

1. Report No. FHWA/TX-09/0-5261-1	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle APPLICATION OF IMAGING TECHNOLOGY TO IMPROVE THE LABORATORY AND FIELD COMPACTION OF HMA		5. Report Date August 2008 Published: April 2009	
		6. Performing Organization Code	
7. Author(s) Eyad Masad, Emad Kassem, and Arif Chowdhury		8. Performing Organization Report No. Report 0-5261-1	
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. Project 0-5261	
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Technical Report: September 2005-May 2008	
		14. Sponsoring Agency Code	
15. Supplementary Notes Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration. Project Title: Using Imaging Analysis Technology to Improve the Laboratory and Field Compaction of HMA URL: http://tti.tamu.edu/documents/0-5261-1.pdf			
16. Abstract Field compaction of asphalt mixtures is an important process that influences performance of asphalt pavements. This study evaluates the relationship between different field compaction patterns and the uniformity of air void distribution in asphalt pavements. A number of projects with different hot mix asphalt (HMA) types were compacted, and cores were taken at different locations from these projects. The X-ray Computed Tomography (X-ray CT) system was used to capture the air void distributions in these cores. The analysis results have revealed that the uniformity of air void distribution is highly related to the compaction pattern and the sequence of using different compaction equipment. More importantly, the efficiency of compaction (reducing air voids) at a point was found to be a function of the location of this point with respect to the roller compactor width. The results in this paper have supported the development of the "Compaction Index (CI)," which quantifies the degree of field compaction. The CI is a function of the number of passes at a point and the position of the point with respect to the compaction roller width. This index was found to correlate reasonably well with percent air voids in the pavement. The CI calculated from field compaction had a good relationship with the slope of the compaction curve obtained from the Superpave gyratory compactor. This relationship offers the opportunity to predict field compactability based on laboratory measurements. The compaction of longitudinal joints was investigated, and recommendations were put forward to improve joint compaction. The air void distributions in gyratory specimens were related to the mixture mechanical properties measured using the Overlay and Hamburg tests.			
17. Key Words Hot-Mix Asphalt, Compaction, Effectiveness Factor, Uniformity, X-ray CT		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 250	22. Price

**APPLICATION OF IMAGING TECHNOLOGY TO IMPROVE THE
LABORATORY AND FIELD COMPACTION OF HMA**

by

Eyad Masad
Associate Research Scientist
Texas Transportation Institute

Emad Kassem
Assistant Research Scientist
Texas Transportation Institute

and

Arif Chowdhury
Assistant Research Engineer
Texas Transportation Institute

Report 0-5261-1

Project 0-5261

Project Title: Using Imaging Analysis Technology to Improve the Laboratory and Field
Compaction of HMA

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

August 2008

Published: April 2009

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

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) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation. The engineer in charge of the project was Eyad A. Masad, Texas #96368.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the Texas Department of Transportation personnel for their support throughout this project, as well as the Federal Highway Administration. We would also like to thank the project director Dr. German Claros and the members of the project monitoring committee, Mr. Ed Oshinski, Mr. Magdy Mikhail, and Ms. Darlene Goehl for their valuable technical comments during this project.

TABLE OF CONTENTS

	Page
LIST OF FIGURES	xii
LIST OF TABLES	xix
CHAPTER 1 INTRODUCTION AND BACKGROUND	1
Overview	1
Problem Statement	1
Tasks and Objectives	2
Task 1: Literature Search	2
Task 2: Conducting Field Experiments to Study the Influence of Mix Type and Compaction Pattern on Air Void Distribution	3
Task 3: Conducting Laboratory Experiments to Improve the Simulation of Laboratory Compaction to Field Cores	5
Task 4: X-ray CT and Image Analysis of Air Void Distributions	5
Task 5: Testing and Computer Simulation of the Performance of Asphalt Mixes	5
Task 6: Analysis of Experimental Measurements	5
Task 7: Preparation of Guidelines and Test Protocol	6
Task 8: Documentation of Findings	6
ORGANIZATION OF REPORT	6
CHAPTER 2 LITERATURE REVIEW	9
Introduction	9
Factors Affecting Compaction	9
Properties of the Materials	9
Environmental Variables	10
Compaction Equipment	13
Effect of Compaction Methods on Mechanical Properties of Asphalt Mixtures	18
Consuegra et al. (1989)	19

Sousa et al. (1991)	21
Harvey and Monismith (1993)	23
Button et al. (1994)	24
Peterson et al. (2004)	26
Effect of Compaction Methods on Air Void Distribution Using Image	
Analysis Techniques	26
Masad et al. (1999a)	27
Masad et al. (1999b)	32
Shashidhar (1999)	34
Tashman et al. (2001)	35
Partl et al. (2003 and 2007)	37
Modeling Compaction on Asphalt Mixes	41
CHAPTER 3 DESCRIPTION OF FIELD COMPACTION PROJECTS	43
Introduction	43
US 281 in Pharr District	44
FM 649 in Laredo District	46
IH 35 in Waco District	46
SH 36 in Yoakum District.....	47
US 87 in Yoakum District	48
US 259 in Tyler District	49
SH 21 in Austin District	51
CHAPTER 4 RELATIONSHIP OF FIELD COMPACTION PATTERN TO AIR	
VOID DISTRIBUTION	53
Introduction	53
Objectives, Significance, and Tasks	53
Field Experiments	54
Relationship between Compaction Pattern and Percent Air Voids	55
Applications of the Compaction Index	64
Relationship of Laboratory Compaction to Field Compaction.....	67

Influence of Compaction Pattern on Uniformity of Air Void Distribution	68
X-ray Computed Tomography	68
Three-Dimensional Air Void Distribution Maps	70
Quantifying Uniformity of Air Void Distribution	74
Compaction of Longitudinal Joints	79
Conclusions	82
CHAPTER 5 COMPARISON OF LABORATORY AND FIELD	
MECHANICAL PROPERTIES	85
Introduction	85
Hamburg Test Results	85
Permeability Test	92
Overlay Test Results	96
Summary of Findings	99
CHAPTER 6 THE EFFECT OF THE AIR VOID DISTRIBUTION ON THE	
OVERLAY TEST AND HAMBURG RESULTS	101
Effect of the Air Void Distribution on the Overlay Test	101
Introduction	101
Materials and Test Procedure	101
Test Results and Discussion.....	102
Effect of the Air Void Distribution on the Hamburg Test	107
CHAPTER 7 THE EFFECT OF THE COMPACTION TEMPERATURE	
ON THE AIR VOID DISTRIBUTION	109
Introduction	109
Experiments	109
Temperature Results	112
Air Void Analysis	116
Summary of Findings	125

CHAPTER 8 FORENSIC EVALUATION OF AIR VOID DISTRIBUTION	
IN ASPHALT PAVEMENT	127
Introduction	127
SH 114 in Fort Worth	128
Overview	128
Objectives	129
Background	130
Project Description	134
GPR Results	137
X-ray CT Analysis and Discussion	140
Conclusions.....	146
 CHAPTER 9 DETERMINATION OF THE MOISTURE DIFFUSION	
COEFFICIENT OF ASPHALT MIXTURES	147
Introduction	147
Objectives	148
Measurements of Suction Using Thermocouple Psychrometers	148
Analysis of Diffusion Coefficients	152
Drying Test Procedure for Determination of α	156
Materials and Test Procedure.....	158
X-ray Computed Tomography	162
Diffusion Coefficients Results	163
Conclusions	171
 CHAPTER 10 CONCLUSIONS	173
Evaluation of Field Compaction	173
Evaluation of Laboratory Compaction	174
Comparison of X-ray CT with Ground Penetrating Radar	175
Air Voids Distribution and Moisture Diffusion	176
 REFERENCES	177

APPENDIX A: Air Voids Analysis Results183

APPENDIX B: Forensic Evaluation of Air Void Distribution205

LIST OF FIGURES

Figure	Page
2-1	Time for Mat to Cool to 80°C versus Mat Thickness for Lines of Constant Mix and Base Temperatures 120°C or 150°C behind Paver (Corps of Engineers, 2000)11
2-2	Time for Mat to Cool to 80°C versus Mat Thickness for Lines of Constant Mix and Base Temperatures 105°C or 135°C behind Paver (Corps of Engineers, 2000)12
2-3	Static Steel Wheel Roller15
2-4	Pneumatic Tire Roller 16
2-5	Vibratory Steel Wheel Roller17
2-6	Superpave Gyratory Compactor18
2-7	Components of X-ray Computed Tomography System (Masad et al., 1999a).....28
2-8	The Process of Analyzing Air Void Distribution in Asphalt Mix Specimens Using X-ray CT and Image Analysis Techniques (Masad et al.,1999a).....28
2-9	An Example of an X-ray CT Image (Masad et al.,1999a)28
2-10	Angle of Inclination (θ_k) (Masad et al.,1999a)29
2-11	Determination of Number of Contacts by Erosion Techniques (Masad et al., 1999a).....31
2-12	Air Void Distribution in SGC and LKC Specimens (Masad et al., 1999a)31
2-13	Distribution of Voids in Gyratory Specimens (Masad et al., 1999b)33
2-14	Distribution of Voids in Field Cores (Masad et al., 1999b).....33
2-15	Variation of Vector Magnitude, Angle of Inclination, and Percent Void with Compaction (Masad et al., 1999b).....34
2-16	Vertical Distribution of Air Voids in Gyratory Specimens and Field Cores (Tashman et al., 2001).....36
2-17	Effect of the Base Plates and Mold Temperature on the Vertical Distribution of Air Voids in Gyratory Specimens (Tashman et al., 2001).....36

2-18	Vector Magnitude of Aggregate Orientation (Tashman et al., 2001).....	37
2-19	Rolling Wheel Compacted Specimens (Partl et al., 2007).....	38
2-20	Air Void Distribution in Marshall Specimen (Partl et al., 2007).....	39
2-21	Air Void Distribution in Gyratory Compacted Specimens (Partl et al., 2003)	39
2-22	Air Void Content in the Top Part of Rolling Wheel Compacted Specimens (Partl et al., 2007).....	40
2-23	Air Void Content in the Bottom Part of Rolling Wheel Compacted Specimens (Partl et al., 2007)	40
2-24	A Decrease of Air Content with the Compaction Level (Partl et al., 2007).....	41
3-1	Unusual Compaction Equipment	46
3-2	Finish Roller on FM 649.....	47
3-3	Field Coring Layout on SH 36.....	48
3-4	Field Coring Layout on US 87.....	49
3-5	Coring Layout on US 259	50
3-6	Coring Layout on SH 21	51
4-1	An Example of Field Coring Layout on SH 21	55
4-2	Number of Passes and Percent of Air Voids across the Mat in the IH 35 Test Section	56
4-3	Number of Passes and Percent of Air Voids across the Mat in US 87 Test Section (Pattern 1)	56
4-4	Number of Passes and Percent of Air Voids across the Mat in the US 259 Test Section (Pattern 1)	57
4-5	Examples of Different Effectiveness Factors of R^2 Values Obtained between Compaction Index and Percent Air Voids When These Factors Are Used	58
4-6	(a) Number of Passes versus the Percent of Air Voids in the IH 35 Test Section, (b) CI versus the Percent of Air Voids in the IH 35 Test Section	60
4-7	(a) Number of Passes versus the Percent of Air Voids in the SH 36 Test Section (Pattern 1), (b) CI versus the Percent of Air Voids in the SH 36 Test Section (Pattern 1).....	61

4-8	(a) Number of Passes versus the Percent of Air Voids in the US 259 Test Section (Pattern 1), (b) CI versus the Percent of Air Voids in the US 259 Test Section (Pattern 1).....	62
4-9	(a) Number of Passes versus the Percent of Air Voids in the US 87 Test Section (Pattern 1), (b) CI versus the Percent of Air Voids in the US 87 Test Section (Pattern 1).....	63
4-10	(a) Number of Passes versus the Percent of Air Voids in the SH 21 Test Section (Pattern 1), (b) CI versus the Percent of Air Voids in the SH 21 Test Section (Pattern 1).....	64
4-11	(a) Air Void Distribution (%) across the Mat for the IH 35 Job (b) The CI and Average Percent of Air Voids across the Mat for the IH 35 Test Section	65
4-12	(a) Air Void Distribution (%) across the Mat for SH 36 Test Section (Pattern 1), (b) The CI and Average Percent of Air Voids across the Mat for SH 36 Test Section (Pattern 1)	66
4-13	The CI versus the Percent of Air Voids	67
4-14	Compaction Index versus the Slope of LN (No. of Gyration) and Percent Air Voids Curve at 8 Percent Air Voids for Different Mixes.....	68
4-15	X-ray CT System at Texas A&M University	69
4-16	Components of X-ray Computed Tomography System	70
4-17	Air Void Distribution (%) along the Depth of the Mat for the US 87 Test Section (Pattern 1)	71
4-18	Air Void Distribution (%) along the Depth of the Mat for the US 87 Test Section (Pattern 2)	71
4-19	Air Void Distribution (%) along the Depth of the Mat for the SH 21 Test Section (Pattern 1)	72
4-20	Air Void Distribution (%) along the Depth of the Mat for the SH 21 Test Section (Pattern 2)	72
4-21	Air Void Distribution (%) Across the Mat at Different Depths for the SH 21 Test Section	73

4-22	Difference between the Percent of Air Voids at the Top and Bottom Parts for the US 87 Test Section (a) Pattern 1, (b) Pattern 2	76
4-23	UI for the US 87 Test Section (a) Pattern 1, (b) Pattern 2	77
4-24	Difference between the Percent of Air Voids at the Top and the Bottom Parts for SH 21 Test Section (a) Pattern 1, (b) Pattern 2	78
4-25	UI for the SH 21 Test Section (a) Pattern 1, (b) Pattern 2	79
4-26	(a) Air Void Distribution (%) across the Mat for the US 259 Test Section (Pattern 1), (b) The CI and Average Percent of Air Voids across the Mat for the US 259 Test Section (Pattern 1)	81
4-27	UI for the US 259 Test Section (Pattern 1).....	82
5-1	Comparison of Field and Lab Compacted Hamburg Specimens.....	88
5-2	Hamburg Test Results with Samples from US 87	90
5-3	Hamburg Test Results with Samples from FM 649.....	90
5-4	Hamburg Test Results with Sample from SH 36.....	91
5-5	Hamburg Test Results with Sample from US 259.....	91
5-6	Hamburg Test Results with Sample from US 21.....	92
5-7	Permeability Test Results with SH 36 Samples.....	93
5-8	Permeability Test Results with FM 649 Samples.....	94
5-9	Permeability Test Results with US 87 Samples.....	94
5-10	Permeability Test Results with SH 21 Samples.....	95
5-11	Permeability Test Results with US 259 Samples.....	95
5-12	Permeability Test Results with IH 35 Field Samples	96
5-13	Schematic Diagram of TTI Overlay Tester System.....	97
6-1	Air Void Distribution across the Depth of the Samples for Case 1	103
6-2	Air Void Distribution across the Depth of the Samples for Case 2.....	103
6-3	Air Void Distribution across the Depth of the Samples for Case 3.....	104
6-4	Air Void Distribution across the Depth of the Samples for Case 4.....	104
6-5	Air Void Distribution across the Depth of the Samples for Case 5.....	105
6-6	Overlay Test Results.....	106
6-7	Average Number of Failure Cycles	106

6-8	The Anticipated Average, Top, and Bottom Percent of Air Voids for Different Cases.....	108
7-1	A Schematic View of the Temperature Measurement System	110
7-2	Experimental Setup.....	111
7-3	The Temperature Profile along the Height of the Specimen for Case 1 (PG 76-22).....	112
7-4	The Temperature Profile along the Height of the Specimen for Case 2 (PG 76-22).....	113
7-5	The Temperature Profile along the Height of the Specimen for Case 3 (PG 76-22).....	113
7-6	The Temperature Profile along the Height of the Specimen for Case 1 (PG 64-22).....	114
7-7	The Temperature Profile along the Height of the Specimen for Case 2 (PG 64-22).....	114
7-8	The Temperature Profile along the Height of the Specimen for Case 3 (PG 64-22).....	115
7-9	Uniformity Index for Temperature Distribution for PG 76-22 Samples	116
7-10	Uniformity Index for Temperature Distribution for PG 64-22 Samples	117
7-11	The Air Void Distribution along the Height of SGC Specimen	118
7-12	Percent Air Voids for 150 mm Diameter Specimens with PG 76-22 Binder	119
7-13	Percent Air Voids for 100 mm Diameter Specimens with PG 76-22 Binder	119
7-14	Percent Air Voids for 150 mm Diameter Specimens with PG 64-22 Binder	120
7-15	Percent Air Voids for 100 mm Diameter Specimens with PG 64-22 Binder	120
7-16	Uniformity Index for Full Height of 150 mm Diameter Specimens with PG 76-22 Binder	121
7-17	Uniformity Index for Middle Third of 150 mm Diameter Specimens with PG 76-22 Binder	121
7-18	Uniformity Index for Full Height of 100 mm Diameter Specimens with PG 76-22 Binder	122
7-19	Uniformity Index for Middle Third of 100 mm Diameter Specimens with PG 76-22 Binder	122

7-20	Uniformity Index for Full Height of 150 mm Diameter Specimens with PG 64-22 Binder	123
7-21	Uniformity Index for Middle Third of 150 mm Diameter Specimens with PG 64-22 Binder	123
7-22	Uniformity Index for Full Height of 100 mm Diameter Specimens with PG 64-22 Binder	124
7-23	Uniformity Index for Middle Third of 100 mm Diameter Specimens with PG 64-22 Binder	124
8-1	Texas Typical Full Depth Asphalt Pavement Structural Sections (Scullion, 2006).....	129
8-2	TTI GPR Equipment (Scullion, 2006).....	131
8-3	Illustration of the Principles of GPR (Scullion, 2006).....	131
8-4	One Individual GPR Trace from a Thick Asphalt Pavement (Scullion, 2006).....	133
8-5	Color-Coded GPR Traces for a 1000 ft Section of Thick Asphalt Pavement (Scullion, 2006).....	133
8-6	GPR Data from a Full Depth Pavement (Scullion, 2006).....	135
8-7	SH 114 Full Depth Asphalt Pavement Structural Sections (Walubita and Scullion, 2007).....	136
8-8	Aggregate Gradations (Walubita and Scullion, 2007)	138
8-9	GPR Data Collected after Construction of the FW-01 Section (Walubita and Scullion, 2007).....	138
8-10	GPR Data after Construction of FW-01 and FW-02 (Walubita and Scullion, 2007).....	139
8-11	GPR Data Showing Low-Density Areas within the 1 inch SF Layer of the FW-01 Section (Walubita and Scullion, 2007).....	139
8-12	Air Void Distribution across the Depth of Core 1 from FW-01 Section (a) Percent Air Voids, (b) Air Void Radius	141
8-13	Air Void Distribution across the Depth of Core 2 from FW-02 Section (a) Percent Air Voids, (b) Air Void Radius	142

8-14	Three-Dimensional of Air Voids across the Depth (a) Core 1 from FW-01 Section, (b) Core 2 from FW-02 Section	143
8-15	Air Void Distribution across the Depth of Core 3 from FW-01 Section	145
8-16	Air Void Distribution across the Depth of Core 4 from FW-01 Section	146
9-1	(a) Seebeck Effect, (b) Peltier Effect (Fredlund and Rahardjo 1993)	149
9-2	Calibration Curve of Thermocouple Psychrometer	151
9-3	Relationship between Microvolt Outputs and Total Suction	151
9-4	Incremental Section with Dimensions Δx , Δy , and Δz	154
9-5	Schematic View of the Drying Test Sample	157
9-6	Schematic View of Test Setup	159
9-7	X-ray CT Image	163
9-8	(a) Distribution of Percent Air Voids Distribution along Depth, (b) Distribution of Average Air Void Radius along Depth	164
9-9	Change of Recorded Microvolts over Time	165
9-10	Change of Suction over Time (Stage II).....	165
9-11	Change in Measured and Theoretical Suction over Time with (a) Higher Percent Air Void above Psychrometers, (b) Less Percent Air Void above Psychrometers	167
9-12	Relationship between Diffusion Coefficients and Percent of Air Voids above Psychrometers.....	170
9-13	Relationship between Diffusion Coefficients and Air Void Size above Psychrometers	170

LIST OF TABLES

Table	Page
2-1	Summary of Average Differences between Field Cores and Laboratory Compacted Specimens (Consuegra et al., 1989).....20
2-2	Mean Squared Error (MSE) Comparison of Compaction Data (Consuegra et al., 1989).....21
2-3	Effect of Compaction Method on Resistance to Permanent Deformation (Sousa et al., 1991).....22
2-4	Effect of Compaction Method on Resistance to Fatigue (Sousa et al., 1991).....23
2-5	Average Permanent Deformation Results: Conventional Asphalts (Harvey and Monismith, 1993).....24
2-6	Consolidated Results from Statistical Analysis (Button et al., 1994).....25
3-1	Summary of Mixture Designs Used in Compaction Study.....44
3-2	Description of Compaction Patterns45
4-1	R-Squared Value57
5-1	Laboratory Tests Conducted with Different Mixtures from Field Compaction Study.....86
5-2	Hamburg Test Results.....87
5-3	Overlay Test Results with Field Compacted Samples98
5-4	Overlay Test Results with Lab Compacted Samples98
6-1	Aggregate Gradation102
7-1	Cases Analyzed for Varying Plates and Mold Temperatures109
9-1	Volumetrics for Limestone and Granite Mixtures (Kassem et al., 2006).....160
9-2	Granite and Limestone Mixture Gradations161
9-3	Summary of the Test Results168
9-4	Diffusion Coefficients of Different Phases within HMA171

CHAPTER 1

INTRODUCTION AND BACKGROUND

OVERVIEW

Evaluation of the performance of asphalt mixtures is done through laboratory testing. The laboratory hot mix asphalt (HMA) specimens should be fabricated in a manner that adequately simulates field pavements in order for laboratory testing to yield reliable mechanical properties. Air void structure is a major factor that affects the performance of asphalt mixtures (Monismith, 1992). When preparing laboratory specimens, only average volumetric parameters including percent air voids is usually matched with asphalt pavements. Quantifying the air void distribution by an average value is not sufficient due to the nonuniform air void distribution in asphalt mix specimens. Ignoring the nonuniform air void distribution could have a critical impact on the design, testing, and development of performance models of asphalt mixtures.

The X-ray Computed Tomography (CT) technique captures the internal structure of asphalt mixtures (Masad et al., 1999a; Masad et al., 1999b; Shashidhar, 1999). The findings of a number of studies demonstrate the capabilities of X-ray CT in capturing the internal structure of asphalt mixtures. The air void distribution results reveal that there is a difference in the air void distribution between laboratory specimens and field cores. Different compaction methods produce asphalt mixtures with different air void distributions and influence the mechanical properties of asphalt mixtures. Therefore, there is a pressing need to improve the simulation between laboratory specimens to asphalt pavements.

PROBLEM STATEMENT

For a laboratory performance test to yield reliable mechanical properties, it is necessary to ensure that laboratory specimens are fabricated in a manner that adequately simulates field compaction. The differences in air void distributions between asphalt mixes can occur even at the same percent air voids due to the differences in compaction method, aggregate shape, aggregate size distribution, and target volumetric values. The

differences in air void structure include air void gradient (change in percent air voids with depth) and different air void size distributions.

The difference in air void distribution is also evident between asphalt pavements. Some asphalt pavements tend to have significantly higher percent air voids in the top one inch than the rest of the lift thickness. Water tends to flow in this high percent air voids portion of the pavement where traffic loading is the highest. Coarser graded HMA mixtures, such as coarse matrix-high binder (CMHB) and Superpave coarser gradations, have a higher tendency to produce mixtures with permeable air voids than conventional dense-graded mixtures. Several studies have clearly shown that differences in the air void structure lead to significant differences in performance. Large voids promote faster damage growth under tensile loading leading to a reduction in fatigue life. Moisture damage was also found to be related to the air void structure. A uniform air void distribution throughout the sample reduces the localization of high strains in the mix and improves performance. All these findings emphasize that there is a pressing need to understand air void distributions and its influence on performance. Such understanding is necessary to design and construct asphalt pavements with optimum air void structure, and consequently, improved performance.

TASKS AND OBJECTIVES

X-ray CT technique was utilized to capture the air void distribution in asphalt mixtures in order to promote a better understanding of the effect of mix design and compaction on the air void distribution. Guidelines were developed with the aim of improving the simulation of laboratory compaction to the field conditions, and compacting the asphalt mixture with the optimum internal structure. The proposed plan for this study has several tasks which are outlined herein.

Task 1: Literature Search

A comprehensive literature search was conducted in order to collect the following pertinent information:

- compaction process and the factors influence the compaction process in the field and the laboratory,

- field and laboratory compaction equipment,
- influence of compaction methods on the mix properties and performance,
- influence of compaction methods on the internal structure of asphalt mixtures,
- modeling the compaction of hot mix asphalt, and
- new technologies in field compaction of hot mix asphalt.

Task 2: Conducting Field Experiments to Study the Influence of Mix Type and Compaction Pattern on Air Void Distribution

Quantifying the air void distribution in field cores compacted under different compaction procedures was the main objective of this task. This task was divided into the five following subtasks.

Subtask 2.1: Identification of Field Projects

Roadway projects with different types of mixes were identified in order to conduct the subtask 2.2 and 2.4. Mix information (e.g., mix design data, aggregate, and asphalt properties) and compaction data (e.g., compaction equipment, compaction pattern, and temperature) were collected for each project.

Subtask 2.2: Field Projects with Different Material Sources and Mix Designs

The air void distributions in field cores from different construction projects, which cover several types of mixture and material sources, were examined. The field conditions which include compaction procedures, compaction patterns, compaction temperature, materials temperature, field density, etc. were documented. The collected field cores were used to conduct task 4 for measuring total air void and air void distribution. Common types of TxDOT mixtures were included in this phase.

Subtask 2.3: Field Test Sections with Different Compaction Patterns

The field cores selected under task 2.1 were expected to be insufficient in providing different compaction patterns to verify its influence on the air void distribution. It was planned for selecting a number of roadway construction projects for varying the compaction equipment and the number of passes for initial rolling, intermediate rolling,

and finish rolling. The data and samples collected during the field projects include but are not limited to:

- ambient, surface, and mixture temperature;
- density data measured using nuclear and non-nuclear density gauges;
- equipment used in the project, (Screed, dump truck or materials transfer device; roller): size, weight, pattern, sequence, number of passes, etc.;
- cores for Saturated Surface Dry (SSD) density, vacuum sealed density, X-ray CT, and performance testing;
- regular quality control/quality assurance information gathered by contractor or TxDOT; and
- plant mixture and virgin aggregate and binder for further testing.

Subtask 2.4: Field Compaction near Longitudinal Joints

The longitudinal joint density of HMA mixture pavement is a major concern of TxDOT. The objective of this task was to examine the effect of the compaction on the longitudinal joint density. Researchers used nuclear density gauge and PQI device to evaluate the joint density for HMA mixture. The field cores obtained under this task were also used to conduct [task 4](#) for measuring total air void and air void distribution with the objective of determining the quality of compaction near longitudinal joints.

Subtask 2.5: Forensic Evaluation of Field Compaction

This task promotes better understanding for the causes of compaction problems in TxDOT construction projects. These projects include the pavement already in service and/or recently constructed. The advisory panel recommended these projects with an explanation of the encountered compaction and air void problems. X-ray CT was used along with other laboratory tests to examine the field cores for the likely causes of the problems encountered during the compaction. The results will assist TxDOT to eliminate or minimize these problems.

Task 3: Conducting Laboratory Experiments to Improve the Simulation of Laboratory Compaction to Field Cores

Laboratory HMA specimens should be fabricated in a manner that adequately simulates the field conditions for yielding reliable mechanical properties. Currently, the air void distribution is simulated by an average value. This is not a realistic assumption due to the heterogeneous nature of air void distribution through the specimen. Superpave gyratory compactor (SGC) was used to compact asphalt mixtures in order to quantify the simulation of the internal structure in laboratory specimens and field cores. The objective of this task aimed to fabricate laboratory specimens that better simulate the air void distribution of field cores.

Task 4: X-ray CT and Image Analysis of Air Void Distributions

X-ray CT technique was utilized to capture the internal structure of HMA specimens. This technique is a nondestructive method and applicable for the HMA mixes with a resolution of 150 micron/pixel. The researchers have already developed image analysis techniques to analyze the size of air voids, percent air void vertically and horizontally, shape of air void, and connectivity of air voids in all directions.

Task 5: Testing and Computer Simulation of the Performance of Asphalt Mixes

Properties of laboratory specimens and field cores were measured using the Hamburg wheel tracking device, an overlay tester, a permeability test, and dynamic loading.

Task 6: Analysis of Experimental Measurements

The statistical analysis of air void distribution was used along with the testing results and computer simulation of the performance in order to:

- determine the influence of air void distribution on permeability and mechanical properties of asphalt mixes;
- evaluate the possible changes to the laboratory compaction procedures to better resemble field compacted asphalt pavements;

- determine the influence of compaction method, aggregate gradation, aggregate shape, and design volumetric properties on air void distribution;
- determine the influence of changing the field compaction pattern on air void distribution and mechanical properties related to the different distresses; and
- investigate the possible changes to laboratory compaction procedure to improve the resemblance of air void distribution in laboratory and field specimens, and consequently, to improve the ability of predicting field performance based on testing laboratory compacted HMA specimens.

Task 7: Preparation of Guidelines and Test Protocol

The findings of the previous tasks yielded guidelines for better compaction simulation between the laboratory specimens and field cores. The expected guidelines addressed a number of changes for both laboratory and field compaction. These proposed changes promote better simulation between the laboratory compacted specimens and field conditions, and enhance the ability to compact asphalt pavements with uniform air void distribution that have better resistance to water infiltration, cracking, and rutting. The second objective of this task was to develop a standard test protocol for the use of X-ray CT in the analysis of the internal structure of asphalt mixtures.

Task 8: Documentation of Findings

The research results and findings were documented in two reports in addition to the technical memorandum submitted to TxDOT. These reports show the progress of the study and its findings in detail.

ORGANIZATION OF REPORT

This report documents the research efforts outlined in Task 1 through 6. [Chapter 1](#) provides the introduction, background, and the list of tasks conducted under this research project. [Chapter 2](#) summarizes the comprehensive literature review conducted under [Task 1](#). [Chapter 3](#) provides a brief description of the field projects and field testing. [Chapter 4](#) documents the evaluation of the relationship between different field compaction patterns and the uniformity of air void distribution. It presents the detail testing efforts and

analyses procedure of air voids distribution using X-ray CT. [Chapter 5](#) provides the testing efforts and results from comparative performance study between field compacted and laboratory compacted specimens. [Chapter 6](#) documents the effort to evaluate the effect of the air void distribution on the performance of HMA using overlay tester and Hamburg wheel tester. The efforts to evaluate the effect of temperature on laboratory compacted specimens are presented in [Chapter 7](#). [Chapter 8](#) describes the testing and results from four forensic projects studied under this research project. [Chapter 9](#) documents the research efforts to develop an experimental procedure for measuring the diffusion coefficient of full asphalt mixtures and to evaluate the effect of air voids on moisture diffusion. [Chapter 10](#) presents the overall conclusions inferred under various tasks. Another report will document the results from the remaining tasks.

CHAPTER 2

LITERATURE REVIEW

INTRODUCTION

Compaction is the process by which the volume of asphalt mixture is reduced (Corps of Engineers, 2000). As a result of the compaction process, the aggregate interlock and interparticle friction increases, percent air voids decreases, and unit weight increases. Compaction has a significant influence on HMA performance in the field. Providing all desirable mix-design characteristics without adequate compaction will lead to poor asphalt pavement performance. HMA pavements with poor compaction will be exposed to permanent deformation “rutting” as a result of further densification under the subsequent traffic especially in the first few years of its service. Studies show that this percent should not fall below 3 to 4 percent for the dense-graded mixtures in order to maintain good resistance to permanent deformation (Roberts et al., 1996). Adequate compaction decreases rutting, increases fatigue life, decreases moisture damage, and decreases low temperature cracking (Corps of Engineers, 2000).

FACTORS AFFECTING COMPACTION

The factors that affect HMA compaction include the properties of the materials in the mixture, environmental variables, conditions at the laydown site, and the method of compaction being used (Corps of Engineers, 2000).

Properties of the Materials

Aggregate

Aggregate characteristics influence the compactive effort required to obtain a proper level of density (Corps of Engineers, 2000). The compactive effort increases with an increase in aggregate angularity, nominal maximum aggregate size, and aggregate hardness. Angular aggregate requires more densification effort due to its resistance to reorientation. Aggregate texture affects the compactive effort. Smooth aggregates are easier to compact than aggregates with high texture of rough surfaces. Rounded shape

aggregates require less compaction effort than cubical or block-shaped aggregates. Dense-graded mixtures need less compaction effort than open-graded mixtures.

Asphalt Binder

The ability to densify the asphalt mixtures is affected by the grade and amount of asphalt binder (Corps of Engineers, 2000). A mix produced with high grade binder is usually stiff and needs more compactive effort to obtain the desired density. A mix that includes too little amount of asphalt binder is stiff and usually needs more compaction effort than the mix with high asphalt binder.

The temperature susceptibility of the asphalt binder affects the workability and the time available for compaction (Corps of Engineers, 2000). A mix containing high temperature-susceptible asphalt binder has less time available for compaction as a result of losing the temperature and being stiffer.

Environmental Variables

The time available for compaction was determined for various HMA mixtures in the early 1970s by the U.S. Army Corps of Engineers (2000). The time available for compaction is the time for the mix to cool from its laydown temperature to a minimum compaction temperature. A study by the U.S. Army of Engineers (2000) defined this minimum compaction temperature to be 80°C. Below this temperature the compaction process is not effective and little density gain is achieved. Six variables influenced the available time for compaction in this study. These factors include layer thickness, air temperature, base temperature, mix laydown temperature, wind velocity and solar radiation. The relationships between these variables and the time available for compaction are illustrated in Figures 2-1 and 2-2. Wind velocity and solar radiation are assumed to be constants in this particular study.

Layer Thickness

Layer thickness significantly influences the time available for compaction. It can be seen from Figure 2-1 that if a mix laydown temperature is 120°C (250°F) and a base temperature is 15°C (60°F), the available time to compact a mat with a thickness of 2

inches is 12 minutes. If a mat thickness is doubled, the time available for compaction increases from 12 minutes to 36 minutes. It can be seen from Figures 2-1 and 2-2 that the time available for compaction is limited for a thick layer, especially in cold weather.

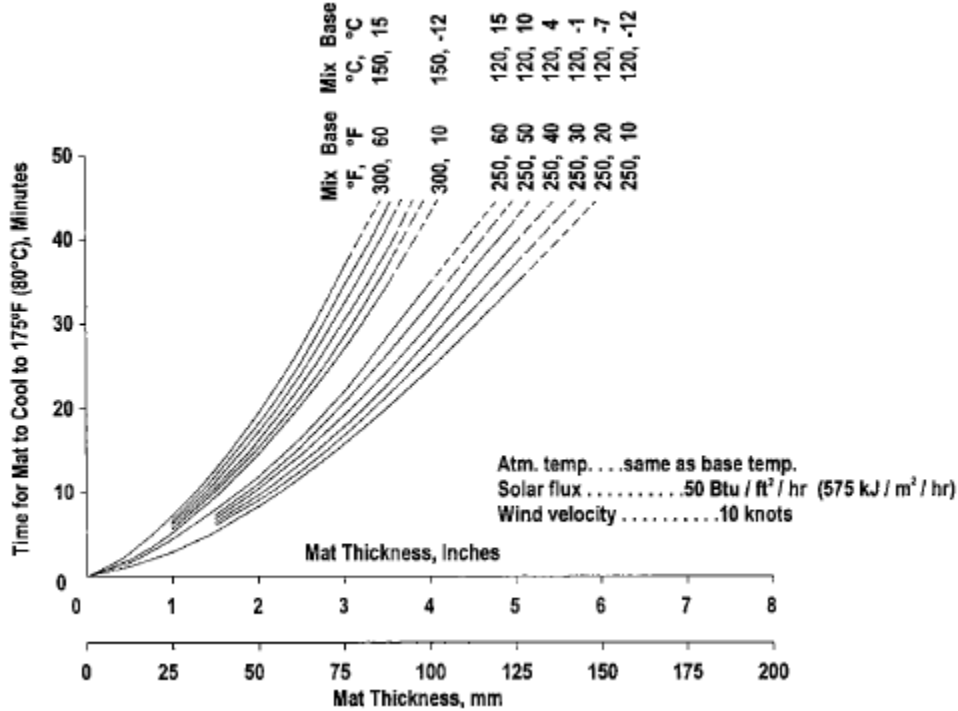


Figure 2-1. Time for Mat to Cool to 80°C versus Mat Thickness for Lines of Constant Mix and Base Temperatures 120°C or 150°C behind Paver (Corps of Engineers, 2000).

Air and Base Temperature

An asphalt layer loses heat to both the air and the layer on which the new layer is placed. Usually, the air temperature and the base temperature are assumed to be the same. The base temperature is considered more important than the air temperature as the cooling rate at the base is more rapid than at the upper surface (Corps of Engineers, 2000). Figures 2-1 and 2-2 show that the time available for compaction increases with an increase in base temperature.

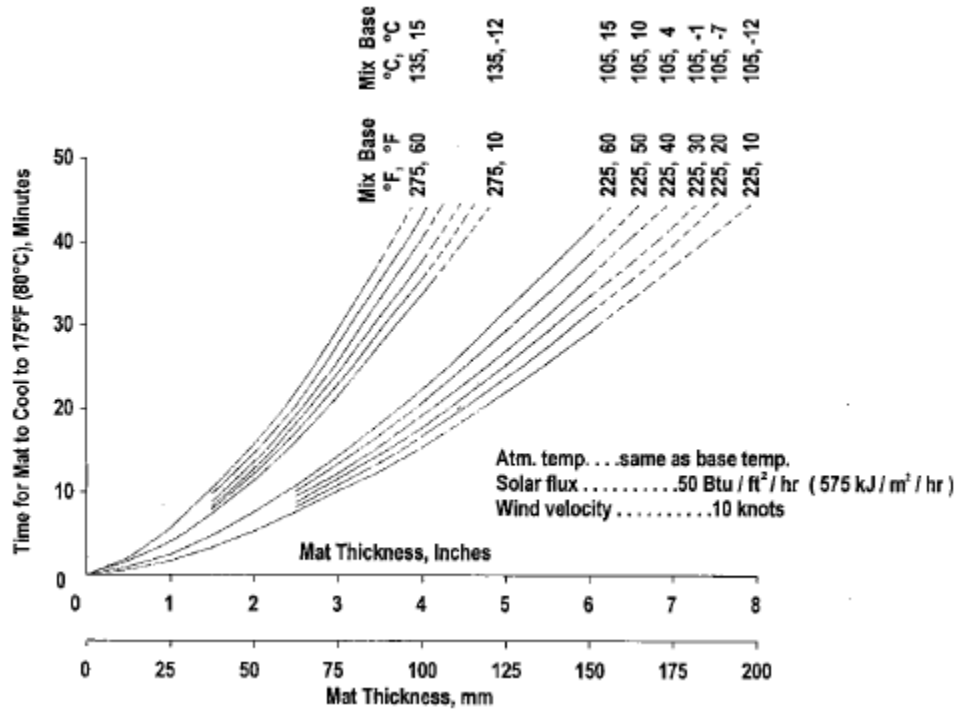


Figure 2-2. Time for Mat to Cool to 80°C versus Mat Thickness for Lines of Constant Mix and Base Temperatures 105°C or 135°C behind Paver (Corps of Engineers, 2000).

Mix Laydown Temperature

Usually, the temperatures of producing asphalt mixtures are between 130°C (270°F) and 165°C (325°F). The plant mixing temperature is not important in determining the time available for compaction as the mix laydown temperature. It can be seen from Figures 2-1 and 2-2 that the time available for compaction increases with an increase in the initial mix temperature. The initial mix temperature is more significant in compaction of thin layers in cold weather (Corps of Engineers, 2000).

Wind Velocity

The cooling rate of the asphalt layer increases if there is a strong wind during compaction. The wind influences the time available for compaction for a thin layer more than a thick one. A crust forms at the top of asphalt layer and should be broken down by a roller before compaction.

Solar Flux

Solar flux is the amount of radiant energy available from the sun, and depends on many variables such as the position of the sun above the horizon, the distance above the sea, and the level of paving project. The solar flux affects the temperature of the base layer. The temperature of the base layer is higher than the ambient temperature on a sunny day. A high base temperature will increase the time available for compaction.

Laydown Site Conditions

As mentioned earlier, layer thickness is the most important factor affecting the compaction ability in order to obtain the desired density level. If the asphalt layer thickness varies in depth due to rutting in the old surface, it is difficult to densify the mix in order to achieve a given density. A pneumatic tire roller is more helpful than a static steel wheel roller in this case because static steel wheel rollers tend to bridge over the ruts, especially when they are narrow and deep.

Compaction Equipment

The density of an asphalt layer is affected by the method of compaction being used. Different density levels can be obtained at the same number of passes when different compaction equipment is used. In this section, the field compaction equipment and laboratory compaction equipment will be discussed in detail.

Field Compaction Equipment

Compaction reduces air voids and increases the unit weight through the application of external forces. Self-propelled compactors are used to provide the compaction energy. This compaction train usually consists of two more rollers in order to achieve the following objectives ([Roberts et al., 1996](#)):

- 1) to obtain the desired density level and meet the specifications, and
- 2) to provide the roadway with a smooth surface.

Self-propelled compactor equipment can be divided into three categories: static steel wheel rollers, pneumatic tire rollers, and vibratory steel wheel rollers.

- Static Steel Wheel Rollers

A static steel wheel roller is shown in [Figure 2-3](#). Static steel wheel rollers weigh between 3 to 14 tons. The diameter of its drum varies from 1.0 to 1.5 m ([Corps of Engineers, 2000](#)). The effective contact pressure between the steel drum and the asphalt layer determines the actual compactive effort supplied by the roller ([Roberts et al., 1996](#)). The contact pressure is dependent on the depth of penetration. As the penetration depth increases, the contact pressure decreases due to the large contact area. As a result, the compaction effort supplied to the mix decreases. The penetration depth decreases gradually under the subsequent passes of the roller as a result of densification of the mix. Static steel rollers equipped with large drums have lower angles of contact than those provided with small drums giving them a lower component of horizontal force that pushes against the asphalt layer ([Roberts et al., 1996](#)).

- Pneumatic Tire Rollers

Pneumatic tire rollers shown in [Figure 2-4](#) are used for intermediate rolling after a static steel wheel or vibratory steel wheel roller and before a static steel finish roller. Occasionally, pneumatic rollers are used for initial or finish rolling. Many factors influence the compactive effort applied by the pneumatic roller. These factors include the wheel load of the rollers, tire pressure, tire design, and depth of penetration of the tire into the mix ([Corps of Engineers, 2000](#)). As the contact pressure between the tires and the mix increases, the compactive effort supplied by the pneumatic roller increases. The desired compaction pressure of the mat can be produced by changing the inflation pressure in the tires ([Roberts et al., 1996](#)).



Figure 2-3. Static Steel Wheel Roller.

Low pressure is preferable for the tender mix as low tire pressure will displace the mix less than higher pressure does. Usually, the pressure of the tires should be maintained constant in the same project, especially if the pneumatic roller is used in the intermediate position. The tire of the pneumatic roller might pick up the mix, so water may be sprayed or a release agent may be applied. There are many advantages of using pneumatic rollers when compacting dense-graded aggregate (Roberts et al., 1996):

- A more uniform degree of compaction is provided by pneumatic rollers than by steel wheel rollers.
- The density provided by pneumatic rollers, occasionally can not be achieved by steel wheel rollers.
- Pneumatic rollers do not cause checking during compaction and help in removing checking that might occur under the steel wheel roller.

Checking is the term used to describe fine, hairline, transverse cracks which occur at the surface of the mat.



Figure 2-4. Pneumatic Tire Roller.

- **Vibratory Steel Wheel Rollers**

Vibratory steel wheel rollers have a dynamic load component, and its weight is lighter than the static steel wheel roller. The dynamic load of the roller is produced by attaching an eccentric weight to the rotating shaft in the center of the drum. The drum diameters are 1.02 m to 1.52 m, and the drum width is between 1.47 m and 2.13 m. The compactive effort supplied by the vibratory rollers is influenced by the static and dynamic load of the machine. The dynamic load is the significant force in densification of the asphalt layer. Vibration reduces mechanical friction during compaction, but yields an increase of mechanical interlock after that (Roberts et al., 1996). In order to achieve a given density level, the frequency and amplitude of a vibratory roller must be selected. Generally,

higher amplitude and a lower frequency are needed for a thicker mat than a thinner one.



Figure 2-5. Vibratory Steel Wheel Roller.

Laboratory Compaction Equipment

Many compaction devices have been used to compact HMA specimens in the laboratory with the aim of simulating the asphalt mixtures in the field. These compaction devices include: Texas gyratory shear device, California kneading compactor, Marshall impact compactor, mobile steel wheel simulator, Arizona vibratory-kneading compactor, and Superpave gyratory compactor (SGC). The focus of the discussion will be on the SGC.

The Superpave gyratory compactor, shown in [Figure 2-6](#), is used to compact HMA specimens in the laboratory. There are some similarities between the SGC and other gyratory compactors, but the SGC is a unique device. The parameters that

control the compaction effort of the SGC are vertical pressure, angle of gyration, and number of gyrations. For the Superpave design procedure, the vertical pressure is set at 600 kPa, while the angle of gyration is set at 1.25° . The Superpave gyratory specimens are either 6 inches (15 cm) or 4 inches (10 cm) in diameter.



Figure 2-6. Superpave Gyrotory Compactor.

EFFECT OF COMPACTION METHODS ON MECHANICAL PROPERTIES OF ASPHALT MIXTURES

Different compaction methods produce HMA specimens with different internal structures which are represented by air void distribution, aggregate orientation, and aggregate contacts. The difference in internal structure is manifested in different mechanical properties. In this section, some of the previous studies on this topic are reviewed, and their findings are presented.

Consuegra et al. (1989)

The main objective of the study was to ensure that laboratory asphalt specimens are fabricated in a manner that adequately simulates field compaction and yield engineering properties similar to field cores. The specific goal was to evaluate the ability of different compaction devices to simulate the compaction in the field in terms of the mechanical properties. Five different laboratory compaction methods were used in this study. These methods were (a) Texas gyratory compactor, (b) California kneading compactor, (c) Marshall impact compactor, (d) mobile steel wheel simulator, and (e) Arizona vibratory-kneading compactor.

Field cores and samples of asphalt, aggregate, and loose mix from the drum were collected and transported to the laboratory. Laboratory specimens were prepared by reheating the loose mix in the laboratory and compacting it at the same percentage of the air content of the field cores. Different compaction patterns used in the field included:

- vibratory rolling for breakdown compaction followed by static rolling for finish compaction,
- static rolling for breakdown compaction followed by pneumatic rolling for intermediate compaction and static rolling for finish compaction, and
- pneumatic rolling for breakdown compaction followed by static rolling for finish compaction.

The field cores and the laboratory specimens were evaluated for indirect tensile strength, indirect tensile creep, and diametral resilient modulus. An average absolute difference (ΔD) is used to evaluate the average differences in means for each of the laboratory compaction methods from the field cores. ΔD was represented by the following equation:

$$\Delta D = \frac{\sum_{i=1}^n \left(\frac{MP_c - MP_s}{MP_c} \right)}{n} \quad (2-1)$$

where, MP_C = average materials property measured on the field cores, which is taken to be a target value, MP_S = average materials property measured on the laboratory specimens, n = number of data point for each compaction device.

Table 2-1 presents the average absolute difference (ΔD) for the different compaction methods. The mean square error (MSE) is used also to compare the mechanical properties for the laboratory specimens to the field cores as a desired value. MSE results are summarized in Table 2-2.

The analysis of the results showed that the engineering mechanical properties of asphalt mixtures are dependent on the compaction method. A Texas gyratory compactor was found to be the best method among those used in this study in terms of lower MSE and less average absolute difference value. The study ranked the compaction methods in terms of simulation of mechanical properties of field cores. The ranking was as follows: (1) Texas gyratory compactor, (2) California kneading compactor, (3) mobile steel wheel simulator, (4) Arizona vibratory-kneading compactor, and (5) Marshall mechanical hammer.

Table 2-1. Summary of Average Differences between Field Cores and Laboratory Compacted Specimens (Consuegra et al., 1989).

<u>Compaction Device</u>	<u>Creep Compliance at 77°F</u>	<u>Indirect Tensile Strength</u>	<u>Tensile Strain at Failure</u>	<u>Resilient Modulus</u>
Arizona Compactor	0.77	0.51	0.47	0.41
Marshall Hammer	0.80	0.35	0.45	0.55
California Kneading	0.59	0.21	0.27	0.42
Steel Wheel Simulator	0.51	0.31	0.11	0.26
Texas Gyratory Shear Compactor	0.44	0.14	0.16	0.37

Note: A zero difference indicates that the laboratory specimens had identical properties of the cores (no difference).

**Table 2-2. Mean Squared Error (MSE) Comparison of
Compaction Data (Consuegra et al., 1989.)**

Laboratory Compaction Method	Average MSE Rankings by Mixture		
	Project	Property	Temperature
Arizona Compactor	5.0	4.8	4.7
California Kneading	2.0	2.0	2.0
Marshall Hammer	4.0	3.5	3.3
Mobile Steel Wheel	1.7	2.8	2.0
Texas Gyratory	2.0	1.5	1.3

Sousa et al. (1991)

The objective of this study was to determine the effect of compaction method on the fundamental engineering properties of HMA. Sousa et al. (1991) stated that laboratory specimens must simulate the in-service mixtures produced by mixing, placement, and compaction in the field for laboratory tests to provide meaningful results. Three compaction methods were evaluated in this study. These compaction devices were (a) Texas gyratory compactor, (b) California kneading compactor, and (c) rolling-wheel compactor. The study evaluated the effect of different compaction methods on the permanent deformation and fatigue properties of asphalt mixtures. The main findings of this study in regard to the effect of compaction method on the performance of the asphalt mixture can be summarized as follows:

- The engineering properties of asphalt mixture are significantly influenced by the compaction method used to prepare the laboratory specimens.
- Specimens prepared using the kneading compactor were the most resistant to permanent deformation, followed by the specimens fabricated using the rolling-wheel compactor and the Texas gyratory compactor. The results of the effect of compaction method on resistance to permanent deformation are summarized in Table 2-3. In general, specimens prepared using the kneading

compactor were the most sensitive to aggregate characteristics, and the specimens prepared using the rolling-wheel compactor were more sensitive to asphalt characteristics.

- Texas gyratory specimens have the most resistance to fatigue followed by the specimens fabricated by the rolling wheel and kneading compactor. The results of the effect of compaction method on resistance to fatigue are presented in [Table 2-4](#).
- The kneading compactor is very effective in producing asphalt mixtures with maximum interparticle contact. This might help in understanding the cause of higher resistance of kneading specimens for the permanent deformation than the specimens prepared using other compaction methods. Kneading specimens are sensitive to the aggregate angularity and surface texture.

Table 2-3. Effect of Compaction Method on Resistance to Permanent Deformation (Sousa et al., 1991).

Compaction Method	Test	Overall Resistance	Ranking in the Twelve Mixtures and Test Variable Comparisons of Tables 4.1 and 4.2		
			Strongest	Intermediate	Weakest
Gyratory	Compressive Creep	Weakest	None	4 Times	8 Times
	Shear Creep	Weakest	1 Time	None	11 Times
Kneading	Compressive Creep	Strongest	10 Times	1 Time	1 Time
	Shear Creep	Strongest	2 Times	2 Times	None
Rolling wheel	Compressive Creep	Intermediate	2 Times	7 Times	3 Times
	Shear Creep	Intermediate	1 Time	10 Times	1 Time

Table 2-4. Effect of Compaction Method on Resistance to Fatigue (Sousa et al., 1991).

Compaction Method	Test	Overall Resistance	Ranking in the Twelve Mixtures and Test Variable Comparisons of Tables 4.6 and 4.7		
			Strongest	Intermediate	Weakest
Gyratory	Flexural Fatigue	N/A	N/A	N/A	N/A
	Diametral Fatigue	Strongest	6 Times	3.5 Times	2.5 Times
Kneading	Flexural Fatigue	Intermediate	3 Times	9 Times	N/A
	Diametral Fatigue	Weakest	None	7.5 Times	4.5 Times
Rolling Wheel	Flexural Fatigue	Strongest	9 Times	3 Times	N/A
	Diametral Fatigue	Intermediate	6 Times	1 Time	5 Times

Harvey and Monismith (1993)

The main objective of the study was to determine the effects of laboratory preparation variables on the mechanical properties of asphalt mixtures, which relate to permanent deformation, fatigue, and flexural stiffness. The mixes used in this study differed in binder type, aggregate type, fines content, air void content, mixing viscosity, and compaction viscosity.

The laboratory compaction methods evaluated were (a) Texas gyratory compactor, (b) University of California at Berkley rolling wheel compactor, and (c) California kneading compactor. The results revealed that the compaction methods produce specimens that are significantly different in terms of resistance to permanent deformation. The results from the repetitive shear permanent deformation are represented in [Table 2-5](#). The analysis of the results revealed that the kneading specimens have the most permanent shear deformation resistance, the rolling wheel specimens have intermediate resistance, and gyratory compacted specimens have the least resistance. This study indicated that the effect of laboratory compaction method on the mix performance is at least equivalent to the effect of aggregate type, binder type, fines content, or air void content. The results also demonstrated that compaction methods can not be used interchangeably.

Button et al. (1994)

This study was carried out in order to determine which of four different compaction methods most closely simulates field compaction. The compaction methods that were used included: (a) Exxon rolling wheel compactor, (b) Texas gyratory compactor, (c) rotating base hammer, and (d) Elf linear kneading compactor.

Table 2-5. Average Permanent Deformation Results: Conventional Asphalts (Harvey and Monismith, 1993).

		Air Voids (%)	N _f (reps)	Air void content	
				low 4% N _f (reps)	High 8% N _f (reps)
Asphalt Type	Valley Ar-4000	5.8	951	1652	191
	Boscan Ac-30	6.2	6432	12663	200
	% difference		148.5	153.8	4.6
Aggregate Type	Pleasanton Gravel	5.9	975	1778	173
	Watsonville Granite	6.1	6189	11716	200
	% difference		145.6	147.3	14.5
Fines Content	Low (2.5%)	6.2	2502	4762	241
	Normal (5.5%)	5.8	4723	8961	132
	% difference		61.5	61.2	58.4
Air-void Content	Low	4.1	6946		
	High	8.0	187		
	% difference		189.5		
Compaction Method	Gyratory	6.0	91	111	69
	Rolling Wheel	5.9	572	951	193
	Kneading	6.0	10464	20610	298
Mix Viscosity	Low	5.8	5594	10517	260
	Normal	6.2	1595	2935	255
	% difference		111.3	112.7	1.9
Compaction Viscosity	Low	6.0	5750	11382	118
	Normal	6.0	1605	2851	255
	% difference		112.7	119.9	73.5

Percent difference = (difference/average) *100 percent

Thirty field cores came from five pavement sites. The same aggregate and binder used in the field were used to fabricate laboratory specimens. The laboratory specimens were compacted in order to simulate the range of the air content in the field cores. The air content in the field cores varied from about 3 to 8 percent. Laboratory tests were utilized in order to evaluate specimens compacted by different compaction methods. These laboratory tests included indirect tension at 25°C, resilient modulus at 0°C, Marshall stability, Hveem stability, and uniaxial repetitive compressive creep followed by compression to failure. The statistical analyses of the results are presented in [Table 2-6](#).

Table 2-6. Consolidated Results from Statistical Analysis (Button et al., 1994).

Site	Compaction Method	Resilient Modulus		IDT Strength	Marshall Stability	Hveem Stability	Compressive Dilation Ration	Creep Test Compressive Strength
		25°C	0°C					
Casa Grande	Gyratory	E	H	H	E	E	E	E
	Marshal	E	H	E	E	-	-	-
	Exxon	L	E	E	E	E	E	E
	Elf	E	H	E	E	E	E	L
Flagstaff	Gyratory	D	E	E	D	E	E	H
	Marshal	H	E	E	E	-	-	-
	Exxon	L	E	L	E	L	E	D
Alberta	Gyratory	E	H	D	E	E	E	E
	Marshal	E	H	H	E	-	-	-
	Exxon	E	E	E	E	L	E	E
	Elf	E	E	E	E	L	E	L
Manitoba	Gyratory	E	E	H	E	H	-	-
	Marshal	H	E	H	H	-	-	-
	Exxon	L	L	L	E	L	E	E
Michigan	Gyratory	E	E	E	E	E	E	E
	Marshal	H	E	H	H	-	-	-

E = Equivalent to
L = Less than
H = Higher than
D = Difference from
} the field compaction

All four compaction methods were not used to prepare specimens from all five locations.

Results of comparisons are described by four categories as follows: equivalent to (E), less than (L), higher than (H), or different from (D) the field cores. Total number of Es was summed for each compaction method and was expressed in a percent of the

maximum possible number of Es. The Texas gyratory compactor most often produces specimens that simulate field cores. It simulated field cores 24 times out of a possible 33 times (73 percent). Exxon rolling wheel compaction simulated field cores 18 times out of a possible 28 times (64 percent). Elf linear kneading compaction simulated field cores 9 times out of a possible 14 times (64 percent). The author stated that these differences are not statically significant (at $\alpha = 0.05$).

Peterson et al. (2004)

This study evaluated the resemblance of laboratory compaction to field compaction by measuring the mechanical properties of asphalt mixtures. The performance characteristics of asphalt mixtures were evaluated by the Superpave shear tester. A Superpave gyratory compactor was used to prepare the asphalt mixture specimens. The specific objective was to determine the influence of various SGC control parameters on properties of asphalt mixtures. These control parameters included the angle of gyration, specimen height, gyratory compaction pressure, and the temperatures of the gyratory mold and the base plates. The field samples were cored from three different field sections that were compacted using different compaction patterns. HMA was collected from the field and delivered to the laboratory for compaction at the same percent air void as the asphalt pavements. The results revealed that a 1.5° angle of gyration along with a specimen height of 50 to 75 mm would better simulate the mechanical properties of the field cores. Also, the results demonstrate that similar compaction results can be obtained by using the current 1.25° angle along with 400 kPa pressure in case the angle of gyration of the gyratory compactor can not be modified.

**EFFECT OF COMPACTION METHODS ON AIR VOID DISTRIBUTION
USING IMAGE ANALYSIS TECHNIQUES**

Compaction methods influence the mechanical properties of asphalt mixtures. An asphalt mix exhibits different mechanical properties when it is compacted using different compaction methods at the same air content due to the differences in the internal structure. A number of studies on the effect of compaction methods on the internal structure of asphalt mixtures are discussed in the following subsections.

Masad et al. (1999a)

This study quantifies the internal structure of asphalt mixtures. The Superpave gyratory compactor and linear kneading compactor (LKC) were used to prepare specimens. The HMA internal structure was quantified by aggregate orientation, aggregate contacts, and air void distribution. X-ray CT was utilized to capture the air void structure in asphalt mixtures.

X-ray Computed Tomography (CT)

X-ray CT is a nondestructive method to capture the internal structure of materials. [Figure 2-7](#) shows the components of X-ray CT. The test specimen is placed between an X-ray source and a detector. X-rays that pass through the test specimen along several different paths in several different directions produce a set of CT images. The intensity of X-rays is measured before it enters the specimen and after it passes through it. Scanning of a slice is complete after collecting the intensity measurements for a full rotation of the specimen. The specimen is then shifted vertically by a fixed amount (the slice thickness), and the entire procedure is repeated to generate additional slices. The resulting X-ray CT image is a map of the spatial distribution of density.

Once images of the internal structure are captured, imaging techniques can be used to extract significant information from the image. [Figure 2-8](#) illustrates the process of analyzing the air void distribution in an asphalt mix specimen using the X-ray CT system and image analysis techniques. The captured image consists of 256 levels of gray intensity that correspond to different densities within the specimen. Air voids (low density) are shown in black ([Figure 2-9](#)). Using a suitable gray intensity threshold value, air voids can be separated from other mix constituents (aggregate and mastic). The threshold level represents a boundary value below which pixels in the analyzed image are considered as part of the air voids. Pixels that have intensity values above the threshold value are considered to belong to the remaining phases. The analysis is capable of quantifying the vertical and horizontal distributions of air voids, size distribution of air voids, and connectivity of air voids.

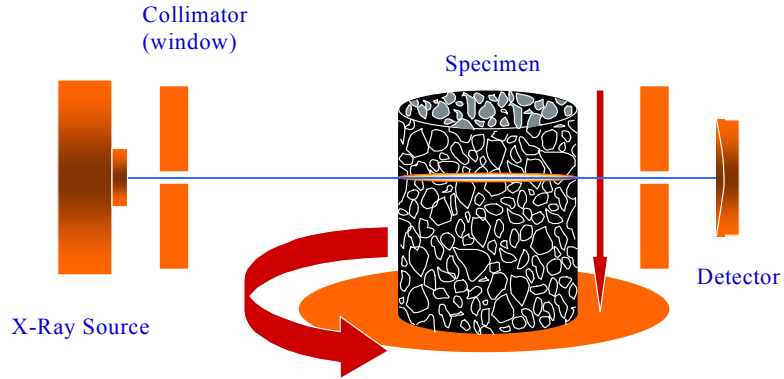


Figure 2-7. Components of X-ray Computed Tomography System (Masad et al.,1999a).

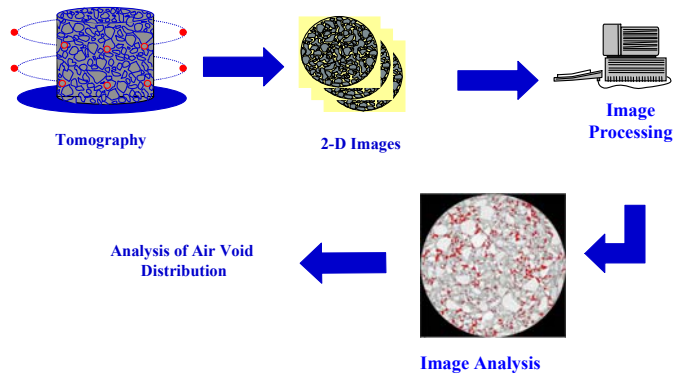


Figure 2-8. The Process of Analyzing Air Void Distribution in Asphalt Mix Specimens Using X-ray CT and Image Analysis Techniques (Masad et al., 1999a).

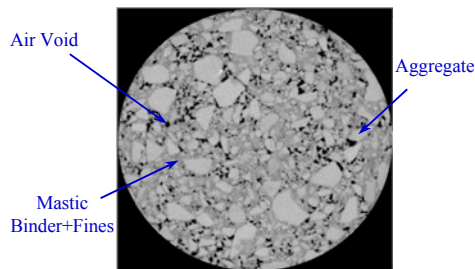


Figure 2-9. An Example of an X-ray CT Image (Masad et al., 1999a).

Aggregate Orientation

The orientation of the aggregate is measured by the angle (θ_k) between the major axis of an aggregate and the horizontal axis of the image (Figure 2-10). The major axis of the aggregate can be defined as the greatest distance between two pixels. After calculating (θ_k), the vector magnitude (Δ) (Equation 2-2) and average angle of inclination (θ) are used to quantify the directional distribution of aggregates. The vector magnitude parameter and average angle of inclination are calculated using Equations 2-2 and 2-3, respectively.

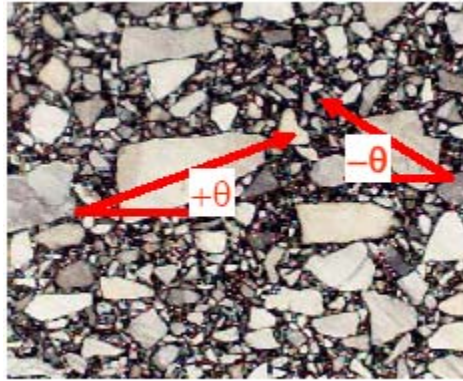


Figure 2-10. Angle of Inclination (θ_k) (Masad et al.,1999a).

$$\Delta = \frac{100}{N} \sqrt{(\sum \sin 2\theta_k)^2 + (\sum \cos 2\theta_k)^2} \quad (2-2)$$

$$\theta = \frac{\sum |\theta_k|}{N} \quad (2-3)$$

where, θ_k = the orientation of an individual aggregate, from -90 to $+90^\circ$, N = number of aggregates on the image.

The vector magnitude parameter (Δ) varies from 0 to 100 percent. Zero percent means that the aggregates have complete random distribution, while 100 percent means the aggregates have exactly the same direction.

Aggregate Contacts

The method to calculate the number of contacts depends on the erosion operation. Erosion is a morphological operation in which pixels are removed from a binary image according to the number of surrounding pixels that have different colors. The effect of the sequence of erosion operations on an image is illustrated in [Figure 2-11](#). At the points of object contact, white pixels are surrounding the black ones. Consequently, the black pixels in contact are removed during the erosion operation. Simultaneously, the size of objectives shrinks, and the small particles disappear after a sufficient number of operations are conducted.

The results from the study revealed the following findings:

- The distribution of the air void in both SGC and LKC is not uniform. The SGC specimens have a higher percentage of air void at the top and the bottom more than the middle part, while the percentage of air voids in LKC specimens increases with the depth as shown in [Figure 2-12](#).
- The average percent of the air void correlated well with the calculated percent of the air void in the laboratory.
- The number of contacts in LKC specimens was more than its counterparts in SGC specimens.
- The orientation results showed that the aggregates have more of a random distribution in kneading specimens comparable with the gyratory specimens which have preferred orientation toward the horizontal direction.

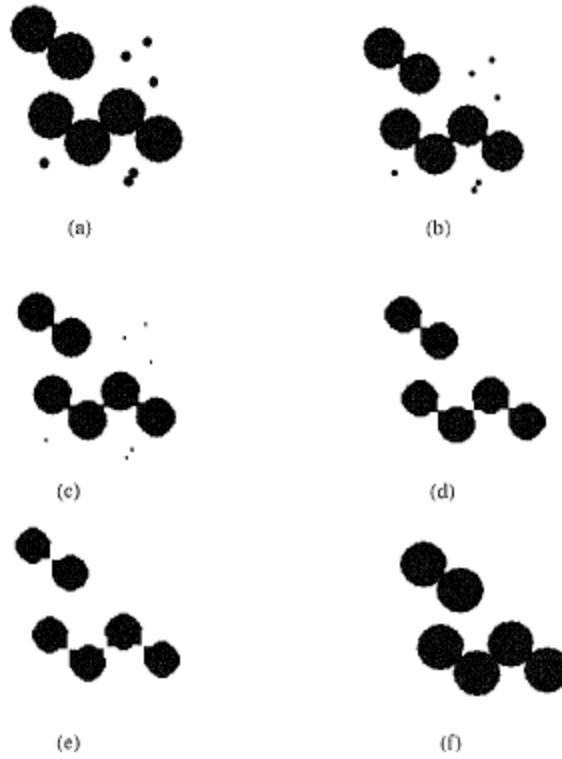


Figure 2-11. Determination of Number of Contacts by Erosion Techniques (Masad et al., 1999a).

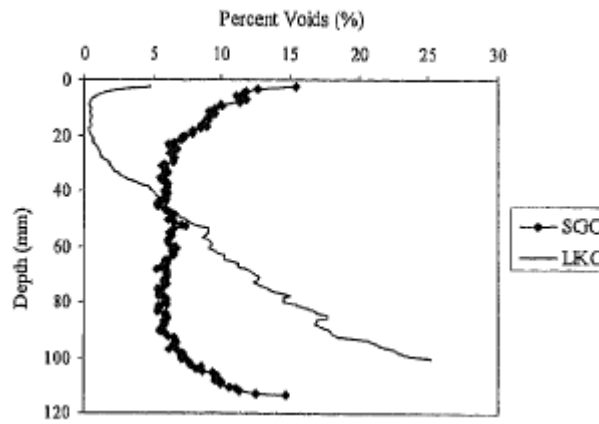


Figure 2-12. Air Void Distribution in SGC and LKC Specimens (Masad et al., 1999a).

Masad et al. (1999b)

This study was carried out in order to quantify the internal structure of asphalt mixtures. In this study the internal structure included the air void distribution, aggregate orientation, and gradation. The internal structure was quantified for SGC specimens prepared at different compaction levels and was compared to the internal structure for field cores.

The results of the air void distribution for gyratory compacted specimen which compacted at different compaction levels and the air void distribution in field cores are presented in Figures 2-13 and 2-14, respectively. The results from the analysis of gyratory compacted specimens revealed that the air void distribution is not uniform, and there is higher air void content at the top and the bottom than in the middle. The compaction of the middle part increases with an increase in compaction. In the field cores, the air void distribution was different than the one in the gyratory compacted specimens.

The vector magnitude, average angle of inclination, and percent of air void were calculated for both the gyratory compacted specimen and field cores, and the results are illustrated in Figure 2-15. These results demonstrated that the average angle of inclination decreases with the compaction levels until a certain level. The orientation angle tends to increase after this certain compaction level. Conversely, the vector magnitude tends to increase until it reaches the same certain compaction level and then starts to decrease with further compaction. The authors stated that preferred orientation increased with compaction until it reached a maximum value which was called the optimum compaction level. In this study, the optimum compaction level was found at about 100 gyrations. Once the orientation reached this maximum value, further compaction caused aggregates to lose preferred orientation and become more random.

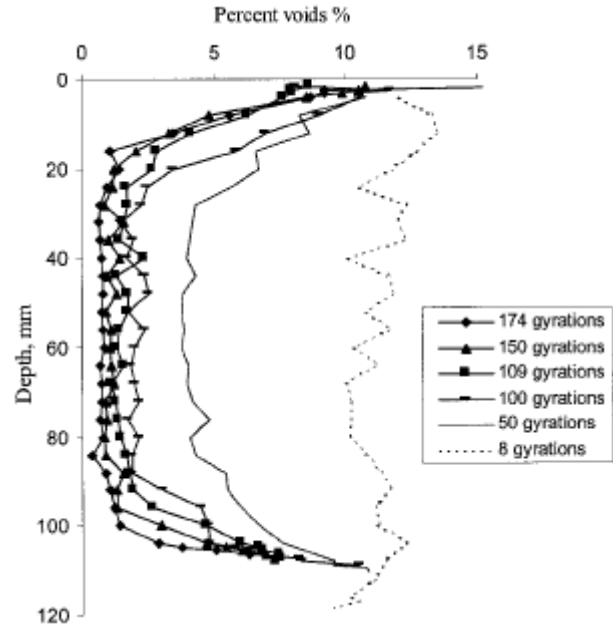


Figure 2-13. Distribution of Voids in Gyrotory Specimens (Masad et al., 1999b).

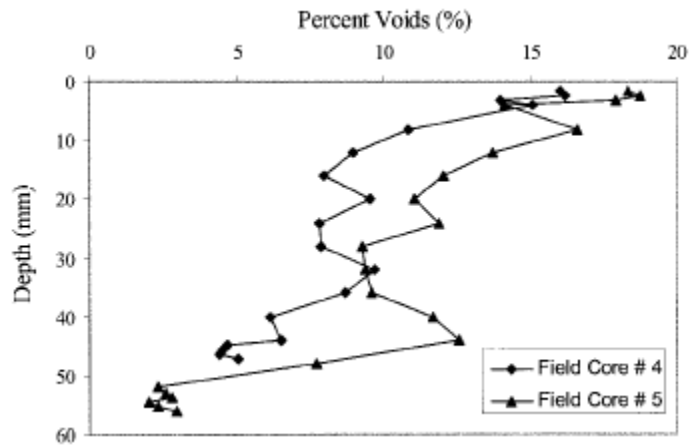


Figure 2-14. Distribution of Voids in Field Cores (Masad et al., 1999b).

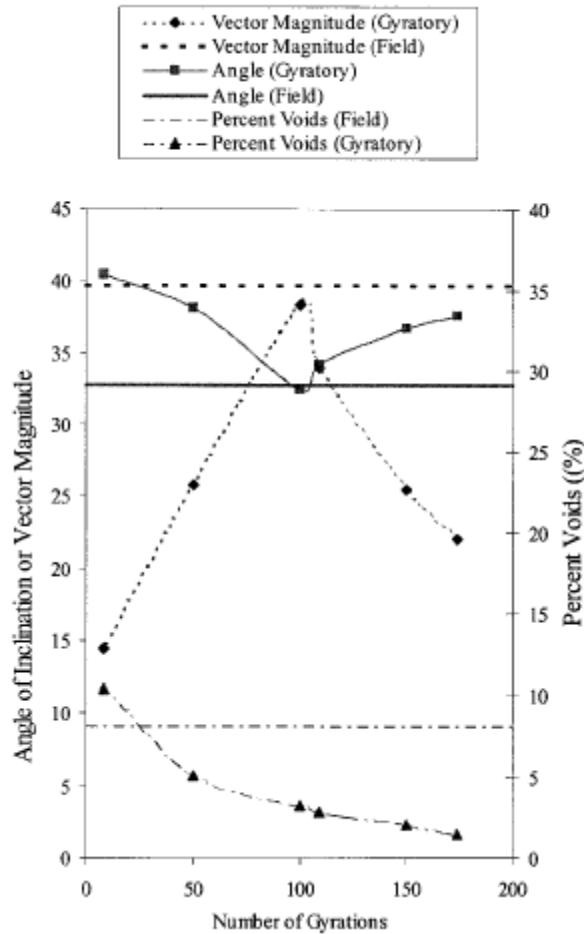


Figure 2-15. Variation of Vector Magnitude, Angle of Inclination, and Percent Void with Compaction (Masad et al., 1999b).

