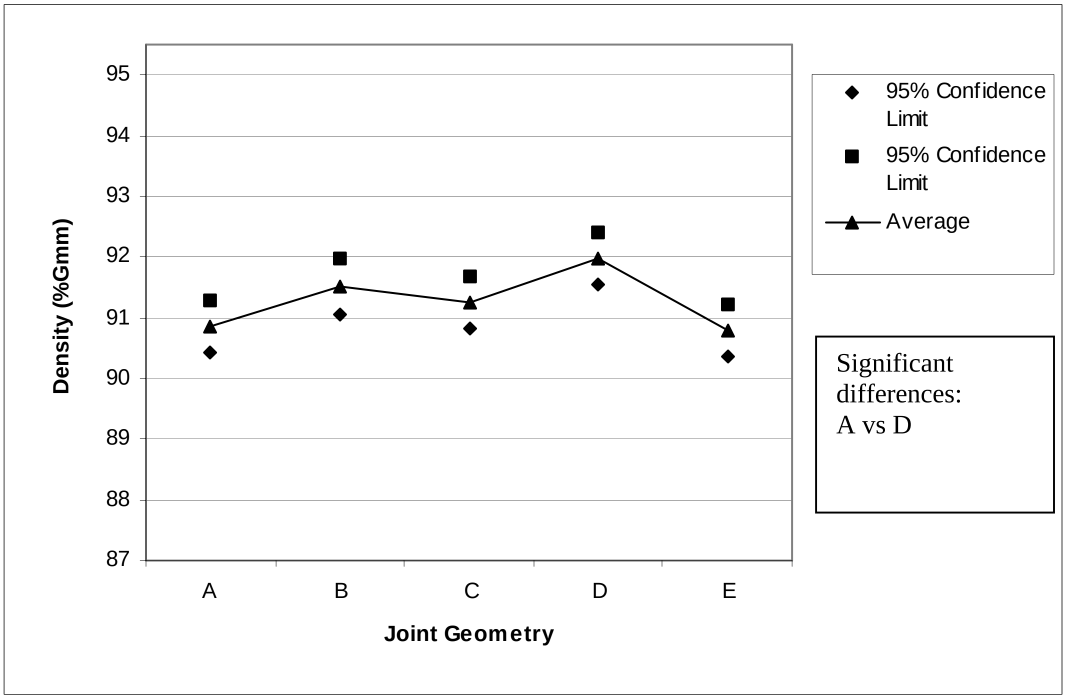


Figure 6 Impact of Joint Geometry on the Cold Joint Density using Cores, US 395 Washoe Valley Project.

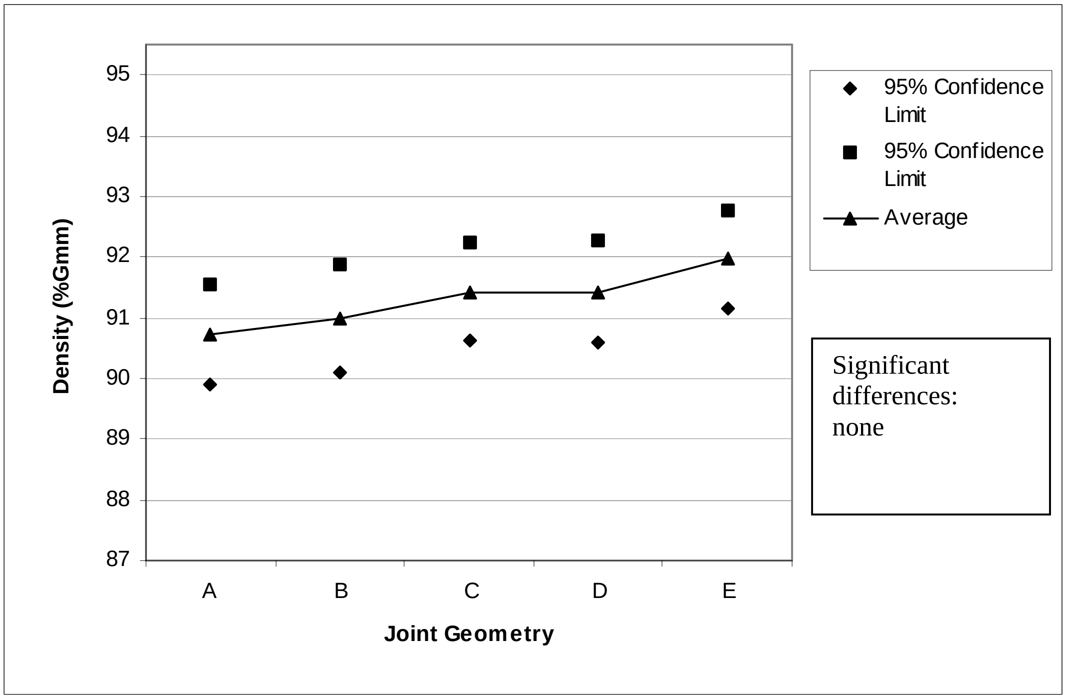


Figure 7 Impact of Joint Geometry on the Cold Joint Density using Nuclear Gauges, US 395 Washoe Valley Project.

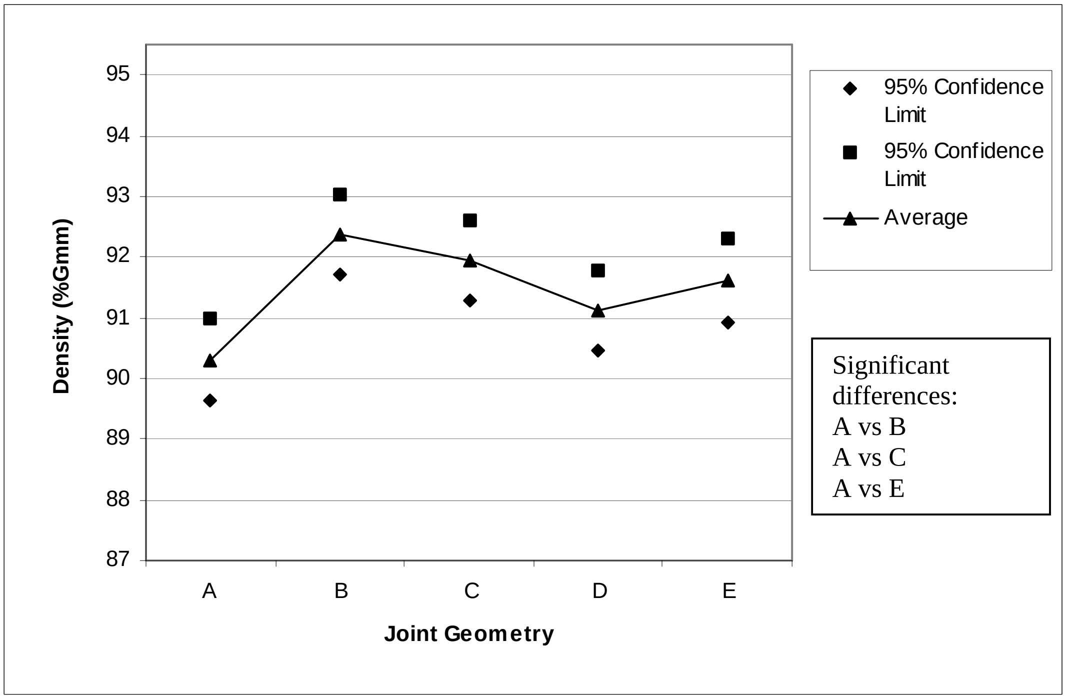


Figure 8 Impact of Joint Geometry on the Hot Joint Density using Cores, US 395 Washoe Valley Project.

