Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-13/0-6132-2		

4. Title and Subtitle NEW GENERATION HMA MIX DESIGNS: ACCELERATED PAVEMENT TESTING OF A TYPE C MIX WITH THE ALF MACHINE	5. Report Date September 2012 Published: July 2013
	6. Performing Organization Code
7. Author(s) Lubinda F. Walubita and Tom Scullion	8. Performing Organization Report No. Report 0-6132-2
9. Performing Organization Name and Address Texas A&M Transportation Institute College Station, Texas 77843-3135 The University of Texas at San Antonio San Antonio, Texas 78249	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-6132
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 2009–September 2012 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Project Title: Development and Field Evaluation of the Next Generation of HMA Mix-Design Procedures

URL: http://tti.tamu.edu/documents/0-6132-2.pdf

16. Abstract

Recent changes to the Texas hot-mix asphalt (HMA) mix-design procedures, such as the adaption of the higher-stiffer performance-grade asphalt-binder grades and the Hamburg test, have ensured that the mixes that are routinely used on Texas highways are not prone to rutting. However, performance concerns have been raised with these HMA mixes, which are now drier, more difficult to compact, and more susceptible to premature cracking. This is particularly problematic with the dense-graded mixes (Type C and D) that are widely used throughout the state of Texas. Several new ideas have been under consideration to either: (a) modify the existing HMA mix-design criteria and/or include new and simpler cracking test procedures, or (b) develop new generation HMA mix-design methods that will optimize HMA field performance, particularly with respect to cracking.

In this study, two HMA mix-design methods, namely the traditional Texas gyratory (TG) and the proposed balanced mix design (BMD) were comparatively evaluated in the laboratory and then validated in the field using accelerated pavement testing (APT) with the accelerated loading facility in Louisiana. A typical Texas dense-graded Type C mix, designed using both the TG (herein called the Control) and the BMD (herein called the Modified) methods, was utilized. This report provides a detailed documentation of the laboratory and field APT test results of the Type C mix, both the Control and Modified designs, respectively. Compared to the traditional TG method, the study findings indicated that the proposed BMD method yields a richer HMA mix design with higher asphalt-binder content and superior crack resistance and constructability (workability and compactability) properties, respectively.

17. Key Words	18. Distribution Statement
Mix Design, Volumetric, Balanced, Texas Gyratory Compactor, TG, TGC, BMD, Hamburg, Rutting, Overlay, Cracking, APT, Infrared, Thermal Imaging, GPR, FWD, ALF, Workability, Compactability, Constructability	No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia 22312 http://www.ntis.gov

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	70	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorize**

NEW GENERATION HMA MIX DESIGNS: ACCELERATED PAVEMENT TESTING OF A TYPE C MIX WITH THE ALF MACHINE

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Report 0-6132-2
Project 0-6132
Project Title: Development and Field Evaluation of the Next Generation of HMA Mix-Design Procedures

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

September 2012
Published: July 2013

TEXAS A&M TRANSPORTATION INSTITUTE
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ACKNOWLEDGMENTS

This project was conducted for TxDOT, and the authors thank TxDOT and FHWA for their support in funding this research project. In particular, the guidance and technical assistance provided by the project director, Dale Rand, P.E., of TxDOT, proved invaluable. The following project advisors also provided valuable input throughout the course of the project: Hector Cantu, Miles Garrison, and Robert Lee.

Special thanks are also extended to Lee Gustavus, Rick Canatella, and Tony Barbosa from the Texas Transportation Institute for their help with laboratory and field work. A word of gratitude is also conveyed to the Louisiana Transportation Research Center and Louisiana State University for their help with the accelerated pavement testing.

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LIST OF NOTATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt-binder content
ALF	Accelerated loading facility
APT	Accelerated pavement testing
AC	Asphalt-binder content
AV	Air void
BMD	Balanced mix design
DM	Dynamic modulus
DR	Discriminatory ratio
DT	Direct-tension test
COV	Coefficient of variation
CTB	Cement-treated base
FWD	Falling weight deflectometer
GPR	Ground-penetrating radar
HMA	Hot-mix asphalt
H-O	Hamburg-Overlay
HWTT	Hamburg wheel tracking test
IDT	Indirect-tension test
IR	Infrared
JCP	Joint concrete pavement
LTE	Load transfer efficiency
LTRC	Louisiana Transportation Research Center
LVDT	Linear variable differential transformer
NMAS	Nominal maximum aggregate size
OAC	Optimum asphalt-binder content
OT	Overlay Tester
PG	Performance grade
QA	Quality assurance
QC	Quality control

RLPD	Repeated load permanent deformation
SCB	Semi-circular bending test
TG	Texas gyratory
TGC	Texas gyratory compactor
TxDOT	Texas Department of Transportation
VMA	Voids in mineral aggregate

CHAPTER 1. INTRODUCTION

Recent changes to the Texas hot-mix asphalt (HMA) mix-design procedures, such as adaption of the higher-stiffer performance-grade (PG) asphalt-binder grades and the Hamburg test, have ensured that the HMA mixes that are routinely used on Texas highways are not prone to rutting. However, performance concerns have been raised about these HMA mixes, which are now drier, more difficult to compact, and more susceptible to both reflective and fatigue cracking. This is particularly problematic with the dense-graded Type C and D mixes that are widely used throughout the state of Texas. Several new ideas are under consideration to either:

- Modify the existing HMA mix-design criteria and/or include new and simpler cracking test procedures.
- Develop new HMA mix-design methods that have the potential to optimize the HMA field performance, particularly with respect to cracking.

RESEARCH OBJECTIVES AND SCOPE OF WORK

As indicated above, the primary objective of this research project was to develop new generation HMA mix-design procedures that optimize both rutting and cracking performance, without compromising the constructability aspects of the HMA mixes. Using the accelerated loading facility (ALF) at the Louisiana Transportation Research Center (LTRC) in the state of Louisiana, the objective of the work presented in this report was to evaluate two HMA mix-design methods, namely:

1. The Texas gyratory (TG) method.
2. The proposed balanced mix design (BMD) method.

Field evaluation of these two HMA mix-design methods was based on the accelerated pavement testing (APT) of a typical Texas dense-graded Type C mix under ALF loading conditions. Primarily, the intent of this APT task was to evaluate and validate the mix-design methods and the associated laboratory test procedures in terms of their potential to predict field rutting and cracking potential of the HMA mix under accelerated loading conditions.

DESCRIPTION OF THE REPORT CONTENTS

This report consists of six chapters including this chapter (Chapter 1), which provides the background, the research objectives, methodology, and scope of work. Chapter 2 provides a description of the HMA mix-design methods that were evaluated including the Type C HMA mix-design characteristics. LTRC's APT facility, the ALF machine, and construction details for the APT test sections are discussed in Chapter 3, followed by the laboratory test results in Chapter 4.

Chapter 5 is a presentation of the APT-ALF test results for rutting, reflective cracking, and fatigue cracking, respectively. Chapter 6 then provides a summation of the report with a list of the key findings and recommendations. Some appendices of important data are also included at the end of the report.

SUMMARY

In this introductory chapter, the background and the research objectives were discussed. The research methodology and scope of work were then described followed by a description of the report contents. In this report, some of the laboratory tests such as the Hamburg and Dynamic Shear Rheometer use standard metric (SI) units, and as such some of the test results (including some dimensions such as length, diameter, etc.) have been reported in metric units.

CHAPTER 2. MIX-DESIGN METHODS, HMA MIX EVALUATED, AND THE EXPERIMENTAL DESIGN PLAN

Two HMA mix-design methods, namely the Texas gyratory (TG) and the proposed balanced mix design (BMD), were evaluated. A typical Texas dense-graded Type C mix was utilized for both laboratory and field (APT) evaluation of the two HMA mix-design methods. These aspects are discussed in the subsequent text of this chapter.

THE TEXAS GYRATORY MIX-DESIGN METHOD

The Texas gyratory is the mix-design method traditionally used by the Texas Department of Transportation (TxDOT) for designing HMA mixes (TxDOT, 2011). It is a volumetric-density-based method, and the optimum asphalt-binder content (OAC) is selected based on meeting a prescribed TG lab density criterion, such as 96 or 97 percent for most dense- to fine-graded Texas HMA mixes. Laboratory sample molding and compaction at a minimum of three trial asphalt-binder contents (ACs) is accomplished with the Texas gyratory compactor (TGC); see Figure 2-1 (TxDOT, 2011).

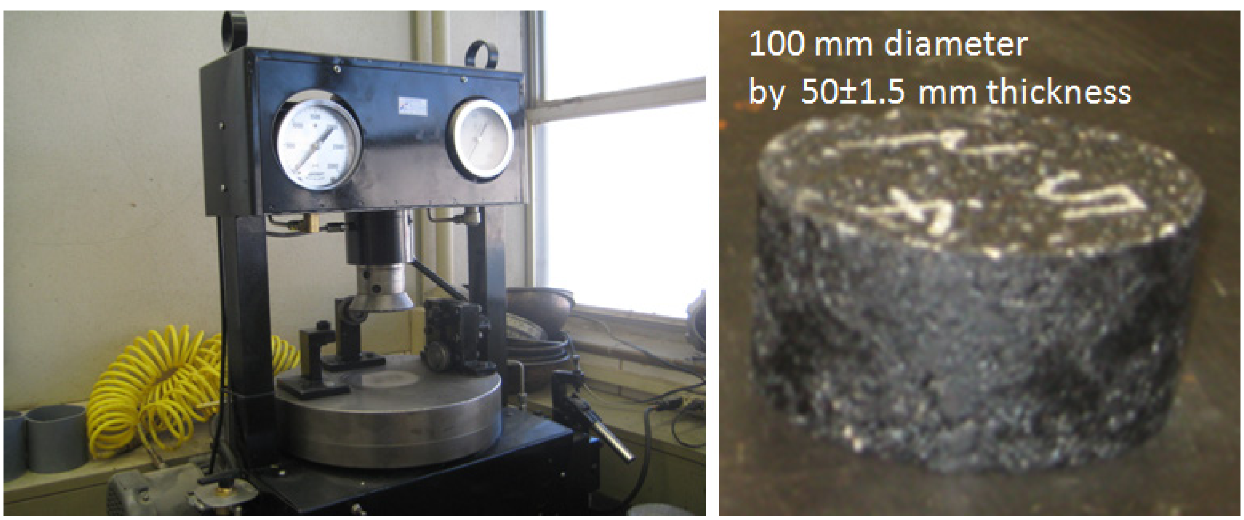


Figure 2-1. The Texas Gyratory Compactor.

Laboratory HMA mix performance evaluation at the selected design OAC and 93±1 percent lab density is achieved with the indirect-tension test (IDT) and the Hamburg wheel tracking test (HWTT), respectively. HMA mix-design acceptance at the design TGC lab density is based on the following criteria (TxDOT, 2004):

- Void in mineral aggregate (VMA)—a minimum of 14 percent for Texas Type C mixes for example, i.e., VMA ≥ 14 percent for Type C mixes. Note however that as specified in the TxDOT standards handbook (TxDOT, 2011), the VMA threshold varies per mix type.
- Hamburg—a rut depth of less than 12.5 mm, i.e., $Rut_{HWTT} < 12.5$ mm in a 50 °C water bath (after 10,000, 15,000, and 20,000 load passes for PG 64-22, PG 70-22, and PG 76-22 mixes, respectively).
- IDT—a dry tensile strength range of 85 to 200 psi, i.e., $85 \leq IDT_{Dry} \leq 200$ psi at ambient temperature.

HMA mixes and/or asphalt-binder contents that simultaneously meet these IDT, HWTT, and VMA criteria are judged as acceptable (TxDOT, 2011). Full details of this HMA mix-design procedure and the TGC can be found in TxDOT test procedures Tex-204-F and Tex-206-F (TxDOT, 2011).

THE PROPOSED BALANCED MIX DESIGN METHOD

The concept of the proposed balanced mix design method is fundamentally centered on designing HMA mixes that are both rutting and cracking resistant (Zhou et al., 2006). As shown in Figure 2-2, the mix-design philosophy is based on designing and selecting an OAC that simultaneously meets certain prescribed laboratory rutting and cracking requirements based on the HWTT and Overlay Tester (OT) tests, respectively, with a minimum of three trial asphalt-binder contents at 93±1 percent lab density.

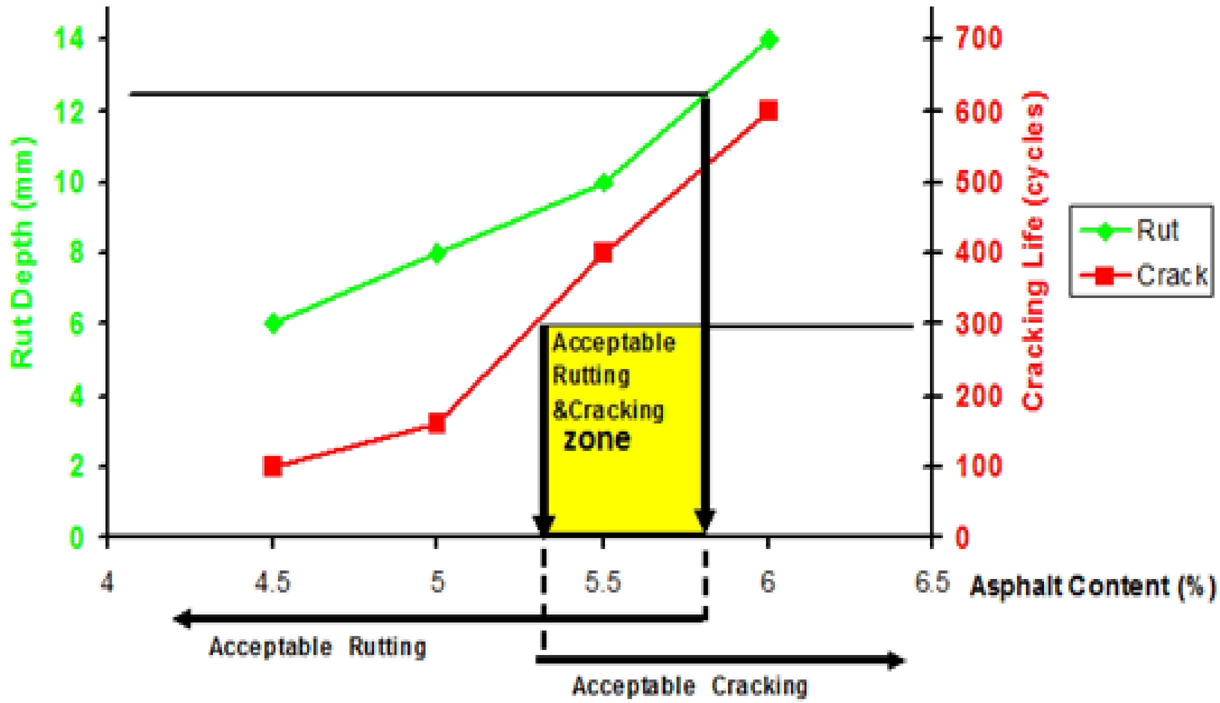


Figure 2-2. Graphical Illustration of the Balanced Mix-Design Concept.

The Hamburg-Overlay Pass-Failure Criteria

Based on Figure 2, the HWTT is the limiting criterion for the maximum selectable design OAC, i.e., the upper limit of the design OAC. The standard HWTT rutting criterion is 12.5 mm (i.e., $Rut_{HWTT} \leq 12.5$ mm). HMA mixes and/or asphalt-binder contents meeting this criterion are judged as acceptable with sufficient lab rutting resistance.

The OT is the limiting criterion for the minimum selectable design OAC, i.e., the lower limit of the design OAC. HMA mixes and/or asphalt-binder contents that last over 300 cycles (i.e., $N_{OT} \geq 300$) prior to crack failure at 93 percent stress reduction are tentatively judged as acceptable with reasonable lab cracking resistance. However, 300 cycles is still a subjective OT criterion that is under review and has not yet been standardized. Both HWTT and OT test samples, with a minimum of three asphalt-binder contents, are gyratory molded to 93±1 percent lab density.

Selection of the Design Asphalt-Binder Content

Figure 2-2 clearly shows that as the asphalt-binder content increases, the rutting resistance decreases, and vice versa for the cracking resistance. Conversely, the opposite result would be expected if the asphalt-binder content were decreased. A balanced OAC design includes an asphalt-binder content in the zone of the asphalt-binder contents in which the HMA mix simultaneously passes both the laboratory HWTT rutting ($Rut_{HWTT} \leq 12.5$ mm) and OT cracking ($N_{OT} \geq 300$) requirements, respectively. Any asphalt-binder content selected as the design OAC within this zone is acceptable and is considered to be representative of a lab rut- and crack-resistant mix (Zhou et al., 2006; Walubita & Scullion, 2008).

THE HWTT AND OT TEST DEVICES

The HWTT is a standard test device used for characterizing the rutting resistance of HMA mixes in the laboratory including stripping susceptibility assessment (moisture damage potential). The OT, on the other hand, is a simple performance test used for characterizing the cracking potential of HMA mixes in the laboratory at an ambient (room) temperature of 25 °C. Figures 2-3 and 2-4 show photographical views of the HWTT and OT devices, respectively, and include the test sample setups. Details of the test loading configurations including the pass-fail criteria are summarized in Table 2-1 (Zhou et al., 2006; TxDOT, 2011).

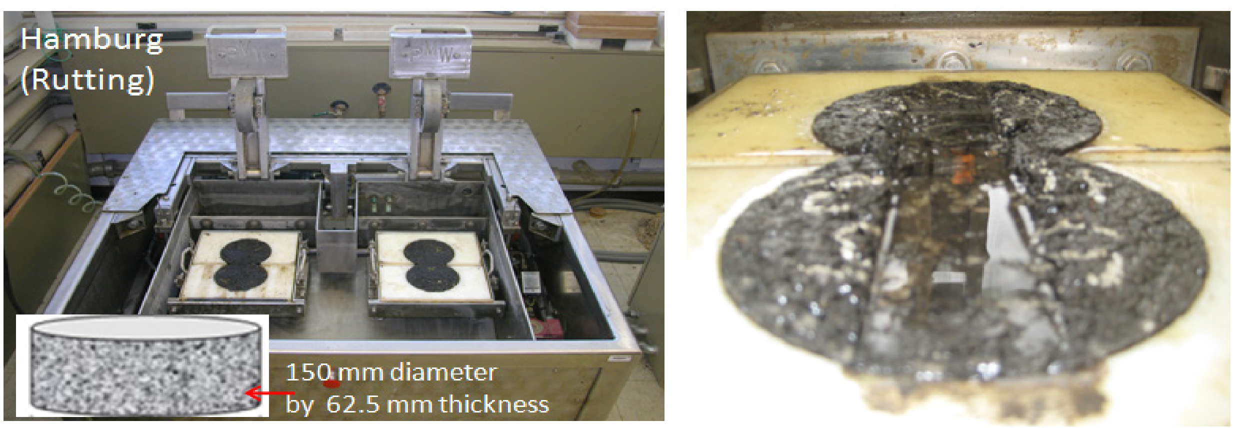


Figure 2-3. The Hamburg Wheel Tracking Test Device.