Shashidhar (1999)

The main objective of this study was to promote better understanding of the aggregate structure in asphalt concrete by utilizing X-ray CT. X-ray CT was used for imaging the internal structure of laboratory compacted specimens and field cores. X-ray CT was found to be an excellent technique for capturing the internal structure of asphalt mixtures. This study has shown qualitatively that air void distribution and aggregate interlock are related to mixture performance.

Tashman et al. (2001)

This study was carried out in order to evaluate the ability of Superpave gyratory compactor to produce laboratory specimens that closely simulate the internal structure of field cores. Also, this study evaluated the influence of different field compaction patterns on the internal structure of field cores. Three field test sections were constructed using different compaction patterns.

The results of the air void distributions in laboratory compacted specimens revealed that there is high percentage of air void at the top and the bottom compared to the middle part. The air void distribution in laboratory specimens is illustrated in [Figure 2-16a](#). Different compaction patterns did not influence the air void distribution in field cores shown in [Figure 2-16b](#). Field cores always had a higher percentage of air void at the top than the bottom. The study evaluated the air void distribution in SGC specimens compacted using two different mold temperatures. Using a higher temperature produced more uniform distribution of air voids ([Figure 2-17](#)).

The different field compaction patterns did not affect aggregate orientation. However, it was found that both gyration angle and height of specimen affected the aggregate orientation. The author suggested that aggregate orientation is controlled by the shear action which was represented in the angle of gyration and specimen height. The aggregate orientation results illustrated in [Figure 2-18](#) show that the short specimens (50 mm and 75 mm) at angle of gyration of 1.5° adequately simulated field cores.

The shear frequency sweep test measured the mechanical response of field cores and gyratory compacted specimens. The results showed that the gyratory specimens compacted at an angle of gyration of 1.5° adequately simulated field cores in terms of the stiffness results.

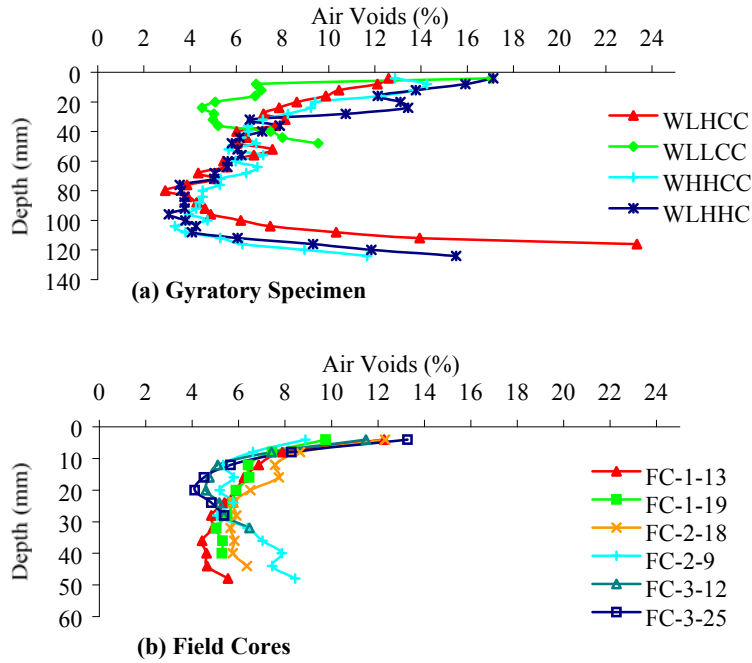


Figure 2-16. Vertical Distribution of Air Voids in Gyratory Specimens and Field Cores (Tashman et al., 2001).

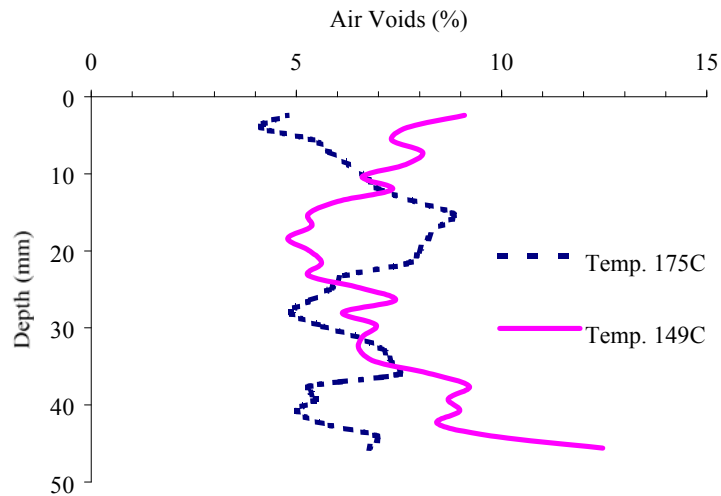


Figure 2-17. Effect of the Base Plates and Mold Temperature on the Vertical Distribution of Air Voids in Gyratory Specimens (Tashman et al., 2001).

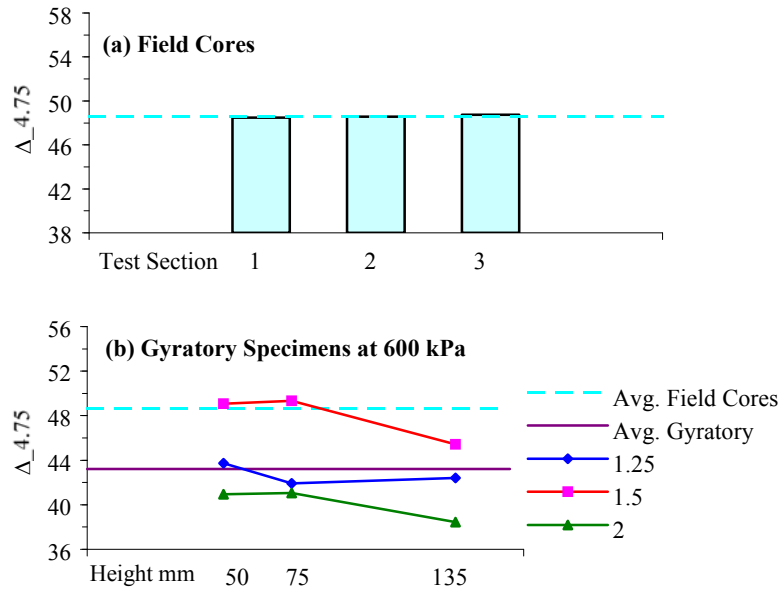


Figure 2-18. Vector Magnitude of Aggregate Orientation (Tashman et al., 2001).

Partl et al. (2003 and 2007)

This study was initiated with the aim of examining the difference in homogeneity and isotropy in asphalt mixtures compacted using different compaction methods. The compaction methods were the Marshall compactor, Superpave gyratory compactor, and rolling-wheel compactor. The air void distribution was investigated at different compaction levels using X-ray CT.

Marshall and gyratory specimens were cored from the center and cut horizontally. Marshall specimens were cut into three parts (top, middle, bottom), while the gyratory compacted specimens were cut into four parts (top, upper middle, lower middle, and bottom). Rolling-wheel compacted specimens were cut into 40 pieces as shown in Figure 2-19. The findings of this study can be summarized as follows:

- The air void distribution in Marshall compacted specimens showed that there is a difference in the air void content between the core and exterior of the specimens. This difference was clear at the initial compaction, as it reached 3.5 percent. This

difference decreased with further compaction. The air void content distribution is illustrated in [Figure 2-20](#).

- In gyratory compacted specimens, the middle part of the core was more compacted than the top and the bottom parts as shown in [Figure 2-21](#). It is believed that the kneading action at the top and the bottom of the base plates is not effective.
- The air void content distribution in rolling-wheel compaction after the initial compaction level was fairly even as shown in [Figures 2-22](#) and [2-23](#). However, the air void distribution became uneven with more compaction and the minimum percent of air voids located at the center of the bottom part. After the final compaction level, it was obvious that the bottom part is less compacted than the top part.
- The comparison between the different compaction methods showed that the relationship between the decrease of air void content and compaction effort varied from compaction method to another as illustrated in [Figure 2-24](#). This relationship looks linear for the Marshall compactor while it is nonlinear for the Superpave gyratory compactor. In regard to the rolling-wheel compactor, the relationship appears to be intermediate behavior between linear and nonlinear.

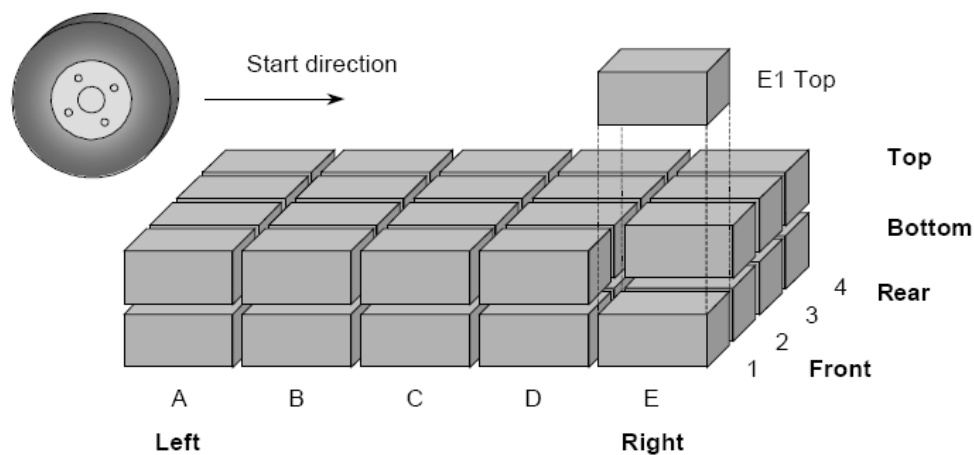


Figure 2-19. Rolling Wheel Compacted Specimens (Partl et al., 2007).

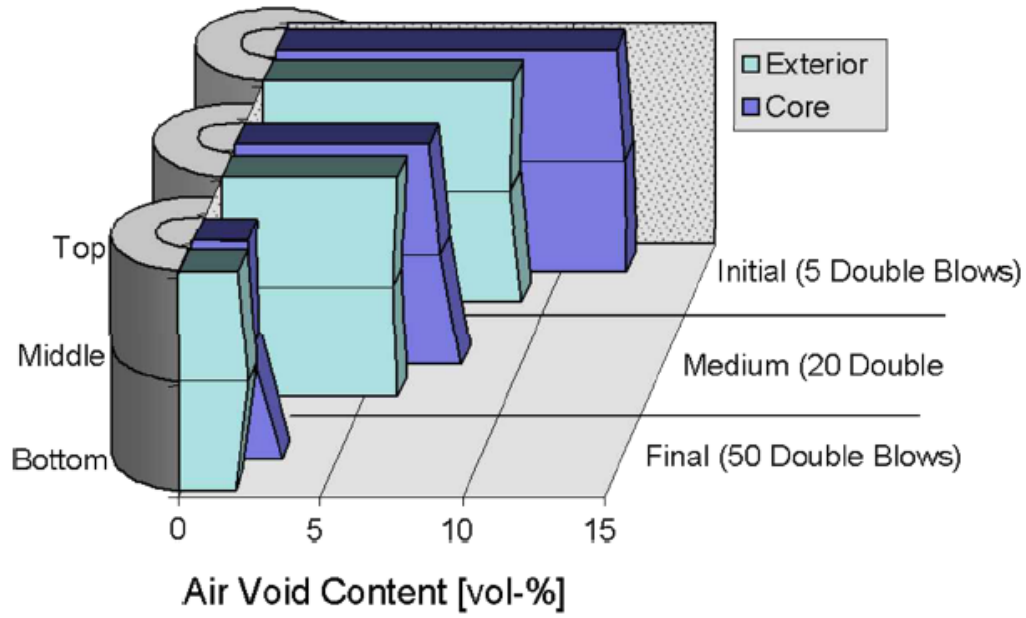


Figure 2-20. Air Void Distribution in Marshall Specimen (Partl et al., 2007).

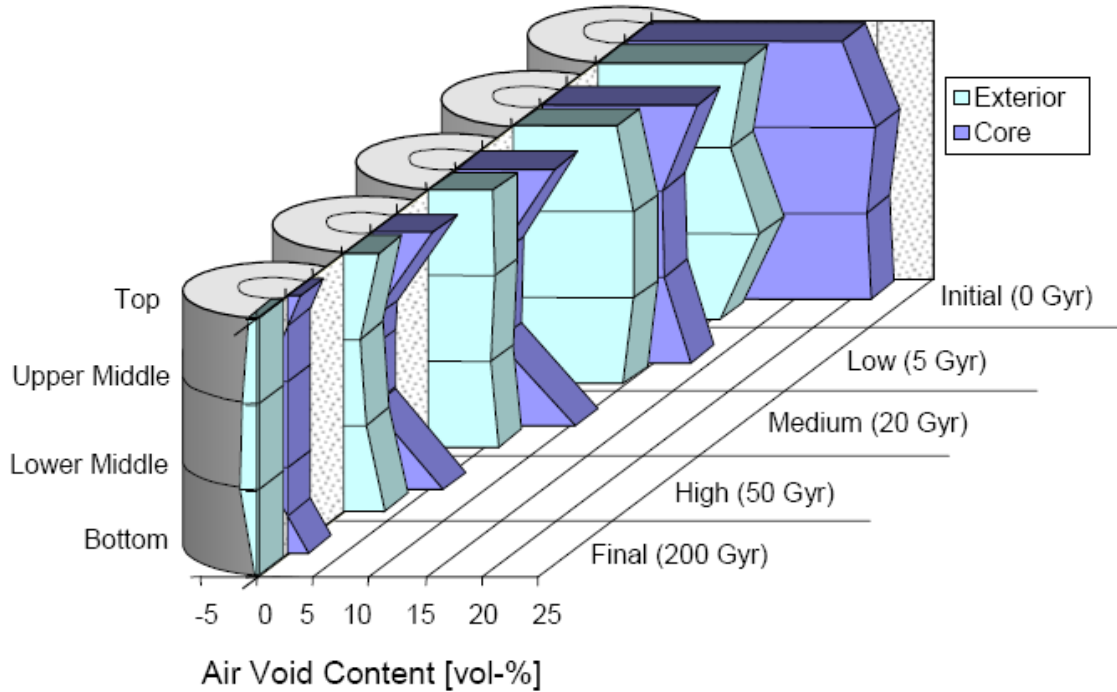


Figure 2-21. Air Void Distribution in Gyratory Compacted Specimens (Partl et al., 2003).

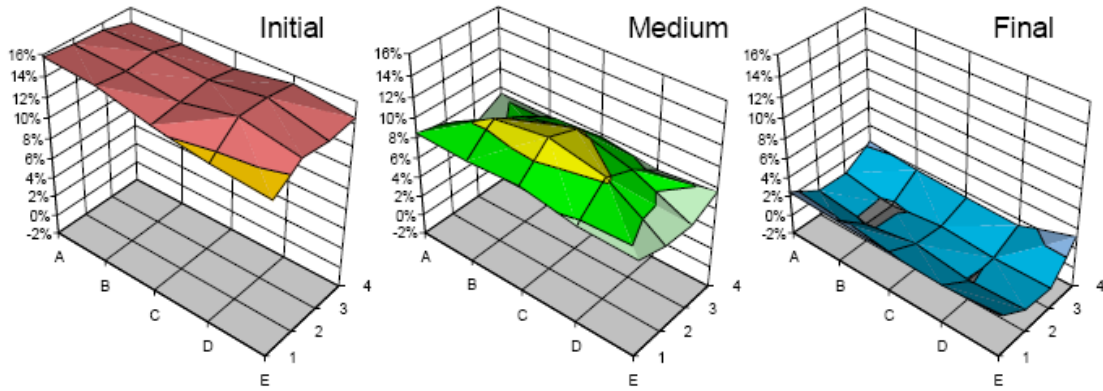


Figure 2-22. Air Void Content in the Top Part of Rolling Wheel Compacted Specimens (Partl et al., 2007).

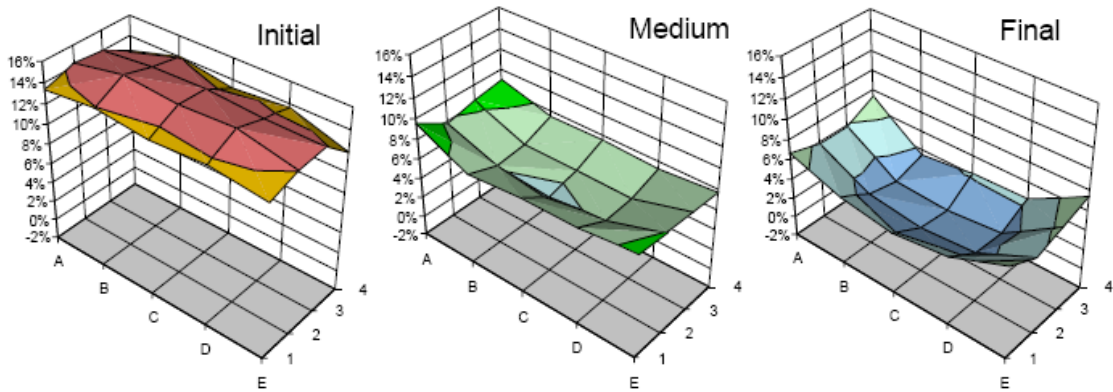


Figure 2-23. Air Void Content in the Bottom Part of Rolling Wheel Compacted Specimens (Partl et al., 2007).

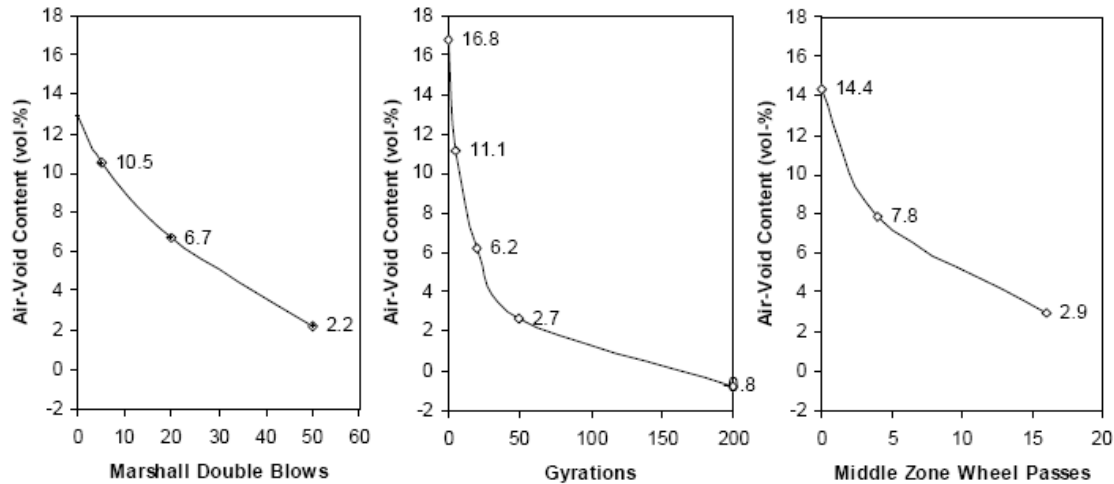


Figure 2-24. A Decrease of Air Content with the Compaction Level (Partl et al., 2007).

MODELING COMPACTION ON ASPHALT MIXES

Very little research has been directed toward modeling HMA compaction and the material properties that influence compactability. Guler et al. (2002) have proposed the use of a porous elasto-plastic (using a modified Gurson-Tvergaard yield function) compaction model. An incremental constitutive relation for the porous material was formulated for this purpose. The researchers focused on obtaining statistically significant parameters for this constitutive relation and obtaining a correlation between the model parameters and mixture variables, i.e., volumetric properties, particle size. Simple linear models were built to predict the model parameters. The displacement field used to represent 3-D compaction is an approximation of the actual motion in an SGC. Also, the model is formulated assuming small strain theory, is time independent, and assumes isothermal conditions (no changes in temperature).

Huerne (2004) from the Netherlands used a modified form of soil critical state theory in modeling asphalt mixture compaction. The critical state theory describes granular material behavior by means of a closed yield locus, which gives a boundary between stress states that cause elastic (recoverable) deformations and plastic (irrecoverable) deformations. Huerne's implementation simulates void reduction by means of plastic volume changes. The Hveem device was used for determining the

model's parameters. This theory is developed assuming small strain deformation that is limited in modeling the high strains involved in the compaction process. The model also has many parameters that are not directly linked to mixture properties.

Krishnan and Rao (2000) developed a constitutive model for asphalt mixes using mixture theory to model the one-dimensional compaction of asphalt mixtures under a static load. This model utilizes the fundamental balance laws to obtain mathematical relations to describe the performance and characteristics of asphalt mixes. While their work places the modeling within the context of a general framework that takes into account the balance laws of mechanics, it yet ignores certain critical issues concerning the material response such as the fact that the “natural configuration” of the material being compacted evolves with the compaction process. Also, such an approach to modeling compaction of HMA is limited by the restrictive experimental techniques available to measure the various mixture properties involved in the model.

CHAPTER 3

DESCRIPTION OF FIELD COMPACTION PROJECTS

INTRODUCTION

The researchers identified several field projects with the help of the project monitoring committee. Assistance was sought from different districts to volunteer for candidate HMA projects. A number of districts volunteered to participate in the modification of field compaction patterns. The researchers are thankful to the respective TxDOT districts for allowing them to test the following roadways:

1. US 281 in Pharr District
2. FM 649 in Laredo District
3. IH 35 in Waco District
4. SH 36 in Yoakum District
5. US 87 in Yoakum District
6. US 259 in Tyler District
7. SH 21 in Austin District
8. US 290 in Houston District
9. FM 529 in Houston
10. SL 368 in San Antonio
11. SH 114 in Fort Worth

Projects 8 through 11 are included in forensic evaluation part of this task. This chapter will focus on the first seven projects that were used to analyze the influence of field compaction patterns on air void distribution and mechanical properties. The researchers recorded field compaction effort; conducted tests in the field; obtained field cores, plant mix, and virgin materials; and conducted laboratory tests on laboratory compacted specimens and field cores. [Table 3-1](#) provides a description of mixtures used in these seven projects, and [Table 3-2](#) summarizes the compaction patterns. The following paragraphs briefly describe the research efforts and construction projects included in this part of the study.

US 281 IN PHARR DISTRICT

In February 2006, the researchers visited the first construction job located on northbound US 281 near the Pharr city limit. This stretch of highway was totally new construction and had very thick asphalt layers. The focus of this study was only on the SMA layer compacted on top of a recently compacted Superpave mixture. This SMA layer was later overlaid with PFC mixture. Initially there was an expectation of changing the compaction pattern in this job. Due to some unavoidable circumstances the idea of changing the compaction pattern was dropped. The original compaction pattern adopted by the paving contractor (Bellinger Corp.) was recorded and samples obtained from the site.

The SMA mixture was designed using a local river gravel from Fordyce Gravels (Shower quarry). The mixture contained 6.3 percent PG 76-22S binder from Valero Asphalt. The lift thickness was 2 inches (5 cm). The paving contractor used a tri-dem steel wheeled roller, a large truck loaded heavy load at the rear end (Figure 3-1), as well as regular pneumatic tire roller as compactor.

Table 3-1. Summary of Mixture Designs Used in Compaction Study.

Highway ID	Mixture Type	Date of Field Testing	Aggregate (major)	Binder	Optimum AC %	Max Rice Sp Gr.	VMA at Op. AC.	Design Air Void, %
US 281, PHR	SMA	Feb 2006	Siliceous River Gravel	PG 76-22S	6.3	2.383	18.3	4.0
FM 649, LRD	Type C	March 2006	Limestone	PG 76-22	4.9	2.427	15.0	4.0
IH 35, WAC	SMA	May 2006	Traprock & Limestone	PG 76-22	6.0	2.563	18.3	4.0
SH 36, YKM	Type D	July 2006	Limestone	PG 64-22	4.9	2.447	15.1	3.5
US 87, YKM	Type C	Oct 2006	Siliceous River Gravel	PG 76-22S	4.3	2.460	13.8	4.0
US 259, TYL	Type C	March 2007	Sandstone & Limestone	PG 70-22S	4.3	2.478	13.1	3.0
SH 21, AUS	Type C	June 2007	Limestone	PG 70-22	4.7	2.467	14.3	3.0

Table 3-2. Description of Compaction Patterns.

Highway ID	Compaction Pattern 1			Compaction Pattern 2		
	BD	IM	FS	BD	IM	FS
US 281, PHR	Steel Wheel Static	Steel wheeled vibratory, Heavy pneumatic (truck wheel) and Regular Pneumatic tire roller	Steel Wheel Static	N/A	N/A	N/A
FM 649, LRD	Steel Wheel Vibratory Roller	Pneumatic Wheel	Steel Wheel Static	Pneumatic wheeled vibratory	Steel wheeled vibratory roller	Static steel wheeled
IH 35, WAC	Two Steel Wheel Vibratory Rollers	N/A	Steel Wheel Static	N/A	N/A	N/A
SH 36, YKM	Steel Wheel Vibratory and Steel Wheel Static	Pneumatic Wheel (High Speed – 10 mph)	Steel Wheel Static	Steel Wheel Vibratory	Pneumatic Wheel (High Speed – 10 mph)	Steel Wheel Static
US 87, YKM	Steel Wheel Vibratory and Steel Wheel Static	Pneumatic Wheel	Steel Wheel Static	Pneumatic Wheel	Steel Wheel Vibratory	Steel Wheel Static
US 259, TYL	Steel Wheel Vibratory	Pneumatic Wheel	Pneumatic Wheel	Steel Wheel Vibratory (progressive motion)	Pneumatic Wheel	Pneumatic Wheel
SH 21, AUS	Steel Wheel Vibratory	Pneumatic Wheel	Steel Wheel Static	Pneumatic Wheel	Steel Wheel Vibratory	Steel Wheel Static

BD: Breakdown, IM: Intermediate, FS: Finish



Figure 3-1. Unusual Compaction Equipment.

FM 649 IN LAREDO DISTRICT

FM 649 in Laredo provided the researchers with the opportunity to study two different rolling patterns. The research team visited this site in March 2006. FM 649 is a two-lane, undivided highway in rural area. A 2-inch thick Type C mixture was placed on this highway. The mixture contained limestone from the Martin Marietta Beckmann quarry in San Antonio. The mixture contained 4.9 percent PG 76-22 binder from Valero asphalt. This is the only project where the contractor used a vibratory pneumatic roller. [Figure 3-2](#) shows the finish roller.

IH 35 IN WACO DISTRICT

This test section was located on the southbound inside lane between Waco and Hillsboro. Only one type of compaction pattern was studied in this project. The overlay in this project used SMA mixture with traprock and limestone. The binder content of this mixture was 6.0 percent (PG 76-22). The SMA mixture was laid on top of a freshly placed seal coat. The lift thickness was 2.0 inches (5 cm). The contractor (Young

Brothers) used two steel wheel vibratory rollers side by side as breakdown rollers to cover the entire paving width. The paving width was approximately 15 ft (4.57 m) including the inside shoulder.



Figure 3-2. Finish Roller on FM 649.

SH 36 IN YOAKUM DISTRICT

This project site was located in Austin County under the Yoakum District. The project was executed under the supervision of the Victoria area office. SH 36 is a two-lane undivided highway. The research team took part in this project site in July 2006. Type D mixture with 2 inches (5 cm) compacted mat thickness was laid on top of a recently applied seal coat. Hunter Industries, the paving contractor, hauled the mixture from their Rosenberg plant (approximately 25 miles from the job site). This Type D mixture had limestone from Colorado materials and 11 percent field sand, 4.9 percent PG 64-22 binder, and 1 percent lime.

The researchers intended to use a pneumatic roller as a breakdown roller in the compaction Pattern 2. But this roller was static and rather small, so the modified rolling pattern consisted of breakdown with vibratory steel wheel roller. [Figure 3-3](#) shows the coring layout on SH 36.

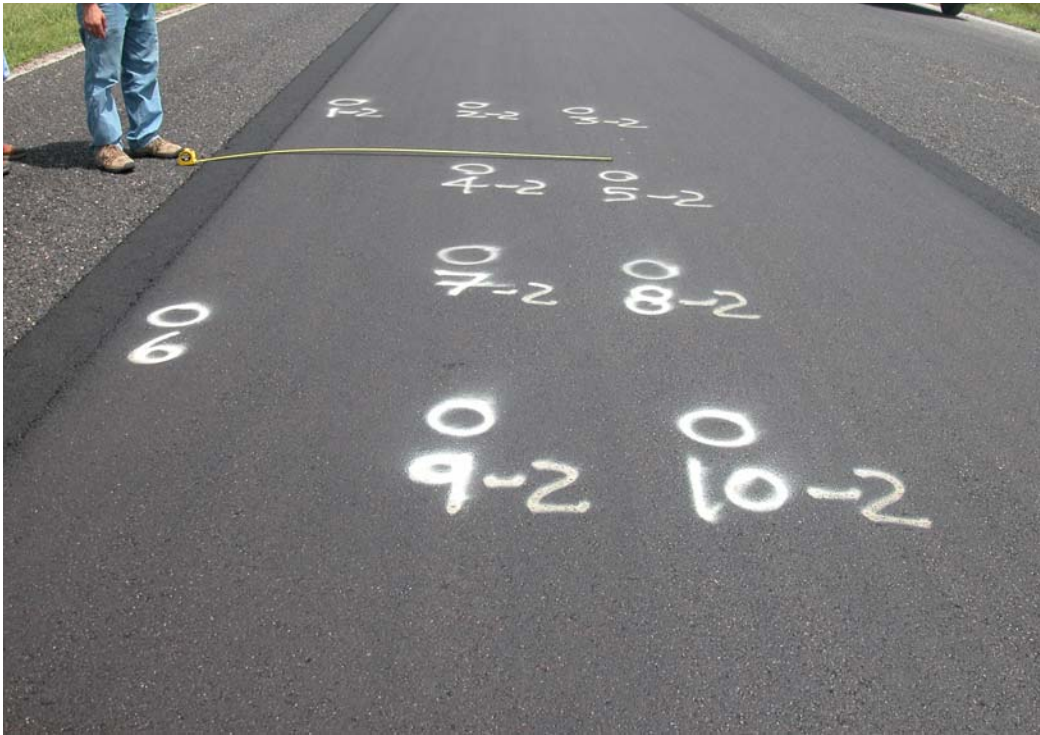


Figure 3-3. Field Coring Layout on SH 36.

US 87 IN YOAKUM DISTRICT

The research team worked the US 87 job near Port Lavaca in Calhoun County in October 2006. Hunter Industries was the paving contractor for this job. They hauled their mixture from their Colorado Materials Plant in Nursery, Texas, which is about 50 miles from the jobsite. US 87 is a four-lane divided highway. The test sections were located on the northbound outside lane. The mixture was Type C (TxDOT 1993 Specification) designed with Fordyce Gravel and Colorado Materials limestone screening with 4.3 percent PG 76-22s binder. This Type C mixture was laid on Type B mat and according to

the construction plan, TxDOT will lay another PFC layer on top of the Type C layer. The thickness of the Type C layer was 2 inches (5 cm).

The paving contractor laid the mixture with a 16 ft (4.8 m) mat width, of which 1.5 ft (45 cm) on one side was tapered. Specimens were obtained from wheel path, between the wheel path, and longitudinal joint (retrained and unrestrained) from each of those two sections. [Figure 3-4](#) shows the coring layout on US 87.



Figure 3-4. Field Coring Layout on US 87.

US 259 IN TYLER DISTRICT

The researchers participated in this HMA project in February 2007. This section of US 259, which is four-lane divided highway, located in Rusk County. The overlay in this project used a Type C surface mixture compacted in 2 inch (5 cm) lift thickness. The coarse part of the aggregate was sandstone while the intermediate and fine size particles

were limestone. The mix had 11 percent field sand and 4.3 percent PG 70-22S binder. The paving contractor A. L. Helmcamp, Inc. hauled the mixture from a plant located in Timpson (approximately 20 miles from the jobsite).

The test sections were in the southbound outside lane. Type C mix was laid on top of recently compacted Type D level-up course. The paving width was approximately 15 ft (4.57 m) (including shoulder). The contractor maintained vertical longitudinal joint. The general rolling pattern can be described as breakdown by steel wheel vibratory roller and pneumatic wheel roller as both intermediate and finish type. In the modified roller pattern the vibratory steel wheel roller was moved progressively in transverse directions. Like the original pattern, the pneumatic wheel roller acted as both intermediate and finish roller. Field cores were obtained from the wheelpath, between the wheelpath, and near the longitudinal joints for both test sections. The coring layout on US 259 is shown in [Figure 3-5](#).



Figure 3-5. Coring Layout on US 259.

SH 21 IN AUSTIN DISTRICT

The researchers participated in the construction on SH 21 in Lee County under Austin District in May 2007. This part of SH 21 is a four-lane undivided highway without any center lane and limited or no shoulder on either side. At one area there is a turning lane of almost 1000 ft (300 m) in length. Local TxDOT personnel offered that turning lane for testing and sample collection. The researchers with the help of the construction inspector divided that 1000 ft turning lane into two sections for two different types of roller patterns.

The mixture in this project was Type C surface mix including limestone from two different sources and 10 percent field sand. PG 70-22 binder (4.7 percent) from Martin Asphalt was used in this mixture. The lift thickness of the surface mix was approximately 2 inches (5 cm). Prior to the surface mix, there was a recent Type D level-up course followed by a one layer seal coat. [Figure 3-6](#) shows the coring layout on SH 21.



Figure 3-6. Coring Layout on SH 21.

CHAPTER 4

RELATIONSHIP OF FIELD COMPACTION PATTERN TO AIR VOID DISTRIBUTION*

INTRODUCTION

This chapter includes the evaluation of the relationship between different field compaction patterns and the uniformity of air void distribution in asphalt pavements. A number of projects with different hot mix asphalt (HMA) types were compacted, and cores were taken at different locations from these projects. The X-ray Computed Tomography (X-ray CT) system was used to capture the air void distributions in these cores. The images were used to develop maps of air void distributions across the pavement surface and depth that were useful to study the uniformity of air void distributions. These distributions were further quantified by computing a Uniformity Index and the differences in percent air voids across the depth.

The analysis results revealed that the uniformity of air void distribution is highly related to the compaction pattern and the sequence of using different compaction equipment. More importantly, the efficiency of compaction (reducing air voids) at a point is a function of the location of this point with respect to the roller compactor width. The results in this chapter have supported the development of an index termed the “Compaction Index (CI)” that is a function of number of passes at a point and the position of the point with respect to the compaction roller width.

OBJECTIVES, SIGNIFICANCE, AND TASKS

The primary objective was to investigate the influence of different compaction patterns on asphalt pavement uniformity in terms of air void distribution.

*Reprinted with the permission from “Influence of Field Compaction Pattern on Asphalt Pavement Uniformity” by Kassem, E., Masad, E., Chowdhury, A., and Claros G., 2008, *Journal of the Association of Asphalt Paving Technologists*, AAPT, Vol. (77).

The findings of this study assist in providing a better understanding of the compaction factors that influence uniformity. This understanding is necessary in order to compact more uniform asphalt pavements with improved performance. The objective was achieved by executing the following tasks:

- 1) Conduct field compaction of a number of asphalt pavements using different compaction patterns.
- 2) Obtain field cores from different locations in the pavement.
- 3) Measure the air void distribution in the cores using X-ray CT and image analysis techniques.
- 4) Develop maps of horizontal and vertical air void distributions in the pavement.
- 5) Quantify the uniformity of air void distributions using mathematical functions and indices.
- 6) Relate air void distribution to the compaction pattern, and put forward recommendations for improving pavement uniformity.
- 7) Compact laboratory samples and compare laboratory compaction data with field compaction data.

FIELD EXPERIMENTS

The researchers recorded field compaction information such as type of compaction equipment, number of passes, location of each pass, and mat temperature. In addition, they conducted tests in the field and obtained field cores, plant mix, and virgin materials. The description of the field projects is given in [Chapter 3](#). Specimens were obtained from the wheel path, between the wheel path, the center of lane, and the longitudinal joint (restrained and unrestrained) from each of those test sections. Typically, longitudinal joints samples were obtained 1 ft away from the joint. Field core locations of all the test sections were not uniform since the paving width and rolling patterns were different. In some cases, there were also restrictions regarding the number

of cores that can be taken from a roadway. [Figure 4-1](#) shows an example of field coring layout from the SH 21 test section.

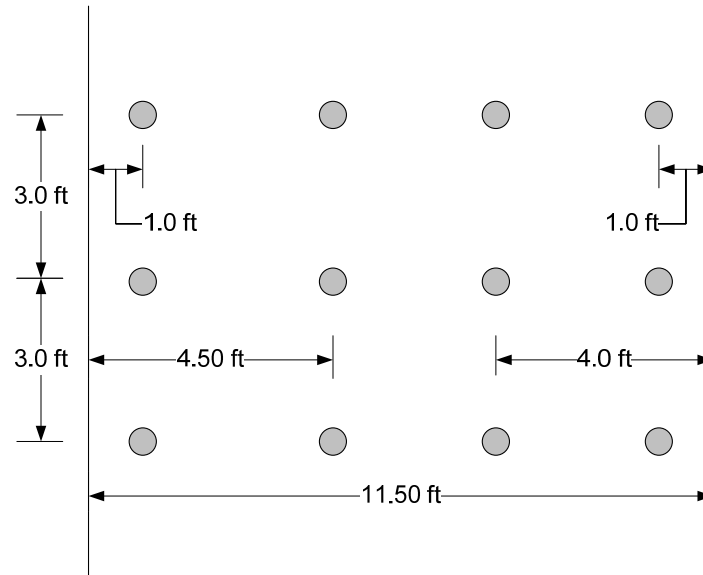
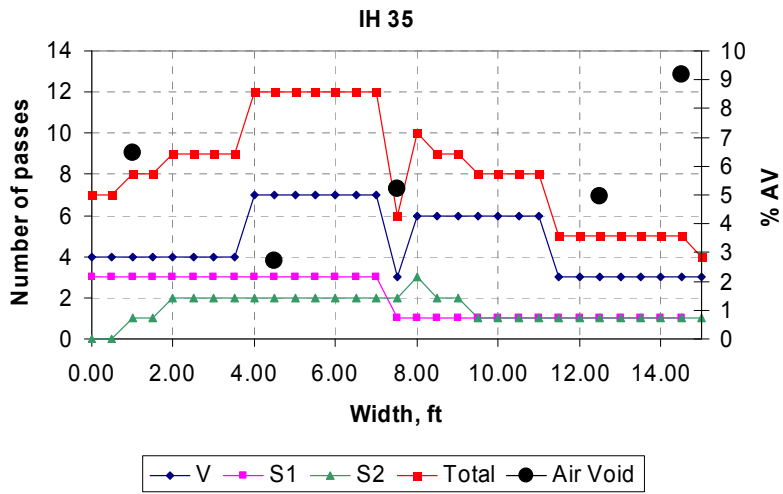


Figure 4-1. An Example of Field Coring Layout on SH 21.

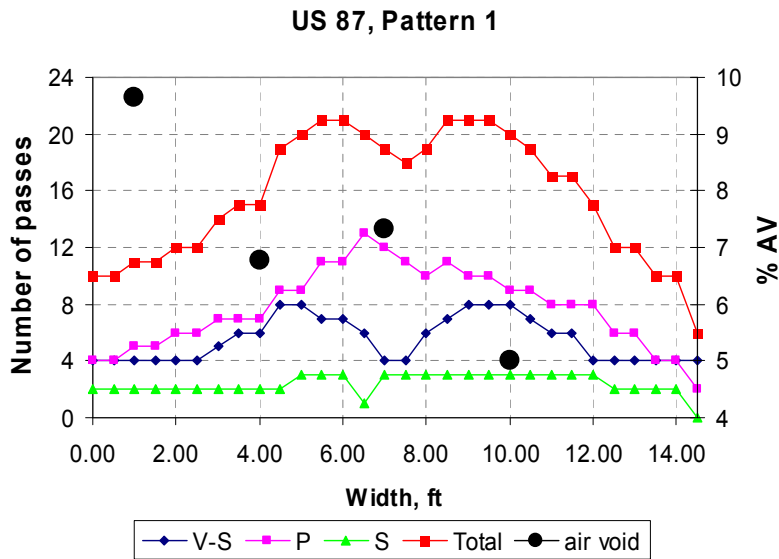
RELATIONSHIP BETWEEN COMPACTION PATTERN AND PERCENT AIR VOIDS

The percent air void of each core was measured using the Saturated Surface Dry (SSD) Procedure (AAHTO T 166). Then the percent air voids was plotted along with the number of roller passes and location as shown in the examples in [Figures 4-2](#) through [4-4](#). Each point represents the average percent of air voids of at least two cores taken longitudinally at a given distance from the pavement section edge. [Figures A-1](#) through [A-6](#) in [Appendix A](#) present the results for the other test sections. The r-squared value (R^2) was used to evaluate the correlation of the percent of air voids with the number of passes of different rollers as shown in [Table 4-1](#). It can be seen from [Table 4-1](#) that there is a weak correlation, if any, between percent air voids and number of passes of different rollers.



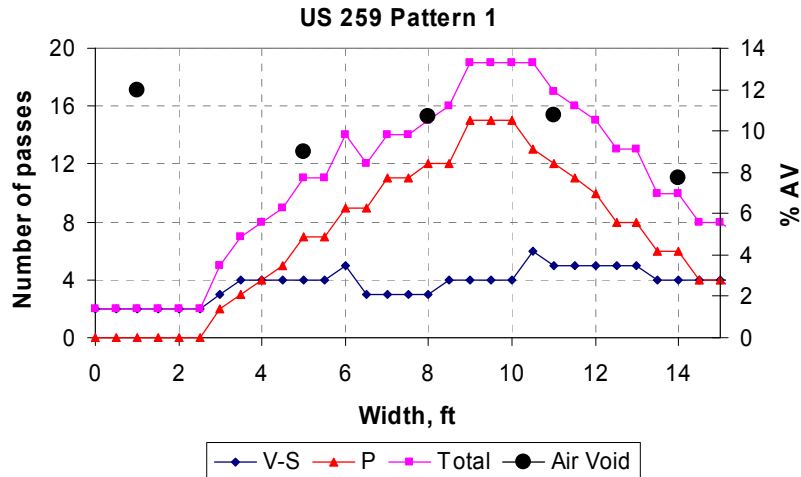
Note: Breakdown roller: vibratory (V), intermediate roller: static (S1), finish roller: static (S2).

Figure 4-2. Number of Passes and Percent of Air Voids across the Mat in the IH 35 Test Section.



Note: Breakdown roller: vibratory then static (V-S), intermediate roller: pneumatic (P), finish roller: static (S).

Figure 4-3. Number of Passes and Percent of Air Voids across the Mat in the US 87 Test Section (Pattern 1).



Note: Breakdown roller: vibratory and static (V-S), finish roller: pneumatic (P).

Figure 4-4. Number of Passes and Percent of Air Voids across the Mat in the US 259 Test Section (Pattern 1).

Table 4-1. R-Squared Value.

Highway ID	Compaction Pattern #	Total Number of Passes		
		All Rollers	Pneumatic Roller	Vibratory and Static Rollers
IH 35	1	0.47	*	0.47
SH 36	1	(-)0.19	(-)0.15	(-)0.24
	2	(-)0.02	(-)0.02	(-)0.02
US 87	1	0.73	0.25	0.87
	2	0.80	0.47	0.93
US 259	1	0.04	0.02	0.25
	2	0.43	0.32	0.62
SH 21	1	0.44	0.23	0.04
	2	0.24	0.49	0.15
Average R ²		0.33	0.20	0.34

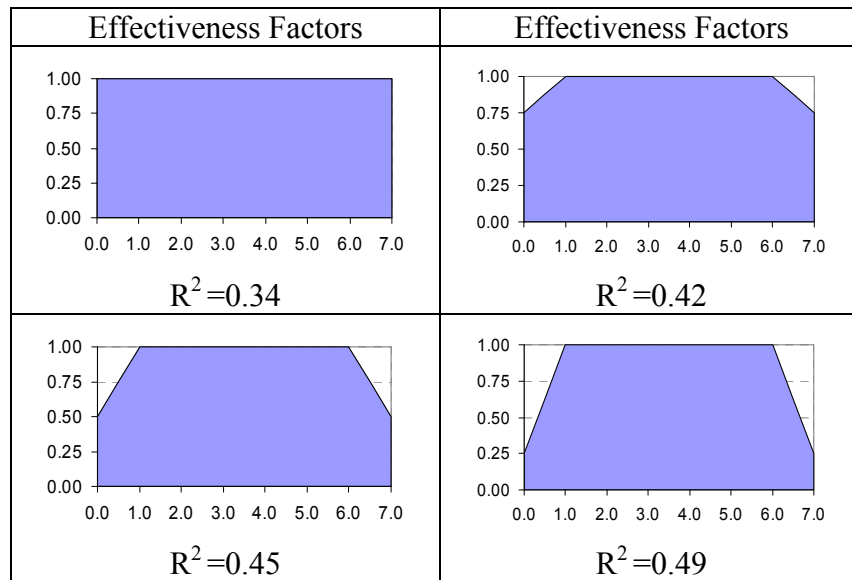
* Not applicable

(-) Correlation in the opposite direction

Researchers observed that cores compacted close to the center of the roller width (static or vibratory) tended to have a higher density than cores compacted at the edge of the compactor even if cores were taken from the middle of the mat and away from the

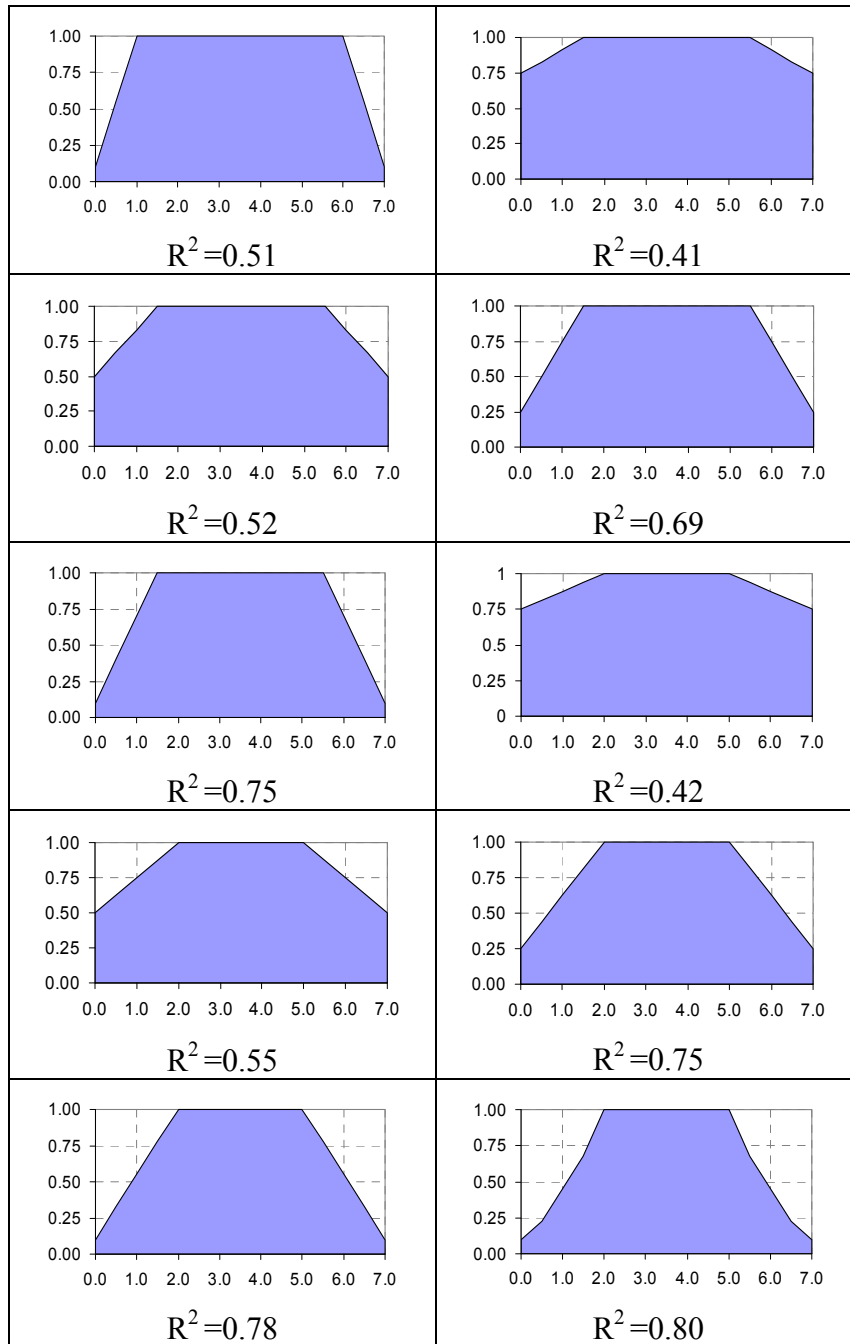
joint. However, there was no relationship between the location of the core with respect to the pneumatic tire compactor and change in percent air voids. Therefore a statistical correlation analysis was conducted to determine the relationship of percent air voids as a function of number of passes of static and vibratory rollers and the location of the core with respect to the compactor width. Each pass was multiplied by an effectiveness factor which is a function of the location of the core with respect to roller width. Consequently, the percent air voids was plotted versus the summation of number of passes multiplied by the effectiveness factor corresponding to each pass. This summation is termed here as the Compaction Index (CI).

Examples of the different effectiveness factors across the roller width are shown in Figure 4-5. The y-axis in these plots represents the effectiveness factor, while the x-axis represents the distance from the roller edge. The numbers shown below to the plots are the R^2 values obtained between CI and percent air voids when these effectiveness factors are used.



Note: The x-axis is the distance from a roller edge in ft and y-axis is the effectiveness factor.

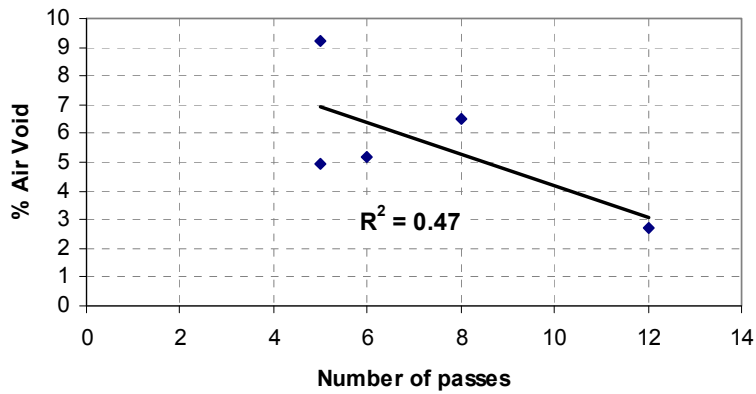
Figure 4-5. Examples of Different Effectiveness Factors of R^2 Values Obtained between Compaction Index and Percent Air Voids When These Factors Are Used.



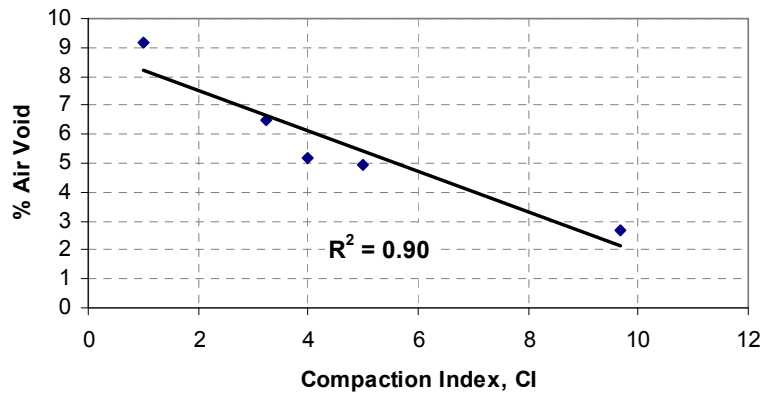
Note: The x-axis is the distance from a roller edge in ft and y-axis is the effectiveness factor.

Figure 4-5. Examples of Different Effectiveness Factors of R^2 Values Obtained between Compaction Index and Percent Air Voids When These Factors Are Used (Continued).

The best correlation (R^2 equal to 0.8) between percent air voids and CI was achieved by using the last effectiveness factor in Figure 4-5. The results indicate that the effectiveness of compaction decreases as the distance from the roller edge decreases to less than 2 ft. Examples of the relationships of number of passes and CI with percent air voids are shown Figures 4-6 through 4-10. Figures A-7 through A-10 in Appendix A show the results for the remaining test sections.

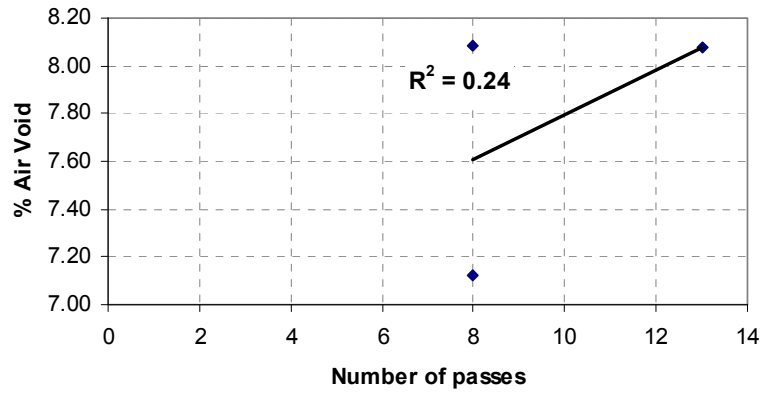


(a)

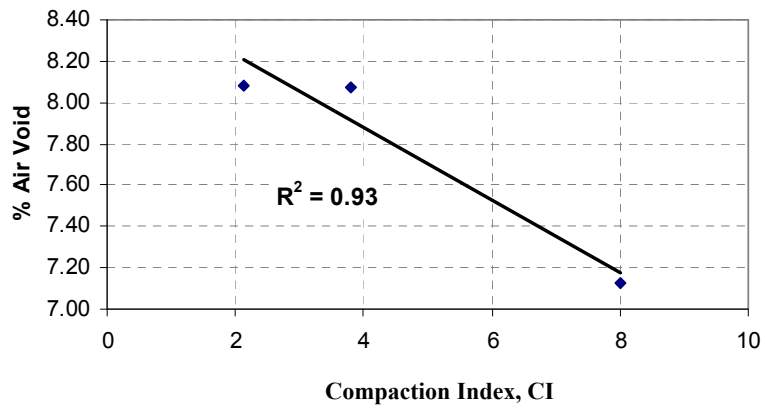


(b)

Figure 4-6. (a) Number of Passes versus the Percent of Air Voids in the IH 35 Test Section, (b) CI versus the Percent of Air Voids in the IH 35 Test Section.

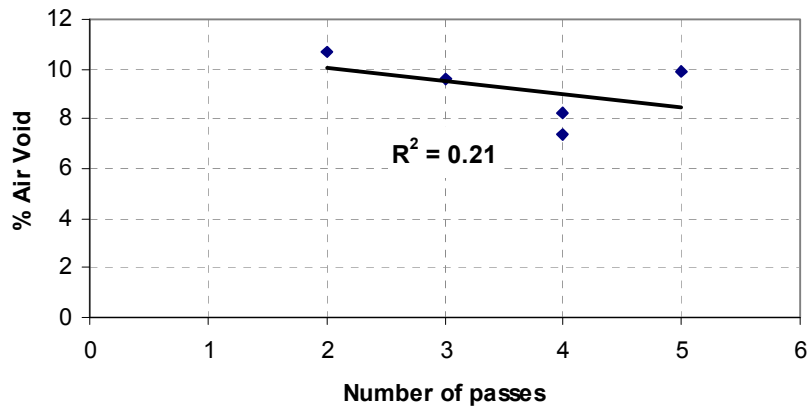


(a)

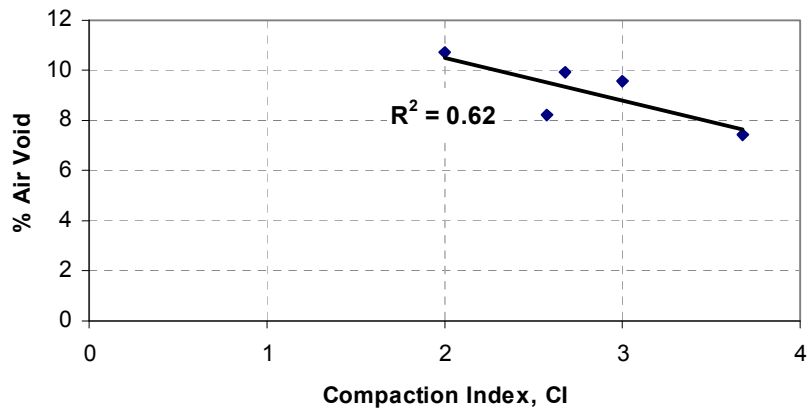


(b)

Figure 4-7. (a) Number of Passes Versus the Percent of Air Voids in the SH 36 Test Section (Pattern 1), (b) CI Versus the Percent of Air Voids in the SH 36 Test Section (Pattern 1).

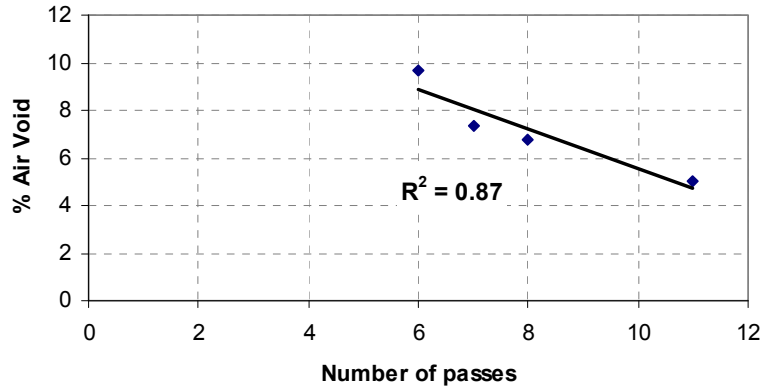


(a)

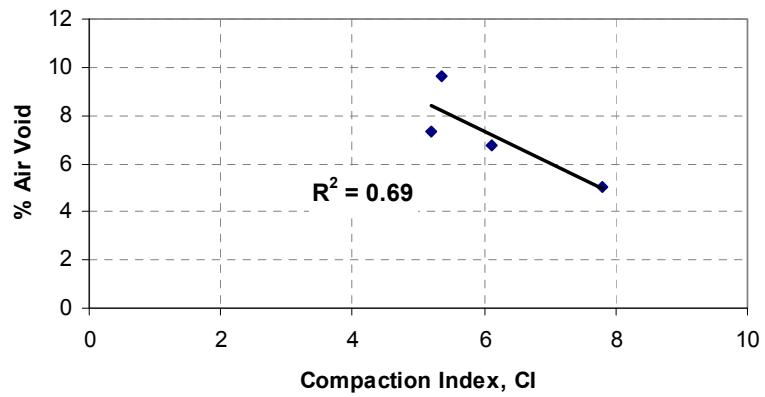


(b)

Figure 4-8. (a) Number of Passes versus the Percent of Air Voids in the US 259 Test Section (Pattern 1), (b) CI versus the Percent of Air Voids in the US 259 Test Section (Pattern 1).



(a)



(b)

Figure 4-9. (a) Number of Passes versus the Percent of Air Voids in the US 87 Test Section (Pattern 1), (b) CI versus the Percent of Air Voids in the US 87 Test Section (Pattern 1).

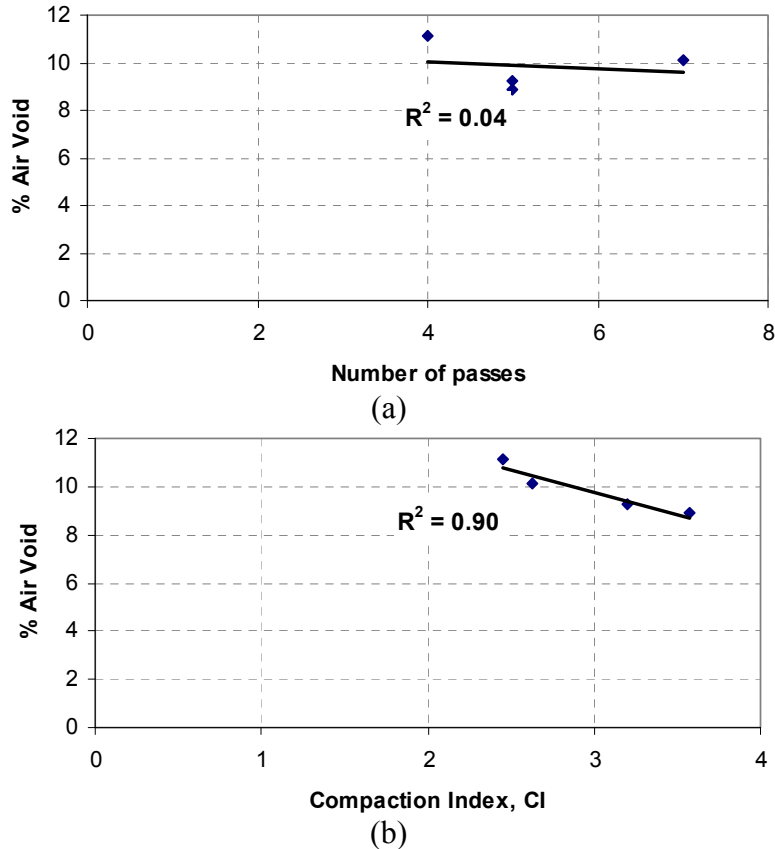
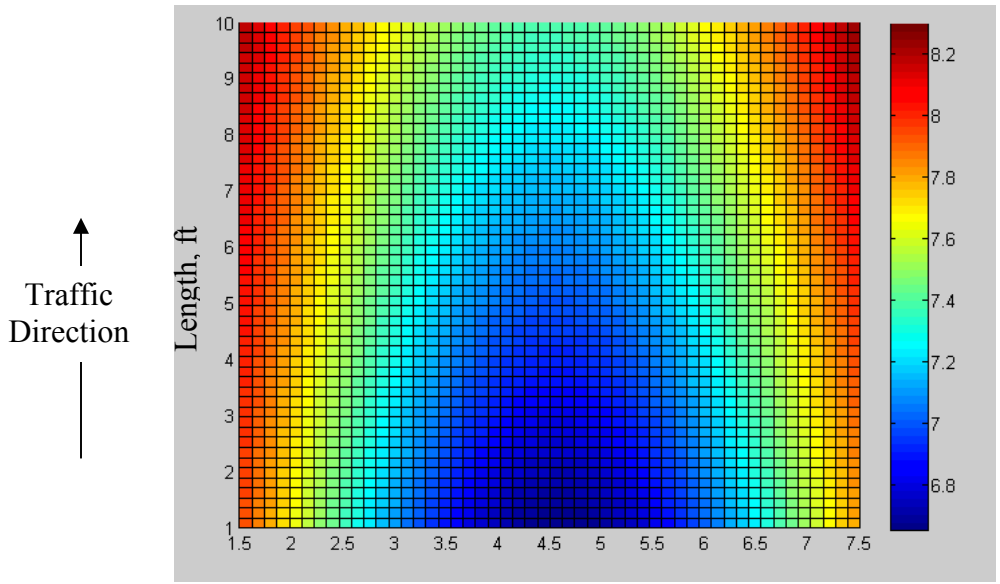


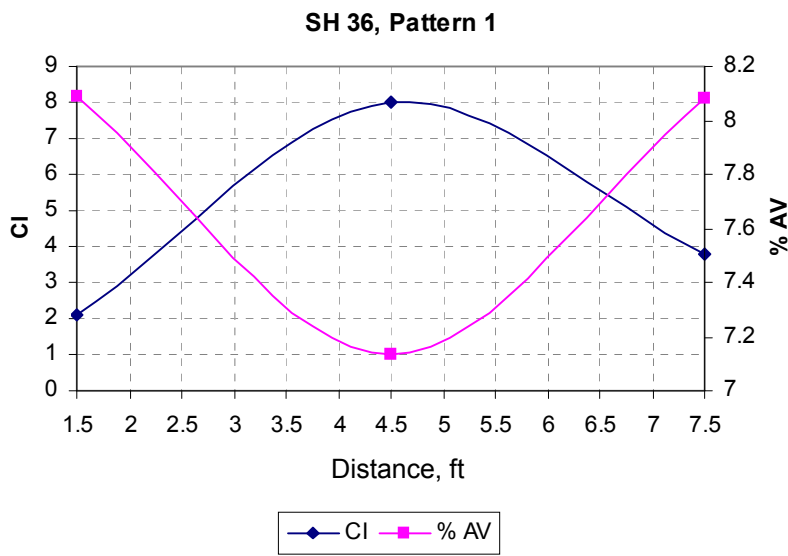
Figure 4-10. (a) Number of Passes versus the Percent of Air Voids in the SH 21 Test Section (Pattern 1), (b) CI versus the Percent of Air Voids in the SH 21 Test Section (Pattern 1).

APPLICATIONS OF THE COMPACTION INDEX

The relationship between percent air voids and CI can be very useful to set up the compaction pattern (number of passes and location of these passes). The compaction pattern can be adjusted to achieve uniform CI distribution across the pavement section, which corresponds to uniform air void distribution. This point is illustrated in Figures 4-11 and 4-12, which were generated by inputting the location of each core and its percent air voids to the Matlab 7.1 software (2004). Then an interpolation algorithm in Matlab was used to predict percent air voids in the whole pavement section. Figures A-11 through A-17 in Appendix A show the results for the remaining test sections.



Edge Distance, ft
(a)



(b)

Note: The total width of the mat is 14 ft.

Figure 4-12. (a) Air Void Distribution (%) across the Mat for SH 36 Test Section (Pattern 1), (b) The CI and Average Percent of Air Voids across the Mat for SH 36 Test Section (Pattern 1).

The CI can also be used to determine the sensitivity of a mixture to the compaction effort. Relationships of CI to percent air voids are shown in Figure 4-13. Percent air voids changes at different rates as more compaction effort is applied (increase in CI). It is interesting to note that the SH 36 mixture was not sensitive to changes in CI as the other mixtures were. The SH 36 mixture consisted of small size relatively soft limestone aggregates with a 9.5 mm nominal maximum size. The results in Figure 4-13 indicate that this mixture can be easily compacted using relatively small compaction effort. Continuing increase in compaction effort (increase in CI) did not help in decreasing percent air voids.

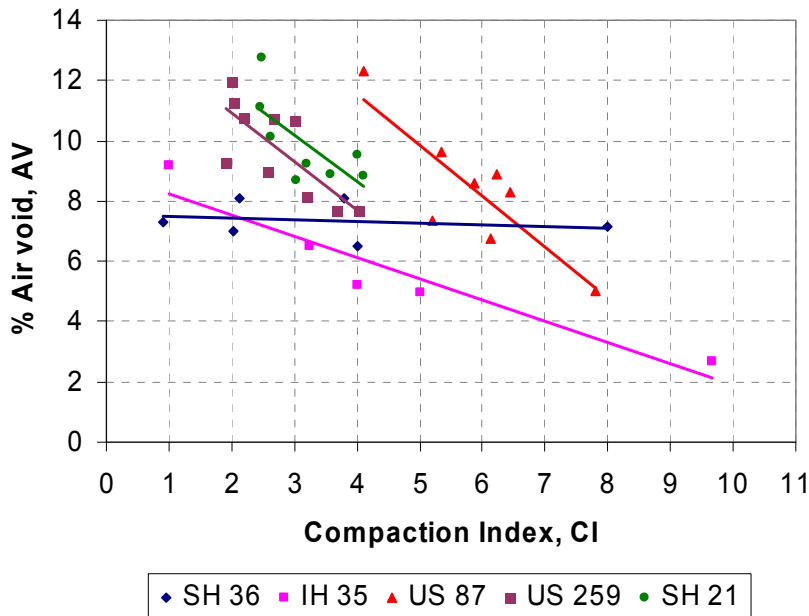


Figure 4-13. The CI versus the Percent of Air Voids.

RELATIONSHIP OF LABORATORY COMPACTION TO FIELD COMPACTION

Four SGC specimens (150 mm diameter and approximately 63.5 mm in height) were compacted at a 1.25° gyration angle, and two specimens were compacted at a 2.0° gyration angle from each mixture. Slope of percent air voids to number of gyrations in

logarithmic scale was calculated. Figure 4-14 shows the relationship between the average slope up to 8 percent air voids in the laboratory versus the CI at this percent air voids. Samples with higher slope in the laboratory needed less CI in the field (less compaction effort). This relationship offers the potential to estimate the required compaction effort in the field (i.e., CI) based on the slope of number of gyrations and percent air voids in the laboratory.

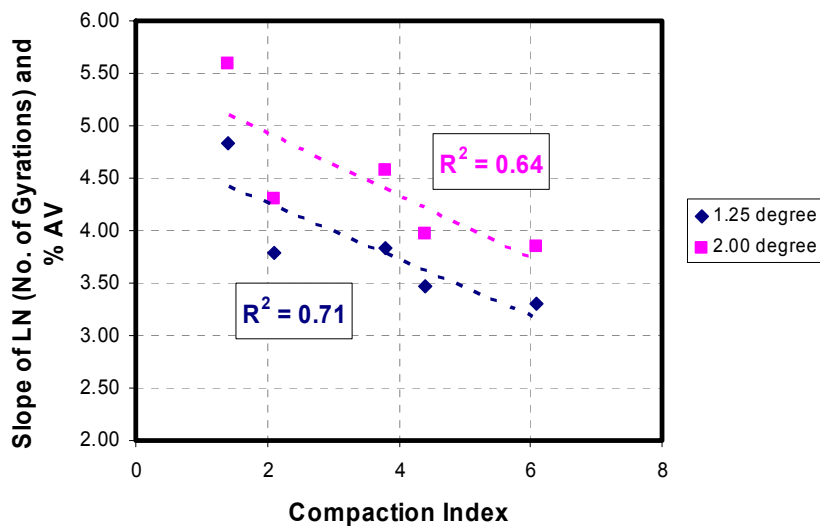


Figure 4-14. Compaction Index versus the Slope of LN (No. of Gyration) and Percent Air Voids Curve at 8 Percent Air Voids for Different Mixes.

INFLUENCE OF COMPACTION PATTERN ON UNIFORMITY OF AIR VOID DISTRIBUTION

X-ray Computed Tomography

X-ray CT is a nondestructive test used to capture the internal structure of materials. Various applications of this method are discussed by Masad (2004). The X-ray CT setup at Texas A&M University is shown in Figures 4-15 and 4-16. This setup includes two separate systems placed in the same shielding cabinet. The mini-focus system has a 350 kV X-ray source and a linear detector, while the micro-focus system has a 225 kV X-ray source and an area detector.

The mini-focus source can penetrate thicker and denser specimens than the micro-focus source. The micro-focus system is capable of achieving a better resolution than the mini-focus system. All the experimental measurements in this study were conducted using the mini-focus 350 kV X-ray source system which has the necessary power to penetrate the asphalt mix specimens with a reasonable resolution. More details on the different X-ray CT configurations and their capabilities can be found in the paper by Masad (2004)

The densities of the different components of the mixture are represented in an image that consists of 256 gray intensity levels as low density material is represented by a darker color. The images were captured every 1 mm in the vertical direction and with a horizontal resolution equal to about 0.17 mm/pixel. The X-ray CT images were processed in order to separate air voids from the other mix constituents (aggregate and asphalt), and these images were analyzed to determine average percent air voids in each image ($\%AV_{image}$) as shown in Equation (4-1):

$$\%AV_{image} = \frac{A_{TV}}{A_T} \quad (4-1)$$

where, A_{TV} is the total area of the air voids in a CT image and A_T is the total cross-sectional area of a CT image. The analysis was conducted using macros that were developed in Image-Pro® Plus software (1999).



Figure 4-15. X-ray CT System at Texas A&M University.

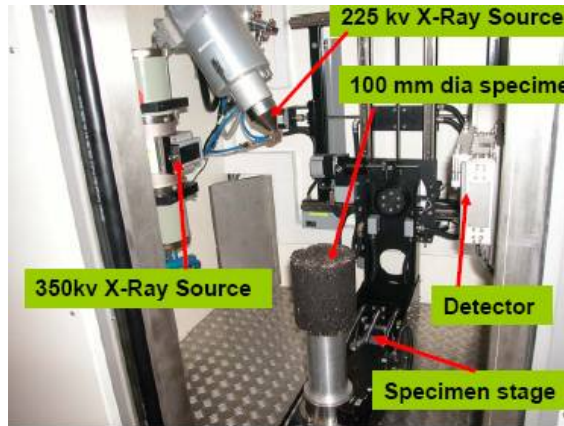
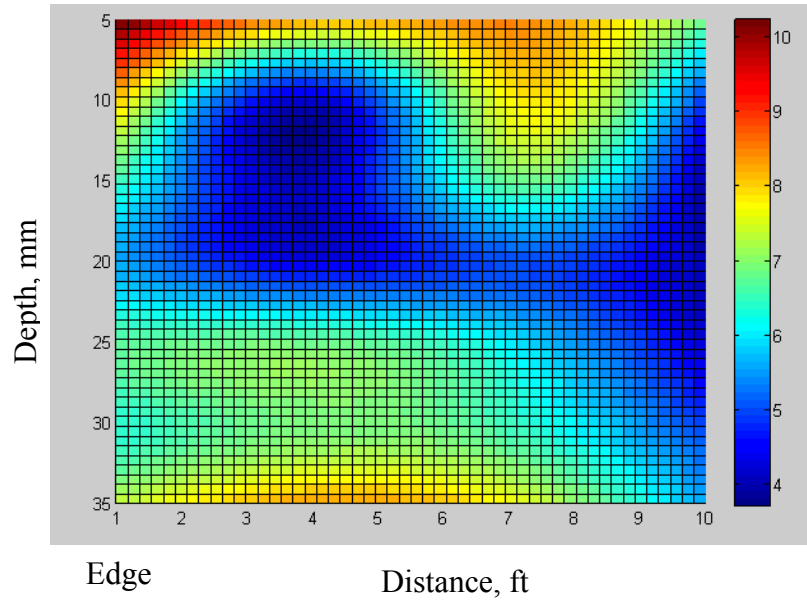


Figure 4-16. Components of X-ray Computed Tomography System.

