Title

Development of Hot Mix Asphalt Pavement Performance Properties for Long-life Pavement Designs: Caltrans District 2, Interstate 5, Weed, California

Authors

Signore, James M.

Tsai, Bor-Wen

Monismith, Carl L.

Publication Date

2016-10-01

May 2014
Technical Memorandum: UCPRC-TM-2014-04

Development of Hot Mix Asphalt Pavement Performance Properties for Long-Life Pavement Design: Caltrans District 2, Interstate 5, Weed, California

Version 1

Authors:
James M. Signore, Bor-Wen Tsai, and Carl L. Monismith

Work Conducted as Part of Partnered Pavement Research Center
Strategic Plan Element No. 3.18.2:
Long-Life Pavement Design for District 2, Interstate 5, Red Bluff and Weed

PREPARED FOR:

California Department of Transportation
Division of Research, Innovation and System Information (DRISI)

PREPARED BY:

University of California
Pavement Research Center
UC Davis, UC Berkeley

DOCUMENT RETRIEVAL PAGE				**UCPRC Technical Memorandum No.: UCPRC-TM-2014-04**
Title: Development of Hot Mix Asphalt Pavement Performance Properties for Long-life Pavement Designs: Caltrans District 2, Interstate 5, Weed, California				
Authors: J. Signore, B.-W. Tsai, and C. L. Monismith				
Caltrans Technical Lead: Imad Basheer				
Prepared for: California Department of Transportation, Division of Research, Innovation and System Information (DRISI)		**FHWA No.:** CA172356A	**Date Work Submitted:** October 4, 2012	**Date:** October 2016
Strategic Plan Element No.: SPE 3.18.2	**Status:** Stage 6	**Caltrans Project No.:** 2356		**Version No.:** 1

Abstract: In the period 2012 to 2014 Caltrans designed and built three long-life asphalt pavement (LLAP) rehabilitation projects. Two were in District 2 on Interstate 5 and one was in District 4 on Interstate 80. This technical memorandum describes the processes that were followed to develop the performance criteria for a pavement section to be designed and constructed as a long-life asphalt pavement (LLAP) section on Interstate 5 through and north of Weed, California. Appropriate layers of the structural pavement included 25 percent reclaimed asphalt (RAP), based on the availability of this material. Two designs were included in the development process. The planned structural pavement design included the following two hot mix asphalt mixes:

- An HMA surface course containing a polymer-modified asphalt (PG 64-28PM) and a representative aggregate from the Weed area treated with 1.2 percent lime (marinated) plus 15 percent RAP, and
- An HMA intermediate course containing a conventional asphalt binder (PG 64-16) and the same lime-treated aggregate as the surface course plus 25 percent RAP.

Caltrans headquarters staff from the Office of Asphalt Pavement designed the structural pavement sections using results for material parameters developed from AASHTO T 320 shear, and AASHTO T 321 fatigue and stiffness testing. To properly establish testing protocols and parameters, it was also necessary to investigate the impact of traffic-loading and environmental factors as part of the study. These test results provided the basis of the performance and testing criteria included in the project specifications and bid documents.

In addition to the AASHTO T 320 and AASHTO T 321 results used for design and performance-related specifications, results from AASHTO T 324 Hamburg Wheel-Track Testing (HWTT) were required in the performance-based specifications as a consideration for moisture sensitivity of the asphaltic mixes. The HWTT results were not used in the structural design process.

Keywords: long-life asphalt pavement; reclaimed asphalt pavement (RAP) up to 25 percent; HMA shear testing; fatigue testing; stiffness testing; Hamburg Wheel-Track Testing; HMA performance-based specifications

Proposals for Implementation: Use HMA shear, fatigue, and stiffness data for structural pavement section design; use these test data and HWTT data to develop performance-based HMA specifications; provide systematic and periodic pavement performance evaluations for at least five years after construction, and preferably longer.

Related Documents:

- Monismith, C.L., J.T. Harvey, B.-W. Tsai, F. Long, and J. Signore. 2009. The Phase 1 I-710 Freeway Rehabilitation Project: Initial Design (1999) to Performance after Five Years of Traffic (2008), Summary Report, UCPRC-SR-2008-04, UC Pavement Research Center.
- Signore, J.M., Bor-Wen Tsai, and C.L. 2014. Monismith. Development of Hot-Mix Asphalt Pavement Performance Properties for Long-Life Pavement Design: Caltrans District 2, Interstate 5, Red Bluff, California (UCPRC-TM-2014-03.
- Signore, J.M., and C.L. Monismith. Development of Hot-Mix Asphalt Pavement Performance Properties for Long-Life Pavement Design: Caltrans District 4, Interstate 80, Solano County, California. (UCPRC-TM-2014-05).

Signatures

J. Signore **First Author**	J. T. Harvey **Technical Reviewer**	D. Spinner **Editor**	C. L. Monismith/ J. Signore **Principal Investigators**	Imad Basheer **Caltrans Technical Lead**	T. J. Holland **Caltrans Contract Manager**

DISCLAIMER STATEMENT

PROJECT OBJECTIVES

Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 3.18.2 was devised to prepare mix designs and to establish performance criteria for the characteristics of the mixes to be used in construction of a long-life asphalt pavement in Caltrans District 2, on Interstate 5 through and north of the city of Weed. After completion of the work to develop these criteria, they were to be used in the design of the structural pavement section for the site and included in the mix specifications incorporated into the project's bid documents.

The planned structural pavement design included the following:

- An HMA surface course containing a polymer-modified asphalt (PG 64-28PM) and a representative aggregate from the Weed area treated with 1.2 percent lime (marinated) plus 15 percent RAP, and
- An HMA intermediate course containing a conventional asphalt binder (PG 64-16) and the same lime-treated aggregate as the surface course plus 25 percent RAP.

Performance test data for the mixes were a requisite for the design the pavement section. The data gathered to fulfill this requirement included results from repeated simple shear test at constant height (RSCH) testing (AASHTO T 320) * and both flexural fatigue and stiffness testing (AASHTO T 321).* With the data from these tests, Caltrans staff, used the *CalME* flexible pavement design methodology for the design of the structural section. Subsequently, these performance test results were also included in the bid documents as performance requirements for the two mixes. Hamburg Wheel-Track Testing (HWTT) (AASHTO T 324) (*2*) was also conducted to investigate and mitigate the effects of moisture, and these results were also later incorporated into the mix performance requirements.

---

* Modified according to the Caltrans Lab Procedure LLP-AC2 *(1)*.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
ASTM	American Society for Testing and Materials
CT	Caltrans
HMA	Hot mix asphalt
HWTT	Hamburg Wheel-Track Testing
ICM	Integrated Climate Model
JPCP	Jointed plain concrete pavement
LLAP	Long-life asphalt pavement
LMLC	Laboratory-mixed, laboratory-compacted
ME	Mechanistic-Empirical
NCDC	National Climate Data Center
PPRC	Partnered Pavement Research Center
RAP	Reclaimed Asphalt Pavement
RSCH	Repeated simple shear test at constant height
RWC	Rolling wheel compaction
SF	Shift factor
SHRP	Strategic Highway Research Program
SPE	Strategic Plan Element
SSP	Standard Special Provisions
TCF	Temperature Conversion Factor
UCPRC	University of California Pavement Research Center

LIST OF TEST METHODS AND SPECIFICATIONS

AASHTO T 209	Standard Method of Test for Theoretical Maximum Specific Gravity (Gmm) and Density of Hot Mix Asphalt (HMA)
AASHTO T 320	Standard Method of Test for Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST)
AASHTO T 321	Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending
AASHTO T 324 (Modified)	Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)
AASHTO PP3-94	Standard Practice for Quantifying Roughness of Pavements
ASTM D7312	Standard Test Method for Determining the Permanent Shear Strain and Complex Shear Modulus of Asphalt Mixtures Using the Superpave Shear Tester (SST)
ASTM D7460	Standard Test Method for Determining Fatigue Failure of Compacted Asphalt Concrete Subjected to Repeated Flexural Bending
LLP – AC2	Caltrans – Sample Preparation and Testing for Long-Life Hot Mix Asphalt Pavements

1 INTRODUCTION

In early December 2009, a Long-Life Asphalt Pavement (LLAP) Technical Working Group for Northern California (consisting of Caltrans Headquarters staff, Industry representatives, and researchers from the University of California Pavement Research Center [UCPRC]) was convened to develop long-life pavement projects on the state highway system in Northern California. In 2010, a number of meetings were held in which potential sites were discussed. In December of that year, Caltrans District 2—on the recommendation of Mr. A. Benipal, the State Pavement Engineer—agreed to the use of two pavement sections on Interstate 5 (I-5) for design and construction as LLAP sections. One section is just north of the City of Red Bluff (Tehama County, Post Mile 37.0 to Post Mile 41.5 NB/SB) and the other is north of the City of Weed (Siskiyou County, Post Mile 19.0 to Post Mile 25.3 NB/SB). In 2012, a third LLAP project was initiated on Interstate 80 in District 4 (Solano County Post Mile 30.6 to Post Mile 38.70). This memorandum documents the collaboration between Caltrans and the UCPRC to finalize the mix designs, perform laboratory mix testing, and establish performance criteria for construction of the Weed section. The principles of long-life pavement design used for these three projects have been built on those used in the state's first LLAP project, the multiphase rehabilitation of the Long Beach Freeway, Interstate 710, in Los Angeles County, which began in 2001. Monismith et al. summarized the lessons learned from the initial design through the performance of that project after five years of traffic *(3)*.

The Weed LLAP section was to be designed by Headquarters staff using *CalME* design methodology. The existing pavement consisted of a number of types of different structural sections. These sections included jointed plain concrete pavement (JPCP) without dowels that had been cracked, seated and overlaid with asphalt concrete (AC). The existing AC overlay had deteriorated after many years of traffic and the effects of the environment which experiences long freezing periods and many freeze/thaw cycles each year.

Based on the availability of reclaimed asphalt pavement (RAP) materials at the project location, a decision was made that consideration should be given to the use of more than 15 percent RAP (an option available to contractors in the current Caltrans hot mix asphalt [HMA] specifications) in the appropriate layers of the structural pavement sections. Further, based on the experience of District 2 staff with a number of local aggregate sources, a decision was also made that all the HMA used in the project should contain 1.2 percent lime (based on the weight of the virgin aggregate) applied using the process of *marination* rather than the alternative process consisting of the application of dry lime on damp aggregate.