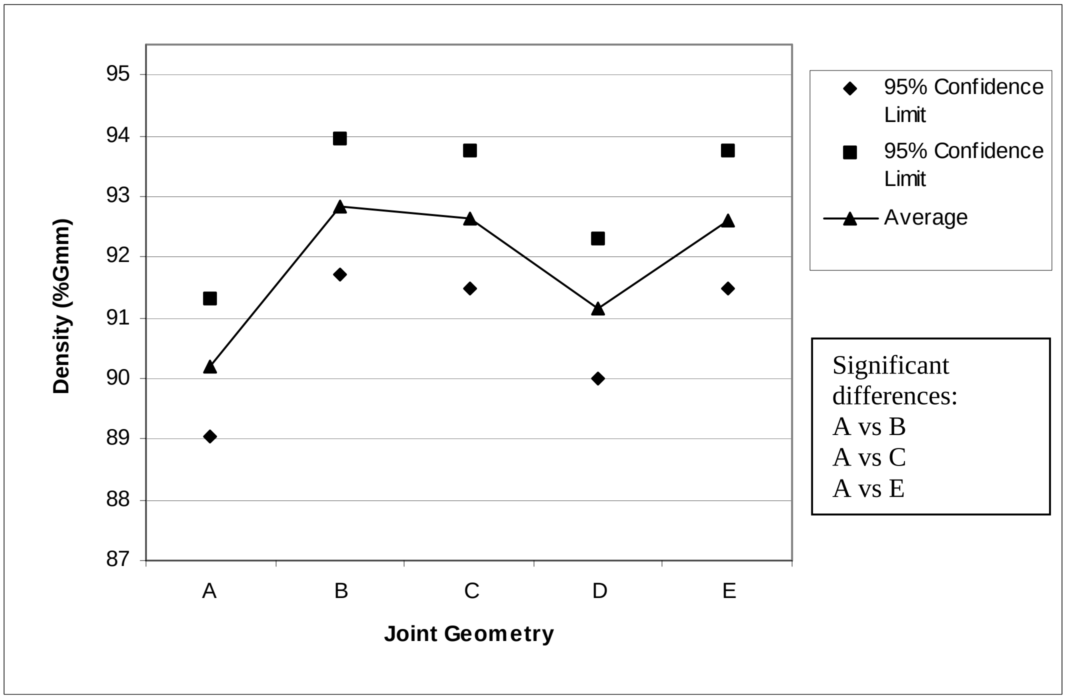


Figure 9 Impact of Joint Geometry on the Hot Joint Density using Nuclear Gauges, US 395 Washoe Valley Project.

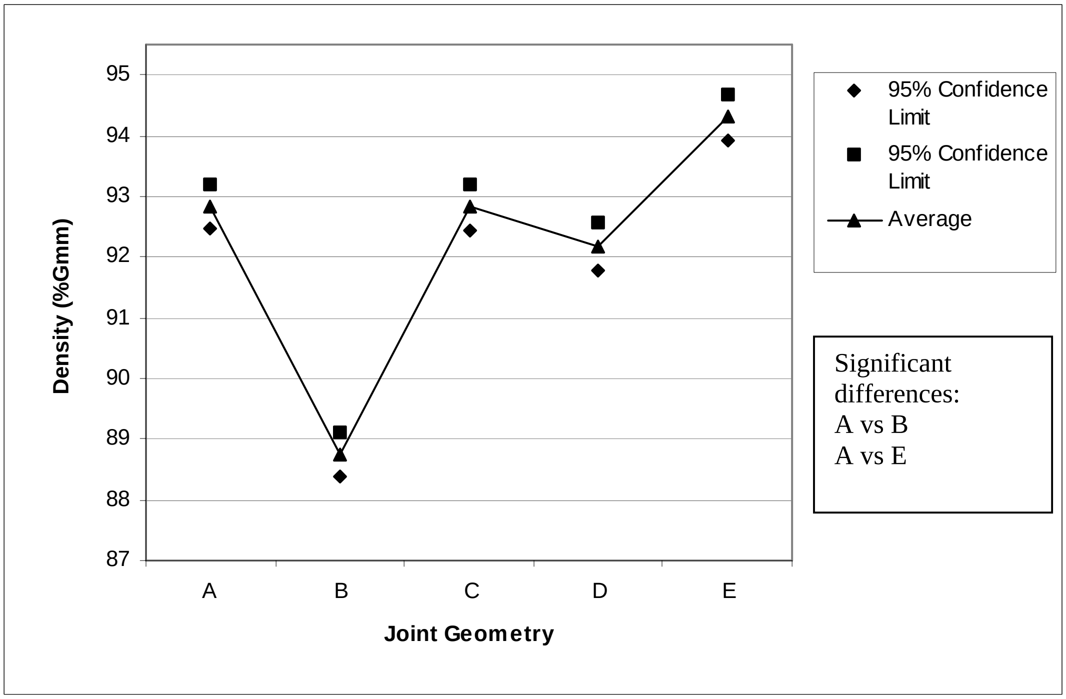


Figure 10 Impact of Joint Geometry on the Cold Joint Density using Cores, US 95 Las Vegas Project.

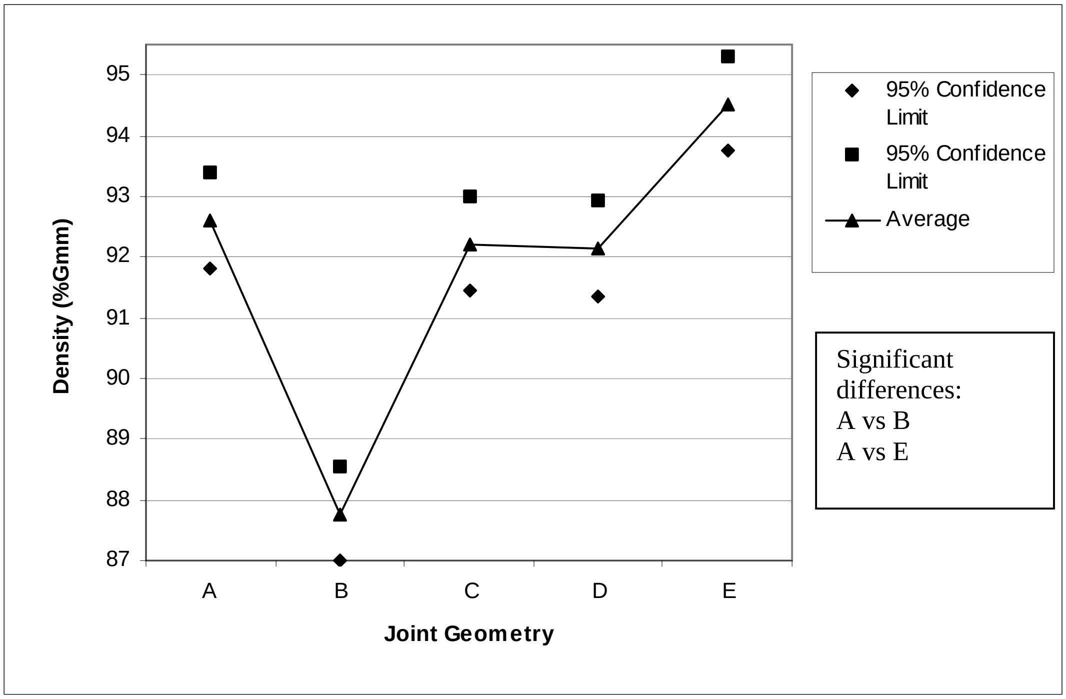


Figure 11 Impact of Joint Geometry on the Cold Joint Density using Nuclear Gauges, US 95 Las Vegas Project.