Three-Dimensional Air Void Distribution Maps

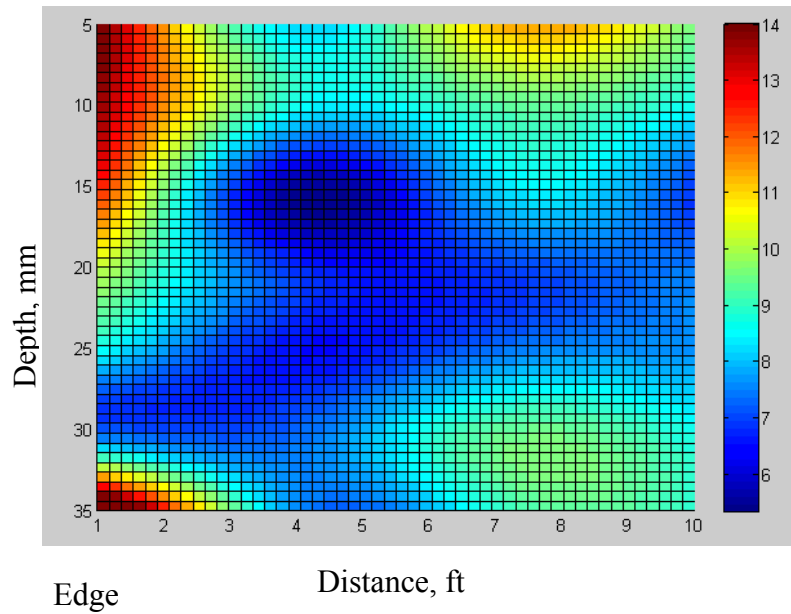
Three-dimensional maps of air void distribution in pavement sections were generated by inputting percent air voids as a function of depth (from X-ray CT images) and the location of cores in the pavement to the Matlab 7.1 software. This application provides an estimate of percent air voids at any point in the pavement section every 1 mm of depth. As such, one can determine the detailed three-dimensional distribution of air voids.

Figures 4-17 through 4-20 show examples of the vertical distribution of air voids in pavement sections. Figures A-18 through A-21 in Appendix A show the results for more test sections. The results from compaction Pattern 1 have all shown that the middle part of the pavement has less percent of air voids or is more compacted than the top and the bottom parts. It is interesting to note that the use of a pneumatic tire compactor in the breakdown stage in projects US 87 and SH 21 resulted in a more uniform distribution and a higher density in the top two-thirds of the pavement thickness. This can be seen by comparing Figure 4-18 versus Figure 4-17 and Figure 4-20 versus Figure 4-19. In order to better illustrate this point, Figure 4-21 shows the percent air voids for the SH 21 test section in 5 mm increments across the depth for both compaction patterns. The results confirm that the top 25 mm had more uniform percent air voids and was more compacted in compaction Pattern 2, where a pneumatic tire roller was used in breakdown, compared with Pattern 1.



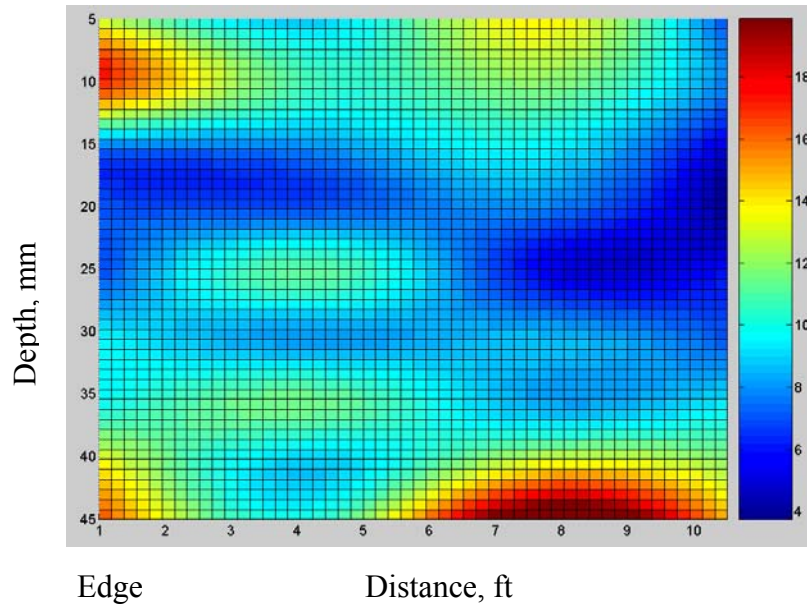
Note: Total width of the mat is 14.5 ft.

Figure 4-17. Air Void Distribution (%) along the Depth of the Mat for the US 87 Test Section (Pattern 1).



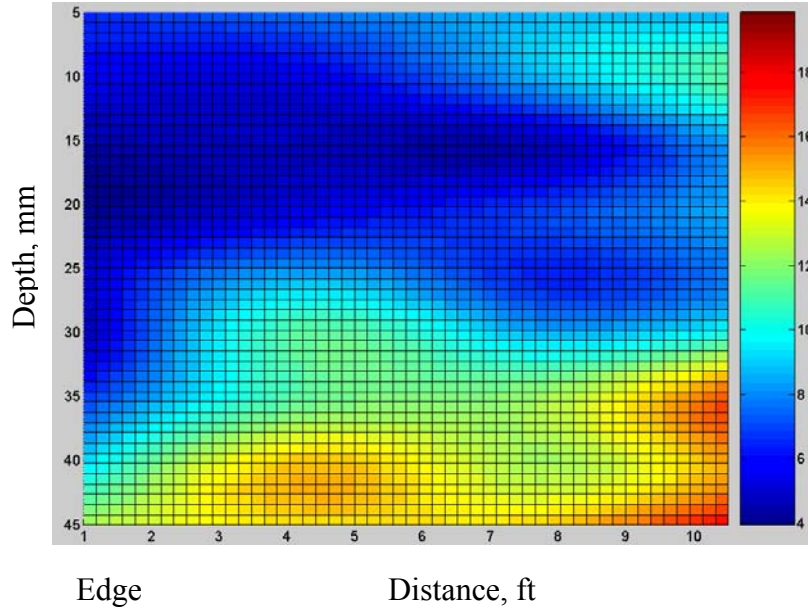
Note: Total width of the mat is 14.5 ft.

Figure 4-18. Air Void Distribution (%) along the Depth of the Mat for the US 87 Test Section (Pattern 2).



Note: Total width of the mat is 11.5 ft.

Figure 4-19. Air Void Distribution (%) along the Depth of the Mat for the SH 21 Test Section (Pattern 1).



Note: Total width of the mat is 11.5 ft.

Figure 4-20. Air Void Distribution (%) along the Depth of the Mat for the SH 21 Test Section (Pattern 2).

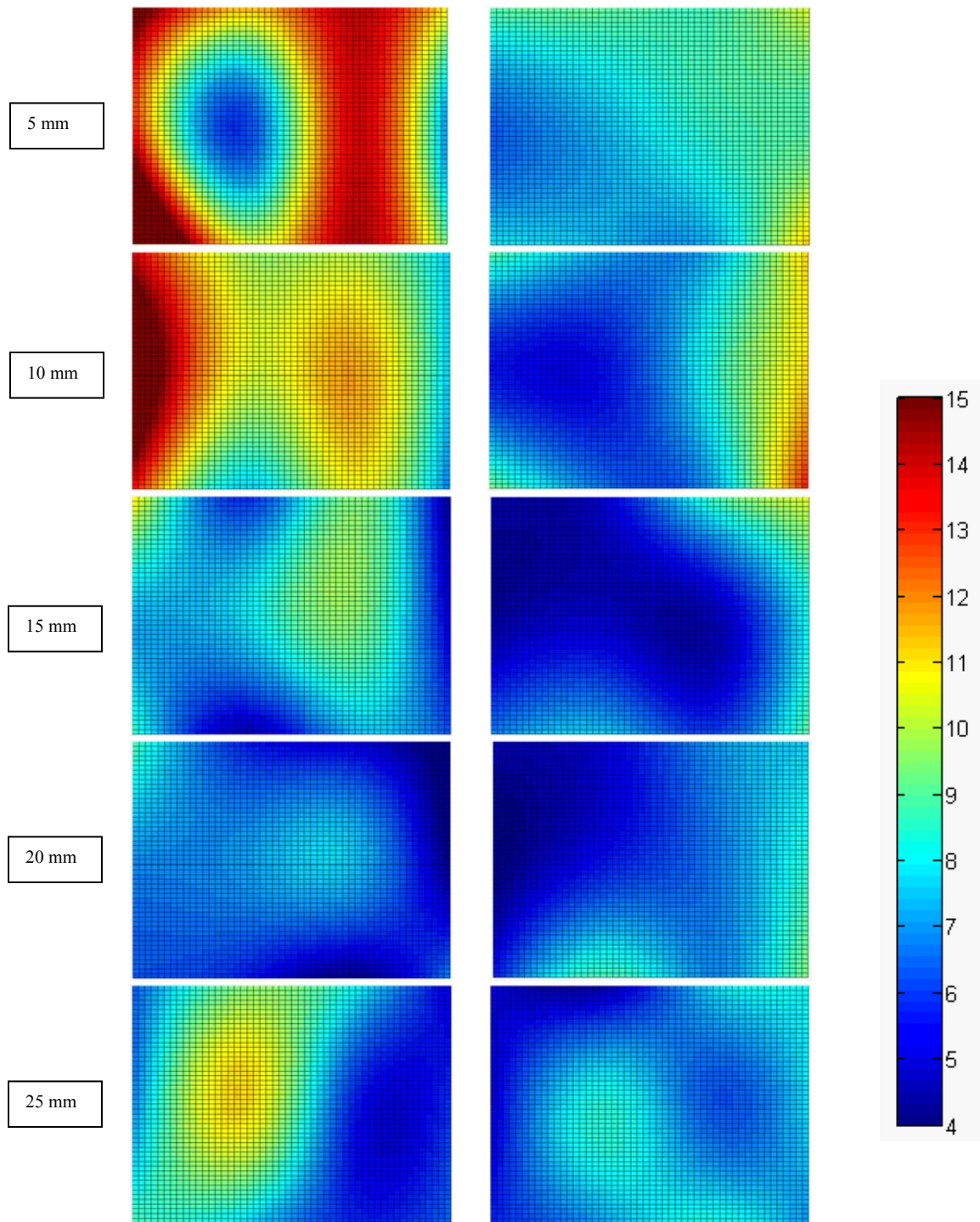
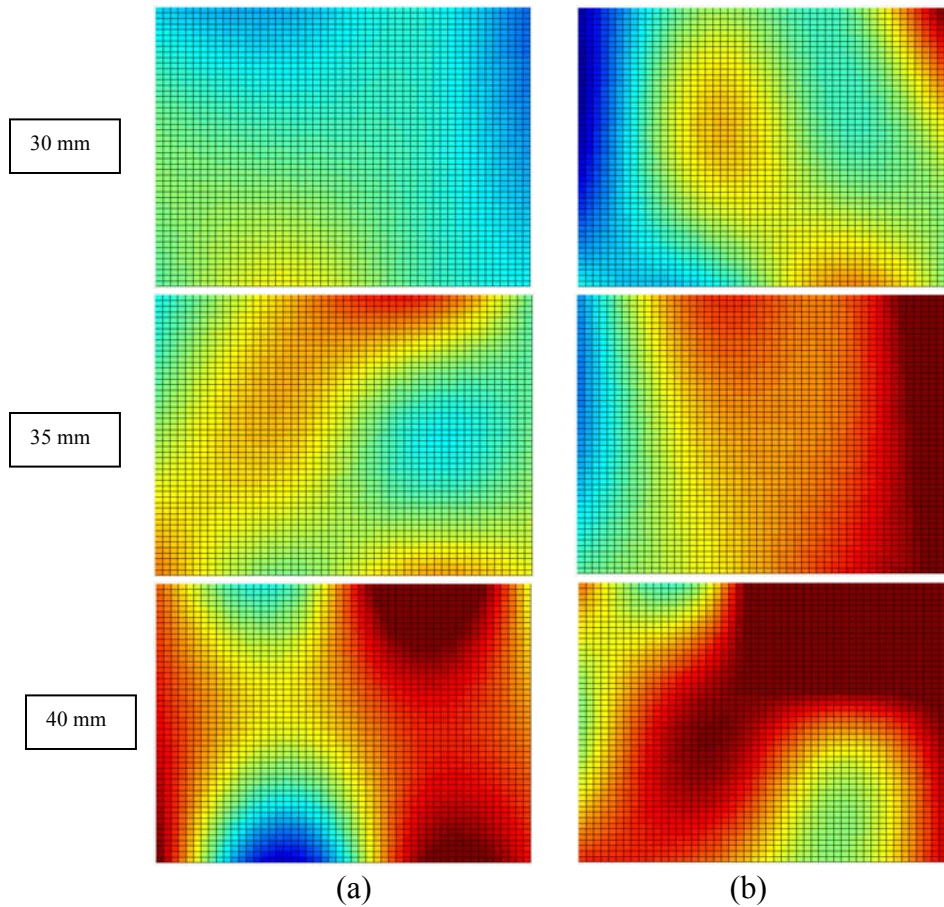


Figure 4-21. Air Void Distribution (%) across the Mat at Different Depths for the SH 21 Test Section.



Note: The x-axis is 9.5 ft, and y-axis is 6 ft (a) Pattern 1 (b) Pattern 2.

Figure 4-21. Air Void Distribution (%) across the Mat at Different Depths for the SH 21 Test Section (Continued).

Quantifying Uniformity of Air Void Distribution

The uniformity of air void distribution is quantified using two indices. The first index is the difference in air voids between the top and bottom halves of a core (%AV (Top) - %AV (Bottom)). The second index is termed the Uniformity Index (UI) and is calculated as follows:

1. Plot percent air voids $f(x)$ against the core depth x .
2. Fit a fourth order polynomial for $f(x)$.
3. Calculate the derivate $f'(x)$ of the function $f(x)$.
4. Calculate the UI using [Equation \(4-2\)](#).

$$UI = \frac{1}{b-a} \int_a^b [f'(x)]^2 dx \quad (4-2)$$

The fourth order polynomial was found to fit the percent air voids function very well. The UI is equal to zero for a straight line function representing uniform distribution, and it increases with an increase in nonuniformity. The integration limits depend on the thickness over which the analysis is conducted. For a core with thickness equal to h , the analysis is conducted for the whole core ($a=0$, $b = h$), for the top half ($a=0$, $b=h/2$), and for the bottom half ($a=h/2$ and $b=h$).

The UI is given in Figures 4-23 and 4-25. In these figures, the field cores are labeled according to their locations in the mat as follows; right longitudinal joint (RJ), right wheel path (RW), center of paving lane (Cen.), left wheel path (LW), and left longitudinal joint (LJ). The results for US 87 are shown in Figures 4-22 and 4-23. The use of the pneumatic tire roller in breakdown in the second compaction pattern resulted in less percent air voids in the top as indicated with the mostly negative values in Figure 4-22b compared with the mostly positive values in Figure 4-22a. Also, the second compaction pattern results in less UI (more uniform air void distribution) especially in the top half as indicated in Figure 4-23. These results support the discussion in the previous section that the use of the pneumatic tire roller in breakdown is more effective in inducing more compaction toward the pavement surface.

The results for SH 21 are shown in Figures 4-24 and 4-25. The difference in percent air voids between the top and the bottom became more negative in Pattern 2 indicating less percent air voids in the top. The uniformity in the top improved (UI decreased) in compaction Pattern 2 compared with compaction Pattern 1. These results are consistent with the findings from US 87. Figures A-22 through A-33 in Appendix A show the findings for the remaining test sections.

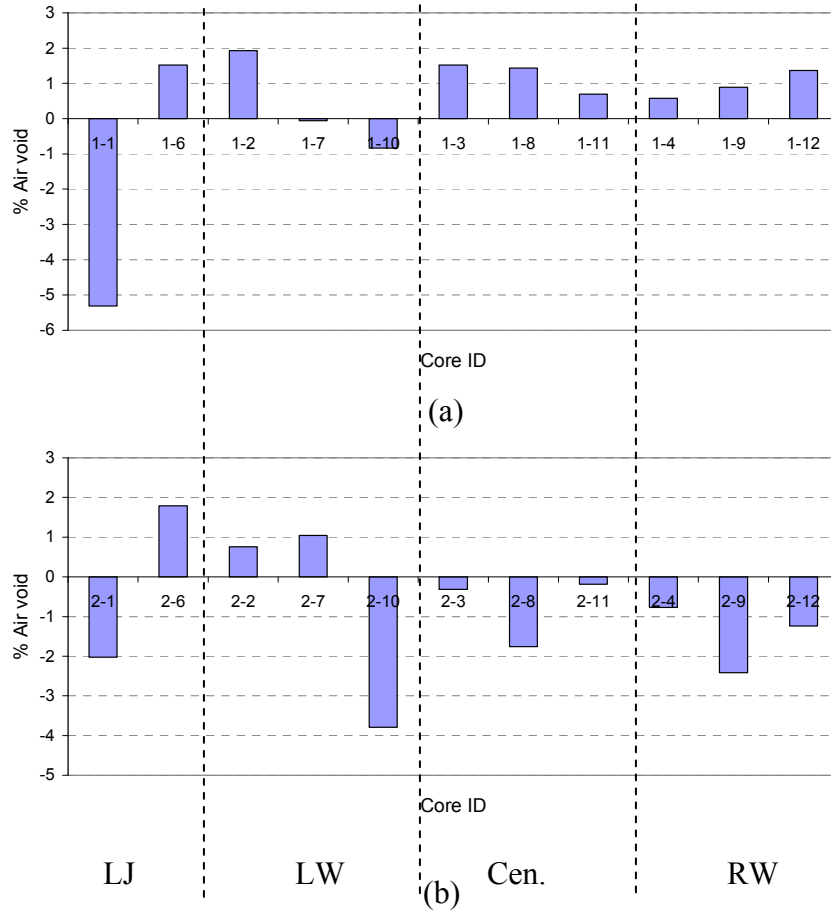
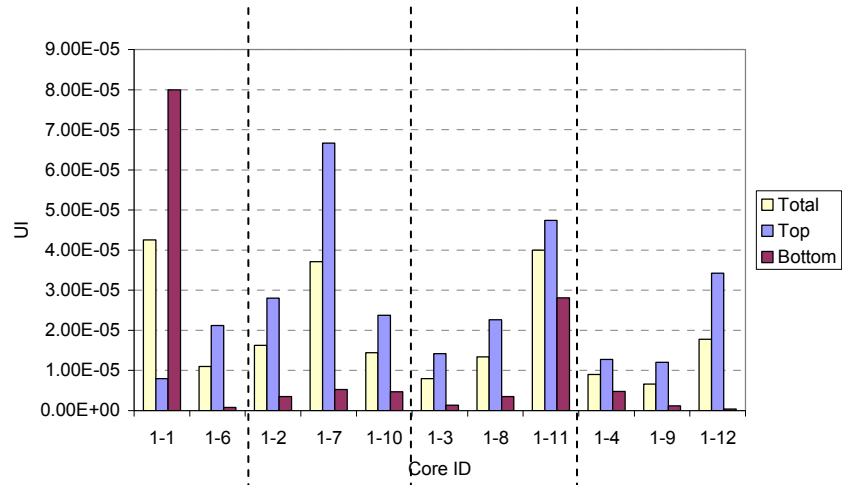
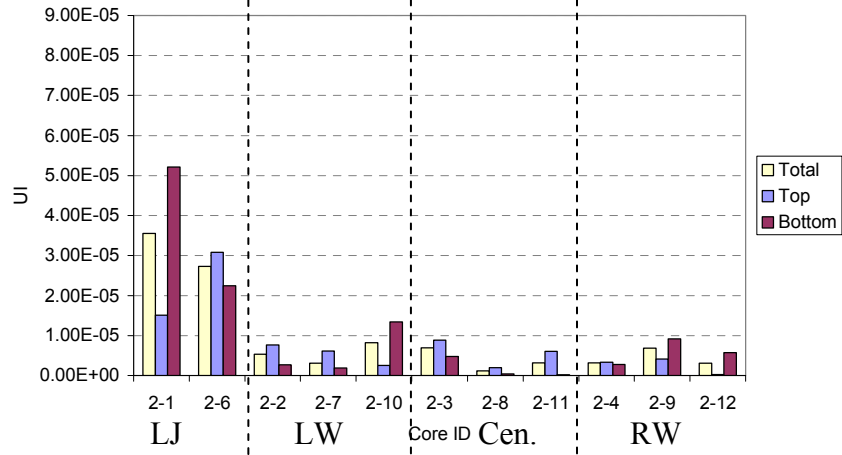


Figure 4-22. Difference between the Percent of Air Voids at the Top and Bottom Parts for the US 87 Test Section (a) Pattern 1, (b) Pattern 2.



(a)



(b)

Figure 4-23. UI for the US 87 Test Section (a) Pattern 1, (b) Pattern 2.

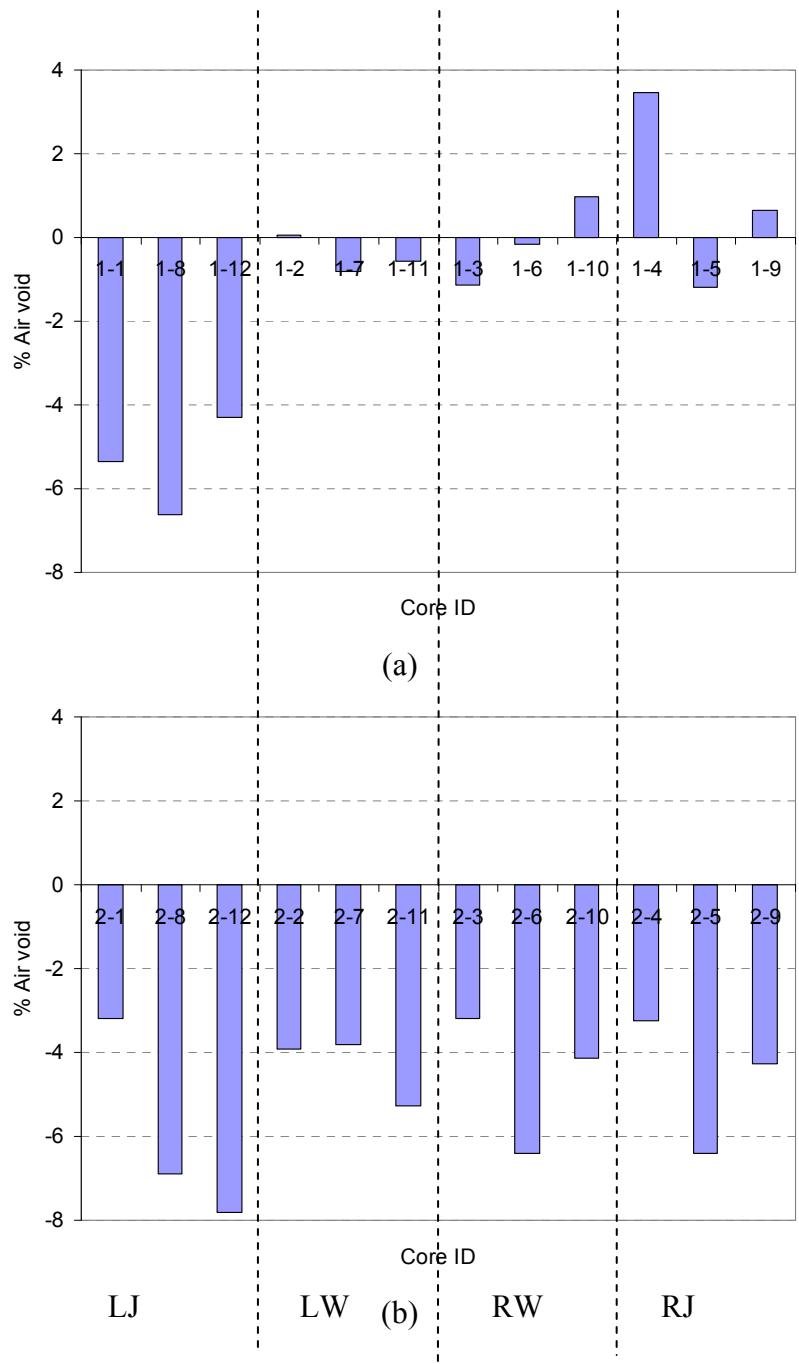


Figure 4-24. Difference between the Percent of Air Voids at the Top and the Bottom Parts for the SH 21 Test Section (a) Pattern 1, (b) Pattern 2.

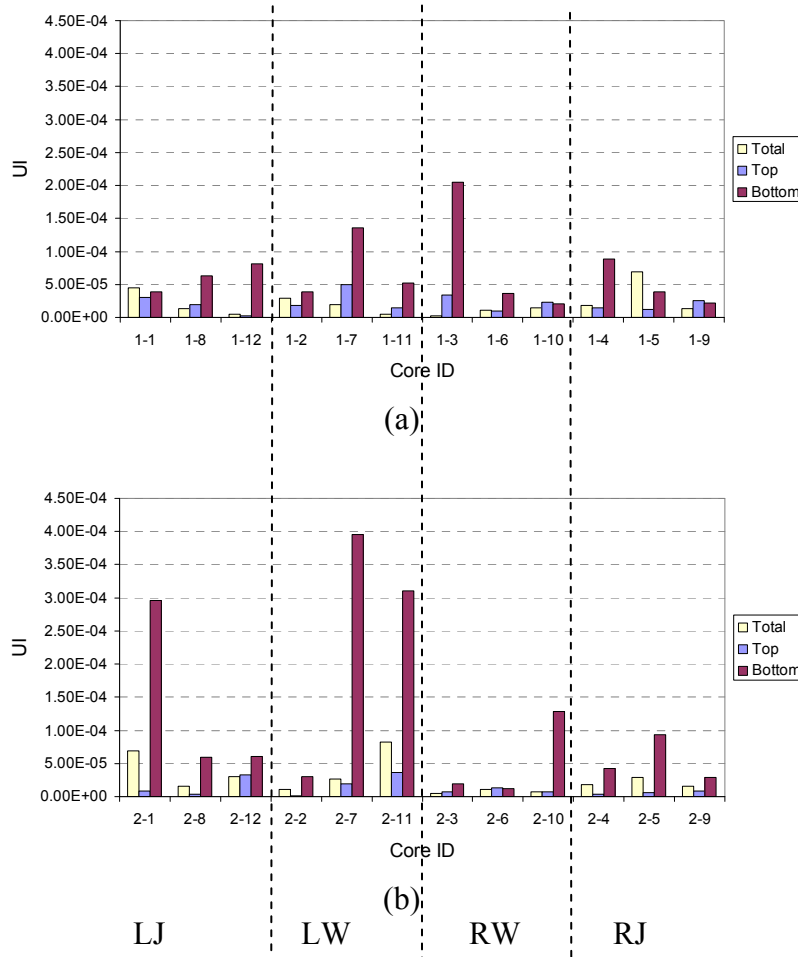


Figure 4-25. UI for the SH 21 Test Section (a) Pattern 1, (b) Pattern 2.

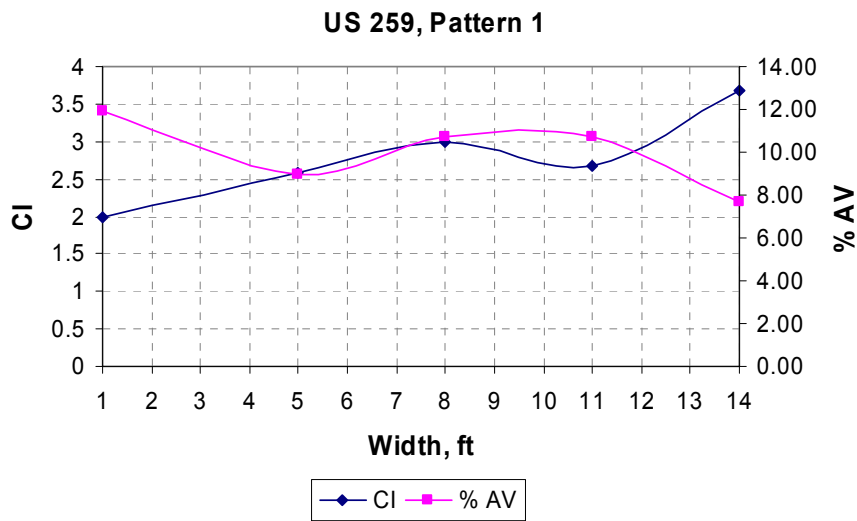
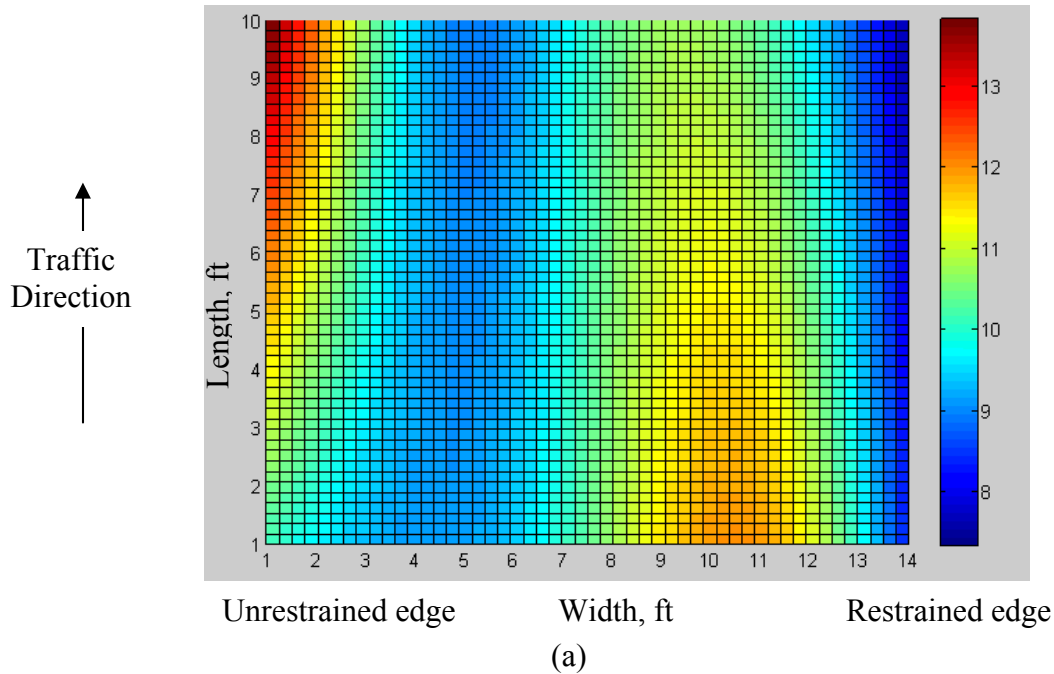
COMPACTION OF LONGITUDINAL JOINTS

It is well accepted that asphalt pavement close to the longitudinal joint tends to be less compacted than toward the center of the pavement. This is caused by the tendency to apply fewer passes at the joints. Also, the low confinement at some types of joints (unrestricted or unconfined joints) and the higher rate at which the mixture at the joint loses heat reduce the efficiency of compaction at the joint compared with the pavement center. In this study, the compaction of longitudinal joints and the possible methods that can improve this compaction are discussed in this section.

The research team obtained field cores from different locations of the mat as well as from near the longitudinal joints. The joint construction was not the same for all projects (vertical versus tapered or confined versus unconfined). Left and right longitudinal joints of the IH 35 test section were confined and unconfined vertical joints, respectively. Both edges of the SH 36 mat had unconfined tapered (wedge) longitudinal joints. Left and right longitudinal joints of the US 87 test section were confined and unconfined tapered joints, respectively. The right edge of the US 259 mat was free (shoulder), whereas the left edge of the same mat had a vertical longitudinal joint. Both edges of the SH 21 test section mat had tapered confined longitudinal joints.

As expected, the air void of specimens near the longitudinal joints had a higher percent of air voids than the other parts across the mat. However, percent air voids near the confined or restrained longitudinal joints were closer to the center of the mat compared with the unconfined joints.

In this study as discussed in [Figure 4-5](#), it was found that the effectiveness factor decreases at the edge of the roller. An important aspect influencing joint compaction is overhanging of roller edge at a distance of about 1.5 ft to 2 ft from the longitudinal joint. One example is given in [Figure 4-26](#) which shows the percent of air void distribution and CI across the mat in the US 259 test section. As can be seen, the cores taken from the right edge (restrained joint) had the lowest percent of air voids which corresponds to the highest CI across the mat. In this particular case, the steel wheel roller had 2 ft overhanging from the restrained joint, resulting in a higher CI at that location. Interestingly, there are some areas within the mat that have less density than the ones at the restrained longitudinal joints. These areas were subjected to a lower CI as a result of poor overlapping.



(b)
 Note: The total width of the mat is 15 ft.

Figure 4-26. (a) Air Void Distribution (%) across the Mat for the US 259 Test Section (Pattern 1), (b) The CI and Average Percent of Air Voids across the Mat for the US 259 Test Section (Pattern 1).

The air void distribution was found to be more uniform at the restrained joint than the unrestrained one as can be seen from Figure 4-27. The UI, explained in Equation 4-2, for total depth at unrestrained joint samples is higher than the UI of samples obtained

from the restricted joint. The authors recommend the overhanging of steel rollers to be at least 2 ft.

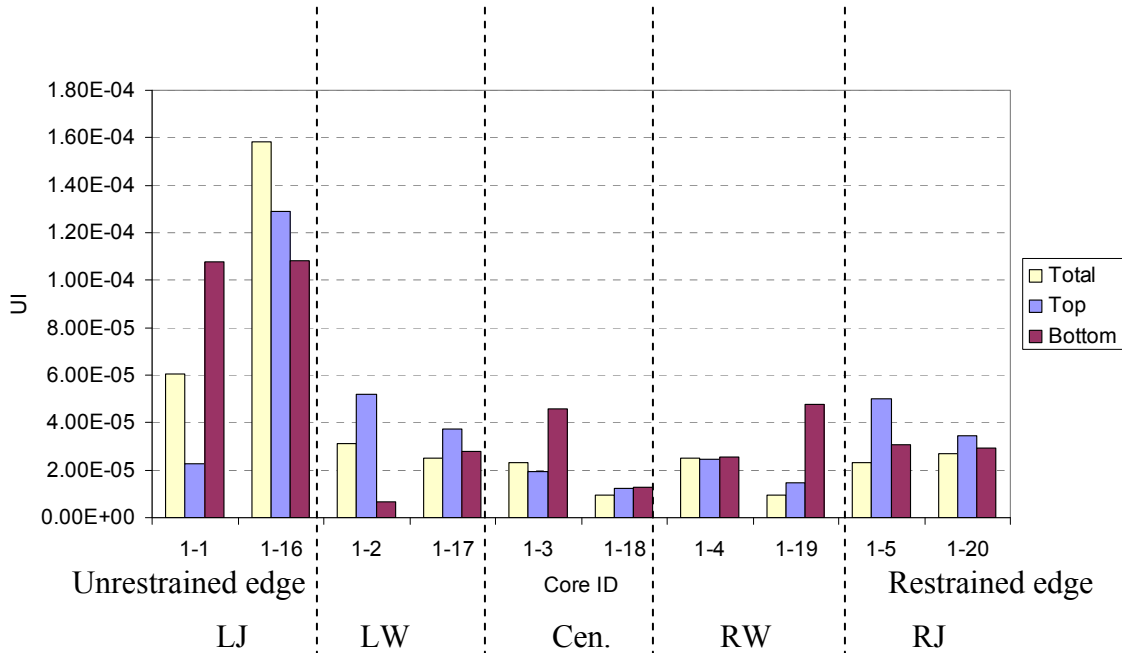


Figure 4-27. UI for the US 259 Test Section (Pattern 1).

CONCLUSIONS

This study provided experimental evaluation of the influence of the field compaction pattern on level of compaction and the uniformity of air void distribution in asphalt pavements. The findings showed that the efficiency of compaction at a given point in the pavement is a function of the location of the roller with respect to this point. The efficiency of compaction at the center of the roller is better than at the edge of the roller. Therefore, a new index referred to as the Compaction Index (CI) is proposed to quantify the compaction effort at any point in the pavement. This index is the summation of the multiplication of each pass with an effectiveness factor, which is a function of distance from the edge of the roller. The CI is useful to set up the compaction pattern in order to achieve the desired percent air voids uniformly across the pavement section; a more uniform CI corresponds to more uniform air void distribution. In terms of compaction sequence, the use of the

pneumatic roller in the breakdown stage was found to be effective in reducing the percent air voids and improving uniformity in the top half of the lift thickness.

The CI can also be used to determine the sensitivity of a mixture to the compaction effort. Some mixtures achieve a certain level of percent air voids and further increase in compaction effort or CI does not help in reducing percent air voids.

This study demonstrated that there is a relationship between slope of a laboratory compaction curve and CI values. This relationship can be used to determine the required field compaction effort based on laboratory compaction data.

It has been reported in the past that the mixture near longitudinal joints is usually less compacted than the rest of the pavement section. This has been attributed to the lower confinement, typically lower number of passes and the faster rate of heat loss at the joint compared with the center of the pavement. Based on the results of this study, the low compaction at the joint is also attributed to the low effectiveness factor because a joint is typically compacted using the roller edge. Consequently, joints need to be compacted to a higher CI compared with the center of the pavement in order to compensate for the other factors that reduce joint compactability. This can be achieved by overhanging of the steel rollers by at least 2 ft.

CHAPTER 5

COMPARISON OF LABORATORY AND FIELD MECHANICAL PROPERTIES

INTRODUCTION

The researchers obtained field cores from the seven construction projects discussed in [Chapter 3](#). Field cores from all projects were tested to measure density (both vacuum sealed or CoreLok and Saturated Surface Dry or SSD methods), air void distribution using X-ray CT, permeability, rutting resistance using Hamburg wheel tracking device, and fatigue resistance using overlay tester. In addition, specimens were compacted in the laboratory using virgin materials obtained from the HMA plants for selected projects where compaction patterns were varied in the field (FM 649, SH 36, US 87, US 259, and SH 21). Plant mixes obtained from the field sites were tested to determine maximum specific gravity, binder content, and gradation. [Table 5-1](#) presents the summary of tests conducted with specimens obtained from each construction project.

HAMBURG TEST RESULTS

The Hamburg test was conducted following TxDOT standard Tex-242-F “Hamburg Wheel-tracking Test.” Laboratory specimens were compacted using both 1.25° and 2.0° gyratory angles to achieve 7±1 percent air void. [Table 5-2](#) summarizes the Hamburg test results. Figures [5-1](#) through [5-5](#) graphically present the Hamburg test results for the five projects in which field compaction was varied.

All the tests were set to run for 20,000 cycles or 12.5 mm rut depth, whichever came first. In some cases the specimens failed (rut depth of 0.5 inch or 12.5 mm) before reaching 20,000 cycles, and in some cases the test stopped slightly before a 12.5 mm rut depth. In order to compare the results, the average rutting rate was calculated according to [Equation 5-1](#). The shaded cells in [Table 5-2](#) represent those results where the tests were continued until the rut depth reached 12.5 mm.

$$Rutting\ Rate = \frac{rut\ depth\ in\ mm}{\log(number\ of\ load\ cycles)} \quad (5-1)$$

Table 5-1. Laboratory Tests Conducted with Different Mixtures from Field Compaction Study.

Highway ID	Comment	Tests with Field Cores					Tests with Lab Mixed Lab Compacted Specimens					
		Density	X-ray CT	Hamburg	Permeability	Overlay	Comment	Density	X-ray CT	Hamburg	Permeability	Overlay
US 281, PHR	One Compaction Pattern	CoreLok & SSD	Yes	Yes	Yes	Yes	1.25° angle	CoreLok & SSD	Yes	N/A	N/A	N/A
FM 649, LRD	Two Compaction Patterns	CoreLok & SSD	Yes	Yes	Yes	Yes	1.25° & 2.0° angle	CoreLok & SSD	Yes	Yes	Yes	Yes
IH 35, WAC	One Compaction Pattern	CoreLok & SSD	Yes	Yes	Yes	Yes	1.25° angle	CoreLok & SSD	Yes	N/A	N/A	N/A
SH 36, YKM	Two Compaction Patterns	CoreLok & SSD	Yes	Yes	Yes	Yes	1.25° & 2.0° angle	CoreLok & SSD	Yes	Yes	Yes	Yes
US 87, YKM	Two Compaction Patterns	CoreLok & SSD	Yes	Yes	Yes	Yes	1.25° & 2.0° angle	CoreLok & SSD	Yes	Yes	Yes	Yes
US 259, TYL	Two Compaction Patterns	CoreLok & SSD	Yes	Yes	Yes	Yes	1.25° & 2.0° angle	CoreLok & SSD	Yes	Yes	Yes	Yes
SH 21, AUS	Two Compaction Patterns	CoreLok & SSD	Yes	Yes	Yes	Yes	1.25° & 2.0° angle	CoreLok & SSD	Yes	Yes	Yes	Yes

Table 5-2. Hamburg Test Results.

Highway ID	No. of load cycles to reach 12.5 mm rut depth			Rut depth (mm) at 20,000 load cycles			Average Rutting Rate
	Left Wheel	Right Wheel	Average	Left Wheel	Right Wheel	Average	
FM 649 Field Compaction 1	13925	11820	12873	N/A	N/A	N/A	3.04
FM 649 Field Compaction 2	14480	15400	14940	N/A	N/A	N/A	2.99
SH 36_Field Compaction 1	6501	3901	5201	N/A	N/A	N/A	3.36
SH 36_Field Compaction 2	7250	6350	6800	N/A	N/A	N/A	3.26
SH 36_1.25 D_T1_Lab Molded	5950	7002	6476	N/A	N/A	N/A	3.28
SH 36_1.25 D_T2_Lab Molded	7360	8112	7736	N/A	N/A	N/A	3.21
SH 36_2.0 D_T1_Lab Molded	9885	9421	9653	N/A	N/A	N/A	3.14
SH 36_2.0 D_T2_Lab Molded	8402	8290	8346	N/A	N/A	N/A	3.19
US 259 Field Compaction 1	21000	17400	19200	N/A	N/A	N/A	2.92
US 259_1.25 D_T1_lab Molded	14300	15200	14750	N/A	N/A	N/A	3
US 259_2.0 D_T1_lab Molded	22800	17800	20300	N/A	N/A	N/A	2.9
US 281_Pharr Field	4301	6151	5226	N/A	N/A	N/A	3.36
FM 649_1.25 D_T1_lab Molded	N/A	N/A	N/A	3.82	3.53	3.68	0.86
FM 649_2.0 D_T1_lab Molded	N/A	N/A	N/A	2.75	3.26	3.01	0.7
US 87 Field Compaction 1	N/A	N/A	N/A	5.54	3.87	4.7	1.09
US 87 Field Compaction 2	N/A	N/A	N/A	6.82	7.58	7.2	1.67
US 87_1.25 D_T1_lab Molded	N/A	N/A	N/A	3.55	4.17	3.86	0.9
US 87_2.0 D_T1_lab Molded	N/A	N/A	N/A	3.03	3.05	3.04	0.71
FM 529 Field	N/A	N/A	N/A	4.39	4.09	4.24	0.99
US 290 Field	N/A	N/A	N/A	3.34	N/A	3.34	0.78
IH 35_Waco Field	N/A	N/A	N/A	11.65	9.82	10.74	2.5
SH 21 Field Compaction 1	N/A	N/A	N/A	6.13	8.56	7.35	1.71
SH 21 Field Compaction 2	N/A	N/A	N/A	4.78	5.29	5.04	1.17
SH 21_1.25 D_T1_lab Molded	N/A	N/A	N/A	3.02	2.85	2.94	0.68
SH 21_2.0 D_T1_lab Molded	N/A	N/A	N/A	2.75	2.59	2.67	0.62

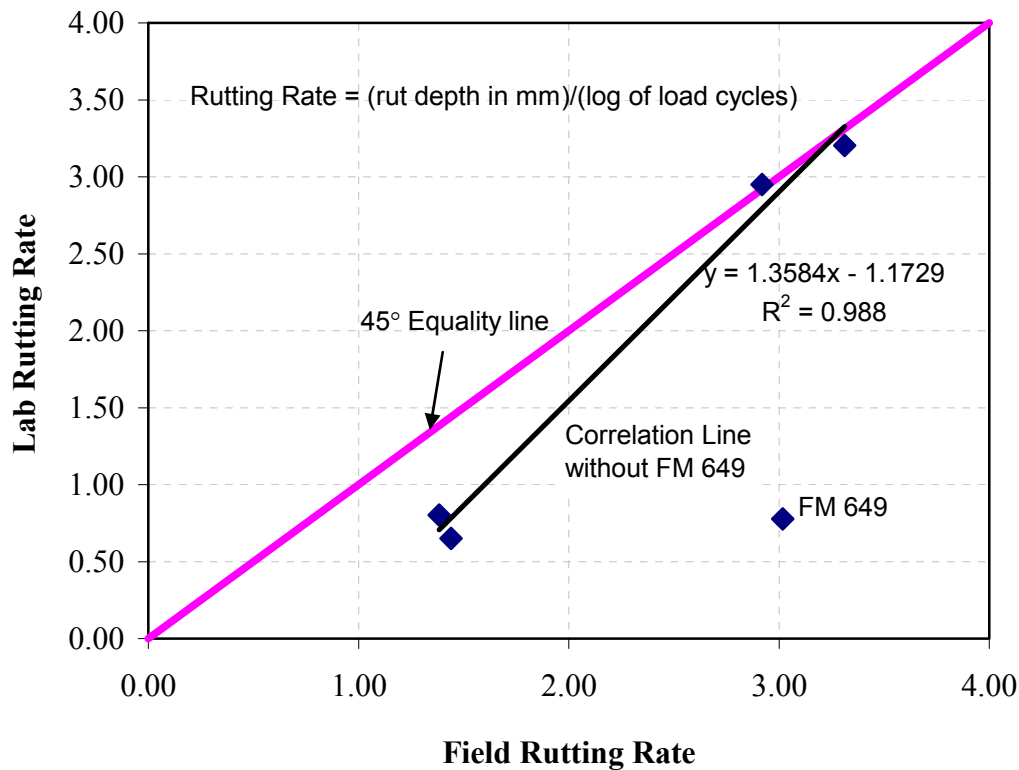


Figure 5-1. Comparison of Field and Lab Compacted Hamburg Specimens.

As shown by the average rutting rate in [Table 5-2](#), specimens compacted in the lab using a 2.0° gyratory angle performed slightly better than samples compacted with a 1.25° gyratory angle. In [Figure 5-1](#), the performance of gyratory compacted samples was comparable to the performance of field samples when the field air void was close to 7 percent (US 87 and SH 36). Field samples from FM 649 (both compaction patterns) performed much worse than those of corresponding gyratory compacted samples because field cores from FM 649 had almost 11 percent air voids.

Among these construction projects, US 87, SH 21, and IH 35 performed very well in the Hamburg tests with both lab and field samples. US 87 Pattern 2 field sample performed slightly worse than Pattern 1. This can be attributed to the difference in percent air voids because US 87 Pattern 2 had almost 2 to 3 percent higher air voids than Pattern 1. The effect of the change of the compaction pattern on rutting of cores from SH 21 project was clear. Cores extracted from Pattern 2 performed better than the corresponding ones in compaction Pattern 1. The average percent of air voids in the test

samples from both patterns were comparable. It is believed that the air void structure in Pattern 2 provided better resistance to rutting. The field cores from Pattern 2 had less percent of air void at the top part compared with the bottom one as indicated in [Figure 4-23](#) in [Chapter 4](#). These results agree with project FM 649. All cores from compaction Pattern 2 showed that the top part had less air voids than the bottom part. The Hamburg results revealed that compaction Pattern 2 performed slightly better than compaction Pattern 1 ([Table 5-2](#)). It seems that having a lower percent of air void at the top might resist rutting.

SH 36 samples (both lab and field) performed relatively poorly. US 259 field samples passed the TxDOT criteria, and it was comparable to the corresponding lab samples compacted at a 2.0° gyratory angle. However, samples compacted at a 1.25° gyratory angle barely failed TxDOT criteria of maximum 12.5 mm rut depth at 15,000 cycles for mixtures with PG 70-22 binder.

In project US 259, the Hamburg results presented in [Table 5-2](#) demonstrate that the field cores taken from the left wheel path performed better than the cores extracted from the right wheel path. The field cores taken from the right wheel path had higher percent of air void than the cores from the left wheel path.

The IH 35 SMA mixture field sample passed TxDOT criteria. On the other hand the US 281 SMA mixture failed very poorly. Visual observation of these samples shows that there was not much aggregate interlock in US 281 samples. Overall the results indicate that the percent air voids is a critical factor in affecting the relationship between lab and field rutting results. The compaction angle has only a slight difference on the Hamburg rut depth results. [Figures 5-2](#) through [5-6](#) show the Hamburg test results of laboratory and field compacted samples from several different highway projects.

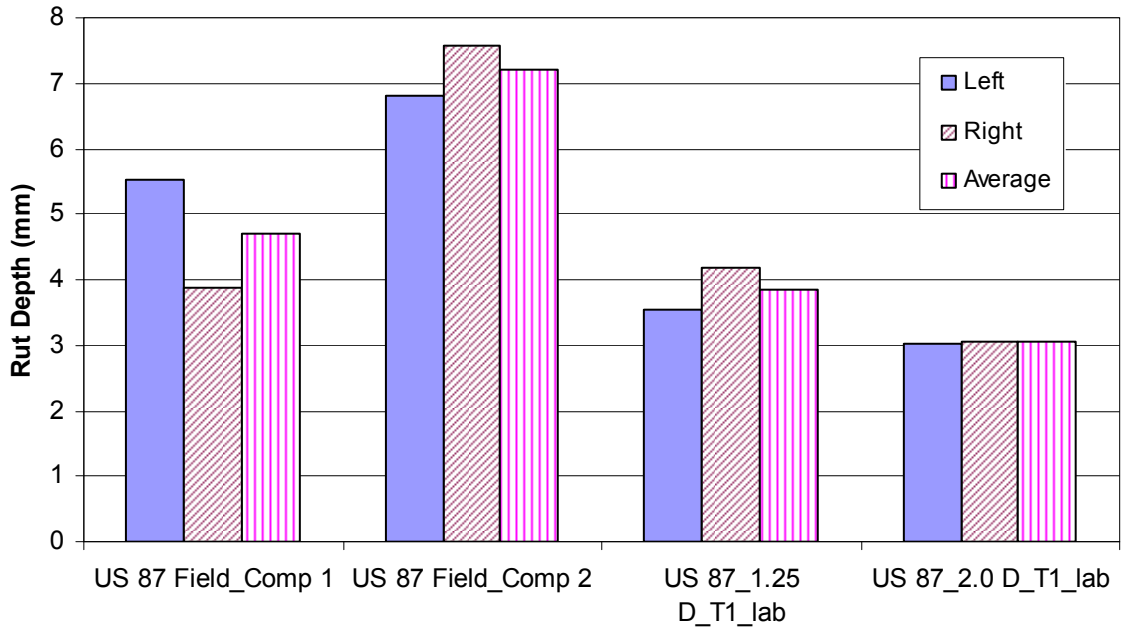


Figure 5-2. Hamburg Test Results with Samples from US 87.

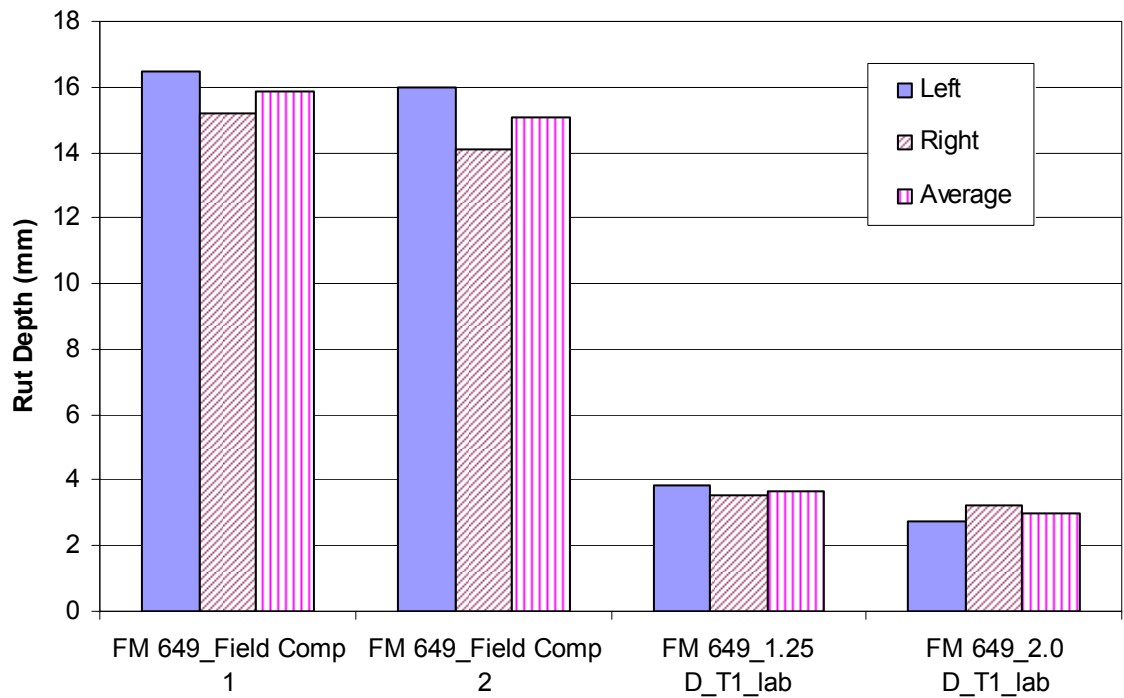


Figure 5-3. Hamburg Test Results with Samples from FM 649.

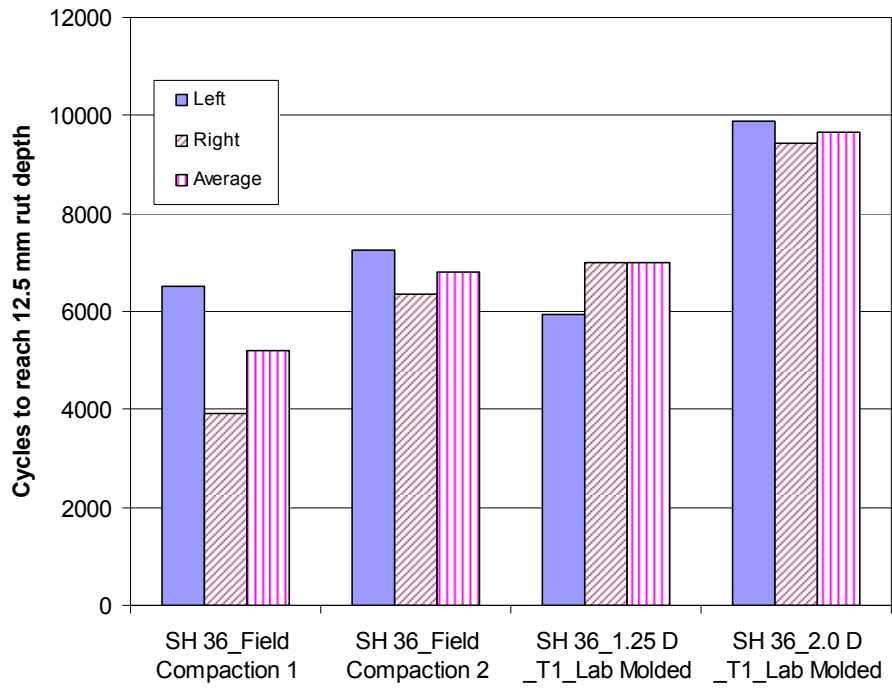


Figure 5-4. Hamburg Test Results with Sample from SH 36.

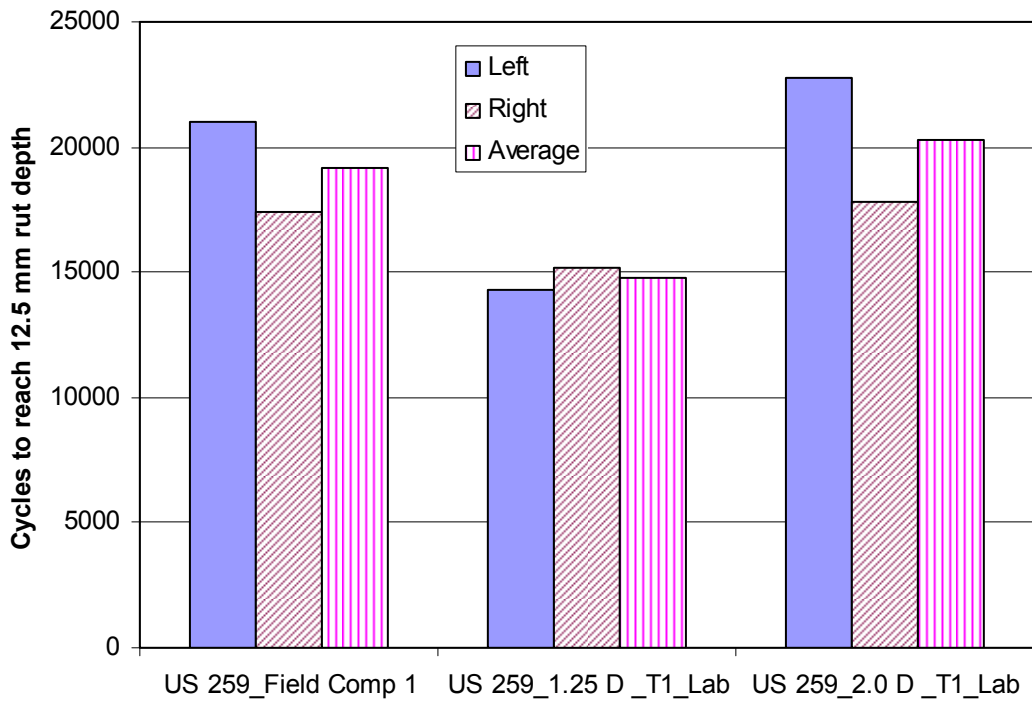


Figure 5-5. Hamburg Test Results with Sample from US 259.

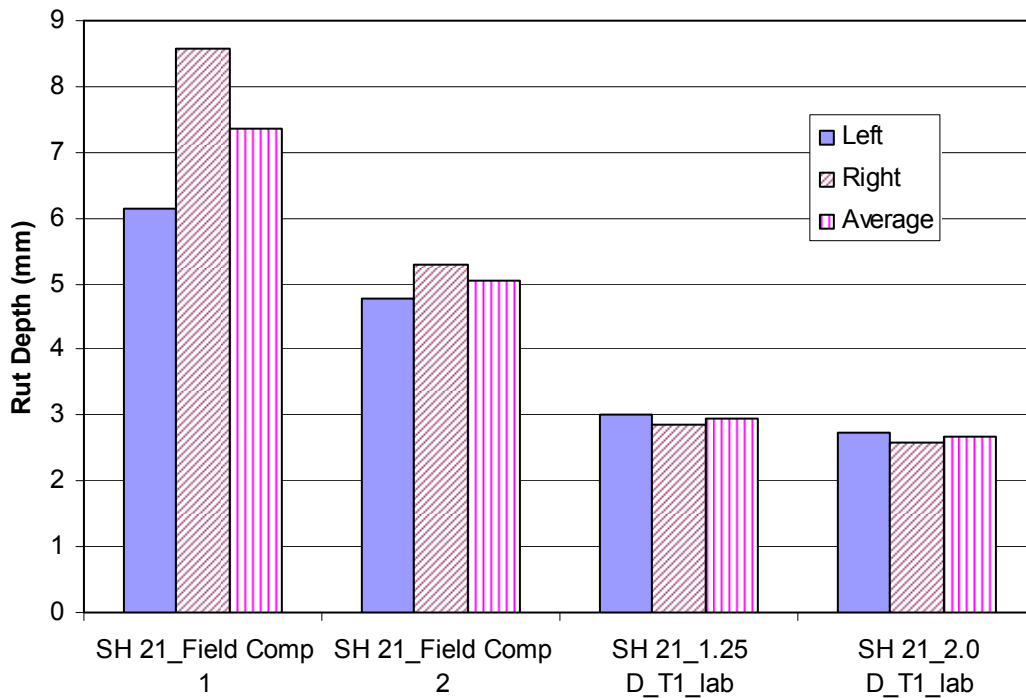


Figure 5-6. Hamburg Test Results with Sample from US 21.

PERMEABILITY TEST

Permeability tests were conducted on field and gyratory compacted samples. This test was conducted following ASTM Standard D5084-03 “Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter.” In some cases, field cores had to be saw cut in order to separate them from the underlying layer or seal coat at the bottom. Researchers believe that during saw cutting sufficient heat is produced to melt the binder, which may ultimately seal some voids.

In general, field samples obtained near longitudinal joints had higher permeability than the cores obtained from inside the lane. Figures 5-7 through 5-12 show the permeability test results from SH 36, FM 649, US 87, SH 21, US 259, and IH 35 projects. Field samples from FM 649 had higher permeability than gyratory compacted samples. This is attributed to the fact that samples from this road had about 4 percent air voids more than the lab samples. On the contrary, the field samples from SH 36 and US 87 had

a much lower permeability than corresponding lab compacted samples. The air voids of field samples from both roads were close to lab air voids. The probable reason could be the saw cutting of field samples from SH 36 and US 87. Field samples from FM 649 were not saw cut at the bottom. In general, there is no trend indicating that permeability in gyratory specimens compacted at a certain angle are higher than the other.

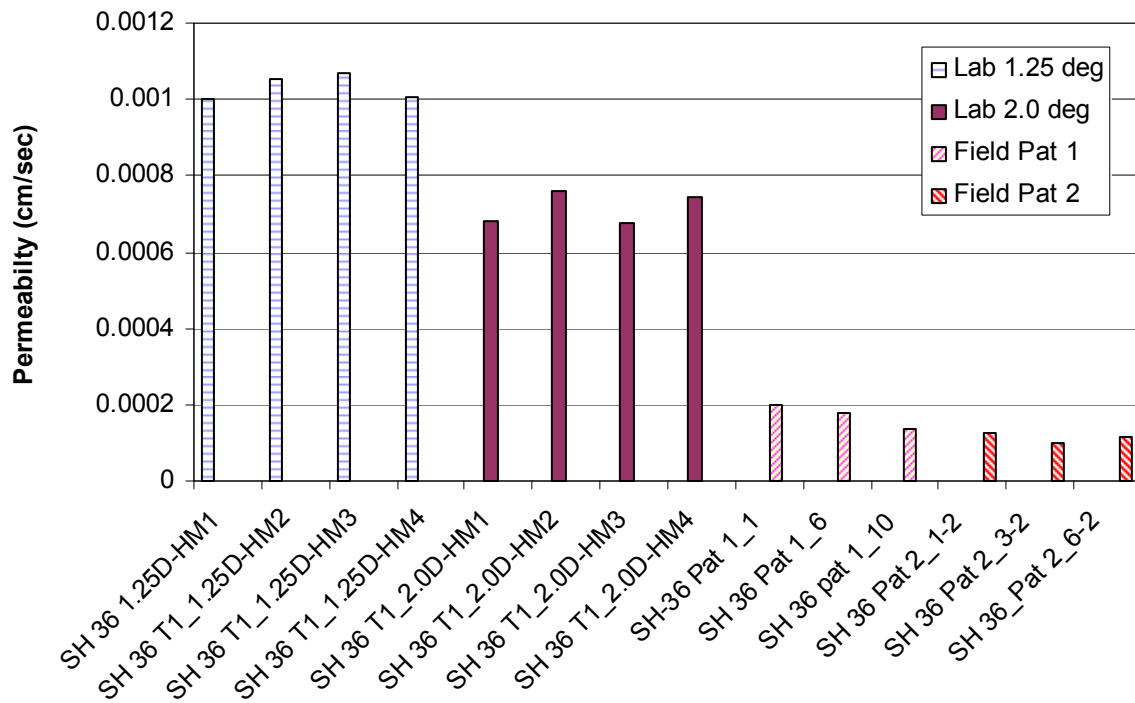


Figure 5-7. Permeability Test Results with SH 36 Samples.

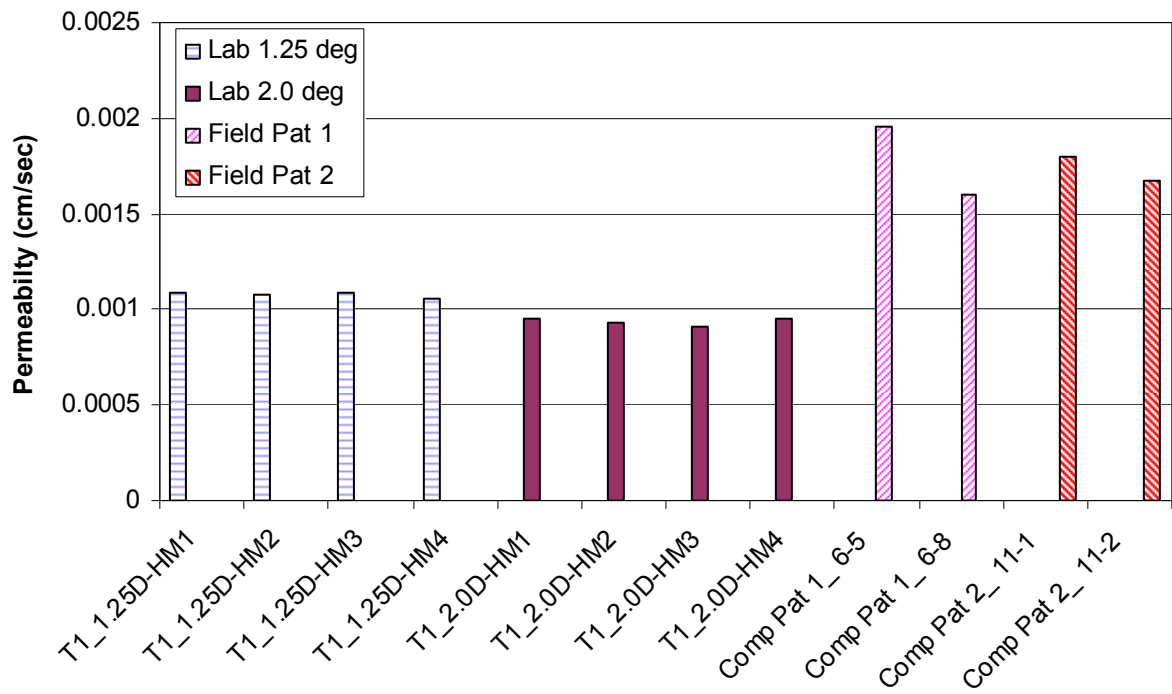


Figure 5-8. Permeability Test Results with FM 649 Samples.

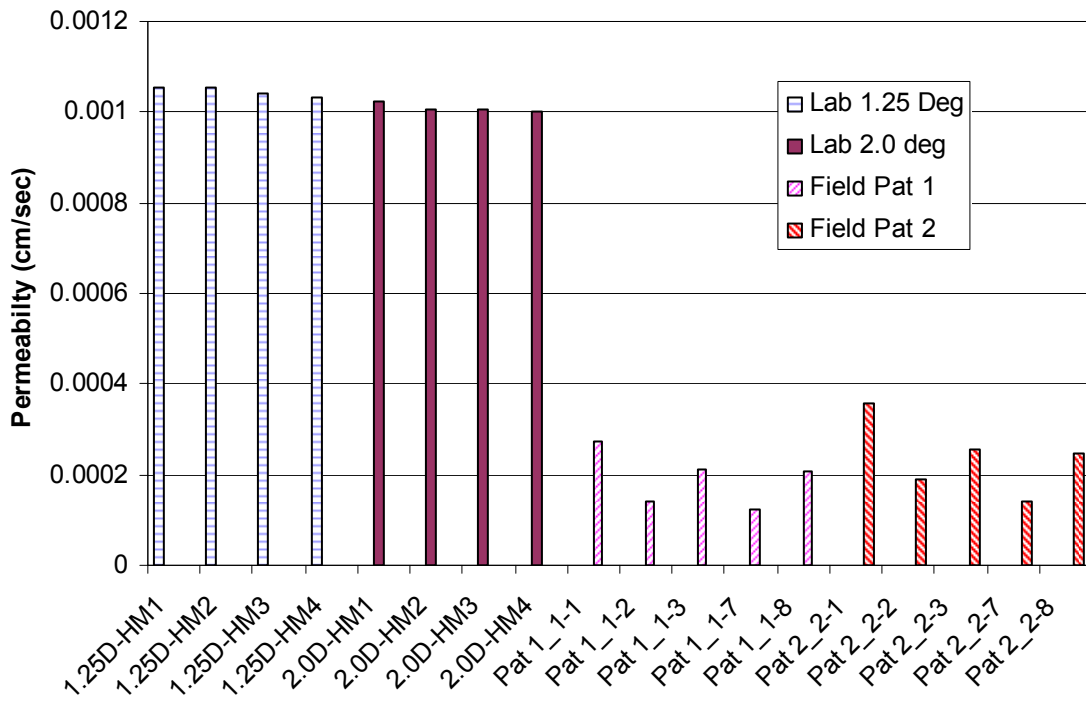


Figure 5-9. Permeability Test Results with US 87 Samples.

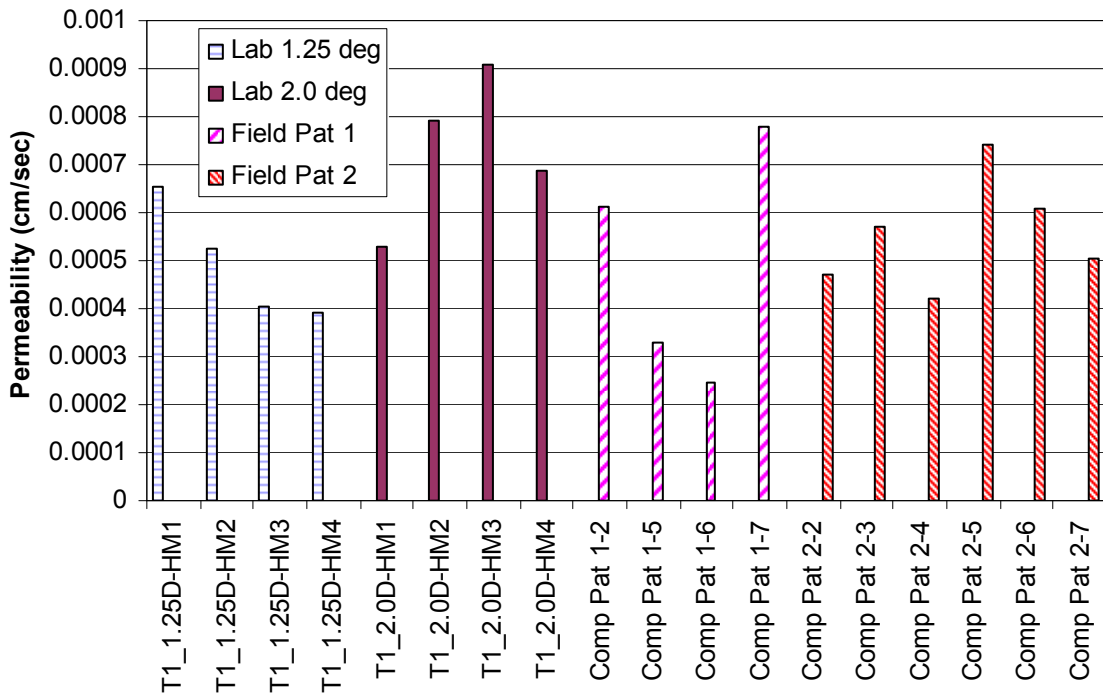


Figure 5-10. Permeability Test Results with SH 21 Samples.

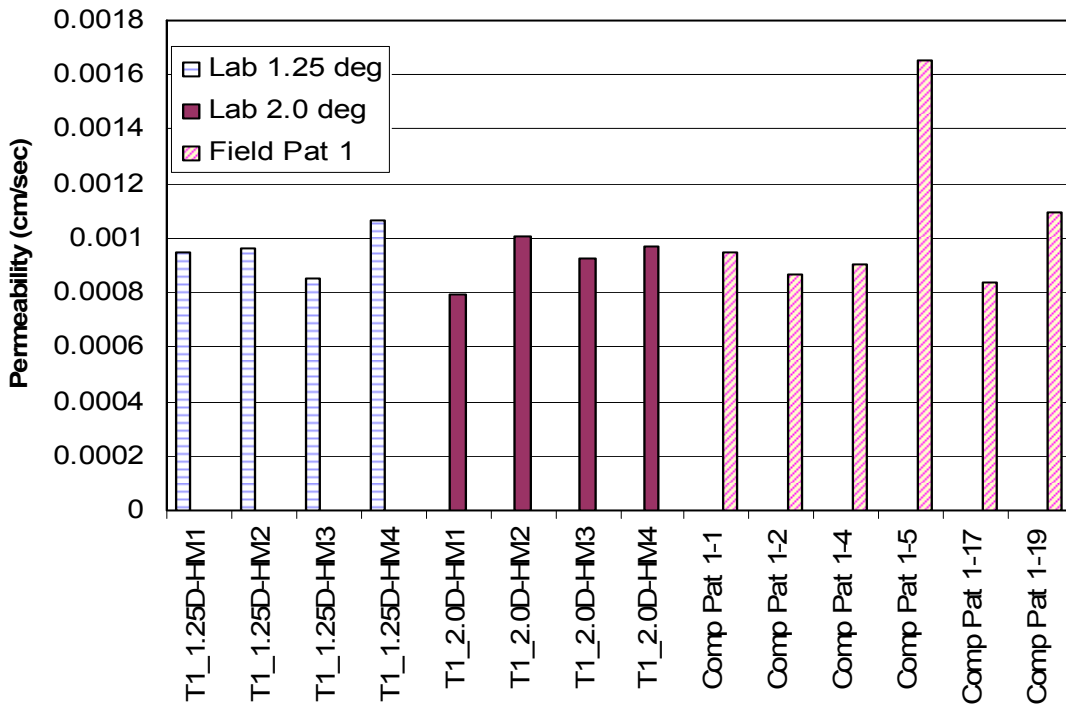


Figure 5-11. Permeability Test Results with US 259 Samples.

