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MOISTURE RESISTANCE OF SULFUR-MODIFIED WARM MIX

By

Nam Tran
Adam J. Taylor

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National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

277 Technology Parkway ■ Auburn, AL 36830

Final Report

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By
Nam Tran, Ph.D., P.E.
Adam J. Taylor

National Center for Asphalt Technology
Auburn University

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EXECUTIVE SUMMARY

Increasing asphalt prices have renewed interest in utilizing sulfur as a binder extender. Instead of adding sulfur in a molten liquid form directly to the asphalt binder as was done in the 1970s, sulfur pellets combined with a warm mix asphalt (WMA) additive, known as the Shell Thiopave[1] system, are introduced into the mixture during production. The Thiopave system developed by Shell Sulfur Solutions allows for mix production around 275°F (135°C), which can significantly reduce hydrogen sulfide emissions.

To accelerate the acceptance of the Thiopave system into qualified product lists in states that have agreed to use the findings from the National WMA Certification Program at the National Center for Asphalt Technology (NCAT) to approve WMA technologies, Shell Sulfur Solutions elected to participate in the program to certify the Thiopave system. The program starts with a mix design process, followed by one-year laboratory and field evaluations to compare the performance of WMA with that of a control hot mix asphalt (HMA) mixture. The control HMA mixture consists of all virgin materials. The binder is a PG 67-22, and a majority of the aggregate in the mix is granite from Lithia Springs, Georgia. This control mix, which has a history of moisture damage in the field, was selected for the certification program because most of the concerns about WMA technologies relate to WMA resistance to rutting and moisture damage.

Previous testing with Thiopave mixtures with marginal stripping aggregates had shown that moisture susceptibility was a concern. Thus, this study was initiated to evaluate various anti-strip additives for use in the Thiopave mixture that would be evaluated in the WMA Certification Program. This report documented the laboratory testing and field evaluation of the control HMA and Thiopave WMA mixtures at the NCAT Pavement Test Track. Based on the data presented in this report, the following key findings, conclusions, and recommendations can be made:

- Use of any of the anti-strip additives evaluated in this study could improve the moisture resistance of the Thiopave WMA. Redicote E-6 was the most effective, followed by ZycoSoil and then hydrated lime.
- Compared to the lab-prepared mixtures, the plant-produced mixes showed equal or better moisture resistance and rutting performance.
- Based on the test results of plant-produced mixes, the Thiopave WMA mixtures, except for the Thiopave WMA with hydrated lime, appeared to have equal or better resistance to rutting and moisture damage than the control HMA mixture.
- The control HMA and three Thiopave WMA mixtures placed on the test track all showed very good rutting performance.
- The Thiopave WMA test sections showed equal or better IRI than the control HMA test section.
- There was no cracking evident on any of the Thiopave WMA test sections, while some hairline cracks did appear in the control HMA test section.

[1] Shell Thiopave is a trade mark of the Shell Group of Companies

1. INTRODUCTION

1.1 Background

Increasing asphalt prices have renewed interest in utilizing sulfur as a binder extender. Instead of adding sulfur in molten liquid form directly to the asphalt binder as was done in the 1970s, sulfur pellets combined with a warm mix asphalt (WMA) additive, known as the Shell Thiopave[2] system (Figure 1), are introduced into the mixture during production. The Thiopave system developed by Shell Sulfur Solutions allows for mix production around 275°F (135°C), which can significantly reduce hydrogen sulfide emissions (Timm et al., 2011).

Figure 1 Thiopave Sulfur Pellets and Compaction Aid (Timm et al., 2009)

To accelerate the acceptance of the Thiopave system into qualified product lists in states that have agreed to use the findings from the National WMA Certification Program at the National Center for Asphalt Technology (NCAT) to approve WMA technologies, Shell Sulfur Solutions elected to participate in the program to certify the Thiopave system. The program starts with a mix design process, followed by one-year laboratory and field evaluations to compare the performance of WMA with that of a control hot mix asphalt (HMA) mixture. The control HMA mixture consists of all virgin materials. The binder is a PG 67-22, and a majority of the aggregate in the mix is granite from Lithia Springs, Georgia. This control mix, which has a history of moisture damage in the field, was selected for the certification program because most of the concerns about WMA technologies relate to the WMA resistance to rutting and moisture damage (Powell and Taylor, 2011).

While the Thiopave system has been used successfully in two test sections at the NCAT Pavement Test Track (Timm et al., 2011), the Thiopave system has never been used in an asphalt mixture that has a history of moisture damage. Previous testing with Thiopave mixtures with marginal stripping aggregates had shown that moisture susceptibility was a concern (Timm et al., 2009 and Tran et al., 2010). Thus, a study was initiated to evaluate various anti-strip additives for use in the Thiopave mixture that would be evaluated in the WMA Certification Program. The study initially included only laboratory testing to evaluate and compare the moisture resistance

[2] Shell Thiopave is a trade mark of the Shell Group of Companies

of laboratory- and plant-produced Thiopave WMA mixtures, using various anti-strip additives with that of the control HMA. The scope of the study was later expanded to include a field evaluation of two Thiopave WMA mixtures using a low dosage of polymer (0.75 percent SBR slurry) at the NCAT Pavement Test Track.

1.2 Objectives

The study was divided into three parts. Parts 1 and 2 were initially planned, and Part 3 was later added to this study. The objective of each part of this study was as follows:

- Part 1 was to determine and compare the moisture resistance of laboratory-prepared HMA and Thiopave WMA mixtures using various anti-strip additives through laboratory testing;
- Part 2 was to evaluate and compare the moisture resistance of plant-produced HMA and Thiopave WMA mixtures selected at the conclusion of Part 1 through laboratory testing; and
- Part 3 was to assess and compare field performance of two sulfur-modified WMA mixtures with a low dosage of polymer to that of the control HMA mixture at the NCAT Pavement Test Track.

1.3 Organization of this Report

This report is divided into four main sections. The first section is the introduction. The second section describes the experimental plan of this study. The third section presents results and analysis. The last section includes conclusions and recommendations drawn based on the results of this study.

2. EXPERIMENTAL PLAN

As previously mentioned, this study was divided into three parts. Table 1 shows the experimental plan for Part 1 in which the resistance of the control HMA and Thiopave WMA mixtures to moisture damage was evaluated using laboratory-prepared mixtures in accordance with the modified Lottman Tensile Strength Ratio (TSR) test, AASHTO T283-07, and the Hamburg Wheel Tracking test, AASHTO T324-04. The dosages of the anti-strip additives shown in Table 1 were recommended by the suppliers. Based on results of Part 1, five asphalt mixes were selected for evaluation in Part 2. Table 2 shows the experimental plan for Part 2 in which the moisture susceptibility of the five mixtures was evaluated using plant-produced mixes. Finally, four asphalt mixes produced at the plant were placed at the NCAT Pavement Test Track. The control HMA, placed in Section E8, and the Thiopave WMA mixture, placed in Section E9, as shown in Table 2, were evaluated as part of the WMA Certification Program. More information about the laboratory testing and field evaluation of the mixtures placed in these two sections can be found in the WMA Certification Program report (Powell and Taylor, 2011). The two Thiopave WMA mixtures placed in sections W2 and W7, shown in Table 2, were evaluated in Part 3 of this study, and results of the field evaluation are presented later in this report. The following subsections briefly describe the mix designs and laboratory- and field-testing programs conducted in this study.

Table 1 Plan for Testing of Laboratory-Prepared Mixtures in Part 1

Description	**Control**		**w/ Hyd. Lime**			**w/ Polymer & Anti-strip**				**w/ Redicote**			**w/ ZycoSoil**		
	HMA	**HMA**	**HMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**
Mix ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Binder Code	+	+	+	+	+	++	++	++	++	+	+	+	+	+	+
% Thiopave System	0	0	0	30	40	1	1	30	40	0	30	40	0	40	40
Percent Sulfur	0	0	0	29	39	0	0	29	39	0	29	39	0	39	39
% Compaction Aid	0	0	0	1	1	1	1	1	1	0	1	1	0	1	1
Design Air Voids,%	4	4	4	3.5	3.5	4	4	3.5	2	4	3.5	3.5	4	3.5	3.5
Anti-strip Code	None	**	*	*	*	**	***	***	***	***	***	***	****	****	****
Anti-strip Dosage,%	0	0.5	1	1	1	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.06	0.06	0.1
TSR (AASHTO T-283)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Wet Hamburg (50°C) (AASHTO T-324)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

+ PG 67-22 without liquid anti-strip
++ Polymer-modified PG 67-22 (provided by Dongre Lab)
* Hydrated Lime as anti-strip
** ArrMaz LOF 6500 liquid anti-strip agent
*** Akzo Nobel Redicote E-6 liquid anti-strip agent
**** ZycoSoil liquid anti-strip agent

Table 2 Plan for Testing of Plant-Produced Mixtures in Part 2

Description	**HMA**	**Thiopave WMA**			
	E8	**E9**	**W2**	**W7**	**Plant Only**
Mix ID	**2**	**11**	**8**	**9**	**4**
Binder Code	+	+	++	++	+
% Thiopave System	0	30	30	40	30
Percent Sulfur	0	29	29	39	29
% Compaction Aid	0	1	1	1	1
Design Air Voids,%	4	3.5	3.5	2	3.5
Anti-strip Code	**	***	***	***	*
Anti-strip Dosage,%	0.5	0.75	0.75	0.75	1
TSR (AASHTO T-283)	x	x	x	x	x
Wet Hamburg (50°C) (AASHTO T-324)	x	x	x	x	x
Field Evaluation	**WMA Certification**		**Moisture Study**		**N/A**

+ PG 67-22 without liquid anti-strip
++ Polymer-modified PG 67-22 (provided by Dongre Lab)
* Hydrated Lime as anti-strip
** ArrMaz LOF 6500 liquid anti-strip agent
*** Akzo Nobel Redicote E-6 liquid anti-strip agent

2.1 Mix Designs

The control HMA mixture used in this study is a 9.5 mm dense-graded mix that is known to have issues with moisture susceptibility (a measured TSR of 27.8 percent). The mixture was designed in accordance with AASHTO T323-07 and AASHTO R35-09, except that the N_{des} was 65 gyrations. The control mixture contained only virgin materials. The binder used in the control mix was a PG 67-22, and a majority of the aggregate is granite quarried in Lithia Springs, GA. Figure 2 shows the design aggregate gradation of the control mix. The aggregate consensus properties are presented in Table 3. The weighted average of these properties indicates this gradation is acceptable for a surface course designed for 10-30 million equivalent singe axle loadings (ESALs), according to AASHTO T323-07.

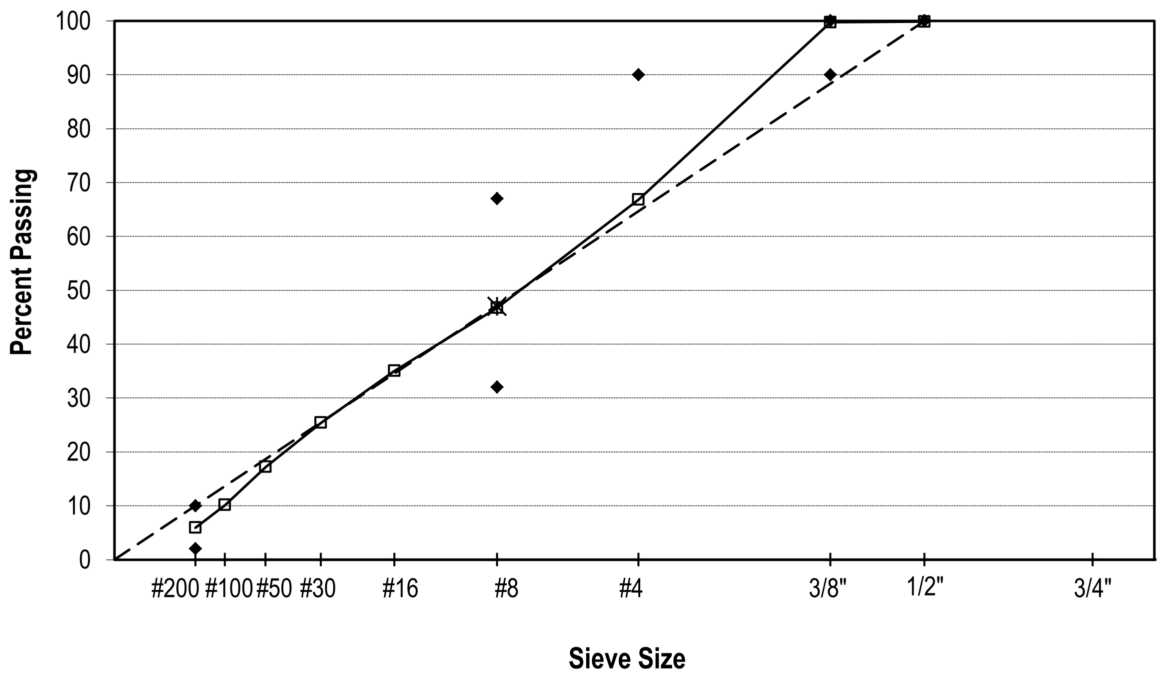


Figure 2 Design Gradation

Table 3 Aggregate Consensus Properties

Stockpile	Percent Fractured Face Count (1 Crushed Face / 2+ Crushed Faces)	Percent 5:1 Flat and Elongated Particles	FAA (%)	Sand Equivalency
Lithia Springs 89s	100/100	0	n/a	n/a
Lithia Springs 810s	n/a	n/a	47.6	82.3
Lithia Springs W10s	n/a	n/a	45.9	92
Weighted Average	100/100	0	46.9	85.8
AASHTO M323*	95/90	<10	>45	>45

* = 10-30 Million ESAL Design, Less than 100 mm from the surface

Based on the mix design of the control HMA mixture, two mix designs for sulfur-extended WMA mixtures with 30 and 40% of Thiopave were conducted using the same PG 67-22 as a base binder. The design gradation of the Thiopave mixtures was the same as that of the control mix. As shown in Table 1, a 30% Thiopave WMA mixture contained 29% of sulfur and 1% of compaction aid based on the weight of the binder blend, and a 40% Thiopave WMA mixture contained 39% of sulfur and 1% of compaction aid. The 30% Thiopave mixture was designed at a design air void level of 3.5%, while the 40% Thiopave mixture was designed at two design air void levels, 2 and 3.5%. At the lower air void levels, the performance of Thiopave WMA mixtures appeared to be improved in a previous study (Timm et al., 2009). The mix design process of the Thiopave mixtures was carried out using a spreadsheet provided by Shell Sulfur Solutions. More information about the design methodology for Thiopave WMA mixtures was presented in a previous report (Timm et al., 2009).