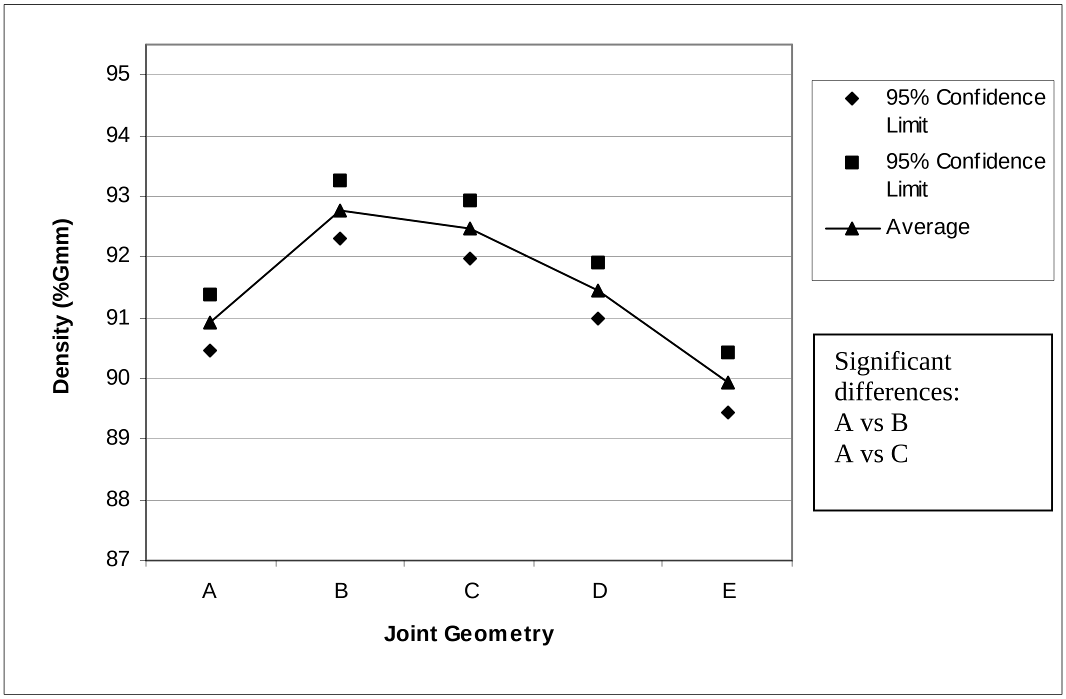


Figure 12 Impact of Joint Geometry on the Hot Joint Density using Cores, US 95 Las Vegas Project.

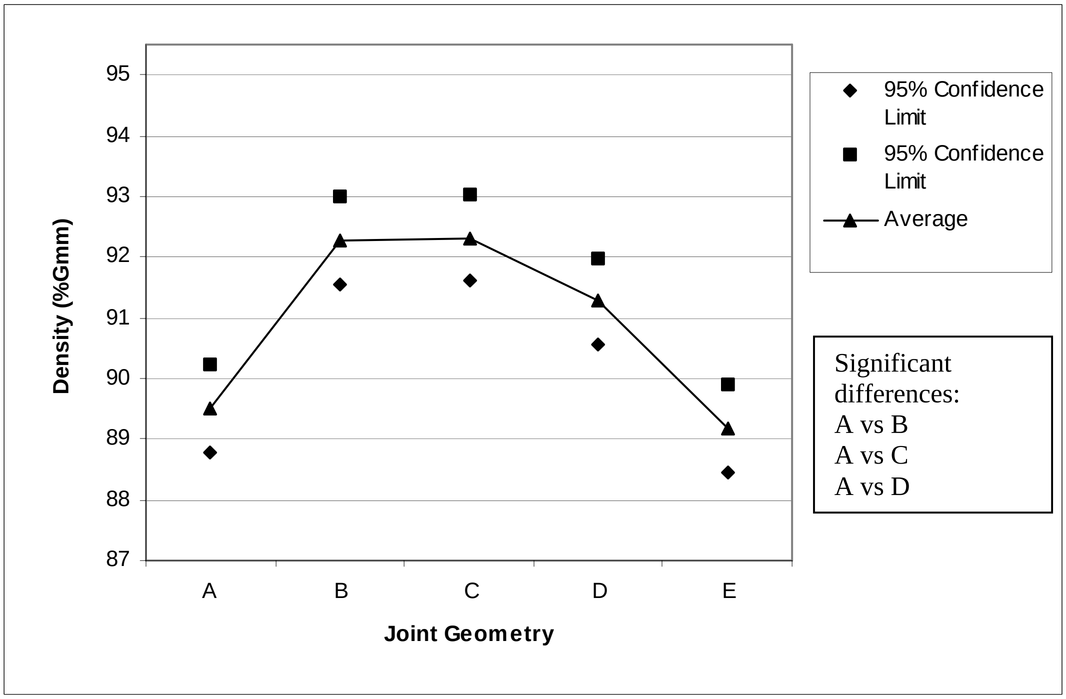


Figure 13 Impact of Joint Geometry on the Hot Joint Density using Nuclear Gauges, US 95 Las Vegas Project.

Analysis of Combined Projects

This analysis evaluated the impact of joint geometry on the densities of the cold and hot joints using the combined data from the two projects. The analysis combined the two rolling patterns resulting in a total of 40 density measurements for each joint geometry. This analysis evaluates the joint geometry on the density while taking into consideration the overall variability that exists within the test sections and between the two different projects. It should be noted that taking into account the overall variability would make it harder to identify the significance of the various joint geometries. In other words, when considering one project at a time, a given joint geometry may prove to be significant since only the variability within each test section is considered but when the two projects are combined, the variability within each section and the variability between the sections on the two projects are considered. Therefore, it is expected that the analysis of the combined data from the two projects will show less significance of the joint geometries than the analysis of the individual projects data.

Figures 14 – 17 present the results of the statistical analyses of the combined data. Looking at the data in figures 14 and 15, it can be observed that there is a significant difference between the densities at the cold joint on the US 395 and US 95 projects. The cold joint densities on the US 395 project are lower than the ones on the US 95 project except for geometry B. The densities on geometry E for the US 395 project differ significantly from the densities obtained at the US 95 project. The large variability between the two projects can be related to the type of device used to produce the tapered joint (i.e. geometry E). A steel plate was used on the Las Vegas project while a steel bar was used on the Washoe Valley project. The steel plate used on the Las Vegas project seems to highly improve the density at the cold joint in comparison to the steel bar used on the Washoe Valley project. Both methods provide the required 3:1 slope at the cold joint, but the steel plate used on the Las Vegas project seems to be more effective in providing additional restrain and better compaction by the paver's screed into the cold joint.

When taking into consideration the overall variability of the measured densities within each section and between the two projects, it can be concluded that none of the joint geometries provided improvements in the cold joint density as compared to the natural slope geometry (A). This can be clearly observed in Figures 14 and 15 by the significant overlap of the ranges of densities at the cold joint. The edge restraining device showed a noticeable reduction in the cold joint density as compared to the other geometries. The reason for this reduction was discussed in the previous section.

The data in Figures 16 and 17 show that the densities at the hot joint exhibit different trends than the densities at the cold joint (Figures 14 and 15). It can be observed that the differences between the hot joint densities measured on the two projects are significantly smaller than the differences observed on the cold joint. In addition, geometries B and C show significant improvements in the hot joint density over geometry A (natural slope). Again, geometry E resulted in the highest difference between the two projects. However, it is interesting to note that the steel plate on the US 95 resulted in a hot joint density that is lower than the one obtained by the steel bar on the US 395 project. Apparently the improvements provided by the steel plate on the cold joint did not carry through on the hot joint, which reduces the overall effectiveness of the tapered joint even with the steel plate device.

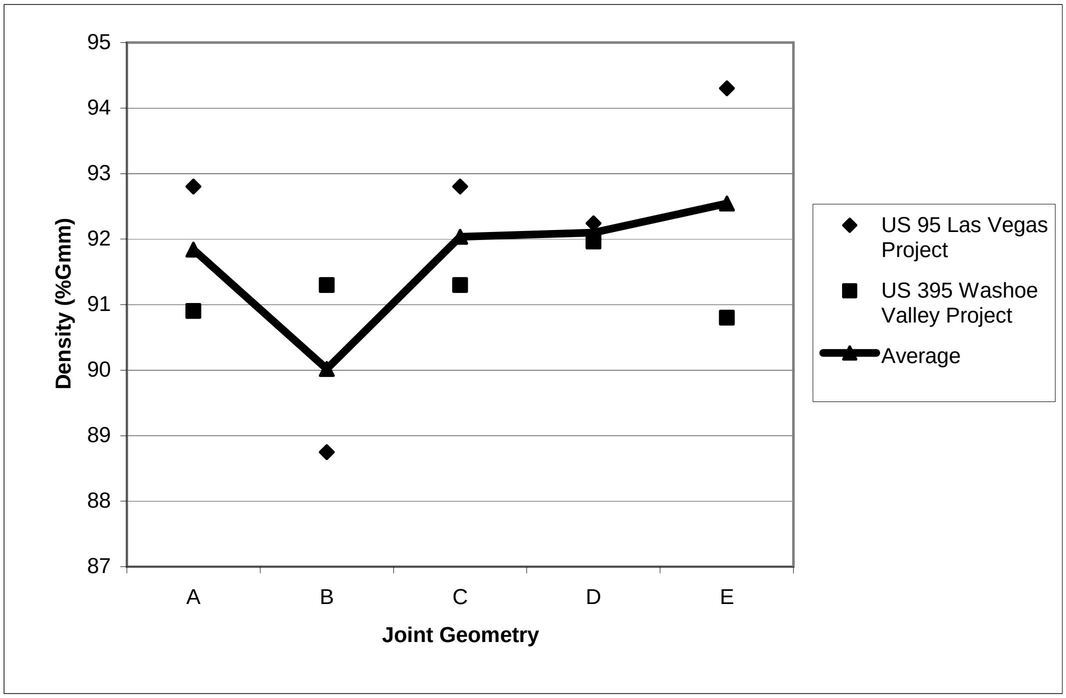


Figure 14 Ranges of Core Densities at the Cold Side of the Joint.