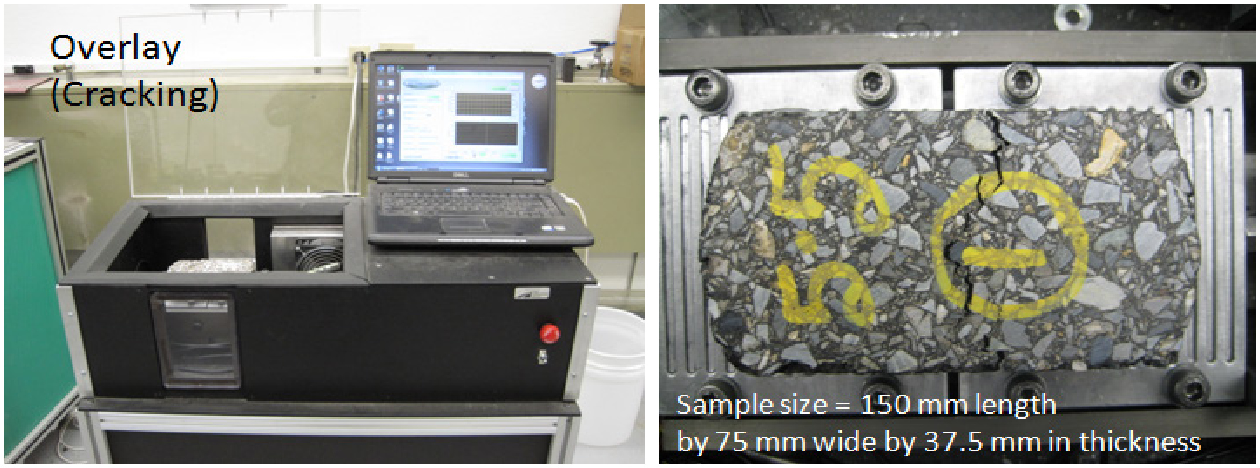


Figure 2-4. The Overlay Tester.

Table 2-1. Test Loading Configuration for the Hamburg and Overlay.

Item	Hamburg	Overlay
Test objective	Laboratory characterization of the rutting resistance and stripping potential of HMA mixes	Laboratory characterization of cracking potential of HMA mixes
Load magnitude	158 lbf	0.025 inches of horizontal displacement
Loading mode	Repetitive passing	Cyclic triangular displacement-controlled waveform
Loading frequency	52 passes per minute	10 s per cycle (5 s loading and 5 s unloading)
Test temperature	122 °F (50 °F)	77 °F (ambient ≈ 25 °C)
Specimen dimensions	6 inches in diameter by 2.5 inches thick	6 inches long by 3 inches wide by 1.5 inches thick
Pass-fail criteria	≤ 12.5 mm after 10,000 passes for PG 64-XX mixes ≤ 12.5 mm after 15,000 passes for PG 70-XX mixes ≤ 12.5 mm after 20,000 passes for PG 76-XX mixes	≥ 300 cycles at 93% reduction in the initial peak load (tentative)—still under review

EXPERIMENTAL DESIGN PLAN

Using a similar HMA mix type (i.e., a Type C mix), the experimental design plan was to design and select the OAC using the two different mix-design methods (TG and BMD) and then compare both the laboratory and field APT performance of the HMA mixes. As a way of validating the mix-design methods, the APT-ALF testing served as a means to verify the laboratory performance predictions. The subsequent text presents the HMA mix designs.

THE HMA MIX UTILIZED FOR APT TESTING

A ¾-inch nominal maximum aggregate size (NMAS) dense-graded Type C mix was utilized to comparatively evaluate the TG and the BMD methods under APT-ALF testing (Walubita et al., 2010). Table 2-2, Figure 2-5 thru 2-7, and Appendix A summarize the HMA mix-design characteristics.

Table 2-2. HMA Mix-Design Details for APT Testing.

Item	TG Method	BMD Method
Mix designation	Control	Modified
Mix type	Type C	Type C
Materials	PG 76-22 (Valero) + Limestone (Brownwood)	PG 76-22 (Valero) + Limestone (Brownwood)
Design OAC	4.3%	5.2%
Corresponding TGC lab density (96% ≤ TGC < 98%	96.0%	97.5%
VMA (≥ 15%)	14.0	14.2%
Hamburg rutting (≤ 12.5 mm)	4.7	7.0
Overlay crack cycles (≥ 300)	90	600
IDT (85 ≤ IDT ≤ 200 psi)	165 psi	130 psi
APT placement	Control sections	Modified sections

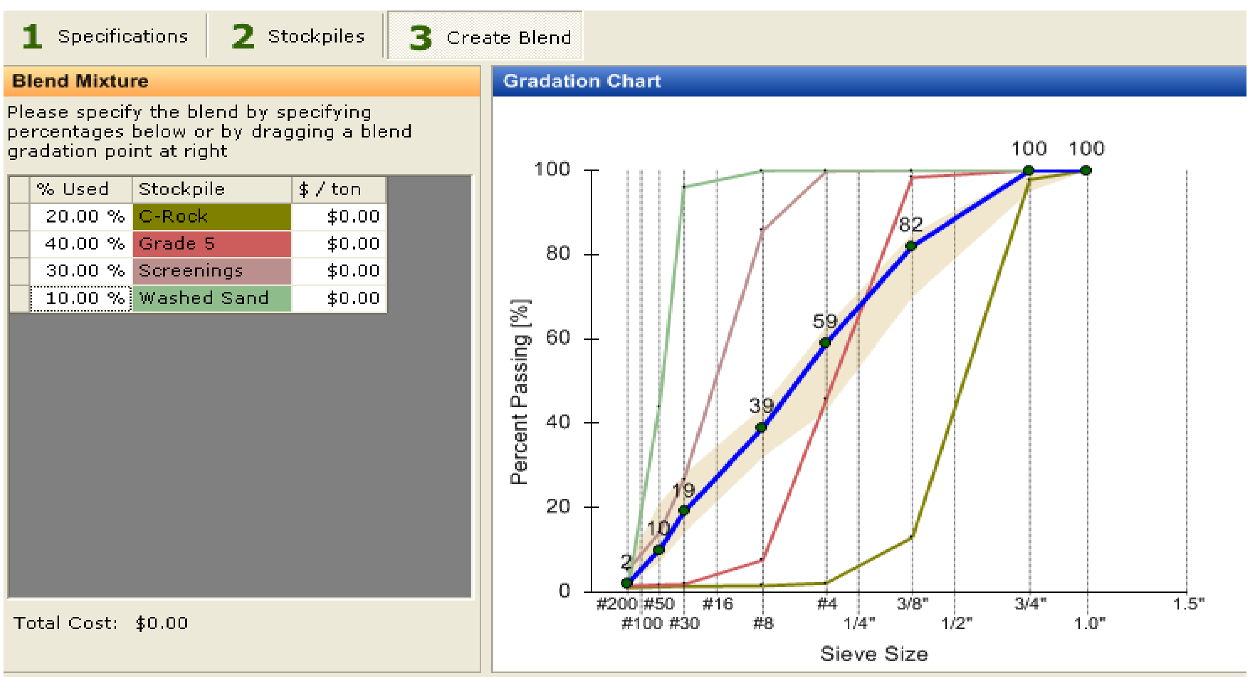


Figure 2-5. Aggregate Gradation for the Type C Mix.

Determination of the Design OAC Using the TG Method

With the TG method, the criterion for selecting the design OAC for this particular mix was 96 percent TGC lab density (TxDOT, 2004, 2011). As shown in Figure 2-6, the asphalt-binder content corresponding to this density level (96 percent) was 4.3 percent; thus, this content was selected as the design OAC based on this method.

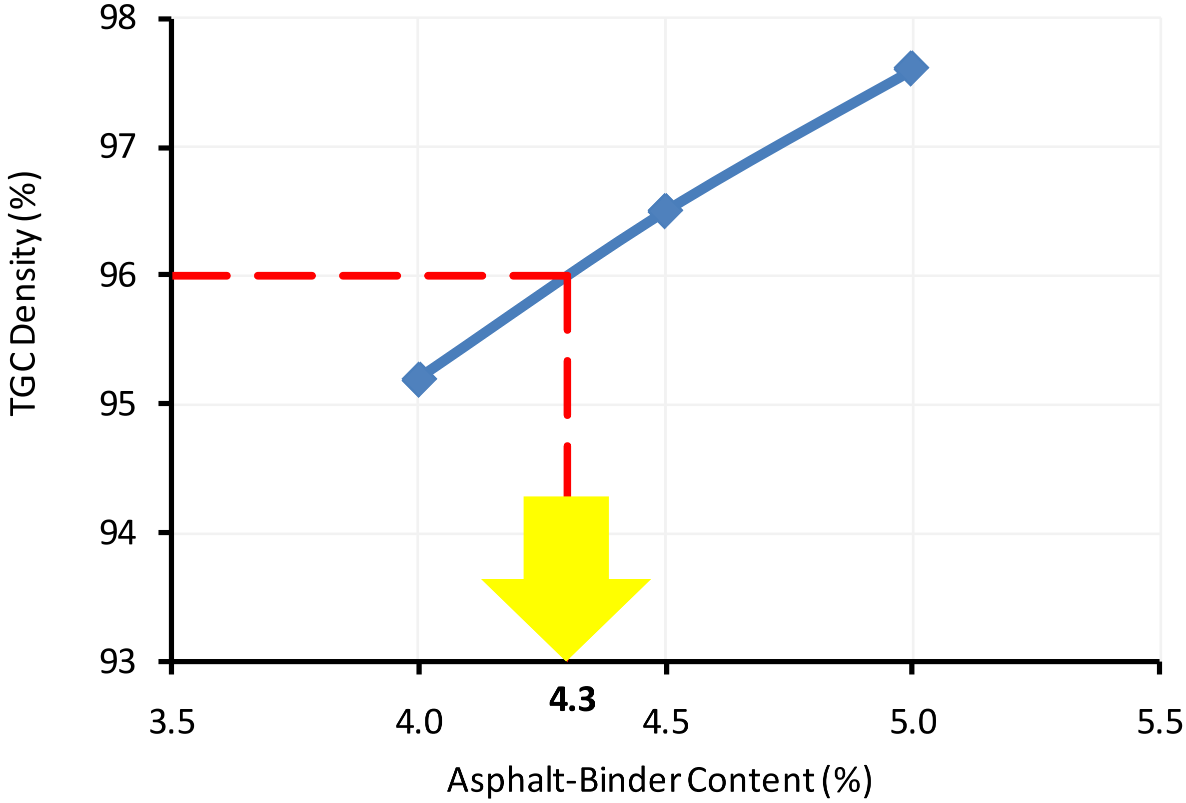


Figure 2-6. TGC Density and Asphalt-Binder Content Results.

At 4.3 percent asphalt-binder content, the measured laboratory indirect tensile strength and rut depth of the HMA mix were 165 psi and 4.7 mm, respectively; see Table 2-2. These values sufficiently met both the Texas IDT ($85 \leq IDT_{Dry} \leq 200$ psi) and HWTT ($Rut_{HWTT} \leq$ 12.5 mm after 20,000 load passes) requirements for laboratory performance evaluation (TxDOT, 2004, 2011). Based on this TG method at 96 percent TGC lab density, 4.3 percent asphalt-binder content was considered satisfactory as the design OAC for this mix.

Determination of the Design OAC Using the Proposed BMD Method

Figure 2-7 shows the Hamburg and Overlay test results for a trial asphalt-binder content range of 4.3 to 6.2 percent.

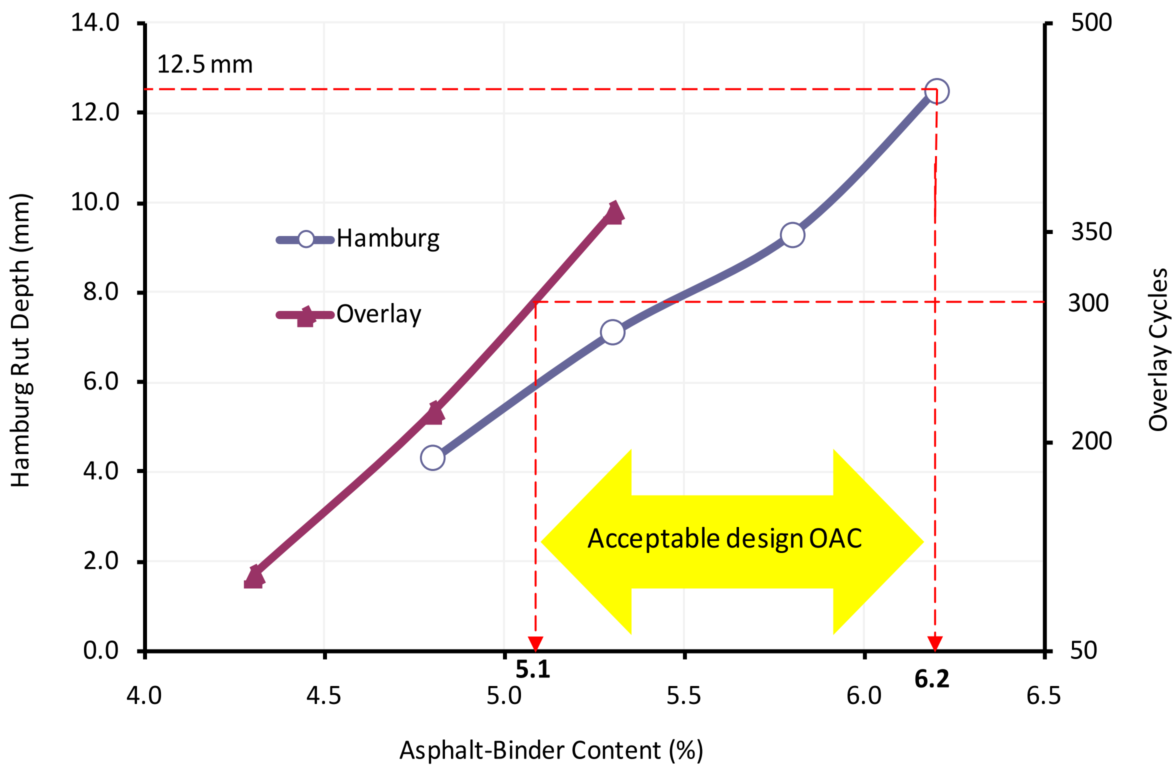


Figure 2-7. Hamburg-Overlay and Asphalt-Binder Content Results.

According to Figure 2-7, the selectable asphalt-binder content range that meets both the Hamburg rutting (i.e., rut depth ≤ 12.5 mm rut depth after 20,000 HWTT load passes for PG 76-22 mixes) and the Overlay cracking (i.e., crack cycles ≥ 300) requirements is from 5.1 to 6.2 percent. To accommodate the field density requirements (i.e., ≤ 98 percent), and for the purposes of practicality, 5.2 percent was selected as the balanced design OAC meeting both the laboratory rutting and cracking requirements; see Table 2-2.

As Figure 2-7 illustrates, the Overlay crack test is the determinant of the lower limit (i.e., ≥ 5.1 percent) for the selectable design OAC. The Hamburg rutting test, on the other hand, is the determinant of upper limit (i.e., ≤ 6.2 percent) of the selectable design OAC.

The Type C mix described in Table 2-2 and Figure 2-5 thru 2-7 is a typical Texas dense-graded HMA mix that is commonly used on Texas highways. Both the asphalt-binder (Valero) and limestone (Brownwood) aggregates were locally sourced in Texas. For easy identification, the design based on the TG (4.3 percent OAC) and the BMD (5.2 percent OAC) was utilized as the Control and Modified mix designs, respectively, for APT testing under ALF loading. For each design OAC, the corresponding laboratory TGC density and VMAs are listed in Table 2-3.

Table 2-3. Design OAC, the Corresponding Lab TGC Density, and VMA.

Mix	Mix Designation	Design OAC	Corresponding Lab TGC Density	VMA (≥ 14)
Type C	Control	4.3%	96.0%	14.0
	Modified	5.2%	97.5%	14.2

SUMMARY

This chapter provided a discussion of the mix-design methods and the HMA mix that was utilized for APT testing under ALF loading at the LTRC facility in Louisiana. A typical Texas dense-graded Type C mix with PG 76-22 asphalt-binder (Valero) and limestone aggregates (Brownwood) was utilized for evaluating two HMA mix-design methods, namely the TG and BMD methods. The experimental design plan included two OAC designs based on the TG and BMD methods, namely the Control at 4.3 percent design OAC and the Modified at 5.2 percent design OAC, respectively.

CHAPTER 3. THE LTRC-APT FACILITY, ALF DEVICE, AND APT TEST SECTION CONSTRUCTION

This chapter provides a description of the LTRC-APT test facility and the ALF machine. Construction details including quality control (QC)/quality assurance (QA) tests are also discussed. Finally, the chapter includes a summary of key points (Walubita et al., 2010).

THE LTRC-APT FACILITY AND THE ALF MACHINE

The Texas Transportation Institute (TTI) developed a contractual agreement with the LTRC to test the Texas mixes at the LTRC-APT facility near Baton Rouge in Louisiana. The climate and environmental conditions in the southern part of Louisiana where the APT facility is located do not differ significantly from those of Texas. Thus, since Texas lacks such an APT facility, it was deemed appropriate to do the APT testing at the LTRC in Louisiana. The LTRC has an established ALF machine, shown in Figure 3-1, and has been actively running accelerated load tests for more than 5 years.

Figure 3-1. LTRC's ALF Machine.

The ALF device is a 100-ft-long, 55-ton accelerated loading device used to simulate truck loading for pavement testing. When running, the weight and traffic movement is simulated repetitively in one direction via a computer-controlled trolley. The LTRC-ALF is a uni-directional APT device with dual wheels that are 9 inches wide, with a 6-inch separation between the tires. The ALF loading is adjustable, ranging from 5 to 10.5 kips per tire, with a maximum operable tire pressure of up to 150 psi. The test area under the ALF is approximately 40 ft long, with a tire contact area of 445 inch^2 at 100 psi. The maximum operable ALF speed is 120 mph.

In total, the LTRC facility consists of 12 individual lanes, each 215 ft long and 13 ft wide. The individual lanes are designable to any pavement structure of interest. TTI utilized only three lanes, for reflective cracking, rutting, and fatigue crack evaluation of the Type C mix, respectively (see Chapter 2 for the mix-design details).

CONSTRUCTION OF THE APT TEST SECTIONS

Construction of the APT test sections was completed in summer 2009. Two lanes (designated as Lanes 2 and 3) with four sections consisted of 3-inch-thick HMA plus 4-inch-thick stone granular base over a 6-inch-thick cement-treated base (CTB) layer. The third lane (designated as Lane 1) consisted of a 2-inch-thick HMA over 8-inch-thick joint concrete pavement (JCP) resting on a 7-inch-thick CTB layer. Figure 3-2 shows a diagrammatical layout of the constructed test sections.

Subgrade, Subbase, and Base Materials

The subgrade consisted of in-situ natural soil material, i.e., a class A-4 soil material type. On Lane 1, the base was JCP and the subbase was a 5 percent CTB layer. For Lanes 2 and 3, the base and subbase were Kentucky limestone and 10 percent CTB layer, respectively.

Construction of Joints in the JCP Sections (TTI Lane 1)

One innovative feature of this APT test site was that the joints constructed in the experimental JCP sections had poor load transfer efficiency (LTE). The LTE of the Control joints was close to 100 percent. However, the LTE was reduced to 50 percent over the other experimental JCP Sections 4 and 5. This was necessary to effectively evaluate the reflective cracking potential of the HMA mixes. Figure 3-3 illustrates the joint construction process.