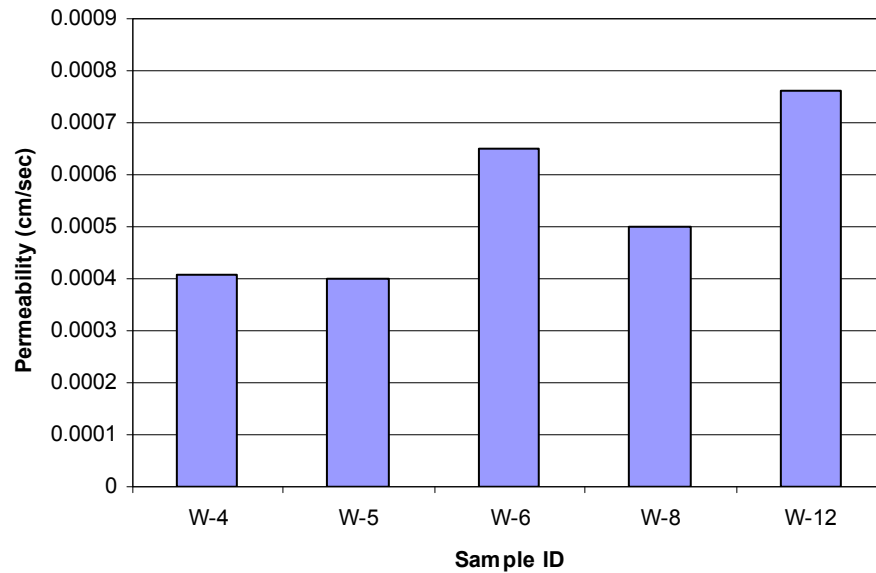


Figure 5-12. Permeability Test Results with IH 35 Field Samples.

OVERLAY TEST RESULTS

Overlay tests were conducted on both field and lab compacted samples following the recommendations by Zhou and Scullion and recently adopted TxDOT standard Tex-248-F “Overlay Test.” [Figure 5-13](#) depicts the key parts of the overlay apparatus. This overlay tester consists of two steel plates; one is fixed, and the other moves horizontally to simulate the opening and closing of joints or cracks in the old pavements beneath an overlay. The load is applied in a cyclic, triangular waveform with constant magnitude. The overlay test is run at room temperature (77°F) in a controlled displacement mode at a loading rate of one cycle per 10 seconds with a maximum displacement of 0.025 inch until failure occurs ([Zhou and Scullion, 2003](#)).

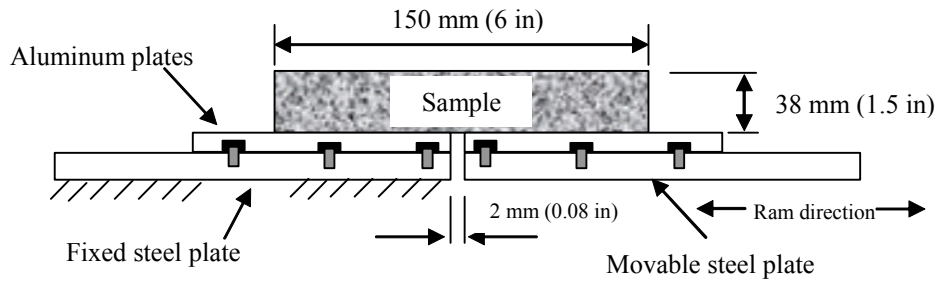


Figure 5-13. Schematic Diagram of TTI Overlay Tester System.

Lab samples were compacted at 1.25° and 2.0° angles of gyrations with a Superpave gyratory compactor, and field samples were obtained from each compaction pattern by coring. Prismatic specimens ($6 \text{ inch} \times 3 \text{ inch} \times 1.5 \text{ inch}$) were sawed from SGC compacted or field cores before testing. Lab samples were prepared for testing only for those highways where the researchers were able to change compaction pattern. Test results from field samples and lab compacted samples are presented in [Table 5-3](#) and [Table 5-4](#), respectively.

Field cores from SMA mixture in IH 35 performed very well, while the SMA mixture in US 281 did not ([Table 5-3](#)). The compaction pattern does not seem to influence the overlay testing results for the mixtures evaluated in this study. Lab compacted samples for FM 649, SH 36, and US 87 failed at a very low number of load cycles regardless of compaction angle. US 259 and SH 21 lab samples performed very good and reasonably well, respectively. For a given mixture, the compaction angle (1.25° or 2.0° angle) did not make much difference for overlay testing.

Table 5-3. Overlay Test Results with Field Compacted Samples.

Highway	Compaction Pattern	Number of Cycles at Failure			
		Spec 1	Spec 2	Spec 3	Avg.
FM 649	1	3	1	N/A	2
	2	2	1	N/A	2
SH 36	1	1	6	4	4
	2	7	11	6	8
US 87	1	205	61	31	99
	2	38	31	78	49
IH 35	N/A	900+	600+	600+	700+
US 281	N/A	86	24	N/A	55
US 259	1	34	71	110	72
SH 21	1	7	8	4	6
	2	14	26	13	18

Table 5-4. Overlay Test Results with Lab Compacted Samples.

Highway	Angle of Gyration	Number of cycles at Failure			
		Spec 1	Spec 2	Spec 3	Avg.
FM 649	1.25°	2	1	1	1
	2.00°	1	1	1	1
SH 36	1.25°	2	3	2	2
	2.00°	3	2	3	3
US 87	1.25°	2	2	1	2
	2.00°	2	2	1	2
US 259	1.25°	776	650	230	552
	2.00°	800	467	326	531
SH 21	1.25°	171	63	209	148
	2.00°	166	168	138	158

SUMMARY OF FINDINGS

Based on three laboratory testings of lab compacted specimens and field cores, the following findings can be summarized:

- In general, laboratory specimens compacted using a 2.0° gyratory angle performed slightly better in Hamburg tests than specimens compacted using a 1.25° gyratory angle.
- Overlay test results did not show any difference among the lab prepared specimens compacted using a 1.25° or 2.0° angle.
- There is no trend indicating that permeability in gyratory specimens is influenced by the angle of gyration.
- Laboratory compacted samples had comparable rut depth to field cores when percent air voids was similar.
- There was a slight influence of compaction pattern on the Hamburg results. However, there was no trend indicating an influence of compaction pattern on the overlay testing results or permeability results. The variability in the overlay testing results might have overshadowed the influence of compaction pattern or resistance to fracture as measured using the overlay tester.
- Hamburg results were found to be more related to the average percent of air void rather than the air void structure. Field cores with a less average percent of air void performed better than the ones that had a higher percent of air void.

CHAPTER 6

THE EFFECT OF THE AIR VOID DISTRIBUTION ON THE OVERLAY TEST AND HAMBURG RESULTS

EFFECT OF THE AIR VOID DISTRIBUTION ON THE OVERLAY TEST

Introduction

In this section, the effect of the air void distribution along the depth of the laboratory samples on the performance of these samples was evaluated using the overlay test. The overlay tester system is described in [Chapter 5](#). Gyratory specimens with 150 mm height and 150 mm in diameter were prepared. The X-ray CT system described in [Chapter 2](#) was utilized to capture the air void distribution along the height of these samples. The samples were cut into short samples of about 37.5 mm height in such a way that the cut specimens had similar average percent air voids but different air void distributions. The cut samples were classified into five groups according to the air void distribution.

Materials and Test Procedure

SGC specimens were fabricated using crushed river gravel aggregates with PG 64-22 binder. The aggregate blend includes 18 percent of Fordyce C rock, 57 percent of Fordyce D/F rock, 10 percent of manufactured sand, 14 percent of limestone screening, and 1 percent of lime. The gradation and the proportions of each material are shown in [Table 6-1](#). The asphalt content was 5.6 percent by weight of the mixture.

X-ray CT was utilized to scan the test samples in order to capture the air void distribution along the depth of the samples. The average percent of air void was measured using the Saturated Surface Dry and CoreLok procedures. The X-ray results were used to cut the specimens into smaller ones. The cut samples had similar average percent air voids and different air void distributions. Each cut specimen was 150 mm in diameter and about 37.5 mm in height and had 7.5 ± 0.50 percent air voids. The cut samples were classified into five groups according to the distribution of air voids. The overlay tester was used to test the samples according to the parameters that were previously discussed

in Chapter 5. The failure criterion in this test was taken to be the number of cycles at which a reduction of 7 percent of the initial load was achieved.

Table 6-1. Aggregate Gradation

Sieve Size (mm)	Fordyce C		Fordyce D/F		Man. Sand		limestone Scr.		Lime		Cumulative Total (%)
	Pass (%)	Total (%)	Pass (%)	Total (%)	Pass (%)	Total (%)	Pass (%)	Total (%)	Pass (%)	Total (%)	
19.000	100.0	18.0	100.0	57.0	100.0	10.0	100.0	14.0	100.0	1.0	100.0
12.500	70.0	12.6	100.0	57.0	100.0	10.0	100.0	14.0	100.0	1.0	94.6
9.500	10.0	1.8	95.0	54.2	100.0	10.0	100.0	14.0	100.0	1.0	81.0
4.750	5.0	0.9	50.0	28.5	100.0	10.0	100.0	14.0	100.0	1.0	54.4
2.360	3.0	0.5	15.0	8.6	99.0	9.9	92.0	12.9	100.0	1.0	32.9
1.180	2.5	0.5	5.0	2.9	79.0	7.9	72.0	10.1	100.0	1.0	22.4
0.600	2.0	0.4	4.0	2.3	49.0	4.9	54.0	7.6	100.0	1.0	16.2
0.300	1.5	0.3	3.0	1.7	23.0	2.3	41.0	5.7	100.0	1.0	11.0
0.150	1.0	0.2	2.0	1.1	7.0	0.7	33.0	4.6	100.0	1.0	7.6
0.075	0.5	0.1	1.0	0.6	3.0	0.3	25.0	3.5	100.0	1.0	5.5

Test Results and Discussion

The air void distributions are presented in Figures 6-1 through 6-5 for the different cases. Figure 6-1 shows the air void distribution for case number 1 which is uniform across the sample height. Figure 6-2 shows the air void distribution for case number 2 in which the top part of the sample has a higher percent of air void than the bottom part. Case number 3 is similar to case 2 except that the air void distribution is more uniform at the bottom as shown in Figure 6-3. Figures 6-4 and 6-5 represent the air void distribution for cases 4 and 5, respectively. Both case 4 and 5 have less percent at the top part than the bottom one. However, the air void distribution at the top is more uniform in case 5 than the one at top in case 4 as shown Figure 6-5.

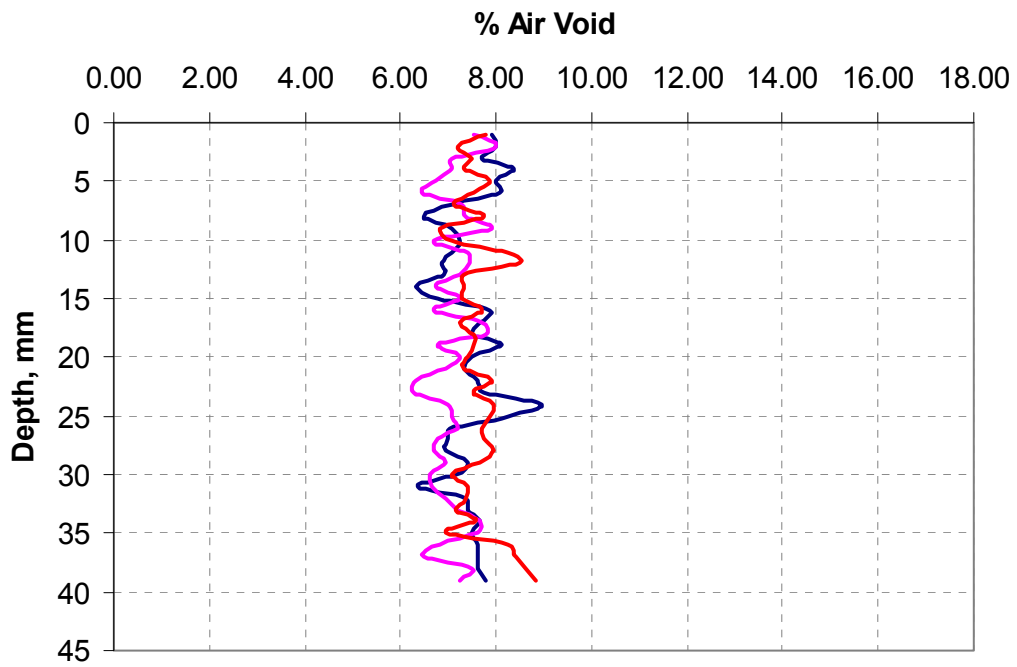


Figure 6-1. Air Void Distribution across the Depth of the Samples for Case 1.

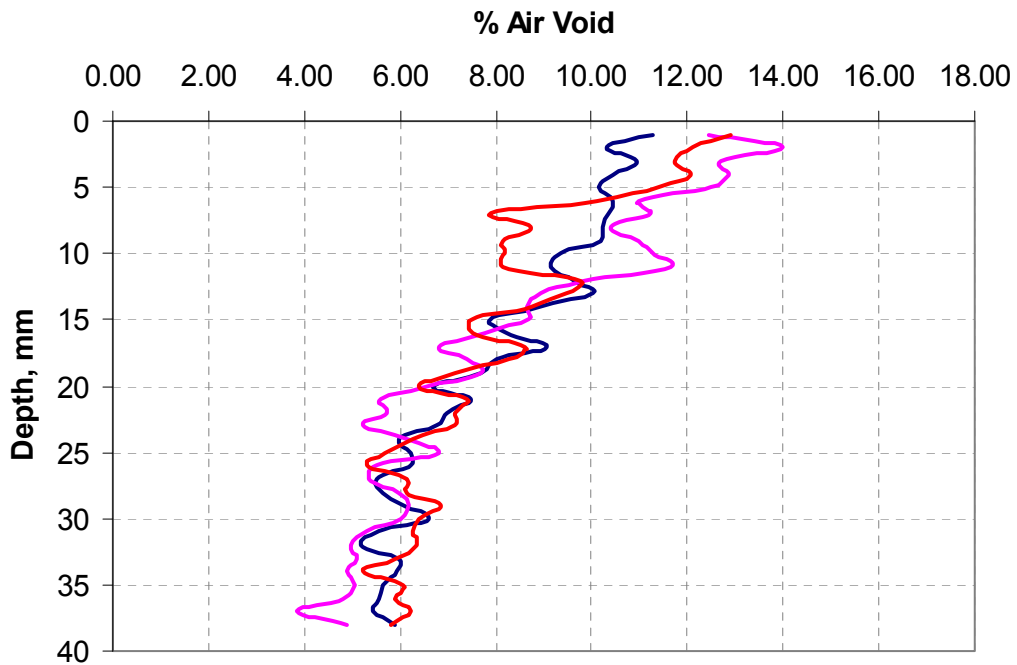


Figure 6-2. Air Void Distribution across the Depth of the Samples for Case 2.

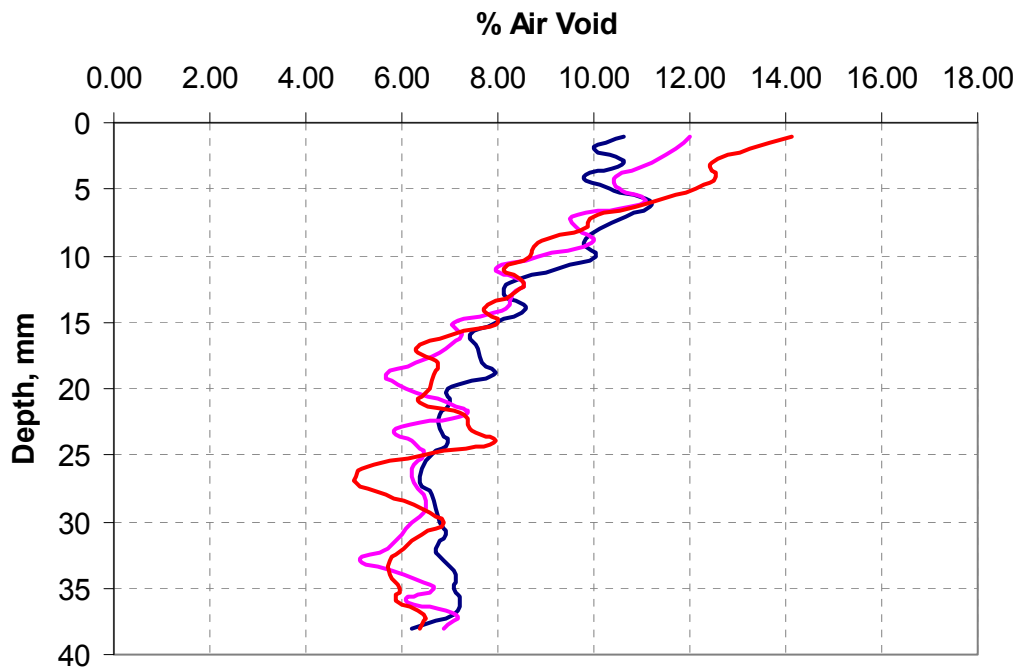


Figure 6-3. Air Void Distribution across the Depth of the Samples for Case 3.

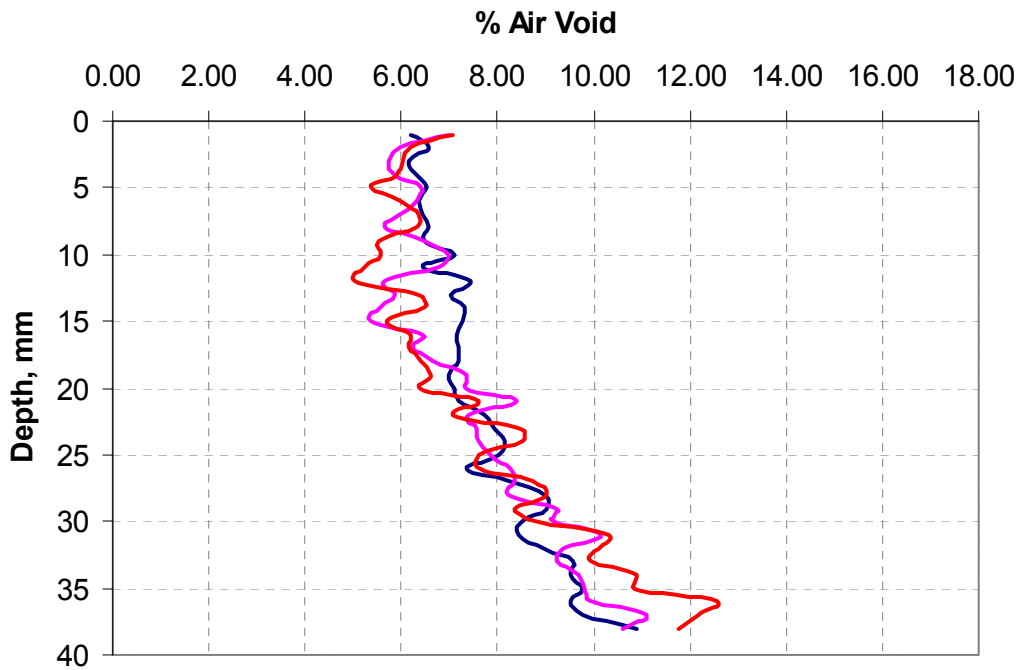


Figure 6-4. Air Void Distribution across the Depth of the Samples for Case 4.

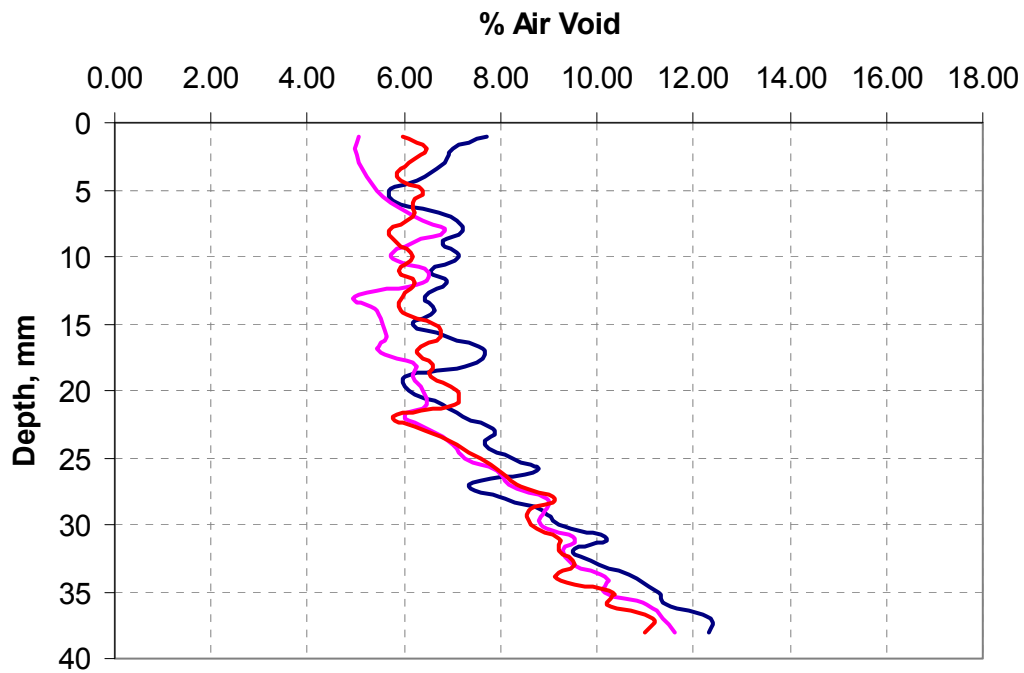


Figure 6-5. Air Void Distribution across the Depth of the Samples for Case 5.

The overlay test results are shown in Figures 6-6 and 6-7. Given the high variability in four of the five cases, it is possible to indicate that air void distribution has a significant effect on the overlay test average results. The results clearly show that case number 1 with a uniform air void distribution had less variation in the number of cycles to failure than all other cases.

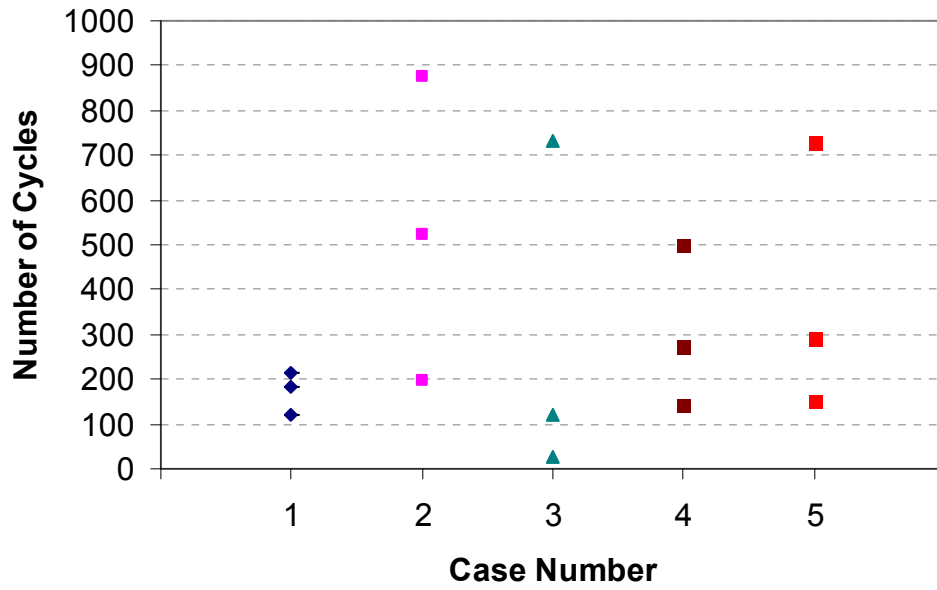


Figure 6-6. Overlay Test Results.

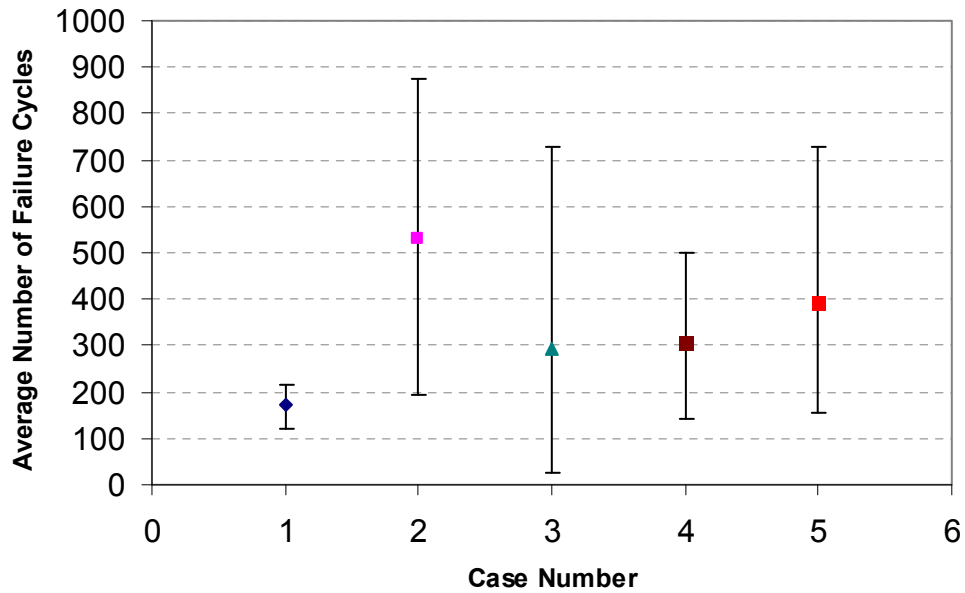


Figure 6-7. Average Number of Failure Cycles.

EFFECT OF THE AIR VOID DISTRIBUTION ON THE HAMBURG TEST

In this section, the effect of the air void distribution on the Hamburg results will be evaluated. The Hamburg results for the field cores as discussed in [Chapter 5](#) were subjected with the average percent air void in the test cores. The effect of the air void distribution on the Hamburg results was not easy to evaluate for the following reasons:

- The field cores have a dissimilar percent of air voids, which make it difficult to correlate the Hamburg results with the air void structure without considering the effect of the percent of air voids.
- The field cores, which have similar percent air voids, did not have the similar air void distribution in all the projects in this study.

For the previous two reasons, it was difficult to get a comprehensive conclusion for all the projects. To overcome this problem, a side study is initiated to eliminate the dissimilarity of the percent of the air voids and the average air void distribution. This study will include testing a number of laboratory samples fabricated in such a way to induce different air void distributions along the height of the samples. These samples will contain 7 percent air voids \pm 0.50 percent air voids. US 259 mix will be used in this study as it has experienced a considerable amount of the rutting.

The test SGC samples are 100 mm (4-inch) height and 150 mm (6-inch) diameter. X-ray CT will be used to capture the air void distribution along the height of the samples. The samples will be cut at specific locations into 63.5 mm (2.5 inch) samples to induce different air void distributions along the height of the samples. Four cases will be considered. Three cases (63.5 mm height) will be cut from long samples (100 mm height), and one case (case 4) will be compacted at 63.5 mm directly such as the conventional way. The anticipated percent air voids for each case is shown in [Figure 6-8](#). The detailed results will be reported in the 5261-2 research report.

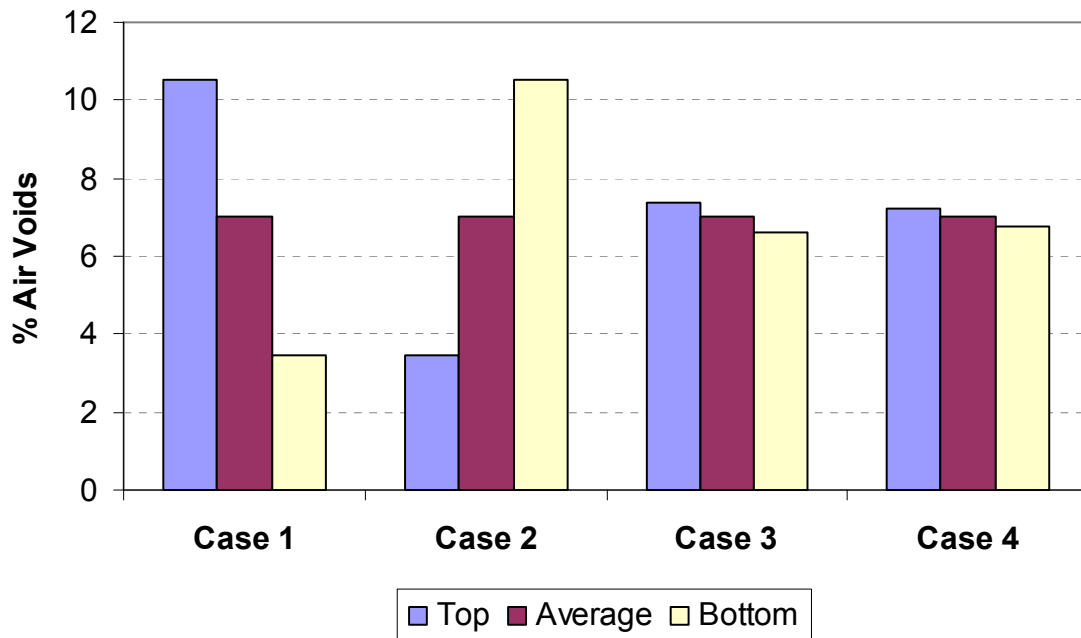


Figure 6-8. The Anticipated Average, Top, and Bottom Percent of Air Voids for Different Cases.

CHAPTER 7

THE EFFECT OF THE COMPACTION TEMPERATURE ON THE AIR VOID DISTRIBUTION

INTRODUCTION

Several studies demonstrated that the air void distribution in Superpave gyratory specimen is nonuniform; the top and bottom have more air voids than the middle. It has been postulated that this is caused by the restriction of aggregate movement close to the plates compared with the middle and the faster rate of heat loss at the top and bottom. Loss of heat causes the mix to become less mobilized which causes higher percent air voids. In order to evaluate the influence of temperature of air void distribution, an experiment was conducted in which the temperatures of a top plate, a base plate, and a mold in the SGC were varied. Consequently, X-ray CT was used to measure air void distribution, and analysis was conducted to examine the uniformity of air void distribution.

EXPERIMENTS

Laboratory SGC samples 6.5 inches (165 mm) height by 6 inches (150 mm) diameter were prepared using two binders PG 76-22 and PG 64-22 and crushed river gravel aggregate. Temperatures of the top plate, base plate, and mold were varied according to the cases shown in [Table 7-1](#). Three specimens were evaluated from each case.

Table 7-1. Cases Analyzed for Varying Plates and Mold Temperatures.

	Temperature of Mold	Temperature of Base Plate	Temperature of Upper Plate	Temperature of Mix
Case 1	T _c	T _c	30 °C	T _c
Case 2	T _c + 30 °C	T _c + 30 °C	30 °C	T _c
Case 3	T _c	T _c	T _c	T _c

Note: T_c = the compaction temperature

The temperature distribution along the height of asphalt specimens was measured using a setup that consisted of a two-piece infrared temperature measurement system with a miniature sensing head and electronics. A schematic view of the temperature measurement system is shown in [Figure 7-1](#).

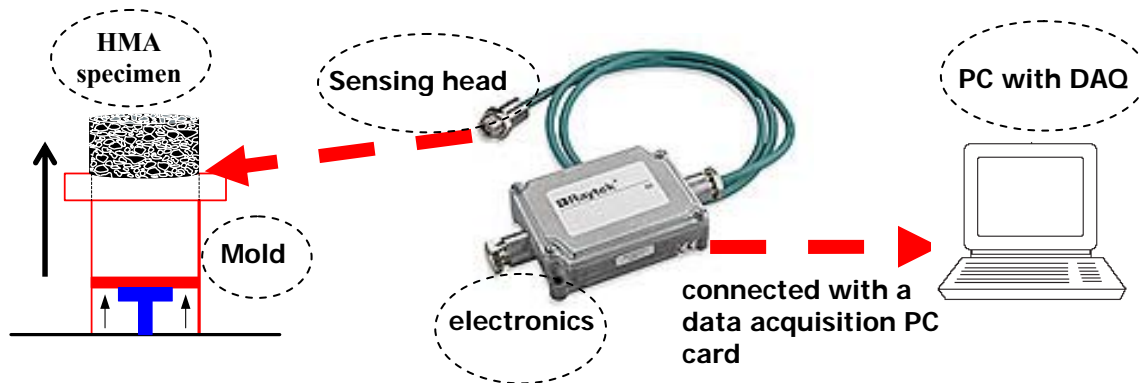


Figure 7-1. A Schematic View of the Temperature Measurement System.

The miniature infrared sensor is a noncontact device that can be used to measure temperature from a distance. This device measures the amount of energy emitted from a certain object and then converts it to a signal. The sensor consists of two pieces. The first piece is a miniature sensing head and the second piece is a separate electronics box. The range of temperature that can be measured by these sensors is 40°C to 600°C. The sensing head is connected to the electronics box. The accuracy of the system is $\pm 1^\circ\text{C}$. The system has 10:1 optical resolution which is expressed as a ratio of the distance to the measurement spot divided by the diameter of the spot. The system has a response time of 150 ms which is as fast or faster than many advanced systems.

Three miniature infrared sensors were employed in this experiment. First, the sensors were inserted into a 10 inch (25 cm) diameter PVC pipe as shown in [Figures 7-2a](#) and [7-2b](#). The PVC pipe was used as a holder for the infrared sensors. The head of the infrared sensors was inside the holder ([Figure 7-2b](#)). Right after the compaction and before extraction of a specimen from the compaction mold ([Figure 7-2c](#)), the sensors'

holder was placed around the compaction mold and the test sample was pushed out of the compaction mold as shown in Figure 7-2d.



(a)



(b)



(c)



(d)

Figure 7-2. Experimental Setup.

The height of the bottom sensor was adjusted to be at the end of the height of the test sample when the sample was pushed all the way out from the compaction mold. The sensor at the middle was 2 inches (5 cm) away from the bottom sensor, and the distance between the middle sensor and the top one was 2 inches (5 cm). The sensor at the bottom

recorded the temperature profile for the full height of the sample while the sensors at the top and in the middle measured the surface temperature for the top 4 inches (10 cm) and 2 inches (5 cm), respectively. The temperature measurements of the top and middle sensors were used to validate the results from the bottom sensor.

TEMPERATURE RESULTS

The temperature measurements of the three cases presented in [Table 7-1](#) are presented in [Figures 7-3](#) through [7-8](#).

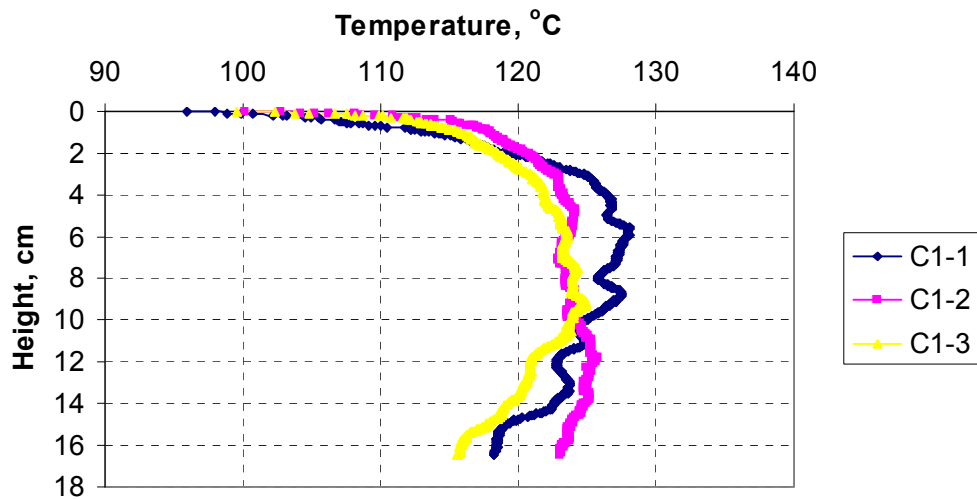


Figure 7-3. The Temperature Profile along the Height of the Specimen for Case 1 (PG 76-22).

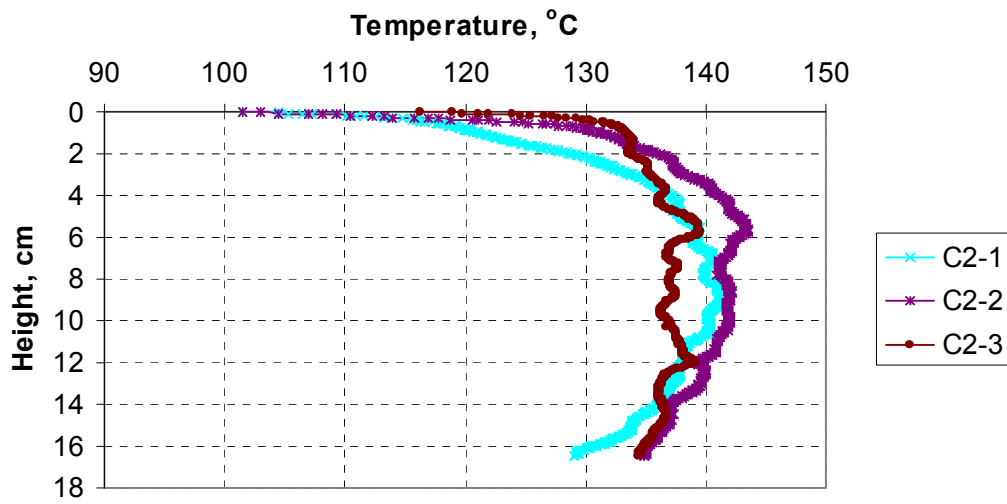


Figure 7-4. The Temperature Profile along the Height of the Specimen for Case 2 (PG 76-22).

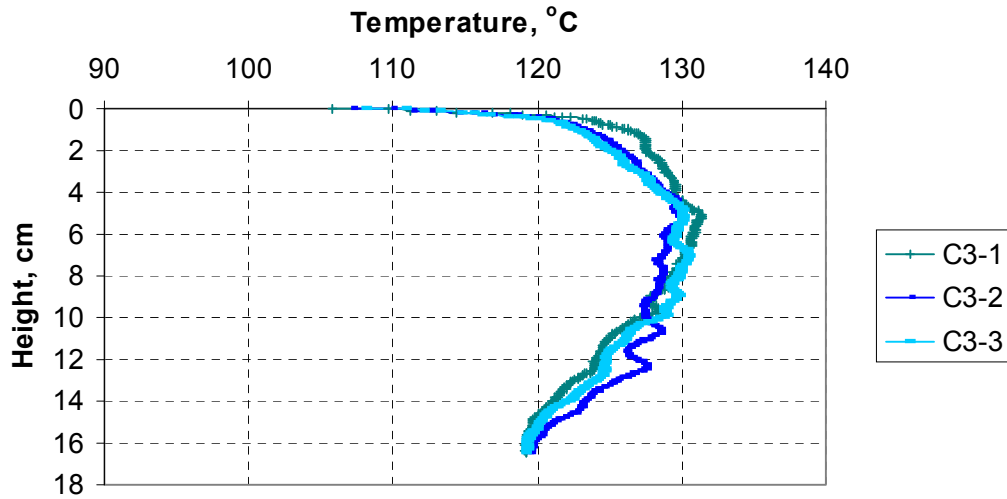


Figure 7-5. The Temperature Profile along the Height of the Specimen for Case 3 (PG 76-22).

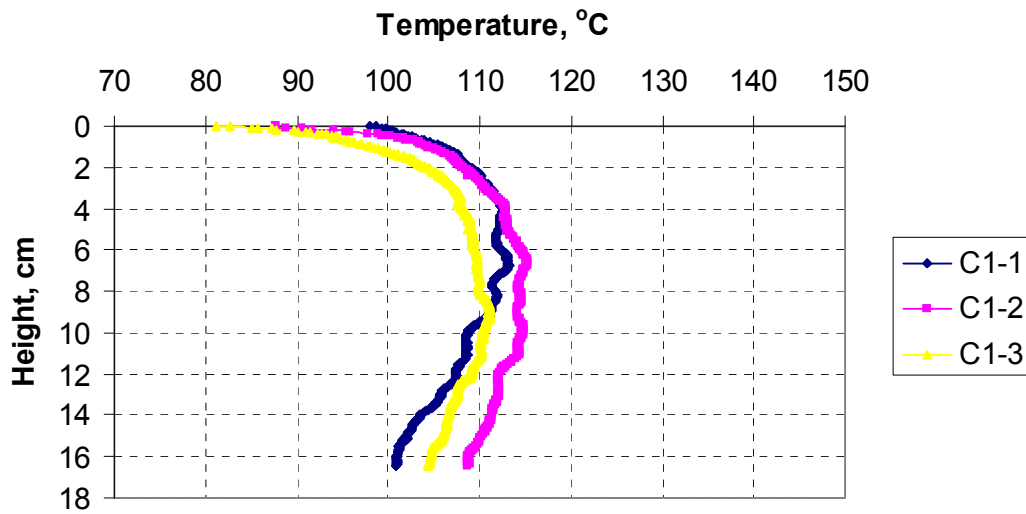


Figure 7-6. The Temperature Profile along the Height of the Specimen for Case 1 (PG 64-22).

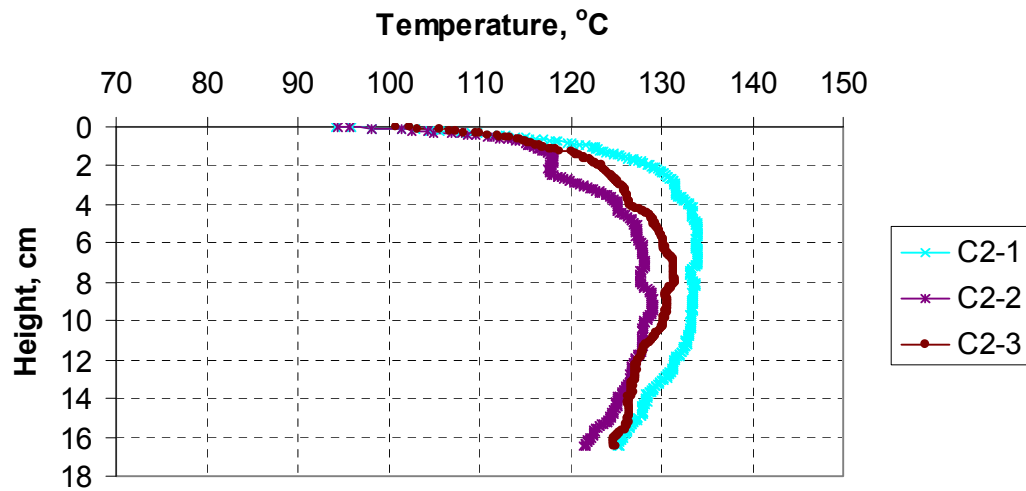


Figure 7-7. The Temperature Profile along the Height of the Specimen for Case 2 (PG 64-22).

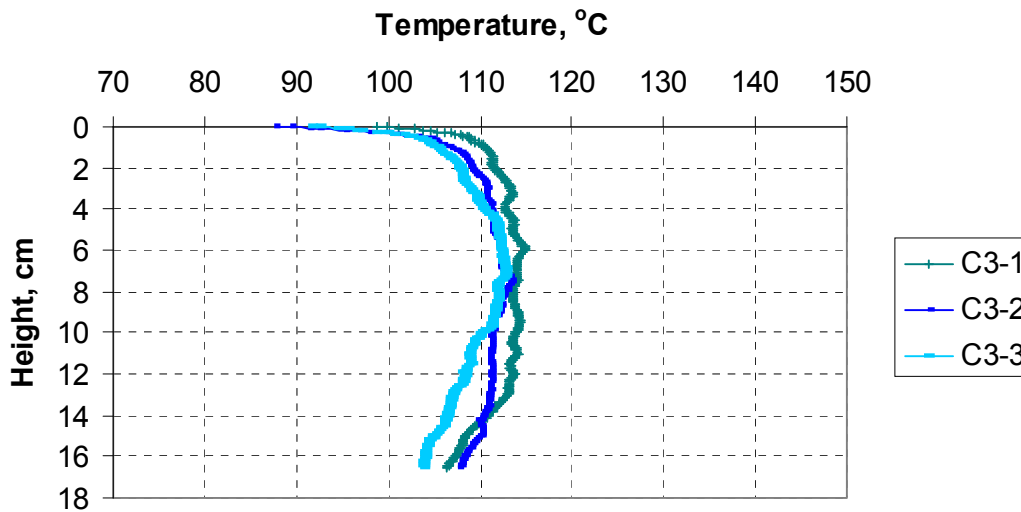


Figure 7-8. The Temperature Profile along the Height of the Specimen for Case 3 (PG 64-22).

It can be seen from Figures 7-3 through 7-8 that different temperature distributions were produced in these cases. The Uniformity Index (UI), which was previously presented in Chapter 4, is calculated for the temperature distribution for different cases. The average UI for each case is presented in Figures 7-9 and 7-10 for binder PG 76-22 and PG 64-22, respectively. It can be seen that the temperature distribution is more uniform, or has less UI in Case 3 for both PG 76-22 and PG 64-22 samples. This means that by heating up the upper plate to the mold and mix temperature produces a uniform temperature along the height of the sample. Case 2 produced the highest UI for both PG 76-22 and PG 64-22 samples. The higher UI is the greater nonuniform distribution of the temperature along the height of the samples.

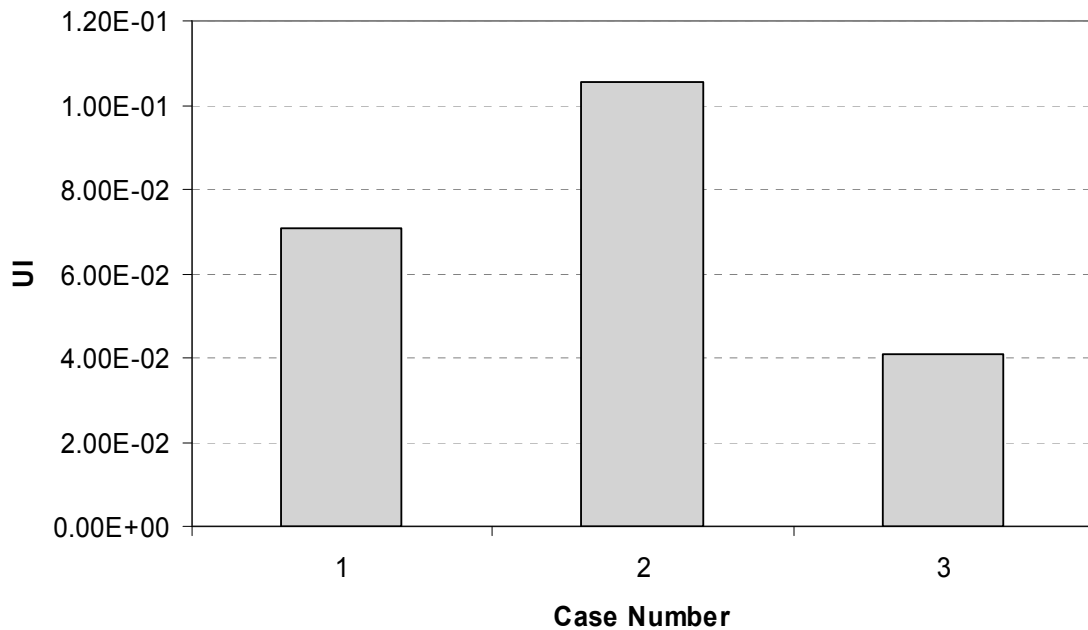


Figure 7-9. Uniformity Index for Temperature Distribution for PG 76-22 Samples.

AIR VOID ANALYSIS

X-ray CT was used to capture the air void distribution along the HMA specimens. An example of air void distribution along the depth is presented in [Figure 7-11](#). The air void distribution was analyzed by dividing the images of a specimen into three regions with equal heights (top, middle or center, and bottom). The percent air voids was calculated for each of the regions using the whole diameter (150 mm diameter) and for a smaller diameter equal to 100 mm. The smaller diameter was used to analyze uniformity across the specimen depth without the influence of air void distribution at the specimen boundary. The average results for the replicates were presented in [Figures 7-12 through 7-15](#). [Figures 7-12 and 7-13](#) show the results for the samples with PG 76-22 binder for the whole diameter (150 mm) and smaller core of 100 mm, respectively.

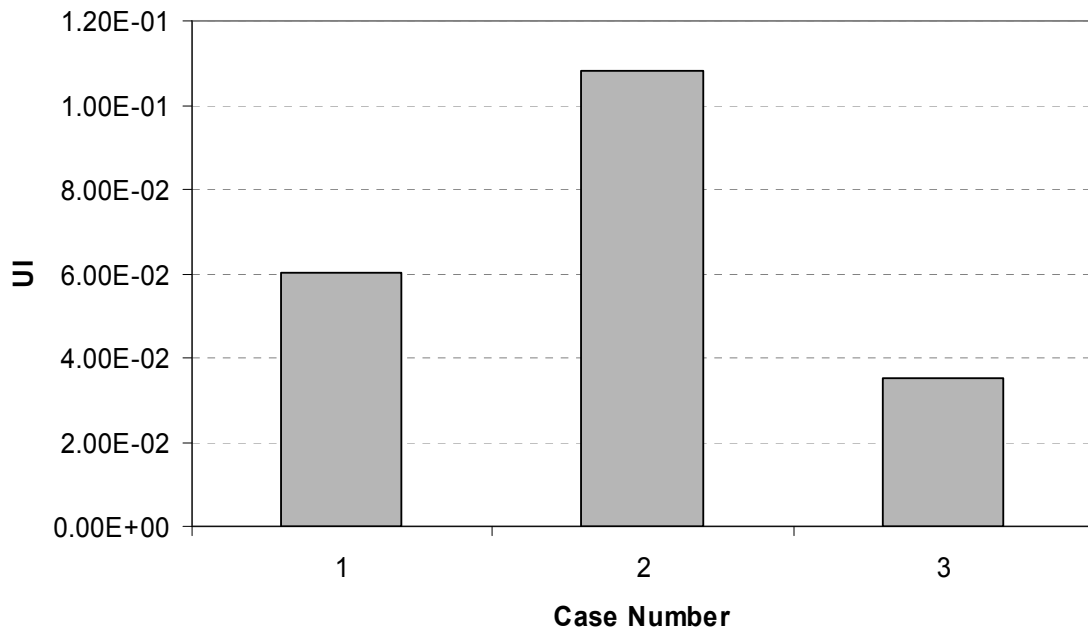


Figure 7-10. Uniformity Index for Temperature Distribution for PG 64-22 Samples.

The results for the samples with PG 64-22 binder were presented in Figures 7-14 and 7-15 for the whole and small diameter, respectively. Specimens for all cases were compacted to similar average percent air voids of about 8.5. These percent air voids values shown in Figures 7-12 through 7-15 did not show trends in terms of the relationships between temperature profiles and percent air voids in different parts of a specimen.

The Uniformity Index (UI) defined in Chapter 4 was used to analyze air void distribution. The UI was calculated for 150 mm diameter and 100 mm diameter images. In addition, the analysis was carried out for images of the whole specimen height and for images that belong to the middle third of the specimen height. The average UI for the replicates from each case for mixes with PG 76-22 are shown in Figures 7-16 through 7-19, and the results for mixes with PG 64-22 are shown in Figures 7-20 through 7-23. The first observation is that the middle part has a smaller UI than the full height. This is consistent with previous findings that the air void distribution tends to be nonuniform toward the top and bottom while the middle part of a specimen tends to be more uniform. It is interesting to note that specimens with PG 64-22 have less UI values

than the PG 76-22 specimens. These results indicate that the compaction effort was more uniformly distributed in the unmodified binder compared with the modified binder. The UI for the middle part for both PG 76-22 and PG 64-22 samples in Case 3 was lower than the corresponding one in Cases 1 and 2. It is believed that the uniformity of the temperature distribution in Case 3 produced a more uniform air void distribution in the middle part of the test samples. The UI results for the full height did not show the same relationship between the UI of air void and temperature for both PG 64-22 and PG 76-22 samples.

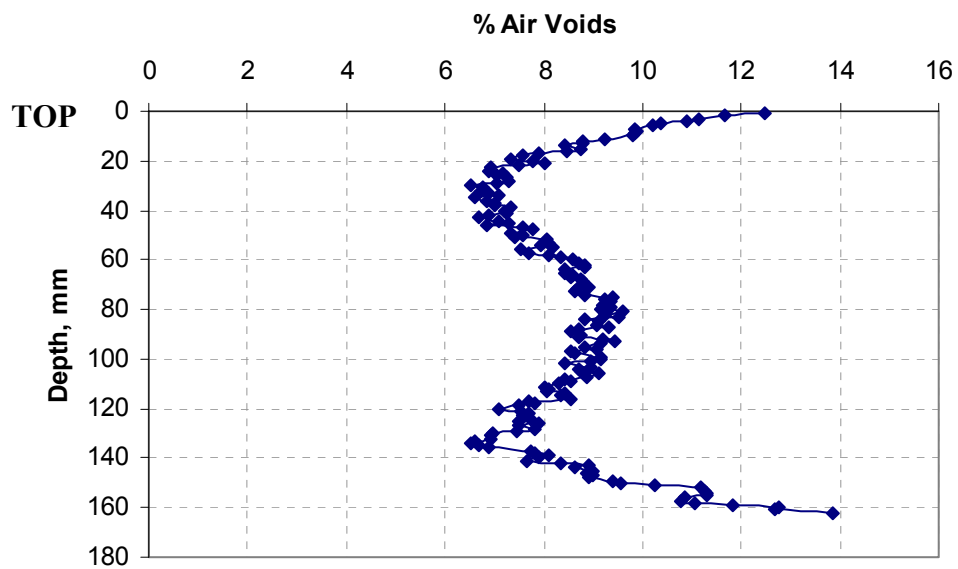


Figure 7-11. The Air Void Distribution along the Height of SGC Specimen.

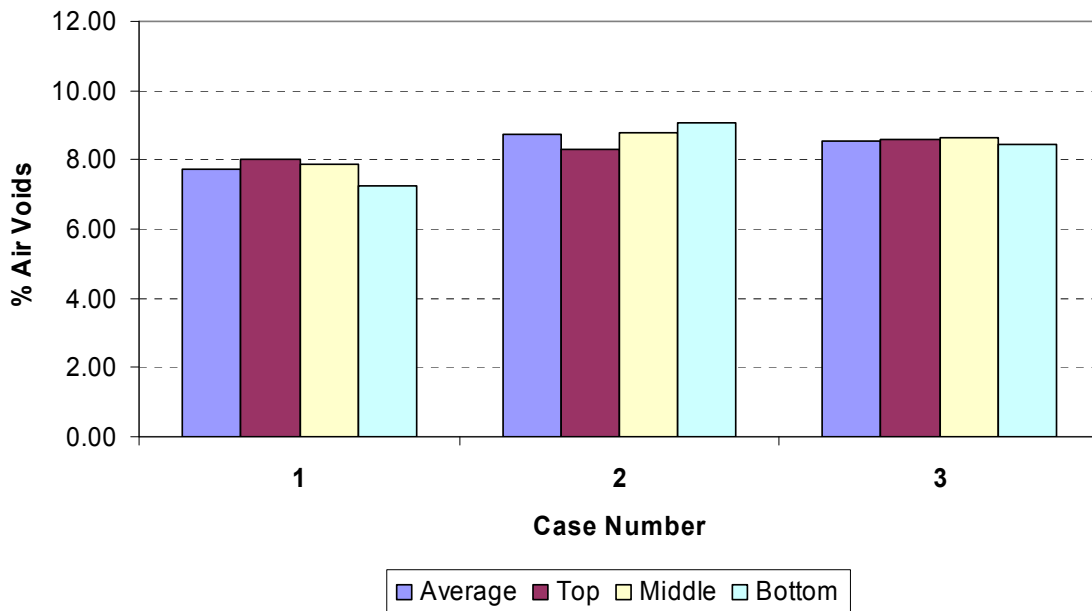


Figure 7-12. Percent Air Voids for 150 mm Diameter Specimens with PG 76-22 Binder.

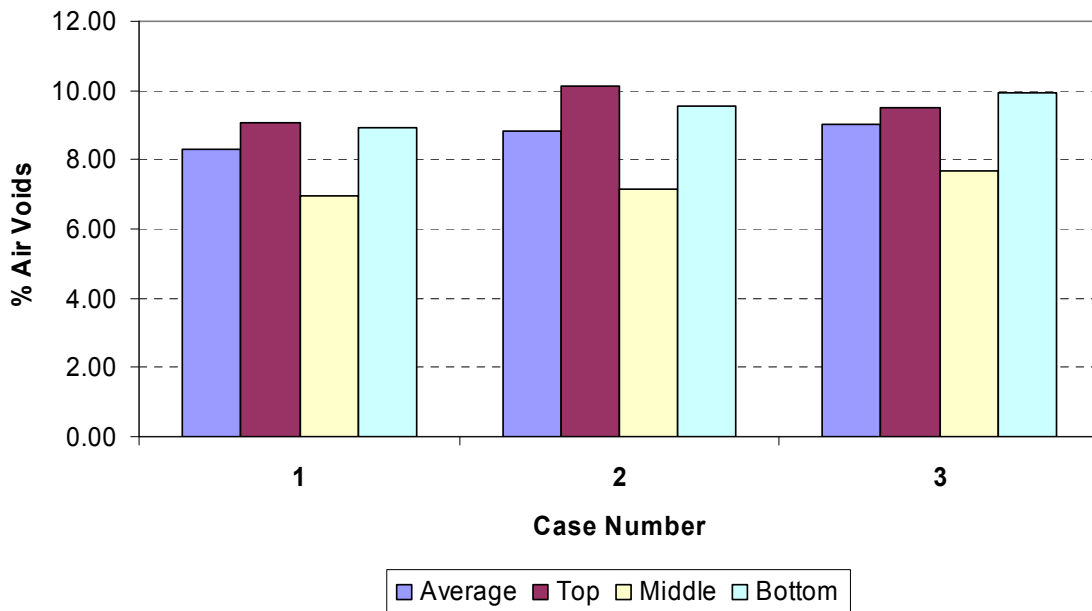


Figure 7-13. Percent Air Voids for 100 mm Diameter Specimens with PG 76-22 Binder.

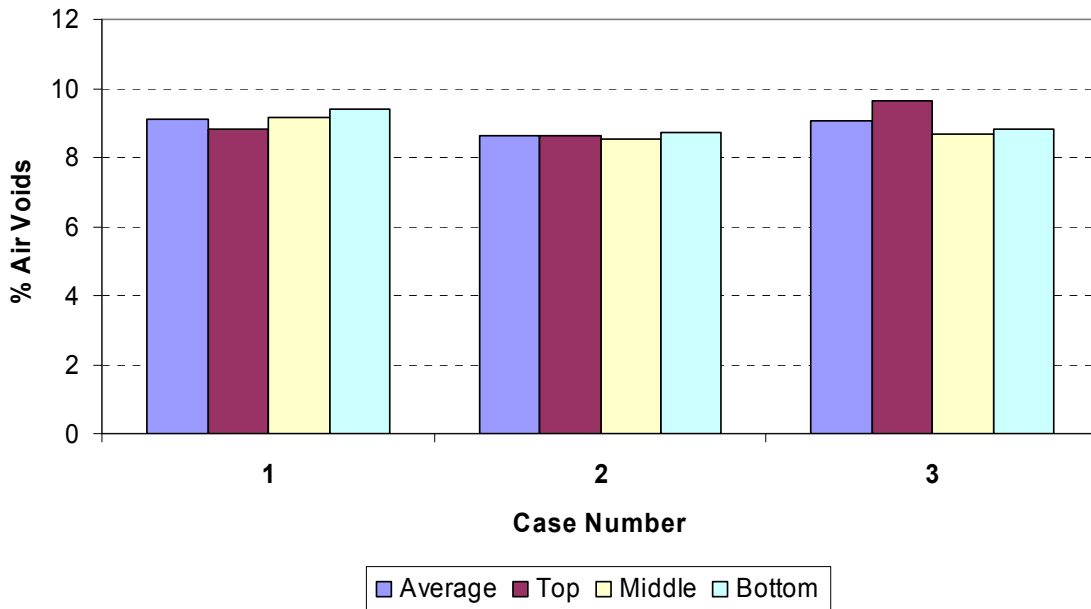


Figure 7-14. Percent Air Voids for 150 mm Diameter Specimens with PG 64-22 Binder.

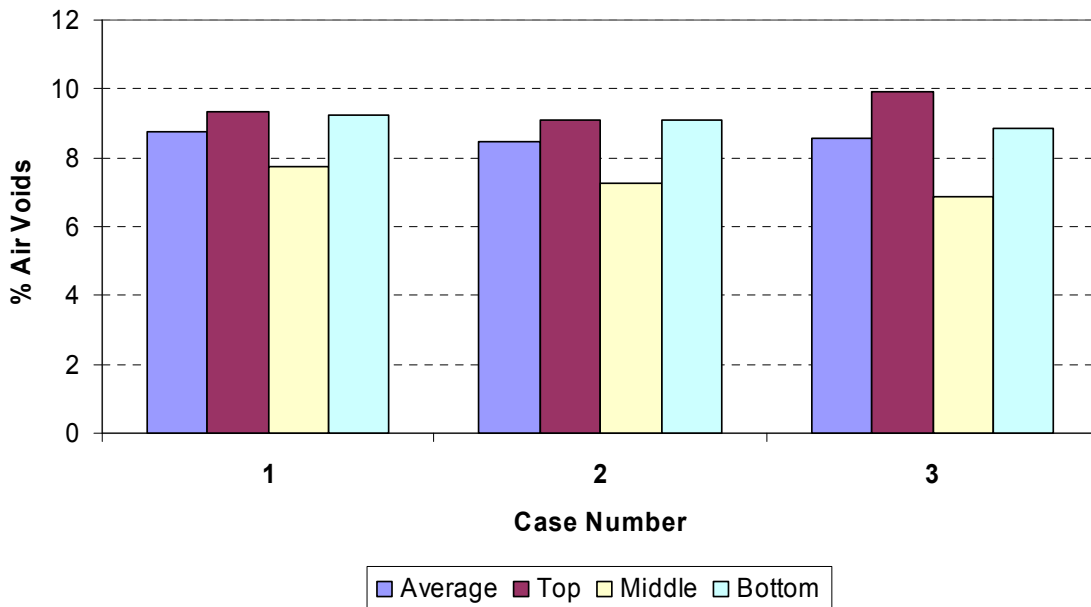


Figure 7-15. Percent Air Voids for 100 mm Diameter Specimens with PG 64-22 Binder.

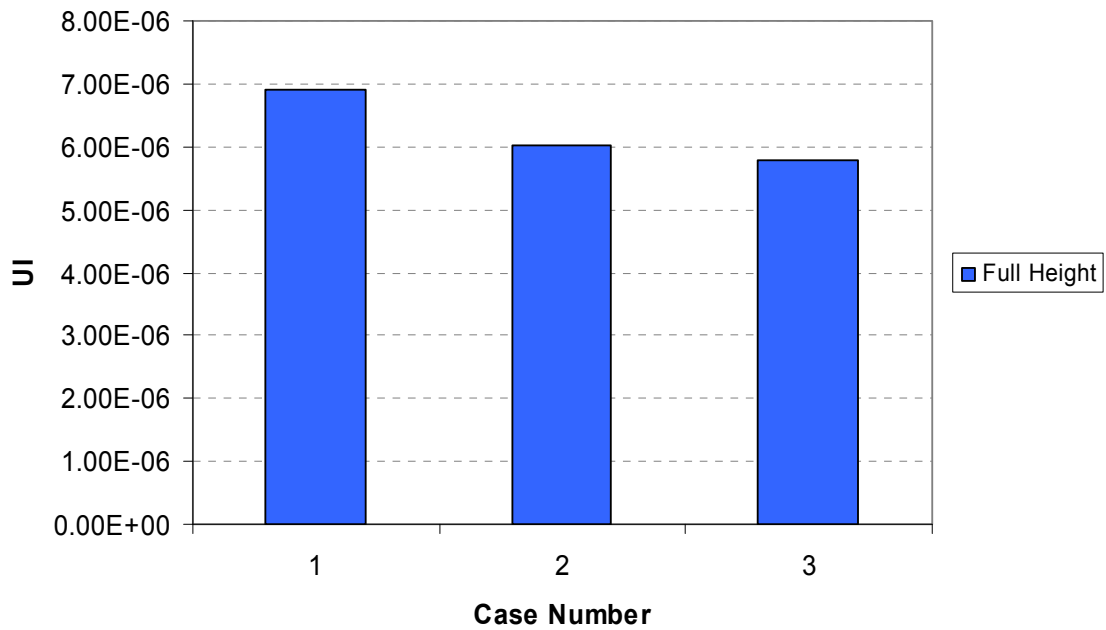


Figure 7-16. Uniformity Index for Full Height of 150 mm Diameter Specimens with PG 76-22 Binder.

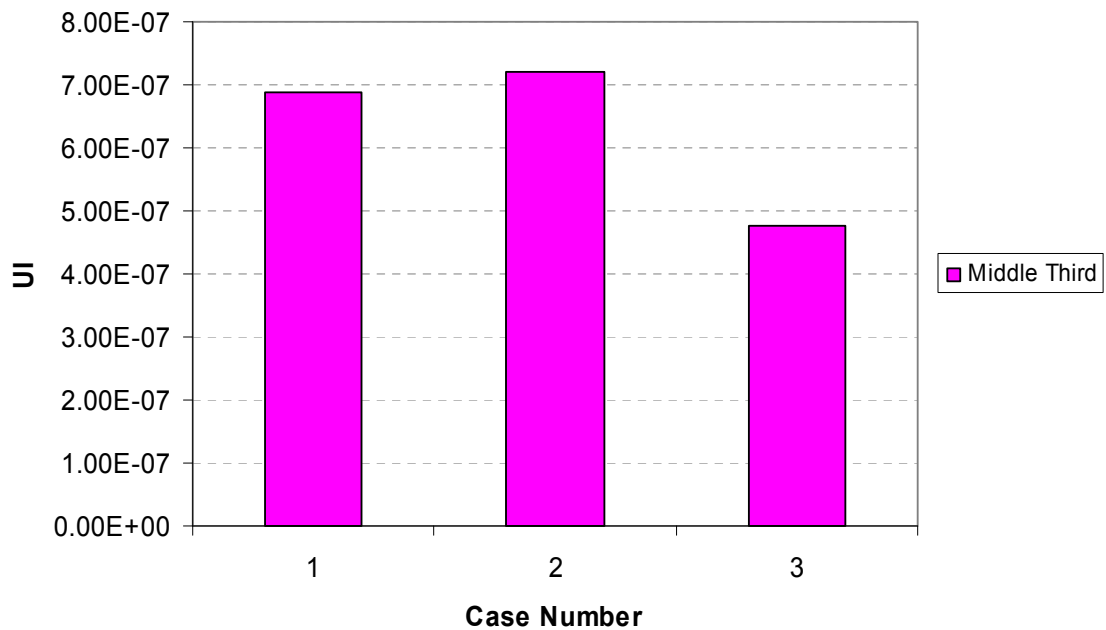


Figure 7-17. Uniformity Index for Middle Third of 150 mm Diameter Specimens with PG 76-22 Binder.

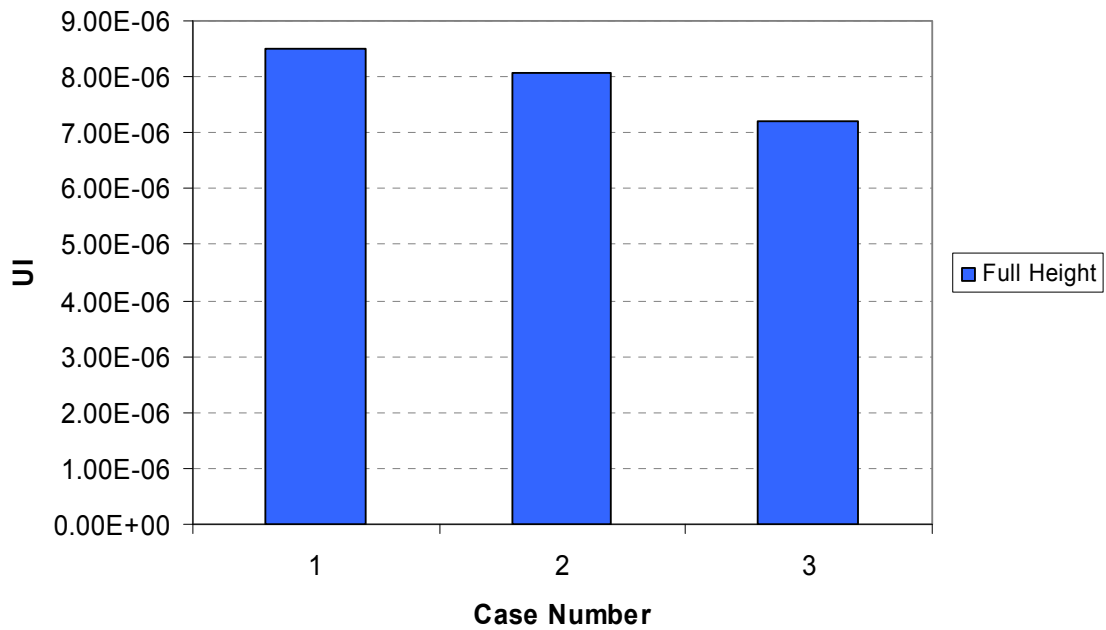


Figure 7-18. Uniformity Index for Full Height of 100 mm Diameter Specimens with PG 76-22 Binder.

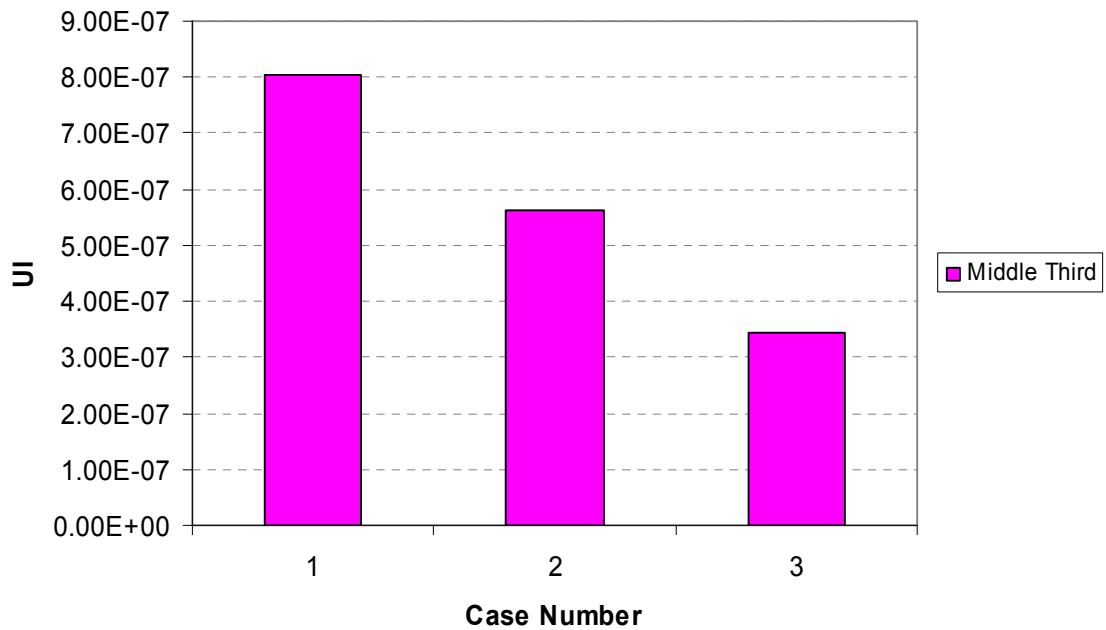


Figure 7-19. Uniformity Index for Middle Third of 100 mm Diameter Specimens with PG 76-22 Binder.

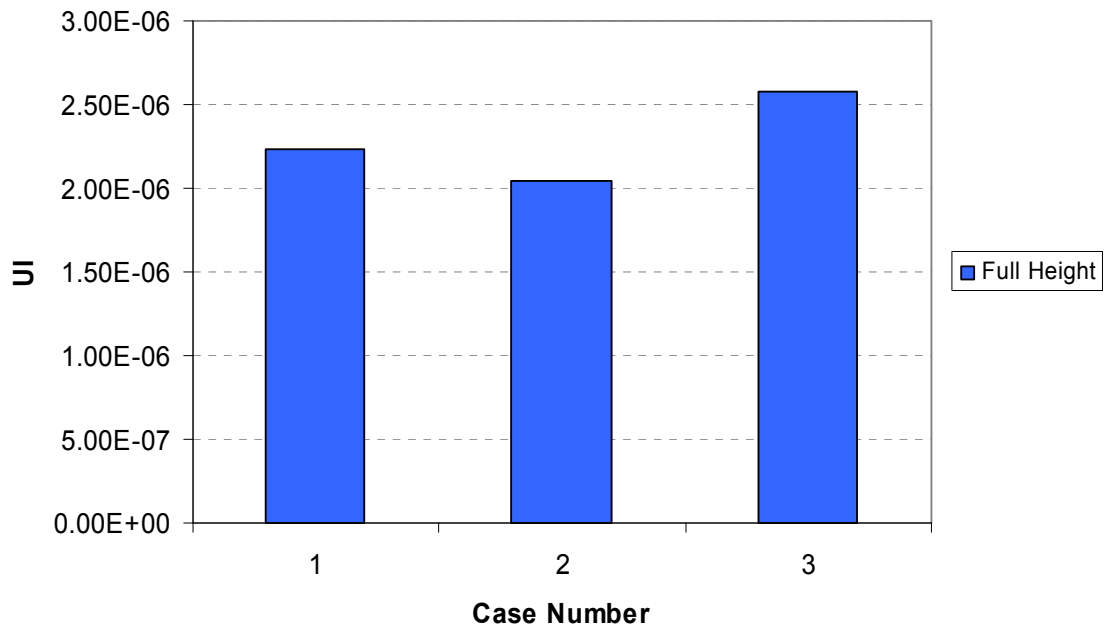


Figure 7-20. Uniformity Index for Full Height of 150 mm Diameter Specimens with PG 64-22 Binder.