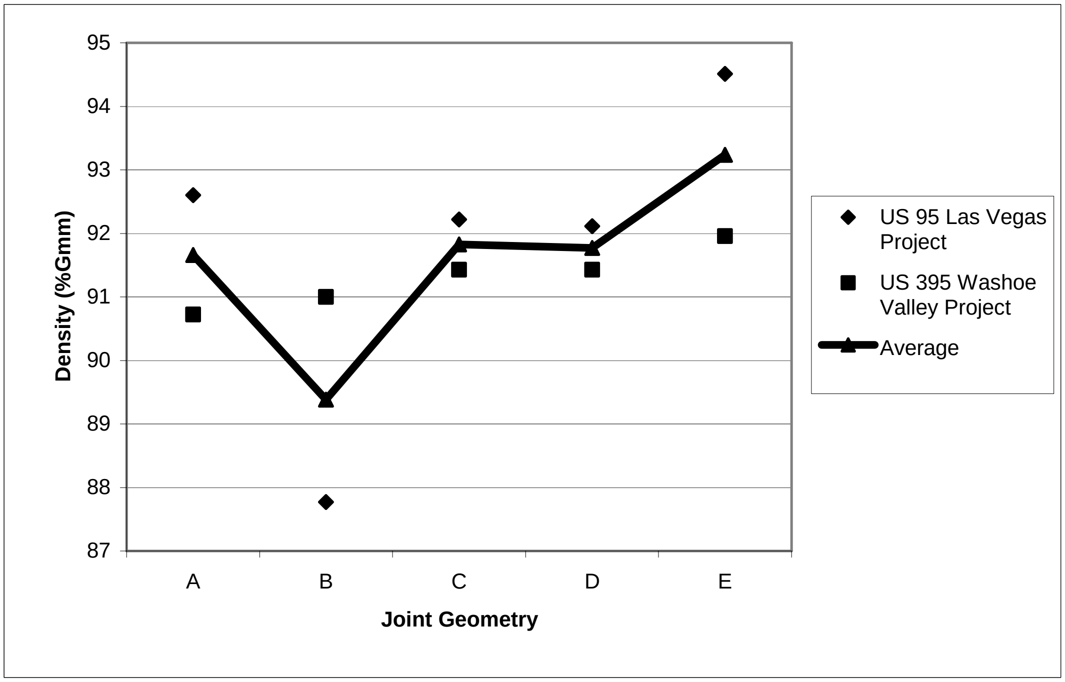


Figure 15 Ranges of Nuclear Densities at the Cold Side of the Joint.

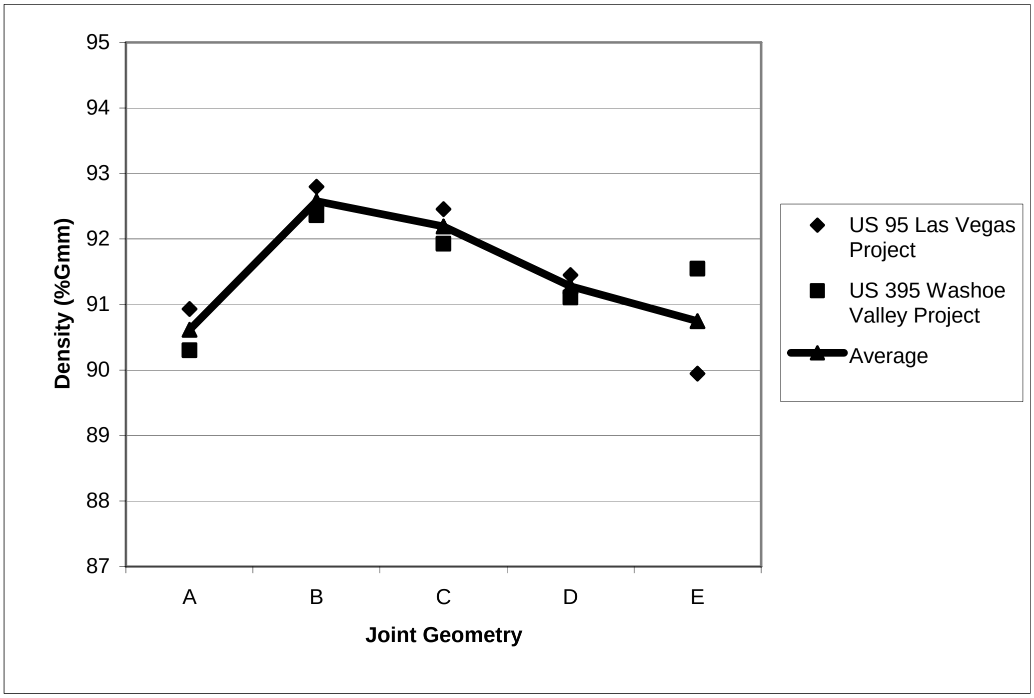


Figure 16 Ranges of Core Densities at the Hot Side of the Joint.

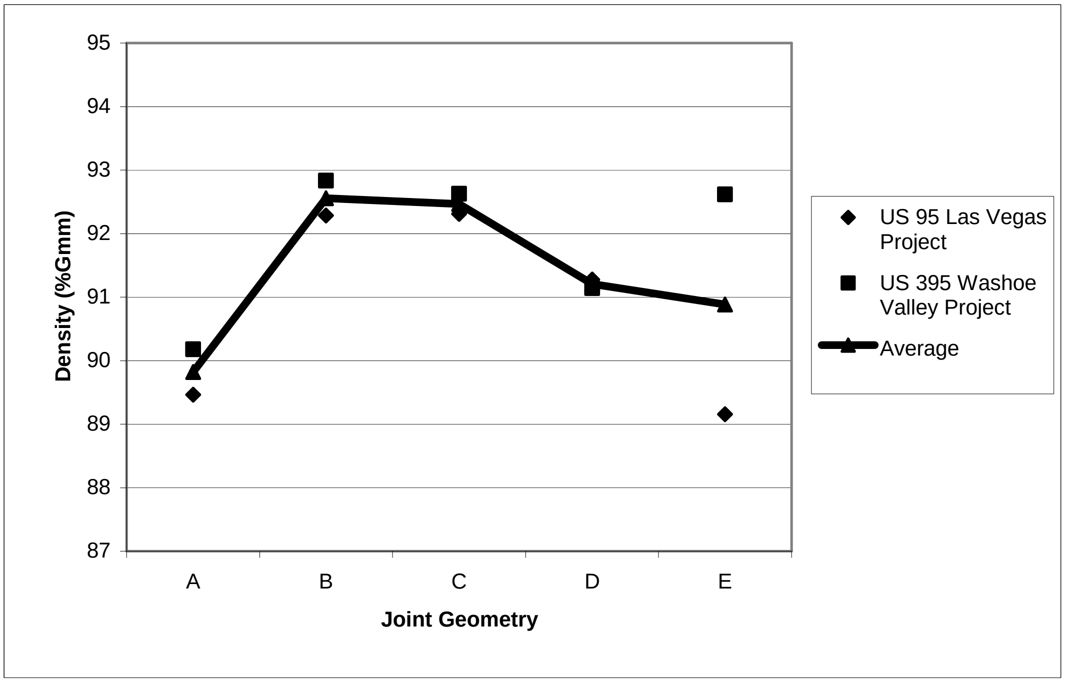


Figure 17 Ranges of Nuclear Densities at the Hot Side of the Joint.

Conclusions and Recommendations Based on the Summer 2004 Projects

Based on the analysis of the data from the summer 2004 field-testing program, the following conclusions and recommendations can be made.