Table 4 compares the volumetric properties of the four mix designs that were used in this study. Based on these four mix designs, the effect of the three anti-strip additives and a polymer on the Thiopave WMA resistance to moisture damage was evaluated in the laboratory and in the field based on the previously described experimental plans.

Table 4 Volumetric Properties

Description	Control	Thiopave Mix		
Binder Code	+	+/++	+/++	+/++
% Thiopave System,% wt of binder	0	30	40	40
Design Air Voids,%	4	3.5	2	3.5
Virgin Binder,% wt of mix	5.7	4.6	4.6	4.3
Thiopave and Compaction Aid,% wt of mix	0	1.9	3.0	2.8
Total Combined Binder (P_b),% wt of mix	5.7	6.5	7.6	7.1
Effective Binder (P_{be}),% wt of mix	5.2	6.2	7.1	6.6
Voids in Mineral Aggregate (VMA),%	15.8	15.7	15.6	16.0
Voids Filled with Asphalt (VFA),%	74.7	77.9	87.1	78.1
Dust Proportion (DP)	1.1	1.0	0.8	0.9
Maximum Specific Gravity (G_{mm})	2.431	2.441	2.436	2.448

\+ PG 67-22 without liquid anti-strip
++ Polymer-modified PG 67-22 (provided by Dongre Lab)

2.2 Preparation of Laboratory Mixtures

As previously mentioned, all testing in Part 1 was conducted using laboratory-prepared mixes. Table 5 summarizes the mixing and compaction temperatures and the short-term aging procedures followed to prepare laboratory mixes for mix design and testing in Part 1.

Table 5 Mixing and Compaction Temperatures and Short-Term Aging Procedures

Mix Samples	Mixing Temperature (^oF)	Compaction Temperature (^oF)	Short-Term Aging
Mix Design			
Control HMA	310	290	2 hrs @ compaction temp (R 30-02)
Thiopave WMA	285	250	2 hrs @ compaction temp (R 30-02)
TSR (T 283-07)			
Control HMA	310	290	T 283-07 for lab-prepared mix
Thiopave WMA	285	250	T 283-07 for lab-prepared mix
Hamburg (T 324-04)			
Control HMA	310	290	4 hrs @ 275^{o}F (R 30 for mechanical test)
Thiopave WMA	285	250	4 hrs @ 250^{o}F*

* While AASHTO R 30 requires that samples prepared for mechanical testing be short-term aged at 275^{o}F, the specified temperature was too high for the Thiopave WMA. Thus, the temperature at which the Thiopave mixes were short-term aged was lowered to 250^{o}F, which was the compaction temperature of the Thiopave WMA.

To prepare each HMA sample in the laboratory, the aggregate was first carefully batched based on the design gradation. Then, the aggregate and the base binder were heated to the mixing temperature in ovens. If a liquid anti-strip agent was used in the mixture, it was blended in the base binder at its recommended dosage shown in Table 1 prior to mixing. If hydrated lime was used as an anti-strip additive in the mixture, the design gradation was slightly modified to reduce 1% of fine aggregate to accommodate 1% of hydrated lime. After the aggregate and the base binder had reached the mixing temperature, they were mixed in a mixing device, short-term aged in an oven, and compacted in a gyratory compactor. The compacted HMA specimens were then tested in accordance with AASHTO T283-07 and AASHTO T324-04.

The preparation process for each Thiopave WMA sample in the laboratory was the same as that for each HMA sample, except that the compaction aid was added to the base binder together with the liquid anti-strip agent, and the sulfur pellets were added to the mixture of hot aggregate and base binder immediately after the start of the mixing process. Since the sulfur crystallization continues after mixing, stiffness of the Thiopave mixes keeps increasing for approximately 2 weeks at ambient temperature, although the initial stiffness is similar to the control mixture. Laboratory performance testing of Thiopave mixtures at NCAT have utilized a two-week cure at ambient temperature to allow for this stiffness increase (Timm et al., 2009). For this project, the compacted specimens for the Thiopave mixes were cured for 24 hours at 60^{o}C in an oven. This accelerated curing procedure was utilized as equivalent to curing for two weeks at ambient temperature for the purposes of more efficiently incorporating the effect of the stiffness increase on the laboratory testing results. This was done at the request of Shell Sulfur Solutions. The compacted specimens were then tested in accordance with AASHTO T283-07 and AASHTO T324-04.

2.3 Production of Plant Mixtures

Based on the laboratory testing results of Part 1, the five mixtures shown in Table 2 were selected and produced at the plant for testing in Part 2. Before production, a sampling plan was developed to determine the amount of material needed per mix to complete the laboratory testing program in Part 2. When a mixture was produced and transported to the NCAT Pavement Test Track for paving, the material was transferred to the material transfer vehicle (MTV). After a sufficient amount of the mixture had been transferred into the paver, the MTV placed the remaining mix into the back of a flatbed truck. The mixture was then taken back to the parking lot behind the test track on-site laboratory for sampling and loading into 5-gallon buckets. The buckets were transported to the main laboratory for testing. The design and as-built volumetric properties of the plant-produced mixtures are summarized in Figure 3 through Figure 6.

To prepare specimens for the laboratory testing shown in Table 2, the WMA was re-heated to 250°F, and the HMA was re-heated to 290°F for compaction. Additionally, the sulfur WMA specimens were cured for 24 hours at 60°C in an oven prior to laboratory testing. This was to allow the time-dependent strength properties of these mixes to become fully developed as the sulfur in the Thiopave WMA mixes crystallized.

2.4 Construction and Field-Performance Evaluation at NCAT Pavement Test Track

As shown in Table 2, four asphalt mixtures were placed in the surface layer of four 200-foot test sections at the NCAT Pavement Test Track. The construction information of the four mixtures is shown in Figure 3 through Figure 6. The control HMA in Section E8 (3.2% QC air voids) and the Thiopave WMA mixture in Section E9 (2.7% QC air voids) were further evaluated under the WMA Certification Program. The two Thiopave WMA mixtures in Sections W2 (3.2% QC air voids) and W7 (1.7% QC air voids) were evaluated in Part 3 of this study.

The four test sections were trafficked using a fleet of five heavy trucks over a year starting on May 11, 2010, the morning after construction. Over 5 million ESALs were applied to these test sections. Performance of the test sections was closely monitored on a weekly basis. Field measurements included rutting, cracking, macrotexture, and roughness.

In each test section, the first and last 25-foot portions were reserved for cutting cores for laboratory testing, and the middle 150-foot portion was used for monitoring field performance. An ARAN inertial profiler equipped with a full lane width dual-scanning laser "rutbar" was used to determine individual wheelpath roughness, right wheelpath macrotexture, and individual wheelpath rutting for each section. Additionally, three random locations were selected within each section in a stratified manner to serve as the fixed location for nondestructive testing of wheelpath densities. Transverse profiles were measured along these same locations regularly so that ARAN rutting measurements would be calibrated with a contact method using a dipstick. Each section was inspected weekly for cracking. If a crack was detected, it was manually marked on the pavement and measured to generate crack maps for monitoring the progress of cracking in each test section.

1/25/2011

Quadrant: E
Section: 8
Sublot: 1

Laboratory Diary

General Description of Mix and Materials

Design Method:	Super
Compactive Effort:	65 gyrations
Binder Performance Grade:	67-22
Modifier Type:	NA
Aggregate Type:	Granite
Design Gradation Type:	Fine

Avg. Lab Properties of Plant Produced Mix

Sieve Size	Design	QC
25 mm (1"):	100	100
19 mm (3/4"):	100	100
12.5 mm (1/2"):	100	100
9.5 mm (3/8"):	100	100
4.75 mm (#4):	67	72
2.36 mm (#8):	47	46
1.18 mm (#16):	35	35
0.60 mm (#30):	25	26
0.30 mm (#50):	17	18
0.15 mm (#100):	10	11
0.075 mm (#200):	5.9	6.1
Binder Content (Pb):	5.7	5.5
Eff. Binder Content (Pbe):	5.2	5.0
Dust-to-Binder Ratio:	1.1	1.2
Rice Gravity (Gmm):	2.431	2.447
Avg. Bulk Gravity (Gmb):	2.334	2.368
Avg Air Voids (Va):	4.0	3.2
Agg. Bulk Gravity (Gsb):	2.614	2.624
Avg VMA:	15.8	14.7
Avg. VFA:	75	78

Construction Diary

Relevant Conditions for Construction

Completion Date:	May 11, 2010
24 Hour High Temperature (F):	82
24 Hour Low Temperature (F):	59
24 Hour Rainfall (in):	0.00
Planned Subot Lift Thickness (in):	1.5
Paving Machine:	Blaw Knox

Plant Configuration and Placement Details

Component	% Setting
Asphalt Content (Plant Setting)	5.4
89 Lithia Springs Granite	41.0
810 Lithia Springs Granite	36.0
W10 Lithia Springs Granite	23.0
As-Built Sublot Lift Thickness (in):	1.5
Total Thickness of All 2009 Sublots (in):	1.5
Approx. Underlying HMA Thickness (in):	22.5
Type of Tack Coat Utilized:	NTSS-1HM
Target Tack Application Rate (gal/sy):	0.07
Approx. Avg. Temperature at Plant (F):	325
Avg. Measured Mat Compaction:	97.2%

Figure 3 As-Built Properties of HMA Mixture in Section E8

1/25/2011

Quadrant: E
Section: 9
Sublot: 1

Laboratory Diary

General Description of Mix and Materials

Design Method:	Super
Compactive Effort:	65 gyrations
Binder Performance Grade:	67-22
Modifier Type:	NA
Aggregate Type:	Granite
Design Gradation Type:	Fine

Avg. Lab Properties of Plant Produced Mix

Sieve Size	Design	QC
25 mm (1"):	100	100
19 mm (3/4"):	100	100
12.5 mm (1/2"):	100	100
9.5 mm (3/8"):	100	100
4.75 mm (#4):	67	70
2.36 mm (#8):	47	43
1.18 mm (#16):	35	33
0.60 mm (#30):	25	25
0.30 mm (#50):	17	17
0.15 mm (#100):	10	10
0.075 mm (#200):	5.9	6.0
Binder Content (Pb):	6.6	6.5
Eff. Binder Content (Pbe):	6.2	6.1
Dust-to-Binder Ratio:	1.0	1.0
Rice Gravity (Gmm):	2.441	2.450
Avg. Bulk Gravity (Gmb):	2.356	2.384
Avg Air Voids (Va):	3.5	2.7
Agg. Bulk Gravity (Gsb):	2.614	2.685
Avg VMA:	15.8	17.0
Avg. VFA:	78	84

Construction Diary

Relevant Conditions for Construction

Completion Date:	May 11, 2010
24 Hour High Temperature (F):	82
24 Hour Low Temperature (F):	59
24 Hour Rainfall (in):	0.00
Planned Subot Lift Thickness (in):	1.5
Paving Machine:	Blaw Knox

Plant Configuration and Placement Details

Component	% Setting
Asphalt Content (Plant Setting)	4.6
89 Lithia Springs Granite	41.0
810 Lithia Springs Granite	36.0
W10 Lithia Springs Granite	23.0
Thiopave	30.0
Compaction Agent	1.0
As-Built Sublot Lift Thickness (in):	1.3
Total Thickness of All 2009 Sublots (in):	1.3
Approx. Underlying HMA Thickness (in):	22.7
Type of Tack Coat Utilized:	NTSS-1HM
Target Tack Application Rate (gal/sy):	0.07
Approx. Avg. Temperature at Plant (F):	275
Avg. Measured Mat Compaction:	96.2%

Figure 4 As-Built Properties of Thiopave WMA Mixture in Section E9

1/25/2011

Quadrant: W
Section: 2
Sublot: 1

Laboratory Diary

General Description of Mix and Materials

Design Method:	Super
Compactive Effort:	65 gyrations
Binder Performance Grade:	67-22
Modifier Type:	SBR
Aggregate Type:	Granite
Design Gradation Type:	Fine

Avg. Lab Properties of Plant Produced Mix

Sieve Size	Design	QC
25 mm (1"):	100	100
19 mm (3/4"):	100	100
12.5 mm (1/2"):	100	100
9.5 mm (3/8"):	100	100
4.75 mm (#4):	67	70
2.36 mm (#8):	47	44
1.18 mm (#16):	35	34
0.60 mm (#30):	25	25
0.30 mm (#50):	17	17
0.15 mm (#100):	10	10
0.075 mm (#200):	5.9	5.9
Binder Content (Pb):	6.8	6.4
Eff. Binder Content (Pbe):	6.3	6.0
Dust-to-Binder Ratio:	0.9	1.0
Rice Gravity (Gmm):	2.441	2.452
Avg. Bulk Gravity (Gmb):	2.356	2.373
Avg Air Voids (Va):	3.5	3.2
Agg. Bulk Gravity (Gsb):	2.614	2.681
Avg VMA:	16.0	17.2
Avg. VFA:	78	81

Construction Diary

Relevant Conditions for Construction

Completion Date:	May 11, 2010
24 Hour High Temperature (F):	82
24 Hour Low Temperature (F):	59
24 Hour Rainfall (in):	0.00
Planned Subot Lift Thickness (in):	1.5
Paving Machine:	Blaw Knox

Plant Configuration and Placement Details

Component	% Setting
Asphalt Content (Plant Setting)	4.6
89 Lithia Springs Granite	41.0
810 Lithia Springs Granite	36.0
W10 Lithia Springs Granite	23.0
Thiopave	30.0
Compaction Agent	1.0
As-Built Sublot Lift Thickness (in):	1.4
Total Thickness of All 2009 Sublots (in):	1.4
Approx. Underlying HMA Thickness (in):	22.6
Type of Tack Coat Utilized:	NTSS-1HM
Target Tack Application Rate (gal/sy):	0.07
Approx. Avg. Temperature at Plant (F):	275
Avg. Measured Mat Compaction:	96.8%

Figure 5 As-Built Properties of Thiopave WMA Mixture in Section W2

1/25/2011

Quadrant: W
Section: 7
Sublot: 1

Laboratory Diary

General Description of Mix and Materials

Design Method:	Super
Compactive Effort:	65 gyrations
Binder Performance Grade:	67-22
Modifier Type:	SBR
Aggregate Type:	Granite
Design Gradation Type:	Fine

Avg. Lab Properties of Plant Produced Mix

Sieve Size	Design	QC
25 mm (1"):	100	100
19 mm (3/4"):	100	100
12.5 mm (1/2"):	100	100
9.5 mm (3/8"):	100	100
4.75 mm (#4):	67	69
2.36 mm (#8):	47	43
1.18 mm (#16):	35	33
0.60 mm (#30):	25	25
0.30 mm (#50):	17	18
0.15 mm (#100):	10	11
0.075 mm (#200):	5.9	6.4
Binder Content (Pb):	7.6	7.3
Eff. Binder Content (Pbe):	7.1	6.9
Dust-to-Binder Ratio:	0.8	0.9
Rice Gravity (Gmm):	2.436	2.444
Avg. Bulk Gravity (Gmb):	2.387	2.403
Avg Air Voids (Va):	2.0	1.7
Agg. Bulk Gravity (Gsb):	2.614	2.716
Avg VMA:	15.6	18.0
Avg. VFA:	87	91