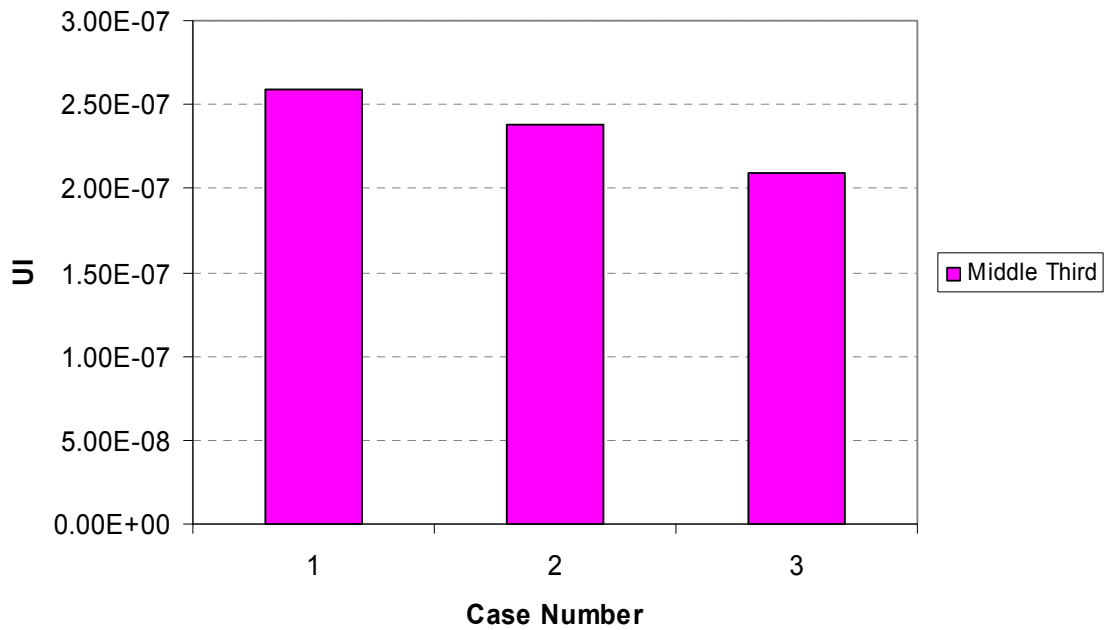


Figure 7-21. Uniformity Index for Middle Third of 150 mm Diameter Specimens with PG 64-22 Binder.

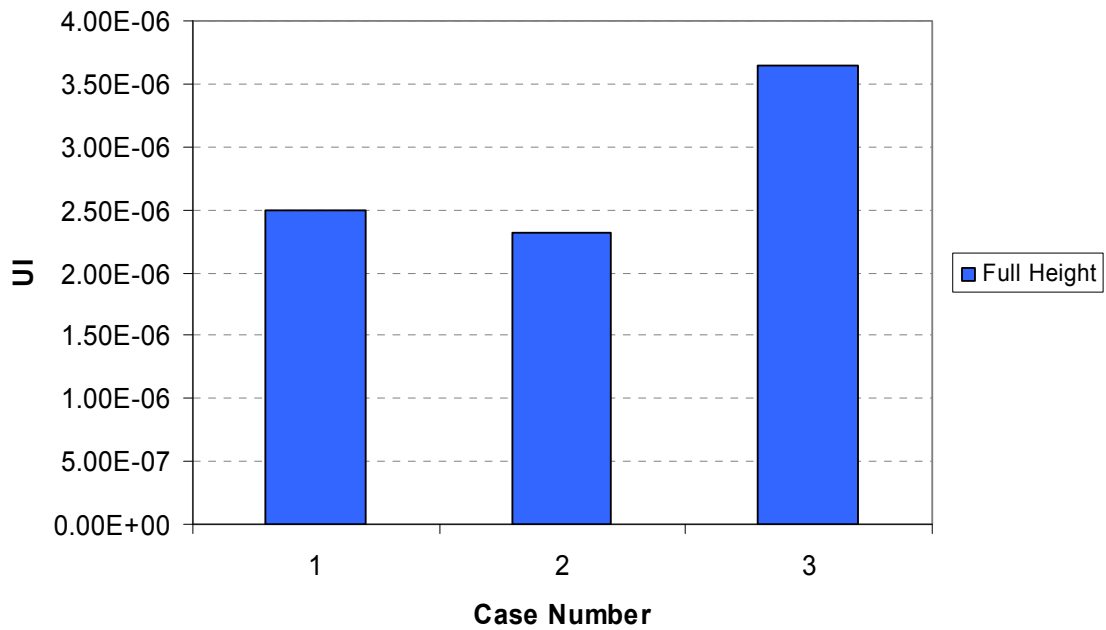


Figure 7-22. Uniformity Index for Full Height of 100 mm Diameter Specimens with PG 64-22 Binder.

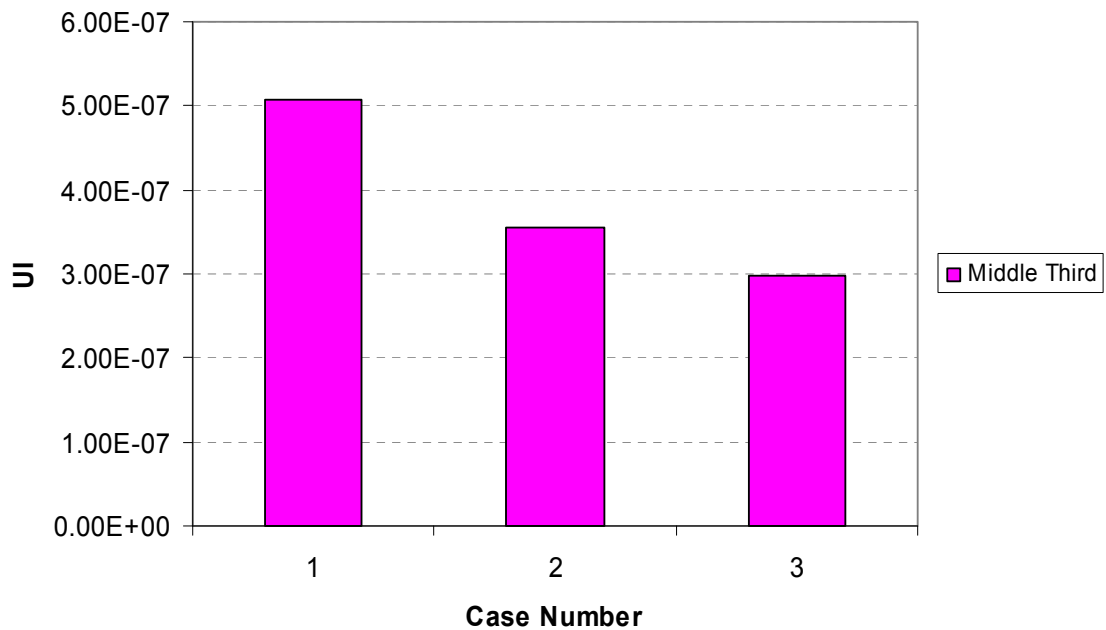


Figure 7-23. Uniformity Index for Middle Third of 100 mm Diameter Specimens with PG 64-22 Binder.

SUMMARY OF FINDINGS

The infrared temperature measurement system was used to measure the temperature profile along the specimen height during extraction of a specimen from the compaction mold. Combinations of top plate, base plate, and mold temperatures were used to generate different temperature profiles. The following are the main findings:

- The results demonstrated a relationship between the temperature profile and air void distribution. Improvement of the uniformity of temperature profile is associated with uniformity in air void distribution. Case 3, which has more uniform temperature profile than the other cases, improved the uniformity of the air distribution in the middle third of the samples. However, this relationship is weak and does not warrant changes to the compaction temperature at this point.
- In general, it appears that compaction against the solid boundaries of the plates and mold rather than the temperature profile is the main cause of air void nonuniformity.
- The air void distribution is more uniform for specimens prepared using a modified binder compared with specimens prepared with an unmodified binder.
- The middle third of a specimen is more uniform than the whole specimen. This is consistent with findings from previous studies.

CHAPTER 8

FORENSIC EVALUATION OF AIR VOID DISTRIBUTION IN ASPHALT PAVEMENT*

INTRODUCTION

Air void distribution is a major factor that affects the performance of asphalt mixture. Quantifying the air void distribution using X-ray CT is a powerful tool for forensic evaluation of HMA compaction related problems. One of the tasks of this research project was to assist TxDOT in conducting forensic evaluations of HMA pavements using X-ray CT. There was no specific objective to test a certain type of HMA mixture or pavements. Construction projects were selected for forensic evaluation based on requests from TxDOT engineers or other researchers. The following projects were included for this specific part of the study:

- SL 368 in San Antonio (Warm Mix)
- US 290 in Houston District
- FM 529 in Houston
- SH 114 in Fort Worth

The results for the first three projects (SL 358, US 290, and FM 529) of the forensic evaluation are given in [Appendix B](#). Our role in these projects was to analyze the air void distribution and send the results with a summary report to the TxDOT districts who requested the analysis. This chapter reports on a comprehensive forensic evaluation that was conducted in SH 114 in collaboration with TxDOT Project 4822.

*Reprinted with the permission from “Evaluation of Full Depth Asphalt Pavement Construction Using X-ray Computed Tomography and Ground Penetrating Radar” by Kassem, E., Walubita L., Scullion, T., Masad, E., and Wimsatt A., 2008, *Journal of Performance of Constructed Facilities*, ASCE, Vol. 22(6).

SH 114 IN FORT WORTH

Overview

In 2001, the Texas Department of Transportation developed guidelines for the design of full depth or perpetual pavements with more than 30 million Equivalent Single Axle Loads (ESALs) (TxDOT, 2001). These guidelines were developed by the Flexible Pavement Design Task Force, which consisted of senior TxDOT engineers and representatives from the Asphalt Institute, Texas Asphalt Pavement Association, and various industry groups. The objectives of the task force were to develop new asphalt mix specifications and pavement designs that could meet the demands of heavy truck traffic.

TxDOT has a long history of successfully constructing full depth hot mix asphalt (HMA) pavements as many of them were constructed in the 1960s and 1970s. The new guidelines recommended constructing pavement structures similar to the perpetual pavement concept developed by the Asphalt Institute (Newcomb et al., 2001). Figure 8-1 shows the proposed pavement structure for the Texas full depth pavements. The top layer is porous friction course (PFC), which has an open-graded structure to provide a good ride quality in terms of reduction in splash, spray, and noise. The second layer is stone matrix asphalt (SMA) mix which is designed to have very good stone-on-stone contacts and a very good resistance to permanent deformation. The next two layers are referred to as stone filled (SF) mixes that were designed to have good resistance to permanent deformation. The bottom asphalt layer, which is referred to as rich bottom layer (RBL), included a high asphalt content to resist fatigue cracking and to have low permeability. The SF and RBL mixes were designed according to the Superpave criteria and special TxDOT specifications (Scullion, 2006). The labels starting with “SS” and shown in parentheses in Figure 8-1 give the numbers for these special specifications.

In total eight full depth pavements were approved for construction in Texas starting in 2002. In 2005 a research study was initiated to evaluate the design, construction, and performance aspects of these new pavement structures (Scullion, 2006). The evaluation included a Ground Penetrating Radar (GPR) survey, field coring, and laboratory testing. Details about the experimental evaluation can be found in Scullion (2006) and Walubita and Scullion (2007). In addition, some field cores were extracted

and analyzed using X-ray Computed Tomography (CT) in order to verify the GPR measurements. This section reports the findings from the field and laboratory evaluations of full depth pavement sections constructed in SH 114.

PFC (SS3231)	1.0"-1.5" Porous Friction Course	Sacrificial Layer
HDSMA (SS3248)	2.0"-3.0" Heavy Duty SMA ½" Aggregate with PG76-XX	Impermeable Load Carrying
SFHMAC (SS3249)	2.0"-3.0" Stone-Filled HMAC ¾" Aggregate with PG76-XX	Transitional Layer
SFHMAC (SS3248)	8.0"-‘variable’ Stone Filled HMAC, 1.0"-1.5" Aggregate with PG76-XX	Load Carrying Layer
Superpave (SS3248)	2.0"-3.0" Superpave or 3146 ½" Aggregate with PG64-XX	Rich Bottom Layer (RBL) or Stress Relieving Impermeable Layer
Stabilized foundation	6.0"-8.0" stiff base or stabilized subgrade. Primarily to serve as construction working table or compaction platform for succeeding layers	

PFC: Porous Friction Course, HMAC: Hot Mix Asphalt Concrete, HDSMA: Heavy Duty Stone Matrix Asphalt, SFHMAC: Stone Filled Hot Mix Asphalt Concrete, SS: Special Specifications, RBL: Rich Bottom Layer)

Figure 8-1. Texas Typical Full Depth Asphalt Pavement Structural Sections (Scullion, 2006).

Objectives

The objective of this study was to use GPR and X-ray CT to evaluate the quality of constructing full depth pavement sections in Texas. In particular, the primary focus was on the level of compaction and uniformity of the SF mix, which is used in layers 3 and 4 of [Figure 8-1](#). This objective is achieved through the following tasks:

- Utilize GPR in order to assess the density uniformity in full depth pavement sections.

- Employ X-ray CT to analyze air void distribution in cores recovered from these sections.
- Evaluate and compare the findings from the GPR and X-ray CT methods.
- Develop recommendations in order to improve the construction of new full depth pavement structures.

Background

In the next section, an overview about the Ground Penetrating Radar (GPR) and its use in asphalt pavements will be given. An overview about the used X-ray CT system at Texas A&M University was given previously in [Chapter 4](#).

Ground Penetrating Radar

The Ground Penetrating Radar sends discrete pulses of radar energy into the pavement system and captures the reflections from each layer interface within the structure. Radar is an electromagnetic wave, and therefore, obeys the laws governing reflection and transmission of e-m waves in layered media. The particular GPR unit used in this study can operate at highway speeds (70 mph), transmit and receive 50 pulses per second, and can effectively penetrate to a depth of 2 feet (60.96 cm). The Texas Transportation Institute's (TTI's) 1-Gigahertz (1-GHz) air-launched GPR unit is shown in [Figure 8-2](#), and a typical plot of captured reflected energy versus time for one pulse is shown in [Figure 8-3](#), as a graph of volts versus arrival time in nanoseconds. The reflection A_1 is the energy reflected from the surface of the pavement, and A_2 and A_3 are reflections from the top of the base and subgrade, respectively. Details on the uses of GPR to compute layer properties and thickness can be found elsewhere ([Scullion and Chen, 1999](#)).



Figure 8-2. TTI GPR Equipment (Scullion, 2006).

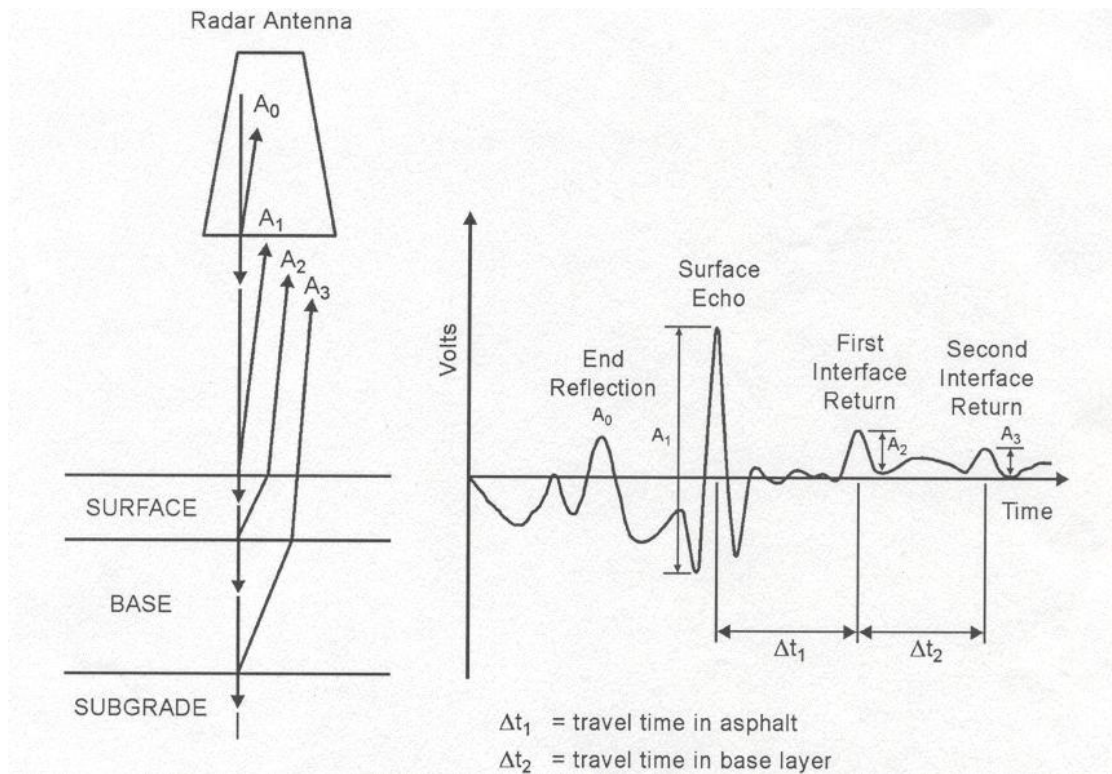


Figure 8-3. Illustration of the Principles of GPR (Scullion, 2006).

In most GPR projects, several thousand GPR traces are collected. A typical display of a GPR trace from a thick asphalt pavement with no defects is shown in [Figure 8-4](#). In this trace there is a clear reflection from the surface and another from the top of the base, with no major reflections between these peaks. This type of reflection is judged as ideal, with no clear subsurface defects.

In order to conveniently display this information, color coding schemes are used to convert the traces into line scans and stack them side-by-side so that a subsurface image of the pavement structure can be obtained. This approach is used extensively in Texas. Color coding consists of converting this trace into a single-line scan of different colors where the high positive volt areas are color coded red, the negatives are blue and the areas around zero volts are green. Using the color coding and stacking scheme, these data are transformed into [Figure 8-5](#), which shows a COLORMAP subsurface image for a 2500 ft section of highway with no defects. The labels on this figure are as follows: A) the surface of the pavement which is plotted as a red line at the top of the figure, B) the top of the base layer, C) the variation in surface reflection (an indication of the top layer uniformity), D) the distance scale in miles and feet, and E) the depth scale in inches. It is noted that zero on the depth scale is the reflection from the surface of the pavement. The pavement is homogeneous, and the layer interfaces are easy to detect.

In contrast to the GPR image shown in [Figure 8-5](#), [Figure 8-6](#) shows data from one of the Texas full depth pavements with some defects. The GPR data in [Figure 8-6a](#) were taken after construction of a 1 inch SF layer but before the placement of the surface layer for a section of approximately 500 ft. In these data, there are several strong reflections (red and blue lines) from within the SF layers. The blue areas indicate locations of low density material, while the red areas are locations of trapped moisture.

[Figure 8-6b](#) shows a GPR reflection from a single location, the positive reflections from the surface and top of the base are clear. However, between these are two large inverted (negative) peaks. Negative peaks occur with a transition from a layer of high to a layer of much lower dielectric. Within the full depth pavement structure, this can only be caused by a very large localized increase in air voids. The two negative reflections in [Figure 8-6b](#) were found to be associated with areas of “honeycombing” at the bottom of the first and second SF layer.

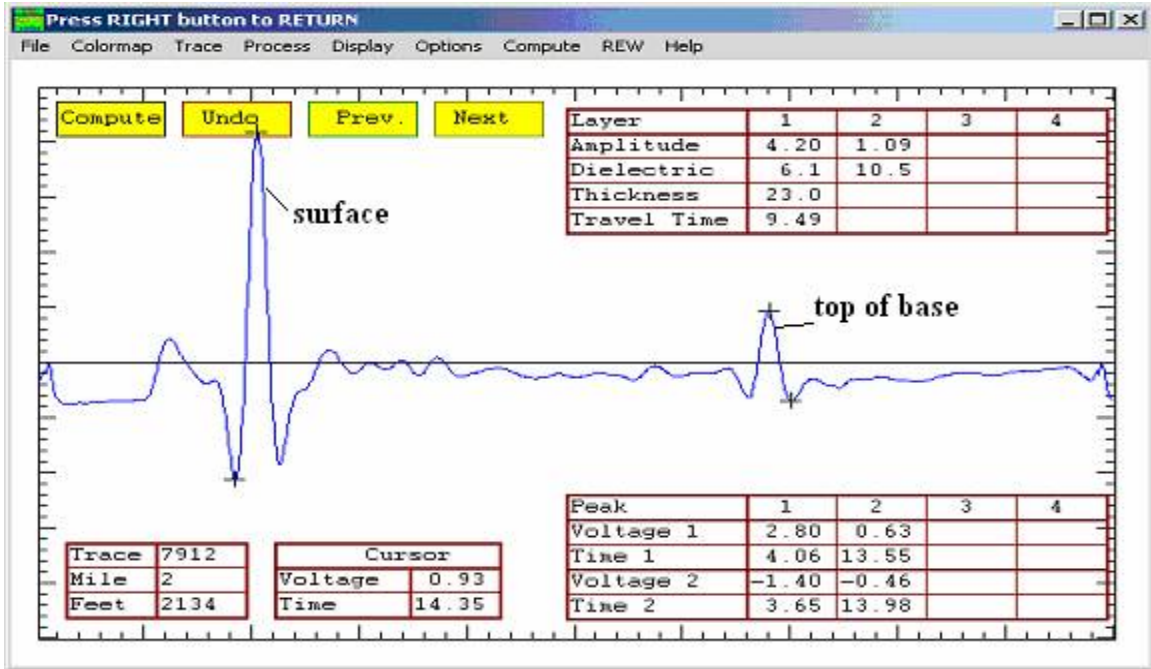


Figure 8-4. One Individual GPR Trace from a Thick Asphalt Pavement (Scullion, 2006).

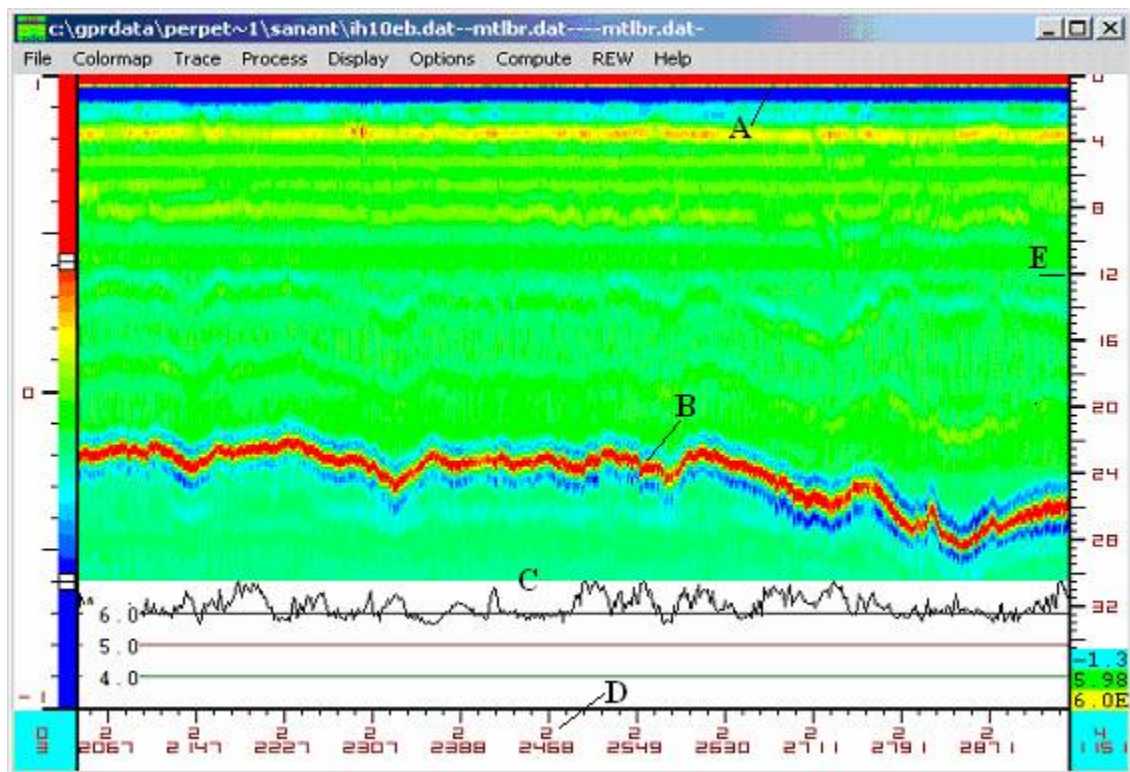


Figure 8-5. Color-Coded GPR Traces for a 1000 ft Section of Thick Asphalt Pavement (Scullion, 2006).

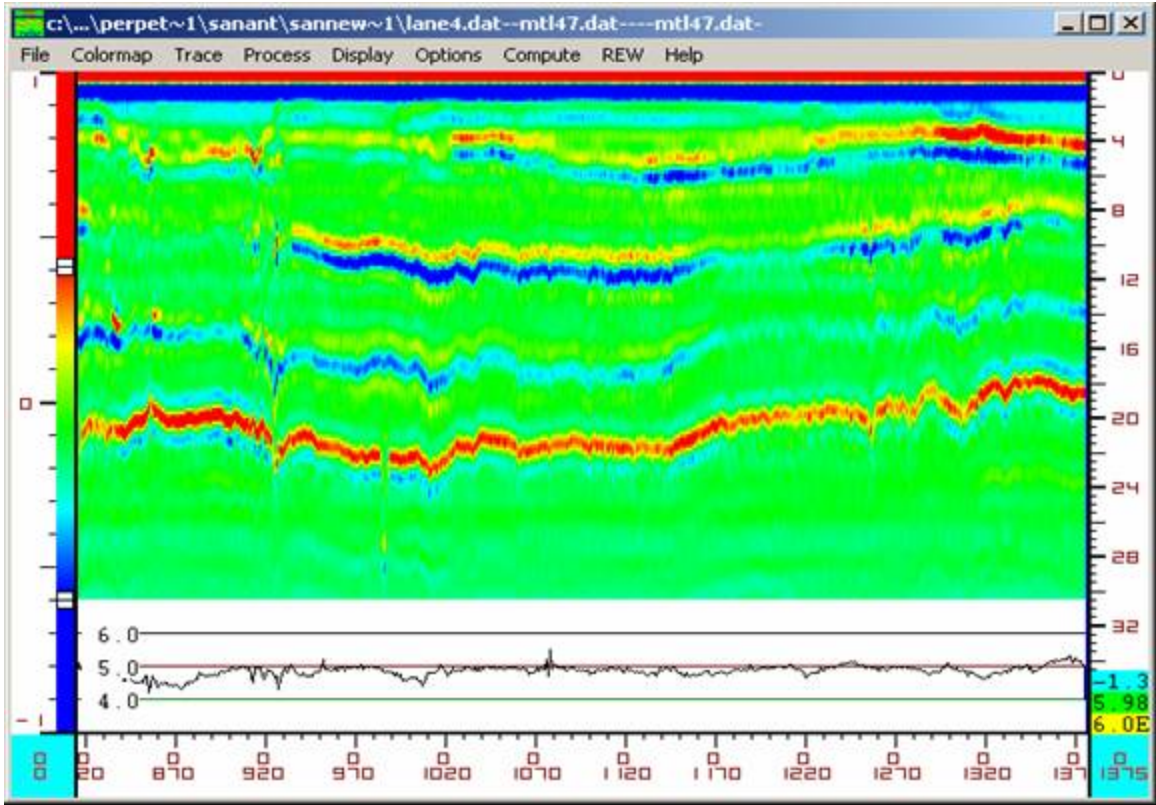
In [Figure 8-6c](#), a different type of GPR pattern is observed. The two positive reflections from the top and bottom of the mix are still present, but this time a very strong positive reflection is observed close to the surface reflection. Very large positive reflections can be caused by the presence of excessive moisture at this interface. This is clearly problematic and will lead to stripping in the mix and premature pavement deterioration.

The GPR data shown in [Figure 8-6](#) indicate that GPR is a good field tool for identifying defects from within HMA layers. The case study presented below is aimed at validating the GPR images with advance laboratory testing on cores extracted from the potential problem areas.

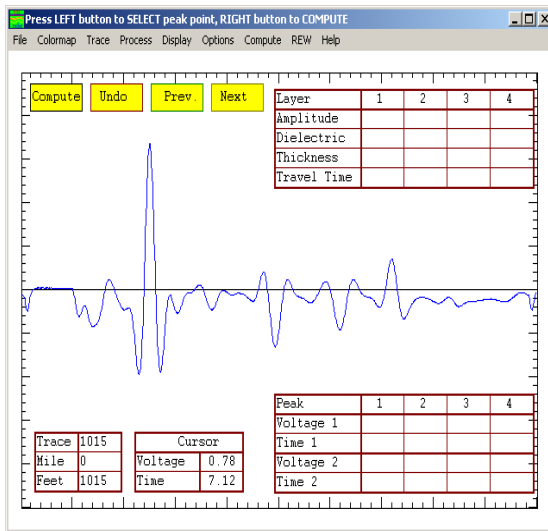
Project Description

The Full Depth Asphalt Pavement (FDAP) project is located in the Fort Worth District of Texas on SH 114 in Wise County. It is approximately a 2.2 mile long project consisting of two 12 ft eastbound main-lanes, a 4 ft inside shoulder, and a 10 ft outside shoulder. SH 114 is a heavily trafficked highway with an average daily traffic (ADT) of approximately 18,000.

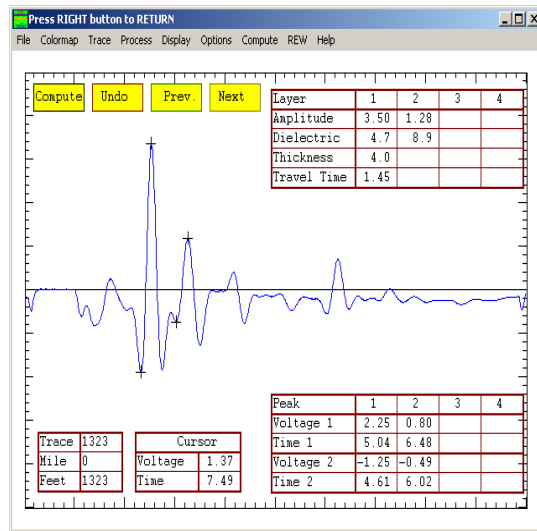
The SH 114 FDAP project was designed according to TxDOT guidelines for full depth asphalt pavements (TxDOT, 2001). As shown in [Figure 8-7](#) the majority of the FW-01 section included SF mixes in layers 2, 3 and 4. The Fort Worth District also decided to include a short section constructed using conventional dense-graded asphalt mixes as shown in the structure labeled FW-02 in [Figure 8-7](#). The FW-01 and FW-02 sections are approximately 1.7 miles and 0.25 miles in length, respectively. The FW-02 section was constructed after the FW-01 section was placed because FW-01 mixes exhibited compaction problems ([Walubita and Scullion, 2007](#)).



a) Color map with reflections from interfaces



b) Voided areas



c) Areas with trapped moisture

Note: Major reflections from layer interfaces. Compaction problems with depth, the red subsurface areas indicate areas of trapped moisture. At the far right of the GPR plot, moisture is trapped 4 inches below the Surface.

Figure 8-6. GPR Data from a Full Depth Pavement (Scullion, 2006).

FW-01: Superpave				FW-02: Conventional			
Layer	Material	Binder + Aggregate	Thickness	Layer	Material	Binder + Aggregate	Thickness
Layer 1	HDSMA	6.8% PG 70-28 + Igneous/Granite	2"	Layer 1	HDSMA	6.8% PG 70-28 + Igneous/Granite	2"
Layer 2	3/4" SFHMAC	4.2% PG 76-22 + Limestone	3"	Layer 2	TxDOT Type C	4.4% PG 70-22 + Limestone	3"
Layer 3	1"SFHMAC	4.0% PG 70-22 + Limestone	13"	Layer 3	TxDOT Type B	4.5% PG 64-22 + Limestone	13"
Layer 4	3/4" SFHMAC (RBL)	4.2% PG 64-22 + Limestone	4"	Layer 4	TxDOT Type C (RBL)	4.3% PG 64-22 + Limestone	4"
Layer 5	Stabilized Subgrade	6% Lime Treated	8"	Layer 5	Stabilized Subgrade	6% Lime Treated	8"
Subgrade			∞	Subgrade			∞

Figure 8-7. SH 114 Full Depth Asphalt Pavement Structural Sections (Walubita and Scullion, 2007).

The SF mixes in section FW-01 were designed according to the Superpave criteria to achieve 4 percent air voids (i.e., 96 percent density) at 100 gyrations. The rich bottom layer (RBL) was designed to have 97 percent density at 100 gyrations. All asphalt mixes passed the TxDOT requirement of a rut depth less than 12.5 mm (0.5 inch) in the Hamburg wheel tracking test (Walubita and Scullion, 2007). Figure 8-8 shows the aggregate gradations for the rut-resistant layers (1 inch SF in FW-01 section and TxDOT Type B in FW-02 section) according to both mix design and extraction from field cores. The 1 inch SF was designed with a coarse aggregate gradation passing below the Superpave restricted zone. The 1 inch SF was coarser than the TxDOT Type B mix. Based on extracted gradations, the 1 inch SF included more of the coarser aggregate (about 15.1 percent cumulative retained on the 3/4 inch sieve instead of the design 10.7 percent) whereas the TxDOT Type B used more of the medium-fine rock (i.e., 74.59 percent cumulative retained on No. 10 versus the design 69.80 percent). Walubita and Scullion (2007) provide more information about the structural design, mix design, field binder content, aggregate gradations, construction details, and the performance of the SH 114 FDAP.

GPR Results

TxDOT construction personnel reported that the 1 inch SF layer was difficult to compact, permeable, and water would flow off the edge of the pavement during periods of heavy rainfall. To evaluate if moisture was trapped within the full depth pavement a GPR survey was conducted, and the results are shown in [Figure 8-9](#). These results clearly show trapped moisture in the asphalt mixes. Based on these findings, there was a major concern in TxDOT that the pavement might deteriorate if traffic is allowed with water trapped at the layer interface. To address this, edge drains were installed in this section, and a chip seal was placed over the top of the ¾ inch SF layer.

The compaction difficulty in the 1 inch SF mix was attributed to the coarse and large aggregate gradation and the cold weather at the time of placement. Most of the lower layers for this pavement were placed from December 2003 to February 2004. Based on the observed construction problems with the FW-01 section, the Fort Worth District constructed the last 0.25 miles of this project using traditional Texas dense graded mixes, designated at FW-02 in [Figure 8-7](#). GPR measurements were taken on both structures in 2006 after the placement of the surface seal and edge drains in the FW-01 section. At that time no moisture was detected in either section, but some density variations were observed on the FW-01 section as shown in [Figure 8-10](#). [Figure 8-11](#) shows some low density areas that were detected in the FW-01 section. This low density problem was primarily centered around the longitudinal construction joints. Radar measurements indicated no evidence of major surface density and thickness variations or presence of moisture on the FW-02 section. In general, the FW-02 section appears to have been better compacted than the FW-01 section. To verify these interpretations of the GPR data, field cores were taken from the different areas and returned to the laboratory for detailed evaluation.

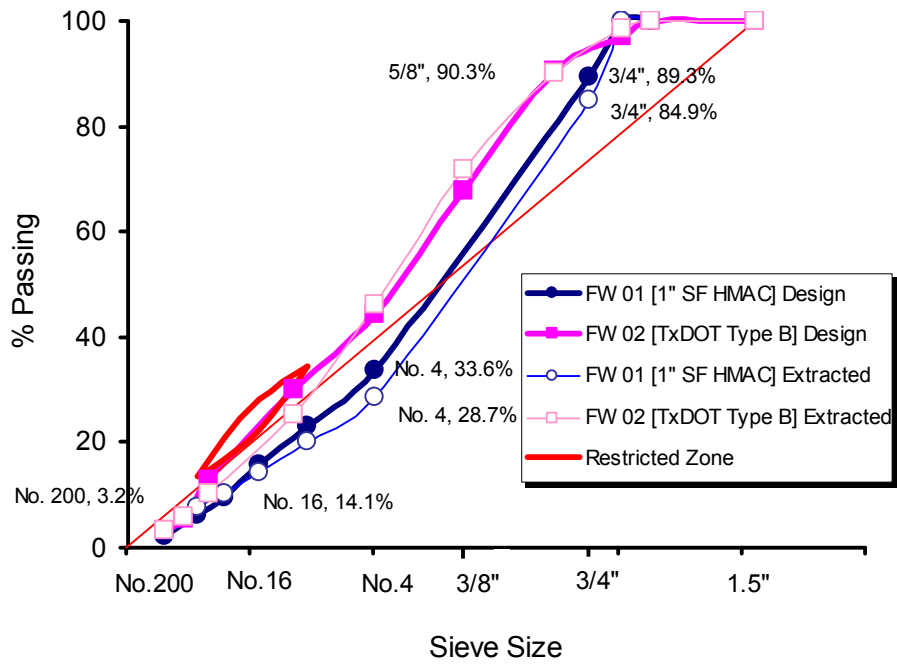


Figure 8-8. Aggregate Gradations (Walubita and Scullion 2007).

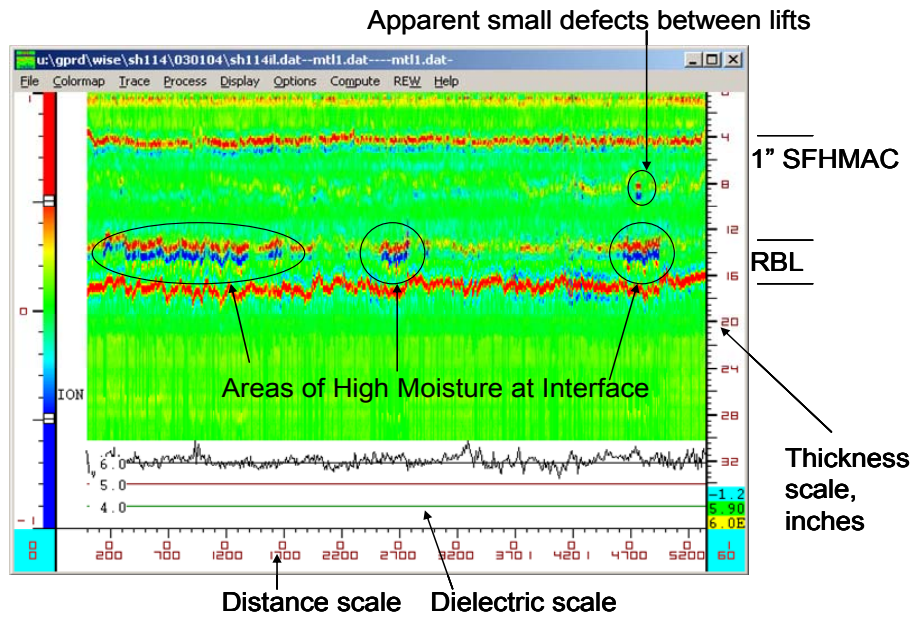


Figure 8-9. GPR Data Collected after Construction of the FW-01 Section (Walubita and Scullion, 2007).

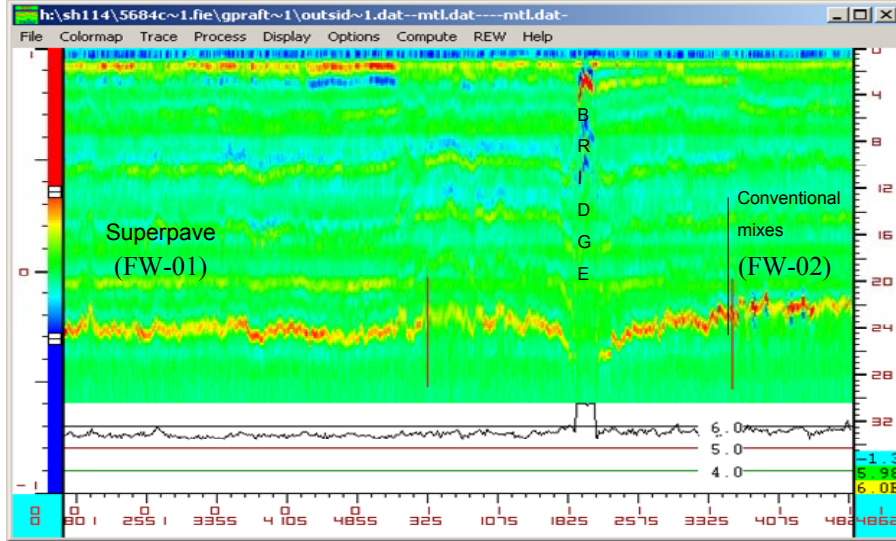


Figure 8-10. GPR Data after Construction of FW-01 and FW-02 (Walubita and Scullion, 2007).

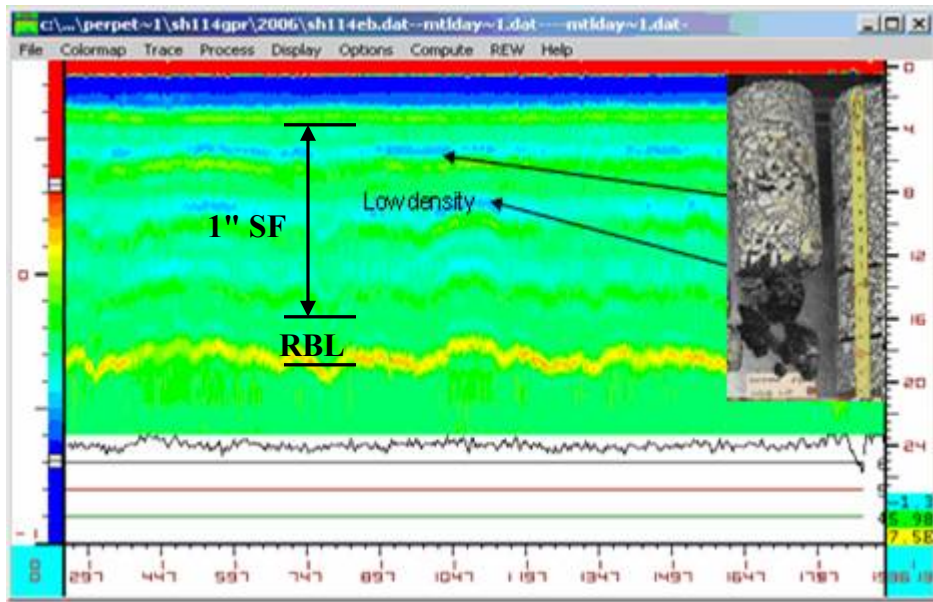


Figure 8-11. GPR Data Showing Low Density Areas within the 1inch SF Layer of the FW-01 Section (Walubita and Scullion, 2007).

X-ray CT Analysis and Discussion

Four field cores were examined in order to characterize the air void distribution. One field core was taken from the FW-02 section, and three field cores were taken from the FW-01 section at different locations.

The X-ray CT images were thresholded in order to separate air voids from the other mix constituents (aggregate and asphalt). The threshold level represents a boundary value below which pixels in the analyzed image are considered as part of the air voids, whereas pixels that have intensity values above the threshold value are considered to belong to the remaining phases. The thresholded images were analyzed to determine average percent air voids for a specimen ($\%AV$), average percent air voids in an image ($\%AV_{image}$), and average air void radius in an image (r) using Equations (8-1), (8-2), and (8-3), respectively.

$$\%AV = \frac{1}{N} \sum_N \%AV_{image} \quad (8-1)$$

$$\%AV_{image} = \frac{A_{TV}}{A_T} \quad (8-2)$$

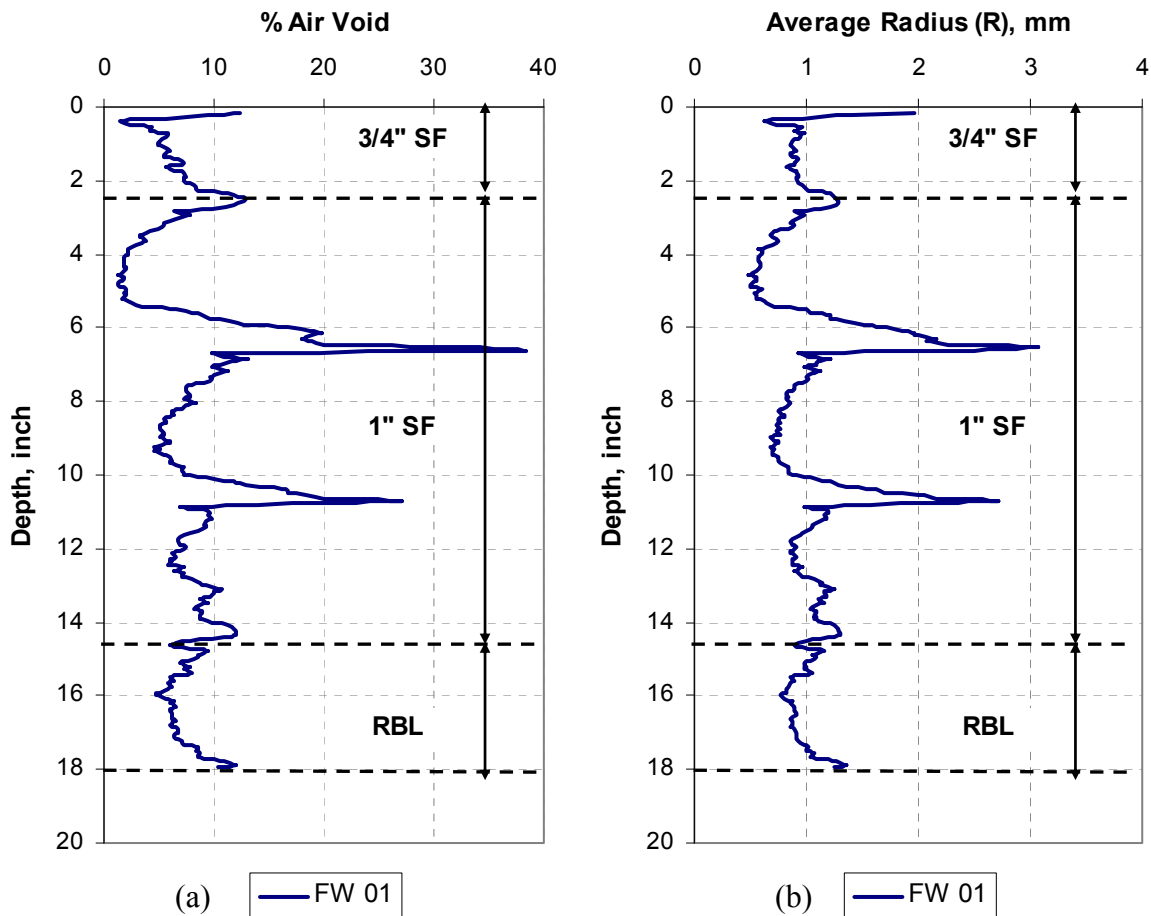
$$r = \sqrt{\frac{A_{TV}}{\pi n}} \quad (8-3)$$

where A_{TV} is the total area of the air voids in a CT image, A_T is the total cross-sectional area of a CT image, N is the number of CT images, and n is the number of the air voids in a CT image. The analysis was conducted using macros that were developed in Image-Pro® Plus software.

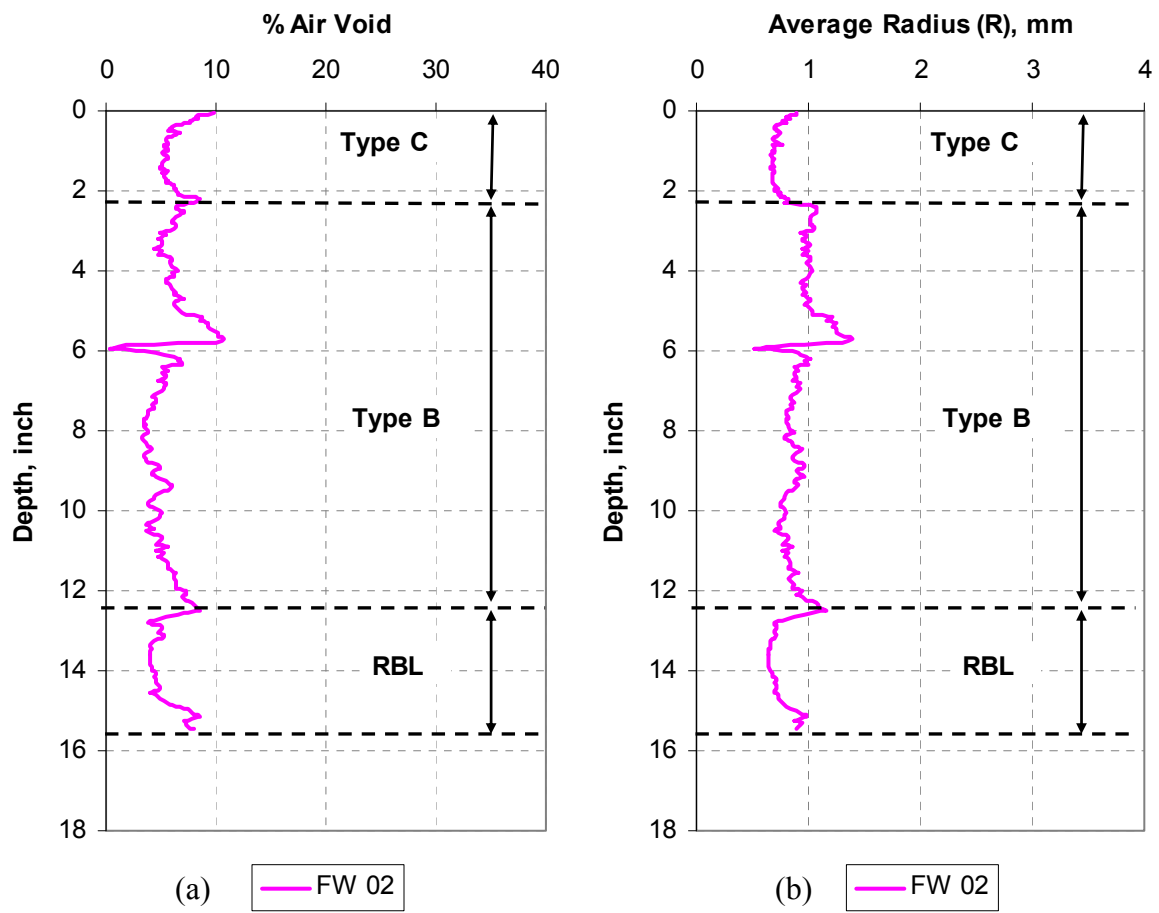
The percent air voids and average radius of air voids for the cores from sections FW-01 and FW-02 are shown in Figures 8-12 and 8-13, respectively. The average radius of air voids at a given depth corresponds well with percent air voids at that depth. As shown in Figure 8-12, there were low density (high air void) areas within the FW-01 pavement structure especially within the 1 inch SF layer at depths of 6 inches and 10 inches. These findings confirm those from the GPR measurements presented in Figure

8-11. In general, the distributions of both percentage of air voids and average radius of air voids for the FW-01 core revealed the poor compaction of this section.

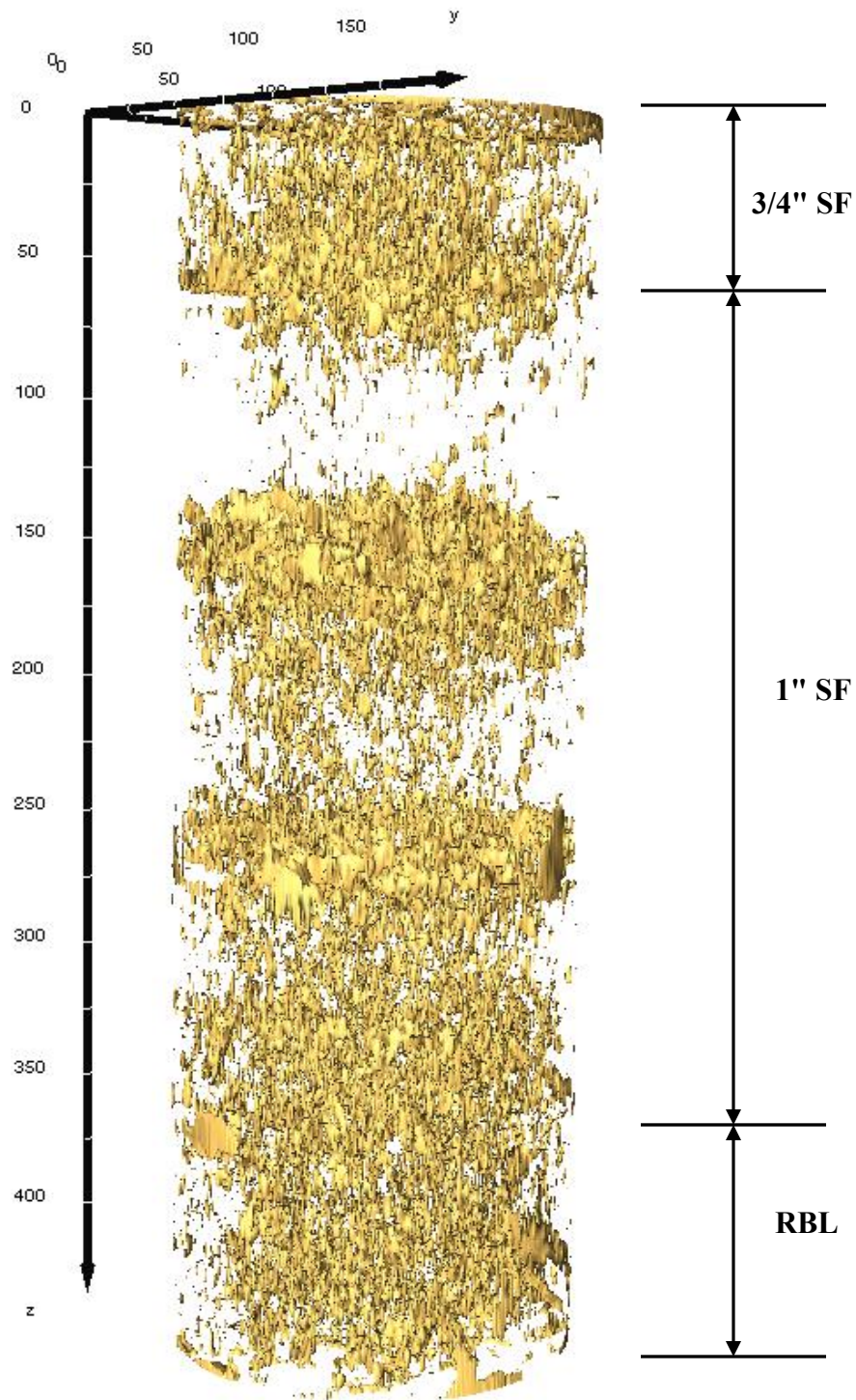
As shown in Figures 8-13a and 8-13b, the percent air voids and air void radius distributions in FW-02 section did not show much nonuniformity indicating that the compaction uniformity of the FW-02 section was better than the compaction of the FW-01 section. The results of the X-ray CT for section FW-02 correlated well with the GPR findings presented in Figure 8-10. The three-dimensional distribution of air voids that correspond to the results in Figures 8-12(a) and 8-13(a) are shown visually in Figures 8-14(a) and 8-14(b), respectively.



**Figure 8-12. Air Void Distribution across the Depth of Core 1 from FW-01 Section
(a) Percent Air Voids, (b) Air Void Radius.**

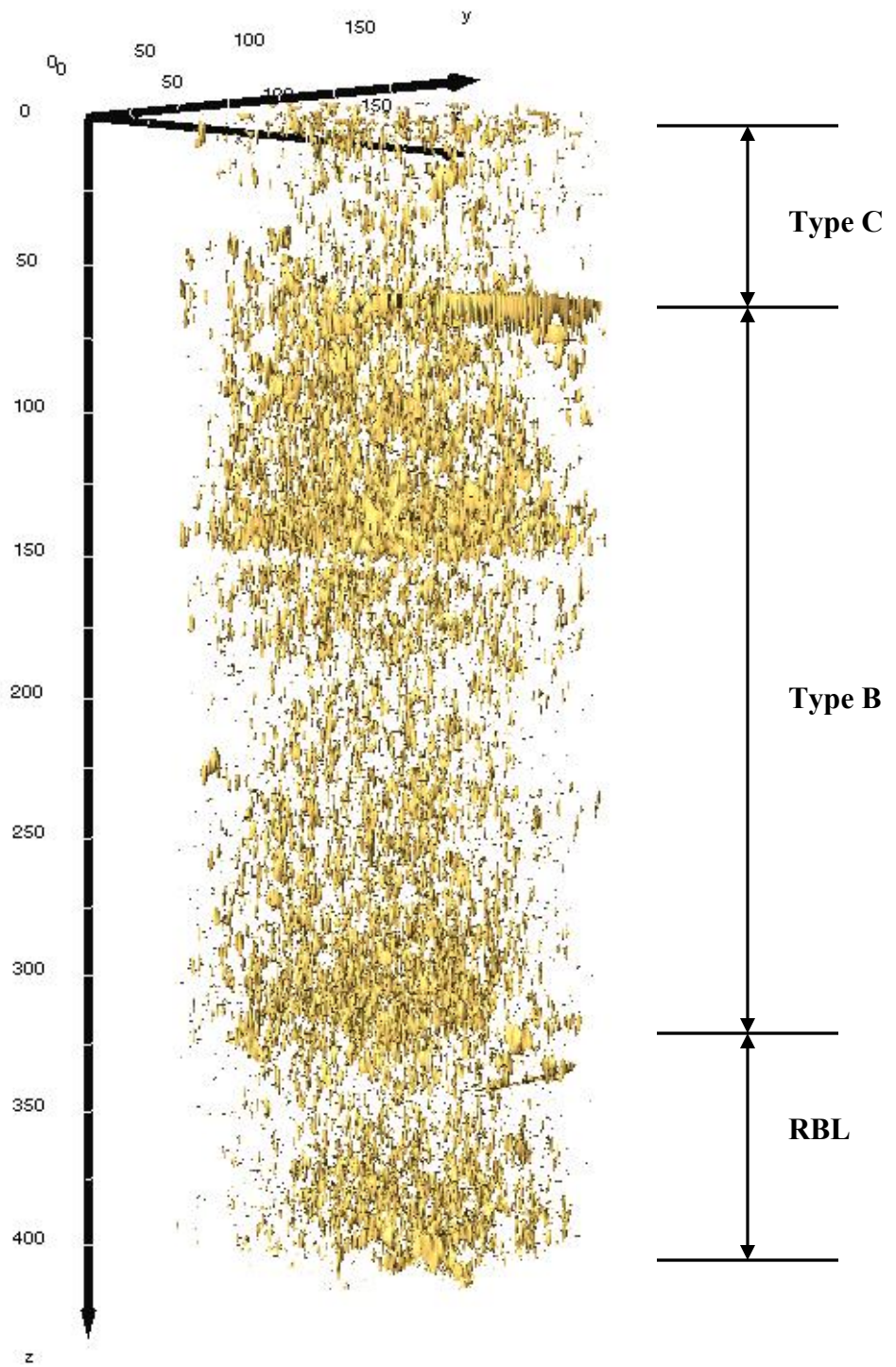


**Figure 8-13. Air Void Distribution across the Depth of Core 2 from FW-02 Section
 (a) Percent Air Voids, (b) Air Void Radius.**



(a)

Figure 8-14. Three-Dimensional of Air Voids across the Depth (a) Core 1 from FW-01 Section, (b) Core 2 from FW-02 Section.



(b)

Figure 8-14. Three-Dimensional of Air Voids across the Depth (a) Core 1 from FW-01 Section, (b) Core 2 from FW-02 Section (Continued).

Based on the initial findings presented in Figures 8-12 and 8-13, two more cores were taken from the FW-01 sections and evaluated using X-ray CT. The results are shown in Figures 8-15 and 8-16. The scanning for the core in Figure 8-15 focused on only 3 inches above the interface between the 1 inch SF mix and the RBL mix, while the scanning was conducted for about 8.5 inches above the interface for the core in Figure 8-16. As can be seen in Figures 8-15 and 8-16, there was a high percentage of air voids which associated with large air voids at the interface between the 1 inch SF layer and the RBL layer and within the 1 inch SF layer for the FW-01 section. This finding correlates well with the GPR traces, which also demonstrated low density areas at the interface and within the 1 inch SF layer.

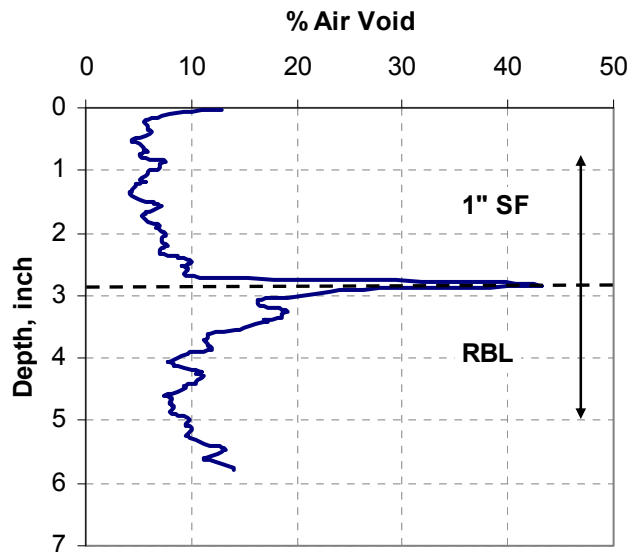


Figure 8-15. Air Void Distribution across the Depth of Core 3 from FW-01 Section.

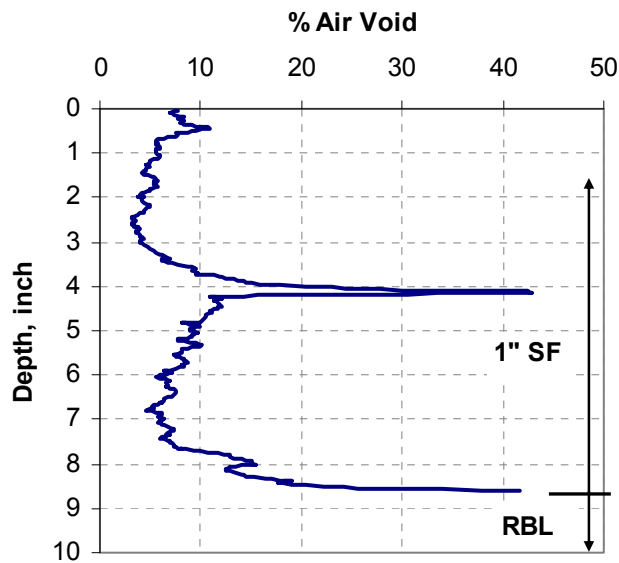


Figure 8-16. Air Void Distribution across the Depth of Core 4 from FW-01 Section.

CONCLUSIONS

The Ground Penetrating Radar and X-ray Computed Tomography were used in order to evaluate the construction of new full depth asphalt pavements. The GPR was able to detect and show the extent of the compaction problem in the new pavement investigated in this study. The GPR detected low density areas typically at the bottom of the stone filled (SF) layers. These layers were placed in 4 inch lifts, and it appears that the bottom 1 inch of the lift was poorly compacted. The color-coded image display of GPR data was very useful in quantifying the depth and extent of both water filled and air filled voids within the HMA layer. This information was used to generate a strategy to drain trapped moisture from the pavement structure.

X-ray CT was used to provide detailed information about the air void distribution in field cores and verify the GPR findings. The X-ray CT results were in very good agreement with the GPR measurements as it showed that the FW-01 section had less uniformity in air void distribution and larger air voids than the FW-02 section. Based on the results, it is recommended to make adjustments to the design of the SF mixes used in Texas to allow better compaction.

CHAPTER 9

DETERMINATION OF THE MOISTURE DIFFUSION COEFFICIENT OF ASPHALT MIXTURES*

INTRODUCTION

Air void distribution is not uniform through the depth of the mat of asphalt pavements. The findings of [Chapter 4](#) showed that the middle part of the mat is more compacted than the top and bottom parts. In this chapter the effect of the nonuniformity of the air void distribution on the moisture diffusion through the asphalt pavements will be evaluated. The presence of the moisture in asphalt pavements causes loss of bond between the aggregate and binder surfaces (adhesive failure) and/or loss of the cohesive bond within the binder (cohesive failure). These two mode failures are manifested in asphalt pavements as loss of binder (striping), loss of aggregate (raveling), cracking, and even permanent deformation. Moisture enters the asphalt pavements through different mechanisms such as infiltration of surface water, capillary rise of subsurface water, and diffusion of water vapor. Most of the research has focused on permeability as a measure of the infiltration of water in the mixture ([Masad et al., 2006](#)). A recent study by Masad et al. ([2007](#)) provided experimental evidence of water capillary rise in asphalt mixtures. Kassem et al. ([2006](#)) developed an experimental method for measuring moisture diffusion coefficients in asphalt mastics (fine aggregate particles mixed with binder). Moisture diffusion is an important mechanism for the cause of moisture damage in areas with low levels of annual rainfall such as New Mexico and Arizona ([Caro et al., 2008](#)). Moisture is transported into the mix under diffusion due to the difference in relative humidity between the pavement surface that has low relative humidity and the pavement underlying layer that has high relative humidity. Kassem et al. ([2006](#)) showed a good

*Reprinted with the permission from “Measurements of the Moisture Diffusion Coefficient of Asphalt Mixtures and Its Relationship to Mixture Composition,” by Kassem, E., Masad, E., Lytton, R., and Bulut, R., 2008., *International Journal of Pavement Engineering*, IJPE, in press, Copyright Taylor & Francis, International Journal of Pavement Engineering is available online at <http://www.informaworld.com>

correlation between the measured diffusion coefficients in the lab and the reported moisture damage from the field.

Kringos and Scarpas (2005a, 2005b) developed a finite element analysis tool to simulate the gradual development of moisture damage in asphalt mixtures as a result of water diffusion. The moisture diffusion coefficients are required inputs for these models. The study herein complements the findings from an earlier study by the authors (Kassem et al. 2006) in which they reported the diffusion coefficients for asphalt mastics. This study aims at developing an experimental procedure for measuring the diffusion coefficient of full asphalt mixtures and evaluating the effect of the nonuniformity air void distribution on the moisture diffusion.

OBJECTIVES

The objective of this study was to develop an experimental procedure for measuring the diffusion coefficient of full asphalt mixtures and to evaluate the effect of air voids on moisture diffusion. Using thermocouple psychrometers to measure the relative humidity in asphalt mixtures under well-defined boundary conditions achieved this objective. The moisture diffusion equation was solved numerically using the specified boundary conditions to determine moisture diffusion coefficients. These coefficients were related to the percent air voids in asphalt mixtures.

MEASUREMENTS OF SUCTION USING THERMOCOUPLE PSYCHROMETERS

Suction can be defined as a free energy state of water in a porous medium (Bulut and Wray 2005, Edlefsen and Anderson 1943). Asphalt mixtures are porous media that have the ability to attract and retain water (Kassem et al., 2006). Equation 9-1 (Fredlund and Rahardjo, 1993) below measures the total suction.

$$h = -\frac{RT}{v_{w0} \omega_v} \ln \left(\frac{\bar{u}_v}{\bar{u}_{v0}} \right) \quad (9-1)$$

where h = total suction, \bar{u}_v = partial pressure of pore-water vapor, \bar{u}_{v0} = saturation pressure of water vapor over a flat surface of pure water at the same temperature, (\bar{u}_v/\bar{u}_{v0})

= relative humidity, R = universal gas constant, T = absolute temperature, v_{w0} = specific volume of water, ω_v = molecular mass of water vapor. Total suction, as can be seen in Equation 9-1, is a function of relative humidity at a given temperature.

The thermocouple psychrometers were utilized herein in order to measure the total suction. Thermocouple psychrometers measure total suction by measuring the relative humidity in a confined space. Psychrometers operate based on the temperature difference between two surfaces, the evaporating surface (wet bulb), and the non-evaporating surface (dry bulb). The operation of thermocouple psychrometers depends on two principles—the Seebeck effect and the Peltier effect (Fredlund and Rahardjo, 1993). In a closed circuit of two different metals, an electromotive force is generated when the two junctions of the circuit have a temperature difference (Figure 9-1a). This principle is known as the Seebeck effect (Fredlund and Rahardjo, 1993). The induced electromotive force is a function of the temperature difference between the two junctions. Inducing a current through a closed circuit that consists of two different metals generates different thermal conditions at both junctions (Figure 9-1b). One junction gets cooler while the other gets warmer, which is known as the Peltier effect (Fredlund and Rahardjo, 1993).

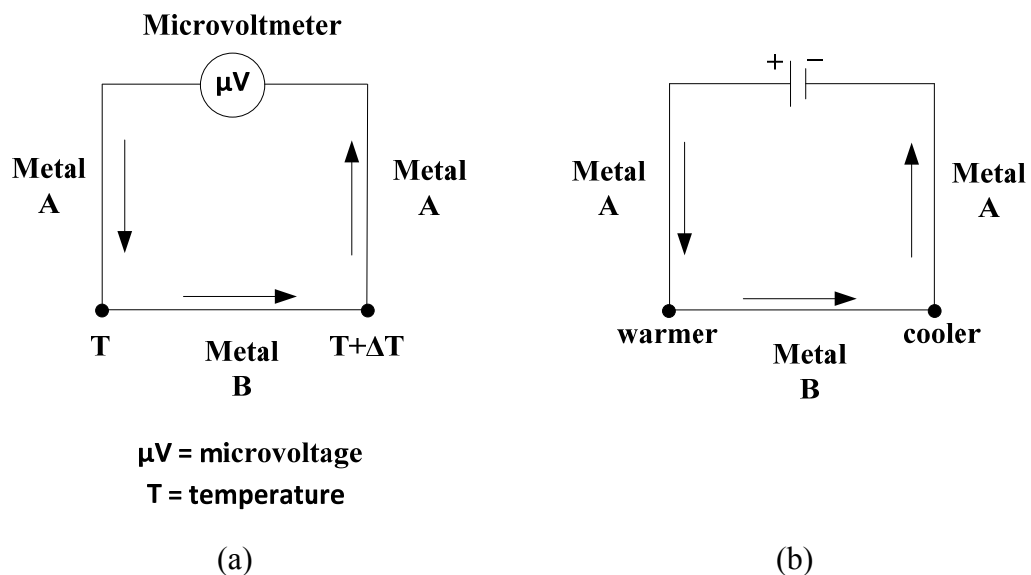


Figure 9-1 (a) Seebeck Effect, (b) Peltier Effect (Fredlund and Rahardjo, 1993).

The thermocouple psychrometer uses the Peltier effect to cool its junction until it reaches the dewpoint. Therefore, water vapor condenses on this junction. The condensed water starts to evaporate once the cooling current stops, leaving a temperature difference between the junction and the surrounding atmosphere. The temperature reduction of the junction depends on the evaporation rate, which is influenced by water vapor pressure or suction in the atmosphere. The difference in the temperature of both junctions generates an electromotive force in the circuit, according to the Seebeck effect. A microvoltmeter measures the generated electromotive force, or microvolts, in the circuit.

Calibration reveals the relationship between different suction levels and microvolts in the circuit of thermocouple psychrometer. In the calibration process, salt solutions with different concentrations, which correspond to different suction levels, are used to generate the relationship between total suction and recorded microvolts (Figure 9-2). The recorded microvolts increase proportionally with an increase in the suction level over a certain range. This range differs slightly from one psychrometer to another. For most of the psychrometers, this range is from about 3.67 pF (4.5 bar) to about 4.68 pF (47 bar) where $pF = \text{Log}(1019.8h)$; h in bar. If the suction level is below the lower limit of this range, the recorded microvolts are either negative values or equal to zero as shown in Stage I of Figure 9-3. Stage II in Figure 9-3 shows the measurements within the psychrometer's range, where the psychrometers function properly. In Stage III of Figure 9-3, the suction levels increase beyond the upper limit of psychrometer's range causing the microvolt reading to decrease until it reaches zero or negative values. Stage II of Figure 9-3 generates the calibration curve of a thermocouple psychrometer as shown in Figure 9-2. See Fredlund and Rahardjo (1993), Kassem (2005), and Bulut and Leong (2008) for more information about operational principles for psychrometers.