- On the US 395 Washoe Valley, the densities measured using cores showed a significant difference from the densities measured using the nuclear gauges while the difference between cores and nuclear densities were minimal on the US 95 Las Vegas project. This issue should be further investigated to identify the source of variations on the US 395 project.

- The analysis of the densities across the pavement on the summer 2004 projects showed that the geometry of the joint significantly impacts the densities at the mid-width of the hot and cold mats. However, there is no specific pattern for such impact, i.e. no single joint geometry always impacted or always did not impact the mid-width densities of the hot and cold mats. There is no logical explanation for this impact and its existence should be further investigated. Under normal construction conditions, it is unjustifiable to have significantly different densities at the center of the two adjacent mats.

- The statistical analysis of the density data on the summer 2004 projects conducted to identify any interaction between joint geometry and rolling pattern indicated that the rolling pattern does not have a significant impact on the joint density, if any of these two rolling patterns is used. Therefore it is recommended that NDOT specifies the use of these two joint rolling patterns and leaves it up to the contractor to select the pattern that best fit the project.

- When analyzing the individual projects data and taking into consideration the achieved densities at the mid-width of the mat, the following conclusions can be made:

  - At the cold joint, the taper joint geometry improved the density relative to the natural slope. This improvement was not clear on the US 395 project because of the unachieved density at the mid-width of the mat.

  - At the hot joint, the restrain edge, the cut edge, and the taper edge all improved the density relative to the natural slope. The increase in the joint density achieved by the taper joint geometry on the US 95 project was overshadowed by the significantly reduced density at the mid-width of the hot mat.

- When analyzing the combined data from the two projects, the following conclusions can be made:

  - The analysis of the cold joint densities indicated that there is a significant difference between the densities at the cold joint on the US 395 and US 95 projects. The cold joint densities on the US 395 project are lower than the ones on the US 95 project except for geometry B with the nuclear measurement. When taking into consideration the variability of the measured densities within each section and between the two projects, it can be concluded that none of the joint geometries provided improvements in the cold joint density as compared to the natural slope geometry (A). The edge restrain device showed a noticeable reduction in the cold joint density as compared to the other geometries.

  - The analysis of the hot joint densities indicated that the differences between the two projects are significantly smaller than the differences observed on the cold joint. In addition, geometries B and C showed significant improvements in the hot joint density over geometry A (natural slope).

- Considering the analyses of all the data that were generated from the 20 sections on the two field projects, it can be concluded that the cut edge and taper geometries has the potential of improving the densities on both sides of the joint as compared to the natural slope geometry. The taper joint geometry has a good potential of improving the joint density if its variability can be controlled through a standard design of the wedge device that can lead to a stable cold joint and a dense hot joint.

SUMMER 2005 FIELD-TESTING PROGRAM

The summer 2005 field-testing program evaluated the three most promising joint geometries based on the recommendations the summer 2004 field-testing program. The selected geometries were:

- ***Natural Slope (Geometry A)***
- ***Cut Edge with Rubberized Asphalt Tack Coat (Geometry C)***
- ***Tapered Joint at 3:1 (Geometry E)***

Section Layout

Three test sections were constructed for each joint geometry for a total of nine test sections on the entire project. Each test section was 700 feet long. The locations of the individual test sections throughout the project were randomly selected as shown in Figure 18.

Density Measurements

The density measurements followed the same plan as shown in Figure 2 except that no nuclear density measurements were taken. A 4” core was cut at each of the following locations: middle of cold mat (CM), cold joint (CJ), hot joint (HJ), and middle of hot mat

(HM). The four cores were obtained at 10 longitudinal locations within each test section starting at 125 feet from the beginning of the section and spaced at 50 feet thereafter. A total of 40 cores were obtained from each section.

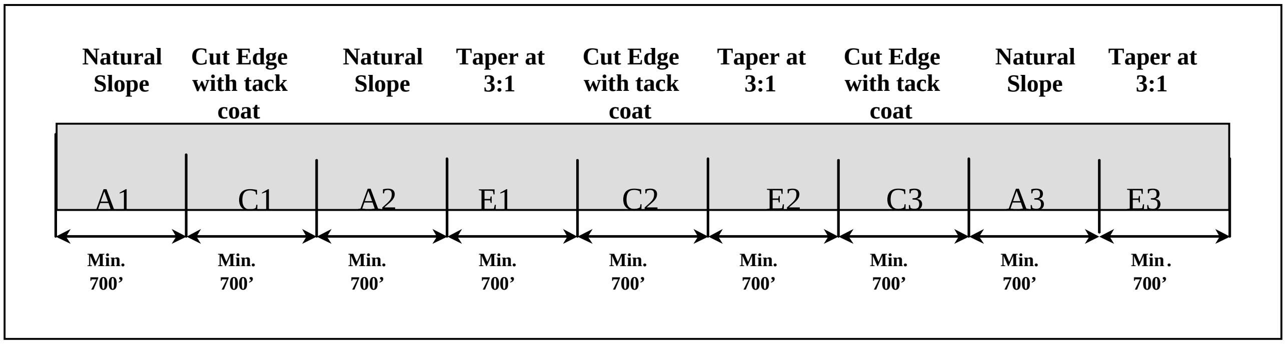


Figure 18 Layout of Test Sections on the US 395 Cold Springs Project.

US 395 Cold Springs Project

The project constructed under the summer 2005 field-testing program was Contract 3264 on highway US 395 in Cold Springs, in the southbound direction starting at the California state line. The project consisted of a 2” cold milling and the placement of a 2.5” plantmix bituminous surface and ¾” open-graded wearing course. The constructed longitudinal joint lays between the travel lane and the passing lane in the southbound direction.

Construction of the test sections started at 8:30 a.m. on June 27, 2005 and was completed in the same day. Cores were obtained between June 29 and July 1, 2005. The contractor for the project was Granite Construction Company. The HMA mix was produced at the Lockwood plant and had the following properties:

- Mix design asphalt content of 5.50% dwa
- Binder grade: PG 64-28NV
- Coarse aggregates were marinated for 48 hours with 1% lime by dwa and the fine aggregates were marinated with 2% lime by dwa.
- The aggregate gradation employed in the project is shown in Table 18.

The mix arrived at the site at a temperature between 300° F and 320° F. The mix was laid into a windrow and picked up by the paver (CAT AP1000B). The breakdown rolling was performed by a steel drum roller (CAT CB634D). The other rollers were a steel drum roller (CAT CB534C) and a pneumatic roller (CAT PS-180). The breakdown rolling consisted of three passes, forward and back in vibration mode. The pneumatic roller applied forward and back motion in the same track, upon returning to the point of origin, the roller moved over one wheel width and resumed the process for a total of four passes. The finishing roller applied three passes: in the forward motion the front drum in vibration and the rear drum in static and in the reverse both drums in static. The rubberized asphalt tack coat was applied by a private contractor.

Table 18 Aggregate Gradation – US 395 Cold Springs Project.

Sieve Size	% Passing	Job-Mix formula	Specifications
1”	100	100	100
¾”	91	88 - 95	88 - 95
½”	78	71 – 85	70 - 85
3/8”	68	61 – 75	60 - 78
No. 4	51	44 – 58	43 - 60
No. 10	33	30 – 37	30 - 44
No. 40	16	12 - 20	12 - 22
No. 200	6	4 - 8	3 - 8

Collection of Density Data

Field Cores

A total of 40 cores were obtained from each test section resulting in a total of 360 cores from the entire project. The cores were cut at both ends to isolate the layer under study and to provide a smooth surface on the top and bottom of each core. AASHTO Test Procedures T 166-00 Method A, T 209-99, and T 269-97 were used to determine the bulk specific gravity, theoretical maximum specific gravity, and air voids of the samples, respectively (2).

Theoretical Maximum Specific Gravity

The theoretical maximum specific gravity employed in the density calculations was obtained from field samples used for the quality control testing performed by NDOT personnel. Additionally, loose mix samples were collected by the UNR personnel to corroborate the theoretical maximum specific gravity data. The average maximum theoretical specific gravity measured at NDOT was 2.484 and the average specific gravity measured at UNR was 2.476. The range of the NDOT and UNR specific gravities is 0.008 which compares favorably with AASHTO acceptable range of 0.019. The maximum theoretical specific gravity measured by NDOT was used in the calculation of air-voids.