After a review of as-built information and field investigations by staff from District 2, Caltrans Headquarters, and the UCPRC, it was decided that the pavement's structural sections should consist of the following components:

- An HMA surface course containing a polymer-modified asphalt (PG 64-28PM) and a representative aggregate from the Weed area treated with 1.2 percent lime (marinated) plus 15 percent RAP, and
- An HMA intermediate course containing a conventional asphalt binder (PG 64-16) and the same lime-treated aggregate as the surface course plus 25 percent RAP.

The LLAP Working Group agreed that UCPRC staff would conduct the necessary performance tests, provide the required data for the structural pavement designs to Caltrans staff, and provide the requisite data for the mix performance requirements based on the traffic and environment in the Weed areas. In order to provide the necessary mix performance information for the *CalME* asphalt (flexible) pavement design methodology, UCPRC conducted the repeated simple shear test at constant height (RSCH), fatigue, and stiffness tests on the two mixes for the Weed Project.

This technical memorandum provides a summary of all of the performance tests conducted, analyses of the test data, and the recommended mix performance requirements to be included in the project bid documents. This memo also includes the results of Hamburg Wheel-Track Testing (HWTT) carried out on the mixes, as well as recommended specification criteria for the testing—which was performed because of the moisture sensitivity of some aggregates in the District 2 area.

Chapter 2 discusses the materials that were used in this project to create test specimens: aggregates, asphalt binder, reclaimed asphalt concrete (RAP), and lime. Chapter 3 explains the importance and use of traffic and temperature in design and in determining material testing parameters. Chapter 4 presents the results of laboratory testing of the HMA mixes. Chapter 5 covers the development of the mix performance criteria for fatigue and fatigue stiffness. Chapter 6 explains the process of specification development for HMA shear testing. Chapter 7 provides a project overview and a recommendation based on this investigation. Appendices A through E present detailed results of the performance-based testing.

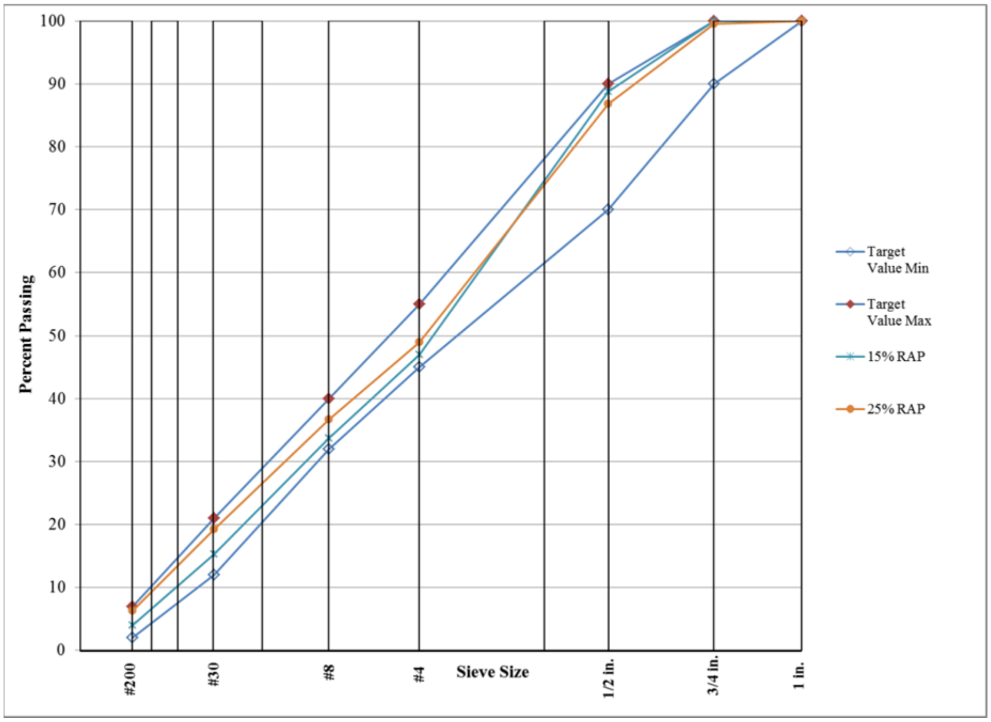
2 MATERIALS

2.1 Aggregates

District 2 staff obtained aggregate samples from a representative source: Indian Creek near Montague. The virgin aggregate samples included four fractions termed *dust, sand, 3/8 in.*, and *3/4 in.* Gradings from representative samples of each of the fractions were determined by wet sieving. These grading data were then used to prepare mixes to select binder contents for mix design and performance testing. Two gradings were required for the Weed Project: one with 15 percent RAP and the other with 25 percent RAP. The two combined gradings are shown in Figure 2.1. Information already available about some of the properties of both aggregates was supplied by District 2 staff based on two samples taken 10 months apart, as summarized in Table 2.1.

Table 2.1: Aggregate Properties

	Source	Test Results Weed, Indian Creek		Caltrans Spec.
	Date Tested:	5/08	3/09	
Test Method	**Property**			
CT 205	Crushed particles, coarse aggregate One fractured face (%)			
	Crushed particles, coarse aggregate Two fractured faces (%)	100	100	98
	Crushed particles, fine aggregate (#4x#8) One fractured face (%)	100	100	98
CT 211	LA Rattler, loss at 100 rev. (%)	2	3	10
	LA Rattler, loss at 500 rev. (%)	10	12	25
CT 217	Sand equivalent (avg.)	62	64	50
AASHTO T 304 (Method A)	Fine aggregate angularity (%)		47.6	45
ASTM D4791	Flat and elongated particles % by mass @ 3:1			
	Flat and elongated particles % by mass @ 5:1		6.0	Report
CT 204	Plasticity index		NP	
CT 229	Fine aggregate durability index	68	74	65
	Coarse aggregate durability index	78	82	50
CT 303	K_c factor (not mandatory until further notice)	1.0		
	K_f factor (not mandatory until further notice)	1.2		
CT 206	Bulk specific gravity (oven dry), coarse aggregate	2.79	2.793	
	Absorption, coarse aggregate	1.1	1.0	
CT 207	Bulk specific gravity (SSD) of fine aggregate		2.702	
LP-2	Bulk specific gravity (oven dry) of fine aggregate		2.607	
CT 207	Absorption of fine aggregate		3.5	
CT 208/LP-2	Apparent specific gravity of supplemental fines			
LP-2	Bulk specific gravity of aggregate blend	2.58	2.675	
CT 208	Specific gravity of fines apparent	2.83	2.879	



Weed gradings

Figure 2.1: Aggregate gradings with 15 percent and 25 percent RAP.

2.2 Asphalt Binders

Two binders, PG 64-16 and PG 64-28PM, were supplied by the Valero Refinery in Benicia, California. The test properties for these binders, as summarized in Table 2.2, were obtained from the Certificate of Compliance from the laboratory at the Valero Benicia Asphalt Plant.

It should be noted that the Valero refinery does not supply the PG 64-10 binder listed in the Weed project specifications. While a PG 64-10 binder was called for, the PG 64-16 binder was acceptable to Caltrans since it was determined that it met all of the specification requirements for the PG 64-10 binder based on a comparison performed by the researchers of the PG 64-16 binder test data from the Certificate of Compliance with the PG 64-10 binder specification requirements. *Note: In this technical memorandum, wherever PG 64-10 is referred to in figures or in binder or performance testing tables, PG 64-16 was actually tested.*

While the PG 64-16 binder was available throughout the year, it should be noted that during the investigation it was necessary for UCPRC to obtain the PG 64-28PM binder in two batches. The first batch provided an amount sufficient for conducting the required performance tests for the Red Bluff project. The second batch of the PG 64-28PM binder was obtained from the 2011 production in time for performance testing for the Weed project.

The second batch of PG 64-28PM for Weed was tested on June 4, 2011. Data from these tests appear in Table 2.2. While not presented, the binders produced in 2010 and 2011 had essentially the same performance characteristics. The PG 64-16 binder was tested on December 13, 2010, close to the time that UCPRC had requested both binders.

Table 2.2: Binder Properties: Weed Project

Property	Caltrans Spec. PG 64-16	Test Results Weed (Same Binder as Red Bluff)	Caltrans Spec. PG 64-28PM	Test Results Weed PG 64-28PM (Second Supply)	AASHTO Test Method
	Original Binder				
Flash Point, Min. C.O.C., ºC	230	296	230	280	T 48
Viscosity at 135ºC; Pa.s	3.0	0.430	3.0	0.748	T 316
Dynamic Shear: Test Temp, ºC	64	64	64	64	T 315
Min. G*/sinδ, kPa	1.0	1.61	1.0	1.89	
Solubility in TCE Percent, Min.	99	100	98.5	99.8	T 44
	RTFO Test Aged (RAP) Binder				
RTFO Test Mass Loss, Max. %	-1.0	-0.121	-1.0	-0.159	T 240
Dynamic Shear: Test Temp. ºC	64	64	64	64	T 315
Min. G*/sinδ, kPa	2.20	3.95	2.20	3.95	
Max. δ@G*sinδ = 2.2 kPa, degrees	n/a	n/a	80	65	
Min. Ductility at 25°C, cm	75	100+	n/a	n/a	T 51
Min. Elastic Recovery@25%	n/a	n/a	75	83	T 301
PAV Aging Temperature °C	100	100	100	100	R 28
	PAV Test Aged (RAP) Binder				
Dynamic Shear: Test Temp, ºC	28	28	22	22	T 315
Max. G*sinδ, kPa	5,000	2,580	5,000	1,550	
Bending Beam Rheometer:					T 313
Test Temp. °C	-6	-6	-18	-18	
Max. S-Value, MPa	300	79	300	94	
Min. M-Value	0.300	0.386	0.300	0.356	

n/a, not applicable

2.3 Reclaimed Asphalt Pavement Material

Time constraints stymied efforts to fully characterize the RAP from Weed, so instead results from characterization testing of Red Bluff RAP samples were used to inform the mix design process for Weed.