Construction Diary

Relevant Conditions for Construction

Completion Date:	May 11, 2010
24 Hour High Temperature (F):	82
24 Hour Low Temperature (F):	59
24 Hour Rainfall (in):	0.00
Planned Subot Lift Thickness (in):	1.5
Paving Machine:	Blaw Knox

Plant Configuration and Placement Details

Component	% Setting
Asphalt Content (Plant Setting)	4.4
89 Lithia Springs Granite	41.0
810 Lithia Springs Granite	36.0
W10 Lithia Springs Granite	23.0
Thiopave	40.0
Compaction Agent	1.0
As-Built Sublot Lift Thickness (in):	1.4
Total Thickness of All 2009 Sublots (in):	1.4
Approx. Underlying HMA Thickness (in):	22.6
Type of Tack Coat Utilized:	NTSS-1HM
Target Tack Application Rate (gal/sy):	0.07
Approx. Avg. Temperature at Plant (F):	275
Avg. Measured Mat Compaction:	99.0%

Figure 6 As-Built Properties of Thiopave WMA Mixture in Section W7

3. RESULTS AND ANALYSIS

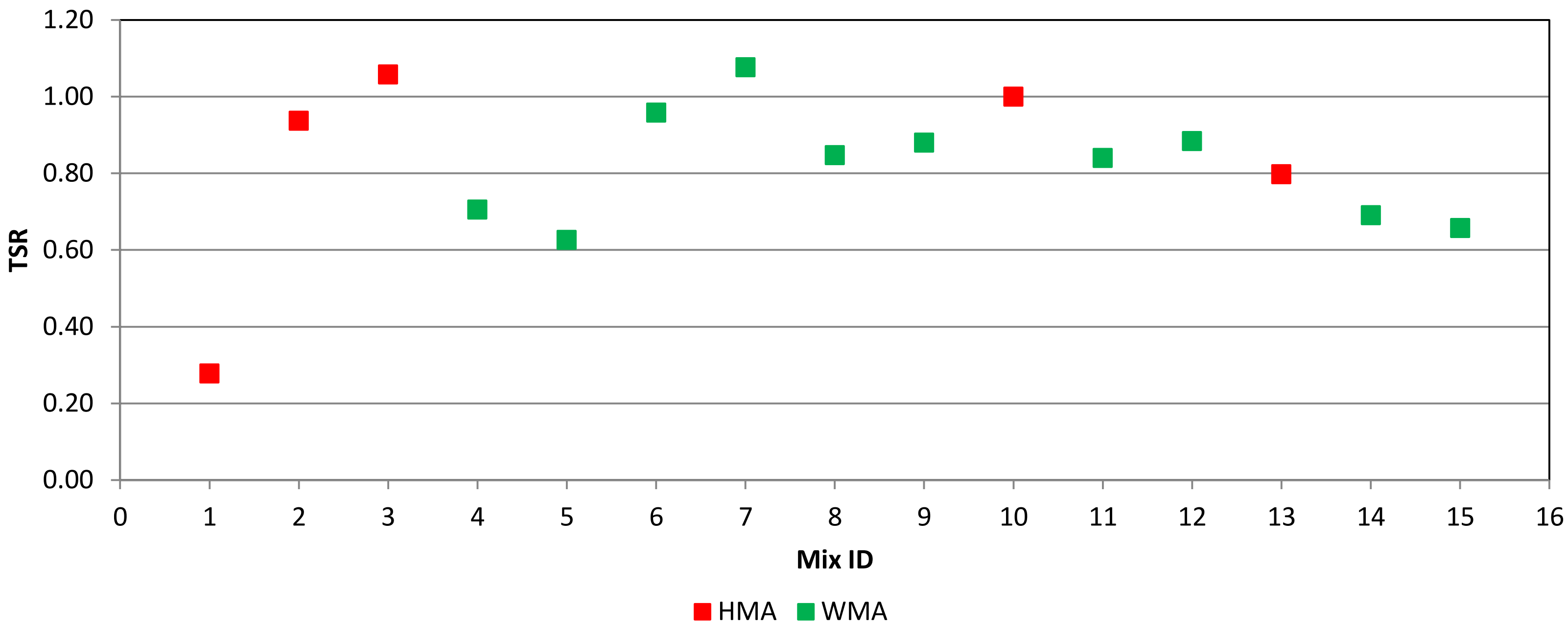
3.1 Part 1 – Testing of Laboratory-Prepared Mixtures

Detailed results of Part 1, during which laboratory testing was conducted on lab mixes, are included in Appendices A and B. Figure 7 through Figure 11 compare the results of all the mixtures tested in Part 1. Figure 21 through Figure 24 included in Appendix E show the analysis of variance (ANOVA) of the test results at the 95% confidence level. The following observations are drawn from the analysis of test results with focus on the tensile strength ratio (TSR), with 0.80 being a passing result, and the stripping inflection point (SIP), with 5000 cycles being a passing result, according to AASHTO T283-07 and AASHTO T324-04, respectively. The two parameters have been used to characterize the mix moisture susceptibility.

- As shown in Figure 7, the HMA mixture without an anti-strip additive (Mix 1) had the lowest TSR. While this mix was in Group A (Figure 21 in Appendix E) that had the statistically highest unconditioned indirect tensile strength, it was in Group F (Figure 22 in Appendix E) that had the statistically lowest conditioned indirect tensile strength. As previously mentioned, this mix has a history of moisture susceptibility in the field. All the anti-strip additives evaluated in this study could improve the TSR and conditioned indirect tensile strength (Figure 9) of this mixture significantly. To improve the TSR, the hydrated lime (Mix 3) and Redicote E-6 (Mix 10) were the most effective, followed by LOF 6500 (Mix 2) and ZycoSoil (Mix 13). The HMA mixture without an anti-strip additive also had a low SIP (Figure 11). Use of an anti-strip additive evaluated in this study could improve the SIP of this mixture. However, only Mix 2 with LOF 6500 exhibited a statistically higher SIP than Mix 1 (Figure 24 in Appendix E).
- As shown in Figure 7 and Figure 11, the two WMA mixtures without sulfur (Mixes 6 and 7) had the highest TSR and SIP values. When comparing Mix 6 with its corresponding HMA (Mix 2) and Mix 7 with Mix 10, use of the base binder modified with a low polymer dosage and the compaction aid would result in statistically equal or better conditioned indirect tensile strength (Figure 22 in Appendix E) and SIP (Figure 24 in Appendix E).
- As shown in Figure 7 and Figure 11, adding the sulfur pellets to the WMA mixtures could lower their TSR and SIP values. When comparing Mixes 4 and 5 with Mix 3, Mixes 8 and 9 with Mix 7, Mixes 11 and 12 with Mix 10, and Mixes 14 and 15 with Mix 13, the WMA mixtures with Thiopave had lower TSR and statistically lower conditioned indirect tensile strength (Figure 22 in Appendix E). When comparing Mixes 4 and 5 with Mix 3, and Mixes 8 and 9 with Mix 7, the WMA mixtures with sulfur had statistically lower SIP values. However, when comparing Mixes 11 and 12 with Mix 10, and Mixes 14 and 15 with Mix 13, the WMA mixtures with Thiopave had statistically equal SIP values.
- Three Thiopave WMA mixtures (Mixes 8, 9, and 11) had both the TSR greater than 0.8 and the SIP greater than 5,000 cycles. As shown in Figure 7 and Figure 11, Redicote E-6 was the most effective, followed by ZycoSoil and then hydrated lime in improving the TSR and SIP of the Thiopave WMA mixtures.

- Comparing Mix 8 with Mix 11 and Mix 9 with Mix 12 showed that use of the polymer resulted in statistically lower conditioned indirect tensile strength (Figure 22 in Appendix E) and statistically equal or lower SIP of the Thiopave WMA mixtures.
- As shown in Figure 10 and Figure 23 (in Appendix E), ZycoSoil appeared to reduce the HMA resistance to rutting the most. Use of the Thiopave system improved the WMA resistance to rutting, except when it was used with hydrated lime (Mixes 4 and 5).

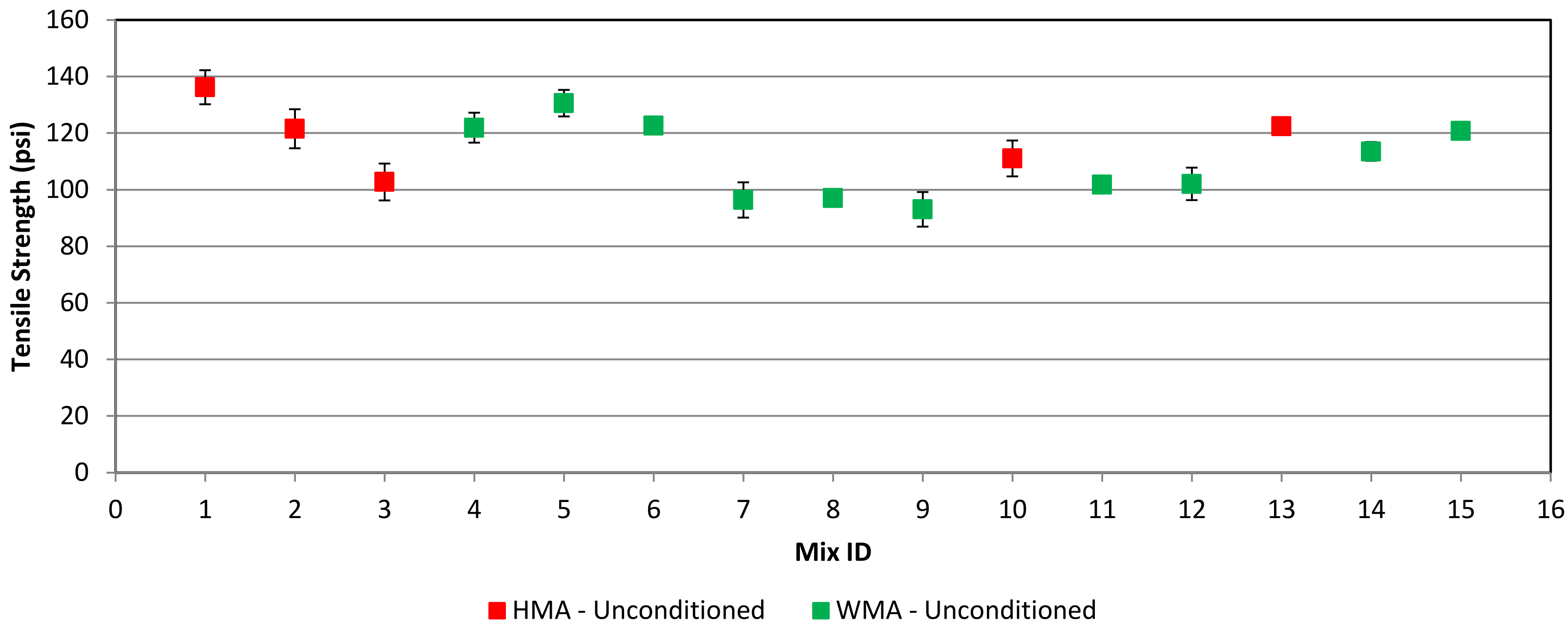
Based on the results of Part 1, it was decided to evaluate the moisture susceptibility of four Thiopave WMA mixtures (Mixes 4, 8, 9, and 11) against that of the control HMA mixture (Mix 2) produced at the plant in Part 2. However, only three Thiopave WMA mixtures (Mixes 8, 9, and 11) and the control HMA mixture (Mix 2) were paved on the test track for field evaluation; the other Thiopave WMA mixture (Mix 4) was plant-produced but not paved on the track. As previously mentioned, the field performance of Mix 11 was compared with that of Mix 2 in the WMA Certification Program final report (Powell and Taylor, 2011), and the field performance of Mixes 8 and 9 is compared with that of Mix 2 later in this report.



Description	Control		w/ Hyd. Lime			w/ Polymer & Anti-strip				w/ Redicote			w/ ZycoSoil		
	HMA	**HMA**	**HMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**
Mix ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Binder Code	+	+	+	+	+	++	++	++	++	+	+	+	+	+	+
% Thiopave System	0	0	0	30	40	1	1	30	40	0	30	40	0	40	40
% Sulfur	0	0	0	29	39	0	0	29	39	0	29	39	0	39	39
% Compaction Aid	0	0	0	1	1	1	1	1	1	0	1	1	0	1	1
Design Air Voids,%	4	4	4	3.5	3.5	4	4	3.5	2	4	3.5	3.5	4	3.5	3.5
Anti-strip Code	None	**	*	*	*	**	***	***	***	***	***	***	****	****	****
Anti-strip Dosage,%	0	0.5	1	1	1	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.06	0.06	0.1

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; **** ZycoSoil; +Unmodified binder; ++Modified binder

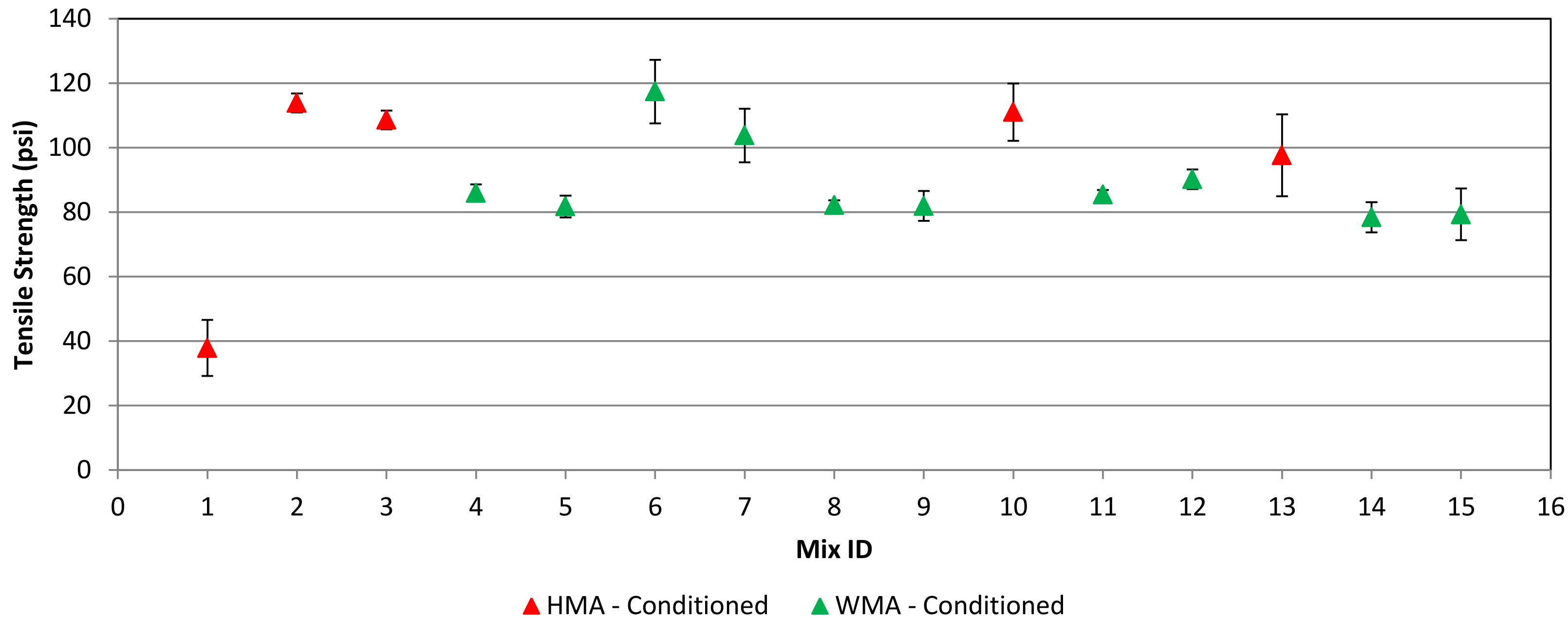
Figure 7 Tensile Strength Ratios of Laboratory-Prepared Mixtures