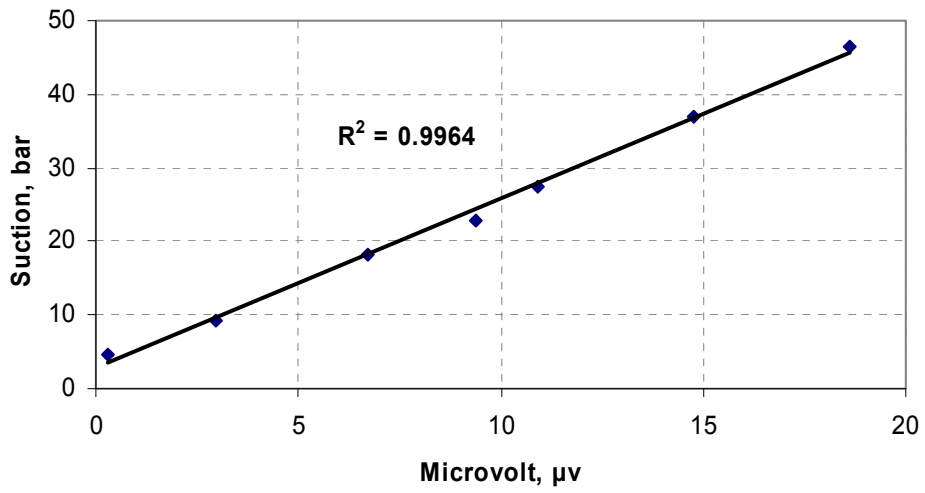


Figure 9-2. Calibration Curve of Thermocouple Psychrometer.

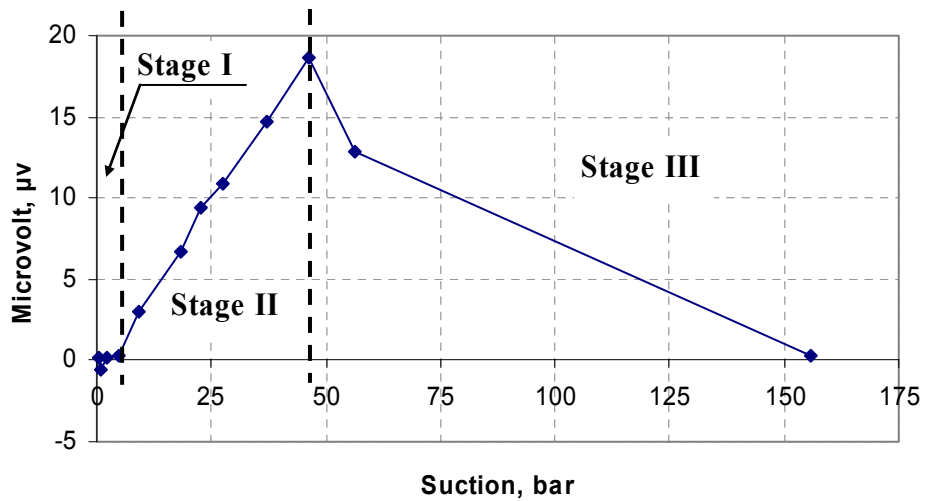


Figure 9-3. Relationship between Microvolt Outputs and Total Suction.

ANALYSIS OF DIFFUSION COEFFICIENTS

Mitchell (1979) proposed a simplified approach for solving the general mass-transport diffusion equation. He utilized Laliberte and Corey's (1967) permeability equation given by Equation 9-2 and the mass balance equation for unsteady fluid flow to develop a simplified formulation of moisture diffusion.

$$k(h) = k_0 \left(\frac{h_0}{h} \right)^n \quad (9-2)$$

where, $k(h)$ = permeability as a function of total suction (unsaturated permeability), k_0 = saturated reference permeability, h_0 = a reference value of total suction, h = total suction, n = positive constant depending on material's type.

Mitchell (1979) assumed the n value in Equation 9-2 to be 1, which is valid for low permeability and tight materials, such as very high plastic clays. The permeability value k from Equation 9-2 is then substituted into Darcy's law given in Equation 9-3 to get Equation 9-4. Darcy's equation describing one-dimensional unsaturated flow is given by:

$$v = -k(h) \left(\frac{dh}{dx} \right) \quad (9-3)$$

where, v = flow velocity, $\frac{dh}{dx}$ = head (suction) gradient.

A combination of Equations 9-2 and 9-3 leads to the following non-linear relationship:

$$v = -k_0 \left(\frac{h_0}{h} \right) \left(\frac{dh}{dx} \right) \quad (9-4)$$

Mitchell (1979) took the following steps to reduce the non-linear relationship presented in Equation 9-4 into a linear one. Equation 9-4 can be rearranged to become:

$$v = -k_0 h_0 \left(\frac{dh/h}{dx} \right) \quad (9-5)$$

The dh/h term in Equation 9-5 can be represented as follows:

$$\frac{dh}{h} = d(\log_e h) = \frac{1}{0.434} d \log_{10} h \quad (9-6)$$

Substituting Equation 9-6 into Equation 9-5 gives:

$$v = -\frac{k_0 h_0}{0.434} \frac{d \log_{10} h}{dx} \quad (9-7)$$

where $\log_{10} h$ = the total suction in pF units, which is termed u . Therefore, Equation 9-7 can be written as:

$$v = -\frac{k_0 h_0}{0.434} \frac{du}{dx} = -p \frac{du}{dx} \quad (9-8)$$

where $p = \frac{k_0 h_0}{0.434}$ is a constant.

In Figure 9-4, Mitchell (1979) considered an incremental section of the porous material with the dimensions Δx , Δy , and Δz for using the conservation of mass principle. The section proposed by Mitchell has a source of moisture generated in the material at a rate per unit volume defined by $f(x,t)$.

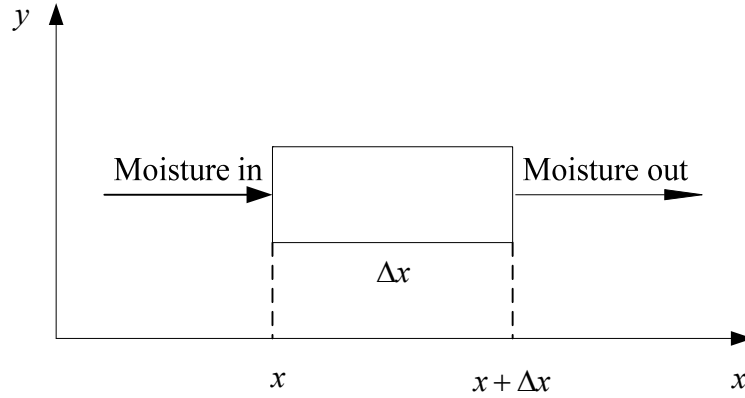


Figure 9-4. Incremental Section with Dimensions Δx , Δy , and Δz .

Equation 9-9 represents the net flow into the body for the case of one-dimensional flow in the x direction:

$$\Delta Q = v_x \Delta y \Delta z \Delta t \Big|_x - v_x \Delta y \Delta z \Delta t \Big|_{x+\Delta x} + f(x, t) \Delta x \Delta y \Delta z \Delta t \quad (9-9)$$

Substituting v_x from Equation 9-8 into Equation 9-9 gives:

$$\Delta Q = -p \Delta y \Delta z \left(\frac{\partial u}{\partial x} \right)_x \Delta t - \left\{ -p \Delta y \Delta z \left(\frac{\partial u}{\partial x} \right)_{x+\Delta x} \Delta t \right\} + f(x, t) \Delta x \Delta y \Delta z \Delta t \quad (9-10)$$

$$= p \Delta x \Delta y \Delta z \frac{\left(\frac{\partial u}{\partial x} \right)_{x+\Delta x} - \left(\frac{\partial u}{\partial x} \right)_x}{\Delta x} \Delta t + f(x, t) \Delta x \Delta y \Delta z \Delta t \quad (9-11)$$

$$\Delta Q_{\Delta x \rightarrow 0} = p \Delta x \Delta y \Delta z \frac{\partial^2 u}{\partial x^2} \Delta t + f(x, t) \Delta x \Delta y \Delta z \Delta t \quad (9-12)$$

Mitchell (1979) defined the relationship between moisture content and suction as shown in Equation 9-13:

$$c = \frac{dw}{du} \quad (9-13)$$

where, c = the slope of the suction-moisture characteristic curve, w = gravimetric water content, u = suction in pF .

The water content is defined as:

$$w = \frac{W_w}{W_s} \quad (9-14)$$

where, W_w = weight of water, W_s = weight of solids. The amount of stored moisture can be expressed by Equation 9-15:

$$\Delta Q = \frac{\Delta W_w}{\gamma_w} = \frac{\Delta w W_s}{\gamma_w} = \Delta x \Delta y \Delta z (\Delta u c \frac{\gamma_d}{\gamma_w}) \quad (9-15)$$

where, γ_d = dry density, γ_w = water density

The amount of stored moisture given in Equation 9-15 equals the net flow into the body given by Equation 9-12. Hence, combining Equations 9-12 and 9-15 gives:

$$p \Delta x \Delta y \Delta z \Delta t \frac{\partial^2 u}{\partial x^2} + f(x, t) \Delta x \Delta y \Delta z \Delta t = \Delta x \Delta y \Delta z (\Delta u c \frac{\gamma_d}{\gamma_w}) \quad (9-16)$$

$$p \frac{\partial^2 u}{\partial x^2} + f(x, t) \frac{\gamma_d c}{\gamma_w} \frac{\partial u}{\partial t} \quad (9-17)$$

Equation 9-17 can be rewritten as:

$$\frac{\partial^2 u}{\partial x^2} + \frac{f(x,t)}{p} = \frac{\gamma_d c}{\gamma_w p} \frac{\partial u}{\partial t} \quad (9-18)$$

or

$$\frac{\partial^2 u}{\partial x^2} + \frac{f(x,t)}{p} = \frac{1}{\alpha} \frac{\partial u}{\partial t} \quad (9-19)$$

Equation 9-19 is the diffusion equation, where $\alpha = \frac{\gamma_w p}{\gamma_d c}$ is the diffusion coefficient.

Diffusion coefficient is assumed to be constant over small changes in suction. The one-dimensional diffusion equation can easily be extended into a three-dimensional flow as follows (Mitchell, 1979):

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} + \frac{f(x,y,z,t)}{p} = \frac{1}{\alpha} \frac{\partial u}{\partial t} \quad (9-20)$$

DRYING TEST PROCEDURE FOR DETERMINATION OF α

The diffusion coefficient can be measured using the drying (evaporation) test in which the change of the total suction of an asphalt mixture specimen is monitored as moisture leaves the specimen as a function of time. In this test, an impermeable membrane encloses a cylindrical asphalt mixture specimen from all sides except the top. The moisture flows out of the sample through the top surface, which is exposed to a known atmospheric suction. Figure 9-5 presents a schematic view of the test setup.

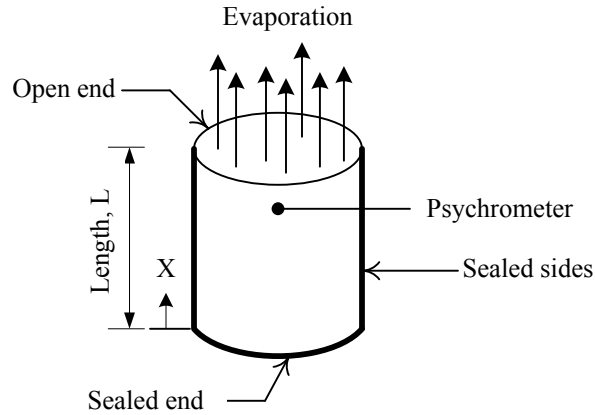


Figure 9-5. Schematic View of the Drying Test Sample.

Mitchell (1979) developed a solution for Equation 9-20 using the boundary conditions of the experiment. Substituting $f(x, y, z, t)$ as zero simplifies Equation 9-20 to Equation 9-21:

$$\alpha \frac{\partial^2 u}{\partial x^2} = \frac{\partial u}{\partial t} \quad (9-21)$$

The boundary conditions for this problem are as follows.

Sealed boundary:

$$\frac{\partial u(0, t)}{\partial x} = 0 \quad (9-22)$$

Open boundary:

$$\frac{\partial u(L, t)}{\partial X} = -h_e [u(L, t) - u_a] \quad (9-23)$$

Initial suction:

$$u(X, 0) = u_0 \quad (9-24)$$

Using the Laplace Transform method, Equation 9-25 provides the solution to Equation 9-21:

$$u = u_a + \sum_{n=1}^{\infty} \frac{2(u_0 - u_a) \sin z_n}{z_n + \sin z_n \cos z_n} \exp\left(-\frac{z_n^2 \alpha t}{L^2}\right) \cos\left(z_n \frac{X}{L}\right) \quad (9-25)$$

where: u = suction (pF) as a function of the position and the time, u_a = atmospheric suction in (pF), u_0 = initial suction (pF), t = time, x = distance from closed end, L = the total length of the sample, h_e = evaporation coefficient cm^{-1} , z_n is the solution of $\cot z = z_n / h_e L$. Matching the measured suction values at various times with Equation 9-25 determines the diffusion coefficient.

MATERIALS AND TEST PROCEDURE

This study used 10 asphalt mix specimens (4 inch diameter and 4 inch height). Six samples were prepared using Florida limestone aggregate (WR), and four samples were prepared using Georgia granite (GA) aggregate. These specimens were tested previously to investigate the effect of material properties and air void structure on moisture damage (Birgisson et al., 2003. Birgisson et al., 2004) and investigate the relationship between water content and total suction (Kassem et al., 2006). Tables 9-1 and 9-2 present the properties of the tested samples and the gradation, respectively. In Tables 9-1 and 9-2, the letter C stands for coarse-graded mixture, and the letter F stands for fine-graded mixture (Birgisson et al., 2003). All test samples were compacted at 7 percent air voids. A summary of the procedure for the test setup and suction measurements follows:

1. Drilled hole in a specimen using a bit with a diameter of 0.95 cm (3/8 in) diameter—depth of the hole half of the diameter of a specimen (5 cm); distance between the top of a specimen and top of the hole approximately 1 cm (Figure 9-5).
2. Saturated specimen with water using vacuum saturation; kept specimen in a room at a temperature of 25°C for one hour.
3. Cleaned hole from free standing water; inserted head of thermocouple psychrometer all the way into the hole.
4. Sealed hole with plastic tape to prevent loss of moisture.

5. Enclosed test specimen in clear wrap, aluminum foil, and heavy plastic tape from all sides except the top to allow evaporation (Figure 9-5).
6. Placed specimens under isothermal conditions at 25°C (Figure 9-6); used water bath to provide the test specimens with an isothermal condition throughout the test; used temperature control unit to maintain water temperature at 25°C; test specimens kept in empty plastic tubes (Figure 9-6).
7. Connected psychrometers to CR-7 datalogger which has the capability of recording the microvolts for 40 psychrometers at the same time every 10 minutes; connected CR-7 datalogger to a computer to retrieve the measurements (Figure 9-6).

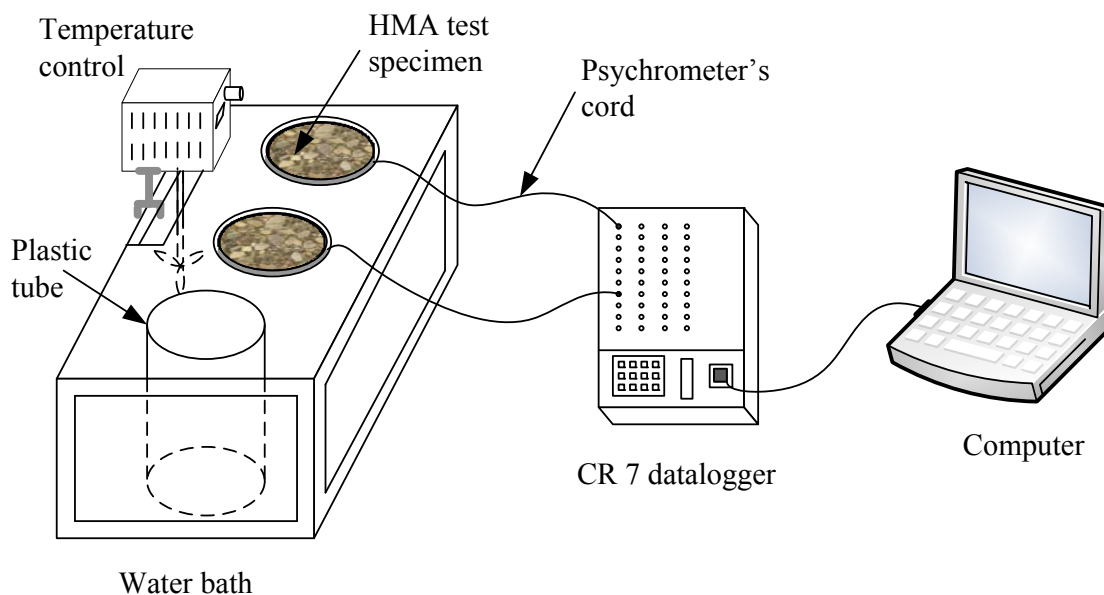


Figure 9-6. Schematic View of Test Setup.

Table 9-1. Volumetrics for Limestone and Granite Mixtures (Kassem et al., 2006).

Volumetric Property	Limestone						Granite			
	WR-C1	WR-C2	WR-C3	WR-F1	WR-F2	WR-F3/C4	GA-C2	GA-C3	GA-F1	GA-F2
Max. Specific Gravity (G_{mm})	2.328	2.347	2.349	2.338	2.375	2.347	2.500	2.492	2.473	2.532
Binder Specific Gravity (G_b)	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035	1.035
Bulk Specific Gravity (G_{mb})	2.235	2.255	2.254	2.244	2.281	2.254	2.399	2.391	2.473	2.433
Percent Binder (P_b)	6.5	5.8	5.3	6.3	5.4	5.6	5.26	5.25	5.68	4.56
Aggregate Specific Gravity (G_{sb})	2.469	2.465	2.474	2.488	2.489	2.468	2.687	2.686	2.686	2.687
Aggregate Effective Specific Gravity (G_{se})	2.549	2.545	2.528	2.554	2.565	2.537	2.719	2.709	2.706	2.725
Absorbed Percent Binder P_{ba}	1.1	1.3	0.9	1.1	1.2	1.1	0.43	0.31	0.28	0.53
Effective Percent Binder P_{be}	5.3	4.6	4.5	5.3	4.2	4.5	4.85	4.96	5.42	4.06
Voids in Mineral Aggregates VMA (%)	15.4	13.8	13.6	15.6	13.2	14.0	15.4	15.7	16.6	13.6
Design Percent Air Voids V_a (%)	4.0	3.9	4.0	4.0	3.9	3.9	4.0	4.1	4.0	3.9
Voids Filled with Asphalt VFA (%)	74.0	71.6	70.2	74.2	70.1	71.8	73.8	74.2	75.9	71.2
Dust to Asphalt Ratio D/A	1.0	0.8	1.2	0.8	1.4	1.0	0.8	0.9	0.6	1.2

Table 9-2. Granite and Limestone Mixture Gradations.

Sieve Size (mm)	Granite: Percent Passing			
	GA-C2	GA-C3	GA-F1	GA-F2
19	100	100	100	100
12.5	90.9	97.3	94.7	90.5
9.5	72.9	89.5	84	77.4
4.75	45.9	55.4	66.4	60.3
2.36	28.1	33.9	49.2	43.2
1.18	18.9	23	32.7	34
0.6	13.2	16	21	23
0.3	9.2	11.2	12.9	15.3
0.15	5.6	6.8	5.9	8.7
0.75	3.9	4.7	3.3	5.4

Sieve Size (mm)	Limestone: Percent Passing					
	WR-C1	WR-C2	WR-C3	WR-F1	WR-F2	WR-F3/C4
19	100	100	100	100	100	100
12.5	97	91	98	96	91	95
9.5	90	74	89	85	78	85
4.75	60	47	57	69	61	67
2.36	33	30	36	53	44	37
1.18	20	20	24	34	35	26
0.6	15	14	18	23	24	20
0.3	11	10	13	15	16	14
0.15	7.6	6.7	9.2	9.6	9.1	8.6
0.75	4.8	4.8	6.3	4.8	6.3	5.8

X-RAY COMPUTED TOMOGRAPHY

The experiment used X-ray Computed Tomography, which is a nondestructive technique, to capture the percentage of air voids distribution in test specimens under dry conditions (Masad, 2004). The test asphalt specimen is placed between an X-ray source and a detector. X-rays pass through the test specimen, and the intensity of X-rays is measured before entering the specimen and after it penetrates the specimen. The loss of X-ray intensities determines the linear attenuation coefficients of the materials in the test samples. The density distribution within the test sample is determined as a function of the attenuation coefficients.

The X-ray CT images were captured in one millimeter increments in the vertical direction. The captured image consists of 256 levels of gray intensity that correspond to different densities within the specimen, as shown in Figure 9-7. The black areas represent air voids (low density). Using a suitable gray intensity threshold value, air voids can be separated from other mix constituents (aggregate and mastic). The threshold level represents a boundary value below which pixels belong to the air void and above which the pixels belong to remaining constituents. Equations 9-26, 9-27, and 9-28 compute the average percent air voids for a specimen (%AV), average percent air voids in an image (%AV_{image}), and average air void radius in an image (*r*), respectively.

$$\%AV = \frac{1}{N} \sum_1^N \%AV_{image} \quad (9-26)$$

$$\%AV_{image} = \frac{A_{TV}}{A_T} \quad (9-27)$$

$$r = \sqrt{\frac{A_{TV}}{\pi n}} \quad (9-28)$$

where A_{TV} is the total area of the air voids in a CT image, A_T is the total cross-sectional area of a CT image, N is the number of CT images, and n is the number of the air voids in a CT image.

The analysis was carried out with macros that were developed in Image-Pro® Plus software (1999). Figure 9-8 presents an example of typical air void distribution along the depth of a test specimen. Some of the test specimens were trimmed from the top to produce different percents of air voids above the psychrometer's level.

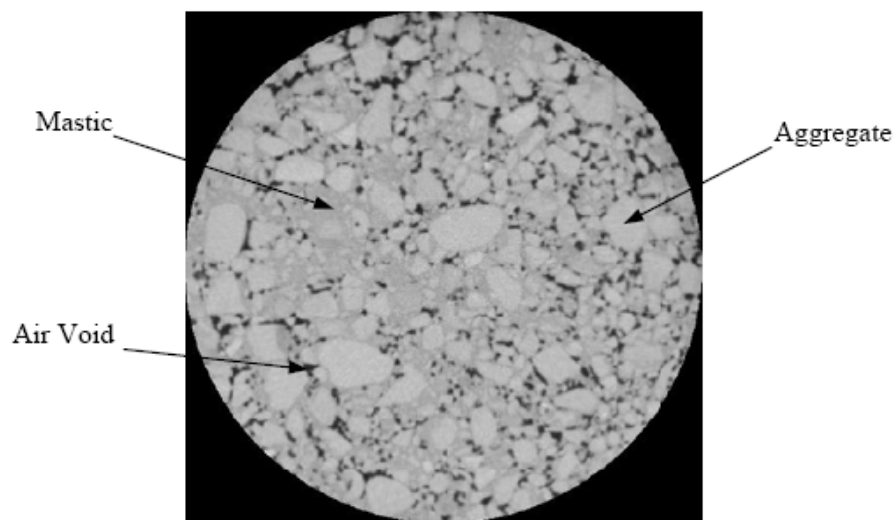
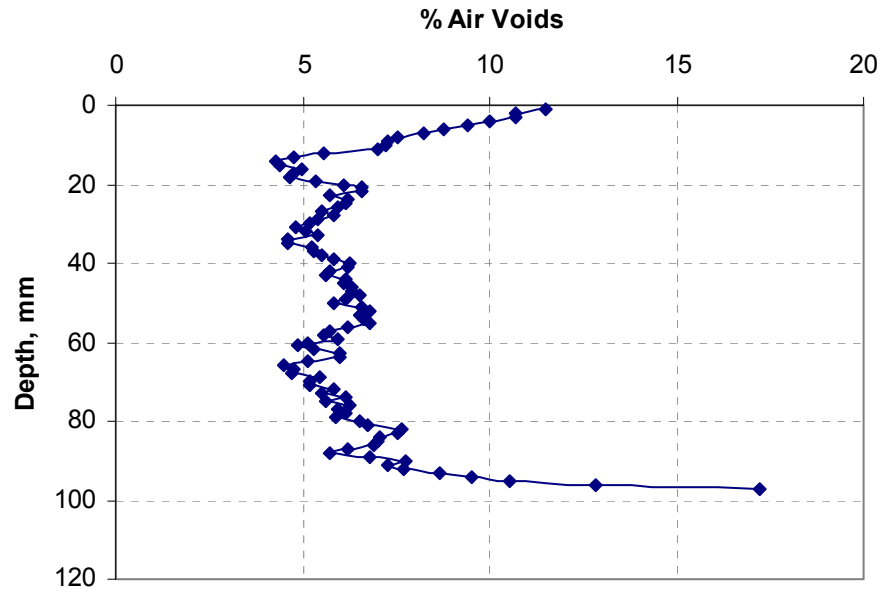


Figure 9-7. X-ray CT Image.

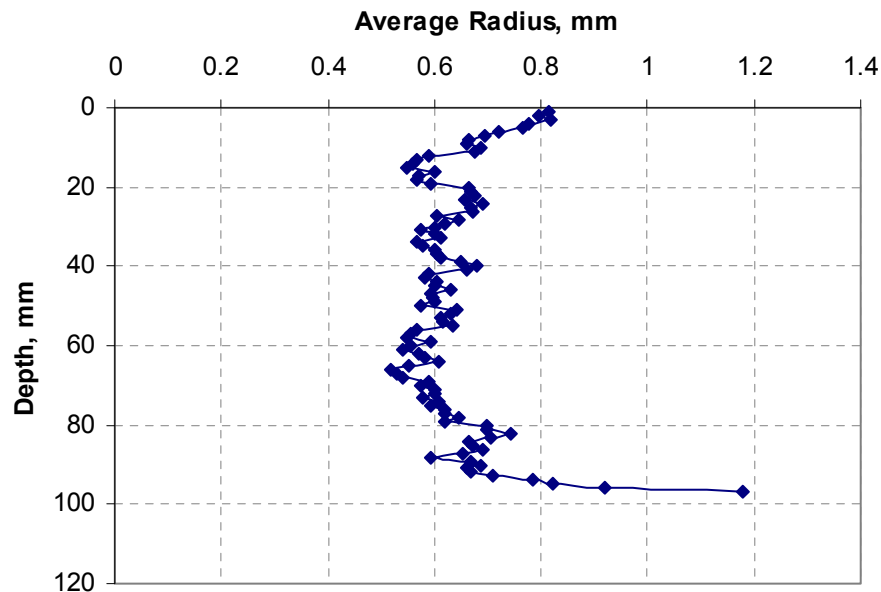
DIFFUSION COEFFICIENTS RESULTS

The CR-7 datalogger recorded the microvolts measured by the psychrometers. Figure 9-9 shows an example of the change of the recorded microvolts over time for a test specimen. This pattern was similar for all test specimens. Because of water evaporation from the open end to the surrounding environment, the suction increased and hence the recorded microvolts increased as well. The three stages shown in Figure 9-9 correspond to those discussed earlier in Figure 9-2. In Stage I and Stage III the suction values were out of the psychrometer's range, and only microvolt values recorded in Stage II were considered in determining the diffusion coefficient. Calibration curves

similar to the one shown in Figure 9-3 were used to convert microvolt values in Stage II to suction values as shown in Figure 9-10. All psychrometers operated successfully within the range of 3.75 pF to 4.5 pF .



(a)



(b)

Figure 9-8. (a) Distribution of Percent Air Voids Distribution along Depth, (b) Distribution of Average Air Void Radius along Depth.

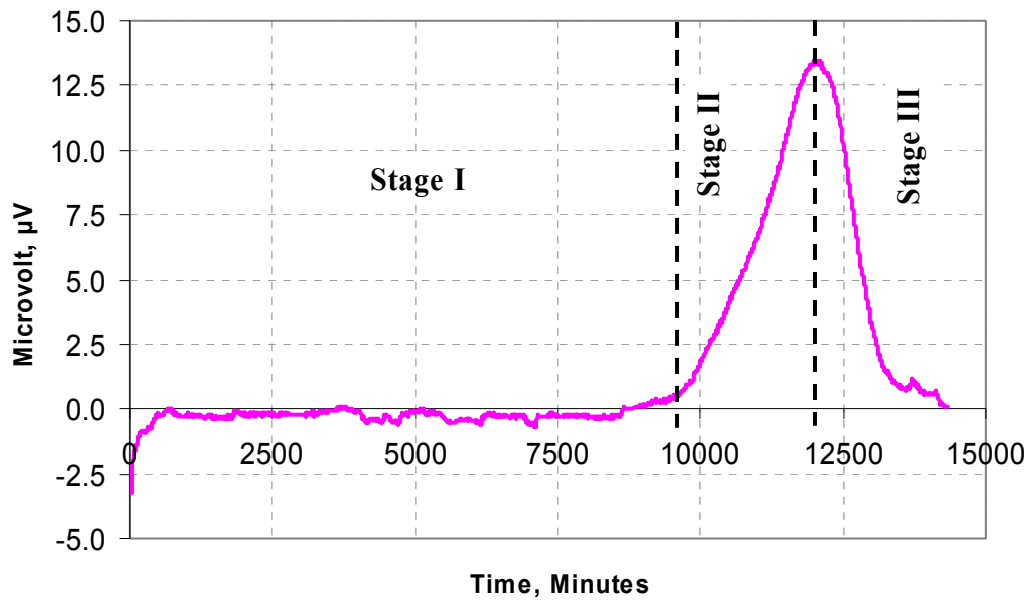


Figure 9-9. Change of Recorded Microvolts over Time.

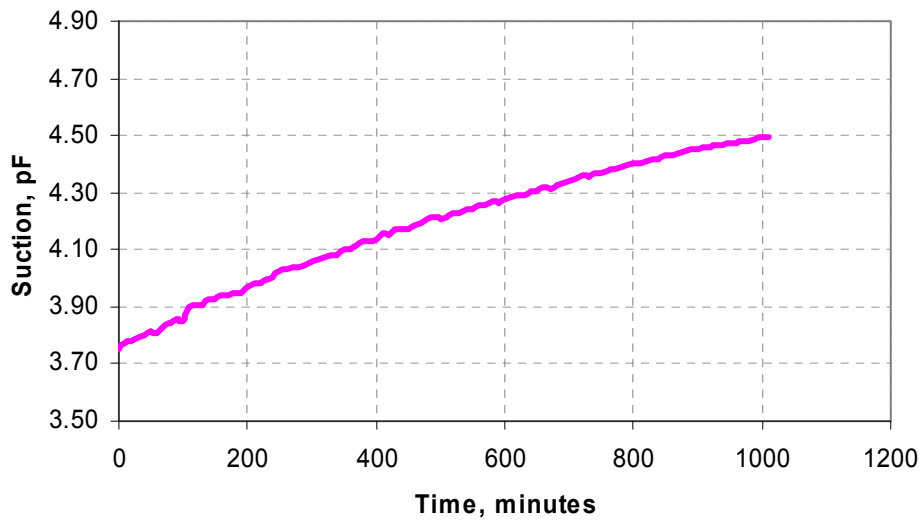


Figure 9-10. Change of Suction over Time (Stage II).

The atmospheric suction is required for the solution of [Equation 9-25](#). The atmospheric suction of the air in the laboratory was determined by measuring the relative humidity in the air with a Sling psychrometer. A Sling psychrometer consists of two thermometers (wet-bulb thermometer and dry-bulb thermometer). The wet-bulb

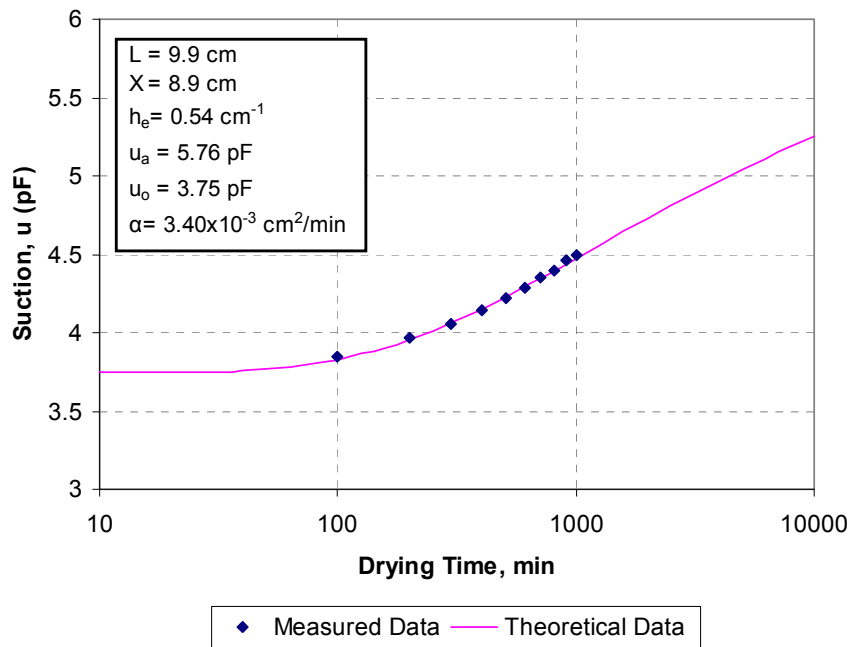
thermometer measures the saturation temperature, (T_{wb}) while a dry-bulb thermometer measures the air temperature (T_{db}). The wet bulb has a cloth wick over its bulb. Before taking readings, the cloth wick was dipped in water, and the instrument was rotated or whirled. The water evaporates from the cloth wick and cools the wet bulb. The degree of cooling depends on the evaporation rate, which depends on the relative humidity in the surroundings. The measured T_{wb} and T_{db} are employed to determine the relative humidity using psychrometric charts (Sood, 2005). The measured relative humidity was around 66 percent, which corresponds to an atmospheric suction of 5.76 pF at 25°C using Equation 9-1. The diffusion coefficients of test specimens were determined as follows:

- Assumed an initial value of diffusion coefficient and refined by iteration; used this value to calculate the theoretical suction value in Equation 9-25.
- Determined the square difference or error (E^2) between the theoretical suction using Equation 9-25, and the suction measured using the psychrometer over time as follows:

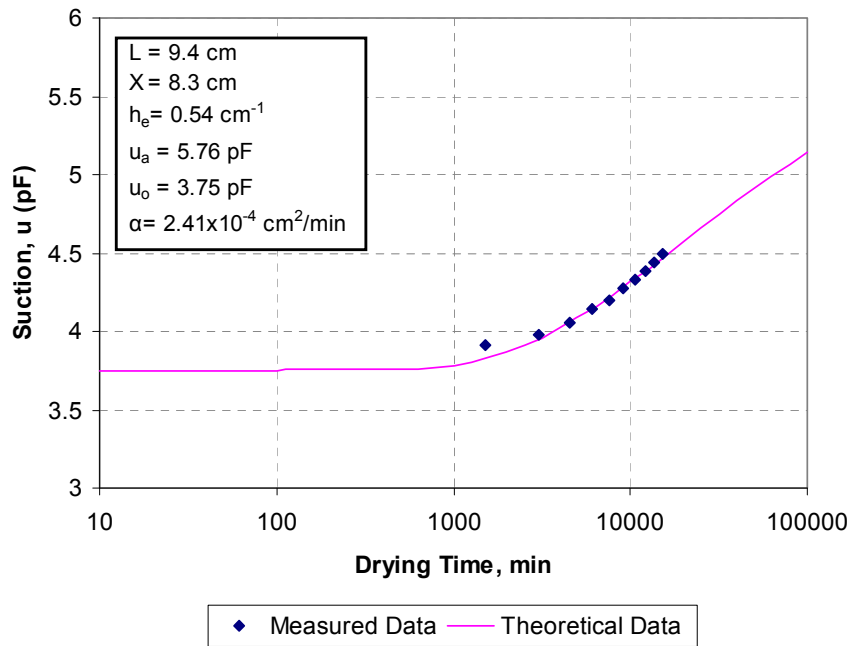
$$E^2 = \sum (u_{Theoretical} - u_{measured})^2 \quad (9-29)$$

- Determined the diffusion coefficient which minimized the square error.

The calculated diffusion coefficient was used to generate the theoretical change of suction over time using Equation 9-25. Figure 9-11 presents an example of change of theoretical suction and measured suction over time. It can be seen that there is very good correlation between the laboratory suction measurements and the theoretical curve.



(a)



(b)

**Figure 9-11. Change in Measured and Theoretical Suction over Time with
 (a) Higher Percent Air Void above Psychrometers,
 (b) Less Percent Air Void above Psychrometers.**

Table 9-3 presents the diffusion coefficient values measured in the laboratory in this research study. Table 9-3 also gives the percent of total air voids, average radius of percent air voids, percent of connected air voids, and average radius of percent connected air voids within the asphalt mixture from the location of the psychrometer to the open-end of the specimen where the moisture evaporation takes place. These air void characteristics were determined by analyzing the X-ray CT images that belong to the region above the psychrometer. A wide range of diffusion coefficients (from $5.67 \times 10^{-5} \text{ cm}^2/\text{sec}$ to $2.92 \times 10^{-6} \text{ cm}^2/\text{sec}$) were obtained for the given asphalt concrete samples.

Table 9-3. Summary of Test Results.

Sample	Length of specimens	Distance from closed end	α	Total Air Voids		Connected Air Voids	
				% Air Voids	R, mm	% Air Voids	R, mm
WR-C1	9.90	8.90	5.12E-05	11.86	0.962	9.75	1.120
WR-C2	9.90	8.90	5.67E-05	12.88	1.018	10.53	1.274
WR-C3	9.90	9.00	3.47E-05	10.13	0.739	7.72	0.894
WR-C1(2)	9.10	8.00	4.02E-06	6.03	0.623	2.17	0.576
WR-C3(2)	9.00	7.80	3.47E-06	7.30	0.606	3.85	0.634
WR-F1	6.50	5.60	4.57E-06	6.37	0.528	4.28	0.604
WR-F2	6.40	5.40	9.52E-06	4.69	0.568	2.98	0.720
WR-F3	9.40	8.20	6.22E-06	7.57	0.623	3.48	0.662
WR-F3(2)	10.00	8.60	6.77E-06	7.90	0.590	4.00	0.644
GA-C2	8.90	7.95	5.12E-06	4.91	0.607	2.54	0.563
GA-C3	8.40	7.30	2.92E-06	4.81	0.559	1.73	0.486
GA-F1	9.30	8.40	2.92E-06	6.23	0.529	1.74	0.730
GA-F2	8.80	7.60	3.47E-06	5.72	0.522	3.28	0.584

The measured diffusion coefficients varied among the different specimens although all specimens were prepared with approximately 7 percent air voids. In the region of the asphalt mixture specimen above the psychrometer, however, the diffusion coefficient values were related to the percent air voids. This can be attributed to the fact that moisture loss and change in suction occur more rapidly toward the open side of the specimen (top side) where the psychrometer was placed. Initially, the researchers employed three psychrometers in the test specimen—one at the top (1 centimeter below the top surface), one in the middle of the test samples, and one near to the sealed end. The psychrometers placed in the middle and close to the bottom of a specimen experienced no change in suction measurements. This can be attributed to the fact that the diffusion coefficient of HMA is small, and it might need more time for the middle and end psychrometers to detect the change in suction. Therefore, we concluded that the measurements conducted by the psychrometer represent the suction level and moisture diffusion in the region above the psychrometer's level.

[Figure 9-12](#) shows the relationship between the measured diffusion coefficients and total percent air voids and connected percent air voids above the psychrometers. [Figure 9-13](#) presents the relationship between the average air void size for total and connected air voids and the measured diffusion coefficients. It is interesting to note that the average air void size of connected air voids is higher than the average size of total air voids, which indicates that the connected air voids are larger than the unconnected air voids. The diffusion coefficient strongly correlates to the average percent of air voids and the average radius of the air voids above the psychrometers. However, better correlation exists between the diffusion coefficients and connected air voids. The results show that moisture diffusion is controlled by air void percent and size. This is caused by the fact that moisture diffusion in air voids is much higher than in the other phases (aggregates and mastic) as shown in the diffusion values in [Table 9-4](#).

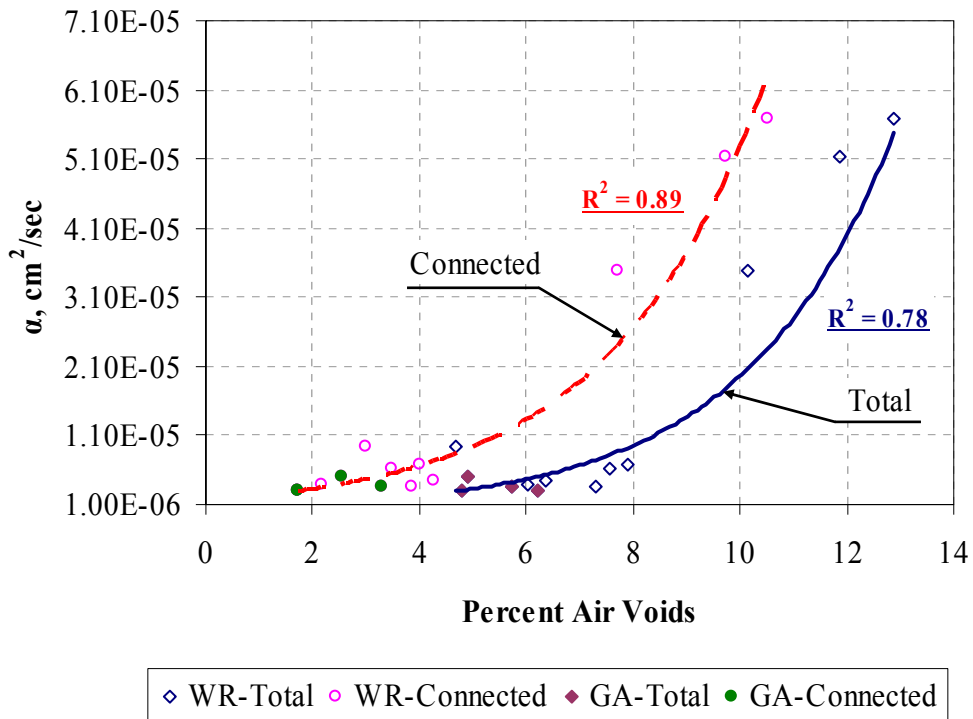


Figure 9-12. Relationship between Diffusion Coefficients and Percent of Air Voids above Psychrometers.

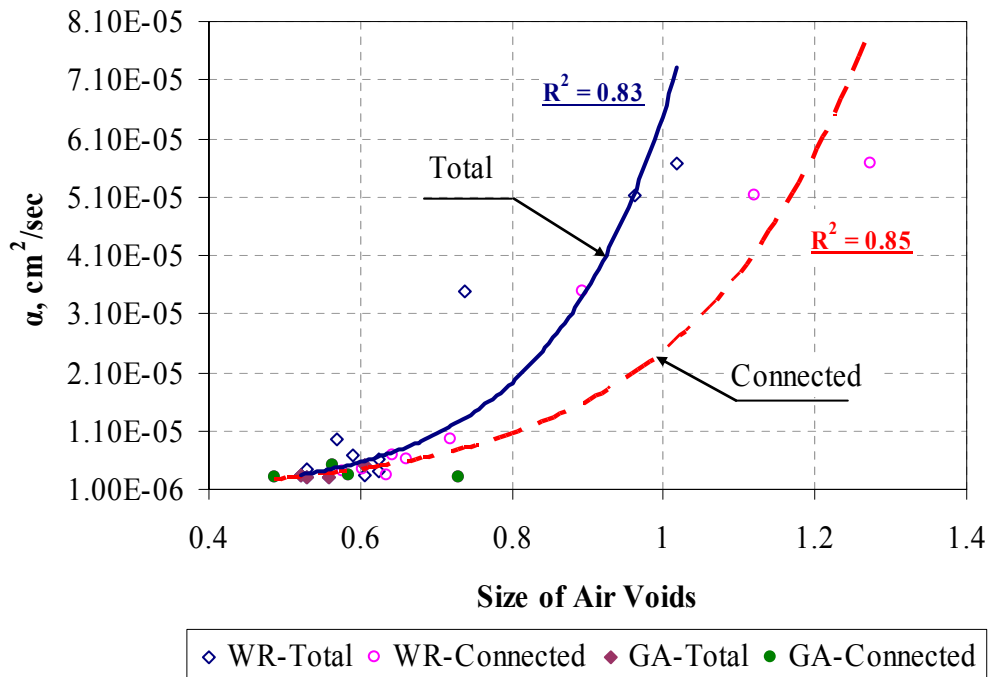


Figure 9-13. Relationship between Diffusion Coefficients and Air Void Size above Psychrometers.

Table 9-4. Diffusion Coefficients of Different Phases within HMA.

Phase	Range of Diffusion Coefficient cm²/sec	Reference
Air Void	0.264	Montgomery (1947)
	0.260	Geankoplis (1993)
Mastic	6.43×10^{-8} to 3.5×10^{-7}	Kassem et al. (2006)
Aggregates	Limestone: 3.33×10^{-7} to 2.42×10^{-6}	Kringos et al. (2007)
	Granite: 8.06×10^{-7} to 1.94×10^{-6}	

CONCLUSIONS

Moisture diffusion is one mechanism by which the water can get into an asphalt mixture causing moisture damage. In a previous study, the authors measured the diffusion coefficient of asphalt mastic. In this study, an experimental procedure was developed to measure the diffusion coefficient of full asphalt mixtures. To the best knowledge of the authors, the diffusion coefficient for asphalt mixtures was not measured in the past.

The experimental procedure relies on measuring the change in suction during moisture evaporation in asphalt mixtures. The range of the diffusion coefficients of asphalt mixtures was determined to be in between 5.67×10^{-5} and 2.92×10^{-6} cm²/sec.

The air void phase within asphalt mixtures was found to control the rate of moisture diffusion in asphalt mixtures. The correlation of the diffusion coefficient value with connected air voids was better than the correlation with total percent air voids. The measured diffusion coefficient is a necessary input for modeling moisture transport and predicting moisture damage in asphalt mixtures.

CHAPTER 10

CONCLUSIONS

This study focused on evaluating the influence of different field compaction patterns on uniformity of air void distribution in asphalt pavements. It also examined the influence of changing some parameters in the laboratory compaction on mechanical properties and resemblance of laboratory compaction to field compaction. Researchers have also conducted forensic evaluation in which the air void distribution measured using X-ray CT was compared with the results of Ground Penetrating Radar. The effect of nonuniformity of the air void distribution on the moisture diffusion through the asphalt pavements was evaluated by measuring diffusion coefficients of asphalt mixtures. The following points summarize the main findings from this study.

EVALUATION OF FIELD COMPACTION

- The analysis results of various pavement sections compacted using different patterns provided experimental evaluation of the influence of the field compaction pattern on the uniformity of air void distribution in asphalt pavements. The X-ray CT images along with the locations of the cores were used to generate air void maps in the pavement. These maps are useful to relate air void distributions to the compaction pattern.
- The efficiency of compaction at a given point is a function of the location of this point with respect to the roller width. Therefore, a new index referred to as the Compaction Index (CI) is proposed to quantify the compaction effort at any point in the pavement. This index is the summation of the multiplication of each pass with an effectiveness factor. The effectiveness factor at a point is a function of the location of the point with respect to the roller width. A point on the mat closer to the center of the roller is subjected to more effective compaction than a point closer to the edge of the roller.
- It is demonstrated that the CI is useful to set up the compaction pattern in order to achieve uniform percent air voids; a more uniform CI corresponds to more uniform air voids.

- The use of the pneumatic roller in the breakdown stage was found to be effective in reducing the percent air voids and improving uniformity in the top half of the lift thickness of the mixtures used in this study.
- It has been reported in the past that the mixture near longitudinal joints is usually less compacted than the mixture toward the center of the pavement. This has been attributed to the lower confinement, typically lower number of passes and the faster rate of heat loss at the joint compared with the center of the pavement. Based on the results of this study, the low compaction at the joint is also attributed to the low effectiveness factor due to the relative location of the joint with respect to the roller width.
- The results suggest that the joints need to be compacted to a higher CI compared with the center of the pavement to compensate for the other factors that reduce joint compactability. This can be achieved by overhanging the steel rollers by at least 2 ft from the edge. The compaction of a confined joint resulted in lower and more uniform air voids than compaction of an unconfined joint.

EVALUATION OF LABORATORY COMPACTION

- In general, laboratory specimens compacted using a 2.0° gyratory angle performed slightly better in Hamburg tests than specimens compacted using a 1.25° gyratory angle.
- Overlay test results did not show any difference among the lab prepared specimens compacted using 1.25° or 2.0° angles.
- There is no trend indicating that permeability in gyratory specimens is influenced by the angle of gyration.
- Laboratory compacted samples had comparable rut depth to field cores when percent air voids was similar.
- There was a slight influence of compaction pattern on the Hamburg results. However, there was no trend indicating an influence of compaction pattern on the overlay testing results or permeability results. The variability in the overlay testing results might have overshadowed the influence of compaction pattern or resistance to fracture as measured using the overlay tester.

- Hamburg results were found to be more related to the average percent of air void rather than the air void structure. Field cores with less average percent of air void performed better than the ones that had higher percent of air void.
- The overlay test results clearly show that specimens prepared to have uniform air void distribution had less variation in the failure number of cycles than all other cases. Based on this finding, it is recommended to cut the top and the bottom parts of the laboratory samples for the overlay test in order to improve air void uniformity and reduce the test variability.
- There is a relationship between temperature profile and air void distribution. Improvement of the uniformity of temperature profile is associated with uniformity in air void distribution. However, this relationship is weak and does not warrant changes to the compaction temperature at this point.
- The air void distribution is more uniform for specimens prepared using a modified binder compared with specimens prepared with an unmodified binder.
- The middle third of a specimen is more uniform than the whole specimen. This is consistent with findings from previous studies.

COMPARISON OF X-RAY CT WITH GROUND PENETRATING RADAR

- The GPR was able to detect and show the extent of the compaction problem in the new pavement investigated in this study. The GPR detected low density areas typically at the bottom of the stone filled layers. These layers were placed in 4 inch lifts, and it appears that the bottom 1 inch of the lift was poorly compacted.
- The color-coded image display of GPR data was very useful in quantifying the depth and extent of both water filled and air filled voids within the HMA layer. This information was used to generate a strategy to drain trapped moisture from the pavement structure.
- The X-ray CT results were in very good agreement with the GPR measurements as it showed that the section with stone filled mix had more nonuniform air void distribution and larger air voids than the sections with conventional dense graded asphalt mix. Based on the results, it is recommended to make adjustments to the design of the stone filled mixtures used in Texas to allow better compaction.

AIR VOIDS DISTRIBUTION AND MOISTURE DIFFUSION

- The effect of nonuniformity air void distribution on the moisture diffusion was investigated by measuring the moisture diffusion coefficients of asphalt mixtures.
- The diffusion coefficients of asphalt mixtures were measured in laboratory for the first time. The range of the diffusion coefficients was between 5.66E-5 and 2.92E-6 cm²/sec.
- Higher percent of air voids at the top surface of the test samples expedited the moisture flow compared with less percent of air voids at the top.
- The size of air voids was found to be subjected with the percent of air voids. Higher percent of air voids yield larger air void size. The size of air voids at the top surface of the test samples correlated well with the measured diffusion coefficients.

REFERENCES

- Birgisson, B., Roque, R., and Page G. (2003). "Evaluation of Water Damage Using Hot Mix Asphalt Fracture Mechanics," *Journal of the Association of the Asphalt Paving Technologists*, Vol. 72, pp. 424-462.
- Birgisson, B., Roque, R., and Page, G. (2004). "The Use of a Performance-Based Fracture Criterion for the Evaluation of Moisture Susceptibility in Hot Mix Asphalt," In *Transportation Research Record* 3431, TRB, National Research Council, Washington, D.C., pp. 55-61.
- Bulut, R., and Wray, W.K. (2005). "Free Energy of Water – Suction – in Filter Papers," *Geotechnical Testing Journal*, Vol. 28(4), pp. 355-364.
- Bulut, R., and Leong, E. C. (2008). Indirect Measurement of Suction, *Journal of Geotechnical and Geological Engineering*, Vol. 26.
- Button, J.W., Little, D.N., Jagadam, V., and Pendleton, O.J. (1994). "Correlation of Selected Laboratory Compaction Methods with Field Compaction," In *Transportation Research Record* 1454, TRB, National Research Council, Washington, D. C., pp. 193-201.
- Caro, S., Masad, E., Bahsin, A., and Little, D.N. (2008). "Moisture Susceptibility of Asphalt Mixtures, Part 1: Mechanisms," *International Journal of Pavement Engineering*, 8(2), 81-98
- Consuegra, A., Little, D.N., Quintus, H.V., and Burati, J. (1989). "Comparative Evaluation of Laboratory Compaction Devices Based on Their Ability to Produce Mixtures with Engineering Properties Similar to Those Produced in the Field," In *Transportation Research Record* 1228, TRB, National Research Council, Washington, D.C., pp. 80-87.

- Corps of Engineers (2000). "Hot-Mix Asphalt Paving Handbook 2000," AC 150/5370-14A, US Army Corps of Engineers, Washington, D.C.
- Edlefsen, N.E, and Anderson, A.B.C. (1943). "Thermodynamics of Soil Moisture," *Hilgardia*, Vol. 15, pp. 31-298.
- Fredlund, D.G., and Rahardjo, H. (1993). "*Soil Mechanics for Unsaturated Soils*," John Wiley & Sons, Inc., New York.
- Geankoplis, C.J. (1993). *Transport Processes and Unit Operations*, third ed., PTR Prentice Hall Inc., Englewood Cliffs, New Jersey.
- Guler, M., Bosscher, P.J., and Plesha, M.E. (2002). "A Porous Elasto-Plastic Compaction Model for Asphalt Mixtures with Parameter Estimation Algorithm," *Geotechnical Special Publication No.123*, ASCE, pp. 126-143.
- Harvey, J., and Monismith, C.L. (1993). "Effects of Laboratory Asphalt Concrete Specimen Preparation Variables on Fatigue and Permanent Deformation Test Results Using Strategic Highway Research Program A-003A Proposed Testing Equipment," In *Transportation Research Record 1417*, TRB, National Research Council, Washington, D.C., pp. 38-57.
- Huerne, H.L. (2004). "Compaction of Asphalt Road Pavements: Using Finite Elements and Critical State Theory," Thesis Project, CT&M Dept., University of Twente, Enschede, Netherlands.
- Image-Pro[®] Plus (1999). Media Cybernetics, L.P. Georgia, M.D. Version 4.1.
- Kassem, E.A. (2005). "Measurements of Moisture Suction in Hot Mix Asphalt Mixes," MSc. Thesis, Texas A&M University, College Station, Texas.

- Kassem, E., Masad, E., Bulut, R., and Lytton, R. (2006). "Measurements of Moisture Suction and Diffusion Coefficient in Hot Mix Asphalt and Their Relationships to Moisture Damage," *Transportation Research Record: Journal of the Transportation Research Board*, 1970, pp. 45-54.
- Kringos, N., and Scarpas, A. (2005a). "Raveling of Asphaltic Mixes Due to Water Damage: Computational Identification of Controlling Parameters," *Transportation Research Record: Journal of the Transportation Research Board*, 1929, pp. 79-87.
- Kringos, N., and Scarpas, A. (2005b). "Simulation of Combined Mechanical-Moisture Induced Damage in Asphaltic Mixes," *In First International Workshop on Moisture Damage*, Delft University of Technology, Delft, Netherlands, 2005b (in CD-ROM).
- Kringos, N., Scarpas, A., and Kasbergern, C. (2007). "Three Dimensional Elasto-Viscoplastic Finite Element Model for Combined Physical-Mechanical Moisture Induced Damage in Asphaltic Mixes," *Journal of the Association of Asphalt Paving Technologists*, Vol. 76.
- Krishnan J.M., and Rao, C.L. (2000). "Mechanics of Air Voids Reduction of Asphalt Concrete Using Mixture Theory," *International Journal of Engineering Science*, Vol. 38(12), pp. 1331-1354.
- Laliberte, G.E., and Corey, A.T. (1967). "*Hydraulic Properties of Disturbed and Undisturbed Soils. Permeability and Capillary of Soils*," ASTM, Philadelphia, pp. 56-71.
- Masad, E., Muhunthan, B., Shashidhar, N., and Harman, T. (1999a). "Internal Structure Characterization of Asphalt Concrete Using Image Analysis," *Journal of Computing in Civil Engineering (Special Issue on Image Processing)*, ASCE, Vol. 13(2), pp. 88-95.

- Masad, E.A., Muhunthan, B., Shashidhar, N., and Harman, T. (1999b). "Quantifying Laboratory Compaction Effects on the Internal Structure of Asphalt Concrete," In *Transportation Research Record, Journal of the Transportation Research Board 1681*, pp. 179-184.
- Masad E. (2004). "X-ray Computed Tomography of Aggregates and Asphalt Mixes," *Materials Evaluation/July*, pp. 775-783.
- Masad, E., Al-Omari, A., and Lytton, R. (2006). "Simple Method for Predicting Laboratory and Field Permeability of Hot Mix Asphalt," In *Transportation Research Record 1970*, TRB, National Research Council, Washington, D.C., pp. 55-63.
- Masad, E., Arambula, E., Ketcham, R., Abbas, A., and Epps Martin, A. (2007). "Nondesructive Measurements of Moisture Transport in Asphalt Mixtures," *Journal of the Association of Asphalt Paving Technologists*, Vol. 76, pp. 919-952.
- Matlab Software (2004). The MathWorks Inc., Natick, Massachusetts, Version 7.
- Mitchell, P.W. (1979). "*The Structural Analysis of Footings on Expansive Soil*," Report Research No. 1, K.W.G. Smith and Assoc. Pty. Ltd., Newton, South Australia.
- Monismith, C.L. (1992). "Analytically Based Asphalt Pavement Design and Rehabilitation," In *Transportation Research Record 1354*, TRB, National Research Council, Washington, D.C., pp. 5-26.
- Montgomery, R.B. (1947). Viscosity and Thermal Conductivity of Air and Diffusivity of Water Vapor in Air, *Journal of Meteorology*, 4, 193-196.

- Newcomb, D.E, Buncher, M., and Huddleston, I.J. (2001). "Concepts of Perpetual Pavements." *Transportation Research Circular on Perpetual Bituminous Pavements*, TRB, Washington D.C., pp.4-11.
- Partl, A., Flisch, A., and Jönsson, M. (2003). "Gyratory Compaction Analysis with Computer Tomography." *International Journal of Road Materials and Pavement Design*, Vol. 4(4), pp. 401-422.
- Partl, A., Flisch, A., and Jönsson, M. (2007). "Comparison of Laboratory Compaction Methods Using X-ray Computer Tomography." *International Journal of Road Materials and Pavement Design*, Vol. 8(2), pp. 139-164.
- Peterson, B., Mahboub, K., Anderson, M., Masad, E., and Tashman, L. (2004). "Comparing Superpave Gyratory Compactor Data to Field Cores," *Journal of Materials in Civil Engineering, ASCE*, Vol. 16(1), pp. 78-83.
- Roberts F.L., Kandhal, P.S., Brown, E.R., Lee D., and Kennedy, T.W. (1996). "*Hot Mix Asphalt Materials, Mixture Design and Construction*," National Asphalt Pavement Association, Research and Education Foundation, Lanham, Maryland.
- Scullion, T., and Chen, Y. (1999). "COLORMAP Version 2, User's Manual with Help Menus," TTI, 1702-4, College Station, Texas.
- Scullion, T. (2006). "Perpetual Pavements in Texas: The State of the Practice," TTI, 4822-1, College Station, Texas.
- Shashidhar, N. (1999). "X-ray Tomography of Asphalt Concrete," In *Transportation Research Record, Journal of the Transportation Research Board 1681*, pp. 186-191.

Sood, E. (2005). "Determination of Diffusion Coefficient for Unsaturated Soils," M.S. Thesis, Department of Civil Engineering, Texas A&M University, College Station, Texas.

Sousa, J.B., Harvey, J., Painter, L., Deacon, J.A., and Monismith, C.L. (1991). "Evaluation of Laboratory Procedures for Compacting Asphalt –Aggregate Mixtures," Report No. SHRP-A-UWP-91-523, Strategic Highway Research Program, National Research Council, Washington D.C.

Tashman, L., Masad, E., Peterson, B., and Saleh, H. (2001). "Internal Structure Analysis of Asphalt Mixes to Improve the Simulation of Superpave Gyratory Compaction to Field Conditions," *Journal of the Association of Asphalt Paving Technologists*, Vol. 70, pp. 605-645.

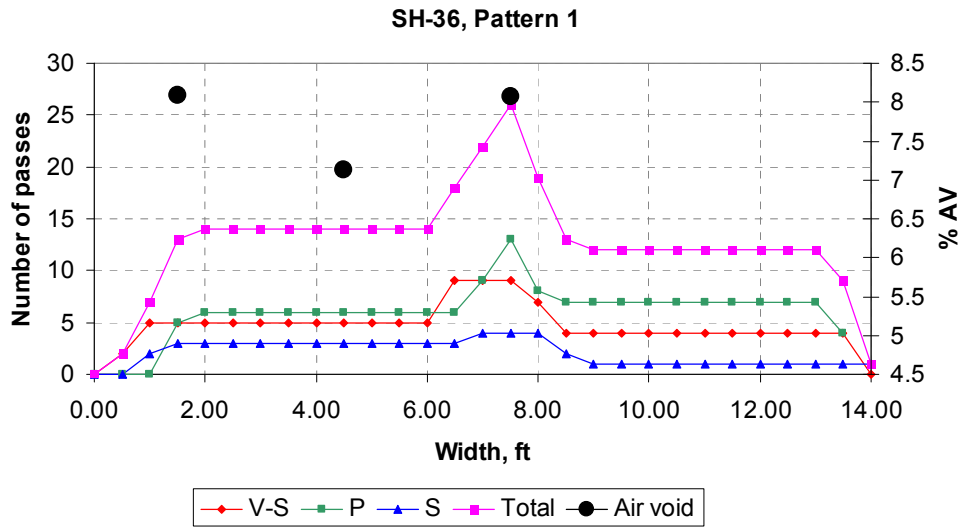
TxDOT (2001). "Memorandum on Full-depth Asphalt Pavements, Flexible Pavement Design Task Force Implementation," Texas Department of Transportation (TxDOT), Austin, Texas.

Walubita, L., and Scullion, T. (2007). "Perpetual Pavements in Texas: The Fort Worth SH 114 Project in Wise County," TTI, 4822-2F, College Station, Texas.

Zhou, F., and Scullion, T. (2003). "Upgraded Overlay Tester and Its Application to Characterize Reflection Cracking Resistance of Asphalt Mixtures," Research Report FHWA/TX-04/4467-1, TTI, College Station, Texas.

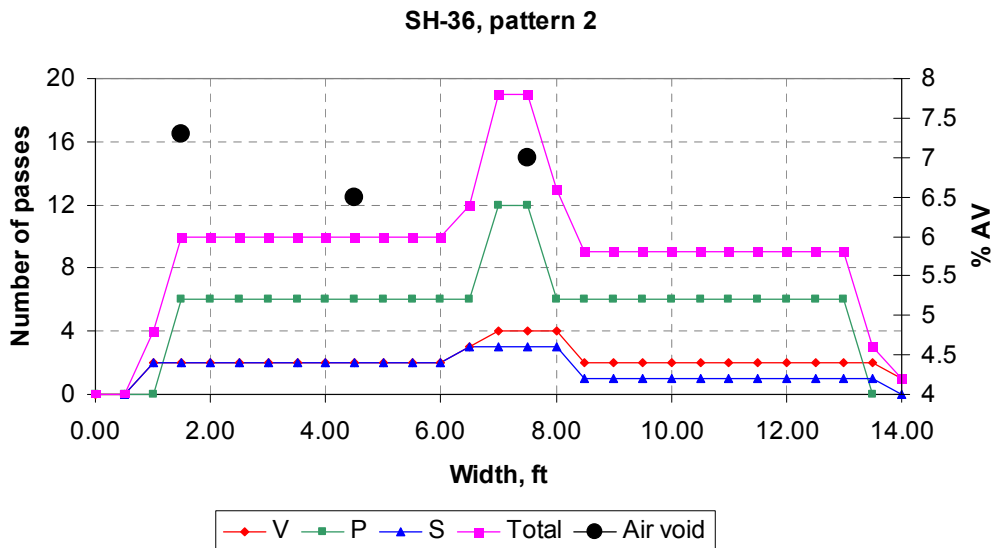
APPENDIX A

AIR VOIDS ANALYSIS RESULTS



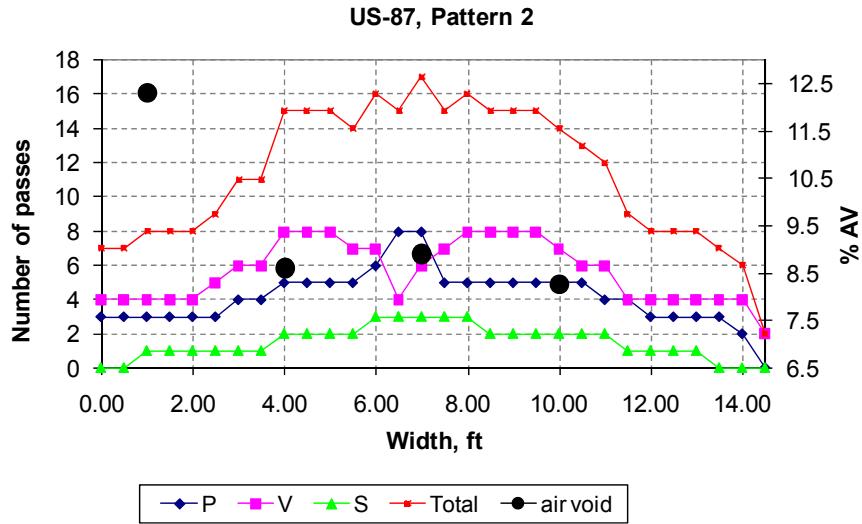
Note: Breakdown roller: vibratory and static (V-S), intermediate roller: pneumatic (P), finish roller: static (S).

Figure A-1. Number of Passes and the Percent of Air Voids across the Mat in SH-36 Test Section (Pattern 1).



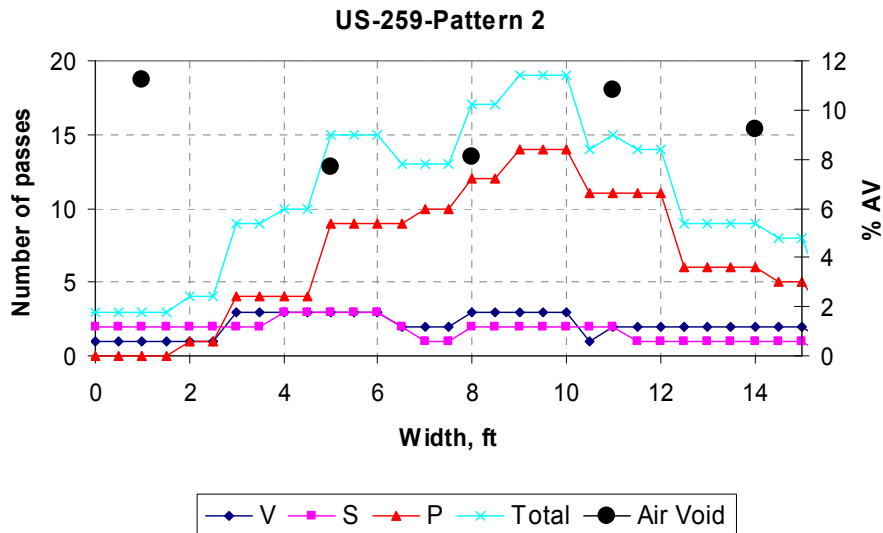
Note: Breakdown roller: vibratory (V), intermediate roller: pneumatic (P), finish roller: static (S).

Figure A-2. Number of Passes and the Percent of Air Voids across the Mat in SH-36 Test Section (Pattern 2).



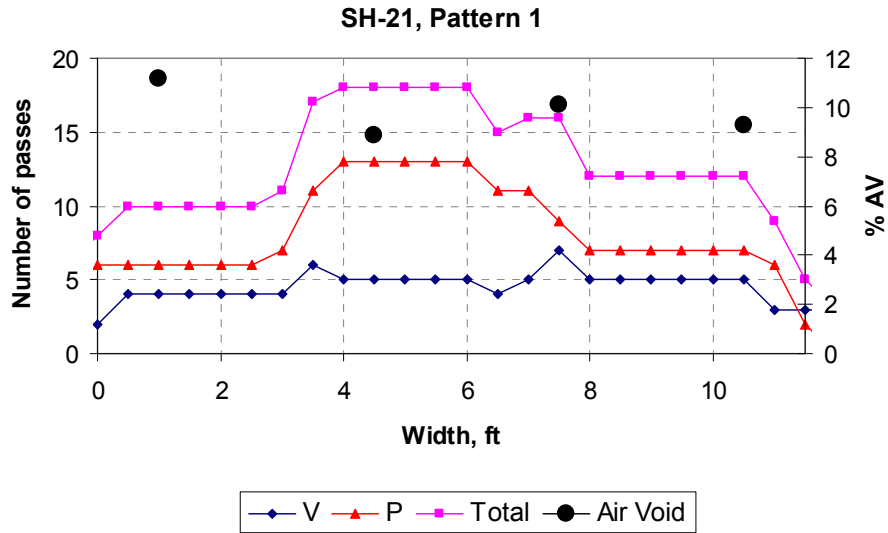
Note: Breakdown roller: pneumatic (P), intermediate roller: vibratory (V), finish roller: static (S).

Figure A-3. Number of Passes and the Percent of Air Voids across the Mat in US 87 Test Section (Pattern 2).



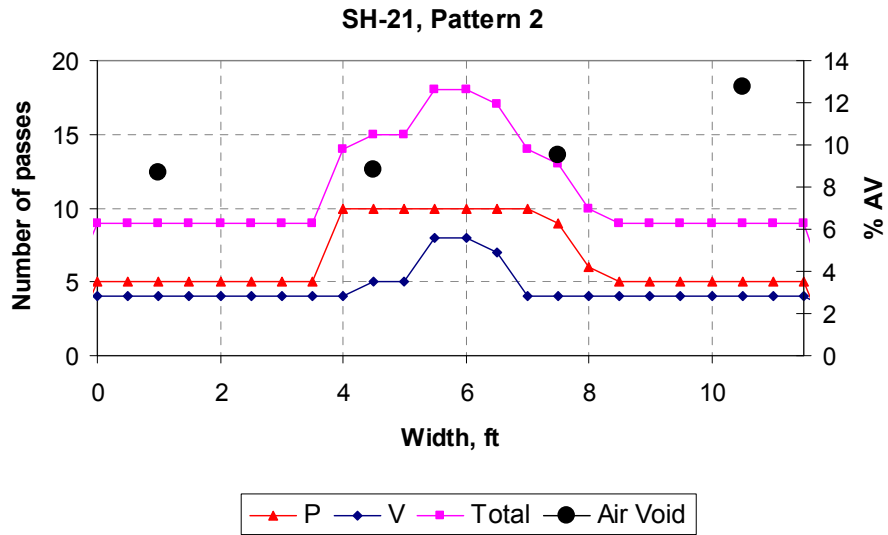
Note: Breakdown roller: vibratory (V), intermediate roller: static (S), finish roller: pneumatic (P).

Figure A-4. Number of Passes and the Percent of Air Voids across the Mat in US-259 Test Section (Pattern 2).



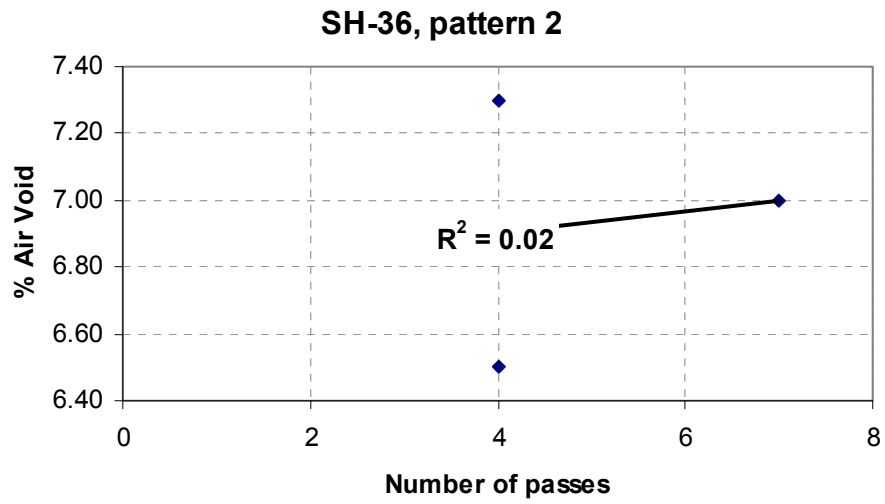
Note: Breakdown roller: vibratory (V), intermediate roller: pneumatic (P), finish roller: static (S). The static rollers were applied after the mat cooled down and not included herein.

Figure A-5 Number of Passes and the Percent of Air Voids across the Mat in SH-21 Test Section (Pattern 1).

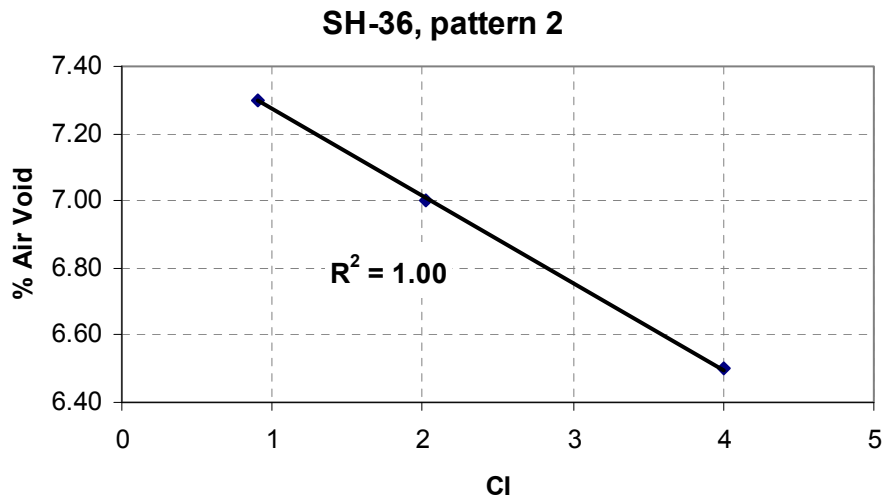


Note: Breakdown roller: pneumatic (P), intermediate roller: vibratory (V), finish roller: static (S). The static rollers were applied after the mat cooled down and not included herein.