In the Red Bluff project, District 2 supplied the UCPRC with samples that were considered representative of the HMA in the existing pavement near the Red Bluff project rather than the actual RAP intended for use. This had to be done because the actual RAP intended for Red Bluff was unavailable in sufficient quantities at the time of testing to determine the extracted binder properties, approximate binder contents, and the gradations of the extracted aggregates of the RAP. To compensate for this shortage, UCPRC also obtained a number of 3 in. diameter cores of the HMA pavement layer(s) to be used as RAP in order to complete the testing. Both the cores and the District 2 RAP material were then sent to the MACTEC Engineering and Consulting, Inc. laboratory in Phoenix, Arizona, to determine the extracted binder properties and approximate binder contents of the RAP millings and cores as well as the gradations of the extracted aggregates. The PG 64-16 binder supplied by Valero was also sent to MACTEC so that data on the blends using the new (virgin) binder and the extracted binders could be collected. Blends of the two materials (binders) were obtained using the extracted binder contents from the cores and RAP millings, proportion of RAP, and estimated binder content for the HMA consisting of the new aggregate and RAP blend. Table 2.3 contains the results of the MACTEC tests on the PG 64-16 binder received from Valero in December 2010, together with tests on the binders extracted from the cores and RAP millings. Tests performed on blends of the original binder and the extracted binders from the RAP are summarized in Table 2.4.

Determination of the proportions of the PG 64-16 and extracted binders were based on the following: (1) binder content of the cores determined by extraction was 4.77 percent (by weight of aggregate basis), 25 percent RAP, and 5.0 percent binder (by weight of aggregate basis) in the resulting mix; and (2) binder content of the RAP millings of 5.51 percent (by weight of aggregate basis), 25 percent RAP, and 5.0 percent binder content (by weight of aggregate basis) for the mix. It should be noted that the resulting blends for the two combinations yielded the same grade classification, PG 70-22, although the blend for the mix containing the millings resulted in a binder temperature slightly higher, actual 75°C versus 73°C, for the core data. These results suggest that rutting and low-temperature cracking in the pavements should not be of concern for this area with the addition of RAP.

Table 2.3: Binder Properties MACTEC Tests

Property	Caltrans Spec. PG 64-16	Test Results: Original Binder PG 64-16	Binder Extracted from Cores	Binder Extracted from RAP	AASHTO Test Method
	Original Binder				
Flash Point, Min. C.O.C., ºC	230	285	n/a	n/a	T 48
Viscosity at 135ºC; Pa.s	3.0	0.466			T 316
Dynamic Shear: Test Temp, ºC	64	64			T 315
Min. G*/sinδ, kPa	1.0	1.48			
Solubility in TCE Percent, Min.	99	n/a			T 44
	RTFO Test Aged Binder		Tests on Original Recovered Asphalt		
RTFO Test Mass Loss, Max. %	-1.0	-0.124	n/a	n/a	T 240
Dynamic Shear: Test Temp. ºC	64	64	70	76	T 315
Min. G*/sinδ, kPa	2.20	3.71	10.22	6.89	
Min. Ductility at 25°C, cm	75	150+	9.5	8.0	T 51
PAV Aging Temperature °C	100	100	100	100	R 28
	PAV Test Aged Binder				
Dynamic Shear: Test Temp, ºC	28	25	37	40	T 315
Max. G*sinδ, kPa	5,000	3,390	3,040	2,115	
Bending Beam Rheometer: Test Temp. °C	-6	-12	0	0	T 313
Max. S-Value, MPa	300	187	135	112	
Min. M-Value	0.300	0.384	0.365	0.346	
Classification Based on Test		PG 64-22	PG 70-10	PG 76-10 (or PG 76-16)	

n/a, not applicable

Table 2.4: MACTEC Binder Test Results

Property	Caltrans Spec.	Test Results Valero PG 64-16 (12/13/10) Sample	Test Results, Blend of Valero Binder and Extracted Binders: From Core Samples	Test Results, Blend of Valero Binder and Extracted Binders: From RAP Millings	AASHTO Test Method
	Original Binder				
Flash Point, Min. C.O.C., ºC	230	285	n/a	n/a	
Viscosity at 135ºC; Pa.s	3.0	0.466	3.08	0.762	T 316
Dynamic Shear: Test Temp, ºC		64	70	70	T 315
Min. G*/sinδ, kPa	1.0	1.48	1.48	2.14	
Solubility in TCE Percent, Min.	99	n/a	n/a	n/a	T 44
	RTFO Test Aged Binder				
RTFO Test Mass Loss, Max. %	-1.0	-0.124	-0.250	-0.300	T 240
Dynamic Shear: Test Temp. ºC		64	70	70	T 315
Min. G*/sinδ, kPa	2.20	3.71	3.15	4.69	
Min. Ductility at 25°C, cm	75	150+	108	34	T 51
PAV Aging Temperature °C	100	100	100	100	R 28
	PAV Test Aged Binder				
Dynamic Shear: Test Temp, ºC		25	28	28	T 315
Max. G*sinδ, kPa	5000	3390	3703	4011	
Bending Beam Rheometer: Test Temp. °C		-12	-12	-12	T 313
Max. S-Value, MPa	300	187	241	248	
Min. M-Value	0.300	0.344	0.322	0.311	
Performance Grade		PG 64-22	PG 70-22	PG 70-22	
Actual Grade		PG 67-22	PG 73-22	PG 75-22	

n/a, not applicable

2.4 Lime

Hydrated lime (high-calcium hydrated lime termed *Hi-Cal Hydrate)* was supplied by the Chemical Lime Company. District 2 staff recommended a lime content of 1.2 percent by weight of aggregate. The lime treatment followed the process of marination rather than the addition of dry lime on damp aggregate. Caltrans Laboratory Procedure LP-7 was followed to marinate the aggregate for the preparation of the performance test specimens.

3 TRAFFIC AND PAVEMENT TEMPERATURE ESTIMATES

Traffic and pavement temperature are two key factors used in determining material test parameters and pavement performance. Since the test parameters for shear testing are directly related to pavement temperature, and mix design is related to traffic estimates, how these were selected is discussed below. The data sources used to obtain these estimates are noted.

3.1 Traffic

As with the I-710 Phase 1 Project, traffic estimates for Weed for rut depth estimates were based on the first five years after opening of the rehabilitated sections to traffic. The traffic estimate for the first five years was 9.0×10^6 ESALs (based on traffic data provided by Caltrans HQ staff), which assumed a three percent linear annual growth rate. To be conservative this estimate was increased to 10.0×10^6 ESALs.

This estimate was used to determine the requirements for the shear test results based on the premise (and experience) that, so long as the mix is properly designed and constructed, the majority of rutting in the HMA layer will occur during the first five years.

The total estimated traffic for a forty-year period was used by Caltrans staff to determine the final structural section, following the *CalME* design methodology, together with both the fatigue and shear test data provided.

3.2 Pavement Temperature for Shear Testing

Temperature data covering a number of years for the Weed Project were obtained from the UCPRC pavement database and the National Climate Data Center (NCDC). This temperature information was then used to determine the temperatures for shear testing of the HMA. Test temperature selection was based on estimation of the pavement temperature at a depth of 2 inches (50 mm) in the HMA. Selection of this depth was based on analyses which suggest that the maximum shear stress from tires that leads to rutting occurs at the edge of the tire at about this depth *(3).* Moreover, the majority of rutting results when temperatures above about 40ºC (104°F) last for an extended period of time (e.g., seven days). Accordingly, the test temperature is based on the daily maximum temperature based on a thirty-year period (if available).

This information permitted determination of the seven-day moving average of daily maximum temperature (ADMT_7). The ADMT_7 data were then plotted as a cumulative distribution function, as illustrated in Figure 3.1. Data for Sacramento, Red Bluff, and Redding were based on a ten-year period (01/01/2001 to 12/31/2010) recorded by the NCDC. Data for Weed were based on a six-year period (01/01/1984 to 07/07/1989) also from the NCDC. Temperature data used for Cottonwood, over an approximate four-year period (11/26/2002 to 08/10/2006), are from the UCPRC Weather Database.

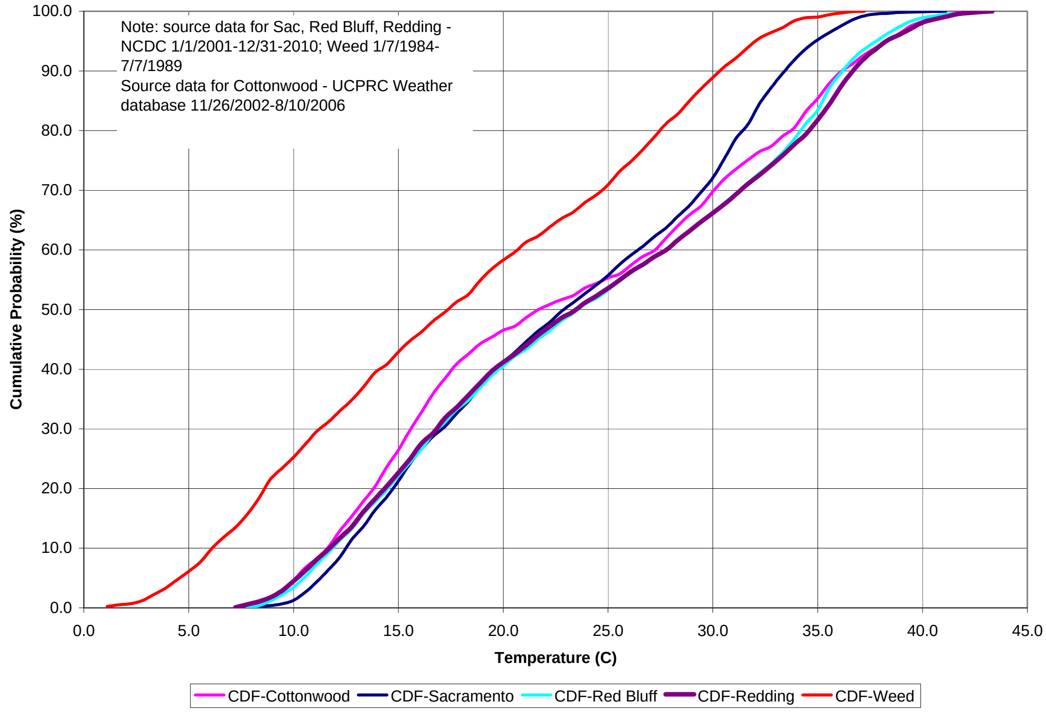


Figure 3.1: Seven-day moving average of maximum daily air temperatures for Cottonwood, Sacramento, Red Bluff, Redding, and Weed.

The pavement temperature distribution with depth came from use of the Integrated Climate Model (ICM) and is the same data used in the *CalME* program. For this computation, temperatures for Sacramento over a period of thirty years were used (01/01/1961 to 12/31/1990) since these were the only temperatures available in *CalME* that would be similar to those at the project sites. Assumptions for this computation included an albedo of 0.95, 10 inch (254 mm) thick asphalt, and constant temperature of 4ºC (9°F) at depth of about160 inches (4 m).