Description	Control		w/ Hyd. Lime			w/ Polymer & Anti-strip				w/ Redicote			w/ ZycoSoil		
	HMA	HMA	HMA	WMA	WMA	WMA	WMA	WMA	WMA	HMA	WMA	WMA	HMA	WMA	WMA
Mix ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Binder Code	+	+	+	+	+	++	++	++	++	+	+	+	+	+	+
% Thiopave System	0	0	0	30	40	1	1	30	40	0	30	40	0	40	40
% Sulfur	0	0	0	29	39	0	0	29	39	0	29	39	0	39	39
% Compaction Aid	0	0	0	1	1	1	1	1	1	0	1	1	0	1	1
Design Air Voids,%	4	4	4	3.5	3.5	4	4	3.5	2	4	3.5	3.5	4	3.5	3.5
Anti-strip Code	None	**	*	*	*	**	***	***	***	***	***	***	****	****	****
Anti-strip Dosage,%	0	0.5	1	1	1	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.06	0.06	0.1

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; **** ZycoSoil; +Unmodified binder; ++Modified binder

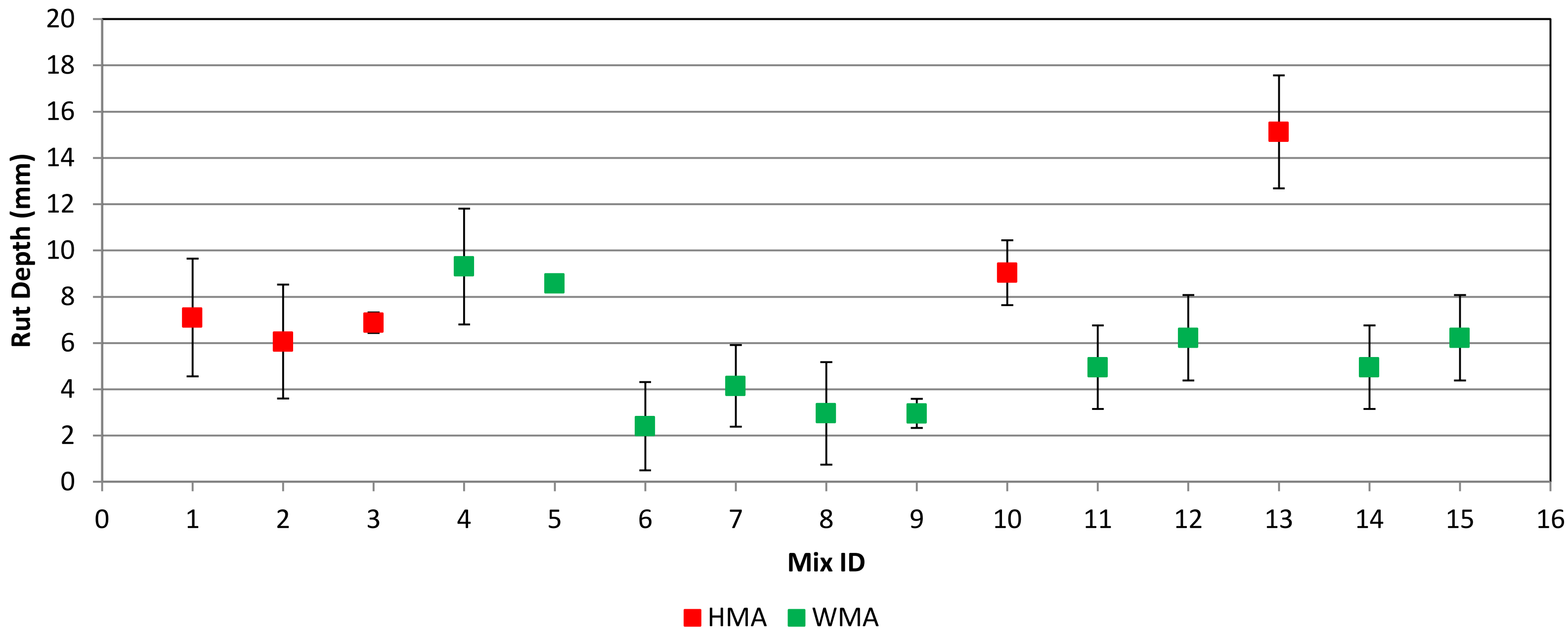
Figure 8 Tensile Strengths of Unconditioned Specimens



Description	Control		w/ Hyd. Lime			w/ Polymer & Anti-strip				w/ Redicote			w/ ZycoSoil		
	HMA	**HMA**	**HMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**
Mix ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Binder Code	+	+	+	+	+	++	++	++	++	+	+	+	+	+	+
% Thiopave System	0	0	0	30	40	1	1	30	40	0	30	40	0	40	40
% Sulfur	0	0	0	29	39	0	0	29	39	0	29	39	0	39	39
% Compaction Aid	0	0	0	1	1	1	1	1	1	0	1	1	0	1	1
Design Air Voids,%	4	4	4	3.5	3.5	4	4	3.5	2	4	3.5	3.5	4	3.5	3.5
Anti-strip Code	None	**	*	*	*	**	***	***	***	***	***	***	****	****	****
Anti-strip Dosage,%	0	0.5	1	1	1	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.06	0.06	0.1

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; **** ZycoSoil; +Unmodified binder; ++Modified binder

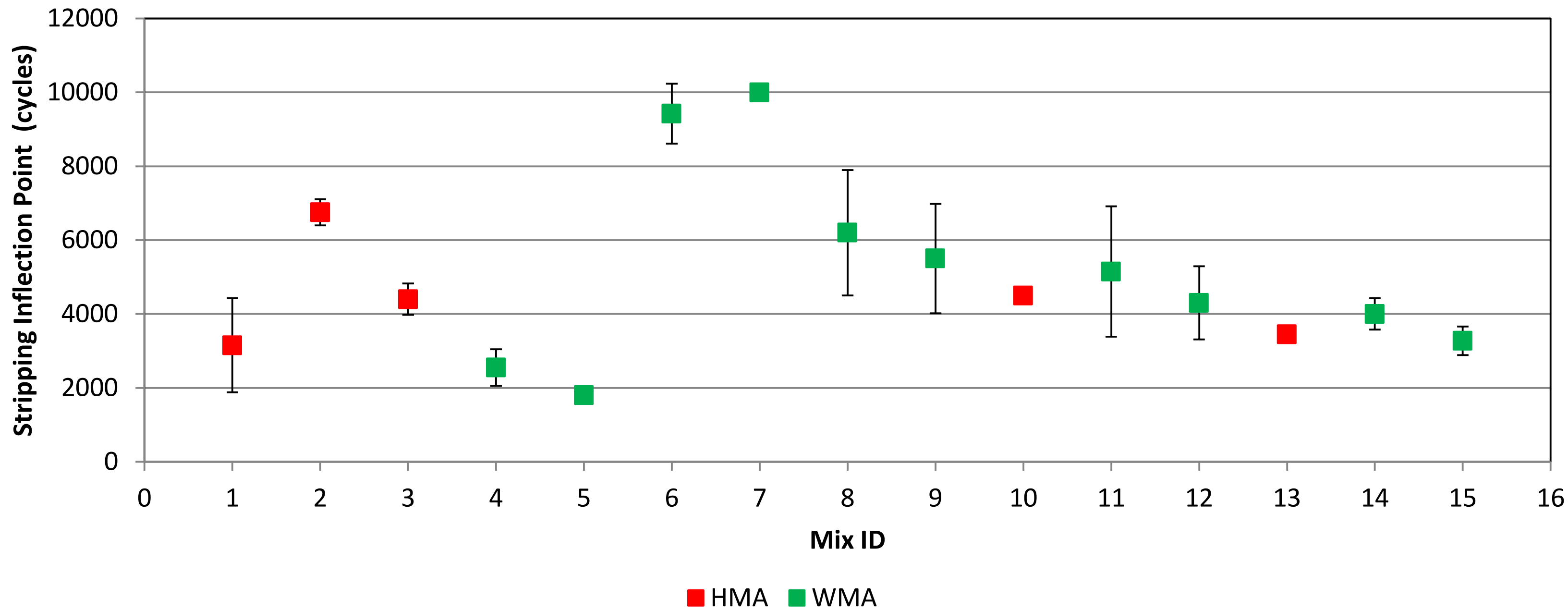
Figure 9 Tensile Strengths of Conditioned Specimens



Description	**Control**		**w/ Hyd. Lime**			**w/ Polymer & Anti-strip**				**w/ Redicote**			**w/ ZycoSoil**		
	HMA	**HMA**	**HMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**
Mix ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Binder Code	+	+	+	+	+	++	++	++	++	+	+	+	+	+	+
% Thiopave System	0	0	0	30	40	1	1	30	40	0	30	40	0	40	40
% Sulfur	0	0	0	29	39	0	0	29	39	0	29	39	0	39	39
% Compaction Aid	0	0	0	1	1	1	1	1	1	0	1	1	0	1	1
Design Air Voids,%	4	4	4	3.5	3.5	4	4	3.5	2	4	3.5	3.5	4	3.5	3.5
Anti-strip Code	None	**	*	*	*	**	***	***	***	***	***	***	****	****	****
Anti-strip Dosage,%	0	0.5	1	1	1	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.06	0.06	0.1

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; **** ZycoSoil; +Unmodified binder; ++Modified binder

Figure 10 Hamburg Rut Depth



Description	Control		w/ Hyd. Lime			w/ Polymer & Anti-strip				w/ Redicote			w/ ZycoSoil		
	HMA	**HMA**	**HMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**
Mix ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Binder Code	+	+	+	+	+	++	++	++	++	+	+	+	+	+	+
% Thiopave System	0	0	0	30	40	1	1	30	40	0	30	40	0	40	40
% Sulfur	0	0	0	29	39	0	0	29	39	0	29	39	0	39	39
% Compaction Aid	0	0	0	1	1	1	1	1	1	0	1	1	0	1	1
Design Air Voids,%	4	4	4	3.5	3.5	4	4	3.5	2	4	3.5	3.5	4	3.5	3.5
Anti-strip Code	None	**	*	*	*	**	***	***	***	***	***	***	****	****	****
Anti-strip Dosage,%	0	0.5	1	1	1	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.06	0.06	0.1

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; **** ZycoSoil; +Unmodified binder; ++Modified binder

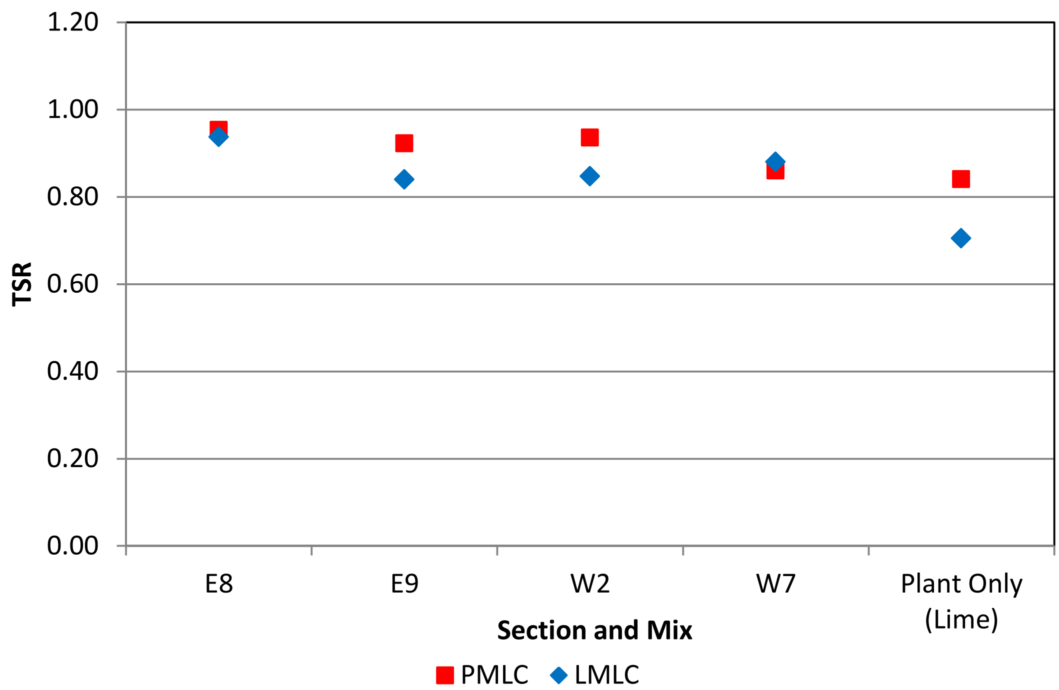
Figure 11 Stripping Inflection Points

3.2 Part 2 – Testing of Plant-Produced Mixtures

Detailed results of Part 2, in which laboratory testing was conducted on plant mixes, are included in Appendices C and D. Figure 12 through Figure 16 compare the results of all the plant mixes tested in Part 2 and the corresponding lab mixtures tested in Part 1. In Figure 12 through Figure 16, the plant mixes were referred to as plant-mixed, lab-compacted (PMLC) samples, and the lab mixes were referred to as lab-mixed, lab-compacted (LMLC) samples. Figure 25 through Figure 28 included in Appendix F show the ANOVA of the test results at the 95% confidence level. The following observations are drawn from the analysis of test results with a focus on the TSR (AASHTO T283-07) and the SIP (AASHTO T324-04).