Analysis of the Density Data

Analysis of Outliers

Due to the large number of density measurements obtained from each test section, an extensive statistical analysis was performed to determine the presence of outliers and to evaluate the variability of the measurements within each section. The following nomenclature was used throughout the analyses: Hot Mat (HM), Hot Joint (HJ), Cold Joint (CJ), and Cold Mat (CM).

The analysis for outliers followed the same procedures used on the summer 2004 data. Table 19 presents the number of outliers and their locations. The total number of densities available at each location within a section is 10. The data in Table 19 show that the number of outliers is low (11 out of 360) and there is no specific trend in the formation of the outliers. Once the outliers were identified and excluded from the analysis, average densities were calculated for each test section and for each project.

Comparative Analyses

The density data collected from field cores were used in two different analyses: a) variability and comparison of densities within each of the sections and b) comparison of densities among test sections.

Table 19 Number of outliers at the Four Locations for each Section based on Core Densities on the US 395 Cold Springs Project.

Test Section	**Number of Outliers**			
	HM	**HJ**	**CJ**	**CM**
A1				1
C1		1		
A2	1	2		
E1	1	1		
C2		1		
E2				
C3				
A3		1		1
E3			1	

Variability of the Density Data along the Test Sections

The objective of this analysis was to assess the variability of the density data throughout each test section as measured by the cores. Table 20 summarizes the cores densities distribution at the four locations throughout each section. The average, standard deviation, and coefficient of variation (CV) were selected as the statistical parameters employed to assess the variability within each test section.

It should be noted that the data presented in Table 20 exclude all outliers that were identified in the previous analysis. The data in Table 20 show a very low variability within each test section. The highest standard deviation and CV of 1.19 and 1.27, respectively, were found at the hot side joint of section A2. The relatively low values of the standard deviation and the coefficient of variation prove that excellent repeatability exists within each test section at the specific location across the pavement.

Table 20 Density Distribution at the Four Locations for each Section on the US 395 Cold Springs Project.

Test Section	**Statistical parameter**	**Cores Densities**			
		LOCATION			
		HM	**HJ**	**CJ**	**CM**
A1	Average	96.0	96.0	95.1	96.9
	Std Dev	1.07	1.15	0.77	0.63
	CV	1.11	1.20	0.81	0.65
C1	Average	96.0	95.9	95.4	96.6
	Std Dev	0.40	0.97	0.53	0.73
	CV	0.42	1.01	0.56	0.75
A2	Average	95.4	94.2	94.6	95.9
	Std Dev	0.64	1.19	0.66	0.90
	CV	0.67	1.27	0.70	0.94
E1	Average	95.9	95.3	94.7	96.7
	Std Dev	0.51	1.09	0.71	0.62
	CV	0.53	1.15	0.75	0.64
C2	Average	96.2	95.9	94.5	97.2
	Std Dev	0.71	0.55	0.56	0.59
	CV	0.74	0.58	0.60	0.61
E2	Average	96.7	96.3	94.6	97.4
	Std Dev	0.43	0.64	0.52	0.39
	CV	0.45	0.66	0.55	0.40
C3	Average	95.5	94.5	94.5	96.6
	Std Dev	0.66	1.06	0.69	0.60
	CV	0.69	1.12	0.73	0.63
A3	Average	95.6	94.4	94.9	97.0
	Std Dev	0.55	0.71	0.83	0.62
	CV	0.57	0.76	0.87	0.64
E3	Average	95.8	94.7	94.6	96.2
	Std Dev	0.46	0.61	0.68	0.53
	CV	0.48	0.64	0.72	0.55

Comparison of Densities across the Pavement

The objective of this analysis was to compare the densities at the different locations transversally across the pavement. For example, the analysis compares the density at the middle of the hot mat (HM) with the density at the hot joint (HJ). Table 21 summarizes the comparison of densities across the pavement. The same contrast comparison analysis previously described for the comparison of densities on the summer 2004 projects was used here.

The data in Table 21 show that there are significant differences among densities measured at various locations across the pavement. This indicates that the geometry of the longitudinal joint influences the achieved density at the hot and cold joints and how the densities at the joint compare to the densities at the mid-mat. The data showed that all comparisons follow the general engineering trend where, in any case that a significant difference exists; the density at the mid-mat is always higher than the density at the joint and the density of the hot joint is always higher than the density at the cold joint. This indicates that all the sections on this project followed normal trends and no inconsistencies were encountered unlike the case of the summer 2004 projects.

The data in Table 21 also show that the density at the hot mat is significantly lower than the density at the cold mat in 7 out of 9 cases and this difference is independent of the geometry of the joint. However, it should be noted that the density data collected from this project as summarized in Table 20 are very tight which makes the statistical analysis very sensitive to small changes. For example, the statistical analysis is identifying the HM density of 96.0 on section A1 as significantly lower than the CM density of 96.9 on section A1 (Table 20).

A comparison of the tightness of the density data from the Cold Springs project as compared to the summer 2004 projects was conducted. It should be emphasized that the same statistical analyses were conducted on the data from the summer 2004 and summer 2005 projects. The comparative analysis indicated that, when the summer 2004 data were analyzed, the statistical analysis identified as significantly different any two density measurements that differ by 1.20 or more while the significantly different threshold for the summer 2005 data was only 0.60. This large difference can be attributed to two factors: 1) the summer 2004 data included two projects and two density measuring techniques which ultimately introduce higher variability and 2) the summer 2005 project had a significantly higher in-place density and very narrow range of densities for all sections when compared with the summer 2004 projects.

Table 21 Comparison of Densities across the Pavement on the US 395 Cold Springs Project.

Difference between Locations	**Test Section**		
	A1	**A2**	**A3**
HM vs HJ		SH	SH
HM vs CJ	SH	SH	SH
HM vs CM	SL		SL
HJ vs CJ	SH		
HJ vs CM	SL	SL	SL
CJ vs CM	SL	SL	SL
Difference between Locations	**C1**	**C2**	**C3**
HM vs HJ			SH
HM vs CJ		SH	SH
HM vs CM	SL	SL	SL
HJ vs CJ		SH	
HJ vs CM	SL	SL	SL
CJ vs CM	SL	SL	SL
Difference between Locations	**E1**	**E2**	**E3**
HM vs HJ			SH
HM vs CJ	SH	SH	SH
HM vs CM	SL	SL	
HJ vs CJ		SH	
HJ vs CM	SL	SL	SL
CJ vs CM	SL	SL	SL

Comparison of Joint Geometries

Employing the average of the ten measured locations within each test section, a statistical analysis was conducted to determine the overall behavior of each joint geometry. In addition, the analysis would determine if a specific geometry shows a significant difference from the densities obtained on the control section (geometry A).

The analysis of variance (ANOVA) was used to test the significance of the differences among the three joint geometries. The statistical analysis was conducted at an alpha level of 0.05, meaning that for each comparison reported as being significantly different; there is a 5% chance that this is not true.

Figures 19 and 20 present the results of the statistical analyses. Each figure presents the average densities along with the upper and lower limits of the 95% confidence limit. In simple terms, any two joint geometries having significant overlap in their confidence limit ranges would not be significantly different. Table 22 summarizes the statistical comparisons of the various joint geometries.

Table 22 Statistical Comparison of the various Joint Geometries on the US 395 Cold Springs Project.