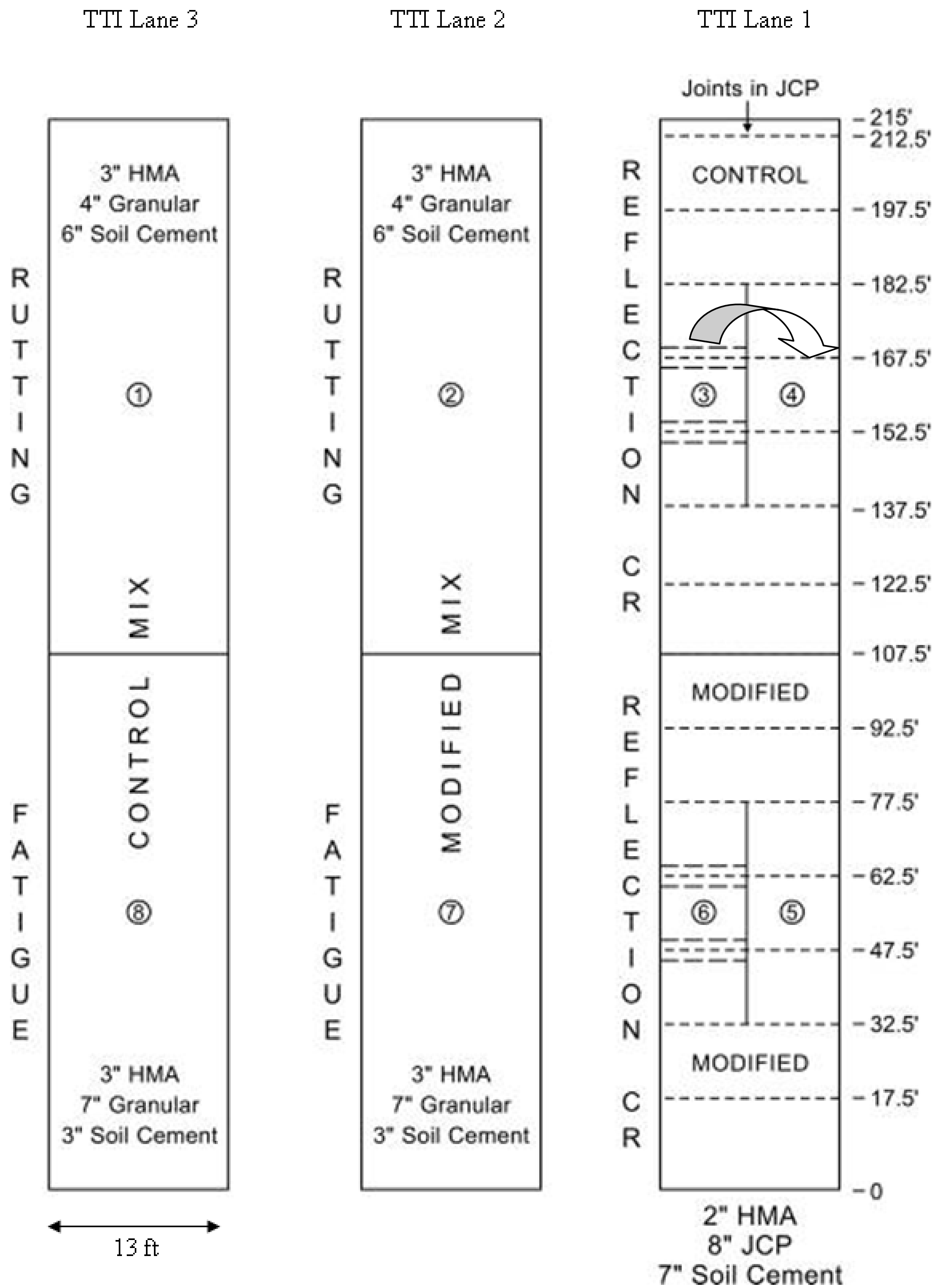


Figure 3-2. LTRC-APT Experimental Test Sections.

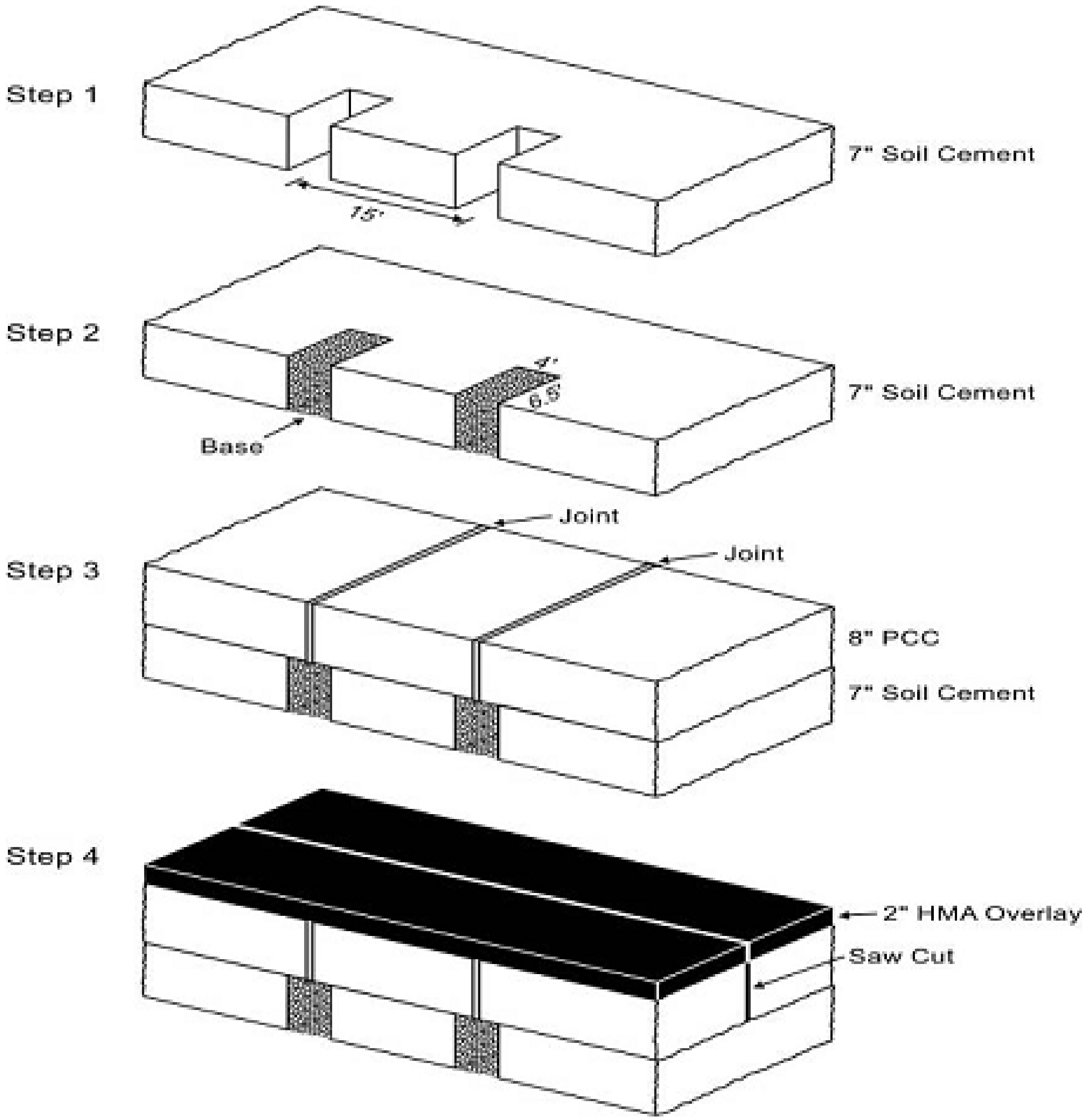


Figure 3-3. Construction of the Low LTE Joints at the LTRC-APT Test Site (TTI Lane 1).

Based on Figure 3-2, the low LTE joints at 50 percent with voiding were initially planned for JCP Sections 3 and 6. Due to site conditions, however, the low LTE joints with voiding were switched over to JCP Sections 4 and 5 during construction; see example in Figure 3-4 for Sections 3 and 4. As seen in Figure 3-4, Section 4 with voiding had poorer LTE joints than Section 3, and thus would be expected to reflectively crack quicker than Section 3.

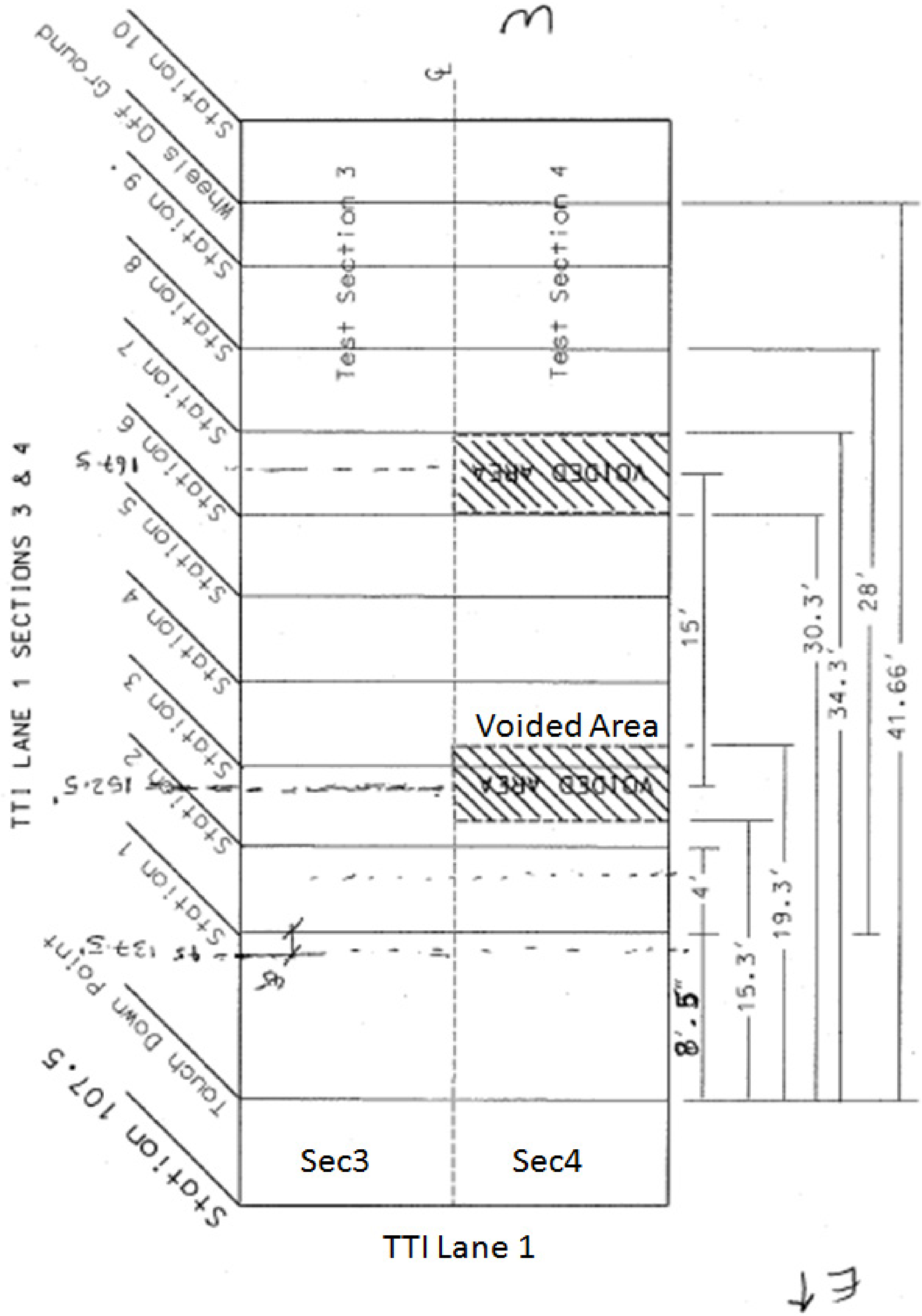


Figure 3-4. Location of Voided Areas and Low LTE Joints on Section 4 (TTI Lane 1).

HMA Placement, Paving, and Compaction Process

HMA (Type C) placement was consistent with the Texas construction specifications (TxDOT, 2004). No material transfer device was engaged in this construction operation. As Figure 3-5 shows, the trucks dumped the hot mix directly into the paver.

Figure 3-5. HMA Placement and Compaction Operations.

The air and surface temperatures at the time of HMA placement were 82 and 105 °F, respectively, which satisfied the Texas construction specification requirements (TxDOT, 2004). To meet the 143 to 145 pcf density requirements, the compaction rolling pattern consisted of two vibrating passes and two static passes of an 18-ton steel wheel roller; see Figure 3-5. An example of the finished HMA mat at the LTRC-APT test site is shown in Figure 3-6.

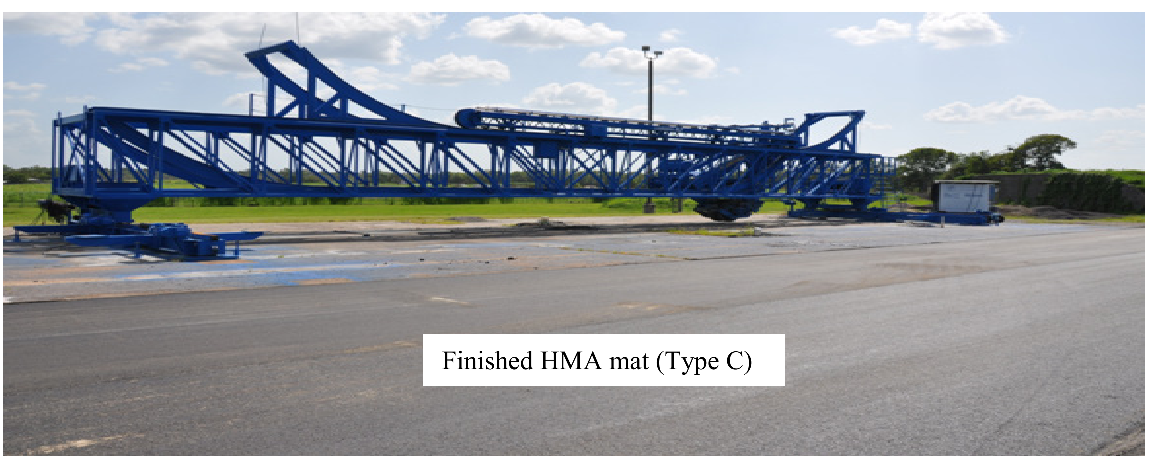


Figure 3-6. Finished HMA Mat at the LTRC-APT Test Site (August 2009).

CONSTRUCTION QUALITY CONTROL/QUALITY ASSURANCE TESTS

The following QC/QA tests were conducted during construction of the APT test sections and are discussed herein: mat temperature measurements, density measurements, ground-penetrating radar (GPR) measurements, and coring.

Infrared (IR) Thermal Imaging

TTI conducted IR temperature measurements during placement of the HMA mix on all three lanes at the LTRC-APT test site. Figure 3-7 shows the IR thermal imaging of the HMA mat (Walubita et al., 2010).

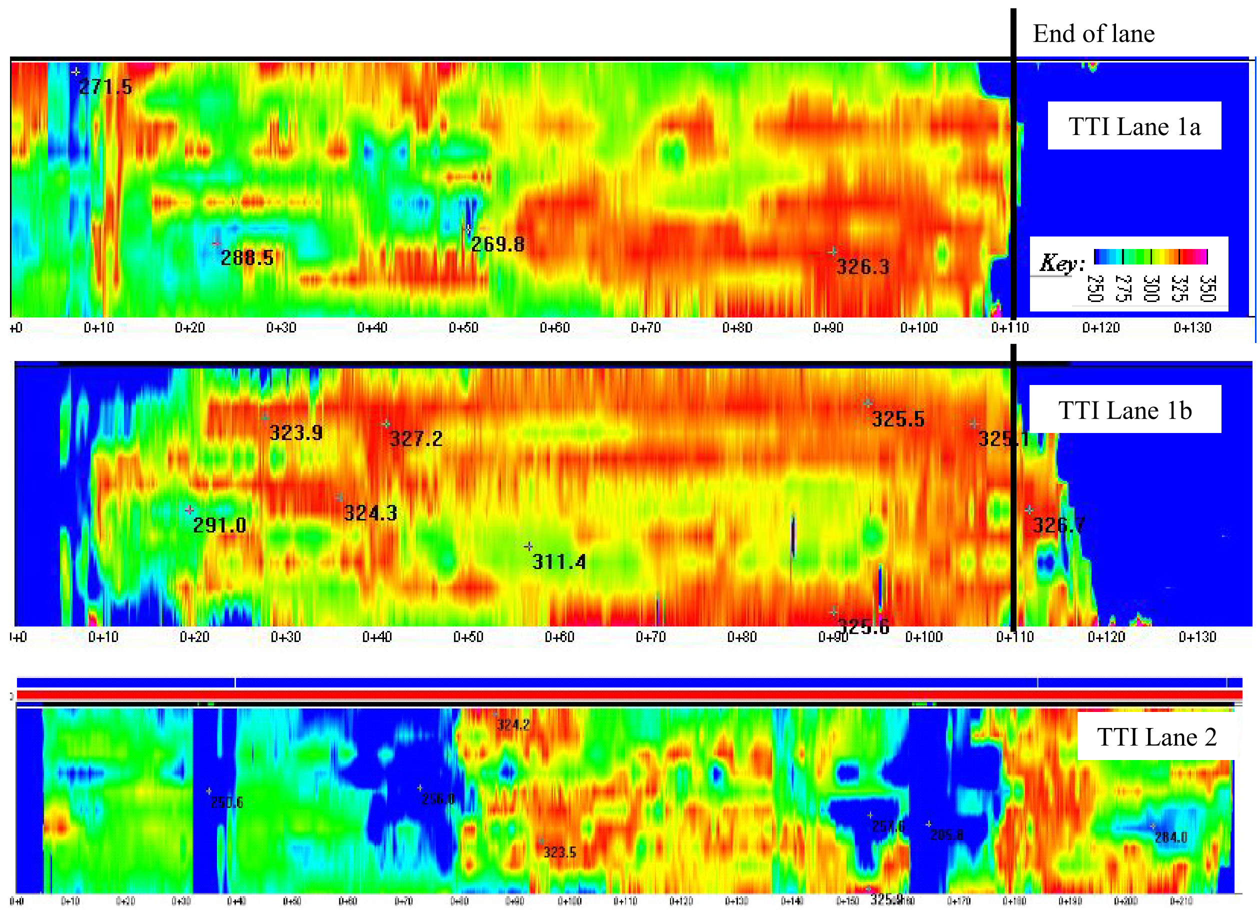


Figure 3-7. IR Thermal Imaging of the HMA (Type C) Mat.

In Figure 3-7, the red colors represent temperatures around 300 °F, whereas the blue colors are temperatures of around 220 °F. The green colors represent temperatures between 235 and 270 °F. The numbers on the plot are the actual temperatures at that location.

In general, blue is the undesired IR thermal color reading, as it often indicates cold spots. For a target HMA mat placement temperature of 300 °F with a tolerance of ±30 °F, the green and red IR thermal color readings would be considered acceptable. As Figure 3-7 shows, the mat temperature was not very uniform, with visual evidence of thermal segregation particularly on Lanes 1a and 2. There are some intermittent cold spots (bluish) of thermal segregation in the mat. On Lane 1b, the mat temperatures were fairly uniform, particularly in the middle part of the lane, with an average of about 290 °F.