- As shown in Figure 12, the TSR of the control HMA (Mix 2) and two Thiopave WMA (Mixes 11 and 8) was greater than 0.9, and the TSR for the other two mixtures (Mixes 9 and 4) was greater than 0.8. Compared with the lab mixes, the plant mixes had equal or higher TSR.
- Figure 13 and Figure 14 compare the unconditioned and conditioned indirect tensile strengths of the plant mixtures tested in Part 2. As shown in the statistical analysis in Figure 25 (Appendix F), the control HMA had the statistically highest unconditioned indirect tensile strength (in group A), followed by Mixes 11 and 4 (in group B), and Mixes 8 and 9 (in group C). The statistical analysis shown in Figure 26 (Appendix F) indicated that the control HMA also had the statistically highest conditioned indirect tensile strength (in group A), followed by Mix 11 (in group B), Mixes 4 and 8 (in group C), and Mix 9 (in group D).
- Also shown in Figure 13 and Figure 14 and in the statistical analyses (Figure 25 and Figure 26 in Appendix F), the plant mixtures had higher indirect tensile strengths than the corresponding lab mixtures, and the differences in the strengths between the plant and lab mixtures were statistically significant.
- As shown in Figure 15 and in the ANOVA (Figure 27 in Appendix F), the plant mix of Thiopave WMA with hydrated lime had the statistically highest rut depth, which was not statistically different from that of the lab mix. The rut depths of the two mixtures were in group A in Figure 27. For other mixtures (Mixes 2, 11, 8, and 9), the rut depths determined using lab and plant mixes were not statistically different. They were in group C in the Tukey's test in Figure 27 (Appendix F).
- Compared to the control mix (Mix 2), the three Thiopave WMA mixtures (Mixes 11, 8 and 9) had statistically similar SIP values when the Hamburg test was conducted on the plant mixes (Figure 16 and Figure 28 in Appendix F). However, Mix 11 had statistically higher SIP than Mixes 8 and 9 (Figure 28 in Appendix F). The Thiopave WMA with hydrated lime (Mix 4) had the statistically lowest SIP.
- Except for Mix 11, in which the plant mix had statistically higher SIP than the lab mix, the other four mixtures (Mixes 2, 8, 9, and 4) had statistically similar SIP for the plant and lab mixes.

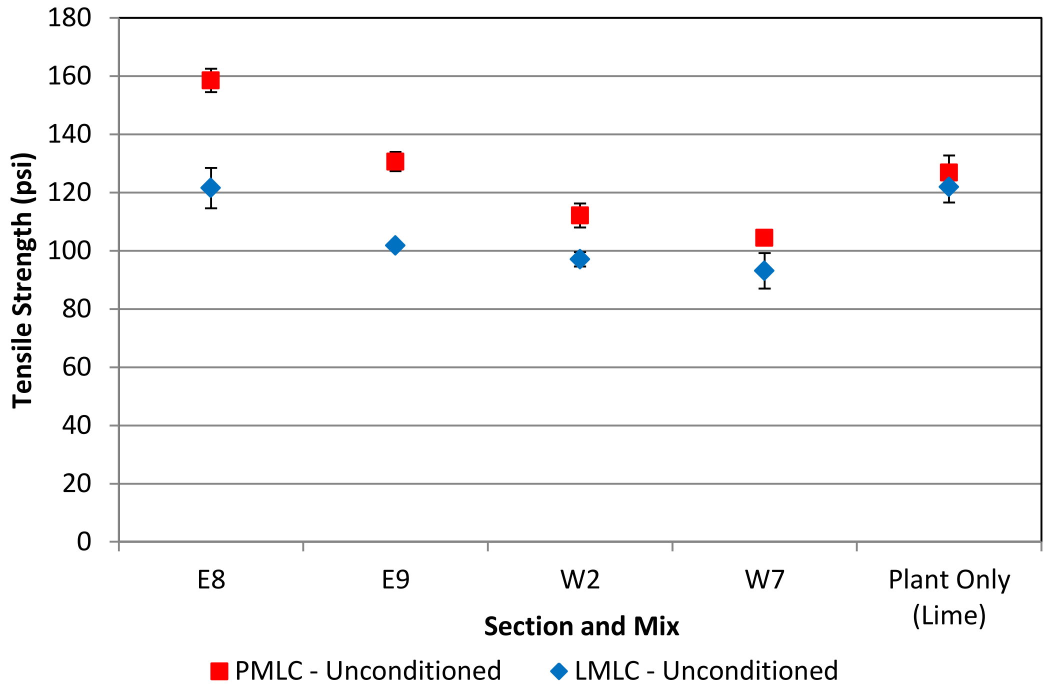
Based on the laboratory testing results of the lab and plant mixes in Parts 1 and 2, it was anticipated that the three Thiopave WMA mixtures (Mixes 11, 8, and 9) placed in Sections E9, W2, and W7 would have equal resistance to moisture and equal or better resistance to rutting than the control HMA mixture placed in Section E8.



Description	**HMA**	**Thiopave WMA**			
Test Section	**E8**	**E9**	**W2**	**W7**	**Plant Only (Lime)**
Mix ID	**2**	**11**	**8**	**9**	**4**
Binder Code	+	+	++	++	+
% Thiopave System	0	30	30	40	30
% Sulfur	0	29	29	39	29
% Compaction Aid	0	1	1	1	1
Design Air Voids,%	4	3.5	3.5	2	3.5
Anti-strip Code	**	***	***	***	*
Anti-strip Dosage,%	0.5	0.75	0.75	0.75	1

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; +Unmodified binder; ++Modified binder

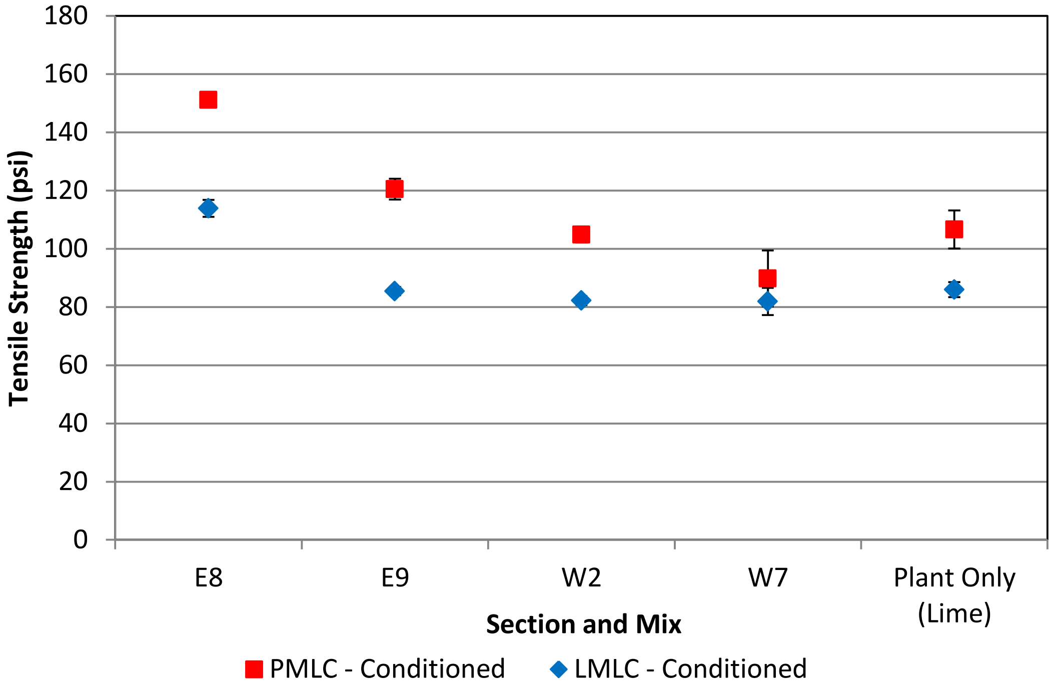
Figure 12 Tensile Strength Ratios of Lab and Plant Mixtures



Description	HMA	Thiopave WMA			
Test Section	**E8**	**E9**	**W2**	**W7**	**Plant Only (Lime)**
Mix ID	**2**	**11**	**8**	**9**	**4**
Binder Code	+	+	++	++	+
% Thiopave System	0	30	30	40	30
% Sulfur	0	29	29	39	29
% Compaction Aid	0	1	1	1	1
Design Air Voids,%	4	3.5	3.5	2	3.5
Anti-strip Code	**	***	***	***	*
Anti-strip Dosage,%	0.5	0.75	0.75	0.75	1

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; +Unmodified binder; ++Modified binder

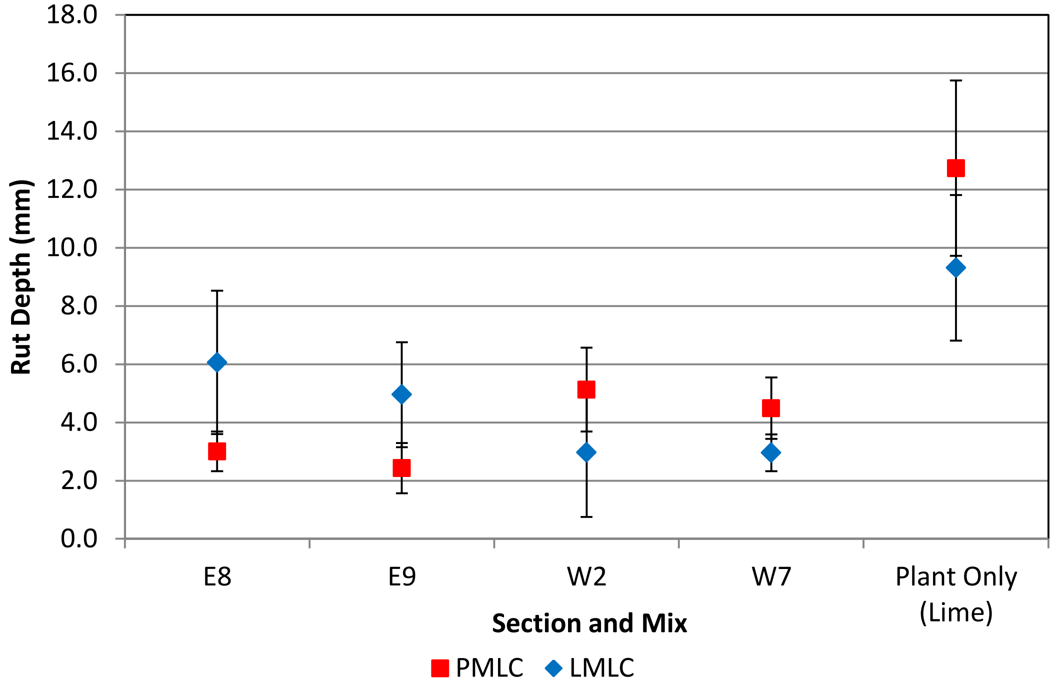
Figure 13 Tensile Strengths of Unconditioned PMLC and LMLC Specimens



Description	**HMA**	**Thiopave WMA**			
Test Section	**E8**	**E9**	**W2**	**W7**	**Plant Only (Lime)**
Mix ID	**2**	**11**	**8**	**9**	**4**
Binder Code	+	+	++	++	+
% Thiopave System	0	30	30	40	30
% Sulfur	0	29	29	39	29
% Compaction Aid	0	1	1	1	1
Design Air Voids,%	4	3.5	3.5	2	3.5
Anti-strip Code	**	***	***	***	*
Anti-strip Dosage,%	0.5	0.75	0.75	0.75	1

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; +Unmodified binder; ++Modified binder

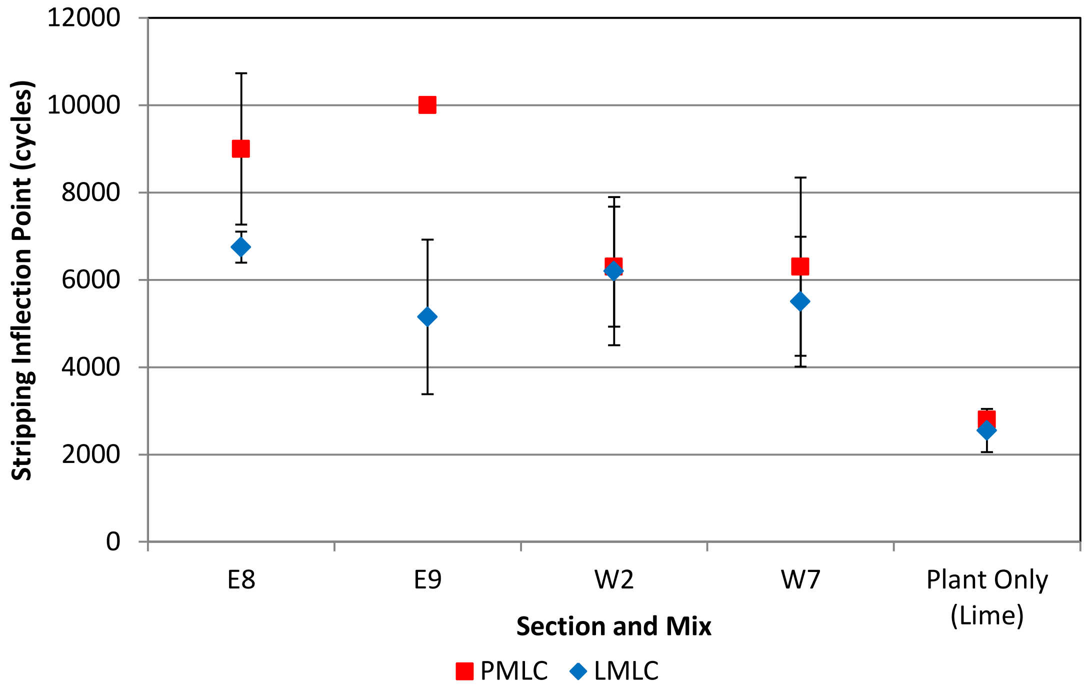
Figure 14 Tensile Strengths of Conditioned PMLC and LMLC Specimens



Description	**HMA**	**Thiopave WMA**			
Test Section	**E8**	**E9**	**W2**	**W7**	**Plant Only (Lime)**
Mix ID	**2**	**11**	**8**	**9**	**4**
Binder Code	+	+	++	++	+
% Thiopave System	0	30	30	40	30
% Sulfur	0	29	29	39	29
% Compaction Aid	0	1	1	1	1
Design Air Voids,%	4	3.5	3.5	2	3.5
Anti-strip Code	**	***	***	***	*
Anti-strip Dosage,%	0.5	0.75	0.75	0.75	1

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; +Unmodified binder; ++Modified binder

Figure 15 Rut Depths of PMLC and LMLC Specimens



Description	HMA	Thiopave WMA			
Test Section	**E8**	**E9**	**W2**	**W7**	**Plant Only (Lime)**
Mix ID	**2**	**11**	**8**	**9**	**4**
Binder Code	+	+	++	++	+
% Thiopave System	0	30	30	40	30
% Sulfur	0	29	29	39	29
% Compaction Aid	0	1	1	1	1
Design Air Voids,%	4	3.5	3.5	2	3.5
Anti-strip Code	**	***	***	***	*
Anti-strip Dosage,%	0.5	0.75	0.75	0.75	1

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; +Unmodified binder; ++Modified binder

Figure 16 Stripping Inflection Points of PMLC and LMLC Specimens

3.3 Part 3 – Field-Performance Evaluation

Figure 17 through Figure 20 show the field performance for the four asphalt concrete mixtures (Mixes 2, 11, 8, and 9) placed in the surface of the four test sections (E8, E9, W2, and W7) at the NCAT Pavement Test Track. Since they were built in May 2010, more than 5 million ESALs have been applied to the test sections. The control HMA section (E8) and the three Thiopave WMA sections showed similar rutting performance, and the field rut depths were approximately 5 mm, even though traffic was initiated the morning after construction (with the sulfur not fully crystallized), and these sections are located on the track curves where shear stresses are higher. Weekly measurements of roughness using the International Roughness Index (IRI) indicated comparable performance between sections E8 and E9. Compared to the control HMA section E8, sections W2 and W7 had lower IRI. There was no cracking evident on any of the Thiopave WMA sections, while some hairline cracks did appear in the control HMA section (E8), as shown in Figure 17. The results of the field-performance evaluation support the conclusion from Part 2 of this study that the Thiopave WMA mixes should perform equivalently to the control HMA in the field.