Figure A-6. Number of Passes and the Percent of Air Voids across the Mat in SH-21 Test Section (Pattern 2).

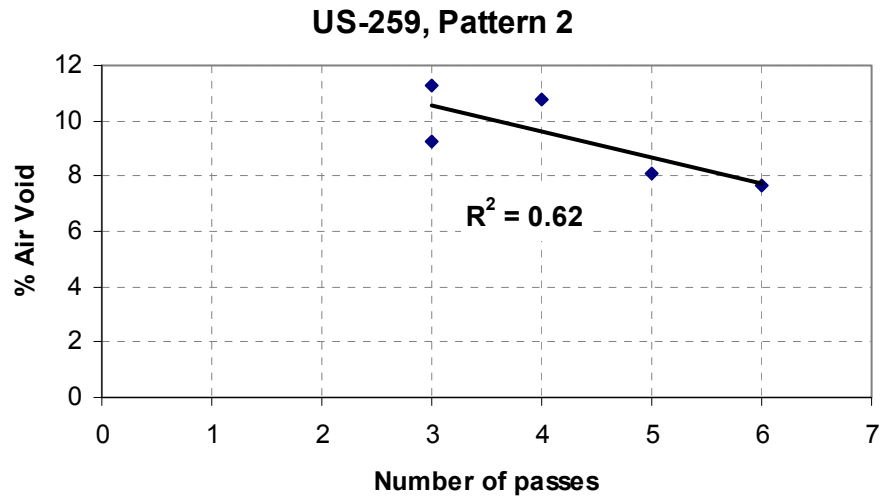


(a)

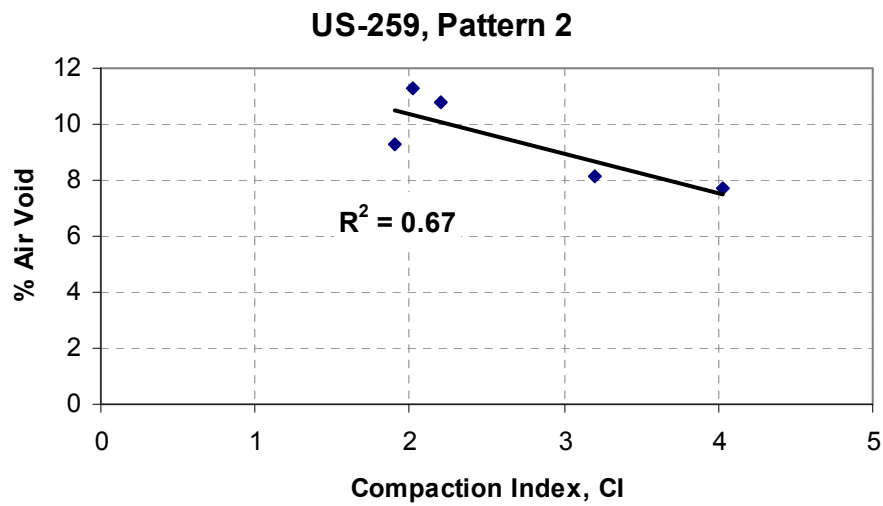


(b)

Figure A-7. (a) Number of Passes versus the Percent of Air Voids in SH-36 Test Section, (b) Compaction Index versus the Percent of Air Voids in SH-36 Test Section.

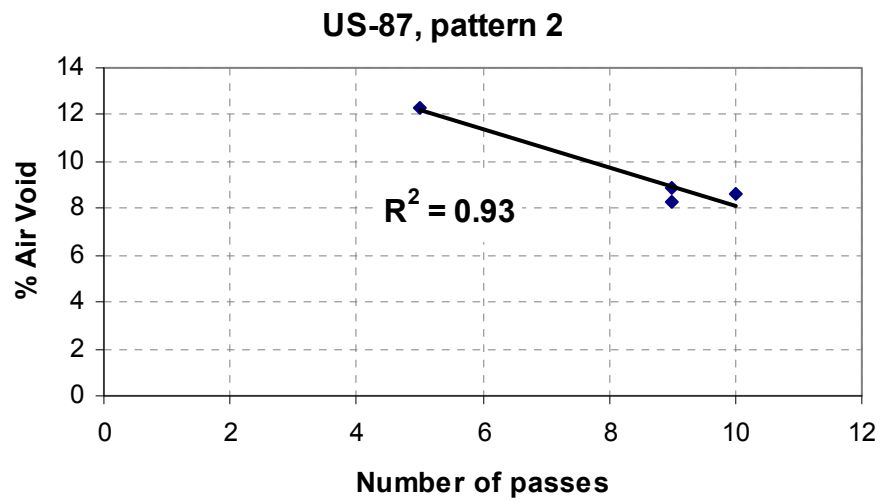


(a)

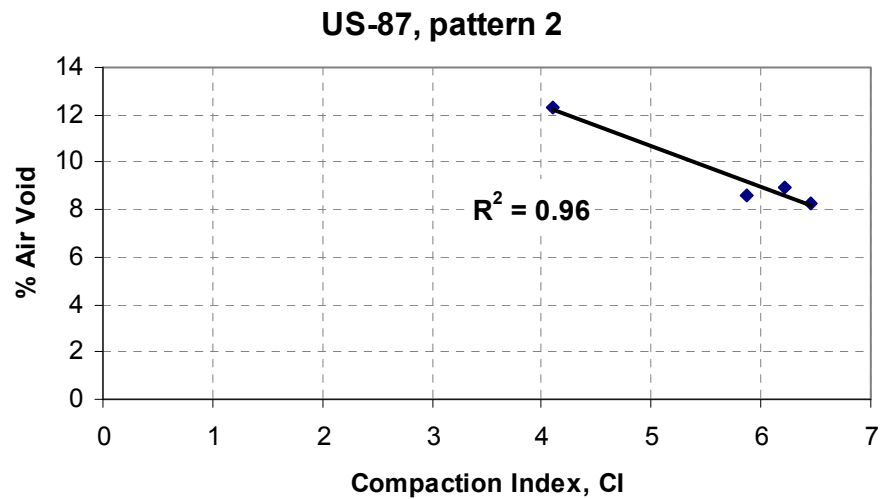


(b)

Figure A-8. (a) Number of Passes versus the Percent of Air Voids in US-259 Test Section, (b) Compaction Index versus the Percent of Air Voids in US-259 Test Section.

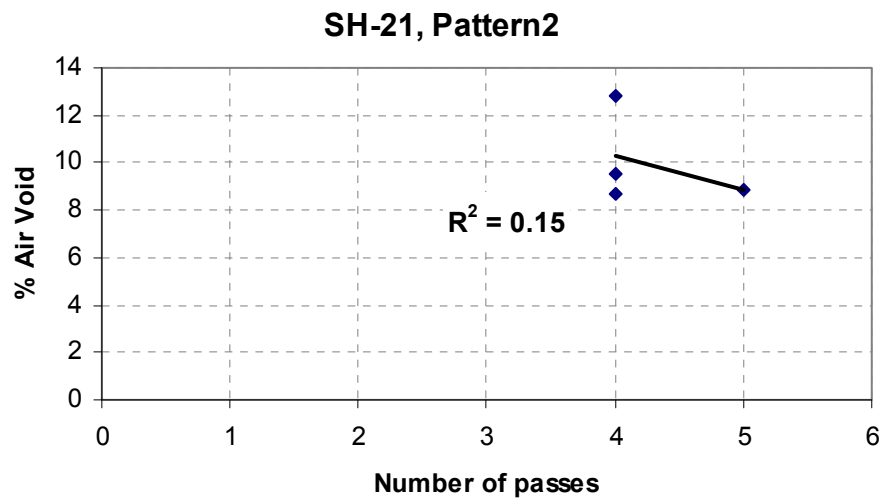


(a)

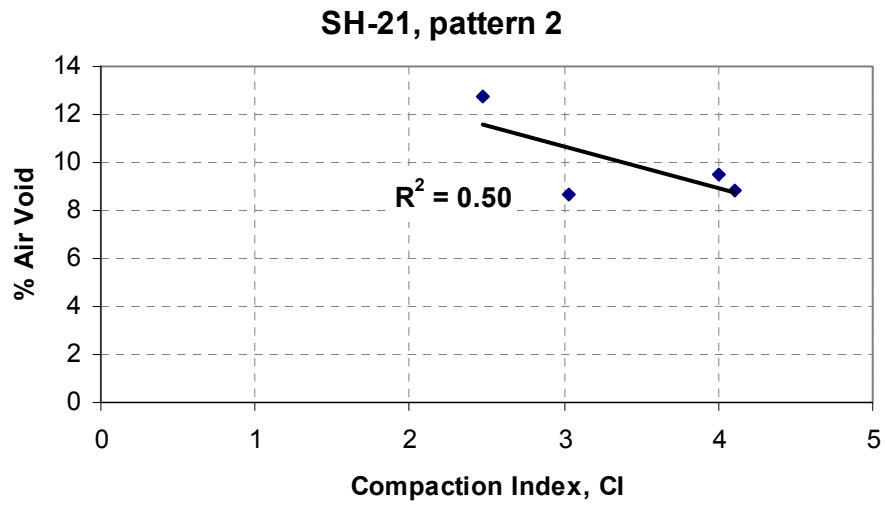


(b)

Figure A-9. (a) Number of Passes versus the Percent of Air Voids in US-87 Test Section, (b) Compaction Index versus the Percent of Air Voids in US-87 Test Section.

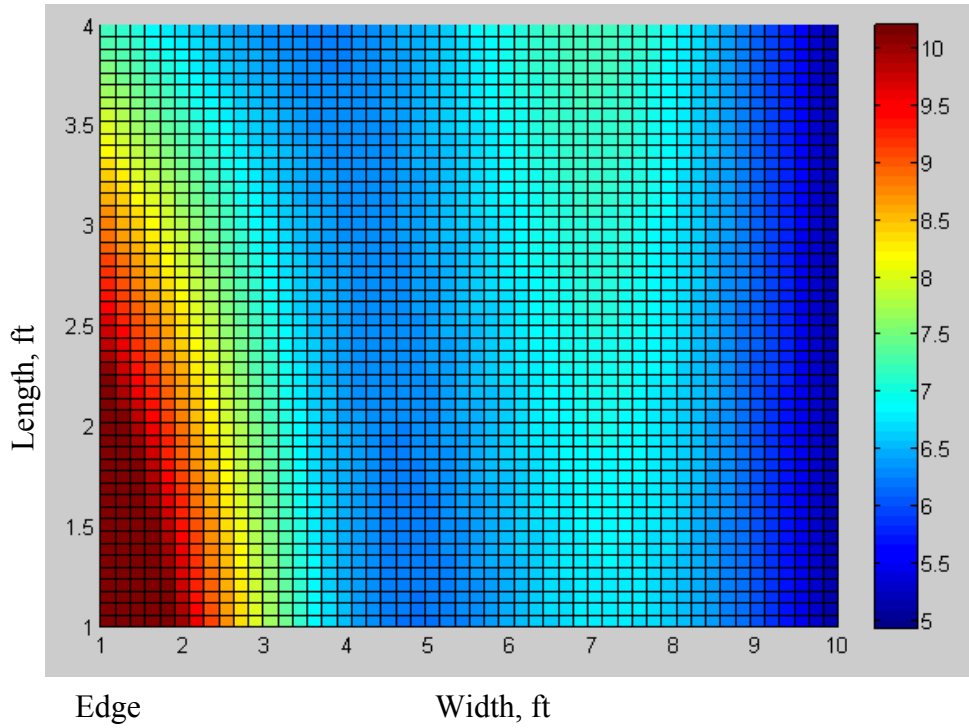


(a)

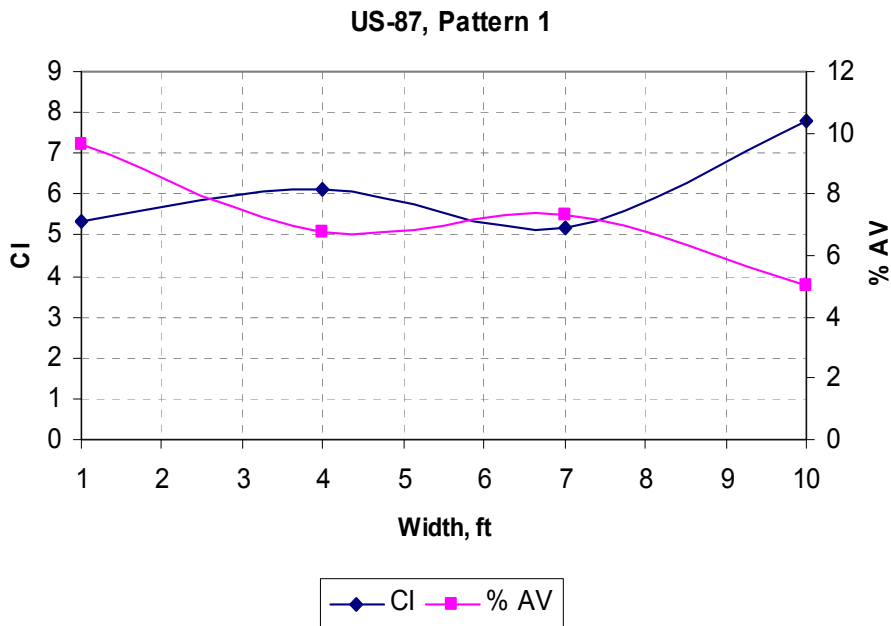


(b)

Figure A-10. (a) Number of Passes versus the Percent of Air Voids in SH-21 Test Section, (b) Compaction Index versus the Percent of Air Voids in SH-21 Test Section.



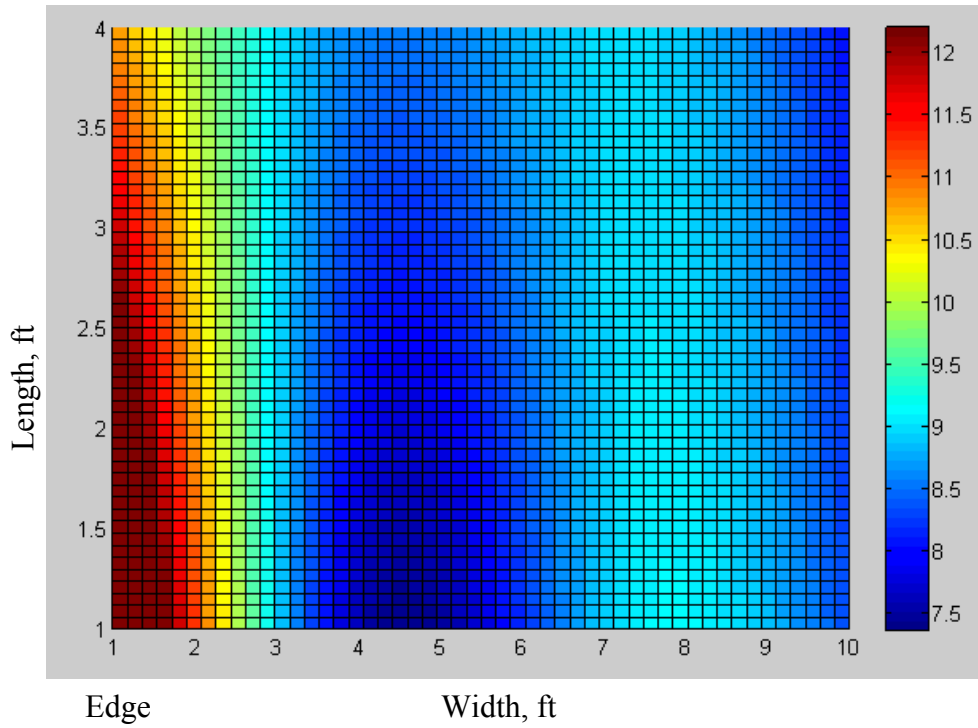
(a)



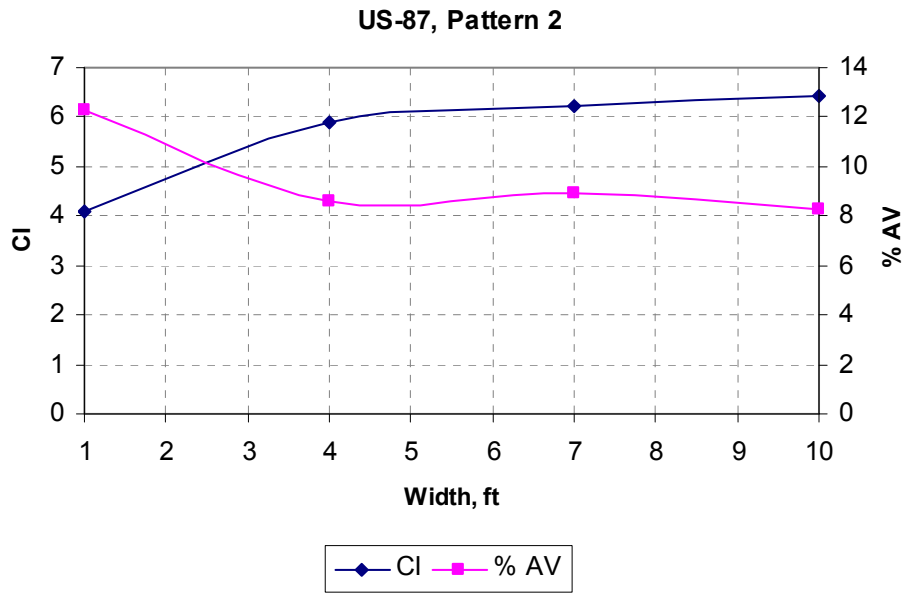
(b)

Note: The total width of the mat is 15 ft.

Figure A-11. (a) Air Void Distribution (%) across the Mat for US-87 Test Section Pattern 1, (b) The CI and Average Percent of Air Voids across the Mat for US-87 Test Section Pattern 1.



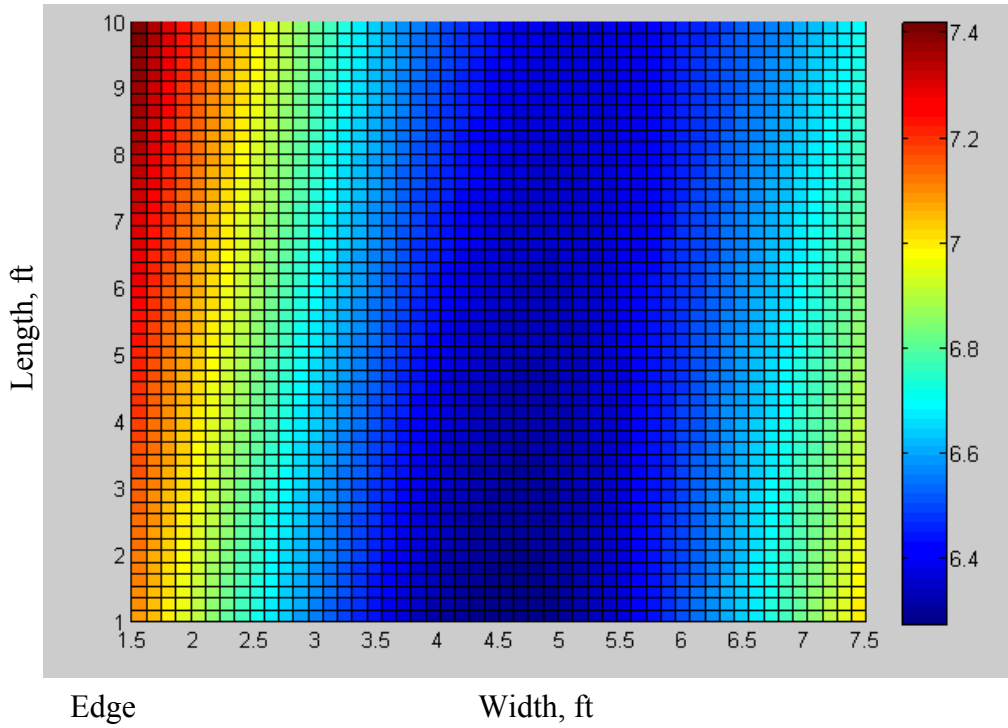
(a)



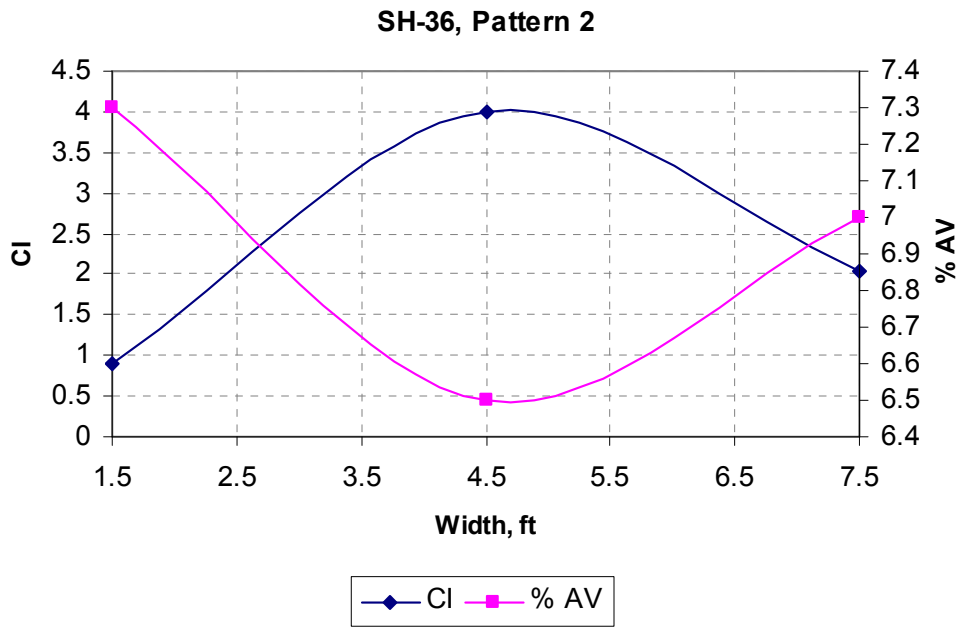
(b)

Note: The total width of the mat is 14.5 ft.

Figure A-12. (a) Air Void Distribution (%) across the Mat for US-87 Test Section Pattern 2, (b) The CI and Average Percent of Air Voids across the Mat for US-87 Test Section Pattern 2.



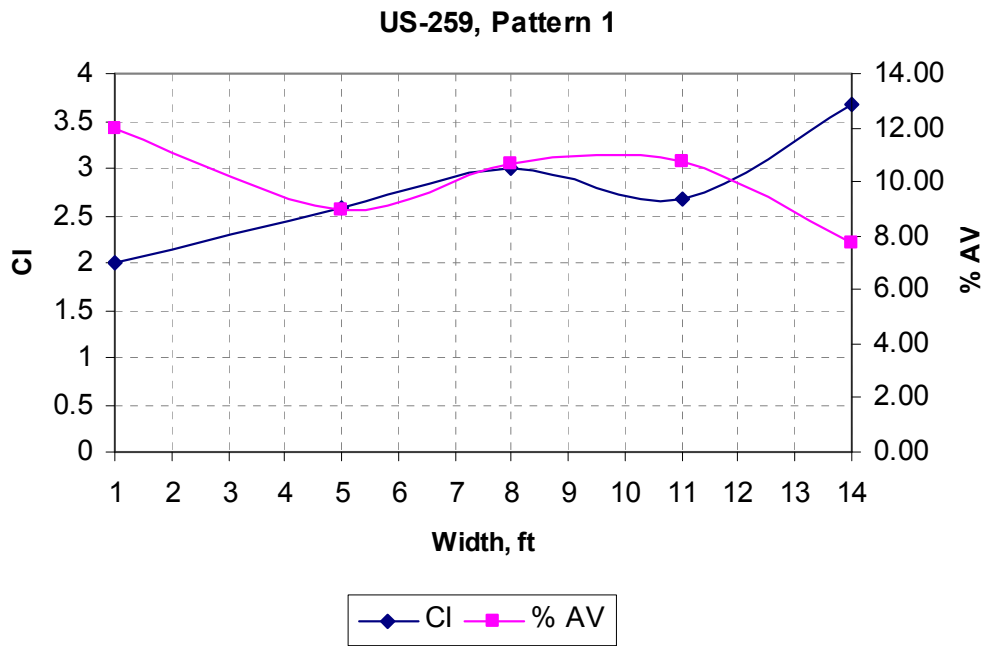
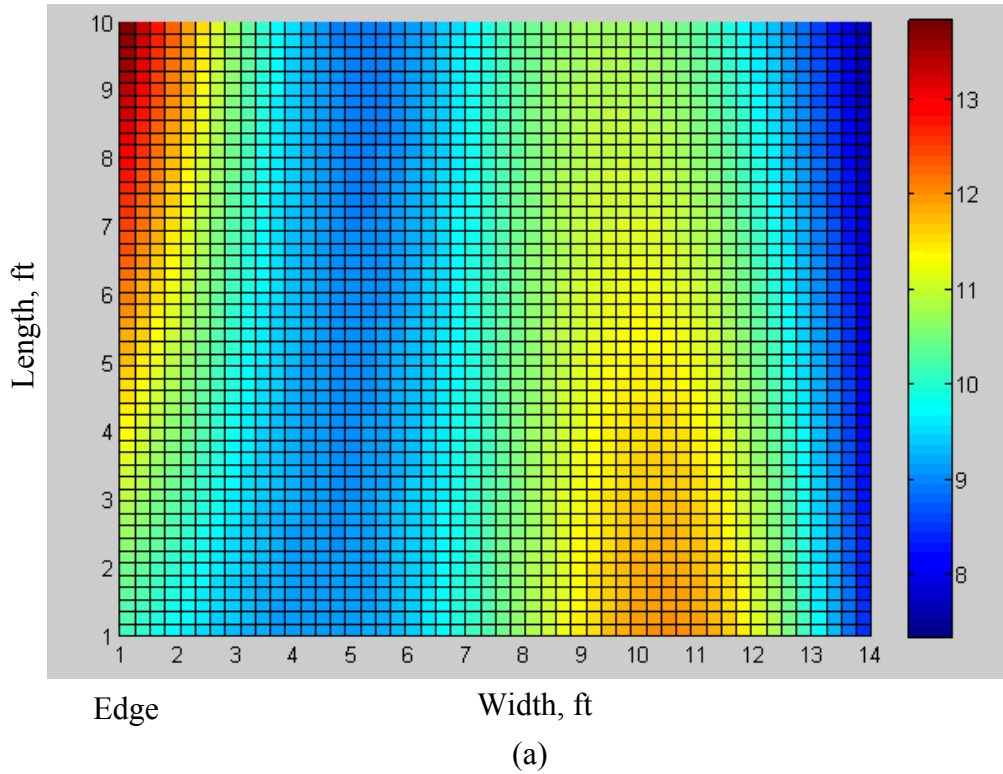
(a)



(b)

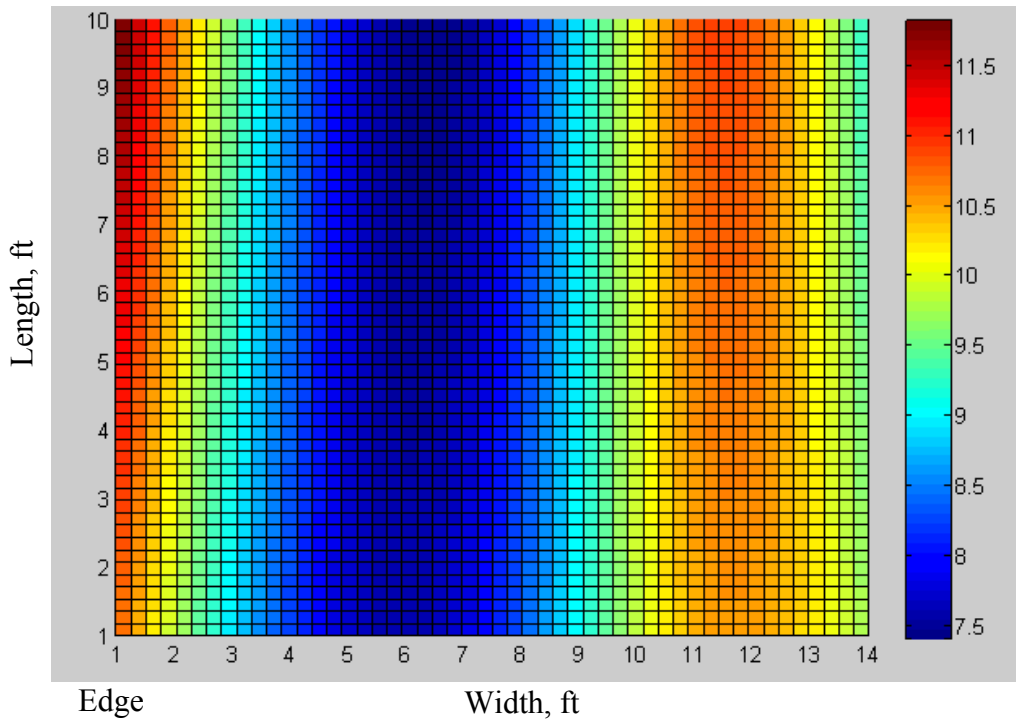
Note: The total width of the mat is 14 ft.

Figure A-13. (a) Air Void Distribution (%) across the Mat for SH-36 Test Section Pattern 2 (b) The CI and Average Percent of Air Voids across the Mat for SH-36 Test Section Pattern 2.

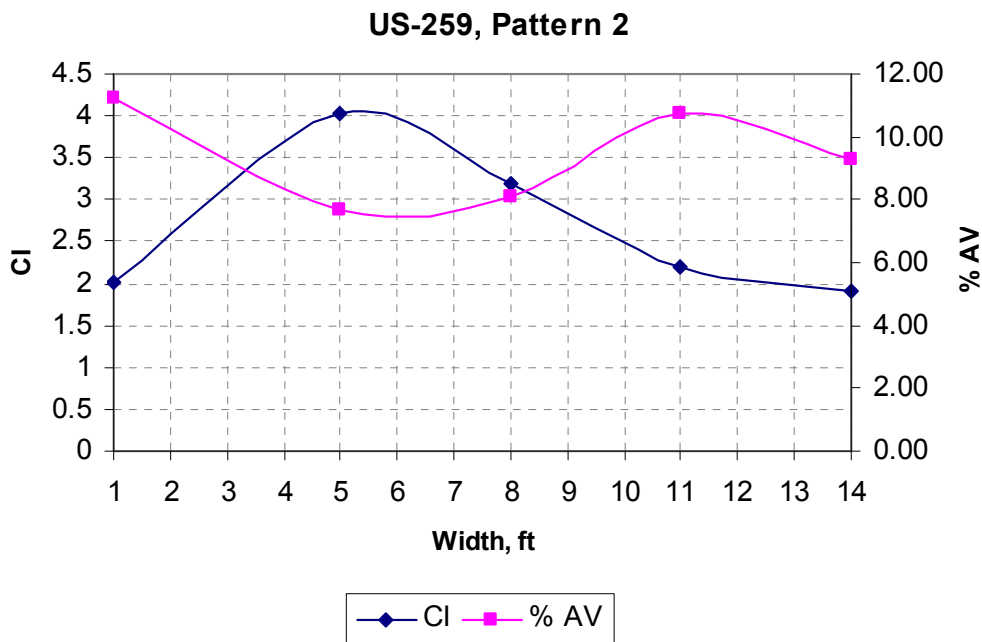


Note: The total width of the mat is 15 ft.

Figure A-14. (a) Air Void Distribution (%) across the Mat for US-259 Test Section Pattern 1 (b) The CI and Average Percent of Air Voids across the Mat for US-259 Test Section Pattern 1.



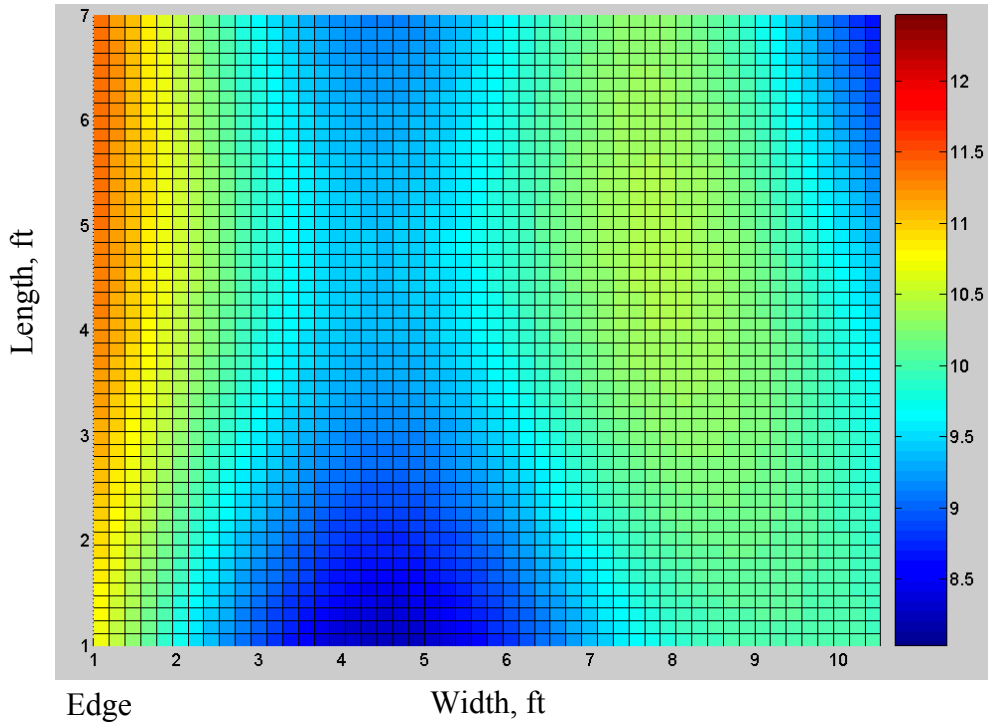
(a)



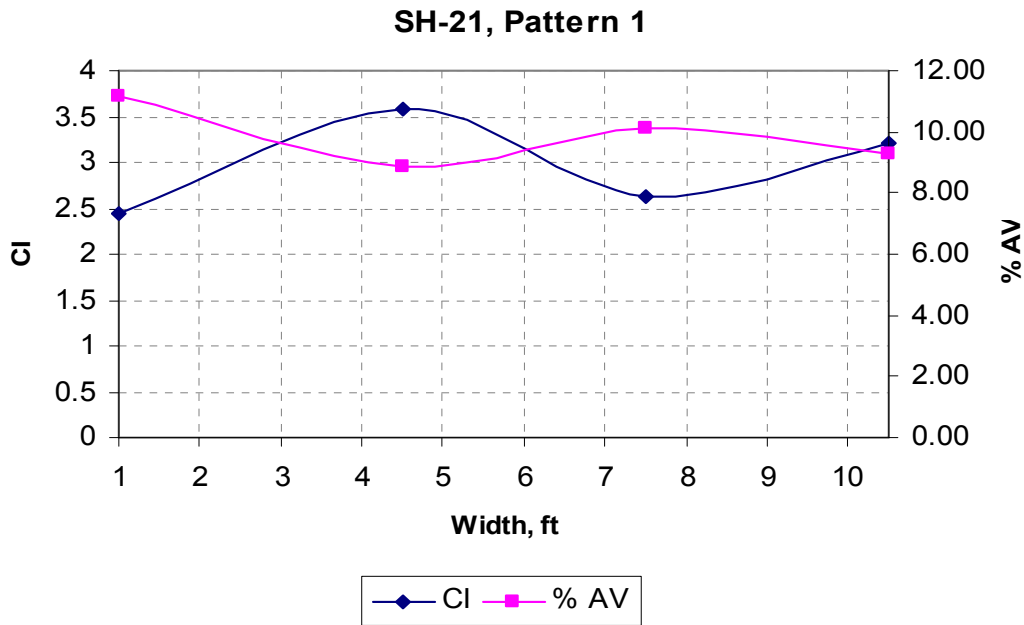
(b)

Note: The total width of the mat is 15 ft.

Figure A-15. (a) Air Void Distribution (%) across the Mat for US-259 Test Section Pattern 2 (b) The CI and Average Percent of Air Voids across the Mat for US-259 Test Section Pattern 2.



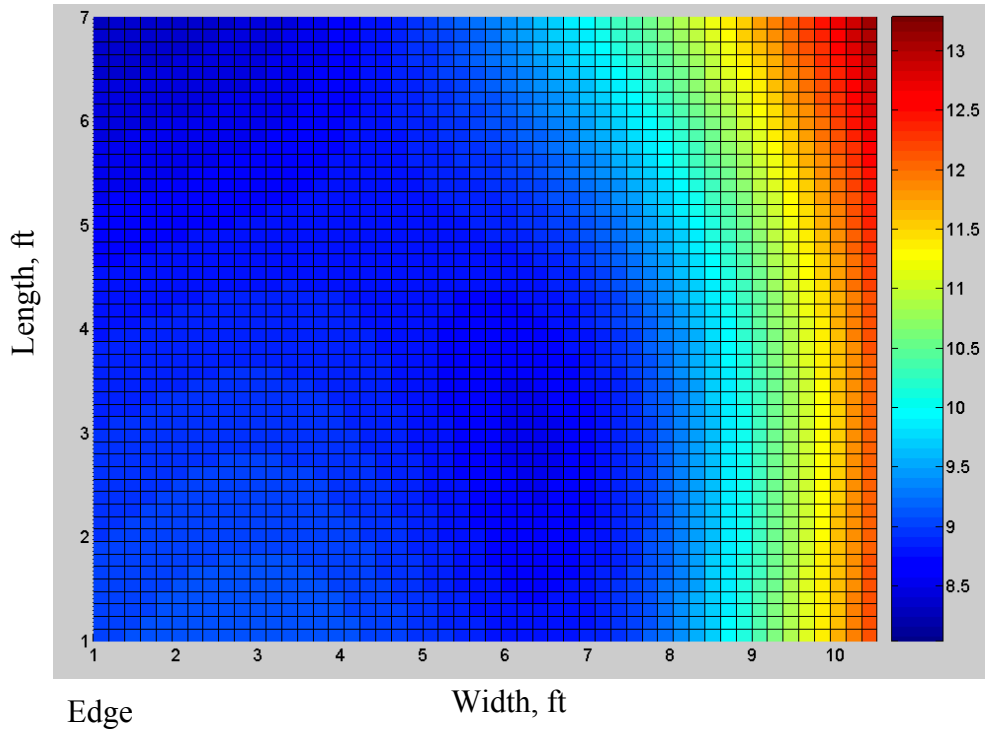
(a)



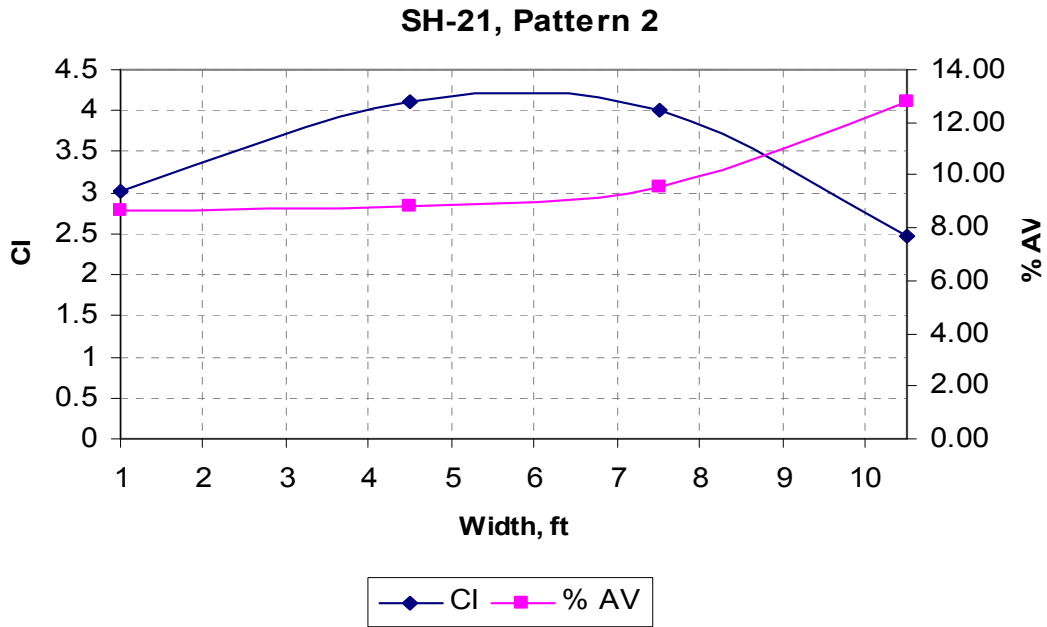
(b)

Note: The total width of the mat is 11.5 ft.

Figure A-16. (a) Air Void Distribution (%) across the Mat for SH-21 Test Section Pattern 1 (b) The CI and Average Percent of Air Voids across the Mat for SH-21 Test Section Pattern 1.



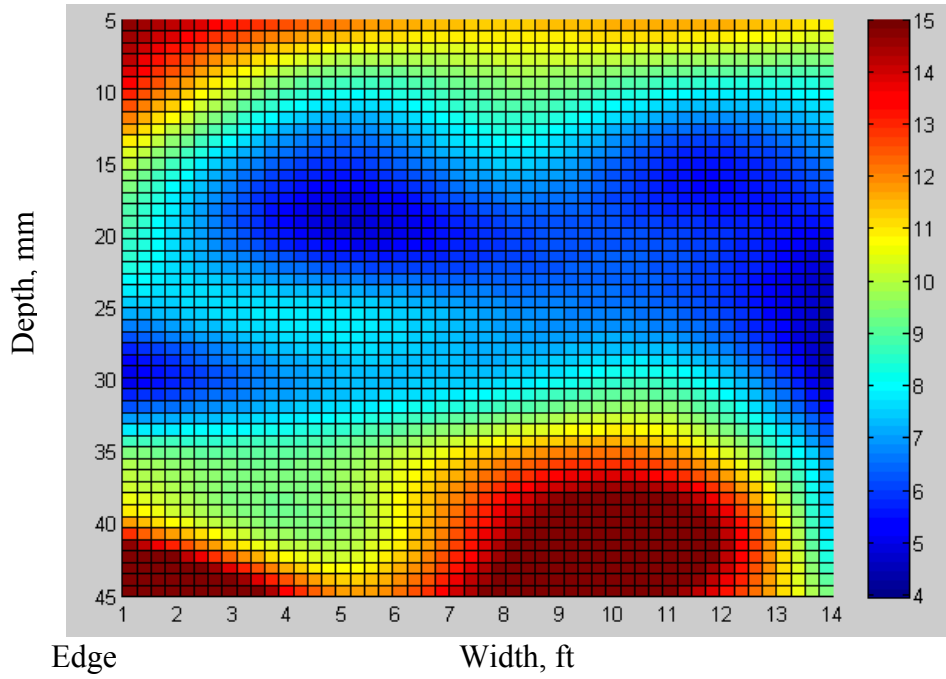
(a)



(b)

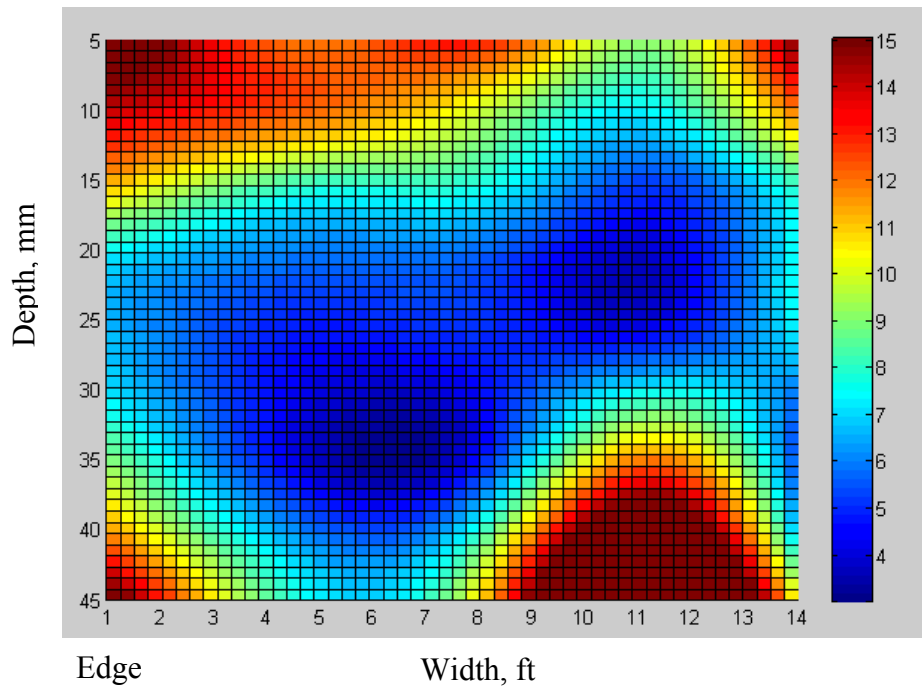
Note: The total width of the mat is 11.5 ft.

**Figure A-17. (a) Air Void Distribution (%) across the Mat for SH-21 Test Section 2
(b) The CI and Average Percent of Air Voids across the Mat for SH-21 Test Section 2.**



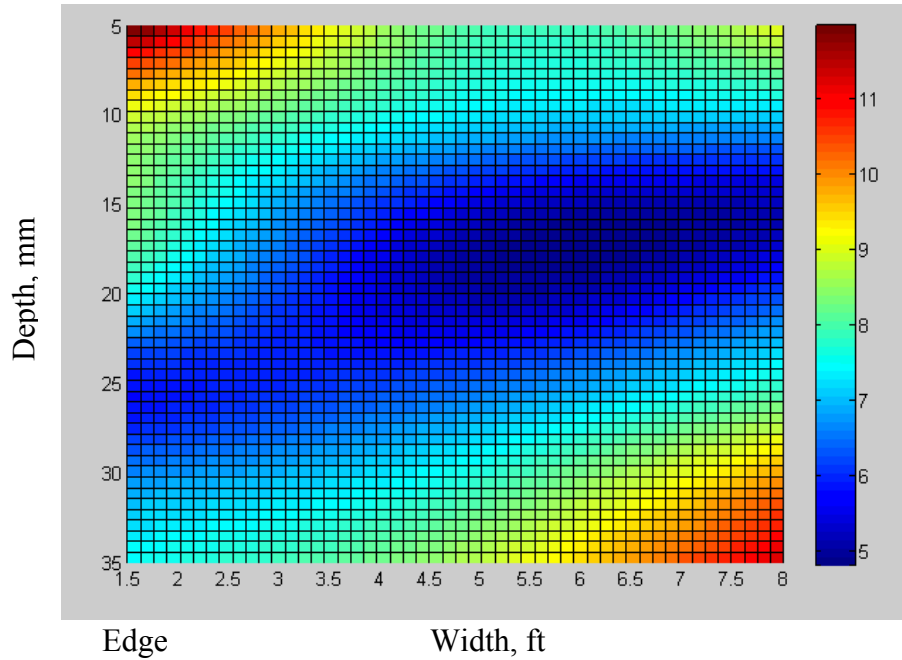
Note: The total width of the mat is 15 ft.

Figure A-18. Air Void Distribution (%) along the Depth of the Mat for US-259 Test Section (Pattern 1).



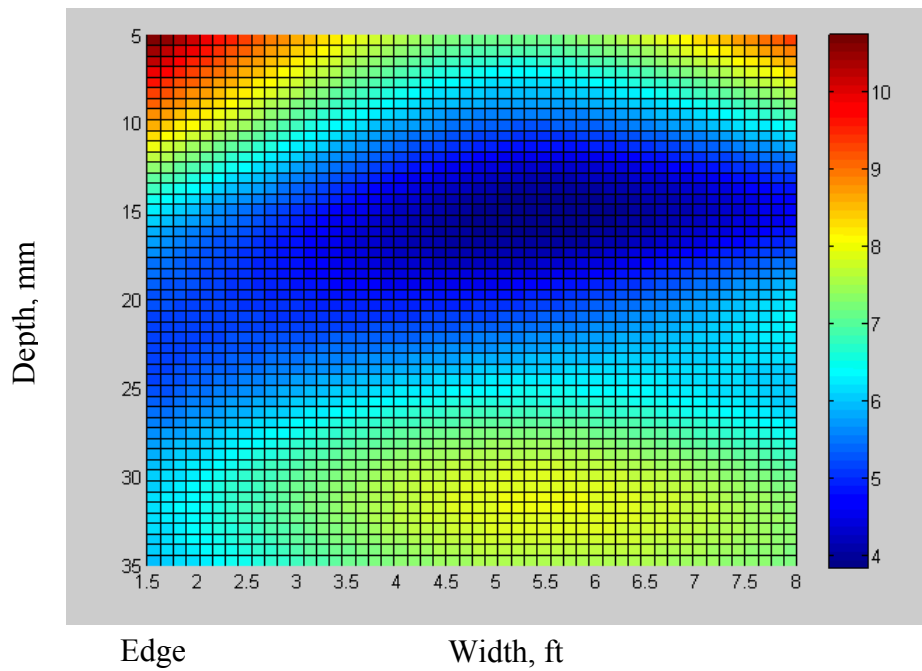
Note: The total width of the mat is 15 ft.

Figure A-19. Air Void Distribution (%) along the Depth of the Mat for US-259 Test Section (Pattern 2).



Note: The total width of the mat is 14 ft.

Figure A-20. Air Void Distribution (%) along the Depth of the Mat for SH-36 Test Section (Pattern 1).



Note: the Total Width of the Mat is 14 ft.

Figure A-21. Air Void Distribution (%) along the Depth of the Mat for SH-36 Test Section (Pattern 2).

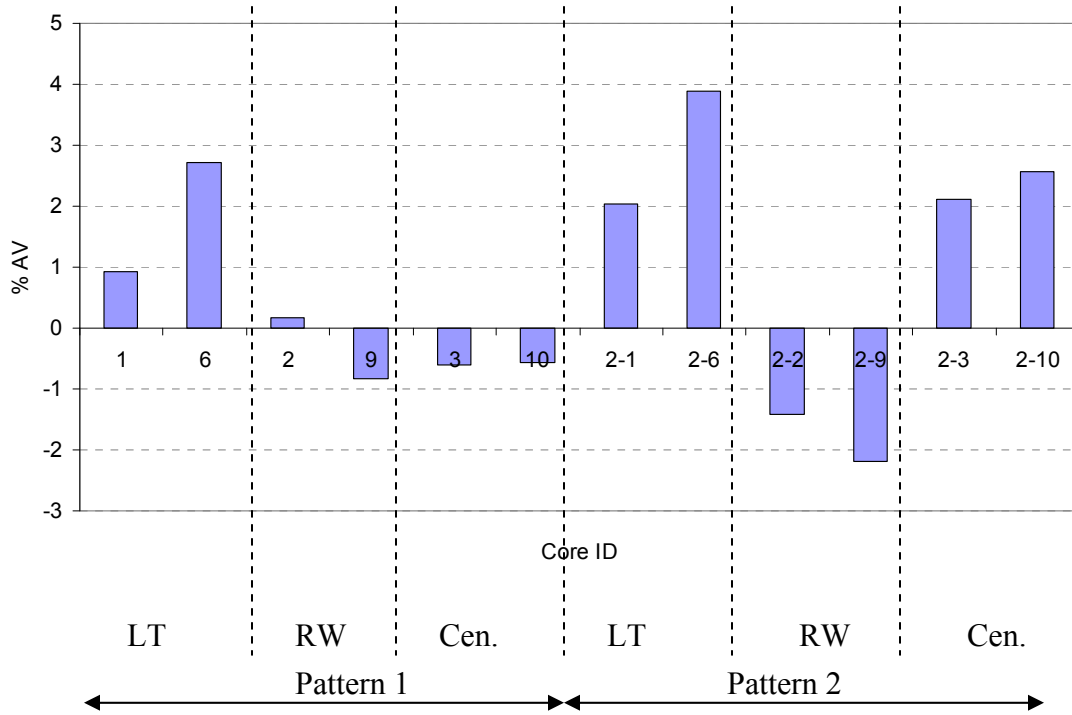


Figure A-22. Difference between the Percent of Air Voids at the Top and the Bottom Parts for SH-36 Test Section.

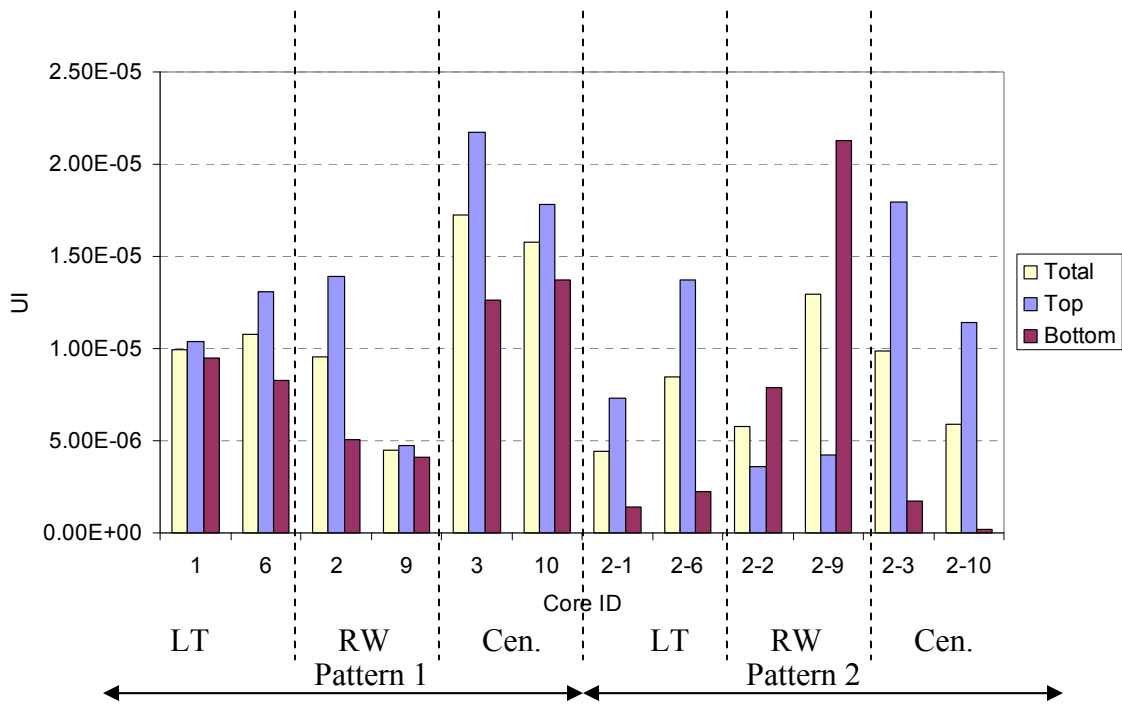


Figure A-23. UI for the SH-36 Test Section.

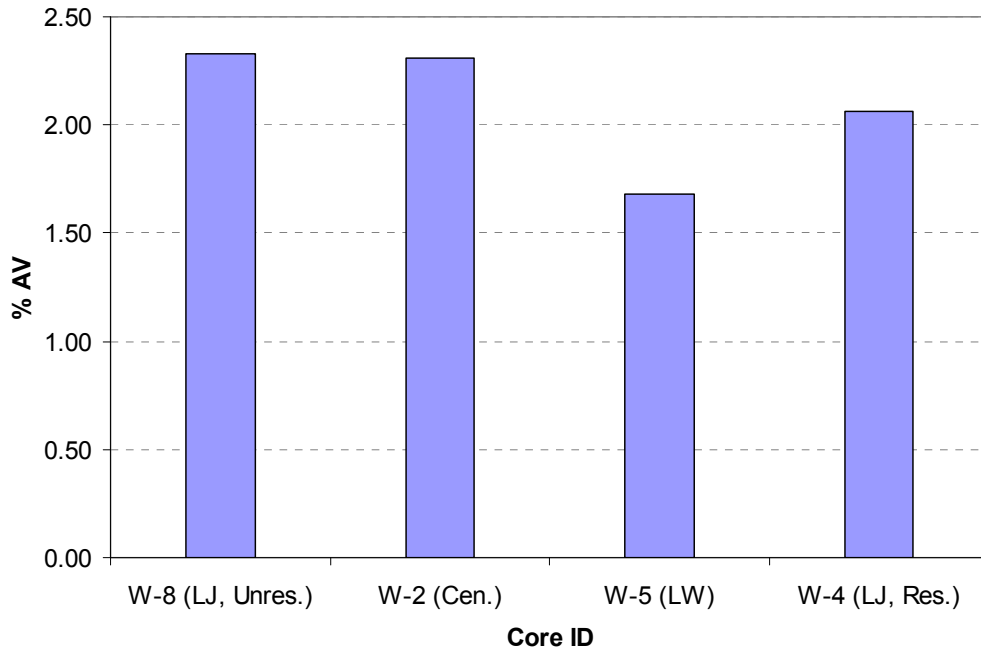


Figure A-24. Difference between the Percent of Air Voids at the Top and the Bottom Parts for IH-35 Test Section.

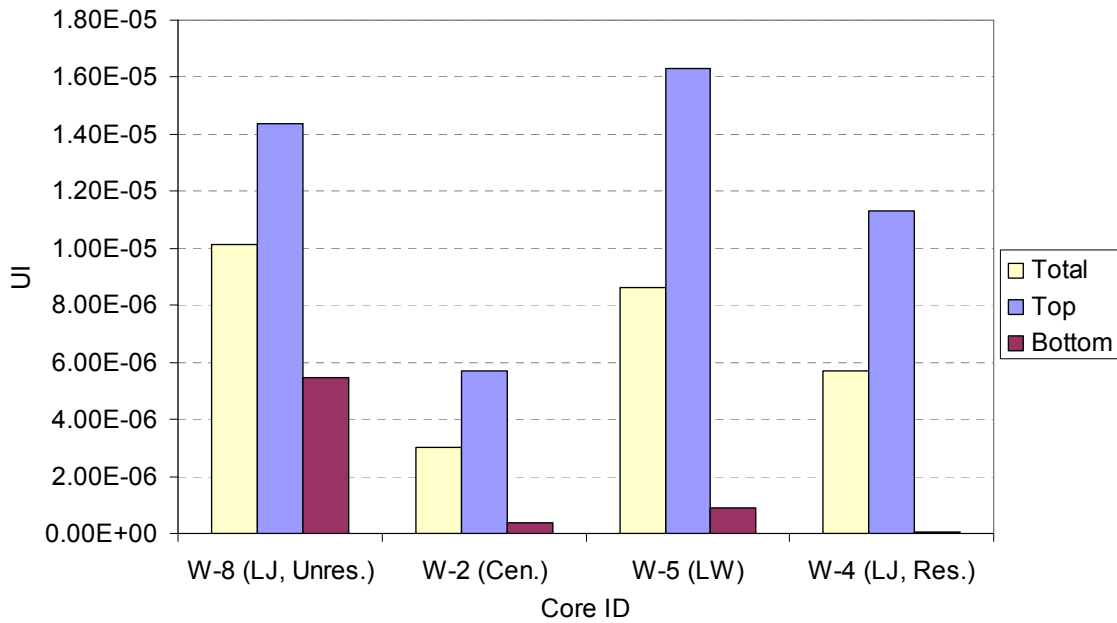


Figure A-25. UI for the IH-35 Test Section.

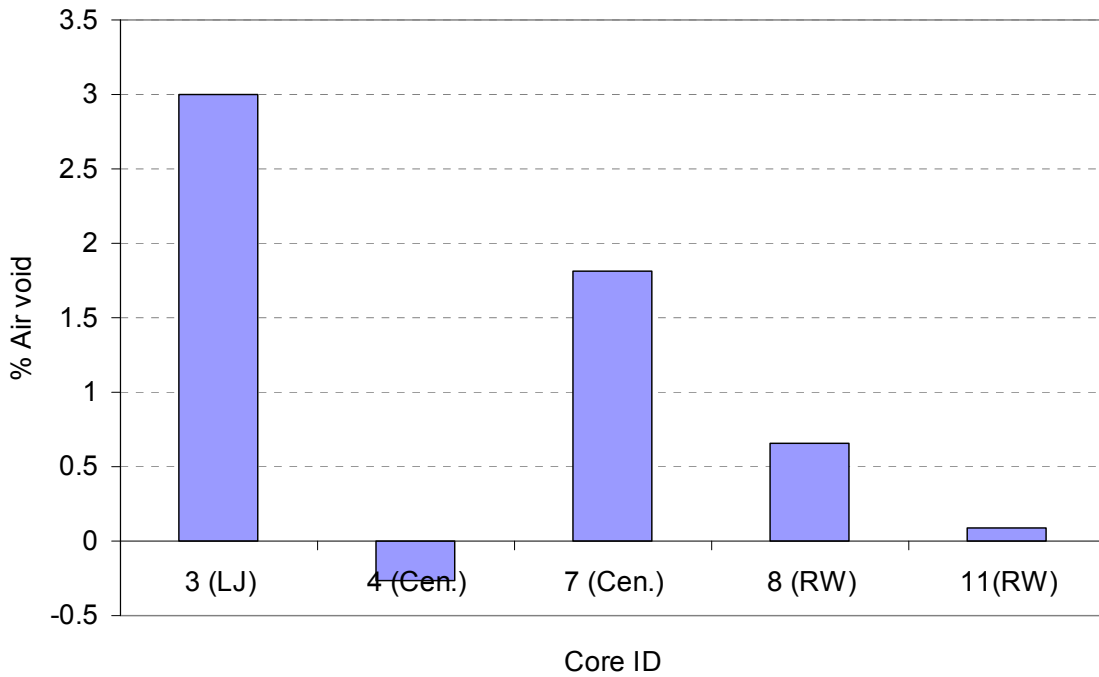


Figure A-26. Difference between the Percent of Air Voids at the Top and the Bottom Parts for US-281 Test Section.

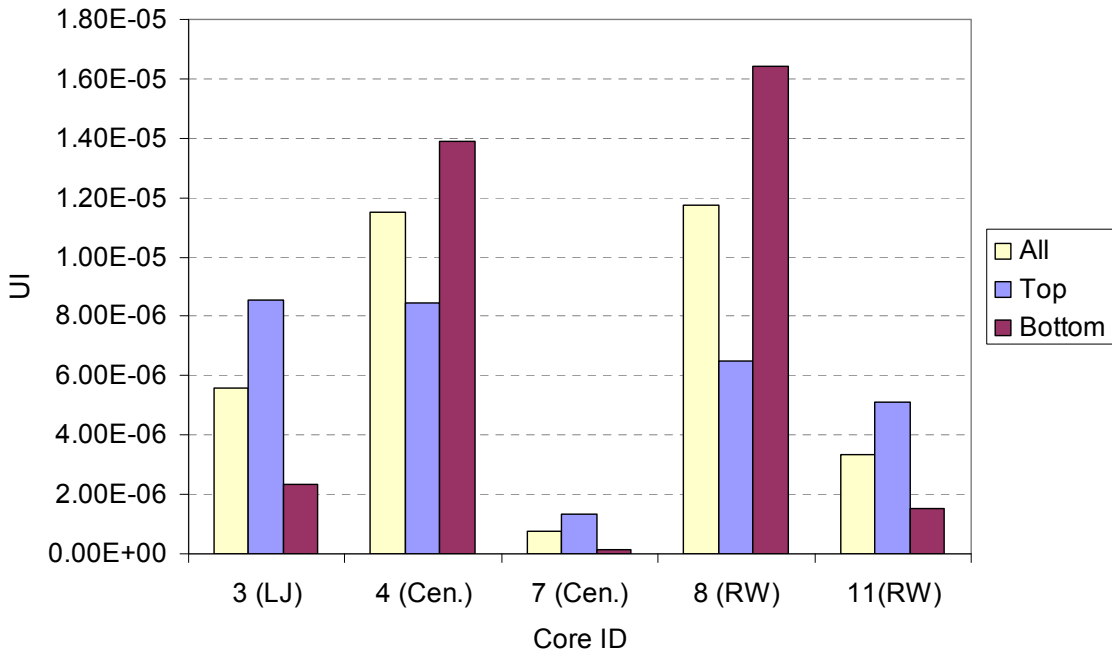


Figure A-27. UI for the US-281 Test Section.

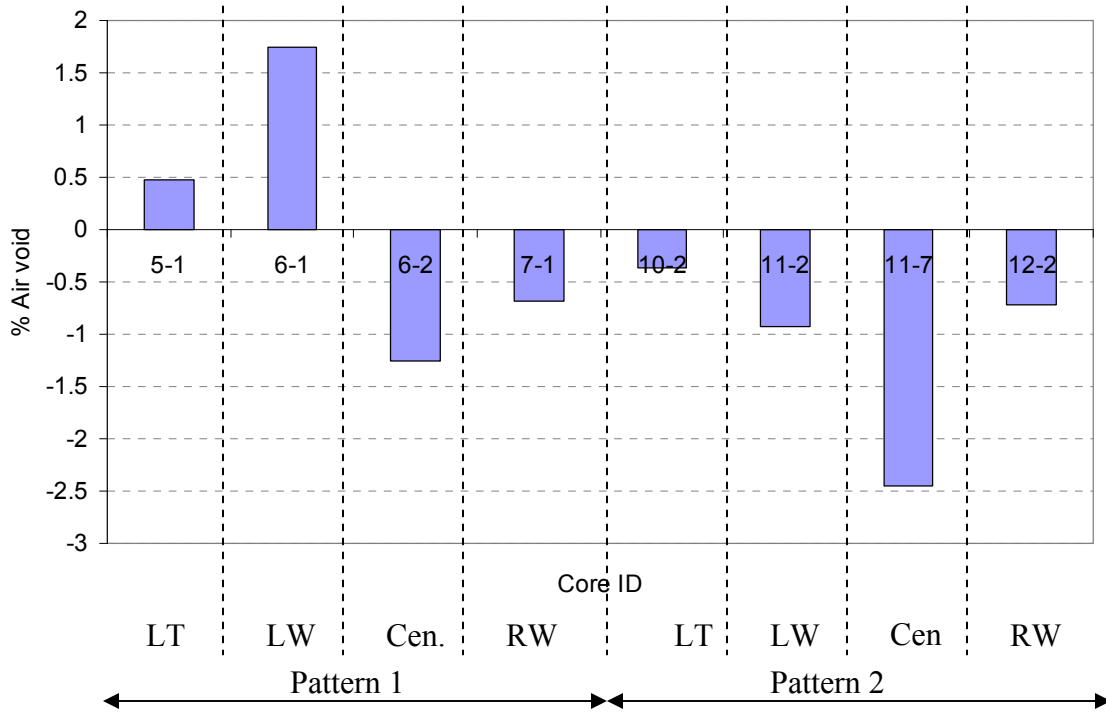


Figure A-28. Difference between the Percent of Air Voids at the Top and the Bottom Parts for FM-649 Test Section.

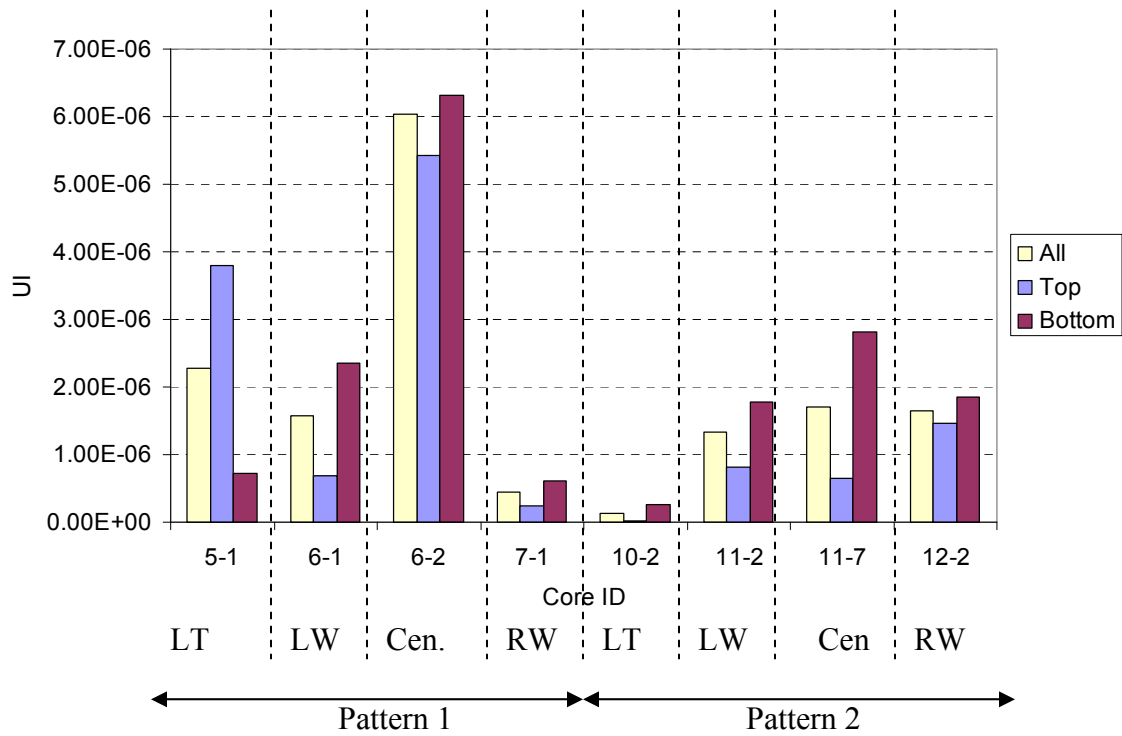


Figure A-29. UI for the FM-649 Test Section.

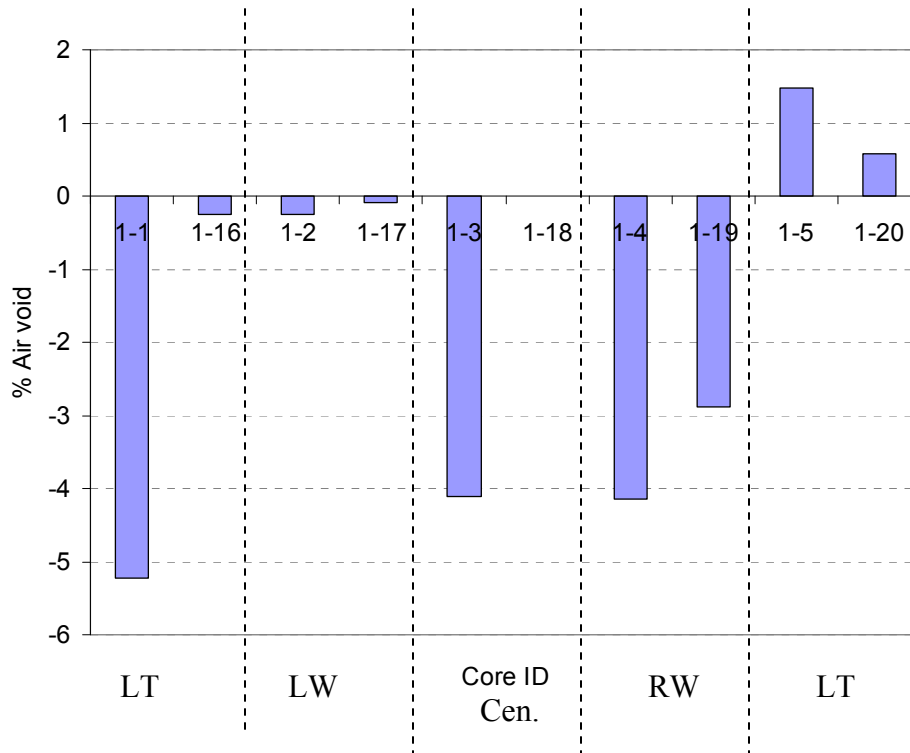


Figure A-30. Difference between the Percent of Air Voids at the Top and the Bottom Parts for US-259 Test Section (Pattern 1).

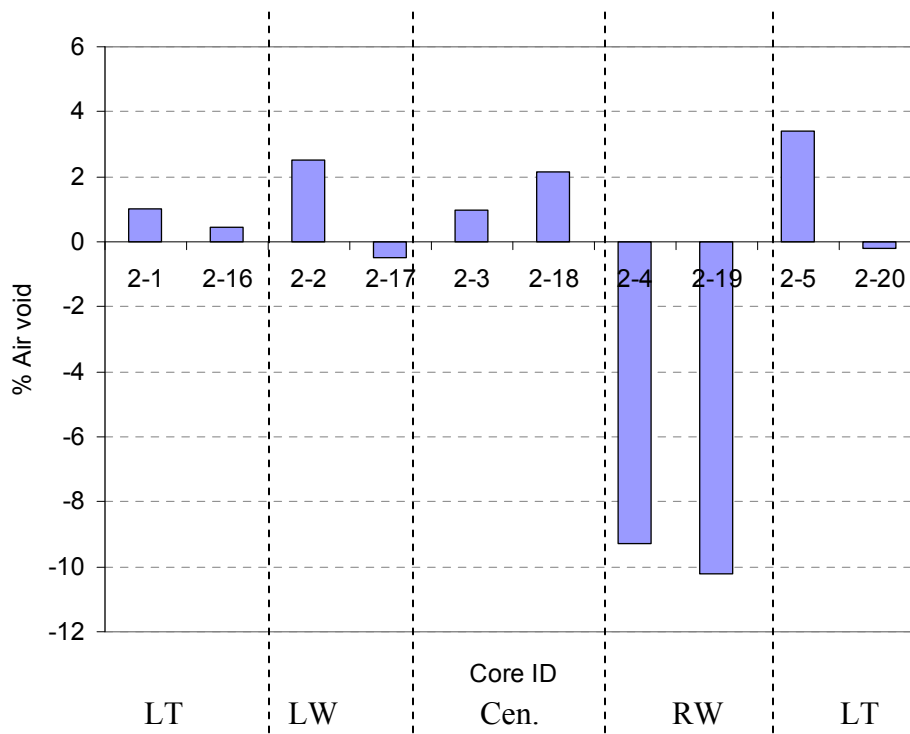


Figure A-31. Difference between the Percent of Air Voids at the Top and the Bottom Parts for US-259 Test Section (Pattern 2).