Computations for the pavement surface temperature and temperature at the 2 inch depth are shown Figure 3.2.

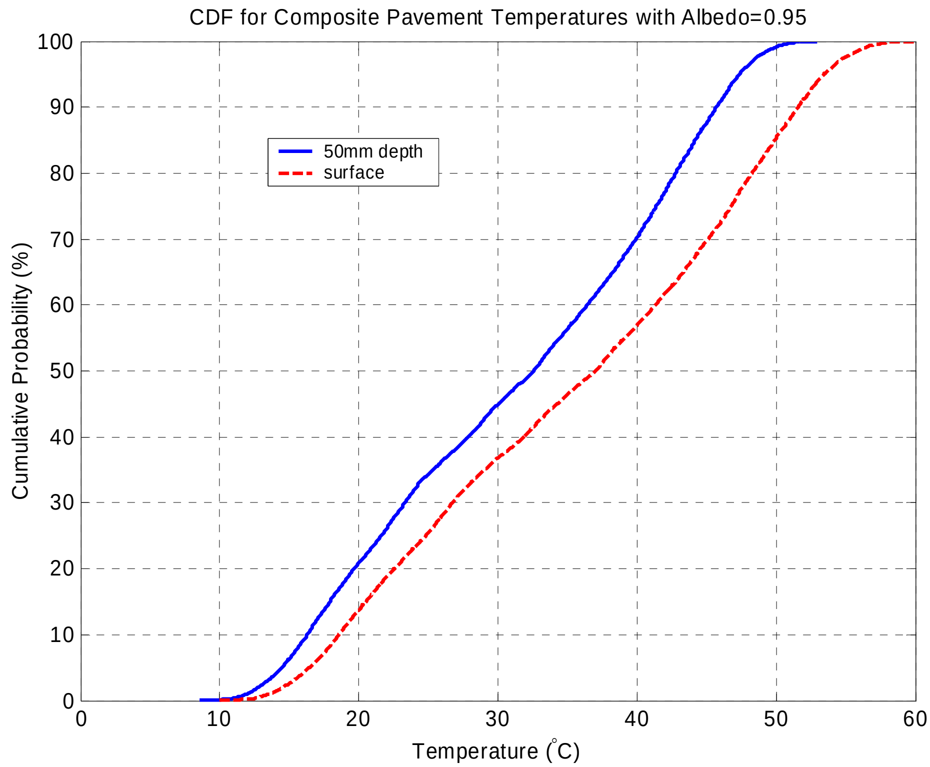


Figure 3.2: Seven-day moving average of maximum daily surface temperatures and temperatures at a depth of 2 inches for Sacramento based on analysis using the ICM.

The test temperature for shear testing for Weed was selected based on the information shown in Figure 3.1 and Figure 3.2. At the 2 inch depth, the temperature corresponding to the 95th percentile for Sacramento is about 48ºC. This was increased to 50°C (122°F) to be on the conservative side. It should be noted that in Figure 3.1 the air temperatures at the 95th percentile for Red Bluff, Cottonwood, and Redding are about 5ºC (9°F) higher than at Sacramento, hence a temperature of (131°F) 55°C was selected for shear testing for the Red Bluff project. Since the air temperatures at Weed are somewhat lower than those at Sacramento (Figure 3.1), a conservative value of 50°C (122°F) was selected for the shear testing for the Weed project.

4 MIX TESTING

The UCPRC subjected samples of the proposed Weed mixes to three performance-related tests—shear, fatigue and stiffness, and moisture sensitivity—in order to gather data that Caltrans could then use to establish baseline performance requirements for the mixes. Once these were determined, Caltrans would then use these requirements in its mix specifications for potential bidders for the contract. The performance test-related results are presented in this chapter. Appendixes A (shear), B (fatigue and stiffness), and C (moisture sensitivity) respectively contain the complete results for each type of testing.

4.1 Overview of Test Methods

The HMA performance requirements were developed using the following AASHTO test procedures.

- AASHTO T 320 (ASTM D7312), the RSCH, was used to select the design binder content for each of the mixes to be used in the Weed Project.
- AASHTO T 321 (ASTM D7460), the flexural fatigue and frequency sweep test, was used to determine mix fatigue and stiffness response at the selected design binder content.
- AASHTO T 324, Hamburg Wheel-Track Testing (HWTT), was used to evaluate the moisture sensitivity response of each of the mixes.
- All of the specimens for the performance tests, except for the HWTT specimens, were prepared using rolling-wheel compaction (RWC) developed during the Strategic Highway Research Program and published as AASHTO PP3-94. The HWTT specimens were prepared by Superpave Gyratory Compaction because that is the current requirement in AASHTO T 324.

To define the performance requirements, the AASHTO procedures were subsequently modified and those modifications have been listed in the Caltrans Flexible Pavement Test Method LLP-AC2 *(1).* The modifications are detailed in the footnotes to Table 6.1, which shows the HMA performance requirements for the Weed project.

4.2 Shear Test Results

RSCH testing was conducted with the goal of determining the design binder contents for the PG 64-28PM surface mix and PG 64-10 intermediate mix in this project and to provide data for the project's performance test specifications. Table A.1 and Table A.2 in Appendix A summarize the shear test data for the project. Plots of the data are shown in Figure A.1 through Figure A.7.

Table A.1 contains the shear test results for the PG 64-28PM with 15 percent RAP for a range of binder contents. Table A.2 contains the shear test results for this mix at the selected design binder content. Shear tests were not performed on the PG 64-16 with 25 percent RAP and lime due to time constraints.

The design binder content for Weed was selected from an examination of the relationship between the natural log of loading cycles at a permanent shear strain (γ_p) of 5 percent (both mean and median values) versus binder content. These data are shown in Figure 4.1. In terms of the numerical value of repetitions, the median values at 5.7 percent and 6.1 percent binder contents are approximately 190 x 10^6 and 27 x 10^6, respectively. After the mixes were examined, it was decided to select the 5.7 percent binder content for ME analysis testing; these data are contained in Table A.2.

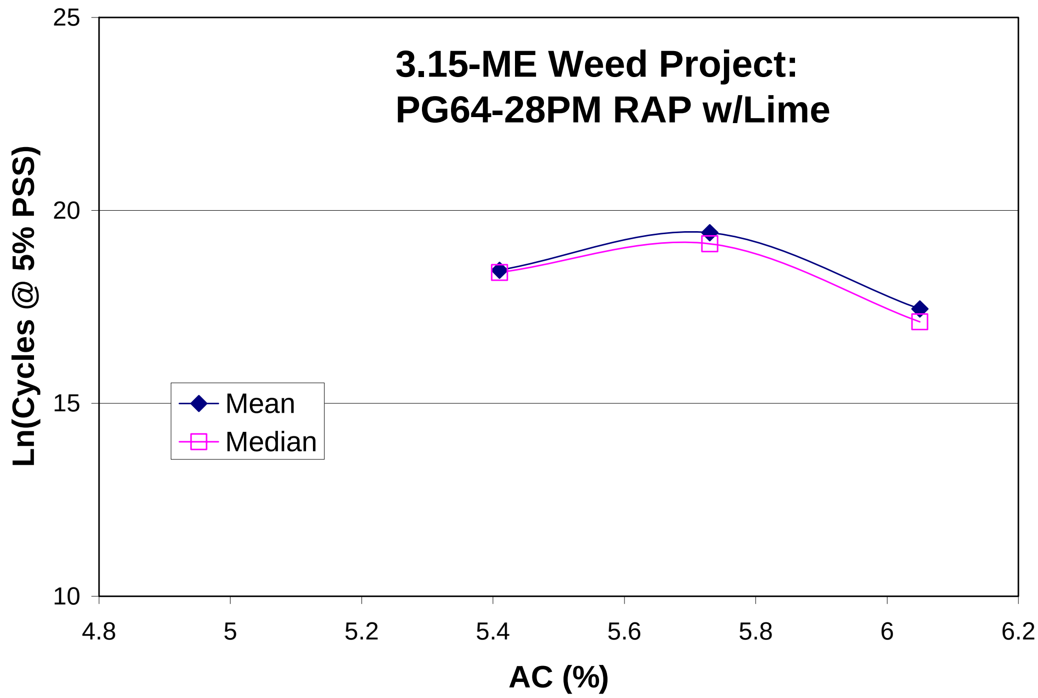


Figure 4.1: Ln (repetitions to 5 percent γ_p) versus binder content at 50°C for Weed PG 64-28PM 15% RAP 1.2% lime mix.

Analyses of the data in Table A.1 and Table A.2 resulted in the following plots: (1) three boxplots for the PG 64-28PM mix with RAP and lime for binder content versus Ln (G*), Ln (γ_p at 5,000 load repetitions), and Ln (load repetitions at γ_p = 5% shear strain) (Figure A.1 through Figure A.3); (2) Ln (Ln γ_p) versus Ln (load repetitions) for the PG 64-16 with RAP and lime, at two temperatures and three stress levels (Figure A.4); and (3) three boxplots for the PG 64-28PM mix with RAP and lime at the design binder content for Ln (G*), Ln (γ_p at 5,000 load repetitions), and Ln (load repetitions at γ_p = 5% shear strain), at three stress levels (Figure A.5 through Figure A.7, respectively).

While shear tests were not performed on the PG 64-16 mix, it will be seen in the following section that fatigue and stiffness tests were performed on the PG 64-16 mix with 25 percent RAP and lime.

4.3 Fatigue and Stiffness Test Results

Following selection of the optimum binder contents for the two mixes and specimen preparation, flexural fatigue test data were obtained at 20ºC for both mixes. These data are summarized in Table B.1. Flexural stiffnesseses from frequency sweep tests were determined at temperatures of 10ºC, 20ºC, and 30ºC, and for a range in frequencies from 0.01 Hz to 15.2 Hz. Table B.2 and Table B.3 contain the flexural stiffness measurements for the test specimens. Master curves of stiffness versus frequency are contained in Table B.2 and Table B.3. Table B.4 summarizes the coefficients for these curves; the equations are shown in the table notes. The relationships are based on the use of the interchangebility of time (frequency) and temperature concept, and the use of a genetic algorithm to define the equations representing the curves.

Figure 4.2 contains plots of ln(strain) versus ln(Nf) cycles-to-failure for the two mixes using the data from Table B.1. Figure 4.3 and Figure 4.4 contain the stiffness master curves and the shift factors, respectively for these mixes.