9/14/2011

Quadrant: E
Section: 8

Surface Mix and Materials		Structural Buildup Information	
Year of Completion:	2010	Study HMA (in):	1.5
HMA Design Methodology:	Superpave	Total HMA (in):	24
Specified Binder:	PG67-22	Base Material:	Granite
Surface Mix Stockpile Materials:	Granite	Subgrade:	Stiff

Research Objective: Hot Control for WMA Certification Program 5/11/10

Preliminary Field Performance Data

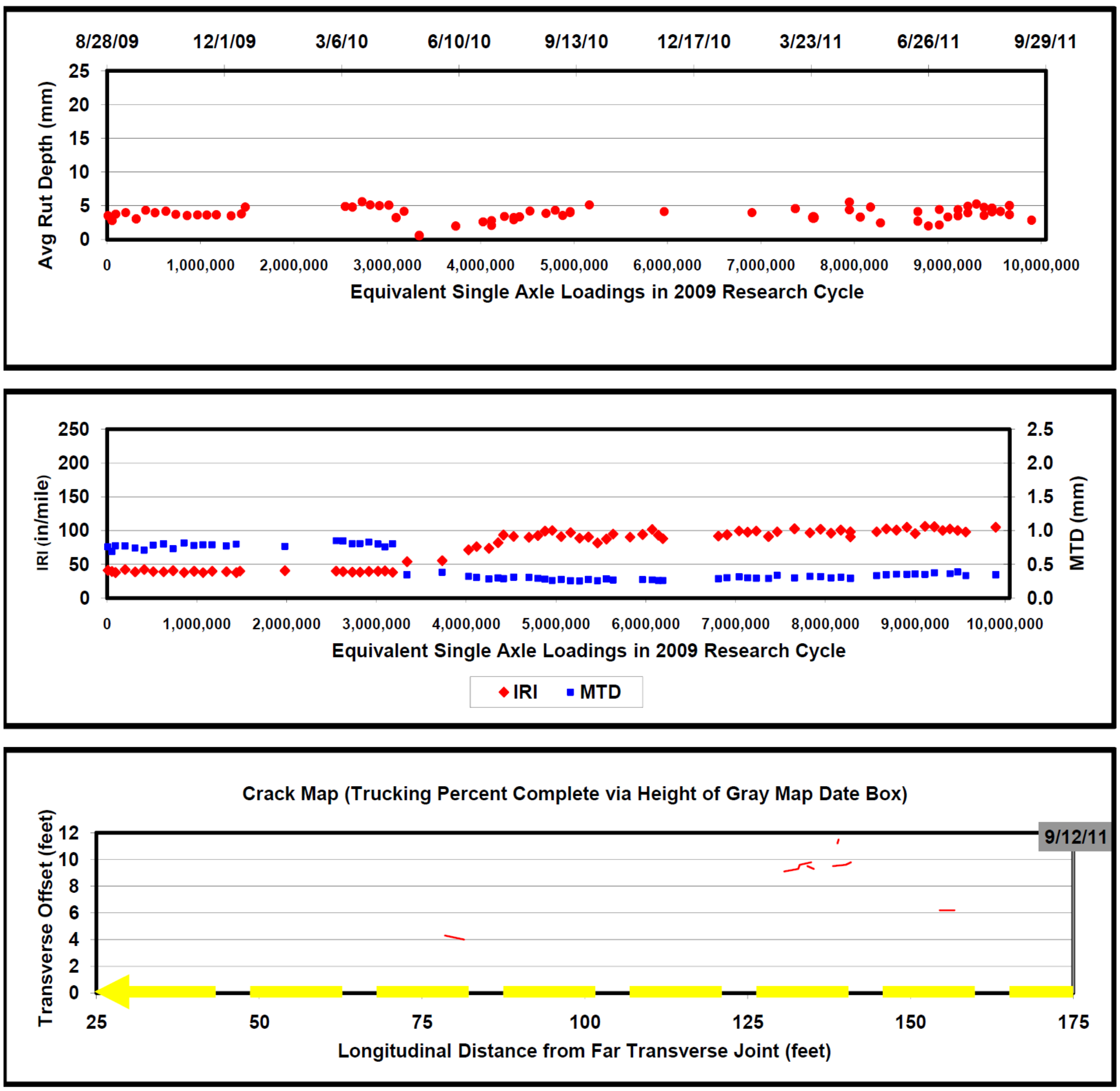


Figure 17 Field Performance of Mix 2 (Control) Placed in Section E8

9/14/2011

Quadrant: E
Section: 9

Surface Mix and Materials		Structural Buildup Information	
Year of Completion:	2010	Study HMA (in):	1.5
HMA Design Methodology:	Superpave	Total HMA (in):	24
Specified Binder:	PG67-22	Base Material:	Granite
Surface Mix Stockpile Materials:	Granite	Subgrade:	Stiff

Research Objective: Shell Thiopave WMA Certification Program 5/11/10

Preliminary Field Performance Data

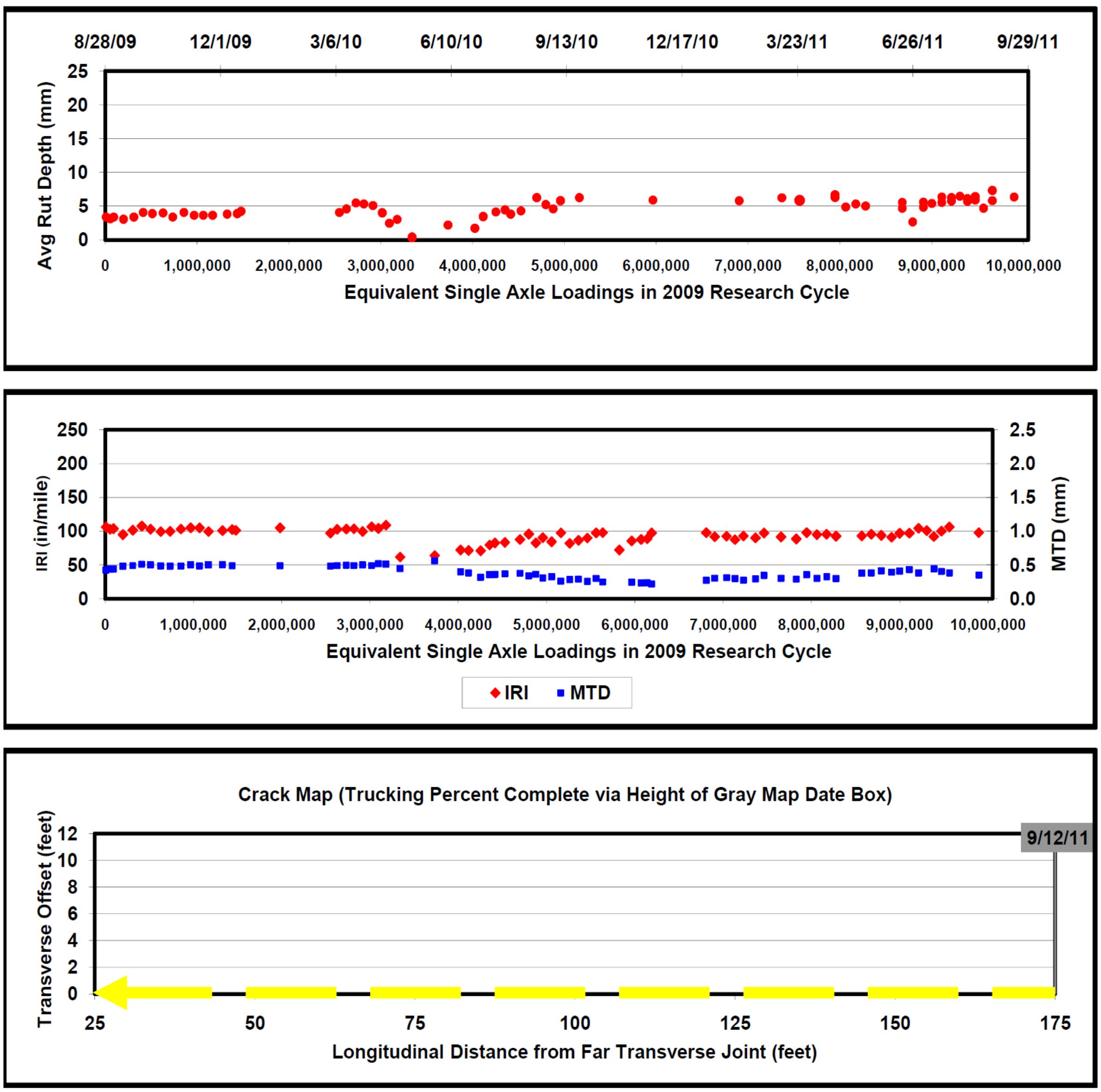


Figure 18 Field Performance of Mix 11 Placed in Section E9

8/8/2011

Quadrant: W
Section: 2

Surface Mix and Materials		**Structural Buildup Information**	
Year of Completion:	2010	Study HMA (in):	1.5
HMA Design Methodology:	Superpave	Total HMA (in):	24
Specified Binder:	PG67-22	Base Material:	Granite
Surface Mix Stockpile Materials:	Granite	Subgrade:	Stiff

Research Objective: Shell Thiopave Demo with Latex 5/11/10

Preliminary Field Performance Data

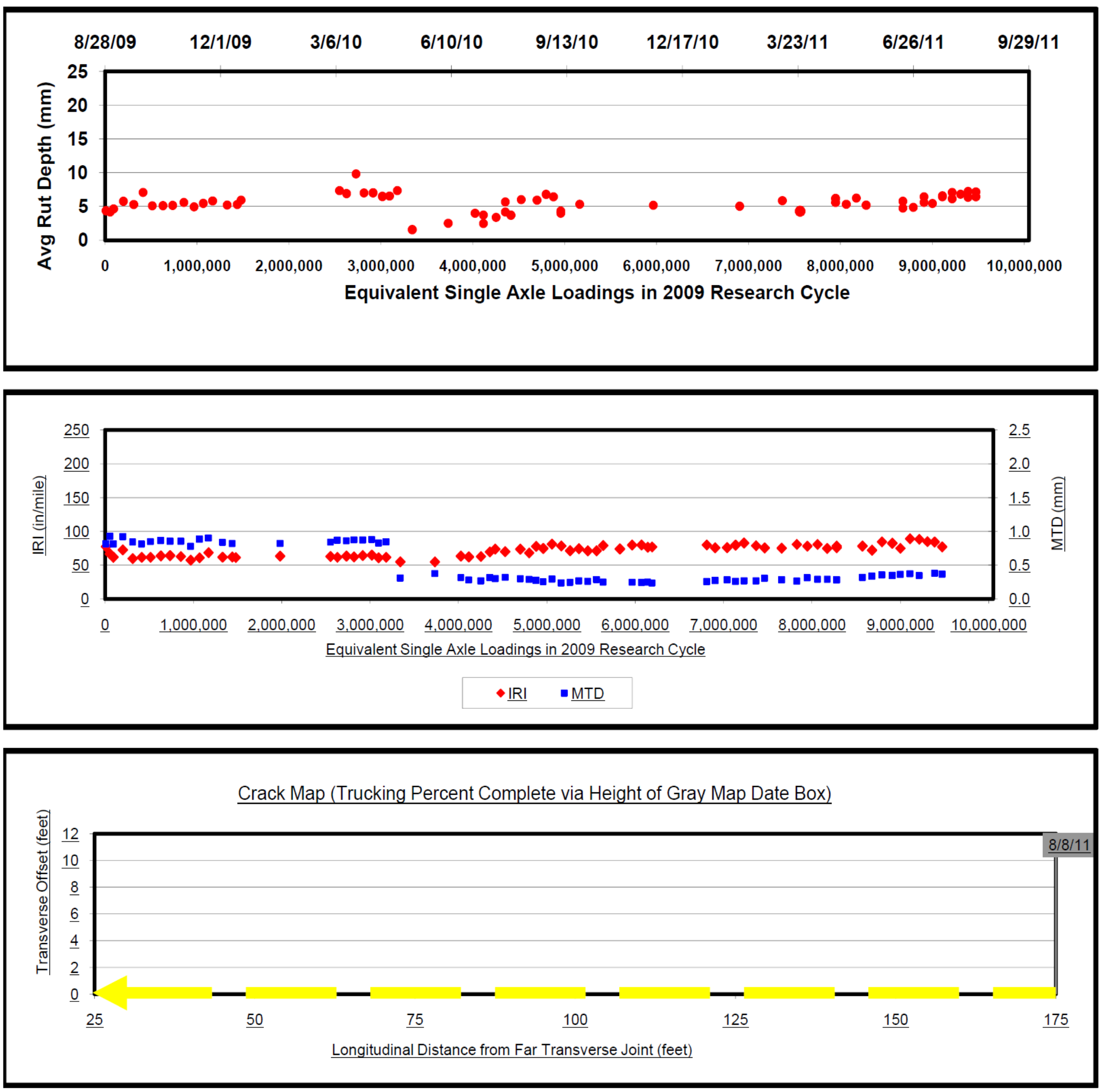


Figure 19 Field Performance of Mix 8 Placed in Section W2

8/8/2011

Quadrant: W
Section: 7

Surface Mix and Materials		**Structural Buildup Information**	
Year of Completion:	2010	Study HMA (in):	1.5
HMA Design Methodology:	Superpave	Total HMA (in):	24
Specified Binder:	PG67-22	Base Material:	Granite
Surface Mix Stockpile Materials:	Granite	Subgrade:	Stiff