As will be discussed in the subsequent sections, this thermal segregation did not appear to have significantly affected the uniformity in the compaction operation. The in-situ densities were fairly consistent and within the target range; see Table 3-1.

Nuclear Density Measurements

With the exception of Test 4 for the Control mix, Table 3-1 shows that the HMA mat densities were satisfactorily within the 143 to 145 pcf range. The coefficient of variation (COV) was less than 1 percent, which is indicative of uniform compaction and consistent density.

Table 3-1. QC Nuclear Density Measurements.

Mix Designation	Test 1	Test 2	Test 3	Test 4	Average	COV	Corresponding %Density
Control	143.0	144.0	144.6	142.7	143.6	0.6%	92.6%
Modified	144.3	143.7	143.5	144.5	144.0	0.3%	93.7%

Ignition Oven Tests for the Asphalt-Binder

As Table 3-2 shows, the burned off asphalt-binder contents from field-extracted cores and plant mixes were slightly less than the design OAC but still within the Texas ±0.3 percent specification tolerance (TxDOT, 2004, 2011). Thus, the contractor satisfactorily met the specification requirements with respect to the asphalt-binder content.

Table 3-2. Asphalt-Binder Content Results Based on the Ignition Oven Test.

Mix Designation	Design OAC	Burned off Asphalt-Binder Content	Deviation by Weight of Total Mix	Meets ±0.3% Tolerance
Control	4.30%	4.13%	-0.17%	Yes
Modified	5.20%	5.10%	-0.10%	Yes

GPR Measurements

Figure 3-8 shows GPR readings taken just after placement of the HMA mat. The GPR readings for Lanes 2 and 3 with some blue coloring suggest density variations within the HMA mat, which may be critical for the rutting performance of the HMA mixes. Density measurements of cores taken from these locations are discussed in the subsequent chapters of this report.

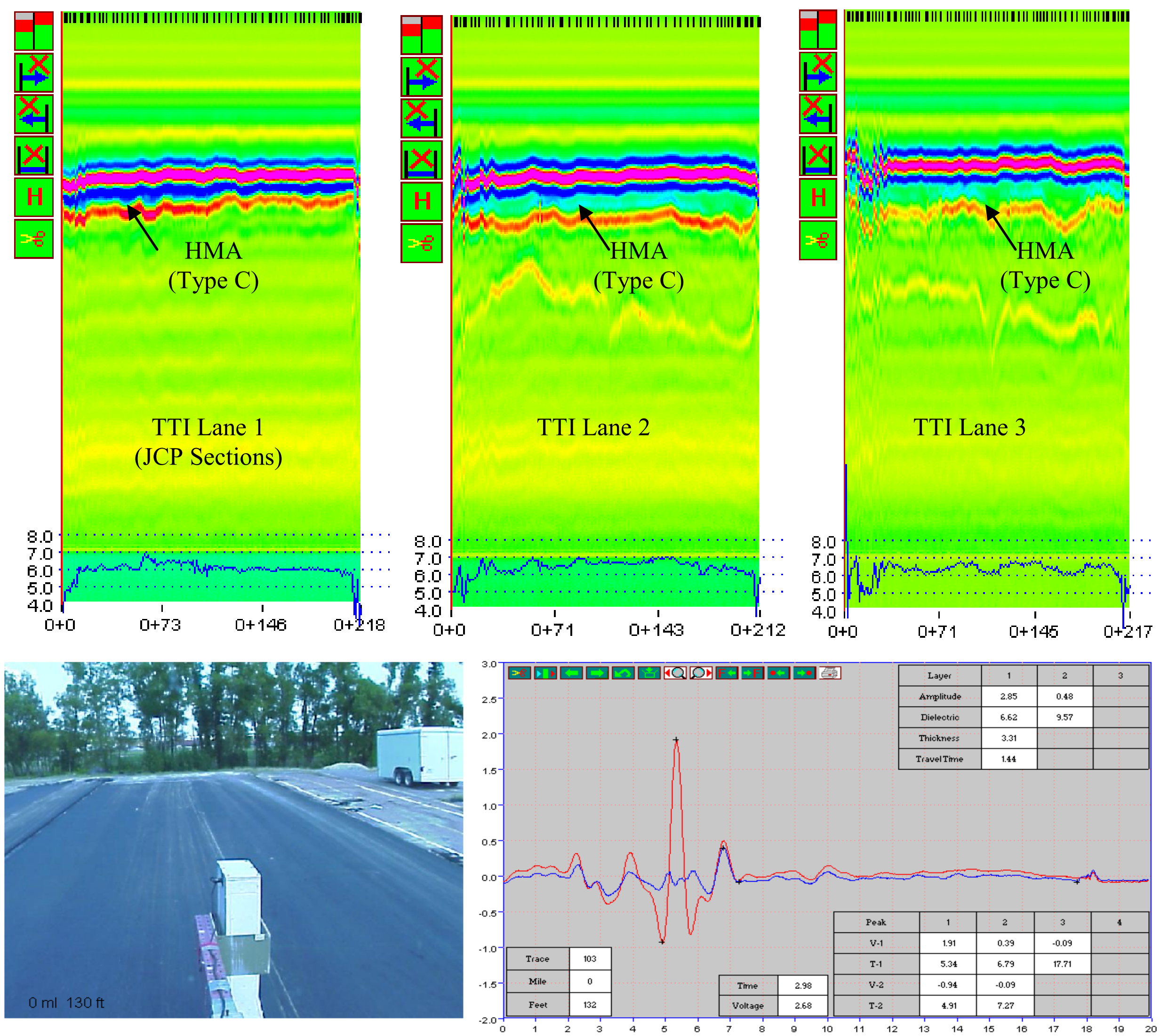


Figure 3-8. GPR Measurements.

As Figure 3-8 shows, both the HMA and the base exhibited inconsistent thickness. This was a construction quality issue that could impact the APT performance of the test sections under ALF loading.

Raw Materials, Plant Mixes, and Cores

Researchers obtained substantial quantities of both the plant-mix and field-extracted cores (both mix designs) from the APT test site for laboratory testing at the TTI lab. HMA specimens were also molded on site using TTI's mobile lab and hauled to TTI for subsequent lab testing. Raw materials including asphalt-binder and aggregates were also obtained for testing at the TTI lab. Chapter 4 includes a discussion of the results of these laboratory tests.

SUMMARY

Construction of the APT test sections in Louisiana was completed in summer 2009. Details of the construction process were discussed in this chapter. The list below provides a summation of the key points from this chapter (Walubita et al., 2010):

- A dense-graded Type C mix with PG 76-22 asphalt-binder (Valero) and limestone aggregates (Brownwood) was placed as the surfacing HMA layer on the APT test sections in Louisiana.
- Two OAC designs based on the TG and BMD methods, namely the Control at 4.3 percent OAC and the Modified at 5.2 percent OAC content, were utilized.
- Construction QC tests were conducted and included IR thermal imaging, nuclear density measurements, GPR measurements, and coring for forensic evaluations.
- The HMA layer thickness for rutting and fatigue crack evaluation was 3 inches, while it was 2 inches for the reflective crack evaluation over a JCP.
- On some of the JCP sections, voiding was incorporated to reduce the LTE over the joints to about 50 percent.
- On all the sections, the subbase consisted of a CTB layer—5 percent for reflective cracking evaluation, and 10 percent for the rutting and fatigue crack evaluations.

CHAPTER 4. LABORATORY TEST RESULTS

Researchers conducted various laboratory tests to comparatively characterize the material properties and predict the performance of the Type C mix, namely the Control and Modified mix designs, respectively. Table 4-1 lists these laboratory tests.

Table 4-1. List of Lab Tests.

#	Test	Test Objective
1	Troxler ignition oven	Asphalt-binder and aggregate extractions.
2	Hamburg	HMA rutting resistance characterization at 50 °C (in a water bath).
3	Overlay	HMA cracking potential assessment at 77 °F.
4	Dynamic modulus (DM)	HMA modulus properties at 14 to 130 °F and 0.1 to 25 Hz.
5	Repeated load permanent deformation (RLPD)	HMA permanent deformation and visco-elastic properties at 77 °F (25 °C) and 104 °F (40 °C).
6	Direct-tension, indirect-tension, and semi-circular bending (SCB)	Characterization of HMA fracture and crack-resistance properties at 77 °F. (As a supplement to the OT test, the DT, IDT, and SCB tests were conducted as surrogate crack tests to provide additional data on the fracture and crack-resistance properties of the HMA mixes.)

For each of the tests listed in Table 4-1, a minimum of three replicate specimens were utilized per mix design (Control and Modified). The target air void (AV) content for all the samples molded from raw materials and plant mixes was 7±1 percent (TxDOT, 2004, 2011). The laboratory test plan incorporated testing of samples fabricated from:

- Raw materials (asphalt binder and aggregates).
- Plant mixes.
- Field-extracted cores.

Thirty percent COV was utilized as a measure of acceptable statistical variability in the test results, i.e., COV ≤ 30 percent. Based on the lab tests listed in Table 4-1, test results for both the Control and Modified Type C mix designs are discussed in the subsequent text. A summary of key findings is then presented at the end of the chapter.

IGNITION OVEN TEST AND AGGREGATE EXTRACTIONS

Although on the lower side, the ignition oven-derived asphalt-binder contents from the plant mixes and cores that are reported in Table 3-2 of Chapter 3 were satisfactorily within the

Texas ±0.3 percent specification tolerance (TxDOT, 2004, 2011). As shown in Figure 4-1, however, the aggregate extraction tests indicated that the combined gradation of the plant mix was out of the design specification on the ¾-inch (19 mm) and ⅜-inch (9.5 mm) sieve sizes. This was primarily attributed to the gradation of the coarse C-rock that was slightly different from the design gradation on these particular sieve sizes; see Appendices A and B.

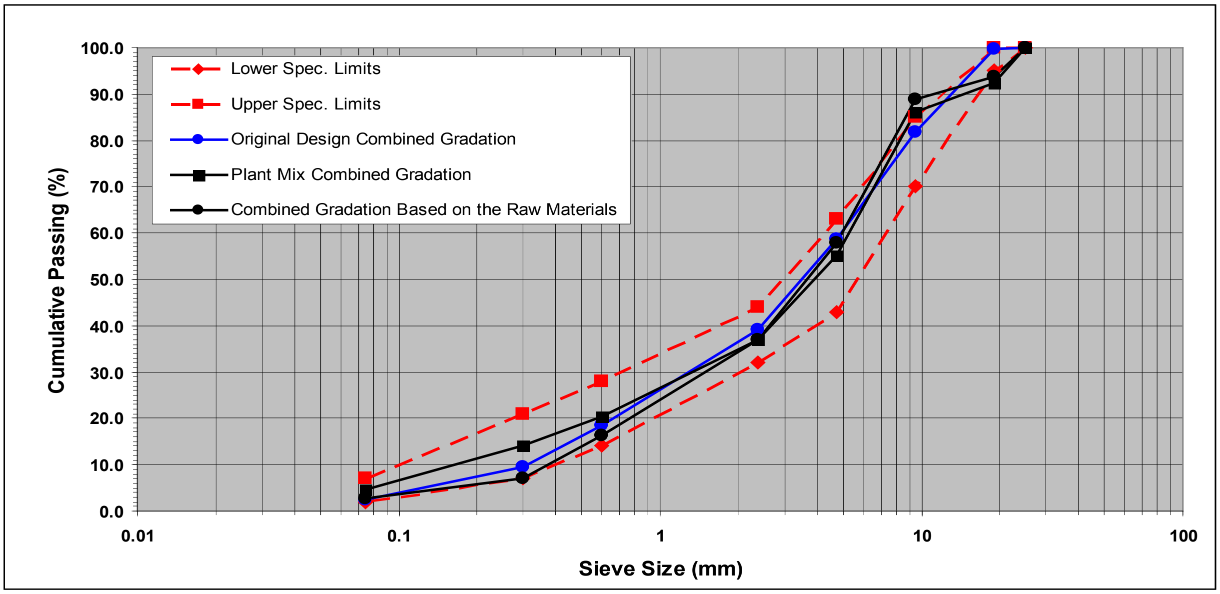


Figure 4-1. Comparison of Combined Aggregate Gradations.

HMA SAMPLE AIR VOIDS AND CORE DENSITY

The average AV for all the lab-molded HMA samples from raw materials and plant mixes was 7±1 percent. For the field-extracted cores prior to ALF trafficking, the AV ranged from 3.3 to 8.5 percent with an average of 5.8 percent and a COV of 29 percent. Based on the core AV measurements in the lab, the average in-situ HMA densities for the APT test sections were approximated to be as follows:

- Control sections with 4.3 percent OAC = 94.3 percent.
- Modified sections with 5.2 percent OAC = 96.0 percent.

HAMBURG AND OVERLAY TEST RESULTS

Table 4-2 summarizes the Hamburg and Overlay test results, and Figure 4-2 shows pictorial views of some test samples (TxDOT, 2011).

Table 4-2. Hamburg and Overlay Results.

Item	Hamburg		Overlay	
	Control	Modified	Control	Modified
Lab molded (TTI lab design)	4.7 mm	7.0 mm	105	330
Plant mix from the APT test site	2.3 mm	4.1 mm	41	446
Field cores (at zero ALF traffic loading)	3.0 mm	4.7 mm	560	1 200+
Raw materials from contractor plant	3.0 mm	7.7 mm	32	306
Criterion utilized	≤ 12.5 mm after 20,000 HWTT load passes		≥ 300 cycles (tentative)	

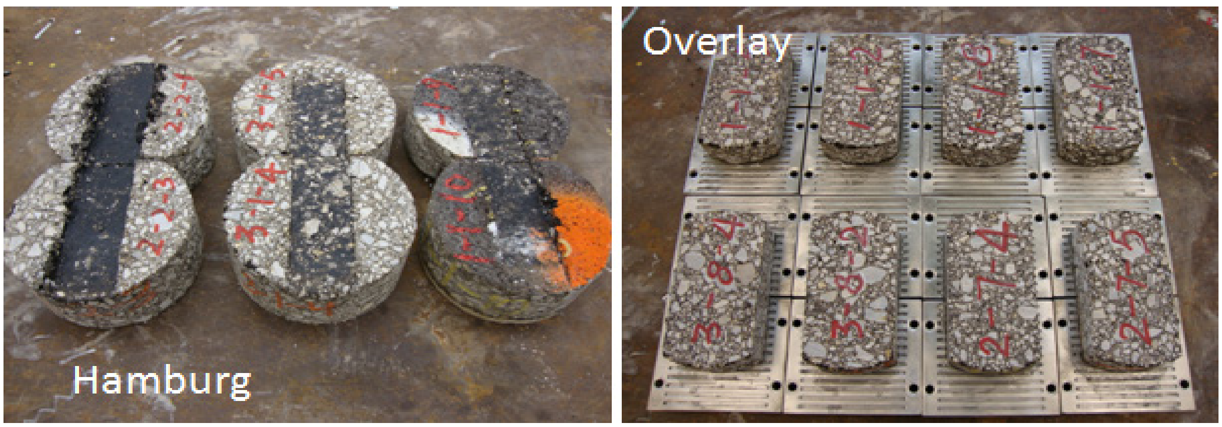


Figure 4-2. Photographs of Hamburg and Overlay Test Samples from Field Cores.

While the Hamburg test results were marginally different, the Modified mix (with 5.2 percent OAC) exhibited better lab crack resistance than the Control mix (with 4.3 percent OAC), as expected. As evident in Table 4-2, the Modified mix lasted over 300 OT cycles for all the samples tested including the field cores. For the Control mix, only the field cores at zero ALF traffic loading lasted over 300 OT cycles, probably due to the relatively higher core density of 94.3 percent (compared to 93 percent for lab-molded samples). Theoretically, these results suggest that the Modified mix would be more crack resistant under ALF trafficking than the Control mix.

DYNAMIC MODULUS TEST RESULTS

Based on dynamic modulus (|E*|) testing at various temperatures (14 to 130 °F) and loading frequencies (25 to 0.1 Hz), |E*| master curves were generated for both the Control and Modified mix designs, respectively (American Association of State Highway and Transportation

Officials [AASHTO], 2001; Walubita et al., 2012). These |E*| master curves, at a reference temperature of 77 °F, are shown in Figure 4-3.

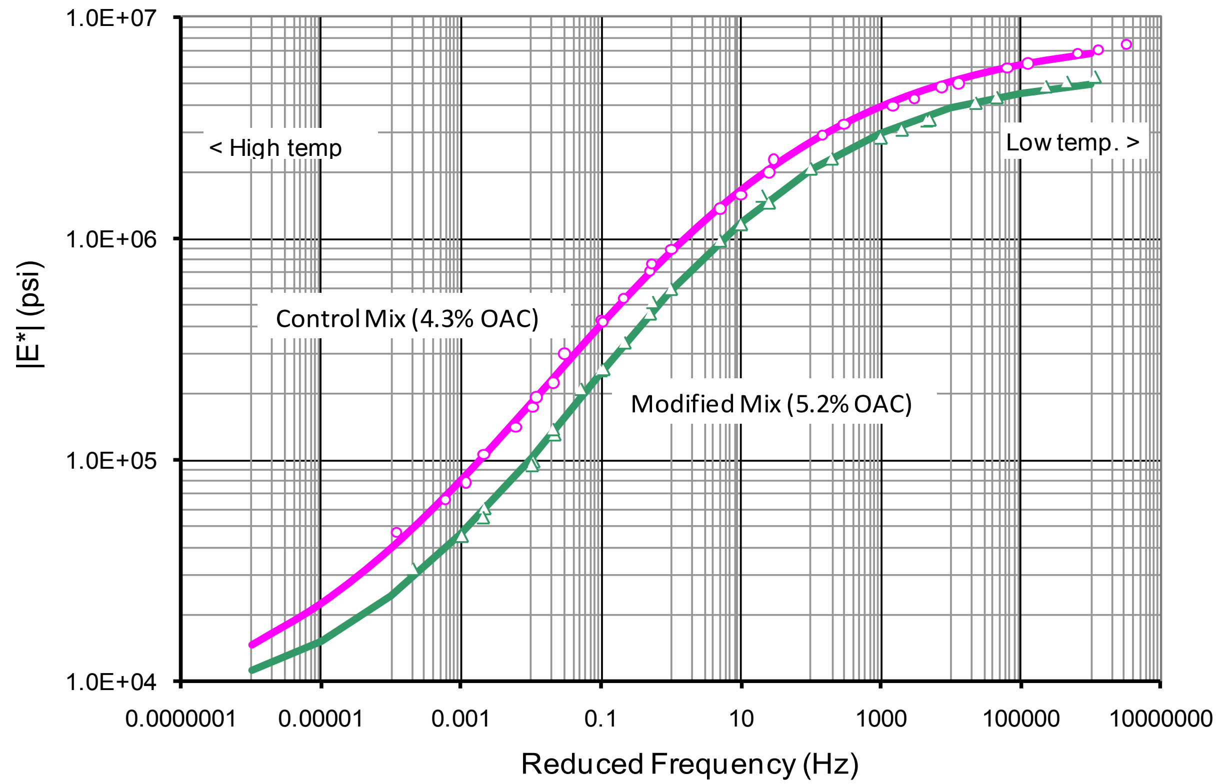


Figure 4-3. |E*| Master Curves at a Reference Temperature of 77 °F.