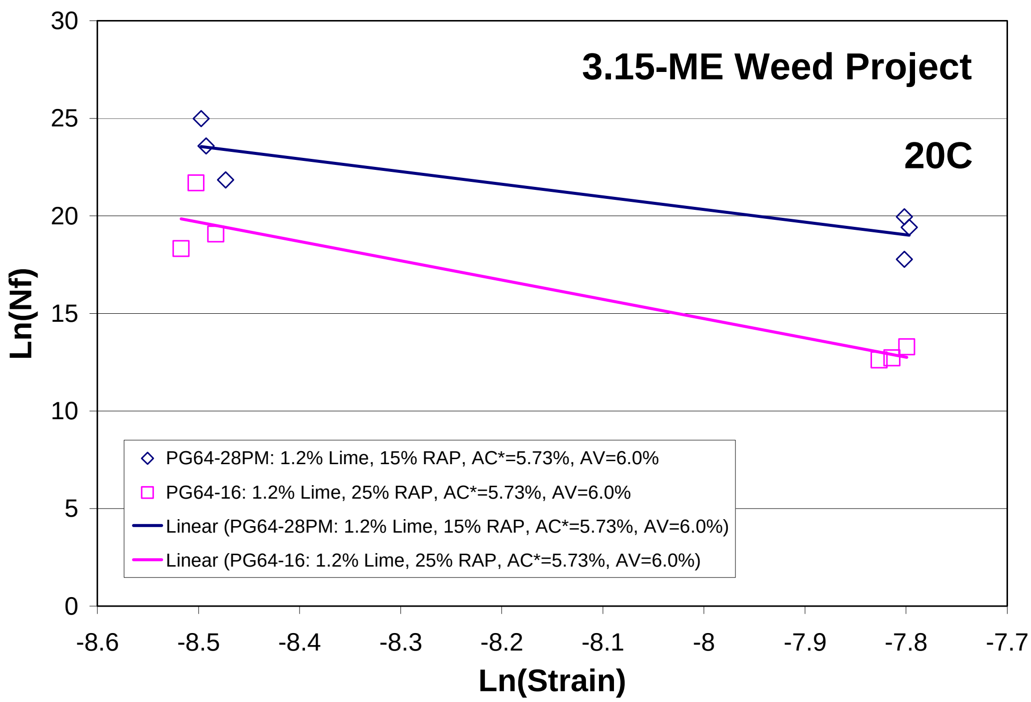


Figure 4.2: Fatigue test summary for the Weed Project.

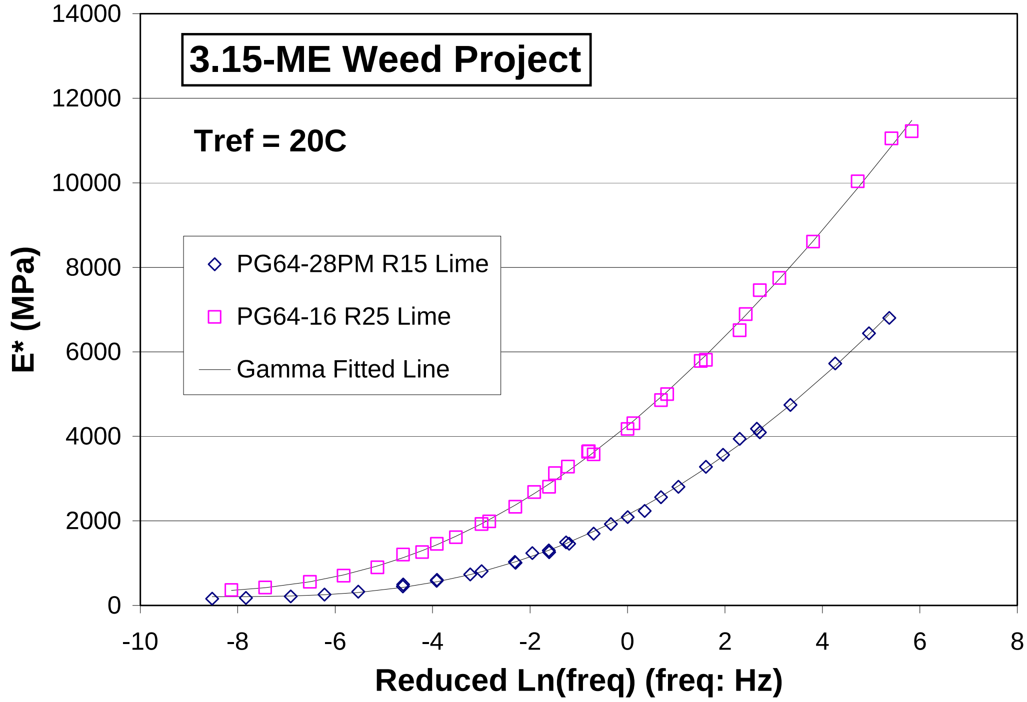


Figure 4.3: Summary of stiffness (E*) master curves, Weed Project.

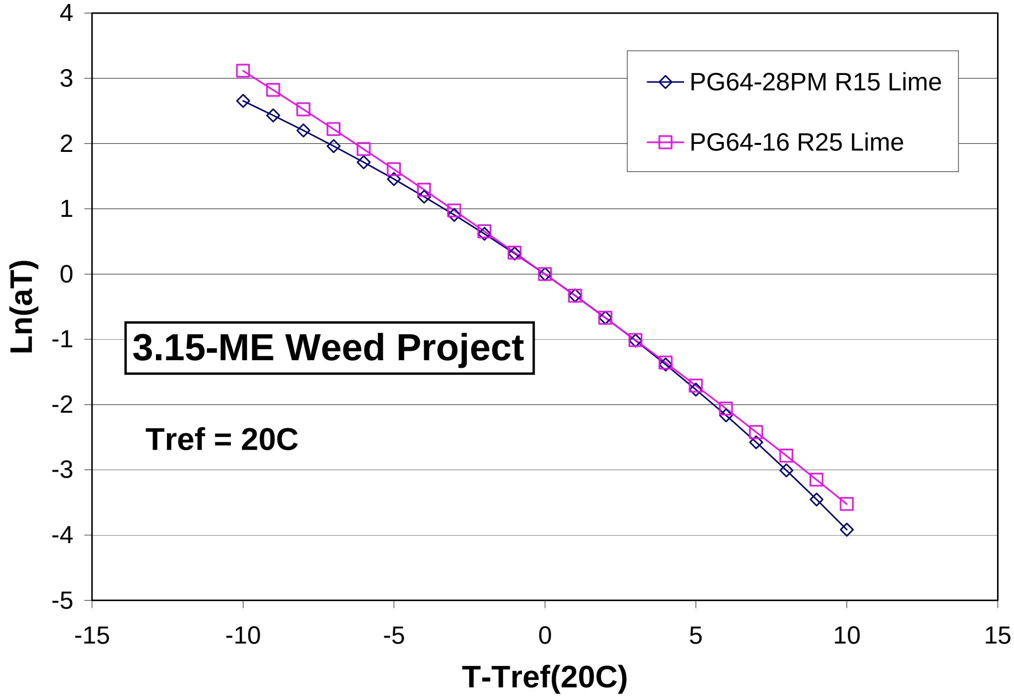


Figure 4.4: Summary of temperature-shifting relationship (ln a_T), Weed Project.

It is important to note that the frequency sweep data shown in Table B.2 and Table B.3 and the resulting stiffness master curves were required only for the design of the structural pavement sections using the *CalME* design methodology. The master curves are not required for the mix performance specifications. Based on the fatigue testing, the performance requirements for the mixes were determined using the following:

- For mix stiffnesses at 20°C, the values are based on the measurements at 50 load cycles in the fatigue tests, which estimates initial stiffness, as discussed in AASHTO T 321. For mix stiffnesses at 30°C the stiffnesses are from the frequency sweep results.
- For fatigue life at 20°C, the values are based on the results at 200 and 400 microstrain and fatigue life assumed to be at 50 percent reduction in stiffness from the stiffness at 50 load cycles.

Appendix B contains plots of the fatigue test data. Figure B.1 and Figure B.2 contain the plots of Ln Strain Repetitions versus the ln (-ln Stiffness Ratio). Figure B.3 through Figure B.5 contain box plots of the stiffness moduli, phase angles, and cycles to failure strains at 200 microstrain and 400 microstrain at 20ºC for the two mixes used for the Weed project.

4.4 Hamburg Wheel-Track Testing Results

Hamburg Wheel-Track Testing (HWTT) data, for moisture sensitivity performance requirements, are included in Figure 4.5 and Figure 4.6. Appendix C contains a summary of the individual test results. The rut depth data shown in Figure 4.5 and Figure 4.6 are averages of the ruts of three middle profile positions from the smoothed plots of the profile data for the individual tests included in Appendix C**.**

HWTT tests were performed both at the UCPRC and Caltrans laboratories for comparative purposes. Test specimens prepared at the UCPRC using gyratory compaction were used by both laboratories.

Results of the individual test data are included in Table C.1. Test specimens prepared at the UCPRC using gyratory compaction were used by both laboratories.

Appendix C also contains individual plots of rutting evolution images and contour plots for the various mixes tested. The plots show the original data for the left (Lt.) and right (Rt.) specimens and the smoothed "Number of Passes" as well. Photographs of the test specimens at the completion of the HWTT for the Weed test specimens are also included in this appendix.

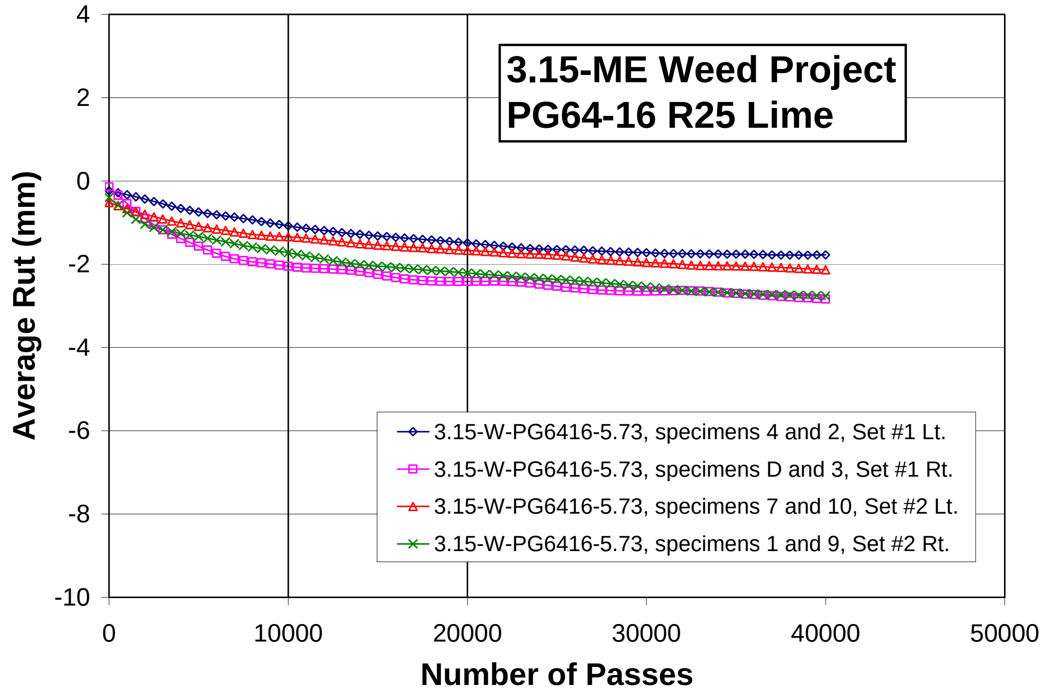


Figure 4.5: Summary of HWTT rut depths (PG 64-16, 25% RAP with 1.2% lime).