Location	Geometry	Density (%)	Geometry	Density (%)	Difference
Hot Joint	A	94.9	C	95.4	Not Significant
	A	94.9	E	95.4	Not Significant
	C	95.4	E	95.4	Not Significant
Cold Joint	A	94.9	C	94.8	Not Significant
	A	94.9	E	94.6	Not Significant
	C	94.8	E	94.6	Not Significant

The statistical analysis of the data from the US 395 Cold Springs project as presented in Figures 19 and 20 and Table 22 indicates that all three joint geometries will produce the same density at both the cold and hot joints. This conclusion may have been influenced by the fact that the in-place densities at all four locations across the pavement (i.e. HM, HJ, CJ, and CM) throughout the entire project were high and very uniform. The causes for this situation were identified as follows:

- The data in Table 20 show that the average densities at the four locations across the pavement for all nine sections fall between 94.5 and 97.4 with 14 out of 36 locations having average densities of 96.0 or higher. The NDOT specification calls for in-place density between 92.0 and 96.0. Compared to the NDOT specifications, this project would be considered as slightly over-compacted. In general over-compaction can be attributed to a high asphalt binder content. This hypothesis was checked by conducting solvent extraction in the UNR laboratory on two field mixed samples. The results showed that the field samples have an

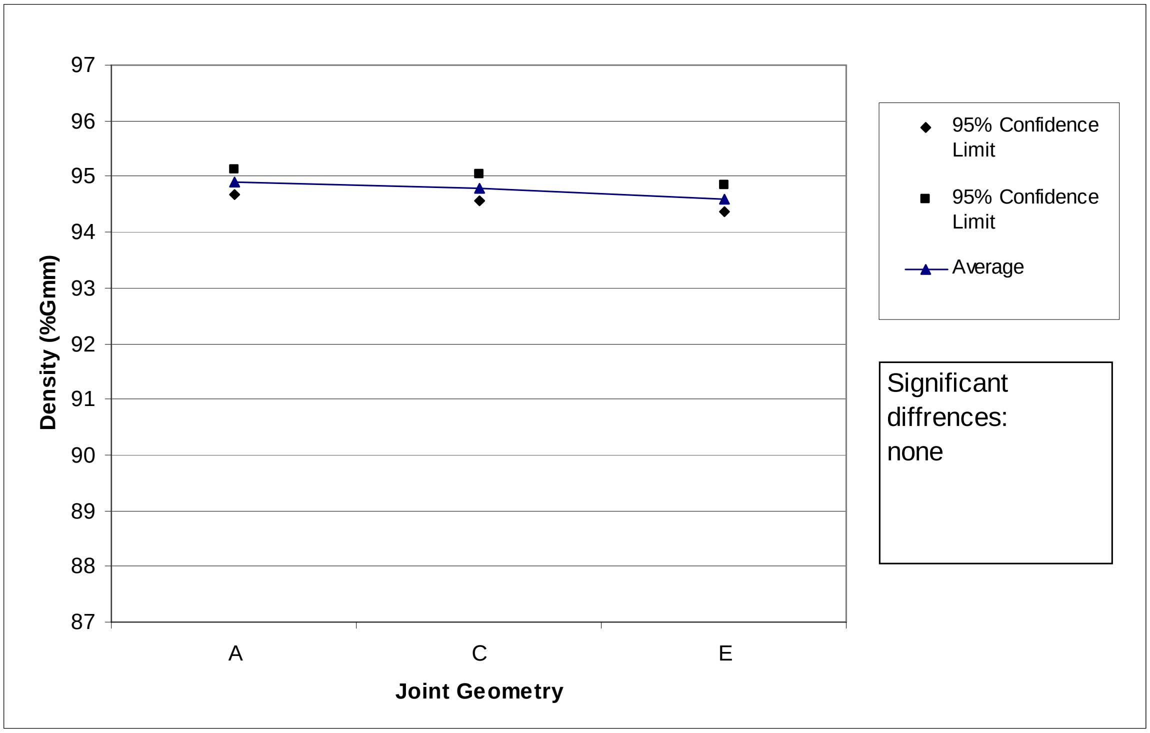


Figure 19 Impact of Joint Geometry on the Cold Joint Density using cores, US 395 Cold Springs Project.

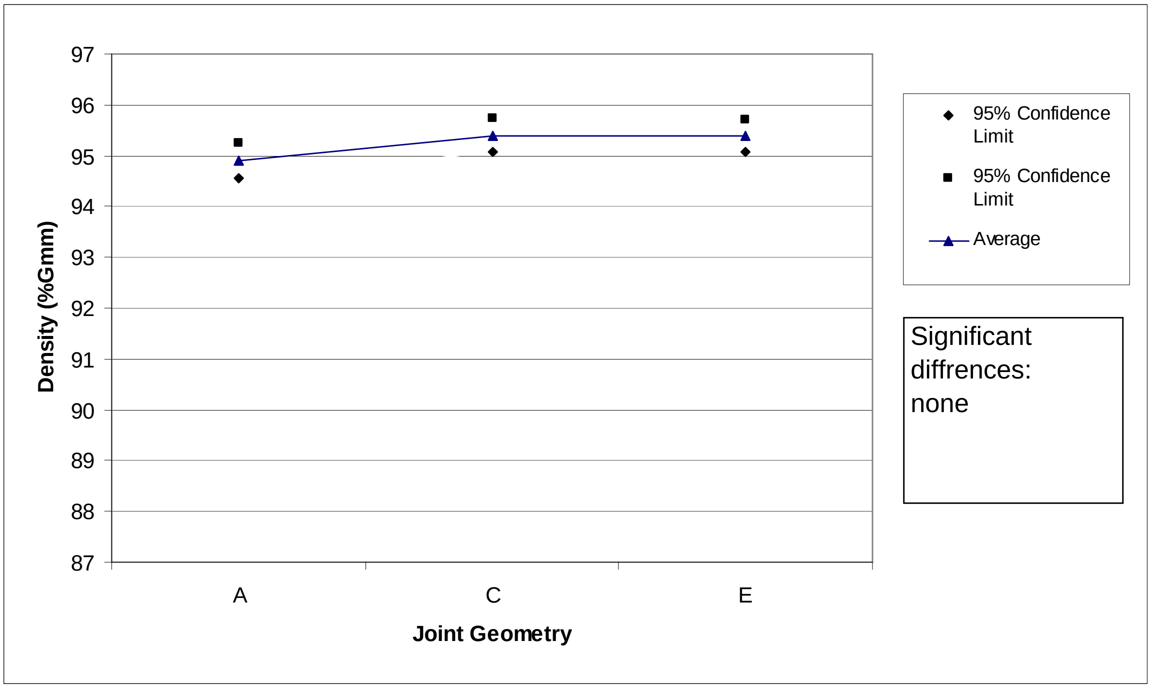


Figure 20 Impact of Joint Geometry on the Hot Joint Density using cores, US 395 Cold Springs Project

average binder content of 5.75%, based on dry weight of aggregate, which is 0.25% higher than the mix design binder content but within the NDOT's acceptable range of 0.40%. A review of the field ignition oven data showed that the average in-place binder content was at 5.85% which is 0.35% higher than the mix design binder content of 5.50%. Based on these data, it was concluded that the relatively high in-place densities were partially caused by the higher binder content of the field mix and partially by the intensive rolling pattern as discussed in the next bullet.

- The data in Table 20 show highly uniform in-place densities throughout the entire project. This is supported by the narrow range of densities (i.e. 94.5 – 97.4) and the extremely low standard deviations and coefficients of variation. This characteristic of the density data can be attributed to the very intensive rolling pattern that the contractor has implemented on this project. A comparison of the rolling pattern implemented on this project with the rolling patterns used on the two summer 2004 projects clearly reveals the higher intensity of the rolling pattern used on the Cold Springs project. This may have been caused by the fact that both NDOT personnel and the research team made a special request to have all mid-mat densities be within the NDOT specification. This request was made to avoid the inconsistencies that occurred on the summer 2004 projects where some of the densities at the mid-mats were below the 92.0 lower limit of the specifications which consequently resulted in a low density at the joint.

Conclusions and Recommendations Based on the Summer 2005 Projects

Based on the analyses of the data collected from the summer 2005 projects, the following conclusions and recommendations can be made.

- The in-place densities throughout all nine sections of the Cold Springs project were relatively high leading to the conclusion that the pavement was slightly over-compacted. The over-compaction can be attributed to the high in-place binder content and the intensive rolling pattern employed on this project.

- When the pavement is effectively compacted, high densities are achievable at both sides of the joint regardless of the joint geometry.

FIELD OBSERVATIONS

Several observations were made during the construction of the field test sections that should be mentioned. These observations will be critical for the implementation of a longitudinal joint specification for the state of Nevada.

- A refined milling process is highly recommended. A poor milling process leaves a very irregular surface, formed by deeper channels at the location of the bits and a slightly shallower elevation in between. These channels make it very difficult to cut the outside edge of the joint (cold side) as the blade or cutting wheel falls into the depressions, it becomes very difficult to control or maneuver.