As expected, Figure 4-3 shows that the Control mix with 4.3 percent OAC was comparatively stiffer (and, theoretically, more rut resistant) than the Modified mix with 5.2 percent OAC. At 77 °F and 10 Hz frequency, the modulus of the Control mix was approximately 33 percent higher than the modulus of the Modified mix in magnitude. Based on Figure 4-3, the HMA moduli at 10 Hz (and 77 °F) were approximately:

- Control mix (4.3 percent OAC) = 1550 ksi.
- Modified mix (5.2 percent OAC) = 1170 ksi.

PERMANENT DEFORMATION TEST RESULTS

The RLPD test was utilized to characterize the permanent deformation and visco-elastic properties of the HMA mixes at the two test temperatures of 77 °F and 104 °F, respectively. Details of the RLPD test protocol are documented elsewhere (Zhou and Scullion, 2004; Walubita and Scullion, 2007). The RLPD test results are summarized in Table 4-3 and Figure 4-4, respectively.

Table 4-3. RLPD Visco-Elastic Parameters, Alpha (α) and Mu (μ).

HMA Mix	Test Temperature	α	Average α	μ	Average μ
Control 4	77 °F (25 °C)	0.6151	0.5828	0.1768	0.1634
Control 5		0.5505		0.1499	
Modified 4		0.6200	0.6215	0.2486	0.2536
Modified 5		0.6231		0.2585	
Control 6	104 °F (40 °C)	0.7556	0.7603	0.5774	0.5806
Control 7		0.7650		0.5839	
Modified 6		0.6974	0.7148	0.5618	0.7195
Modified 7		0.7322		0.8771	

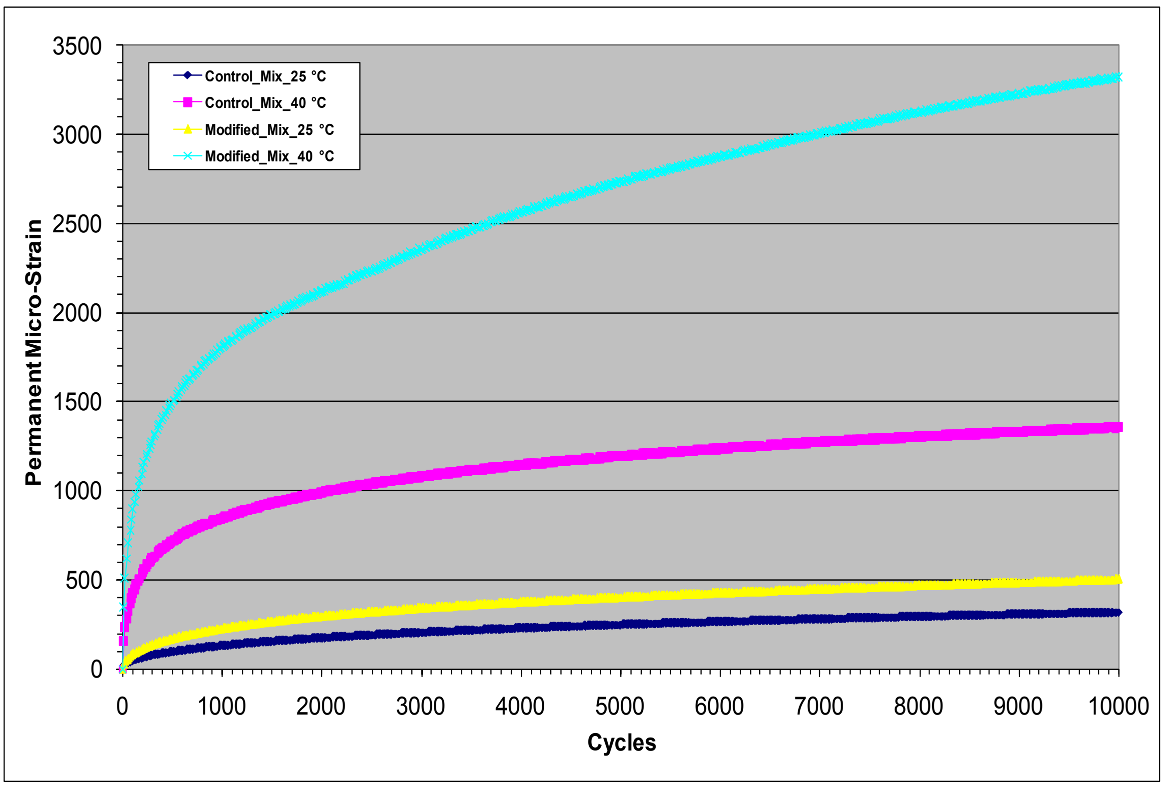


Figure 4-4. RLPD Permanent Deformation Curves.

As expected, both Table 4-3 and Figure 4-4 indicate that the Control mix was more resistant to permanent deformation. After 10,000 RLPD load repetitions at 40 °C, for instance, the Control mix had accumulated less than half the permanent compressive strains accumulated by the Modified mix, e.g., 1,300 versus 3,300 με. Looking at Figure 4-4 and considering the magnitudes of the permanent strains, it is apparent that the Modified mix with high asphalt-binder content at 5.2 percent OAC was comparatively more susceptible to permanent deformation, particularly at elevated RLPD testing temperatures of around 104 °F.

In terms of the visco-elastic properties and deformation characteristics of the mix, the smaller the μ value, the greater the resistance to permanent deformation (Zhou and Scullion, 2004; Walubita and Scullion, 2007). Thus, the Control mix, as Table 4-3 shows, exhibited greater resistance to permanent deformation based on the magnitudes of visco-elastic parameters (μ) at both the two temperatures evaluated than the Modified mix. Theoretically, more rutting would thus be expected with the Modified than the Control mix under ALF traffic loading.

SURROGATE CRACK TEST RESULTS

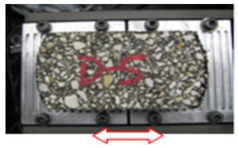
As indicated previously in Table 4-1, the DT, IDT, and SCB tests were conducted as surrogate crack tests to:

- Provide additional data on the fracture and crack-resistance properties of the two mix designs (i.e., the Control mix at 4.3 percent OAC versus the Modified mix at 5.2 percent OAC).
- Supplement the OT test results.

Schematics of these tests and the analysis models are summarized in Tables 4-4 and 4-5, respectively. Walubita et al. (2010) documented full details of the DT, IDT, and SCB test procedures including the loading configurations and the data analysis models. Table 4-5 does not list any analysis models for the OT because data analysis for this test is simply based on the initial measured peak load and the automatically counted number of repetitive load cycles to crack failure at 93 percent reduction in the initial peak load (Zhou et al., 2006).

Like the OT, all the crack tests were conducted at ambient temperature (77 °F), and Table 4-6 summarizes the results.

Table 4-4. List of Crack Tests (Walubita et al., 2010).

Feature\Test	OT	IDT	SCB	DT
Schematic				
Specimen size	6″ L *x* 3″ W *x* 1.5″ T	6″ ϕ *x* 2″ T	6″ ϕ *x* 3″ H *x* 2″ T	4″ ϕ *x* 6″ H
Sample coring/notching	No	No	Yes (0.25″ notching)	Yes (coring)
Sample gluing/curing	Yes/12 hr	No	No	Yes/12 hr
Loading mode	Repeated cyclic	Monotonic	Monotonic	Monotonic
Test parameters	0.0.25 inches @ 77 °F	2 inch/min @ 77 °F	0.05 inch/min, @ 77 °F	0.05 inch/min @ 77 °F
Output data	Peak load & cycles to crack failure	HMA tensile strength, strain, & fracture energy	HMA tensile strength, strain, & fracture energy	HMA tensile strength, strain, & fracture energy
Tentative pass-fail criterion	OT cycles ≥ 300 @ 93% stress reduction (tentative)—still under review (Tex-248-F)	$85 \leq \sigma_{IDT} \leq 200$ psi (Tex-226-F)	Not yet established	$\varepsilon_{IDT} \geq 3\,000$ με (based only on lab data & analytical modeling)

Note: L = length, W = width, T = thickness, H = height, ϕ = diameter.

Table 4-5. Analysis Models Used for the Crack Test Data (Walubita et al., 2010).

Test	Model	Equation #	Description of Model Parameters
IDT	$\sigma_{IDT} = \frac{2P}{\pi t D}$	1	σ_{IDT} = tensile stress/strength, P = axial peak load, t = specimen thickness, D = specimen diameter, ε_{IDT} = horizontal strain, ΔL = average horizontal deformation at peak load, & Lo = initial distance between the LVDT holders, where LVDT stands for linear variable differential transformer.
	$\varepsilon_{IDT} = \frac{\Delta L}{Lo}$	2	
SCB	$\sigma_{SCB} = \frac{4.263P}{tD}$	3	σ_{SCB} = tensile stress/strength (MPa), P = axial peak load (N), t = specimen thickness (mm), ε_{DT} = strain @ peak load (mm/mm), ΔL = average vertical ram displacement at peak load (mm), & D = specimen diameter (mm). (Empirical equation based on SI units.)
	$\varepsilon_{SCB} = \frac{2(\Delta L)}{D}$	4	
DT	$\sigma_{DT} = \frac{4P}{\pi D^2}$	5	σ_{DT} = tensile stress/strength, P = axial peak load, D = specimen diameter, ε_{DT} = tensile strain @ peak load, ΔL = average tensile elongation at peak load, & L_o = initial distance between the LVDT holders.
	$\varepsilon_{DT} = 10^6 \frac{\Delta L}{Lo}$	6	

Table 4-6. Summary of Crack Test Results for Plant-Mix Samples.

Test	Parameter	Control Mix (4.3% OAC)	Modified Mix (5.2% OAC)	Discriminatory Ratio (Modified/Control)
OT	Initial peak load	729	658	0.9
	Number of cycles to failure	41	446	10.9
DT	Tensile strength (psi)	89	61	0.7
	Tensile strain at failure (με)	4767	6646	1.4
IDT	Tensile strength (psi)	165	130	0.8
	Horizontal strain at failure (inch/inch)	0.011	0.021	1.9
	Fracture energy (lb-in/in^2)*	14.84	19.64	1.3
SCB	Tensile strength (psi)	177	159	0.9
	Vertical strain at failure (inch/inch)	0.030	0.047	1.6
	Fracture energy (lb-in/in^2)*	6.20	7.07	1.1

*Fracture energy computed only up to point of peak failure load.

As theoretically expected, the Control mix with a low AC exhibited high tensile strength values while sustaining relatively lower tensile strains to failure than the Modified mix. Clearly, the monotonic DT, IDT, and SCB test results indicate that the Modified was a relatively soft and more ductile mix based on its higher and lower tensile strength and strain values, respectively. This means that if subjected to the same loading and environmental conditions under a similar pavement structure, the Control mix would likely sustain fracture damage and crack failure much quicker than the Modified mix.

Overall, all the crack test results in Table 4-6 indicate that the Modified mix with high AC was a relatively superior mix in terms of resistance to fracture damage and cracking in the laboratory. That is, for the same PG 76-22 asphalt-binder and limestone aggregates, the results from all the crack tests indicate that the Modified 5.2 percent AC design had superior laboratory cracking resistance potential and was more ductile than the Control 4.3 percent AC design, as expected. However, the discriminatory ratio (DR) with a value of 10.9 shows that the OT cycle was much more superior in terms of capturing the differences in the laboratory cracking resistance potential between the two mix designs. With DR values ranging from 1.4 to 1.9, the tensile strain at failure seemed to fall second in line as a potential mix screening fracture parameter for laboratory cracking resistance assessment.

SUMMARY

Various laboratory tests including the HWTT, DM, RLPD, OT, DT, IDT, and SCB were conducted to comparatively characterize the material properties and predict the expected APT field performance of the Control (4.3 percent AC) and Modified (5.2 percent AC) mixes, respectively. For the test conditions considered, analysis of the laboratory test results indicated the following:

- The Control (4.3 percent AC) designed based on the TG method was a relatively stiff mix (i.e., high modulus value) and more rut resistant than the Modified mix. Therefore, the Control mix was theoretically expected to exhibit superior rutting resistance performance in the field under APT testing.
- The Modified (5.2 percent AC) designed based on the BMD method with high AC level exhibited superior fracture properties and was more crack resistant than the Control mix. Therefore, the Modified mix was theoretically expected to exhibit superior cracking resistance performance in the field under APT testing.

CHAPTER 5. FIELD APT-ALF TEST RESULTS

The field APT test results under ALF trafficking are presented and discussed in this chapter. These APT tests included comparative performance evaluation of the two HMA mix designs, the Control at 4.3 percent OAC and Modified at 5.2 percent OAC, in terms of the following distresses:

- Rutting.
- Reflection cracking.
- Fatigue cracking.

Researchers also intermittently conducted numerous auxiliary tests, including the following, during ALF trafficking: (a) weather-related aspects, particularly temperature profiles; (b) density measurements; (c) falling weight deflectometer (FWD) measurements; and (e) coring/forensic evaluation. Some of these data are included in the appendices of this report, i.e., Appendix C through E.

In this chapter, the ALF loading parameters for each test section are discussed first, followed by a presentation of the performance evaluation test results. Results for auxiliary tests are then presented, followed by a bulleted list of key findings that summarize the chapter.

ALF LOADING PARAMETERS

Table 5-1 summarizes the actual ALF loading parameters utilized for each test section, including the axle load, tire pressure, wheel speed, and lateral wander. On some sections, the ALF loading parameters for both the Control and Modified mixes were changed while the ALF trafficking was in progress. This was necessary to accelerate the distress.

Table 5-1. Actual ALF Test Loading Parameters on the TTI Test Sections.

Sec#	Test Period	ALF Load Passes (K= 1 000)	Total ALF Load Passes	Tire Load (lbs)	Lateral Wander	AvgAir Temp. During Trafficking (°F)	HMA Mix	Purpose	Distress Observed
1	Sept – Nov 2009	100K	100,000	9 750	None	74.5	Control	Rut evaluation	8 mm rutting
2	Sept – Nov 2009	100K	100,000	9 750	None	74.5	Modified	Rut evaluation	15 mm rutting
3	Dec 09 – Feb 2010	0-75K	75,000	9 750	None	48.0	Control	Reflection crack evaluation	Cracking was only visible after 175 k load passes
		75-175k	100,000	14 600					
4	Dec 09 – Feb 2010	0-75k	75,000	9 750	None	48.0	Control	Reflection crack evaluation (50% LTE)	Cracking started after 75 k ALF load passes
		75-131 k	56,000	14 600					
5	Dec 10 - Feb 2011	0-75 K	75,000	9 750	None	-	Modified	Reflection crack evaluation	Cracking started after 143 k ALF load passes @ joint location Station +47.5
		75-175 K	100,000	14600	None	-			
6	Dec 10 - Jan 2011	0-75 k	75,000	9 750	None	-	Modified	Reflection crack evaluation (50% LTE)	None
		75-100 k	25,000	14600	None	-			
7	Mar – Jun 2010	0-125K	125,000	9 750	None	73.0	Modified	Fatigue crack evaluation	Cracked @ 150 k; 11 mm rutting after 100k
		125-150K	25,000	14 350	YES	73.0			
8	Mar – Jun 2010	0-125K	125,000	9 750	None	73.0	Control	Fatigue crack evaluation	No cracking; 8 mm rutting after 100 k
		125-150K	25,000	14 350	YES	73.0			
Total			**1,081,000**						

Note: ALF tire pressure = 105 psi (on all test sections); Wheel speed = 10.5 mph (on all test sections); Tire print width = 9 inches (on all test sections)

ALF RUTTING TEST RESULTS

The ALF rutting tests were conducted in summer 2009 between the months of September and November. Up to 75,000 ALF load repetitions were applied on the HMA rutting Sections 1 (Control) and 2 (Modified). The average pavement temperatures during ALF trafficking were as follows:

- Section 1 (Control mix with 4.3 percent AC): 89.3 °F.
- Section 2 (Modified mix with 5.2 percent AC): 88.9 °F.

Consistent with the laboratory test predictions based on the BMD method and as theoretically expected, the Modified mix with more asphalt-binder rutted more than the Control mix under ALF trafficking. After 100,000 ALF load passes under equivalent test temperatures, the rut depth on Section 2 with the Modified mix (at 5.2 percent AC) was almost 50 percent more than that accumulated on Section 1 with the Control mix (at 4.3 percent AC), i.e., 15 versus 8 mm. These results are shown graphically and pictorially in Figures 5-1 and 5-2, respectively.

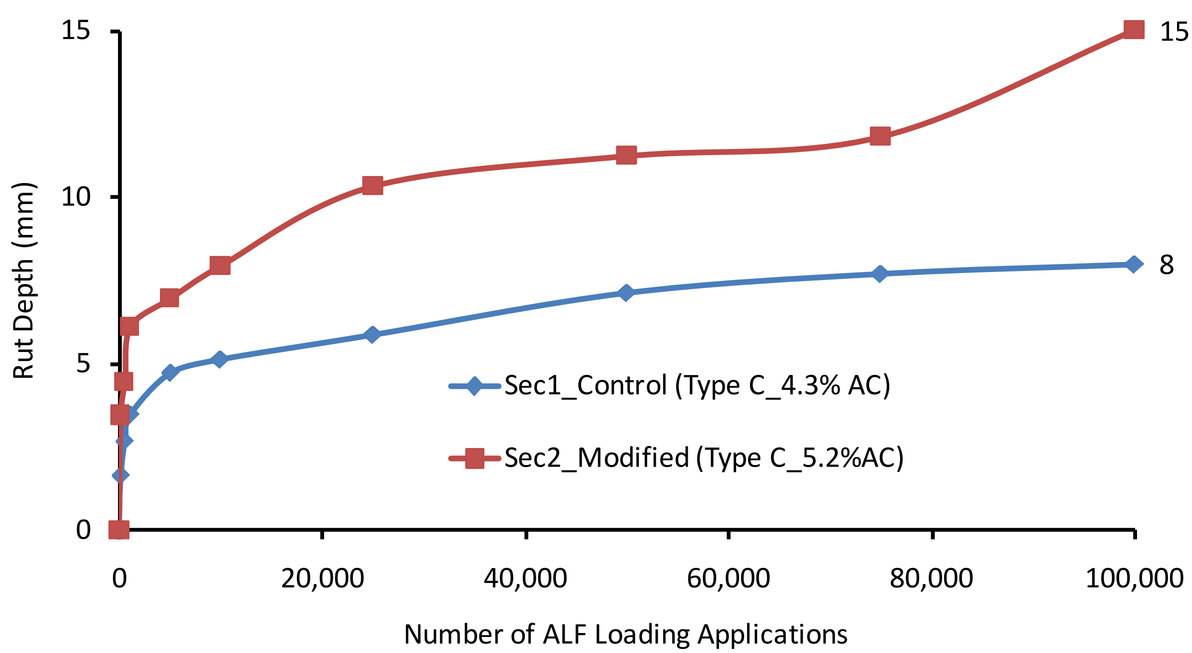


Figure 5-1. Rutting under ALF Load Trafficking.

Figure 5-2. Surface Rutting on Sections 1 (Control) and 2 (Modified).

As shown in Figure 5-3, subsequent trenching of the test sections indicated that all the rutting was coming from the top HMA layer. Deformation in the base and subgrade was marginal.

Figure 5-3. Trenching and Pictorial Comparison of Rutting on Sections 1 and 2.