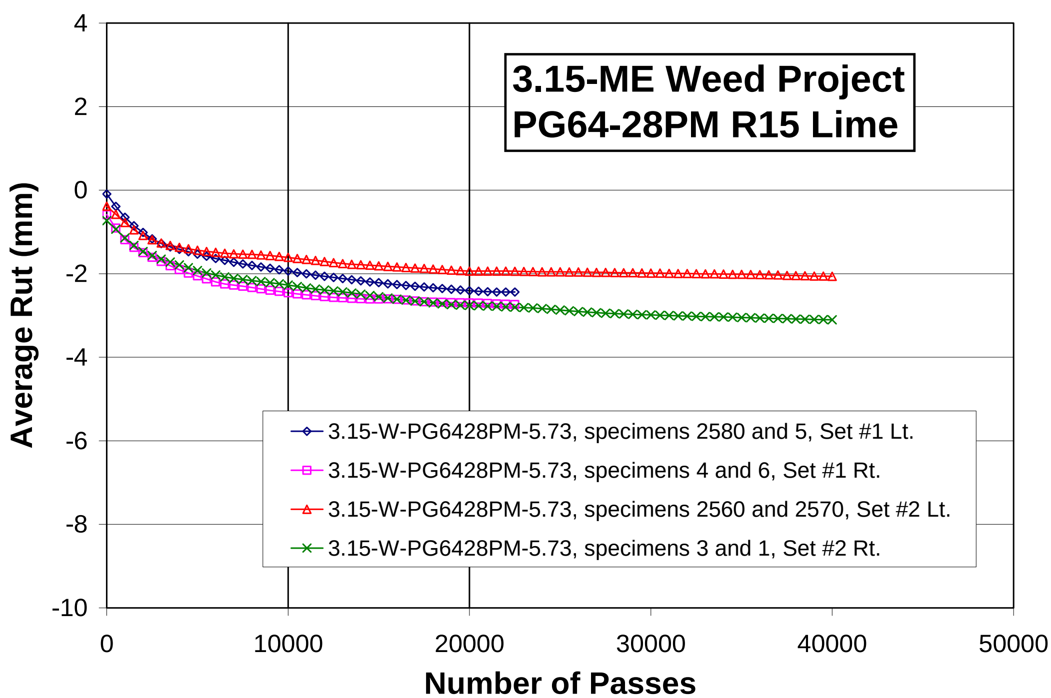


Figure 4.6: Summary of HWTT rut depths (PG 64-28PM, 15% RAP with 1.2% lime).

5 DEVELOPMENT OF FATIGUE AND STIFFNESS MIX PERFORMANCE CRITERIA

5.1 Overview

This section describes the methodology used to determine fatigue and shear performance requirements for the specifications, based on the laboratory performance testing described in Chapter 4. Details are presented in the appendixes.

5.2 Fatigue Specification Development

The I-710 rehabilitation projects showed that when setting mix performance requirements, it is important to recognize the variability of test results when a test is run by different organizations. The approach used on the Weed project was developed based on discussions with Caltrans and the contractors after the initial I-710 project and assumes that all of the variability associated with laboratory specimen preparation and testing should be the responsibility of Caltrans. Mix performance test specifications for I-710 Phase 2 and subsequent phases were determined by this approach. This chapter uses the results obtained from the shear and fatigue testing discussed earlier and presents the performance criteria required for the design mixes. The methodology utilized (with the *S-Plus* statistical package) is based on the developments described in Appendix F of Reference *(3)*. The fatigue and stiffness test data used to develop these performance requirements are included in Appendix B.

Suggested specifications based on these data as well as the shear and HWTT test data are discussed in Chapter 6.

In order to satisfy fatigue performance specification requirements, the mean value of the natural logarithm of fatigue life, Ln(Nf), determined from three fatigue tests at a specified strain level should exceed the specified lower bound of the regression lines. The 95 percent confidence bands for the fatigue response of the PG 64-28PM mix with 15 percent RAP are shown in Figure 5.1. The same information is shown in Appendix D for the PG 64-16 mix with 25 percent RAP.

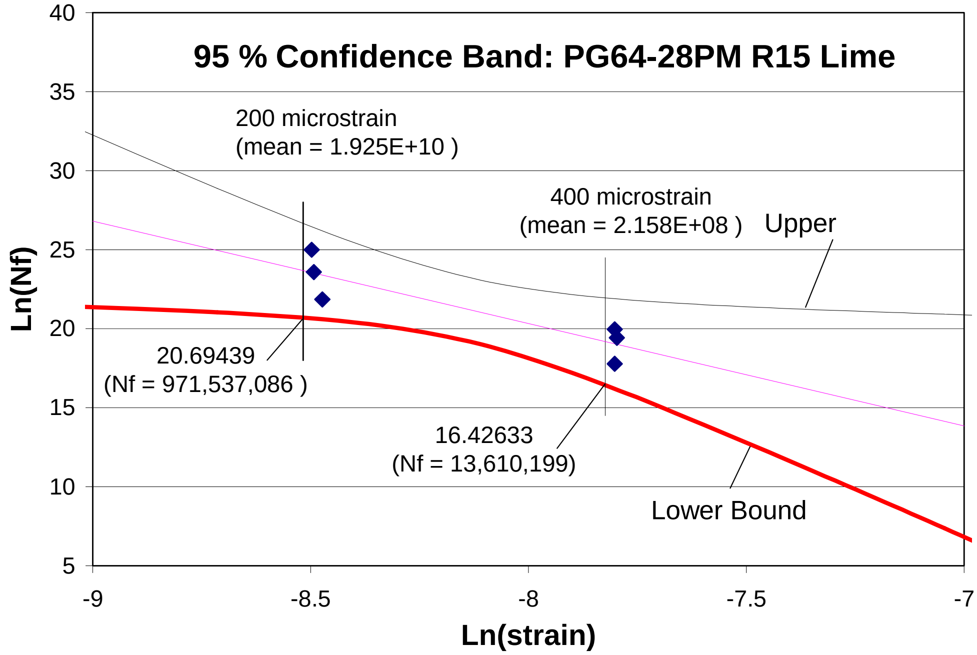


Figure 5.1: Fatigue 95% confidence bands (PG 64-28PM 15% RAP with 1.2% lime, AC* = 5.73% [by weight of virgin aggregate plus lime], AV = 6.0%).

5.3 RSCH Specification Development

As was the case with the I-710 Freeway project, the criteria for the mix designs for the Weed Project have been selected to accommodate the traffic estimated during the first five years of operation *(3)*. Based on the traffic data available, the design value for the five-year period is 10 x 10^6 ESALs for Weed. Using this value, the RSCH criteria for the two mixes listed in Table 6.1 were developed according to the following equations:

$$(N_{supply}) \geq M \cdot (N_{demand}) \quad \textbf{(6.1)}$$

N_{demand} was determined as follows:

$$N_{demand} = \text{Design ESALs} \cdot TCF \cdot SF \quad \textbf{(6.2)}$$

where:

TCF = temperature conversion factor; estimated to be 0.11 for Weed.
SF = shift factor, value of 0.04 was used as developed in Sousa et al., 1994 *(2)*

The development of the parameters for $N_{demand,}$ TCF and SF is documented in the SHRP-A-415 research report *(2)*. The TCF developed for California and the SF values referred to above were taken from tables in Chapter 15 of the A-415 report.. To determine N_{supply}, a reliability multiplier, M, equal to 5 for a reliability level of 95 percent was used based on RSCH test variance *(2)* and an estimate on the variance in ln (ESALs). This value was also taken from tabularized data. For this project, with estimated traffic of 10 x 10^6, and the factors shown in Equation (6.1) and Equation (6.2), N_{supply} was estimated to be 220,000 repetitions.

It should be noted that the shear test results at five percent permanent shear strain shown in Chapter 4 and Appendix A exceed these values significantly for the Weed Project. Accordingly, the analyses described in Section 5.2 for the fatigue and stiffness values were not performed for the shear test because the shear test results indicated that the allowed range of binder contents during mix production would not exceed these values. However, it should also be noted that the shear test mix data for both projects indicate critical mixes. Selection of the design binder contents are based on this information.

5.4 Suggested Fatigue and Stiffness Performance Requirements

The fatigue and stiffness test parameters for both projects are based on the analyses included in this chapter. They are shown Table 5.1 and Table 5.2, The numbers have been rounded to what are considered to be significant figures for the test values. It should be noted that both lower and upper limits were placed on mix stiffness for the PG 64-16 mix with RAP and lime for the Weed Project since the winter temperatures at Weed are lower than those at Red Bluff. The upper limit was set to preclude the potential for low-temperature cracking should there be a delay in placing the surface course with PG 64-28PM binder.

Table 5.1: Suggested Fatigue Specifications at 200 x 10^{-6} and 400 x 10^{-6} Strain for PG 64-28PM R15 and PG 64-16 R25 Mixes, Weed Project

Mix Type	Min. Requirements for Fatigue Life		Regression Line Requirement
	200 microstrain	400 microstrain	
PG 64-28PM R15 with lime	971,537,086	13,610,199	Regression line has to be above the lower bound
Suggested	971,600,000	13,700,000	
PG 64-16 R25 with lime	22,828,493	27,123	Regression line has to be above the lower bound
Suggested	22,900,000	28,000	

Notes:
1. For each mix type, the fatigue test results have to comply with the following requirements:
(a) the fatigue life has to comply with the minimum requirement,
(b) the regression line constructed by three 200 microstrain fatigue tests and three 400 microstrain fatigue tests has to be above the lower bound.
2. The lower bound of PG 64-28PM 15% RAP with 1.2% lime was based on Figure 5.1.
3. The lower bound of PG 64-16 25% RAP with 1.2% lime was based on Figure D.1.