Research Objective: Shell Thiopave Demo with Latex 5/11/10

Preliminary Field Performance Data

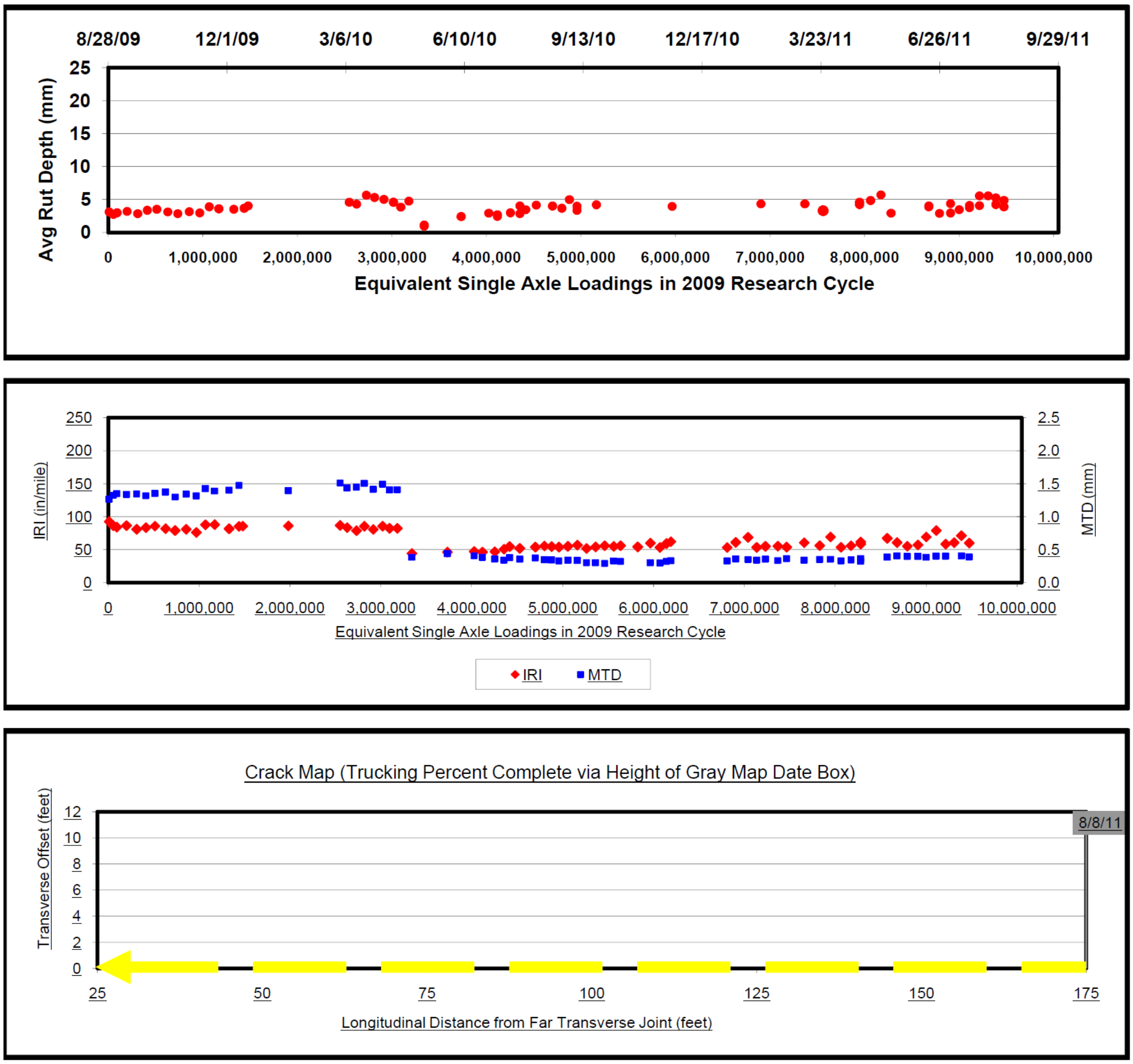


Figure 20 Field Performance of Mix 9 Placed in Section W7

4. CONCLUSIONS AND RECOMMENDATIONS

This report documented the laboratory testing and field evaluation of the control HMA and Thiopave WMA mixtures at the NCAT Pavement Test Track. Based on the data presented herein, the following key findings, conclusions, and recommendations can be made:

- Using any of the anti-strip additives (hydrated lime, Redicote E-6, LOF 6500, and ZycoSoil) evaluated in this study could significantly improve the moisture resistance of the control HMA, which has a history of moisture susceptibility in the field. Based on the testing results of lab-prepared mixes, the use of any of the above anti-strip additives could result in the TSR of HMA greater than 0.8, but only LOF 6500 could help bring the SIP greater than 5,000 cycles.
- Use of any of the anti-strip additives evaluated in this study could improve the moisture resistance of the Thiopave WMA. Redicote E-6 was the most effective, followed by ZycoSoil and then hydrated lime. Only three Thiopave WMA mixtures (Mixes 8, 9, and 11) had both the TSR greater than 0.8 and the SIP greater than 5,000 cycles. Mixes 8 and 11 contained 29% of sulfur and 1% of compaction aid and were designed at 3.5% air voids. Mix 9 contained 39% sulfur and 1% compaction aid and was designed at 2% air voids. Redicote E-6 was used as the anti-strip additive in the three mixtures, and a low dosage of a polymer was used in Mixes 8 and 9.
- Use of the base binder (PG 67-22) modified with a low polymer dosage (0.75% SBR slurry) and the compaction aid could improve the resistance of the control mixture (mixed and compacted at the recommended WMA temperatures) to moisture damage.
- Adding the sulfur-modified Thiopave pellets to the WMA mixtures could reduce the mixture moisture resistance (lowering TSR and SIP). A contributing factor to this observation could be that when a significant portion of the base asphalt binder is replaced with sulfur, the total binder contains less of the anti-strip additive in the mixture. Thus, a higher percentage of anti-strip could be used to improve the moisture resistance of the Thiopave WMA.
- The moisture and rutting susceptibility test results of lab-prepared mixes showed no statistically significant improvement in the Thiopave WMA when a low polymer dosage was used.
- Use of the Thiopave system improved the WMA resistance to rutting except when it was used with hydrated lime.
- Compared to the lab-prepared mixtures, the plant-produced mixes showed equal or better moisture and rutting performance.
- Based on the test results of plant-produced mixes, the Thiopave WMA mixtures, except for the Thiopave WMA with hydrated lime, appeared to have equal or better resistance to rutting and moisture damage than the control HMA mixture.
- The control HMA and three Thiopave WMA mixtures placed on the test track all showed excellent rutting performance.
- The Thiopave WMA test sections showed equal or better IRI than the control HMA test section.
- There was no cracking evident on any of the Thiopave WMA test sections, while some hairline cracks did appear in the control HMA test section.

REFERENCES

1. Strickland, D., J. Colange, P. Shaw and N. Pugh. A Study of the Low-Temperature Properties of Sulphur Extended Asphalt Mixtures. *Canadian Technical Asphalt Association*, 2008.
2. Powell, R. and A. Taylor. *Design, Construction and Performance of Sulfur-Modified Mix in the WMA Certification Program at the NCAT Pavement Test Track.* NCAT Report 11-08, National Center for Asphalt Technology, Auburn University, 2011.
3. Timm, D., N. Tran, A. Taylor, M. Robbins and R. Powell. *Evaluation of Mixture Performance and Structural Capacity of Pavements Using Shell Thiopave®.* Report No. 09-05, National Center for Asphalt Technology, Auburn University, 2009.
4. Tran, N., A. Taylor, D. Timm, M. Robbins, B. Powell, and R. Dongre. *Evaluation of Mixture Performance and Structural Capacity of Pavements Using Shell Thiopave®: Comprehensive Laboratory Performance Evaluation.* Report No. 10-05, National Center for Asphalt Technology, Auburn University, 2010.
5. Timm, D., M. Robbins, J. Willis, N. Tran, and A. Taylor. *Evaluation of Mixture Performance and Structural Capacity of Pavements Utilizing Shell Thiopave - Phase II: Construction, Laboratory Evaluation and Full-Scale Testing of Thiopave Test Sections - One Year Report.* Report No. 11-03, National Center for Asphalt Technology, Auburn University, 2011.

APPENDIX A RESULTS OF TENSILE STRENGTH TESTING OF LAB MIXES

Description	**Control**		**w/ Hyd. Lime**			**w/ Polymer & Anti-strip**				**w/ Redicote**			**w/ ZycoSoil**		
	HMA	**HMA**	**HMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**	**HMA**	**WMA**	**WMA**
Mix ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Binder Code	+	+	+	+	+	++	++	++	++	+	+	+	+	+	+
% Thiopave System	0	0	0	30	40	1	1	30	40	0	30	40	0	40	40
% Sulfur	0	0	0	29	39	0	0	29	39	0	29	39	0	39	39
% Compaction Aid	0	0	0	1	1	1	1	1	1	0	1	1	0	1	1
Design Air Voids,%	4	4	4	3.5	3.5	4	4	3.5	2	4	3.5	3.5	4	3.5	3.5
Anti-strip Code	None	**	*	*	*	**	***	***	***	***	***	***	****	****	****
Anti-strip Dosage,%	0	0.5	1	1	1	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.06	0.06	0.1
Unconditioned	7.0	7.1	7.3	7.3	7.3	7.0	6.9	6.9	6.9	7.2	6.7	7.0	7.2	7.0	6.9
Conditioned	7.1	7.1	7.3	7.3	7.4	7.1	6.8	6.9	6.7	7.2	6.7	7.1	7.2	7.0	6.9
Tensile Strength (psi)															
Unconditioned															
Replicate 1	140	118	108	116	136	120	104	94	88	111	101	104	123	110	118
Replicate 2	139	117	95	125	129	124	93	98	91	105	103	96	122	115	123
Replicate 3	129	129	105	125	127	124	93	98	100	117	101	106	122	116	121
Average	136	122	103	122	131	123	96	97	93	111	102	102	122	114	121
Std. Deviation	6.0	6.9	6.5	5.3	4.7	2.5	6.2	2.5	6.1	6.3	1.0	5.8	0.6	3.3	2.1
Conditioned															
Replicate 1	48	117	111	85	85	107	101	84	78	121	87	87	119	84	71
Replicate 2	33	112	105	84	78	126	113	82	81	108	86	91	100	76	87
Replicate 3	33	112	110	89	83	120	97	81	87	104	84	93	84	75	81
Average	38	114	109	86	82	117	104	82	82	111	85	90	101	78	79
Std. Deviation	8.7	2.9	2.9	2.6	3.4	9.9	8.3	1.5	4.6	8.9	1.5	3.0	17.5	4.7	8.0
TSR	0.28	0.94	1.06	0.71	0.63	0.96	1.08	0.85	0.88	1.00	0.84	0.88	0.82	0.69	0.66

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; **** ZycoSoil; +Unmodified binder; ++Modified binder

APPENDIX B RESULTS OF HAMBURG TESTING OF LAB MIXES

Description	Control		w/ Hyd. Lime			w/ Polymer & Anti-strip				w/ Redicote			w/ ZycoSoil		
	HMA	HMA	HMA	WMA	WMA	WMA	WMA	WMA	WMA	HMA	WMA	WMA	HMA	WMA	WMA
Mix ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Binder Code	+	+	+	+	+	++	++	++	++	+	+	+	+	+	+
% Thiopave System	0	0	0	30	40	1	1	30	40	0	30	40	0	40	40
% Sulfur	0	0	0	29	39	0	0	29	39	0	29	39	0	39	39
% Compaction Aid	0	0	0	1	1	1	1	1	1	0	1	1	0	1	1
Design Air Voids,%	4	4	4	3.5	3.5	4	4	3.5	2	4	3.5	3.5	4	3.5	3.5
Anti-strip Code	None	**	*	*	*	**	***	***	***	***	***	***	****	****	****
Anti-strip Dosage,%	0	0.5	1	1	1	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.06	0.06	0.1
Replicate 1															
Avg. Air Voids,%	7.1	7.2	7.2	7.5	7.5	7.0	7.2	6.8	6.7	7.3	7.4	7.5	7.1	7.4	7.5
Steady-State Slope	0.0009	0.0008	0.0007	0.0011	0.0009	0.0004	0.0005	0.0001	0.0003	0.0010	0.0006	0.0008	0.0017	0.0006	0.0008
Rut Depth, mm	8.9	7.8	6.6	11.1	8.5	3.8	5.4	1.4	3.4	10.0	6.2	7.5	16.8	6.2	7.5
Inflection Point, cyc.	2250	7000	4700	2200	1800	8850	10000	7400	4450	4500	3900	3600	3500	3700	3000
Replicate 2															
Avg. Air Voids,%	7.1	7.2	7.0	7.0	6.8	7.2	7.0	7.2	6.1	7.1	7.1	6.8	7.2	7.1	6.8
Steady-State Slope	0.0005	0.0004	0.0007	0.0008	0.0009	0.0001	0.0003	0.0005	0.0003	0.0008	0.0004	0.0005	0.0013	0.0004	0.0005
Rut Depth, mm	5.3	4.3	7.2	7.5	8.6	1.1	2.9	4.5	2.5	8.0	3.7	4.9	13.4	3.7	4.9
Inflection Point, cyc.	4050	6500	4100	2900	1800	10000	10000	5000	6550	4500	6400	5000	3400	4300	3550
Rut Depth, mm															
Average	7.1	6.1	6.9	9.3	8.6	2.4	4.1	3.0	3.0	9.0	5.0	6.2	15.1	5.0	6.2
Std. Deviation	2.5	2.5	0.4	2.5	0.0	1.9	1.8	2.2	0.6	1.4	1.8	1.8	2.4	1.8	1.8
Inflection Point, cyc.															
Average	3150	6750	4400	2550	1800	9425	10000	6200	5500	4500	5150	4300	3450	4000	3275
Std. Deviation	1273	354	424	495	0	813	0	1697	1485	0	1768	990	71	424	389

*Hydrated lime; **ArrMaz LOF 6500; ***Akzo Nobel Redicote E-6; **** ZycoSoil; +Unmodified binder; ++Modified binder