In general, the APT performance of these rutting test sections was consistent with the laboratory test predictions (Chapter 4) and was as theoretically expected, i.e., the Control (with low AC) performed better in terms of rutting resistance compared to the Modified mix. For the same APT test conditions, the Modified section had rutted almost twice (1.9 times) the rut depth measured on the Control section after equivalent number of 100,000 ALF load applications. This to some extent provides a preliminary validation platform for the proposed balanced mix-design method.

ALF REFLECTIVE CRACKING TEST RESULTS

As Table 5-1 shows, APT sections 3, 4, 5, and 6 were designated for reflective crack evaluations with different levels of LTE. Like for rutting, the reflective cracking sections performed as expected and correlated well with the balanced HMA mix-design and laboratory test predictions:

- The Control sections with low AC (4.3 percent) cracked earlier than the Modified sections with 5.2 percent AC.
- The sections with poor LTE (i.e., LTE = 50 percent) cracked earlier than the sections with good LTE (i.e., LTE > 90 percent).

Under similar ALF trafficking conditions, reflective cracking appeared on the Control Section 4 with poor LTE (i.e., LTE = 50 percent) just after 75,000 ALF load passes; see Figure 5-4 below. In the case of the Control Section 3 with good LTE (i.e., LTE > 90 percent), reflective cracking was only visible after 175,000 ALF load passes, thus further substantiating that LTE has an influence on the rate of reflective crack propagation.

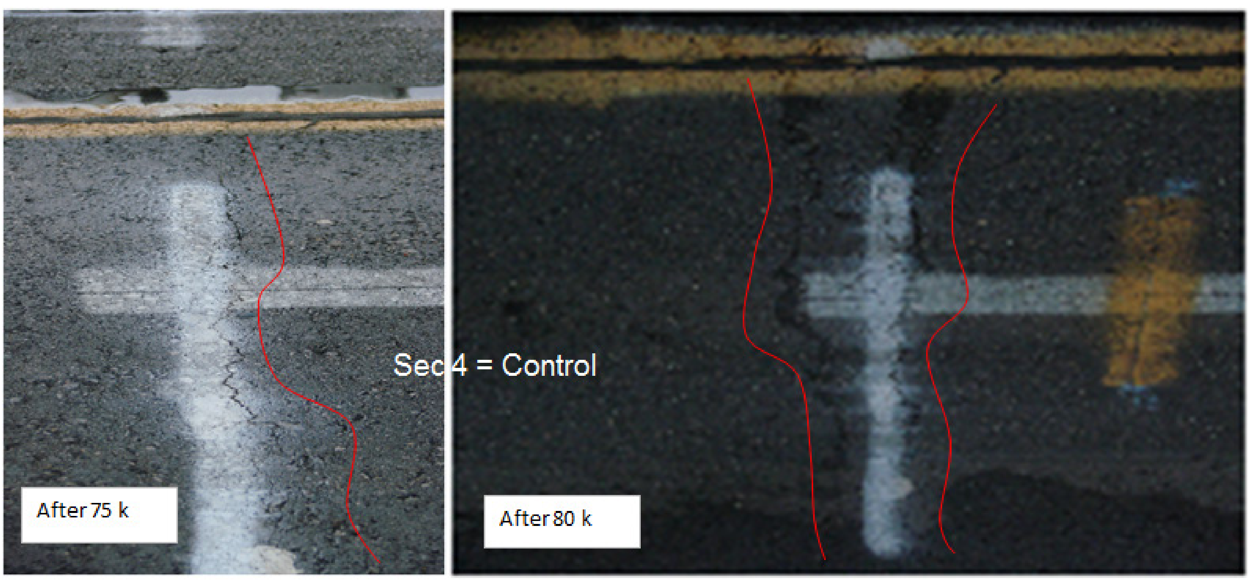


Figure 5-4. Reflective Cracking on Control Section 4 (LTE = 50 Percent).

By contrast however, no cracking was observed on the Modified Section 6 (with LTE = 50 percent) even after applying 100,000 ALF load passes and increasing the tire load; see Table 5-1 and Figure 5-5. For the Modified Section 5 with good LTE (i.e., LTE > 90 percent), cracking started to manifest around the joints after 143,000 ALF load passes—no cracking was observed within the test sections; see Figure 5-6.

Figure 5-5. Reflective Cracking Comparison of Section 4 (Control, LTE = 50 Percent) and Section 6 (Modified, LTE = 50 Percent) after 75,000 ALF Load Passes.

Figure 5-6. Cracking at a Joint on Modified Section 5 with Good LTE (> 90 Percent).

ALF FATIGUE CRACKING TEST RESULTS

In contrast to the laboratory HMA mix-design and test predictions, the fatigue crack test sections performed unexpectedly under ALF loading: the Modified (with high AC) section cracked, while there was no cracking on the Control section with low AC (4.3 percent); see Figure 5-7. Also, both sections unexpectedly accumulated substantially high rutting. As illustrated in Figure 5-8 through 5-10, forensic evaluations suggested the following:

- The Control Section 8 (4 inches) was thicker than the Modified Section 7 (3 inches) in terms of the surfacing HMA layer; see Figure 5-8. This was considered to be due to construction-related issues; see Chapter 3.
- The distresses (particularly rutting) were found to be related to the base and construction problems; see Figure 5-8.
- Coring indicated micro-damage and micro-cracking on the Modified Section 7.
- As can be inferred from Table 5-1, ALF trafficking on these sections was done around summertime during high temperatures, hence the high rutting, particularly on the Control Section 8.

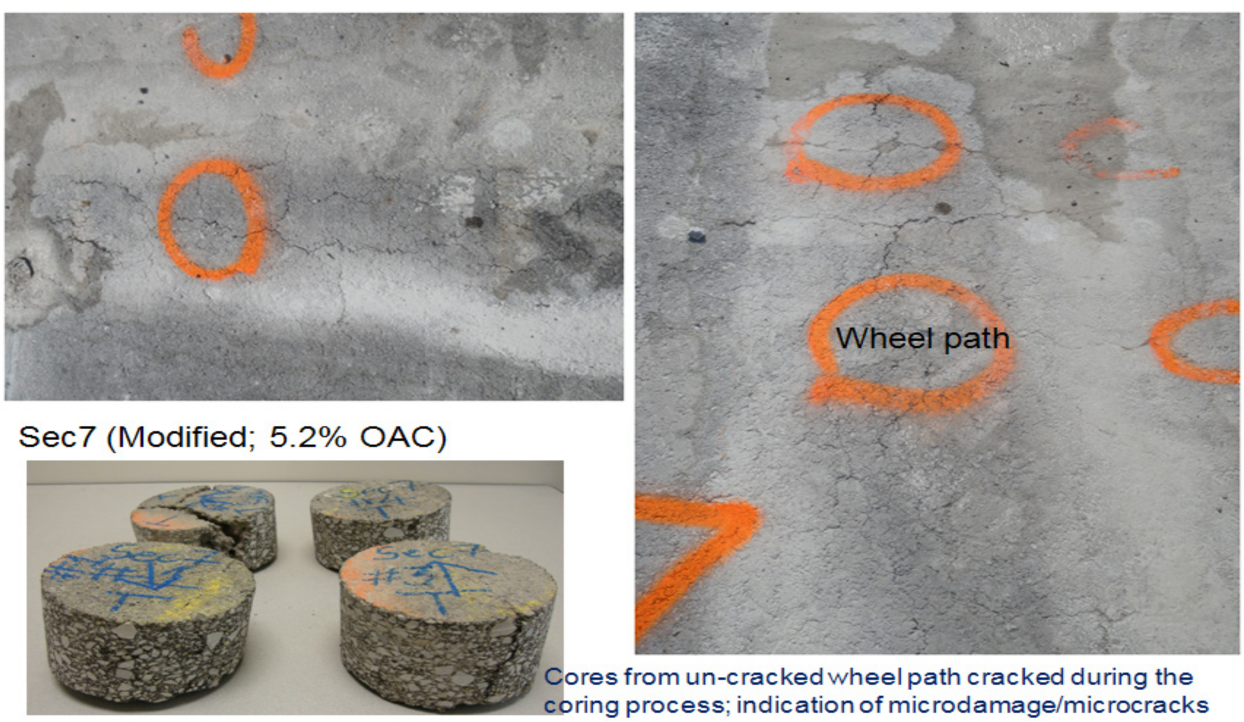


Figure 5-7. Fatigue Cracking on Modified Section 7.

Figure 5-8. Base-Subgrade-Related Rut Failure on the Fatigue Crack Sections 7 and 8.

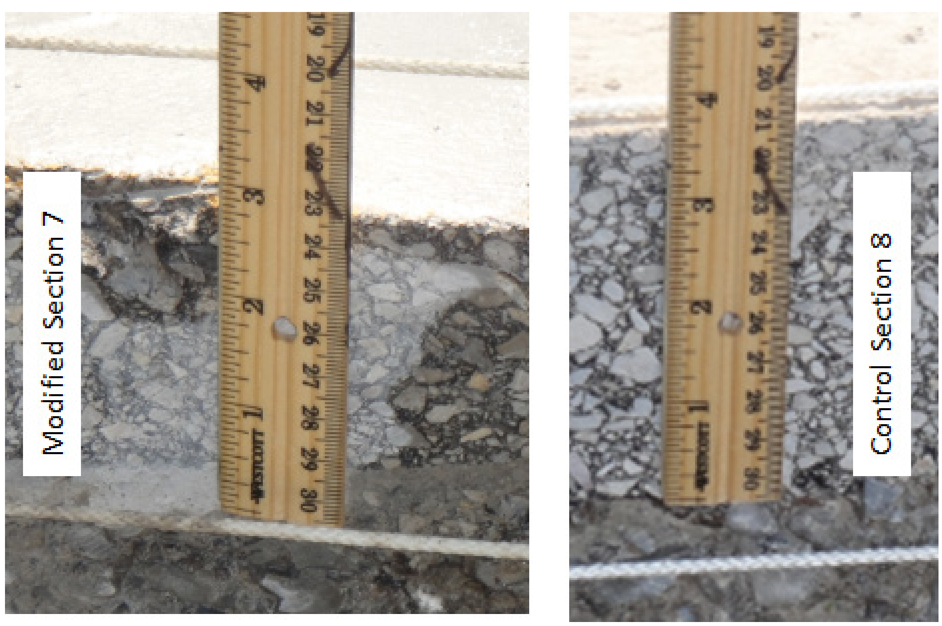


Figure 5-9. Comparison of Type C HMA Layer Thickness for the Fatigue Sections 7 and 8.

Figure 5-10. Cracked and Uncracked Cores from Modified Section 7.

SUMMARY

The bullet list below summarizes the key findings and recommendations drawn from the APT testing with the ALF:

- The rutting sections performed as expected; the Control mix (4.3 percent AC) performed relatively better in terms of rutting resistance than the Modified mix (5.2 percent AC) and correlated with laboratory test predictions.
- The reflective cracking sections performed as expected and correlated with the laboratory test predictions; the Control sections with 4.3 percent AC cracked earlier than the Modified with 5.2 percent AC, and the poor LTE (50 percent) sections cracked earlier than the good LTE (> 90 percent) sections.
- In addition to rutting, the fatigue crack sections performed unexpectedly: the Modified section cracked (but not the Control), predominantly due to base problems, construction issues, and time of ALF trafficking.

Based on these promising APT test results (particularly for rutting and reflective cracking) that exhibited good correlation with the laboratory test predictions, consideration should be undertaken to incorporate both the Hamburg and OT tests in future HMA mix-design methods. Evidently, this means that there is a need to consider standardizing the BMD method.

CHAPTER 6. SUMMARY AND RECOMMENDATIONS

Based on the two HMA mix-design methods evaluated (namely the TG and BMD), the APT performance of the test sections under ALF trafficking was found to be consistent with the laboratory test predictions and theoretical expectations. For the Type C mix (PG 76-22 + limestone) considered, and the laboratory and ALF-APT tests undertaken, the following key findings were concluded:

- The balanced HMA mix-design and laboratory test predictions correlated well with the field APT testing under ALF trafficking for the rutting and reflective cracking evaluations. The Control mix (with low AC) performed better in terms of rutting resistance but poorer in terms of cracking resistance, as expected, and vice versa for the Modified mix (high AC).
- As predicated in the laboratory, the Modified mix design based on the BMD method exhibited superior cracking resistance potential in the field under APT testing with the ALF device. In general, the BMD method yielded very promising results with the following characteristics: (a) it is lab performance-based; (b) it yields high design AC content; (c) it leads to improved HMA mix constructability (workability and compactability) due to increased AC for lubrication; (d) it leads to improved cracking resistance potential; and (e) it leads to improved durability due to increased AC.
- Compared to the traditional TG method, the new BMD method exhibited superiority, particularly in terms of cracking resistance potential of the mix, while at the same time balancing the rutting requirements.
- Consistent with the laboratory test results, field construction monitoring also indicated better constructability characteristics with improved density attainment for the Modified mix that was designed based on the BMD method.
- Utilization of the ALF offers a practical and rapid APT tool for comparatively evaluating mix designs and correlating with laboratory test predictions. Where resources permit, APT should thus be incorporated in studies of this nature, particularly where new test methods and/or materials are being evaluated.

In consideration of these findings and observations, it is therefore recommended to consider incorporating Hamburg (rutting evaluation) and OT (cracking evaluation) testing in the next generation of Texas HMA mix-design methods. Specifically, TxDOT should strongly consider implementing the BMD method for routine mix design and screening; see Appendix F for the tentatively proposed and generalized laboratory performance and screening criteria for OAC selection and HMA mix design.

Overall, this study satisfactorily provided a preliminary APT validation platform for the BMD method. While the method may be associated with an increased bidding/construction cost due to the resultant high AC level, the anticipated superior long-term performance and durability of the designed HMA mix with minimal maintenance activities will generally outweigh the high initial cost. Furthermore, while the BMD method is tailored to improve the constructability and balance performance (cracking) of HMA, proper HMA mix design alone does not preclude the effects of poor structural designs, high traffic loading, adverse environmental conditions, and/or poor construction practices to guarantee satisfactory performance. Additionally, there are challenges of simultaneously addressing other HMA performance/functional requirements such as texture, skid resistance, bleeding/flushing, surface roughness, riding quality, etc.

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	BIN FRACTIONS						
	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7
Aggregate Source:	Vulcan	Vulcan	Vulcan	Pavers Supply			
Aggregate Pit:	Brownwood	Brownwood	Brownwood	Frontier			
Aggregate Number:							
Sample ID:	C Rock	Grade 5	Screenings	Washed Sand			
Rap?:							

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Total Bin	Combined Gradation								
Individual Bin (%):	20.0	Percent	40.0	Percent	30.0	Percent	10.0	Percent		Percent		Percent		Percent	100.0%	Lower & Upper Specification Limits			Restricted Zone			Individual % Retained	Cumulative % Retained	Sieve Size
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's	Lower	Upper	Within Spec's			
1"	100.0	20.0	100.0	40.0	100.0	30.0	100.0	10.0							100.0	100.0	100.0	Yes				0.0	0.0	1"
3/4"	97.8	19.6	100.0	40.0	100.0	30.0	100.0	10.0							99.6	95.0	100.0	Yes				0.4	0.4	3/4"
3/8"	13.0	2.6	98.3	39.3	100.0	30.0	100.0	10.0							81.9	70.0	85.0	Yes				17.6	18.1	3/8"
No. 4	2.1	0.4	45.8	18.3	99.8	29.9	100.0	10.0							58.7	43.0	63.0	Yes				23.2	41.3	No. 4
No. 8	1.5	0.3	7.6	3.0	85.7	25.7	99.9	10.0							39.0	32.0	44.0	Yes				19.6	61.0	No. 8
No. 30	1.4	0.3	1.8	0.7	26.8	8.0	96.0	9.6							18.6	14.0	28.0	Yes				20.4	81.4	No. 30
No. 50	1.3	0.3	1.7	0.7	14.1	4.2	43.8	4.4							9.6	7.0	21.0	Yes				9.1	90.5	No. 50
No. 200	1.1	0.2	1.5	0.6	5.2	1.6	0.9	0.1							2.5	2.0	7.0	Yes				7.1	97.5	No. 200

Figure A-1. Individual Limestone Rock Gradations and Combined Aggregate Gradation (NMAS = ¾ Inch).

Target Density, %:	**96.0**
Number of Gyrations:	**TxDoT Press**

CRM* Content	

TEST SPECIMENS							Mixture Evaluation @ Optimum Asphalt Content			
								Hamburg Wheel Tracking Test		
Asphalt Content (%)	Specific Gravity Of Specimen (Ga)	Maximum Specific Gravity (Gr)	Effective Gravity (Ge)	Theo. Max. Specific Gravity (Gt)	Density from Gt (Percent)	VMA (Percent)	Indirect Tensile Strength (psi)	Number of cycles	Rut depth (mm)	*Overlay Tester Min. Number of Cycles*
4.0	2.399	2.524	2.684	2.520	95.2	14.0				
4.5	2.414	2.499	2.676	2.501	96.5	13.9				
5.0	2.423	2.481	2.677	2.483	97.6	14.1				

Effective Specific Gravity:	2.679

Estimated Percent of Stripping, %:	

Optimum Asphalt Content :	**4.3**
VMA @ Optimum AC:	**14.0**

Interpolated Values	
Specific Gravity (Ga):	2.408
Max. Specific Gravity (Gr):	2.509
Theo. Max. Specific Gravity (Gt):	2.509

Figure A-2. Type C Mix-Design Sheet for the Texas Gyratory Method.

20		BIN FRACTIONS																							
21		Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7											
22	Aggregate Source:	Vulcan		Vulcan		Vulcan		Pavers Supply																	
23	Aggregate Pit:	Brownwood		Brownwood		Brownwood		Frontier																	
24	Aggregate Number:																								
25	Sample ID:	C Rock		Grade 5		Screenings		Washed Sand								Combined Gradation									
26	Rap?:															Total Bin									
27																									
29	Individual Bin (%):	20.0	Percent	40.0	Percent	30.0	Percent	10.0	Percent		Percent		Percent		Percent	100.0%	Lower & Upper Specification Limits			Restricted Zone					
31	Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's	Lower	Upper	Within Spec's	Individual % Retained	Cumulative % Retained	Sieve Size
32	1"	100.0	20.0	100.0	40.0	100.0	30.0	100.0	10.0							100.0	100.0	100.0	Yes				0.0	0.0	1"
33	3/4"	69.0	13.8	100.0	40.0	99.8	29.9	100.0	10.0							93.7	95.0	100.0	No				6.3	6.3	3/4"
34	3/8"	47.0	9.4	98.5	39.4	99.7	29.9	100.0	10.0							88.7	70.0	85.0	No				5.0	11.3	3/8"
35	No. 4	8.6	1.7	42.2	16.9	99.1	29.7	99.4	9.9							58.3	43.0	63.0	Yes				30.4	41.7	No. 4
36	No. 8	2.6	0.5	5.7	2.3	86.0	25.8	98.9	9.9							38.5	32.0	44.0	Yes				19.8	61.5	No. 8
37	No. 30	1.8	0.4	1.9	0.8	29.6	8.9	93.8	9.4							19.4	14.0	28.0	Yes				19.1	80.6	No. 30
38	No. 50	1.7	0.3	1.8	0.7	16.0	4.8	50.2	5.0							10.9	7.0	21.0	Yes				8.5	89.1	No. 50
39	No. 200	1.5	0.3	1.6	0.6	5.9	1.8	1.0	0.1							2.8	2.0	7.0	Yes				8.1	97.2	No. 200

Figure B-1. Aggregate Extraction Results from the Plant Mix.