Table 5.2: Suggested Flexural Stiffness Specifications, Weed Project

Mix Type	Flexural Stiffness at 20°C (10 Hz) 95% Confidence Interval		Flexural Stiffness at 30°C (10 Hz) 95% Confidence Interval	
	Lower Bound MPa (psi)	**Upper Bound MPa (psi)**	**Lower Bound MPa (psi)**	**Upper Bound MPa (psi)**
PG 64-28PM R15 w/lime	3,100 (449,617)	3,567 (517,350)	1,054 (152,870)	3,984 (577,830)
Suggested (psi)	450,000	520,000	160,000	580,000
PG 64-16 R25 with lime	6,131 (889,226)	7,822 (1,134,485)	3,081 (446,861)	5,442 (789,295)
Suggested (psi)	890,000	1,150,000	450,000	790,000

Notes:
1. The flexural stiffnesses at 20°C (10 Hz) were based on the flexural fatigue test results.
2. The flexural stiffnesses at 30°C (10 Hz) were based on the flexural frequency sweep test results (only two data points per mix type).

6 SUGGESTED MIX PERFORMANCE SPECIFICATIONS

The fatigue, stiffness, and shear test parameters are based on the analyses included in Chapter 5. In Table 6.1, the numbers have been rounded to what are considered to be significant figures for the test values.

HWTT requirements are those cited in the Caltrans standard specification.

Table 6.1: Suggested HMA Mix Performance Requirements for Weed Project

Design Parameters	Test Method	Requirement
Permanent deformation (minimum): PG 64-28PM (with RAP lime)[2a] PG 64-16 (with RAP and lime)[2b]	AASHTO T 320 Modified[1]	 220,000 stress repetitions[3,4] 220,000 stress repetitions[3,4]
Fatigue (min.): PG 64-28PM (with RAP and lime)[5a,6] PG 64-16 (with RAP and lime)[5b,7]	AASHTO T 321 Modified[1]	 13,700,000[4,8] 970,000,000[4,9] 28,000 repetitions[4,8] 22,900,000 repetitions[4,9]
Mix Stiffness (minimum): PG 64-28PM (with RAP and lime)[5a,6] PG 64-16 (with RAP and lime)[5b,7]	AASHTO T 321 Modified[1]	 450,000 psi at 20°C 160,000 psi at 30°C At 20°C in the range: 890,000 to 1,200,000 psi
Moisture sensitivity (minimum): PG 64-28PM (with RAP and lime) PG 64-16 (with RAP and lime)	AASHTO T 324 Modified[1]	 20,000 repetitions[10] 20,000 repetitions[10]

Notes:

1. Included in the testing procedure, Caltrans LLP-AC2, "Sample Preparation and Testing for Long-Life Hot Mix Asphalt Pavement," *(1)*.

2a. At proposed asphalt binder content (mix containing 15% RAP and 1.2% lime) and with mix compacted to 3%+/-0.3% air voids.

2b. At proposed asphalt binder content (mix containing 25% RAP and 1.2% lime) and with mix compacted to 3%+/-0.3% air voids.

3. In repeated simple shear test at constant height (RSCH) at a temperature of 50°C and a shear stress of 100 kPa.

4. Minimum test value measured from tests on three specimens

5a. At proposed asphalt binder content (mix containing 15% RAP and 1.2% lime) and with mix compacted to 6%+/-0.3% air voids (determined using AASHTO 209 [Method A]).

5b. At proposed asphalt binder content (mix containing 25% RAP and 1.2% lime) and with mix compacted to 6%+/-0.3% air voids (determined using AASHTO 209 [Method A]).

6. At proposed asphalt binder content (mix containing 15% RAP and 1.2% lime), mix stiffness measured at 20°C and at 30°C, and at a 10 Hz load frequency.

7 At proposed asphalt binder content (mix containing 25% RAP and 1.2% lime), mix stiffness measured at 20°C, and a 10 Hz load frequency.

8. At 400×10^{-6} strain, results shall be reported for this strain level but may be obtained by extrapolation. Minimum number of repetitions required prior to extrapolation defined within test procedure.

9. At 200×10^{-6} strain, results shall be reported for this strain level but may be obtained by extrapolation. Minimum number of repetitions required prior to extrapolation defined within test procedure.

10. Minimum number of repetitions for rut depth of 0.5 in. at 50°C (average of two specimens).

7 DISCUSSION AND RECOMMENDATION

7.1 Summary

The purpose of this technical memorandum has been to provide a summary of the process used to develop the HMA performance-related specifications for the LLAP project on Interstate 5 near Weed. Materials were obtained and traffic and environmental conditions were considered by the UCPRC. The test data developed in this investigation were provided to Caltrans in October 2011 *(5)* for distribution to potential bidders on the contract. The testing data were used by Caltrans HQ staff for the design of the pavement section using *CalME* flexible pavement design methodology. In addition, the test data formed the basis for test specifications that were ultimately included in the bid documents and Standard Special Provisions (SSP) for the Weed project.

UCPRC staff performed this investigation beginning with the understanding that Caltrans wanted to include a higher RAP content (in this case 25 percent) than is usually allowed under current specifications. However, since these projects were to be designed as long-life pavements, the decision was made to conduct this extensive test program and develop performance-based HMA specifications similar to those used for the I-710 projects in the Long Beach area.

7.2 Recommendation

While not a part of this investigation, it is strongly recommended that, following completion of construction, systematic and periodic pavement performance evaluations be conducted for at least five years, and preferably longer, following a similar approach to that used on the I-710 Phase 1 Project *(3)*. This is especially important since this is just the second use of a higher percentage of RAP in HMA mixes for LLAPs.

REFERENCES

1. State of California Department of Transportation Lab Procedure LLP-AC2, "Sample Preparation and Testing for Long-Life Hot Mix Asphalt Pavement," August 4, 2012, available on the web at http://www.dot.ca.gov/hq/esc/Translab/ormt/pdf/LLP-AC2_Sample_Preparation_for_LL_HMA-Pavement.pdf.

2. Sousa, J. B., J. A. Deacon, S. Weissman, J. T. Harvey, C. L. Monismith, R. B. Leahy, G. Paulsen, and J. S. Coplantz. *Permanent Deformation Response of Asphalt-Aggregate Mixes,* Report No. SHRP-A-415, Strategic Highway Research Program, National Research Council, Washington, D. C., 1994.

3. Monismith, C. L., J. T. Harvey, B.-W. Tsai, F. Long, and J. Signore. *The Phase 1 I-710 Freeway Rehabilitation Project: Initial Design (1999) to Performance after Five Years of Traffic (2008).* Summary Report, UCPRC-SR-2008-04. University of California Pavement Research Center, February 2009, 183 pp.

4. Harvey, J. T., S. Weissman, F. Long, and C. L. Monismith. "Tests to Evaluate the Stiffness and Permanent Deformation Characteristics of Asphalt/Binder Aggregate Mixes, and Their Use in Mix Design and Analysis." *Journal of the Association of Asphalt Paving Technologists,* Vol. 70, 2001, pp. 572-604.

5. Signore, J., B.-W. Tsai, and C. L. Monismith. *UCPRC Test Data, Red Bluff and Weed Long Life Pavement Projects, Test Data Summary.* Prepared for the Caltrans Office of Pavements by University of California Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley, October 2011, 26 pp.

APPENDIX A: SHEAR TEST MIX RESULTS

Table A.1: Summary of Mix Design Shear Test Results at 50°C for Weed Project, for the PG 64-28PM, 15% RAP, 1.2% Lime Mix (LMLC)

Specimen Designation	Aggregate Type	AV (%)	AC* (%)	Test Temp. (C)	Test Shear Stress Level (kPa)	Initial Resilient Shear Modulus (MPa)	Permanent Shear Strain at 5,000 Cycles	Cycles to 5% Permanent Shear Strain
315-W-PG6428PM-541-1-1B-7050	Unknown	3.2	5.41	49.6	73.80	181.90	0.014276	22,903,160*
315-W-PG6428PM-541-1-2B-7050	Unknown	3.0	5.41	50.5	74.46	169.20	0.013496	97,100,557*
315-W-PG6428PM-541-1-3B-7050	Unknown	3.2	5.41	49.5	76.19	195.80	0.009540	489,714,330*
315-W-PG6428PM-573-1-1A-7050	Unknown	3.1	5.73	49.5	73.31	157.99	0.007634	5,641,964,621*
315-W-PG6428PM-573-1-2A-7050	Unknown	3.1	5.73	49.7	73.66	149.09	0.014982	17,503,312*
315-W-PG6428PM-573-1-3A-7050	Unknown	3.2	5.73	50.3	73.41	178.90	0.014069	203,629,429*
315-W-PG6428PM-605-1-1A-7050	Unknown	2.9	6.05	50.5	74.53	176.21	0.015081	26,997,661*
315-W-PG6428PM-605-1-2A-7050	Unknown	3.0	6.05	50.3	72.47	145.55	0.019452	6,116,165*
315-W-PG6428PM-605-1-3A-7050	Unknown	3.0	6.05	49.7	74.05	161.58	0.014498	325,438,821*

Notes:

1. "*": extrapolation.
2. AC* content: by weight of virgin aggregate plus lime.
3. Lime: 1.2% by weight of virgin aggregate.
4. R15: 15% RAP by weight of total mix.
5. RICE value: 2.5593 for AC* 5.41%; 2.5579 for AC* 5.73%; 2.5403 for AC* 6.05%.
6. All specimens were laboratory-mixed, laboratory-compacted (LMLC) with lime added.