- After cutting the vertical face of the cold joint, thorough brooming of this edge should be required to remove all dust and debris (broken aggregate) that resulted from the cutting process. Special care should be exercised when using limestone materials.

- Adequate lubrication should be applied to the surface of the cutting wheel and the edge restrain device, due to the possibility of picking up materials from the joint.

- The edge restraining and cutting wheel devices prove to be difficult to handle due to the lack of visibility that the operator has over the location of the device and the joint edge. During the construction of the field test sections it was necessary to assign a guiding person.

- The application of the joint sealant should be performed with adequate equipment. The use of normal crack filling equipment was not adequate for the application of the material at the joint. The end piece wasn't fixed and tends to rotate during the application of the product, leaving some sections without application, forcing the operator to come back and reapply the material at those locations and other sections with too much sealant.

- The use of a steel plate (the Las Vegas and Cold Springs projects) instead of a metal bar (the Washoe Valley project) to form the tapered joint proved to be highly significant. The texture of the joint was more homogeneous and provided a better finish. The joint shape tends to be more stable during its compaction.

APPLICABILITY OF THE INTERIM SPECIFICATION

The first phase of this research recommended an interim specification based on core densities, which stated the following:

- Core density at the joint should be a maximum of 2% less than the corresponding mat density.

AND

- Core density at the joint should be a minimum of 90% of the theoretical maximum density (TMD).

Reviewing the data from the summer 2004 projects on the joint densities and the differences between the mat and joint densities summarized in Tables 14 – 17 lead to the following observations:

- The core densities at the hot and cold joints on both projects are above the minimum required of 90% TMD.

- The differences between the hot mat and hot joint core densities are lower than the maximum of 2% for both projects. However, some of the hot mat densities are below the 92% TMG level.

- The differences between the cold mat and the cold joint core densities depends on the project:
  a) On the US 95 Las Vegas project, the difference is significantly higher than the 2%.
  b) On the US 395 Washoe Valley project, the difference is lower than the 2%.

Applying the interim joint density specification for the two summer 2004 projects leads to the conclusion that when using core densities and discarding the fact that some mat densities are below the 92% TMG, all joint geometries on the US 395 project will be acceptable while only the taper joint geometry on the US 95 would be marginally acceptable.

Reviewing the data from the summer 2005 project on the joint densities and the differences between the mat and joint densities leads to the following conclusion.

- All three joint geometries: natural slope (A), cut edge with rubberized tack coat (C), and tapered joint at 3:1 (E) will meet the recommended joint density specification.

RECOMMENDED JOINT DENSITY SPECIFICATION

Based on the analysis of the data generated from all the field-testing programs, it is recommended that NDOT implements the following joint density specification:

- The density at the joint should be a maximum of 2% less than the corresponding mat density.

AND

- The density at the joint should be a minimum of 90% of the theoretical maximum density (TMD).

An effective implementation of this joint specification would require answering the following two questions: a) can the density at the joint be within 2% of the mid-mat density and b) can a 90% joint density be achieved. The data generated from the two field-testing programs provided the basis to answer these questions as presented below.

Can the Density at the Joint be within 2% of the Mid-Mat Density: to answer this question, a percentile plot of the difference between the density at the joint and the density at mid-mat was prepared as shown in Figure 21. The percentile graph includes all the data from the summer 2004 and summer 2005 projects. It can be seen from Figure 21 that the difference of 2% between mid-mat and joint densities was achieved in 83% of the measurements. Therefore, the answer to the question is that a difference between the density at the joint and the density at mid-mat of 2% or less can be achieved in 83% of the cases.

Can a 90% Joint Density be Achieved: based on both the summer 2004 and summer 2005 projects, it can be concluded that the minimum density of 90% at the joint is achievable as long as the mid-mat density meets the NDOT specification of in-place density between 92 and 96% regardless of the joint geometry. This was proven on all three projects and on both the hot and cold joints.

Therefore, it is recommended that NDOT implement the joint density specification stated above while leaving the joint geometry decision up to the contractor.

It is also recommended to monitor the field performance of the three field projects to verify the recommendations and specifically to evaluate the long-term performance of the cut edge with rubberized tack coat as compared to the other geometries. This performance monitoring is critical since it is anticipated that none of the contractors will select the cut edge with rubberized tack coat geometry unless it is proven to be a superior geometry in the long run. The monitoring of the field test sections will provide an answer to this critical question.

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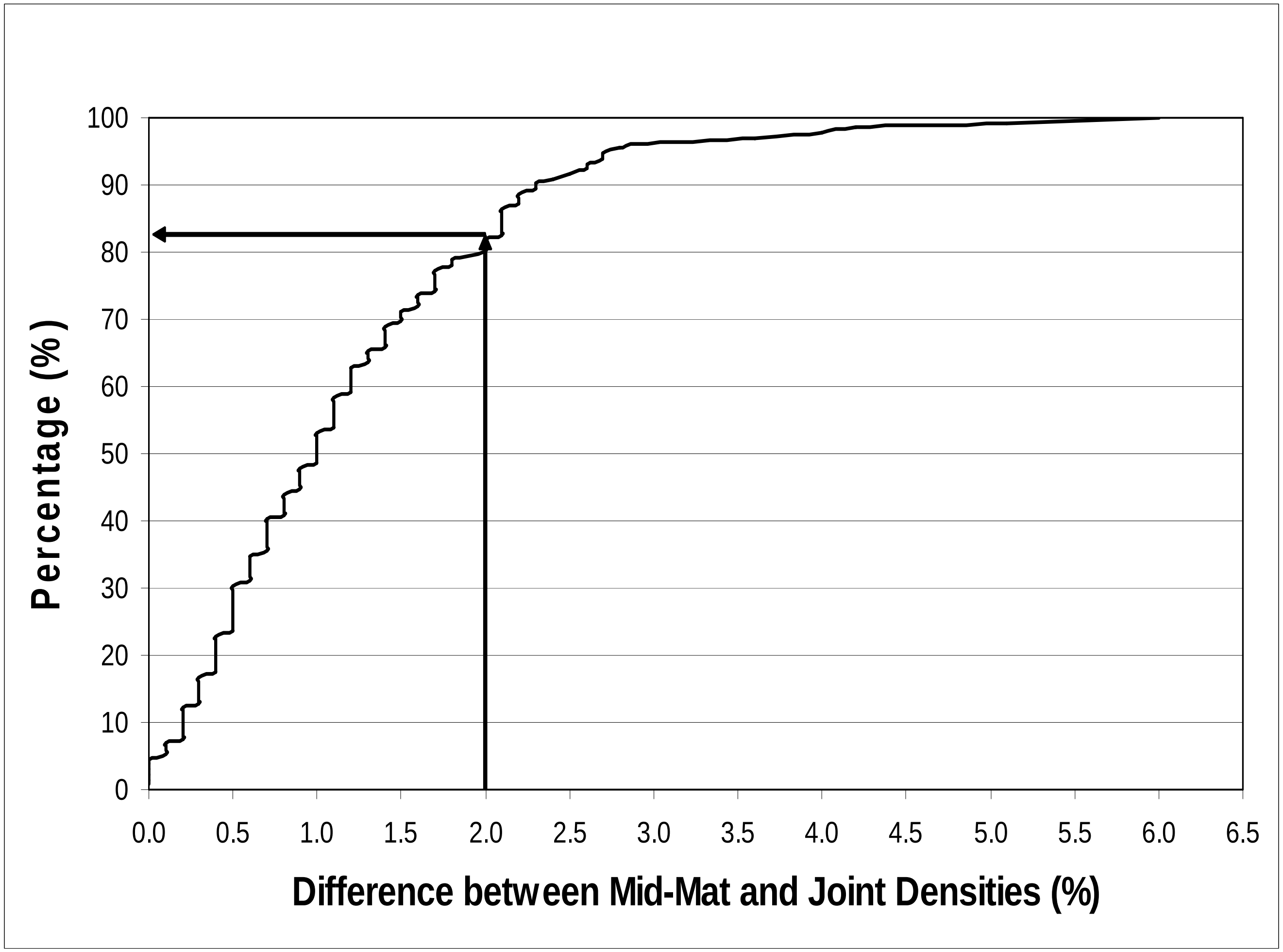

Figure 21 Percentile of the Difference between Mid-Mat and Joint Densities from all Test Sections Combined.

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