Table B-1. DM Test Results.

Temperature, °F	Loading Frequence, Hz	Control Mix (4.3% OAC)	Modified Mix (5.2% OAC)
14	25	7,540,381	5,359,625.5
14	10	7,103,127	5,073,791.8
14	5	6,852,647	4,844,051.6
14	1	6,177,241	4,326,556.1
14	0.5	5,858,230	4,081,151.8
14	0.1	5,005,914	3,399,690.7
40	25	4,838,867	3,426,450.2
40	10	4,294,902	3,089,236.9
40	5	3,958,595	2,844,122.7
40	1	3,264,479	2,289,714.9
40	0.5	2,950,508	2,061,715.2
40	0.1	2,273,036	1,556,547.8
70	25	1,996,448	1,448,712
70	**10**	**1,571,741**	**1,158,201**
70	5	1,366,621	975,852
70	1	890,316	590,776
70	0.5	707,894	457,559
70	0.1	428,261	254,107
100	25	771,566	515,646.3
100	10	534,755	338,736.2
100	5	420,828	257,007.3
100	1	223,504	130,352.9
100	0.5	173,393	98,517.1
100	0.1	106,168	60,589.6
130	25	302,114	209,144.8
130	10	191,994	137,713.6
130	5	140,107	94,746.1
130	1	78,864	55,114.4
130	0.5	65,956	45,433.2
130	0.1	47,101	32,271.0

Table C-1. Weather Data Collected during 75,000 to 100,000 ALF Trafficking of Rutting Section 1 (Control).

TTI WEATHER SEC.1 > 75,000-100,000 PASSES

ID	Year	Date	Time	Temp	Rel. Hum.	Rain In.	Solar Rad.	Baro.	Wind Spd.	Wind Dir.	Min. Temp	Max. Temp	Avg. Temp
1	2009	10/20	800	63.13	86	0	261.1	30.04	6.371	-78.7	62.35	63.13	62.6
1	2009	10/20	900	65.99	83.8	0	350.8	30.04	7.66	-70.4	63.12	66.01	64.75
1	2009	10/20	1000	69.64	81.4	0	405.5	30.05	7.7	-60.3	65.99	69.64	68.03
1	2009	10/20	1100	72.3	79.4	0	529	30.06	5.86	-60.29	69.61	72.3	70.9
1	2009	10/20	1200	76.3	75.2	0	555.5	30.03	12.28	-53.67	72.3	76.5	74.5
1	2009	10/20	1300	77.6	74.8	0	331.2	30	9.88	-59.4	76	77.6	76.9
1	2009	10/20	1400	78.7	72.7	0	419.8	29.97	7.72	-61.31	77.5	79.3	78.5
1	2009	10/20	1500	78.2	74.6	0	317.6	29.94	9.85	-67.72	78	79.7	78.8
1	2009	10/20	1600	76.9	79.1	0	188.8	29.92	13.56	-73.5	76.8	78.6	77.8
1	2009	10/20	1700	75.9	82.2	0	113.6	29.93	7.32	-76.5	75.8	77	76.3
1	2009	10/20	1800	74.9	83.2	0	33.6	29.92	4.355	-75.8	74.8	76	75.4
1	2009	10/20	1900	73.8	84.1	0	0	29.92	6.941	-75.3	73.7	74.9	74.3
1	2009	10/20	2000	73.1	84.9	0	0	29.92	4.72	-73.8	73.1	73.8	73.3
1	2009	10/20	2100	73	85.2	0	0	29.93	4.033	-69.97	72.9	73.3	73.1
1	2009	10/20	2200	72.5	86.1	0	0	29.91	7.86	-66.72	72.5	73	72.8
1	2009	10/20	2300	72.1	87.1	0	0	29.9	4.267	-63.75	72.1	72.6	72.4
1	2009	10/20	2400	72.3	86.8	0	0	29.88	5.787	-59.53	72.2	72.5	72.4
24	Hour	Temp	Min.	62.2	Max.	79.7	Avg.	70.2					
1	2009	10/21	100	72.7	86.9	0	0	29.86	7.63	-55.51	72.3	72.7	72.4
1	2009	10/21	200	72.6	87.1	0	0	29.84	5.758	-51	72.5	72.8	72.6
1	2009	10/21	300	72.8	87.1	0	0	29.83	3.259	-47.55	72.6	72.9	72.7
1	2009	10/21	400	73.2	86.3	0	0	29.82	4.705	-44.48	72.7	73.2	72.9
1	2009	10/21	500	73.9	84.4	0	0	29.81	5.232	-41.99	73.1	73.9	73.5
1	2009	10/21	600	70.9	89.6	0	0	29.82	5.772	-45.92	70.9	73.9	72.5
1	2009	10/21	700	70.7	90.6	0	0.556	29.81	1.914	-44.86	70.3	70.9	70.6
1	2009	10/21	800	71.4	90.7	0	66.69	29.81	1.359	-37.29	70.6	71.5	70.9
1	2009	10/21	900	75.3	89.1	0	532.4	29.8	4.428	5.656	71.4	75.3	73.1
1	2009	10/21	2100	73.8	89.5	0	0	29.67	10.07	21.57	73.5	74.2	73.8
1	2009	10/21	2200	72.9	90.4	0	0	29.67	4.939	25.4	72.8	74.1	73.4
1	2009	10/21	2300	73.1	90.7	0	0.278	29.67	5.392	26.65	72.8	73.3	73
1	2009	10/21	2400	66.87	90.8	0	0.278	29.7	4.516	40.07	66.81	73.5	70.9
24	Hour	Temp	Min.	66.8	Max.	79.6	Avg.	74.4					

Table C-2. Weather Data Collected during 75,000 to 100,000 ALF Trafficking of Rutting Section 2 (Modified).

TTI WEATHER SEC.2 > 75,000-100,000 PASSES

ID	Year	Date	Time	Temp	Rel. Hum.	Rain In.	Solar Rad.	Baro.	Wind Spd.	Wind Dir.	Min. Temp	Max. Temp	Avg. Temp
1	2009	10/25	1100	67.47	77	0	956	29.96	3.083	-75.7	63.2	67.47	65.23
1	2009	10/25	1200	71.2	72.3	0	839	29.96	3.697	-67.2	67.52	71.5	69.61
1	2009	10/25	1300	72.6	71.7	0	877	29.95	5.042	-67.95	70.6	72.8	71.5
1	2009	10/25	1400	73.7	68.58	0	393.1	29.9	5.918	-73.7	72.2	74.1	73.4
1	2009	10/25	1500	74.8	67.18	0	392.1	29.92	3.186	-80.3	73.3	75.4	74.5
1	2009	10/25	1600	71.5	71.8	0	126.6	29.9	7.13	-86	71.5	75	73.1
1	2009	10/25	1700	70.1	73.4	0	106.7	29.91	4.647	-89.2	70	71.4	70.7
1	2009	10/25	1800	68.38	79.2	0	28.06	29.91	8.59	-90.5	68.35	70.3	69.39
1	2009	10/25	1900	67.15	80.9	0	-0.278	29.91	5.641	-89.7	67.05	68.29	67.59
1	2009	10/25	2000	66.41	80.6	0	0	29.9	3.989	-88.6	66.37	67.17	66.81
1	2009	10/25	2100	65.56	78.8	0	0	29.9	2.733	-89.2	65.56	66.44	66.09
1	2009	10/25	2200	64.22	79.4	0	0.278	29.91	1.827	-90.9	64.08	65.64	65.02
1	2009	10/25	2300	63.22	82.5	0	0	29.9	7.06	-90.4	63.17	64.48	63.87
1	2009	10/25	2400	60.96	89.9	0	0.278	29.88	2.879	-59.36	60.9	63.2	61.84
24	Hour	Temp	Min.	55.4	Max.	75.4	Avg.	63.9					
1	2009	10/26	100	60.32	91	0	0	29.88	2.163	-36.63	60.19	60.93	60.5
1	2009	10/26	200	61.04	91.4	0	0	29.86	1.023	-26.56	60.36	61.13	60.76
1	2009	10/26	300	61.09	91.4	0	0	29.83	0.073	-18.89	60.93	61.54	61.22
1	2009	10/26	400	61.39	91.4	0	0	29.8	6.474	-14.39	61.08	61.49	61.28
1	2009	10/26	500	62.31	91.4	0	0	29.77	8.02	-5.85	61.41	62.32	61.94
1	2009	10/26	600	62.88	91.3	0	0	29.76	7.31	-0.863	62.07	62.95	62.47
1	2009	10/26	700	63.17	91.3	0	0	29.76	0.526	0.384	62.69	63.3	62.95
1	2009	10/26	800	63.75	91.3	0	13.35	29.78	2.806	3.069	63.14	63.84	63.48
1	2009	10/26	900	64.43	91.2	0	62.56	29.79	2.543	7.19	63.6	64.59	64.02
1	2009	10/26	1700	63.1	87.5	0.15	136.8	29.75	2.572	-18.22	63.01	63.64	63.31
1	2009	10/26	1800	61.96	88.6	0	31.41	29.77	2.44	-19.56	61.91	63.42	62.71
1	2009	10/26	1900	60.34	89.8	0	0	29.78	1.885	-21.19	60.34	61.98	61.2
1	2009	10/26	2000	59.22	90.4	0	0	29.8	0	-25.61	59.22	60.37	59.71
1	2009	10/26	2100	58.14	90.9	0	0	29.82	0	-21.29	58.1	59.32	58.72
1	2009	10/26	2200	57.08	91.2	0	0	29.83	0.132	-21.3	57.06	58.14	57.69
1	2009	10/26	2300	56.11	91.6	0	-0.278	29.84	0	-22.26	55.98	57.5	56.74
1	2009	10/26	2400	55.03	91.6	0	0.278	29.84	0	-22.26	55.03	56.38	55.75
24	Hour	Temp	Min.	55	Max.	65.4	Avg.	62.3					

APPENDIX D. EXAMPLE FWD DATA COLLECTED DURING APT TESTING

Table D-1. FWD Data from Section 1 at 0 ALF Passes.

StationID	DropID	History	Stress	Force	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15
1	1	FALSE	82.10	8992.00	28.89	19.60	15.35	11.41	8.89	5.87	4.25	3.38	2.93	0.00	0.00	0.00	0.00	0.00	0.00
1	2	FALSE	82.00	8981.00	28.27	19.43	15.28	11.40	8.88	5.89	4.25	3.39	2.93	0.00	0.00	0.00	0.00	0.00	0.00
1	3	FALSE	108.50	11881.00	38.60	26.72	21.02	15.68	12.21	7.94	5.70	4.50	3.85	0.00	0.00	0.00	0.00	0.00	0.00
1	4	FALSE	107.90	11825.00	38.69	27.13	21.40	15.96	12.47	8.02	5.73	4.52	3.88	0.00	0.00	0.00	0.00	0.00	0.00
2	5	FALSE	81.40	8921.00	27.18	19.29	15.68	12.02	9.51	6.21	4.48	3.47	2.89	0.00	0.00	0.00	0.00	0.00	0.00
2	6	FALSE	81.60	8933.00	26.48	19.10	15.58	11.98	9.48	6.20	4.46	3.49	2.94	0.00	0.00	0.00	0.00	0.00	0.00
2	7	FALSE	108.00	11828.00	36.38	26.53	21.58	16.51	13.05	8.41	6.00	4.68	3.95	0.00	0.00	0.00	0.00	0.00	0.00
2	8	FALSE	107.80	11812.00	36.37	26.91	21.98	16.83	13.28	8.52	6.06	4.72	3.96	0.00	0.00	0.00	0.00	0.00	0.00
3	9	FALSE	81.20	8897.00	30.92	21.69	16.64	12.45	9.67	6.15	4.37	3.43	2.95	0.00	0.00	0.00	0.00	0.00	0.00
3	10	FALSE	81.30	8910.00	29.79	21.32	16.50	12.43	9.71	6.22	4.46	3.48	2.96	0.00	0.00	0.00	0.00	0.00	0.00
3	11	FALSE	107.60	11785.00	40.51	29.54	22.81	17.08	13.34	8.44	5.95	4.61	3.94	0.00	0.00	0.00	0.00	0.00	0.00
3	12	FALSE	107.80	11812.00	40.36	29.93	23.26	17.47	13.64	8.59	6.05	4.70	3.99	0.00	0.00	0.00	0.00	0.00	0.00
4	13	FALSE	81.60	8937.00	30.78	21.83	17.44	13.11	10.19	6.56	4.69	3.70	3.14	0.00	0.00	0.00	0.00	0.00	0.00
4	14	FALSE	81.50	8926.00	29.71	21.59	17.33	13.07	10.17	6.54	4.65	3.68	3.08	0.00	0.00	0.00	0.00	0.00	0.00
4	15	FALSE	107.50	11773.00	40.13	29.67	23.70	17.76	13.76	8.73	6.22	4.89	4.11	0.00	0.00	0.00	0.00	0.00	0.00
4	16	FALSE	107.60	11788.00	40.10	30.13	24.17	18.14	14.06	8.87	6.31	4.96	4.17	0.00	0.00	0.00	0.00	0.00	0.00
5	17	FALSE	81.30	8902.00	28.35	21.20	17.19	13.13	10.37	6.65	4.66	3.63	3.11	0.00	0.00	0.00	0.00	0.00	0.00
5	18	FALSE	81.80	8965.00	27.70	20.98	17.12	13.13	10.37	6.70	4.69	3.64	3.08	0.00	0.00	0.00	0.00	0.00	0.00
5	19	FALSE	107.80	11812.00	37.89	28.78	23.46	17.94	14.17	9.02	6.28	4.85	4.13	0.00	0.00	0.00	0.00	0.00	0.00
5	20	FALSE	107.70	11796.00	37.69	28.96	23.71	18.17	14.34	9.15	6.33	4.88	4.15	0.00	0.00	0.00	0.00	0.00	0.00
6	21	FALSE	81.50	8929.00	30.34	21.21	16.16	11.75	9.12	6.11	4.44	3.56	3.07	0.00	0.00	0.00	0.00	0.00	0.00
6	22	FALSE	81.40	8913.00	29.60	20.96	16.06	11.66	9.10	6.09	4.46	3.57	3.05	0.00	0.00	0.00	0.00	0.00	0.00
6	23	FALSE	108.00	11833.00	39.88	28.74	22.15	16.06	12.45	8.26	5.95	4.76	4.03	0.00	0.00	0.00	0.00	0.00	0.00
6	24	FALSE	107.70	11793.00	39.89	28.98	22.41	16.25	12.56	8.31	5.97	4.78	4.02	0.00	0.00	0.00	0.00	0.00	0.00
7	25	FALSE	81.50	8926.00	28.11	20.24	15.94	11.93	9.48	6.33	4.63	3.61	3.08	0.00	0.00	0.00	0.00	0.00	0.00
7	26	FALSE	81.70	8949.00	27.67	20.09	15.87	11.91	9.49	6.35	4.66	3.64	3.11	0.00	0.00	0.00	0.00	0.00	0.00
7	27	FALSE	107.80	11812.00	37.65	27.64	21.82	16.26	12.83	8.50	6.22	4.86	4.15	0.00	0.00	0.00	0.00	0.00	0.00
7	28	FALSE	107.80	11812.00	37.81	27.93	22.11	16.50	12.99	8.58	6.28	4.91	4.19	0.00	0.00	0.00	0.00	0.00	0.00
8	29	FALSE	81.00	8873.00	31.08	21.27	16.45	12.36	9.98	6.77	4.72	3.69	3.09	0.00	0.00	0.00	0.00	0.00	0.00
8	30	FALSE	81.40	8913.00	30.40	21.20	16.49	12.44	10.07	6.77	4.75	3.70	3.12	0.00	0.00	0.00	0.00	0.00	0.00
8	31	FALSE	107.80	11804.00	41.12	29.19	22.71	16.98	13.65	9.13	6.34	4.93	4.11	0.00	0.00	0.00	0.00	0.00	0.00

Table D-2. FWD Data from Section 3 after ALF Trafficking.

StationID	DropID	History	Stress	Force	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15
1	1	FALSE	86.40	9461.00	3.91	3.72	3.63	3.48	3.26	2.91	2.50	2.19	1.92	0.00	0.00	0.00	0.00	0.00	0.00
1	2	FALSE	86.50	9477.00	3.90	3.72	3.63	3.48	3.28	2.89	2.52	2.19	1.93	0.00	0.00	0.00	0.00	0.00	0.00
1	3	FALSE	86.60	9490.00	3.91	3.72	3.64	3.50	3.28	2.90	2.52	2.18	1.94	0.00	0.00	0.00	0.00	0.00	0.00
2	4	FALSE	86.60	9490.00	4.91	4.93	4.66	4.40	4.05	3.52	3.03	2.56	2.22	0.00	0.00	0.00	0.00	0.00	0.00
2	5	FALSE	86.70	9501.00	4.90	4.86	4.67	4.39	4.06	3.52	3.01	2.53	2.22	0.00	0.00	0.00	0.00	0.00	0.00
2	6	FALSE	86.70	9493.00	4.91	4.87	4.69	4.39	4.05	3.54	3.02	2.58	2.22	0.00	0.00	0.00	0.00	0.00	0.00
3	7	FALSE	87.40	9569.00	5.78	5.46	5.37	5.12	4.78	4.22	3.60	3.03	2.63	0.00	0.00	0.00	0.00	0.00	0.00
3	8	FALSE	87.00	9532.00	5.74	5.43	5.33	5.10	4.75	4.19	3.58	3.02	2.61	0.00	0.00	0.00	0.00	0.00	0.00
3	9	FALSE	87.10	9545.00	5.77	5.46	5.35	5.11	4.76	4.20	3.59	3.06	2.61	0.00	0.00	0.00	0.00	0.00	0.00
4	10	FALSE	86.70	9497.00	10.04	10.69	6.51	5.93	5.33	4.39	3.65	3.05	2.59	0.00	0.00	0.00	0.00	0.00	0.00
4	11	FALSE	86.80	9513.00	10.09	10.76	6.53	5.94	5.37	4.43	3.63	3.11	2.61	0.00	0.00	0.00	0.00	0.00	0.00
4	12	FALSE	86.70	9501.00	10.15	10.78	6.54	5.94	5.38	4.43	3.65	3.07	2.61	0.00	0.00	0.00	0.00	0.00	0.00
5	13	FALSE	87.20	9556.00	5.46	5.22	5.10	4.85	4.55	4.05	3.52	3.02	2.61	0.00	0.00	0.00	0.00	0.00	0.00
5	14	FALSE	86.90	9525.00	5.47	5.21	5.09	4.87	4.55	4.06	3.51	3.02	2.60	0.00	0.00	0.00	0.00	0.00	0.00
5	15	FALSE	87.00	9532.00	5.46	5.22	5.08	4.85	4.53	4.02	3.48	3.01	2.59	0.00	0.00	0.00	0.00	0.00	0.00

Table D-3. FWD Data from Section 4 after ALF Trafficking.