APPENDIX C RESULTS OF TENSILE STRENGTH TESTING OF PLANT MIXES

Description	**HMA**	**Thiopave WMA**			
Test Section	**E8**	**E9**	**W2**	**W7**	**Plant Only (Lime)**
Mix ID	**2**	**11**	**8**	**9**	**4**
Binder Code	+	+	++	++	+
% Thiopave System	0	30	30	40	30
% Sulfur	0	29	29	39	29
% Compaction Aid	0	1	1	1	1
Design Air Voids,%	4	3.5	3.5	2	3.5
Anti-strip Code	**	***	***	***	*
Anti-strip Dosage,%	0.5	0.75	0.75	0.75	1
Avg. Air Voids,%					
Unconditioned	7.1	7.0	7.3	7.2	7.0
Conditioned	7.0	7.0	7.2	7.2	7.0
Tensile Strength (psi)					
Unconditioned					
Replicate	162	131	113	104	130
Replicate	159	127	115	103	130
Replicate	154	134	108	107	120
Average	159	131	112	104	127
Std. Deviation	4.0	3.3	4.1	2.3	5.8
Conditioned					
Replicate	150	124	107	98	113
Replicate	154	117	106	79	107
Replicate	150	120	102	92	100
Average	151	120	105	90	107
Std. Deviation	2.6	3.6	2.7	9.6	6.6
TSR	0.95	0.92	0.94	0.86	0.84

APPENDIX D RESULTS OF HAMBURG TESTING OF PLANT MIXES

Description	**HMA**	**Thiopave WMA**			
Test Section	**E8**	**E9**	**W2**	**W7**	**Plant Only (Lime)**
Mix ID	**2**	**11**	**8**	**9**	**4**
Binder Code	+	+	++	++	+
% Thiopave System	0	30	30	40	30
% Sulfur	0	29	29	39	29
% Compaction Aid	0	1	1	1	1
Design Air Voids,%	4	3.5	3.5	2	3.5
Anti-strip Code	**	***	***	***	*
Anti-strip Dosage,%	0.5	0.75	0.75	0.75	1
Replicate 1					
Avg. Air Voids,%	7.4	7.3	7.0	7.0	7.2
Steady-State Slope	0.0003	0.0002	0.0006	0.0006	0.0014
Rut Depth, mm	2.9	2.2	6.2	5.7	14.3
Inflection Point, cyc.	10000	10000	5100	4000	2800
Replicate 2					
Avg. Air Voids,%	7.4	7.5	6.7	7.0	7.5
Steady-State Slope	0.0004	0.0003	0.0004	0.0004	0.0009
Rut Depth, mm	3.7	3.4	3.5	4.0	9.3
Inflection Point, cyc.	7000	10000	7800	7000	2800
Replicate 3					
Avg. Air Voids,%	7.3	7.2	6.9	7.0	7.3
Steady-State Slope	0.0002	0.0002	0.0006	0.0004	0.0015
Rut Depth, mm	2.4	1.7	5.6	3.8	14.7
Inflection Point, cyc.	10000	10000	6000	7900	2800
Rut Depth, mm					
Average	3.0	2.4	5.1	4.5	12.7
Std. Deviation	0.7	0.9	1.4	1.1	3.0
Inflection Point, cyc.					
Average	9000	10000	6300	6300	2800
Std. Deviation	1732	0	1375	2042	0

APPENDIX E ANOVA OF PART 1 TESTING RESULTS

General Linear Model: Unconditioned Tensile Strength versus Mix ID

```
Factor  Type   Levels  Values
Mix ID  fixed      15  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15


Analysis of Variance for Unconditioned, using Adjusted SS for Tests

Source  DF   Seq SS   Adj SS  Adj MS      F      P
Mix ID  14  7582.06  7582.06  541.58  22.96  0.000
Error   30   707.54   707.54   23.58
Total   44  8289.60


S = 4.85640   R-Sq = 91.46%   R-Sq(adj) = 87.48%


Grouping Information Using Tukey Method and 95.0% Confidence

Mix ID  N   Mean  Grouping
 1      3  136.2  A
 5      3  130.6  A B
 6      3  122.6  A B C
13      3  122.4  A B C
 4      3  121.9  A B C
 2      3  121.5    B C
15      3  120.8    B C
14      3  113.5      C D
10      3  111.0      C D E
 3      3  102.7        D E F
12      3  102.1        D E F
11      3  101.7        D E F
 8      3   97.0          E F
 7      3   96.4            F
 9      3   93.1            F

Means that do not share a letter are significantly different.
```

Figure 21 ANOVA of Unconditioned Tensile Strength

General Linear Model: Conditioned versus Mix ID

```
Factor  Type   Levels  Values
Mix ID  fixed      15  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15


Analysis of Variance for Conditioned, using Adjusted SS for Tests

Source  DF   Seq SS   Adj SS  Adj MS      F      P
Mix ID  14  16661.8  16661.8  1190.1  27.98  0.000
Error   30   1275.9   1275.9    42.5
Total   44  17937.7


S = 6.52140   R-Sq = 92.89%   R-Sq(adj) = 89.57%


Grouping Information Using Tukey Method and 95.0% Confidence

Mix ID  N   Mean  Grouping
 6      3  117.4  A
 2      3  113.9  A B
10      3  111.0  A B
 3      3  108.6  A B C
 7      3  103.8  A B C D
13      3   97.6    B C D E
12      3   90.2      C D E
 4      3   86.0        D E
11      3   85.4        D E
 8      3   82.2          E
 9      3   81.9          E
 5      3   81.8          E
15      3   79.3          E
14      3   78.4          E
 1      3   37.9            F

Means that do not share a letter are significantly different.
```

Figure 22 ANOVA of Conditioned Tensile Strength

General Linear Model: Hamburg Rut Depth versus Mix ID

```
Factor    Type   Levels  Values
Mix ID    fixed      15  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15


Analysis of Variance for Rut, using Adjusted SS for Tests

Source    DF   Seq SS   Adj SS  Adj MS     F      P
Mix ID    14  291.848  291.848  20.846  5.98  0.001
Error     15   52.285   52.285   3.486
Total     29  344.133


S = 1.86700   R-Sq = 84.81%   R-Sq(adj) = 70.63%


Grouping Information Using Tukey Method and 95.0% Confidence

Mix ID  N  Mean  Grouping
13      2  15.1  A
 4      2   9.3  A B
10      2   9.0  A B
 5      2   8.6  A B
 1      2   7.1    B
 3      2   6.9    B
15      2   6.2    B
12      2   6.2    B
 2      2   6.1    B
14      2   5.0    B
11      2   5.0    B
 7      2   4.1    B
 8      2   3.0    B
 9      2   3.0    B
 6      2   2.4    B

Means that do not share a letter are significantly different.
```

Figure 23 ANOVA of Hamburg Rut Depth

General Linear Model: Stripping Inflection Point versus Mix ID

```
Factor    Type   Levels  Values
Mix ID    fixed      15  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15


Analysis of Variance for SIP, using Adjusted SS for Tests

Source    DF     Seq SS     Adj SS    Adj MS      F      P
Mix ID    14  152957167  152957167  10925512  13.26  0.000
Error     15   12357500   12357500    823833
Total     29  165314667


S = 907.653   R-Sq = 92.52%   R-Sq(adj) = 85.55%


Grouping Information Using Tukey Method and 95.0% Confidence

Mix ID  N     Mean  Grouping
 7      2  10000.0  A
 6      2   9425.0  A B
 2      2   6750.0  A B C
 8      2   6200.0    B C
 9      2   5500.0      C D
11      2   5150.0      C D E
10      2   4500.0      C D E
 3      2   4400.0      C D E
12      2   4300.0      C D E
14      2   4000.0      C D E
13      2   3450.0      C D E
15      2   3275.0      C D E
 1      2   3150.0      C D E
 4      2   2550.0        D E
 5      2   1800.0          E

Means that do not share a letter are significantly different.
```

Figure 24 ANOVA of Stripping Inflection Point

APPENDIX F ANOVA OF PART 2 TESTING RESULTS

General Linear Model: Unconditioned versus Mix ID, Mix Type

```
Factor    Type   Levels  Values
Mix ID    fixed  5       2, 4, 8, 9, 11
Mix Type  fixed  2       LMLC, PMLC


Analysis of Variance for Unconditioned_1, using Adjusted SS for Tests

Source             DF   Seq SS  Adj SS  Adj MS       F      P
Mix ID              4   6445.2  6445.2  1611.3   79.38  0.000
Mix Type            1   2835.8  2835.8  2835.8  139.70  0.000
Mix ID*Mix Type     4   1038.4  1038.4   259.6   12.79  0.000
Error              20    406.0   406.0    20.3
Total              29  10725.3

S = 4.50536   R-Sq = 96.21%   R-Sq(adj) = 94.51%


Grouping Information Using Tukey Method and 95.0% Confidence

MixID N   Mean  Grouping
 2    6  140.0  A
 4    6  124.4    B
11    6  116.2      C
 8    6  104.6        D
 9    6   98.7        D

Means that do not share a letter are significantly different.


Grouping Information Using Tukey Method and 95.0% Confidence

Mix Type  N   Mean  Grouping
PMLC      15  126.5  A
LMLC      15  107.1    B

Means that do not share a letter are significantly different.


Grouping Information Using Tukey Method and 95.0% Confidence

MixID Mix Type  N   Mean  Grouping
 2    PMLC      3  158.5  A
11    PMLC      3  130.6    B
 4    PMLC      3  126.9    B
 4    LMLC      3  121.9    B C
 2    LMLC      3  121.5    B C
 8    PMLC      3  112.1      C D
 9    PMLC      3  104.4        D E
11    LMLC      3  101.7        D E
 8    LMLC      3   97.0          E
 9    LMLC      3   93.1          E

Means that do not share a letter are significantly different.
```

Figure 25 ANOVA of Unconditioned Indirect Tensile Strength of PMLC and LMLC

General Linear Model: Conditioned versus Mix ID, Mix Type

Factor	Type	Levels	Values
Mix ID	fixed	5	2, 4, 8, 9, 11
Mix Type	fixed	2	LMLC, PMLC

Analysis of Variance for Conditioned_1, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Mix ID	4	7776.4	7776.4	1944.1	95.63	0.000
Mix Type	1	4582.5	4582.5	4582.5	225.42	0.000
Mix ID*Mix Type	4	847.6	847.6	211.9	10.42	0.000
Error	20	406.6	406.6	20.3		
Total	29	13613.0				

S = 4.50871   R-Sq = 97.01%   R-Sq(adj) = 95.67%

Grouping Information Using Tukey Method and 95.0% Confidence

MixID	N	Mean	Grouping
2	6	132.5	A
11	6	103.0	B
4	6	96.3	B C
8	6	93.5	C D
9	6	85.9	D

Means that do not share a letter are significantly different.

Grouping Information Using Tukey Method and 95.0% Confidence

Mix Type	N	Mean	Grouping
PMLC	15	114.6	A
LMLC	15	89.9	B

Means that do not share a letter are significantly different.

Grouping Information Using Tukey Method and 95.0% Confidence

MixID	Mix Type	N	Mean	Grouping
2	PMLC	3	151.1	A
11	PMLC	3	120.5	B
2	LMLC	3	113.9	B C
4	PMLC	3	106.6	C
8	PMLC	3	104.9	C
9	PMLC	3	89.8	D
4	LMLC	3	86.0	D
11	LMLC	3	85.4	D
8	LMLC	3	82.2	D
9	LMLC	3	81.9	D

Means that do not share a letter are significantly different.

Figure 26 ANOVA of Conditioned Indirect Tensile Strength of PMLC and LMLC

General Linear Model: Rut versus Mix ID, Mix Type

```
Factor    Type   Levels  Values
Mix ID    fixed       5  2, 4, 8, 9, 11
Mix Type  fixed       2  LMLC, PMLC


Analysis of Variance for Rut_1, using Adjusted SS for Tests

Source             DF   Seq SS   Adj SS  Adj MS      F      P
Mix ID              4  239.526  239.526  59.882  25.04  0.000
Mix Type            1    0.707    0.707   0.707   0.30  0.593
Mix ID*Mix Type     4   51.012   51.012  12.753   5.33  0.004
Error              20   47.836   47.836   2.392
Total              29  339.081

S = 1.54655   R-Sq = 85.89%   R-Sq(adj) = 79.54%


Grouping Information Using Tukey Method and 95.0% Confidence

MixID N  Mean  Grouping
 4    6  11.0  A
 2    6   4.5    B
 8    6   4.0    B
 9    6   3.7    B
11    6   3.7    B

Means that do not share a letter are significantly different.


Grouping Information Using Tukey Method and 95.0% Confidence

Mix Type   N  Mean  Grouping
PMLC      15   5.6  A
LMLC      15   5.2  A

Means that do not share a letter are significantly different.


Grouping Information Using Tukey Method and 95.0% Confidence

MixID Mix Type  N  Mean  Grouping
 4    PMLC      3  12.7  A
 4    LMLC      3   9.3  A B
 2    LMLC      3   6.1    B C
 8    PMLC      3   5.1    B C
11    LMLC      3   5.0    B C
 9    PMLC      3   4.5      C
 2    PMLC      3   3.0      C
 8    LMLC      3   3.0      C
 9    LMLC      3   3.0      C
11    PMLC      3   2.4      C

Means that do not share a letter are significantly different.
```

Figure 27 ANOVA of Hamburg Rut Depth of PMLC and LMLC

General Linear Model: SIP versus Mix ID, Mix Type

Factor	Type	Levels	Values
Mix ID	fixed	5	2, 4, 8, 9, 11
Mix Type	fixed	2	LMLC, PMLC

Analysis of Variance for SIP_1, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Mix ID	4	102655500	102655500	25663875	19.22	0.000
Mix Type	1	20418750	20418750	20418750	15.29	0.001
Mix ID*Mix Type	4	23527500	23527500	5881875	4.41	0.010
Error	20	26700000	26700000	1335000		
Total	29	173301750				

S = 1155.42   R-Sq = 84.59%   R-Sq(adj) = 77.66%

Grouping Information Using Tukey Method and 95.0% Confidence

MixID	N	Mean	Grouping
2	6	7875.0	A
11	6	7575.0	A
8	6	6250.0	A
9	6	5900.0	A
4	6	2675.0	B

Means that do not share a letter are significantly different.

Grouping Information Using Tukey Method and 95.0% Confidence

Mix Type	N	Mean	Grouping
PMLC	15	6880.0	A
LMLC	15	5230.0	B

Means that do not share a letter are significantly different.

Grouping Information Using Tukey Method and 95.0% Confidence

MixID	Mix Type	N	Mean	Grouping
11	PMLC	3	10000.0	A
2	PMLC	3	9000.0	A B
2	LMLC	3	6750.0	A B C
8	PMLC	3	6300.0	B C
9	PMLC	3	6300.0	B C
8	LMLC	3	6200.0	B C
9	LMLC	3	5500.0	C D
11	LMLC	3	5150.0	C D
4	PMLC	3	2800.0	D
4	LMLC	3	2550.0	D

Means that do not share a letter are significantly different.

Figure 28 ANOVA of Hamburg Stripping Inflection Point of PMLC and LMLC