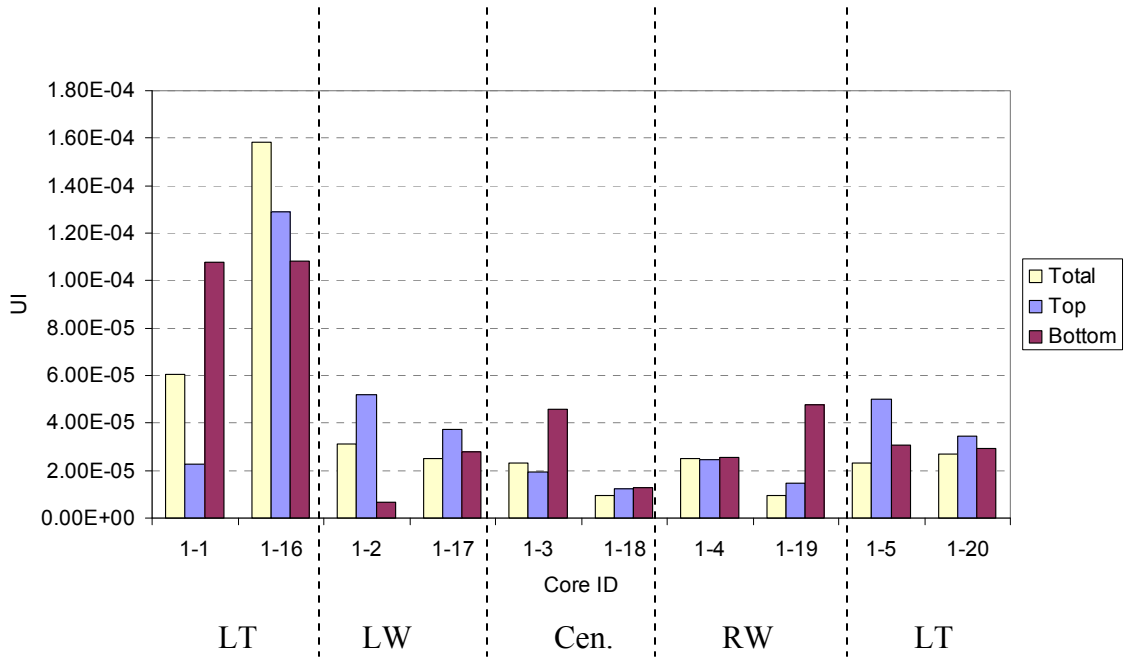


Figure A-32. UI for the US-259 Test Section (Pattern 1).

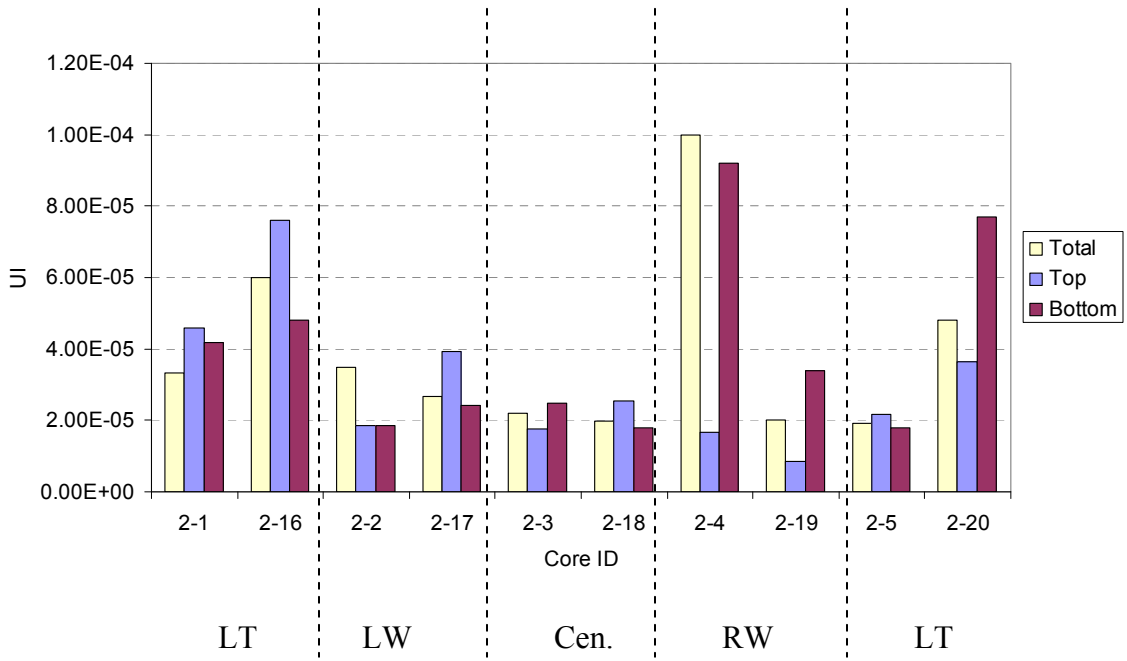


Figure A-33. UI for the US-259 Test Section (Pattern 2).

APPENDIX B

FORENSIC EVALUATION OF AIR VOID DISTRIBUTION

SL 368 IN SAN ANTONIO (WARM MIX)

Introduction

This construction project represents the first warm mix asphalt (WMA) trial placed by the Texas Department of Transportation (TxDOT). Evotherm, developed by MeadWestvaco Asphalt Innovations, Charleston, South Carolina, uses a non proprietary technology that is based on a chemical package that includes emulsification agents; additives to improve aggregate coating, mixture workability, and compaction; as well as adhesion promoters (anti-stripping agents). Evotherm utilizes a high residue emulsion (about 70 percent binder) that improves adhesion of the asphalt to the aggregate. The product enhances mixture workability, while lowering mixing temperatures to as low as 200°F. No plant modifications are required, the mix can be stored in silos, and may be utilized with or without polymer modifier.

The objectives of TxDOT in conducting this field trial include the following:

- to evaluate the production, laydown, and compaction of warm mix as compared with a conventional hot mix control using a standard TxDOT mixture design, and
- to evaluate the short- and long-term performance of the warm mix versus a control hot mix.

The researchers from 0-5261 participated in this project in order to examine the compaction of both control and warm mix as a part of forensic study.

Project Description

This project was in Bexar County within the city limits of San Antonio. The project located on Loop 368 (Old Austin Highway), is a four-lane roadway divided by a median, with curb and gutter and many businesses along each side.

The existing pavement (prior to placement of the warm mix and control) consisted of a cold-milled asphalt surface which had been seal coated with AC-15P and a Grade 4 precoated aggregate. The seal coat had been under traffic for about a month prior to the overlay. All of the paving for this project was conducted at night.

The warm and control mixes were produced by Vulcan Materials of San Antonio and placed by Dean Word Company of New Braunfels. It should also be noted that the field trials were placed within the limits of a much larger HMAC paving project (CSJ 0016-08-027) that was both produced and placed by Dean Word Company.

Mixture Design

The control and warm mixtures met the gradation requirements of a TxDOT Item 341, Type C, Dense-Graded HMAC. The mixture designs were performed by Vulcan Materials laboratory. The asphalt used for the control HMAC was Valero PG 76-22. The base asphalt for the warm mix started as a Valero PG 64-22 prior to modification by MeadWestvaco. Once modified, the warm mix binder met the specifications of PG 76-22. The modified asphalt was then emulsified and provided to Vulcan Materials laboratory to perform the mixture design. Two aggregate sources were used for the mixtures: Vulcan's Helotes Pit limestone and the Harris Pit field sand. Note that the same aggregate sources and gradations were used for both the warm mix and the control. Both warm and control mixtures were designed using a Texas gyratory compactor with a target density of 96.5 percent.

Performance Testing and X-ray CT with Warm Mix

The researchers were able to obtain only a limited number of roadway samples from warm mix and control sections. As a result only X-ray CT and permeability tests were conducted with these samples. [Figure B-1](#) shows the test permeability test results with the roadway cores from both control and warm mix sections. Specimens from the control mix yield a little higher permeability than the warm mix specimens. The bottom of the warm mix samples were all saw cut except two cores (2A-1 and 2B-1) as explained in [Table B-1](#) while the control specimens were not saw cut. Researchers obtained the

specimens that way from TxDOT. The compaction pattern at different days of mixture placement and mixture types did not vary significantly.

Table B-1 shows the locations of road cores and their air voids. There were only two specimens from the control mixture (mixed and compacted at 315 °F and 305 °F, respectively). These two samples had relatively higher air voids and their air voids distributions were dissimilar. WMA specimens compacted (Lot 1 and Sublot 1) in center lane had relatively low air voids (5.4 to 5.8 percent). All four specimens had similar air voids distribution: high air voids at the top and bottom but low air voids at the center. Four other WMA road cores obtained from a close proximity but different lanes and different sublots (Lot 1 Sublot 2; specimens 2E, 2F, 2G, 2H) all had relatively high air voids (7.9 to 8.9 percent). Both Sublot 1 and Sublot 2 had the same asphalt content and comparable compaction temperature. The only possible explanation could be the change in aggregate gradation which needs to be measured. When the average air voids were similar the control mixture and WMA had similar air voids distribution. Figures B-2 through B-12 show the air void distribution and the air void size along the depth of the test samples.

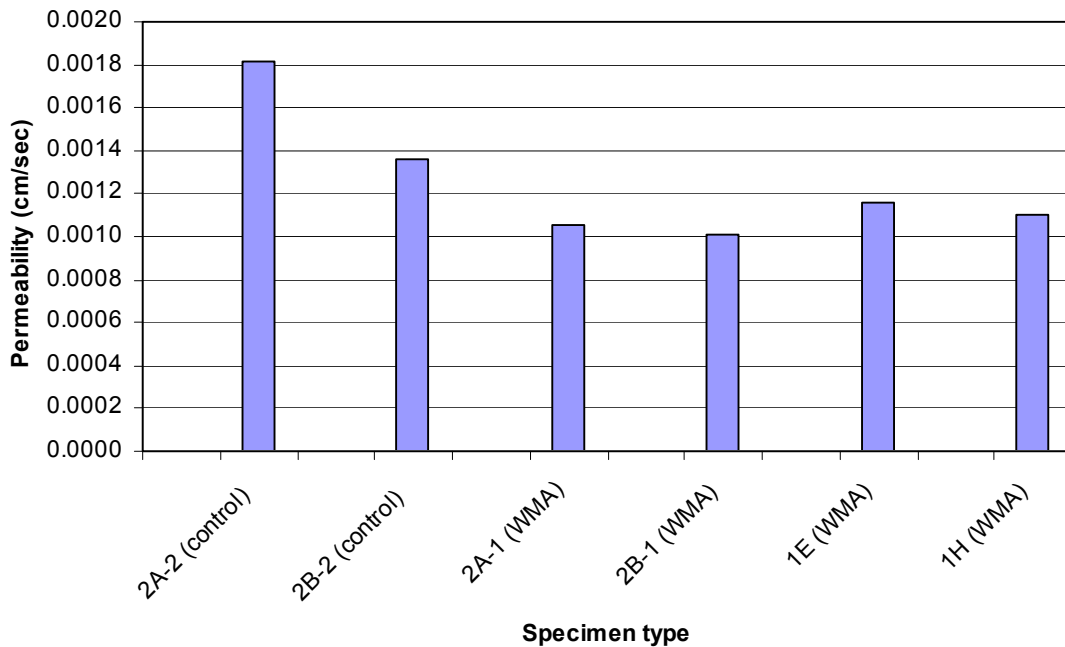
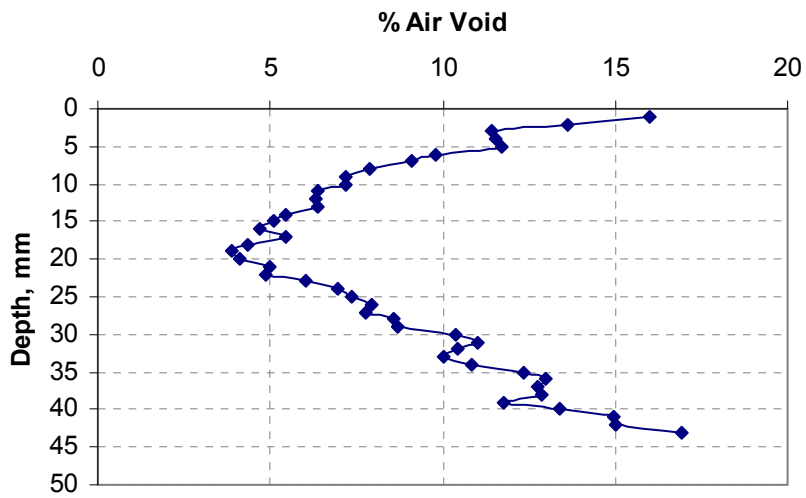


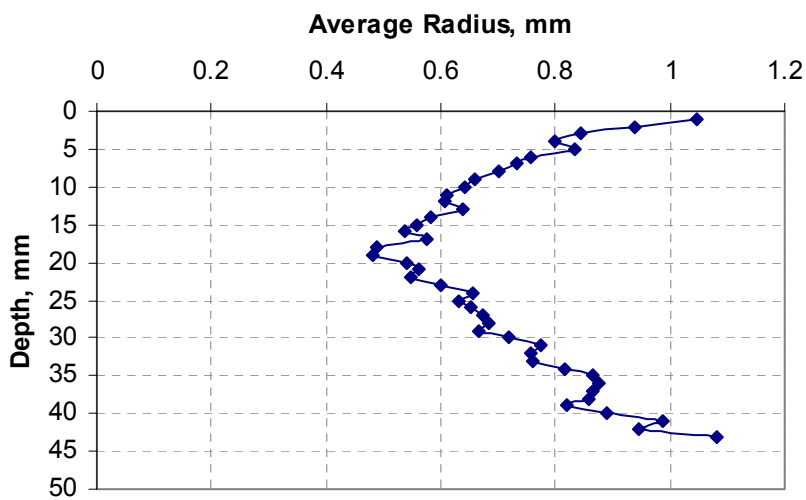
Figure B-1. Comparison of Permeability Test Results between Control and Warm Mix.

Table B-1. Description of Road Cores and Air Voids.

Sample ID	Location	Type	Remark	Air Void Percent
2A-2	36+50, NBOS Lane	Control Mix	uneven bottom	9.3
2B-2	36+50, NBOS Lane	Control Mix	uneven bottom	8.9
2A-1	56+00	WMA, 3rd night	uneven bottom	9.2
2B-1	56+00	WMA, 3rd night	uneven bottom	9.0
1E	15+00, Centerlane; 6 ft offset	WMA, 1st night, Lot 1, Sublot 1	Sawcut Bottom	5.4
1F	15+00, Centerlane; 6 ft offset	WMA, 1st night, Lot 1, Sublot 1	Sawcut Bottom	5.5
1G	15+00, Centerlane; 6 ft offset	WMA, 1st night, Lot 1, Sublot 1	Sawcut Bottom	5.6
1H	15+00, Centerlane; 6 ft offset	WMA, 1st night, Lot 1, Sublot 1	Sawcut Bottom	5.8
2E	15+60 SBOS lane, 7 ft offset	WMA, Lot 1, Sublot 2;	Sawcut Bottom	7.9
2F	15+60 SBOS lane, 7 ft offset	WMA, Lot 1, Sublot 2;	Sawcut Bottom	8.7
2G	15+60 SBOS lane, 7 ft offset	WMA, Lot 1, Sublot 2;	Sawcut Bottom	8.9
2H	15+60 SBOS lane, 7 ft offset	WMA, Lot 1, Sublot 2;	Sawcut Bottom	8.2

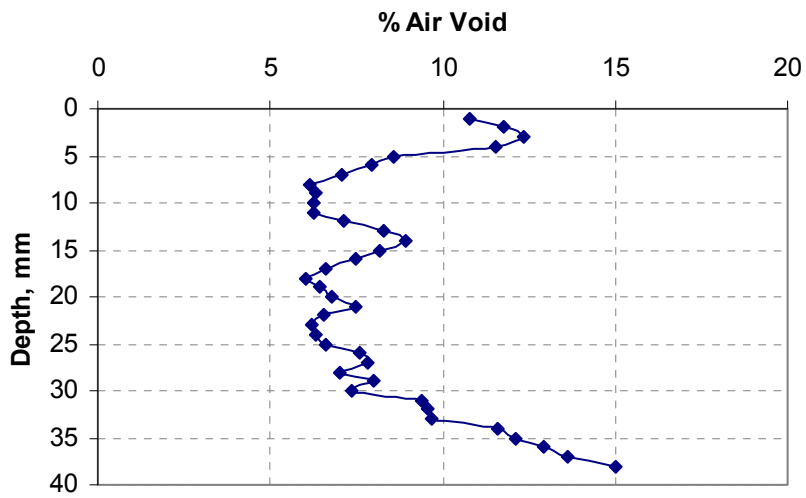


(a)

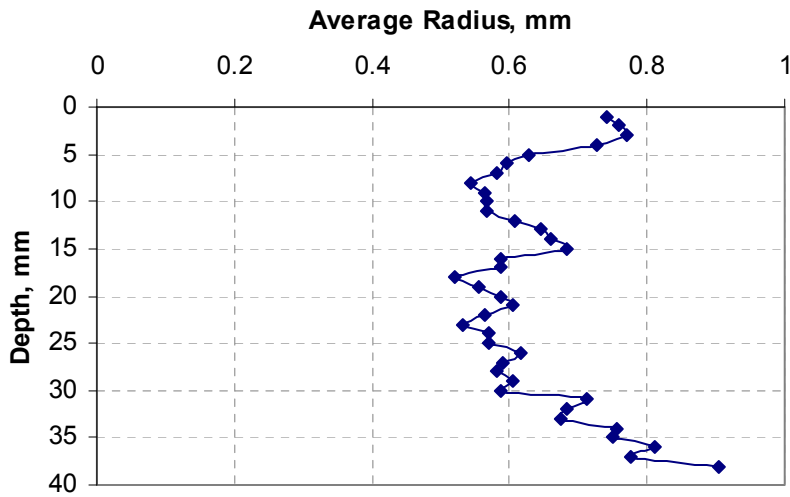


(b)

Figure B-2. (a) Air Void Distribution along the Depth of Core 2A-2, (b) Air Void Size Distribution along the Depth of Core 2A-2.

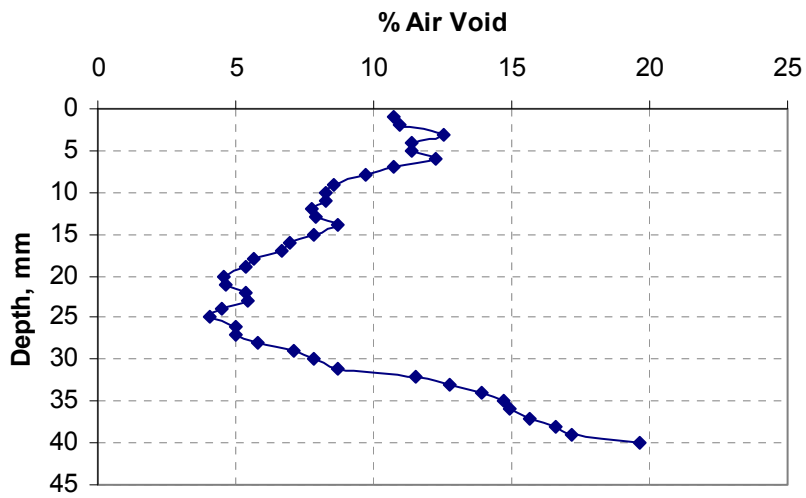


(a)

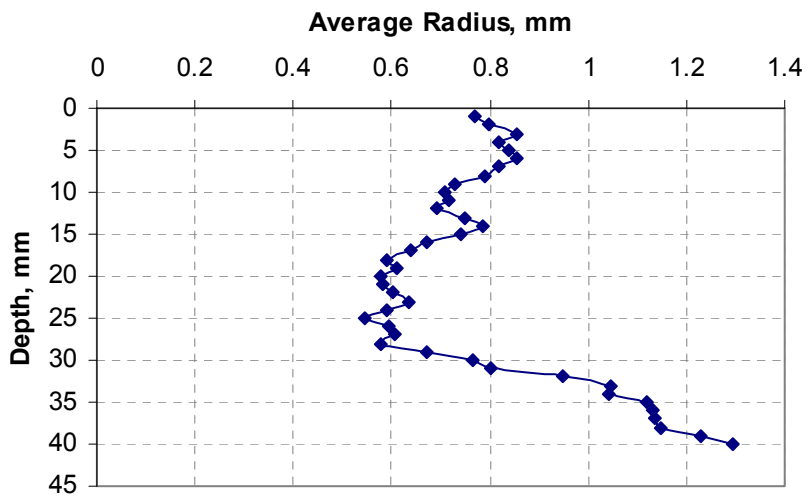


(b)

Figure B-3. (a) Air Void Distribution along the Depth of Core 2B-2, (b) Air Void Size Distribution along the Depth of Core 2B-2.

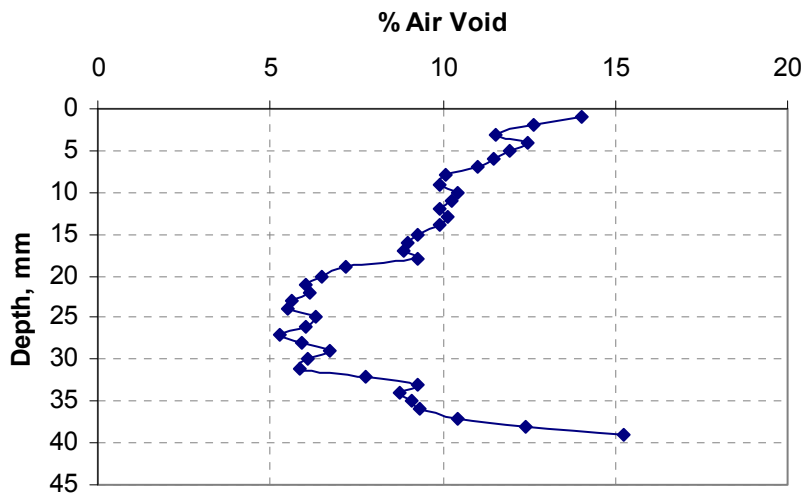


(a)

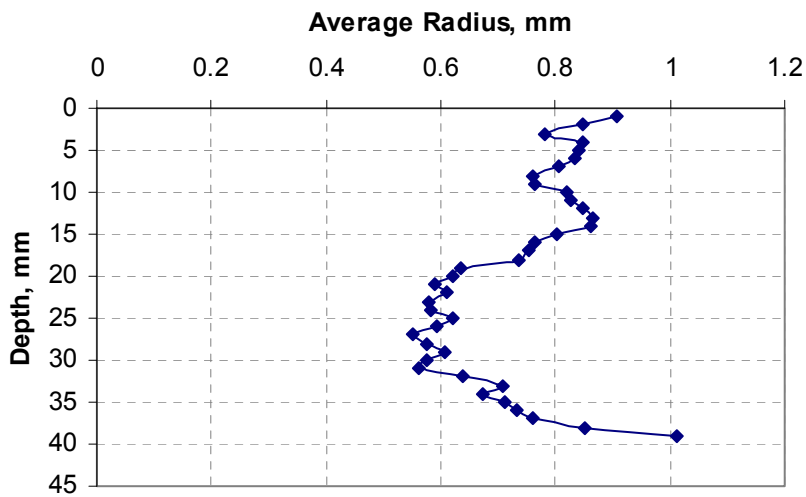


(b)

Figure B-4. (a) Air Void Distribution along the Depth of Core 2A-1, (b) Air Void Size Distribution along the Depth of Core 2A-1.

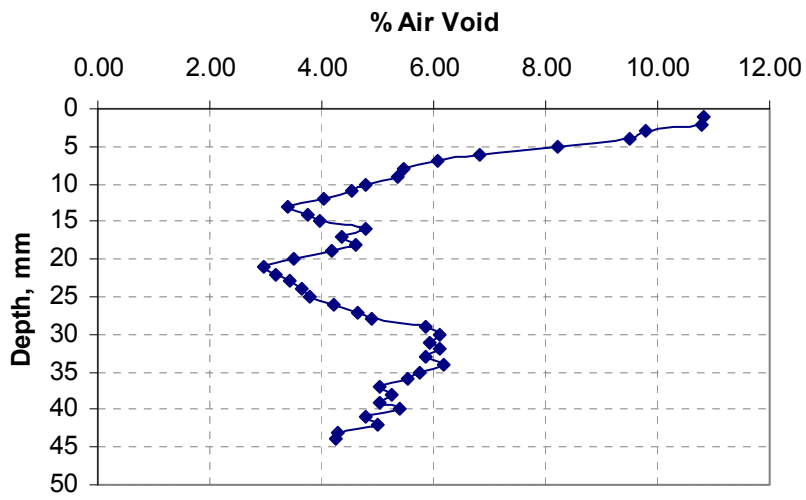


(a)

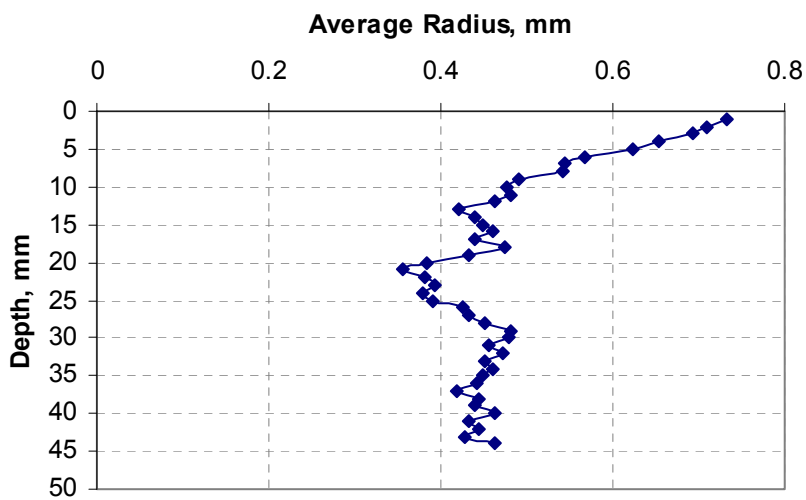


(b)

Figure B-5. (a) Air Void Distribution along the Depth of Core 2B-1, (b) Air Void Size Distribution along the Depth of Core 2B-1.

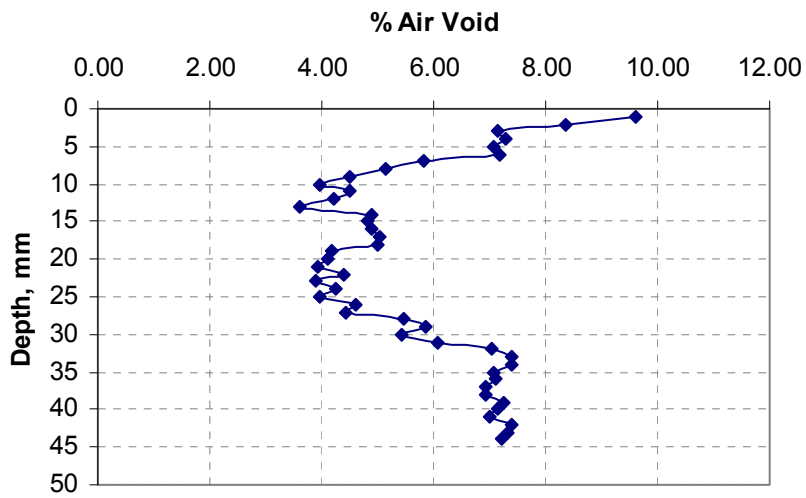


(a)

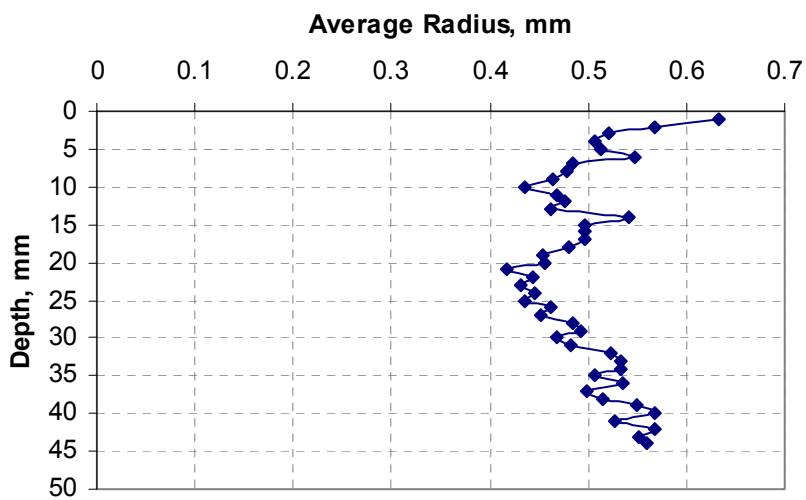


(b)

Figure B-6. (a) Air Void Distribution along the Depth of Core 1E, (b) Air Void Size Distribution along the Depth of Core 1E.

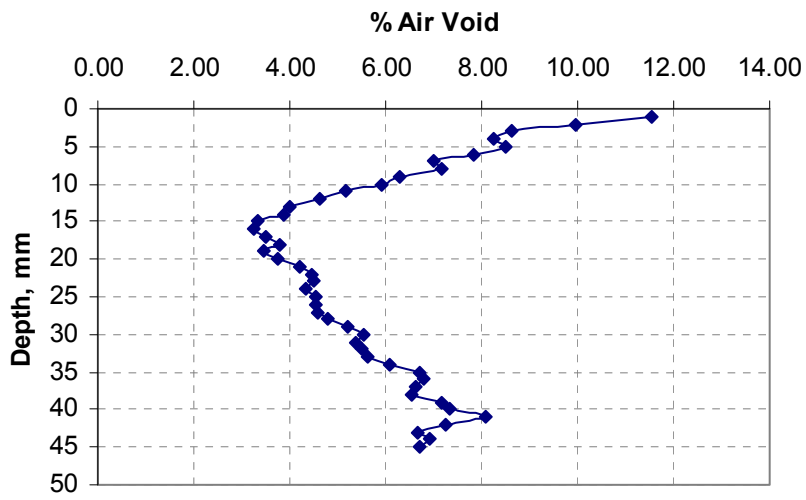


(a)

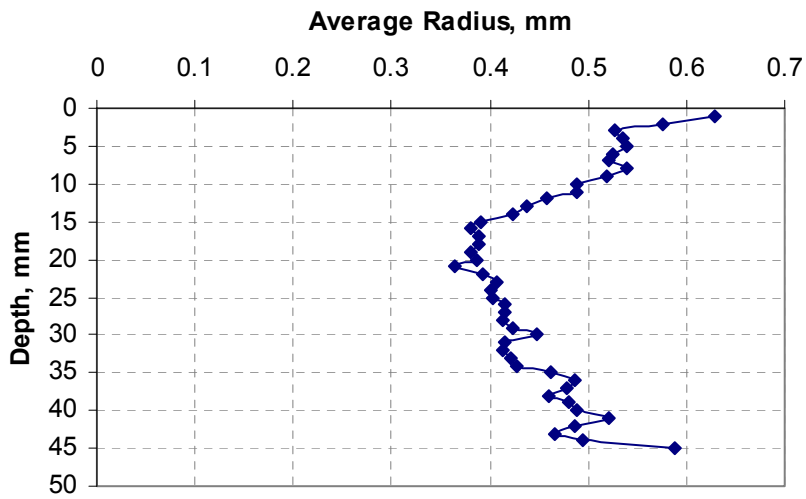


(b)

Figure B-7. (a) Air Void Distribution along the Depth of Core 1F, (b) Air Void Size Distribution along the Depth of Core 1F.

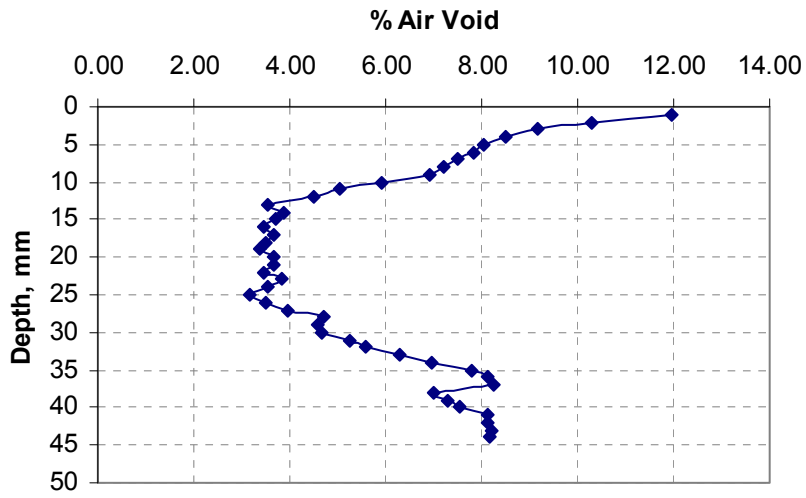


(a)

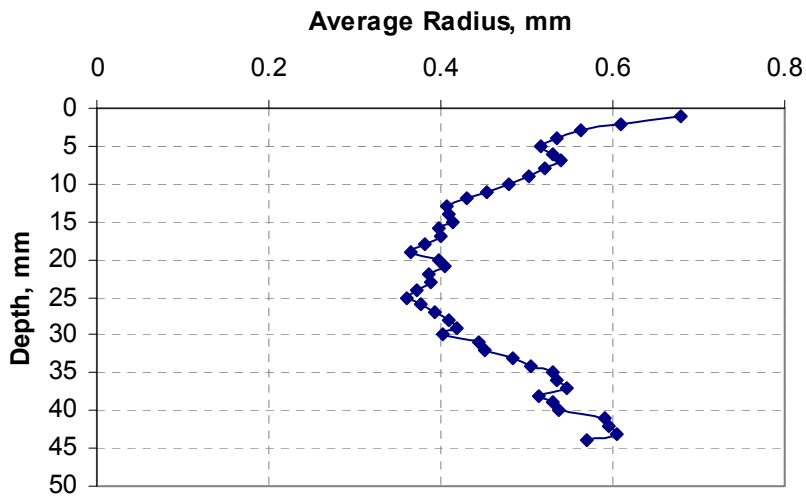


(b)

Figure B-8. (a) Air Void Distribution along the Depth of Core 1G, (b) Air Void Size Distribution along the Depth of Core 1G.

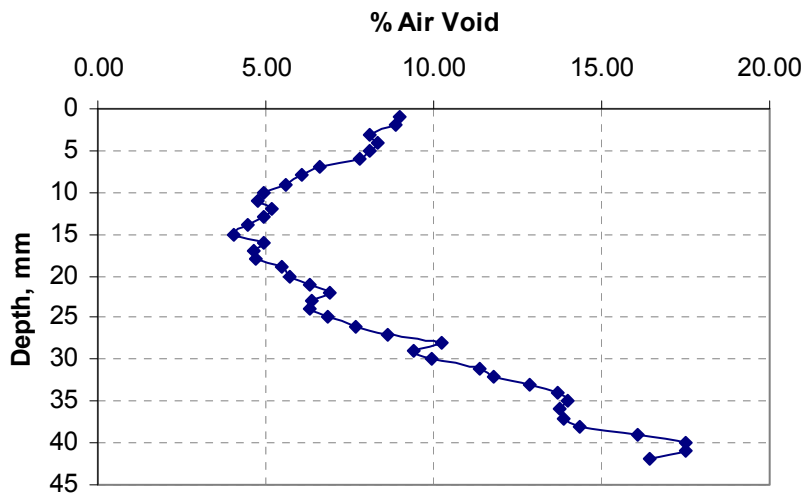


(a)

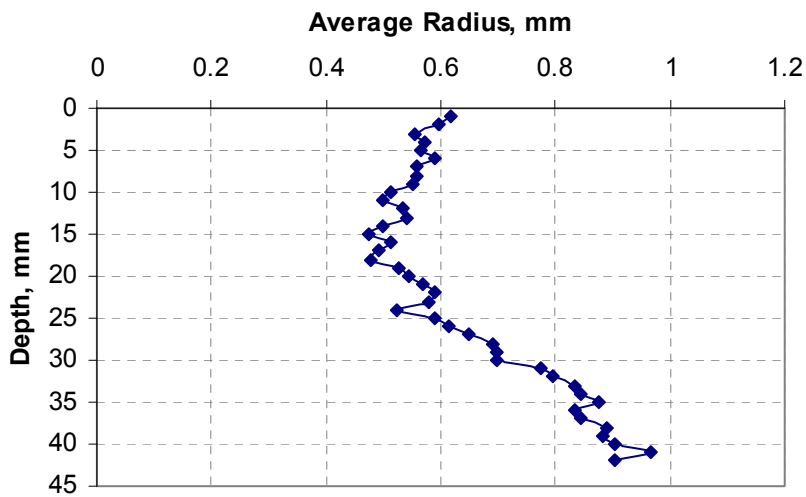


(b)

Figure B-9. (a) Air Void Distribution along the Depth of Core 1H, (b) Air Void Size Distribution along the Depth of Core 1H.

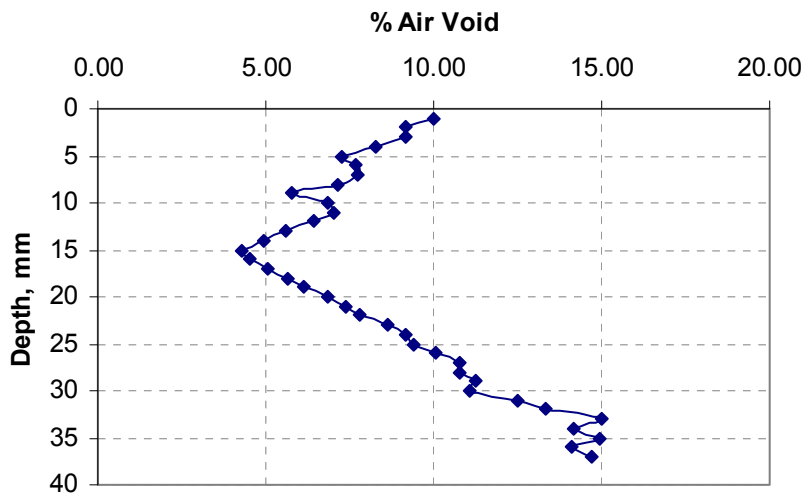


(a)

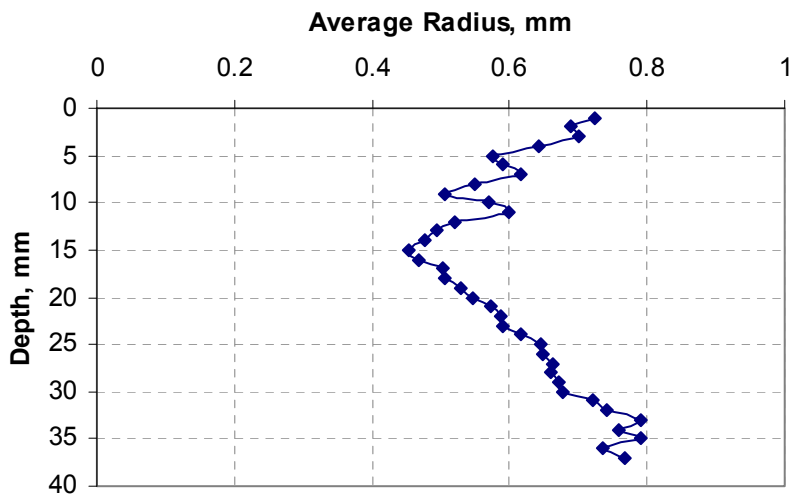


(b)

Figure B-10. (a) Air Void Distribution along the Depth of Core 2F, (b) Air Void Size Distribution along the Depth of Core 2F.

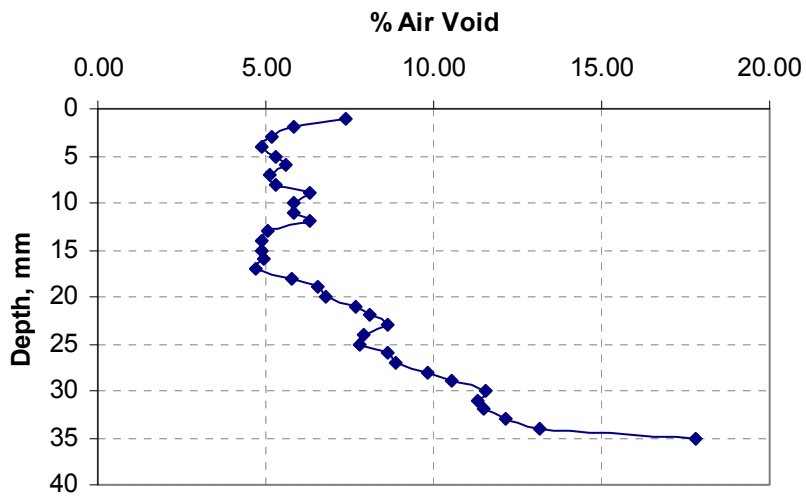


(a)

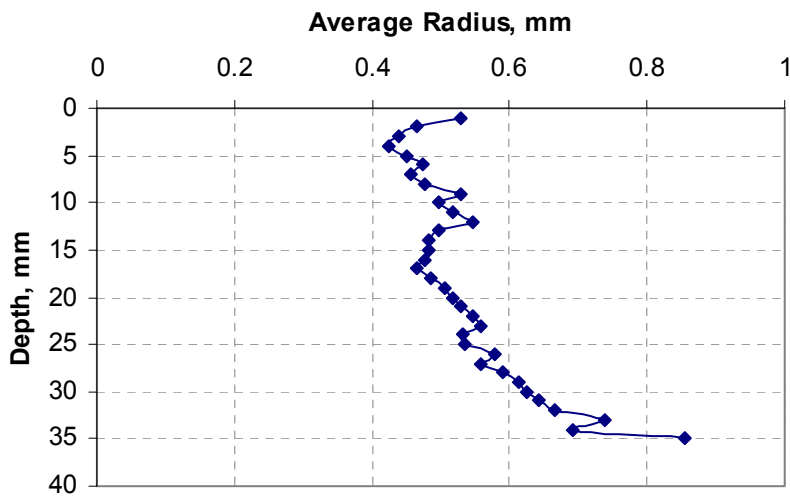


(b)

Figure B-11. (a) Air Void Distribution along the Depth of Core 2G, (b) Air Void Size Distribution along the Depth of Core 2G.



(a)



(b)

Figure B-12. (a) Air Void Distribution along the Depth of Core 2H, (b) Air Void Size Distribution along the Depth of Core 2H.

US 290 AND FM 529

Consulting with engineers from the Houston District, the researchers included certain parts of US 290 and FM 529 in Waller County for further forensic study. Seven cores were obtained from US 290 in Waller County with the assistance of Mr. Tony Yrigoyen from TxDOT's Houston District. The cores were obtained approximately 0.2 miles west of Heger road on the westbound outside lane. The coring layout is shown in [Figure B-13](#).

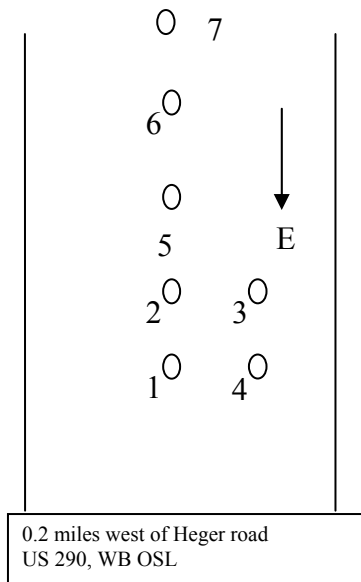


Figure B-13. US 290 Coring Layout.

Cores 3 and 4 are from the right wheel path, whereas cores 1, 2, 5, 6, and 7 are from between wheel paths. The primary focus of this investigation was the top layer which was a 2 inch thick Type C HMA layer. Cores labeled 4 and 6 were tested with X-ray Computed Tomography. Permeability and Hamburg testing were conducted on specimens 3 and 7. The results are shown in [Table B-2](#).

Table B-2. Results from Testing US 290 Cores.

Test	Results
Rutting in Hamburg Test	3.4 mm at 20,000 cycles
Permeability	9.8×10^{-4} cm/sec

Based on the results in [Table B-2](#), the findings from US 290 are summarized as follows:

- Rutting is not a concern for this layer.
- Permeability values are low. It is noted that this layer has been in service under heavy traffic for a few years.

Ten specimens were obtained from FM 529 in Waller County. The coring site was located approximately 1500 ft west of the Harris County line on the westbound lane. The coring layout is shown in [Figure B-14](#). Cores LJ1 and LJ2 were taken near the longitudinal joint, cores WP-3 and WP-4 were from the left wheel path, cores BW1 to BW4 were recovered between the wheel paths, while WP1 and WP2 were taken from the right wheel path. The primary focus of this investigation was the surface layer which was constructed in Fall 2005. The cores were obtained in February 2006. The surface layer was designed as Type F mixture with very high asphalt content. Cores LJ1, BW1, and BW4 were tested for permeability and rutting in Hamburg. Cores WP1, LJ1, WP2, and BW 1 were evaluated using X-ray CT.

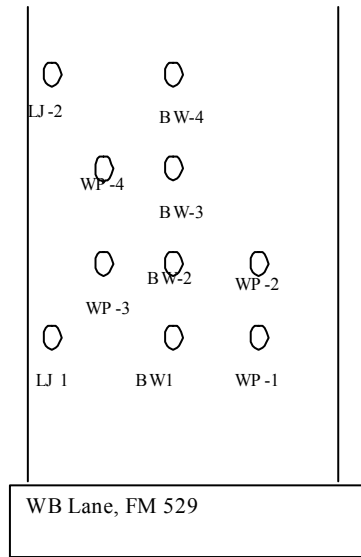


Figure B-14. Coring Layout for FM 529.

The results from testing the FM 529 cores are shown in [Table B-3](#). Based on these results the findings can be summarized as follows:

- Rutting is not a concern for this layer.
- Permeability values are very low.
- Although the percent air voids is relatively high (about 10 percent), the permeability values are very small. This might suggest that the air void sizes in FM 529 are small and not connected.
- There was a very small difference (only 8 percent) between the permeability of the core taken near the longitudinal joint (LJ1) and the two cores from between wheel path (BW1 and BW4).

Table B-3. Results from Testing FM 529 Cores.

Test	Results
Rutting in Hamburg Test	4.25 mm at 20,000 cycles
Permeability	8.85×10^{-4} cm/sec
Percent Air Voids	10.40% (LJ1) 9.45% (Average of WP1 and WP4)

Air Void Distribution Using X-ray Computed Tomography

The X-ray CT and image analysis methods were used to determine the distribution of percent air voids and the radius of air voids across each specimen thickness. The analysis results are summarized in [Table B-4](#). The detailed results for FM 529 are shown in [Figures B-15 to B-22](#) while the results from US 290 are shown in [Figures B-23 to B-26](#). The following is a summary of the findings:

- The comparison of percent air voids from X-ray CT in [Table B-4](#) with the percent air voids measured in the laboratory based on specific gravity in [Table B-3](#) shows that the difference is only 1 percent. This small difference supports the accuracy of X-ray CT in determining the percent air voids in the whole specimen.
- As shown in [Figures B-15 and B-17](#), the air void distributions in the cores recovered from the right and left wheel paths are very similar.
- The comparison of [Figures B-15 and B-17](#) with [Figure B-21](#) reveals that there are similar air void distributions within and outside the wheel paths. The primary difference is in the top 10 mm where the cores within the wheel paths have less percent air voids. This is expected due to the traffic effect on percent air voids close to the surface.
- The comparison between LJ1 in [Figure B-19](#) and cores within the wheel paths in [Figures B-15 and B-17](#) show that the main difference in percent air voids is in the top 10 mm where the cores near the longitudinal joint have more percent air voids.

- The small coefficient of variation for the radius of air voids in FM 529 compared with US 290 indicates that there are less large air voids in FM 529 compared with US 290. This finding explains the low permeability in FM 529 in spite of the relatively high percent air voids (about 10 percent).

Conclusions

- It is clear from Table B-3 that the FM 529 cores had more uniform distributions of percent air voids and size of air voids compared with US 290 cores. This can be seen in the lower standard deviation and lower coefficient of variation for both percent air voids and size of air voids in FM 529.
- The FM 529 mixture has very low permeability in spite of the relatively high percent air voids. This indicates that the air voids in FM 529 are not interconnected. Based on the limited rutting tests conducted in this study, it appears that the FM 529 mix type F has high resistance to rutting.
- A thin asphalt layer such as the one used in FM 529 is expected to have high stresses within the mix. Therefore, it is highly recommended to use aggregates with high abrasion resistance in these types of mixtures.

Table B-4. Summary of the Air Void Distribution Results.

Highway	Specimen ID	Percent Air Voids			Air Void Radius		
		Average (%)	St. Dev.	Coeff. Var.	Average (mm)	St. Dev.	Coeff. Var.
FM 529	WP1	10.739	1.014	9.44	0.688	0.039	5.67
FM 529	LJ1	11.657	0.812	6.97	0.722	0.032	4.43
FM 529	WP2	10.155	0.69	6.79	0.67	0.03	4.48
FM 529	BW1	10.348	1.008	9.74	0.689	0.043	6.24
US 290	4	8.509	1.698	19.96	0.616	0.065	10.55
US 290	6	6.061	1.733	28.59	0.51	0.073	14.31

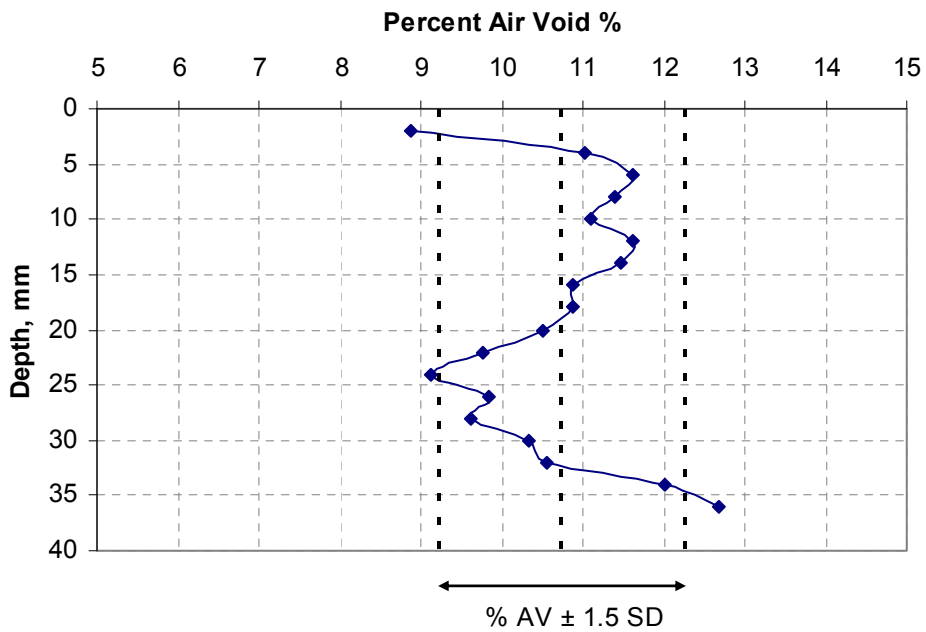


Figure B-15. Percent Air Distribution in Core ID: WP1; Highway: FM 529 and Location: Right Wheel Path.

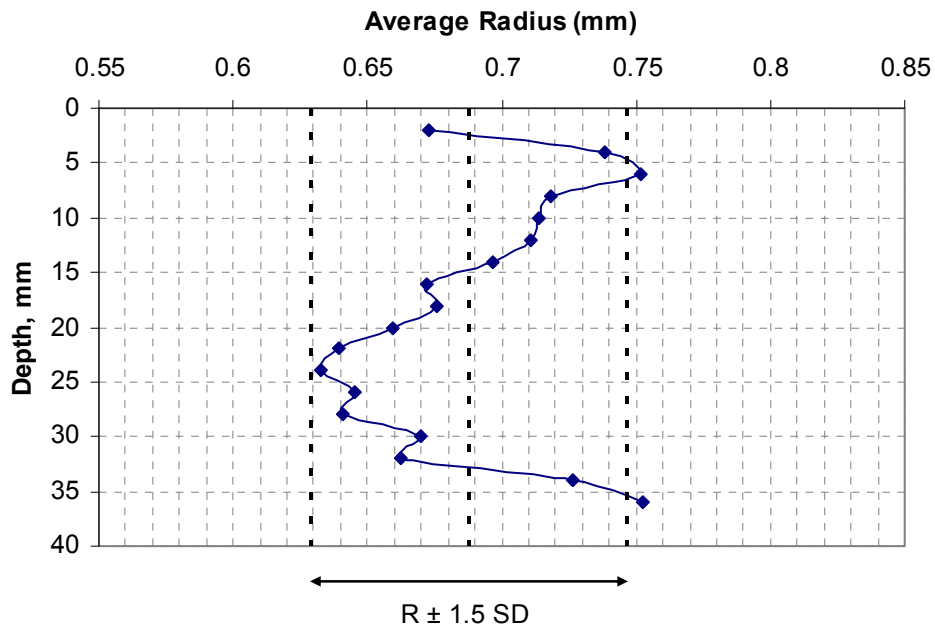


Figure B-16. Air Void Radius Distribution in Core ID: WP1; Highway: FM 529 and Location: Right Wheel Path.

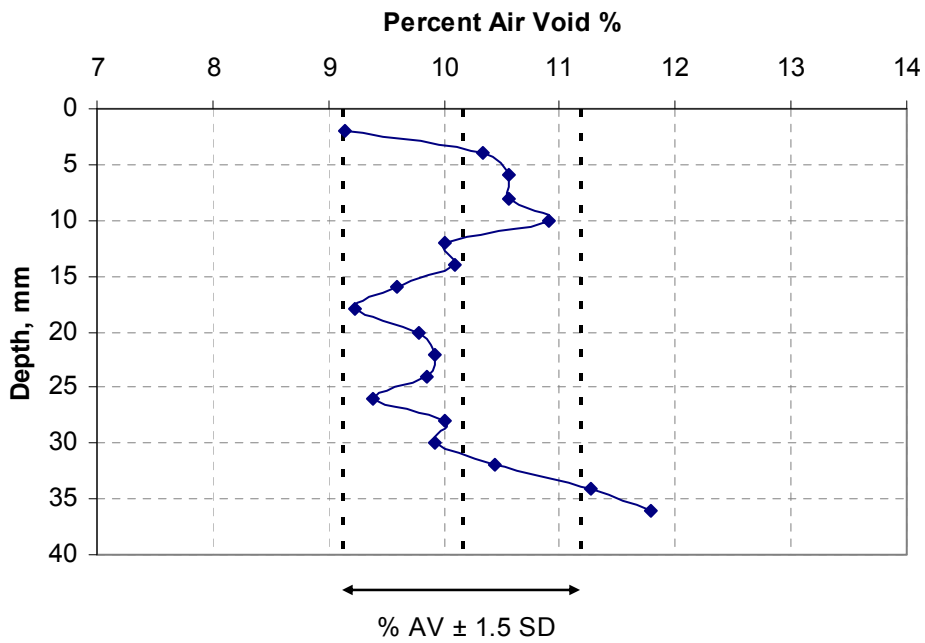


Figure B-17. Percent Air Voids Distribution in Core ID: WP2; Highway: FM 529 and Location: Left Wheel Path.

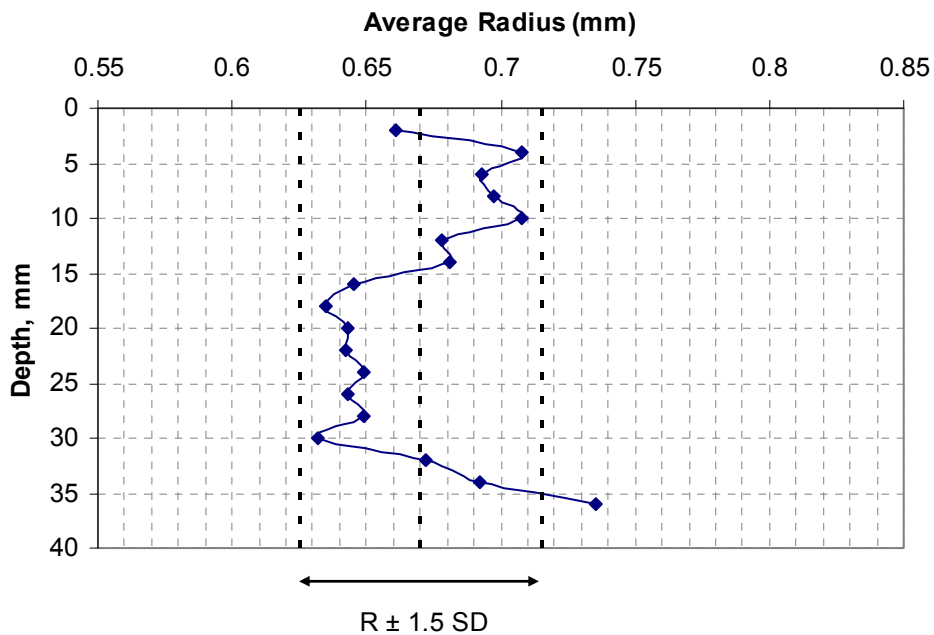


Figure B-18. Air Void Radius Distribution in Core ID: WP2; Highway: FM 529 and Location: Left Wheel Path.

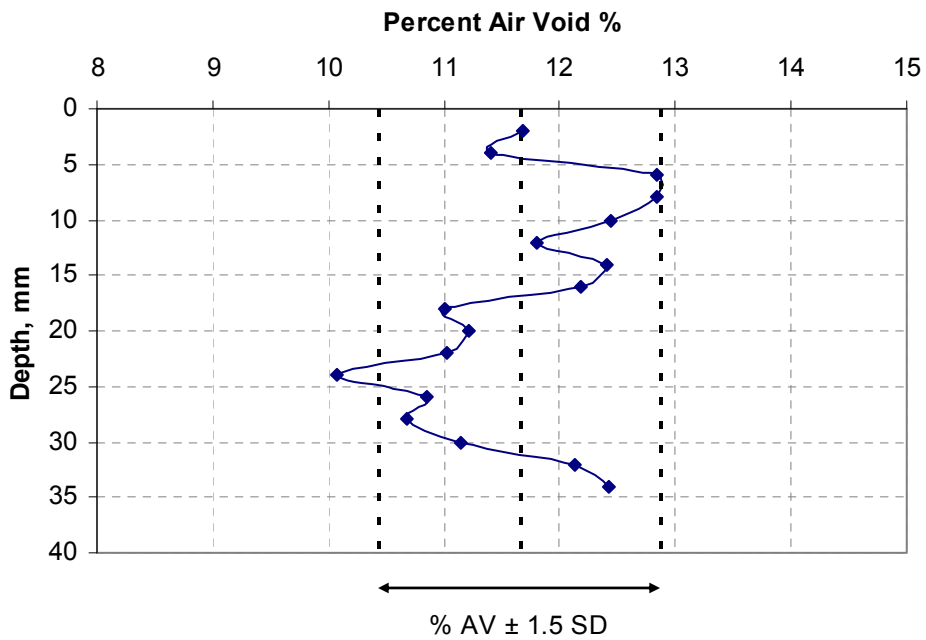


Figure B-19. Percent Air Voids Distribution in Core ID: LJ1; Highway: FM 529 and Location: Near Longitudinal Joint.

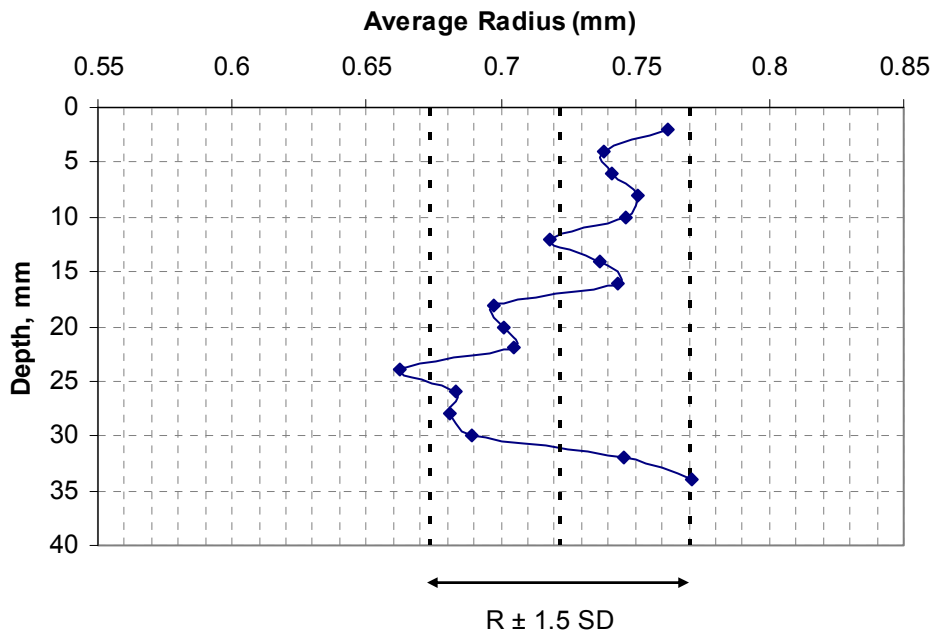


Figure B-20. Air Void Radius Distribution in Core ID: LJ1; Highway: FM 529 and Location: Near Longitudinal Joint.

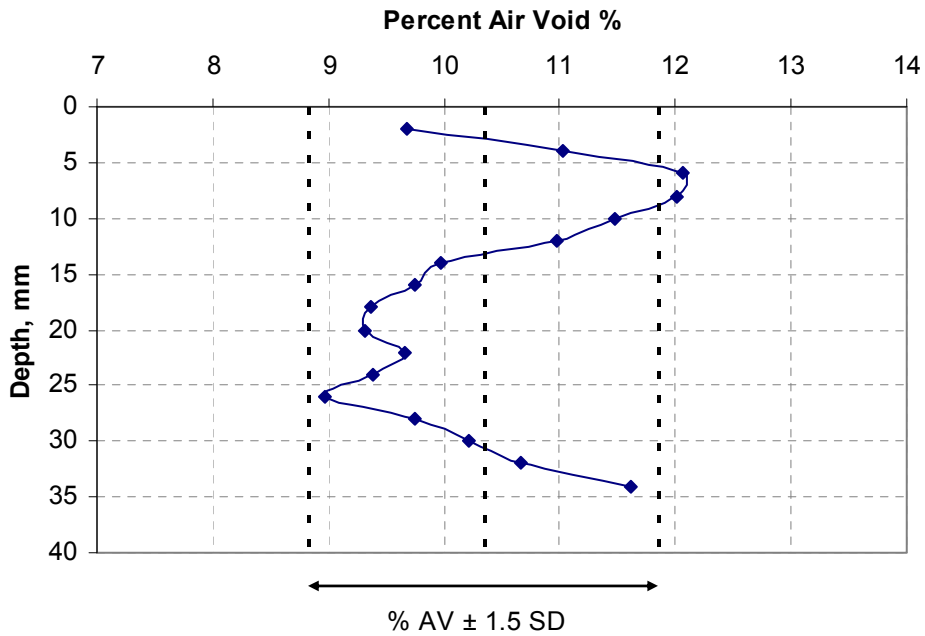


Figure B-21. Percent Air Voids Distribution in Core ID: BW1; Highway: FM 529 and Location: Center of the Lane.

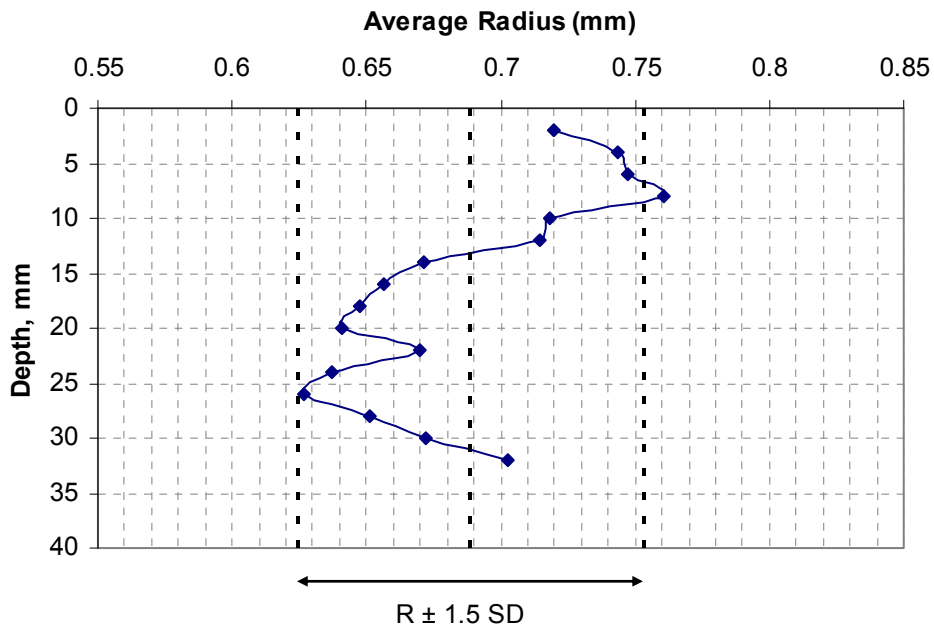


Figure B-22. Air Void Radius Distribution in Core ID: BW1; Highway: FM 529 and Location: Center of the Lane.

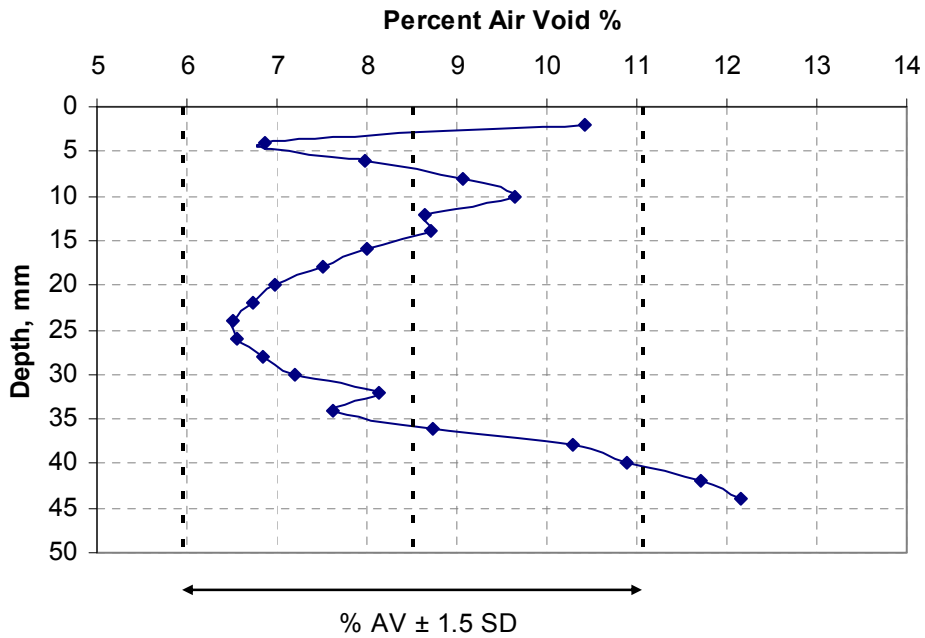


Figure B-23. Percent Air Voids Distribution in Core ID: 4; Highway: US 290 and Location: Right Wheel Path.

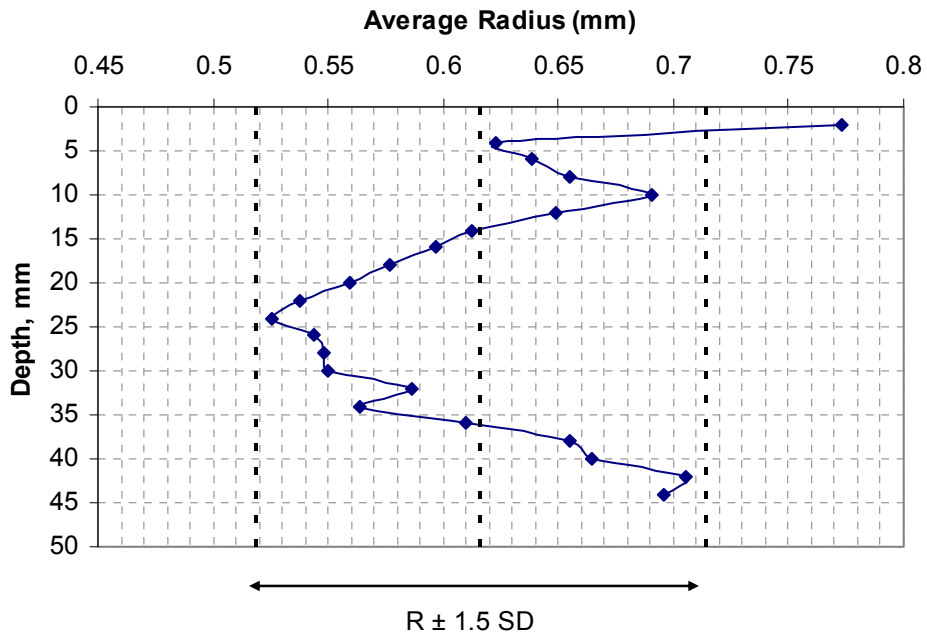


Figure B-24. Air Void Radius Distribution in Core ID: 4; Highway: US 290 and Location: Right Wheel Path.

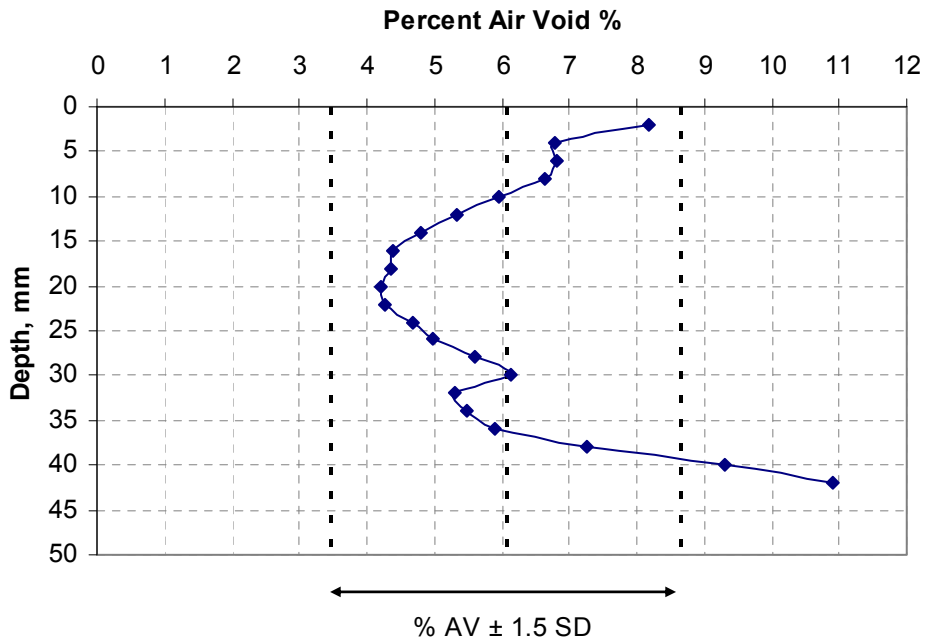


Figure B-25. Percent Air Voids Distribution in Core ID: 6; Highway: US 290 and Location: Between Wheel Paths.

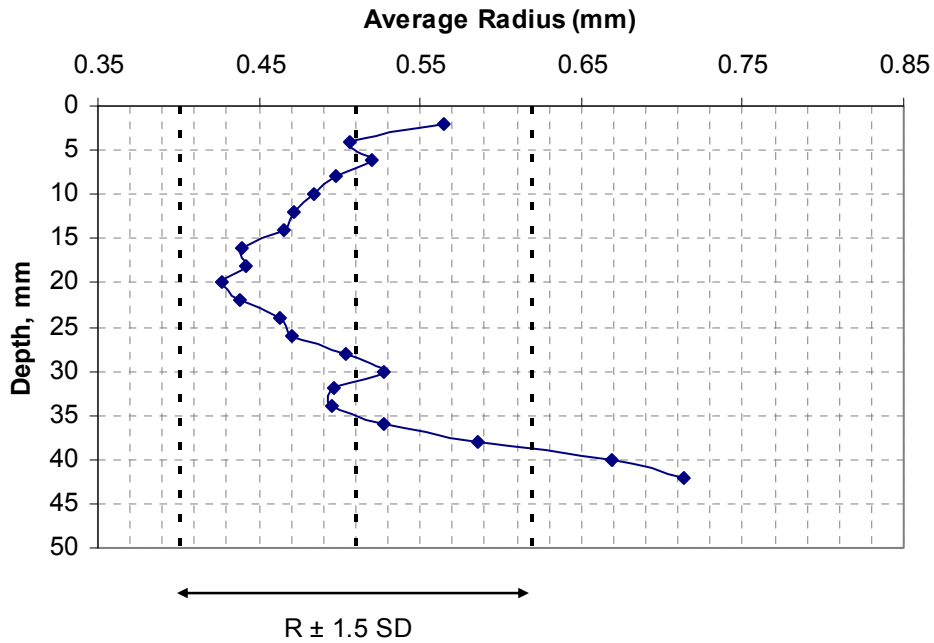


Figure B-26. Air Void Radius Distribution in Core ID: 6; Highway: US 290 and Location: Between Wheel Paths.