StationID	DropID	History	Stress	Force	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15
1	1	FALSE	87.40	9569.00	3.80	3.55	3.49	3.36	3.19	2.87	2.50	2.17	1.95	0.00	0.00	0.00	0.00	0.00	0.00
1	2	FALSE	87.50	9585.00	3.80	3.55	3.50	3.37	3.21	2.85	2.52	2.18	1.96	0.00	0.00	0.00	0.00	0.00	0.00
1	3	FALSE	87.10	9540.00	3.78	3.54	3.48	3.33	3.20	2.85	2.46	2.15	1.96	0.00	0.00	0.00	0.00	0.00	0.00
2	4	FALSE	87.30	9561.00	4.56	4.47	4.40	4.16	3.87	3.43	2.96	2.50	2.20	0.00	0.00	0.00	0.00	0.00	0.00
2	5	FALSE	87.50	9585.00	4.59	4.48	4.43	4.16	3.88	3.43	2.97	2.54	2.20	0.00	0.00	0.00	0.00	0.00	0.00
2	6	FALSE	87.10	9537.00	4.56	4.49	4.39	4.15	3.88	3.41	2.94	2.52	2.18	0.00	0.00	0.00	0.00	0.00	0.00
3	7	FALSE	87.40	9572.00	5.43	5.22	5.12	4.92	4.63	4.11	3.54	3.01	2.57	0.00	0.00	0.00	0.00	0.00	0.00
3	8	FALSE	86.90	9521.00	5.39	5.19	5.11	4.91	4.62	4.09	3.56	3.03	2.57	0.00	0.00	0.00	0.00	0.00	0.00
3	9	FALSE	87.30	9561.00	5.44	5.24	5.13	4.91	4.64	4.11	3.56	3.01	2.57	0.00	0.00	0.00	0.00	0.00	0.00
4	10	FALSE	87.30	9564.00	7.08	6.97	6.97	6.85	6.64	4.07	3.44	2.86	2.48	0.00	0.00	0.00	0.00	0.00	0.00
4	11	FALSE	87.00	9529.00	7.09	7.01	6.99	6.87	6.63	4.08	3.40	2.85	2.46	0.00	0.00	0.00	0.00	0.00	0.00
4	12	FALSE	87.10	9540.00	7.13	7.06	7.04	6.93	6.69	4.06	3.43	2.86	2.44	0.00	0.00	0.00	0.00	0.00	0.00
5	13	FALSE	86.90	9525.00	9.75	10.37	9.93	5.46	4.96	4.13	3.44	2.89	2.46	0.00	0.00	0.00	0.00	0.00	0.00
5	14	FALSE	86.70	9497.00	9.81	10.39	9.85	5.44	4.90	4.11	3.43	2.87	2.44	0.00	0.00	0.00	0.00	0.00	0.00
5	15	FALSE	86.80	9509.00	9.88	10.47	9.97	5.49	4.94	4.15	3.46	2.90	2.48	0.00	0.00	0.00	0.00	0.00	0.00
6	16	FALSE	87.00	9532.00	8.28	7.49	6.99	6.35	5.79	4.69	3.80	3.16	2.69	0.00	0.00	0.00	0.00	0.00	0.00
6	17	FALSE	86.80	9509.00	8.34	7.52	7.02	6.39	5.79	4.71	3.81	3.17	2.69	0.00	0.00	0.00	0.00	0.00	0.00
6	18	FALSE	86.70	9493.00	8.35	7.54	7.05	6.41	5.81	4.73	3.85	3.18	2.67	0.00	0.00	0.00	0.00	0.00	0.00
7	19	FALSE	86.90	9521.00	5.11	4.90	4.83	4.62	4.35	3.87	3.42	2.92	2.52	0.00	0.00	0.00	0.00	0.00	0.00
7	20	FALSE	87.10	9545.00	5.16	4.93	4.83	4.64	4.37	3.91	3.43	2.95	2.56	0.00	0.00	0.00	0.00	0.00	0.00
7	21	FALSE	87.10	9537.00	5.15	4.90	4.85	4.63	4.40	3.90	3.43	2.94	2.58	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX E. TRANSVERSE RUT MEASUREMENTS DURING ALF TRAFFICKING

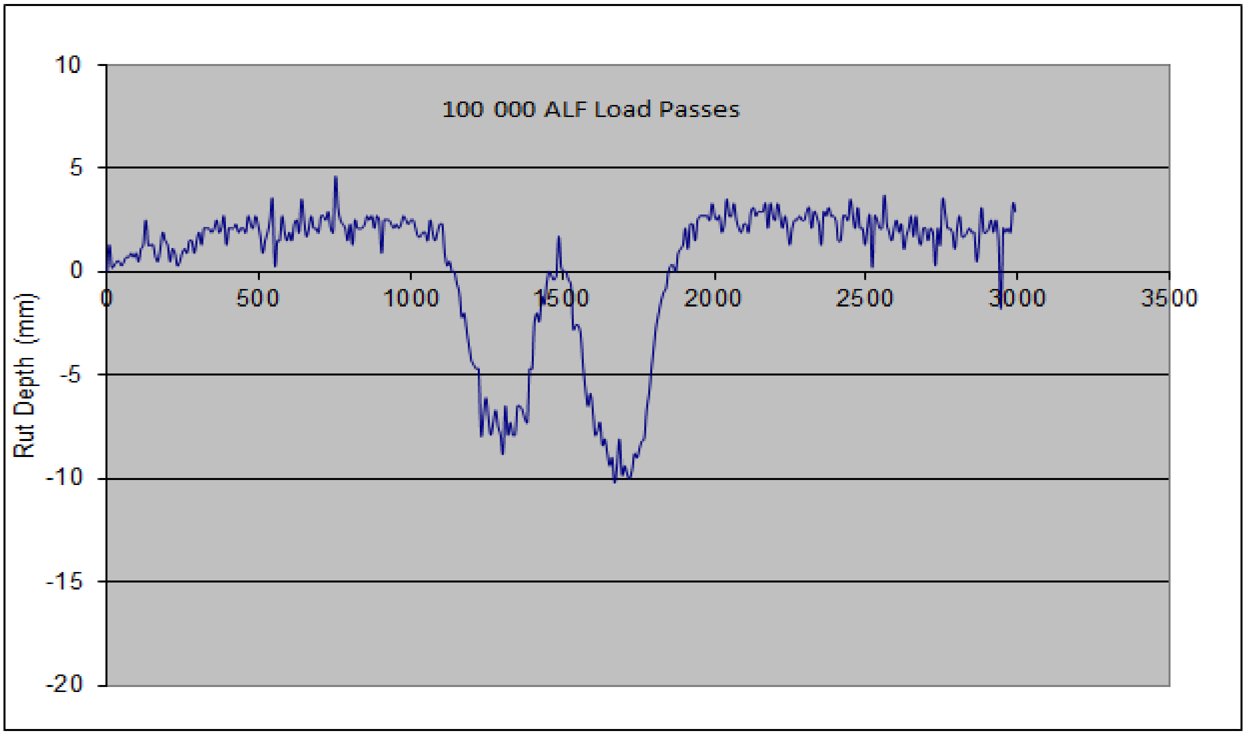

Figure E-1. Transverse Rut Measurements on Control Section 1.

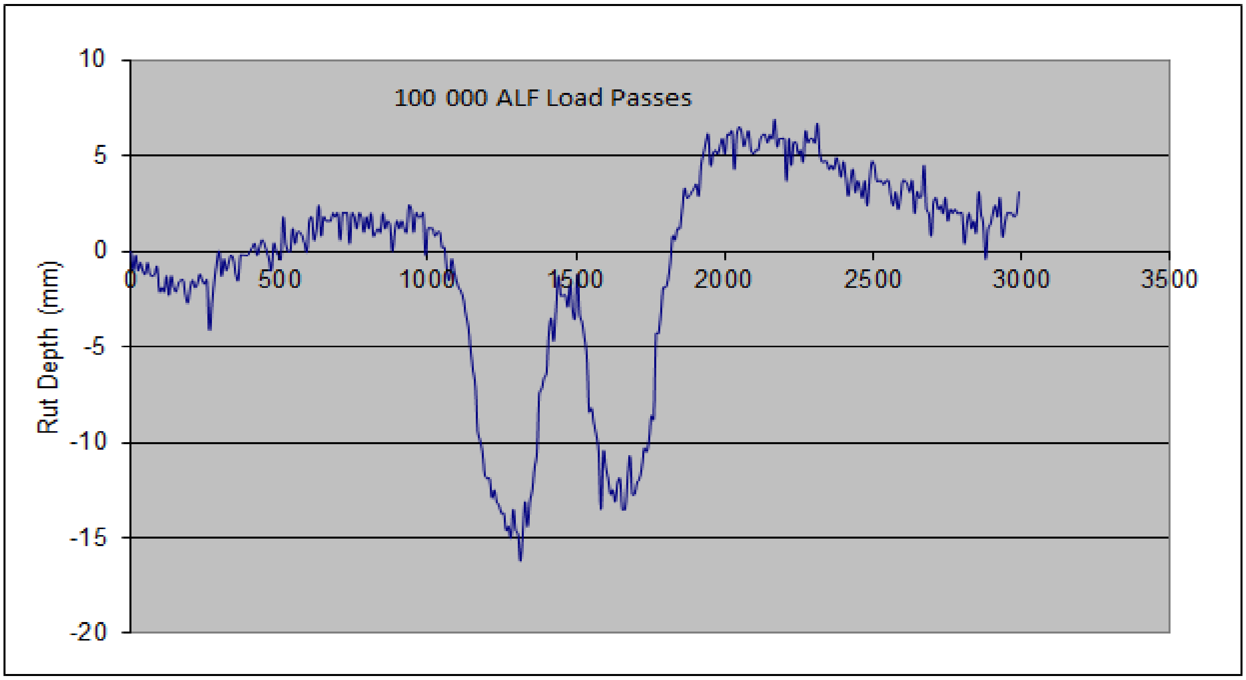

Figure E-2. Transverse Rut Measurements on Modified Section 2.

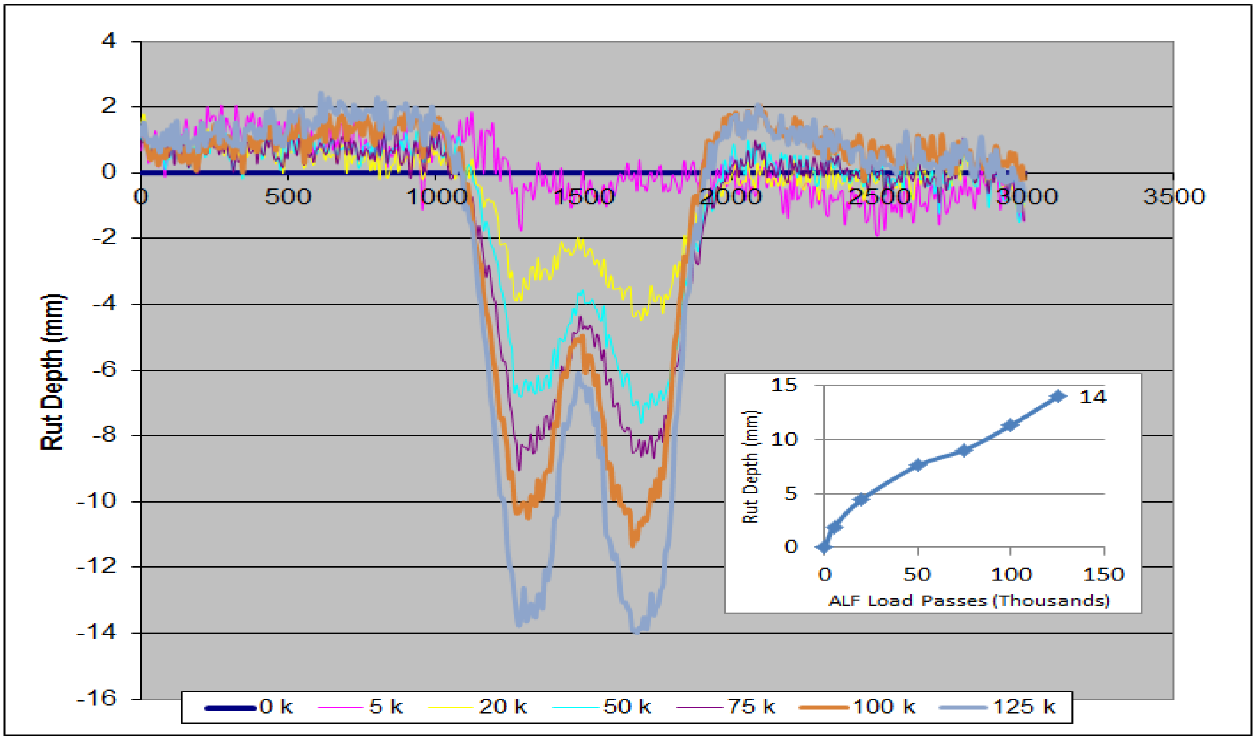

Figure E-3. Transverse Rut Measurements on Control Section 7.

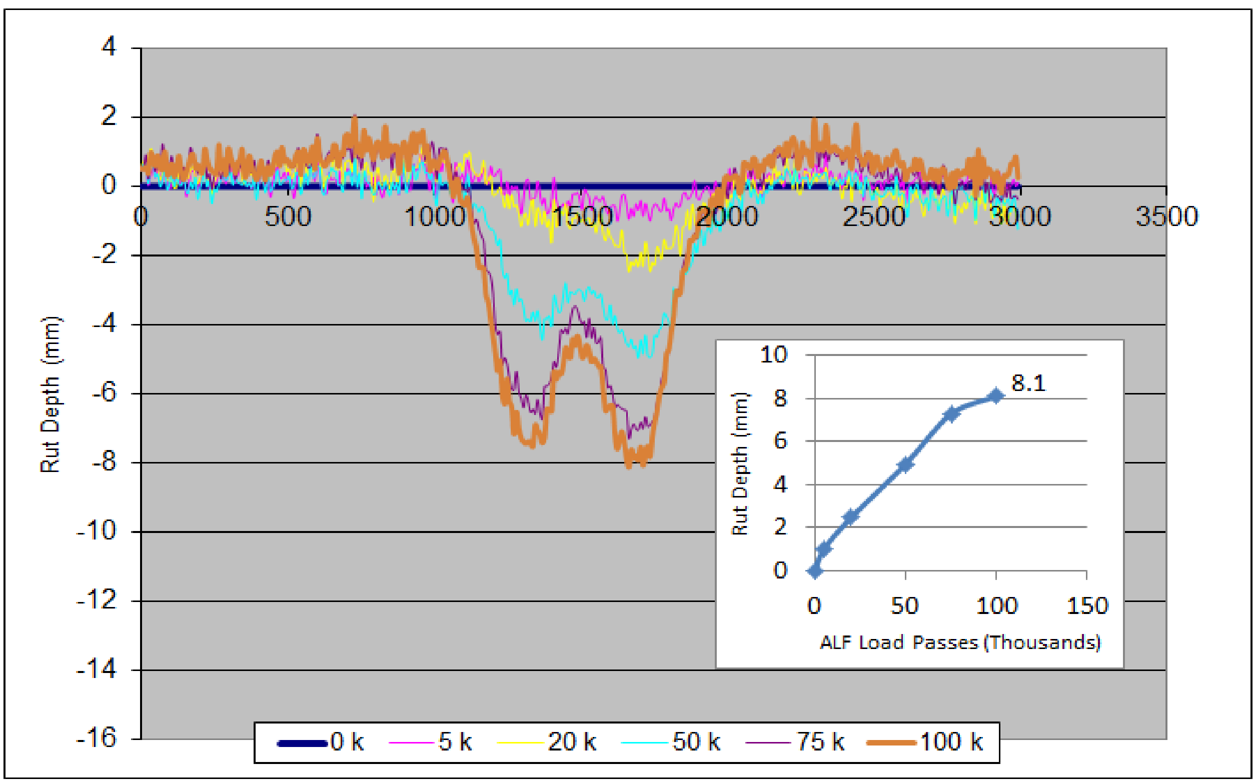

Figure E-4. Transverse Rut Measurements on Modified Section 8.

APPENDIX F. TENTATIVE AND GENERALIZED HWTT-OT PASS-FAIL SCREENING CRITERIA

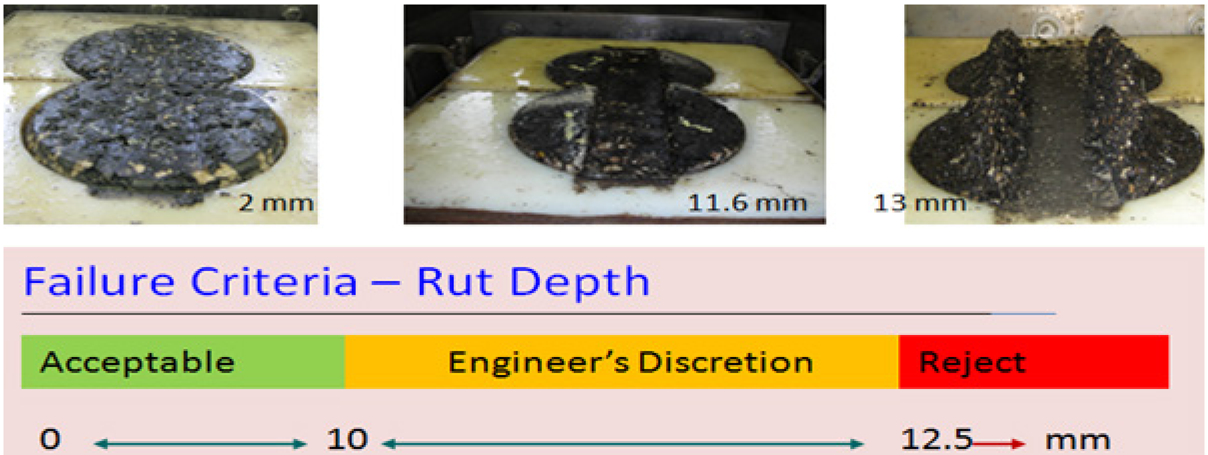

Figure F-1. Laboratory Hamburg Rutting Performance Criteria.

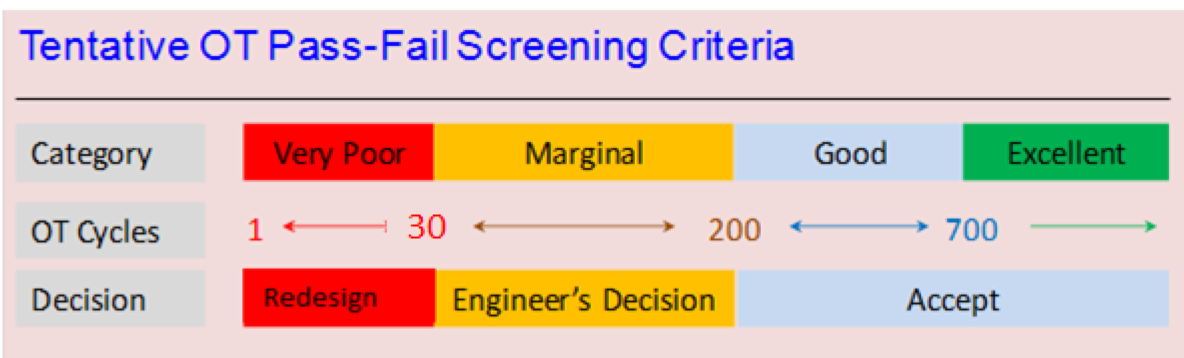

Figure F-2. Proposed Laboratory OT Cracking Performance Criteria.

Theoretically, HMA mixes and/or AC levels not meeting the laboratory performance requirements shown in Figures F-1 and F-2 are considered rutting and/or cracking susceptible, and consideration should be given to redesigning them or rejecting them. Utilization of any mix design that does not meet these laboratory performance requirements should be at the discretion of the engineer.