Table A.2: Summary of Shear Test Results at 50°C for Weed Project for PG64-28PM 15% RAP, 1.2% Lime Mix for ME Analysis (LMLC)

Specimen Designation	AV (%)	AC* (%)	Test Temp. (C)	Test Shear Stress Level (kPa)	Initial Resilient Shear Modulus (kPa)	Permanent Shear Strain at 5,000 Cycles	Cycles to 5% Permanent Shear Strain
315-W-PG6428PM-573-2-1A-7050	3.1	5.73	50.34	73.29	161	0.009536	2.6321E+16*
315-W-PG6428PM-573-2-3A-7050	3.3	5.73	50.43	78.30	179	0.008564	2.0111E+12*
315-W-PG6428PM-573-3-2B-7050	2.7	5.73	50.45	74.37	155	0.016532	2.4364E+08*
315-W-PG6428PM-573-3-1B-10050	2.8	5.73	50.25	104.38	166	0.015795	2.4219E+08*
315-W-PG6428PM-573-3-3B-10050	3.2	5.73	50.43	104.07	154	0.016764	2,997,166*
315-W-PG6428PM-573-5-2B-10050	3.1	5.73	49.56	105.55	139	0.014793	24,272,276*
315-W-PG6428PM-573-4-1A-13050	3.5	5.73	50.41	134.73	257	0.008438	1.6627E+10*
315-W-PG6428PM-573-5-1B-13050	3.1	5.73	50.39	137.52	137	0.029027	121,564*
315-W-PG6428PM-573-5-3B-13050	3.2	5.73	50.39	136.08	170	0.019577	1,524,011*

Note:

1. "*": extrapolation.
2. Percent air-void content was measured using CoreLok method.
3. AC: measured binder content.
4. All specimens were laboratory-mixed, laboratory-compacted (LMLC).

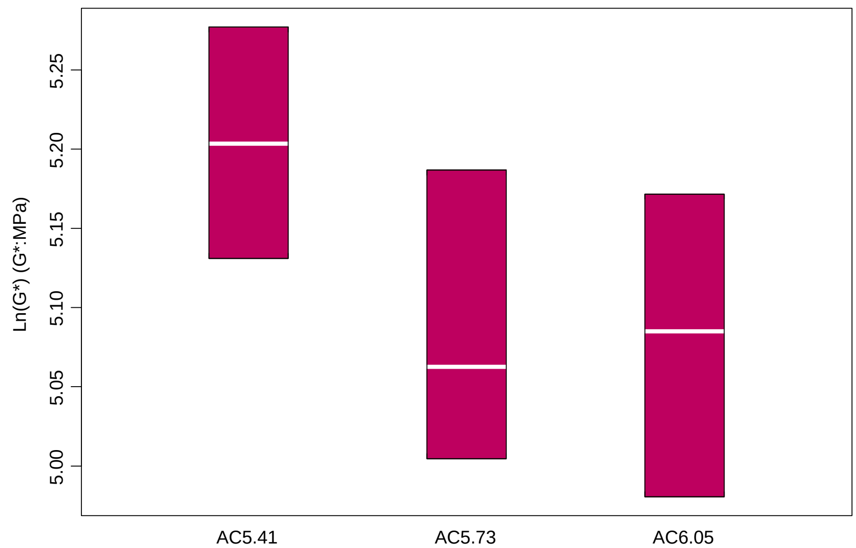


Figure A.1: Ln (G) versus binder content, Weed PG 64-28PM, 15% RAP, 1.2% lime mix (50°C, 70 kPa stress).

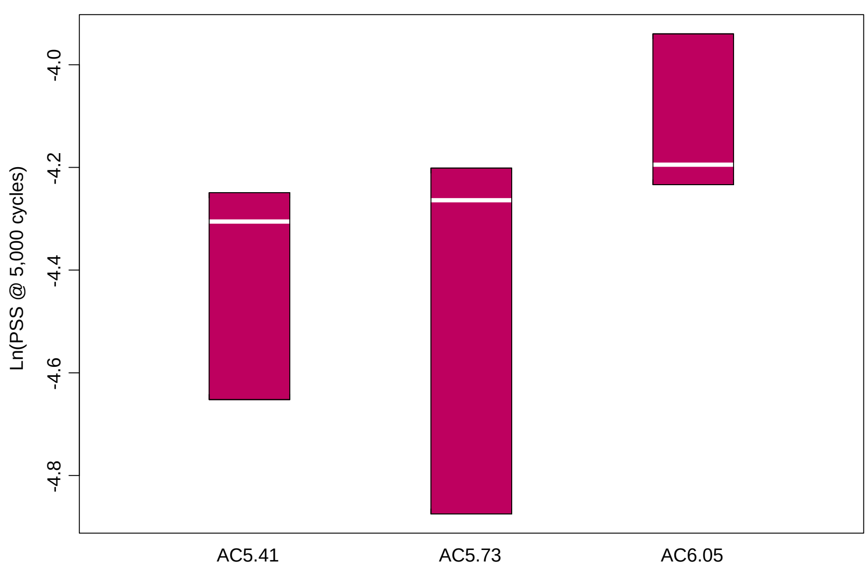


Figure A.2: Ln (γ_p after 5,000 load repetitions) versus binder content, Weed PG 64-28PM, 15% RAP, 1.2% lime mix (50°C, 70 kPa stress).

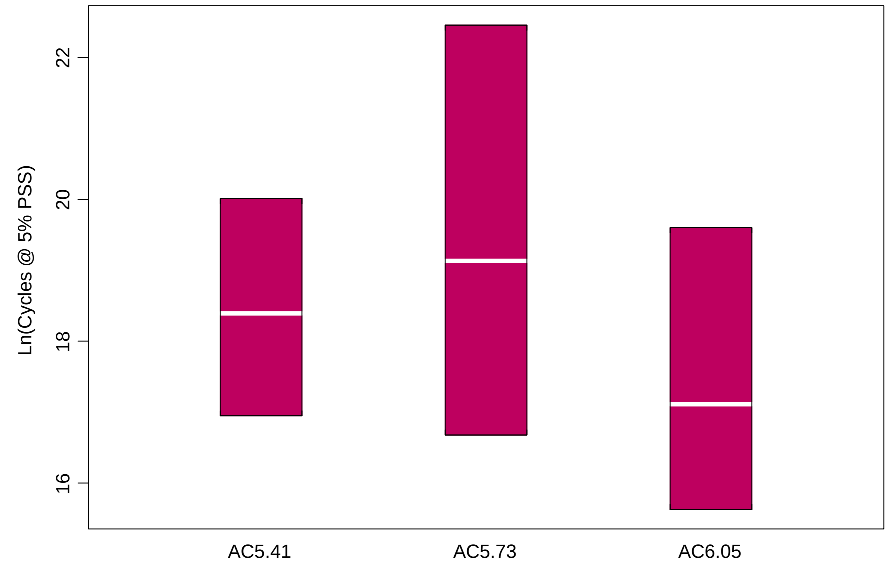


Figure A.3: Ln (repetitions at γ_p= 5%) versus binder content, Weed PG 64-28PM, 15% RAP, 1.2% lime mix (50°C, 70 kPa stress).

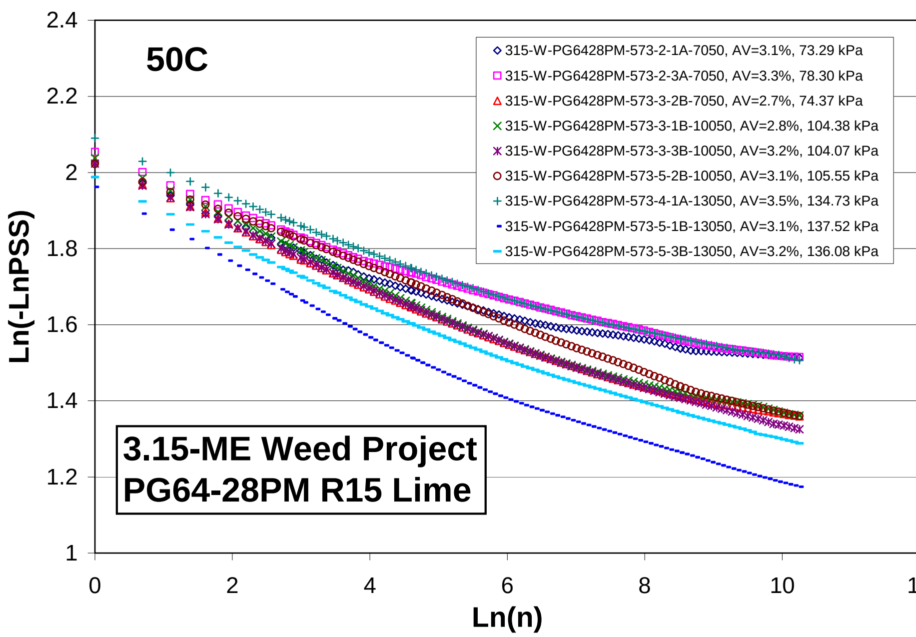


Figure A.4: Summary of shear test results, Ln (Lnγ_p) versus Ln (load repetitions), PG 64-28 mix (ME, Weed Project, AC = 5.73% [by weight of virgin aggregate plus lime], 15% RAP, 1.2% lime, AV = 3.0%, LMLC).

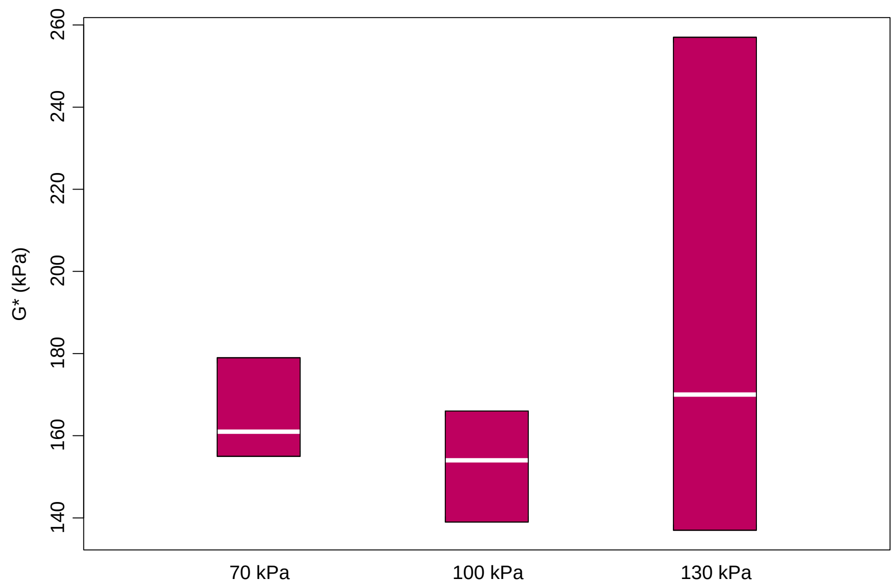


Figure A.5: G*versus shear stress level, PG 64-28PM mix (ME, Weed Project, AC =5.73%, 15% RAP, 1.2% lime, 50°C, LMLC).

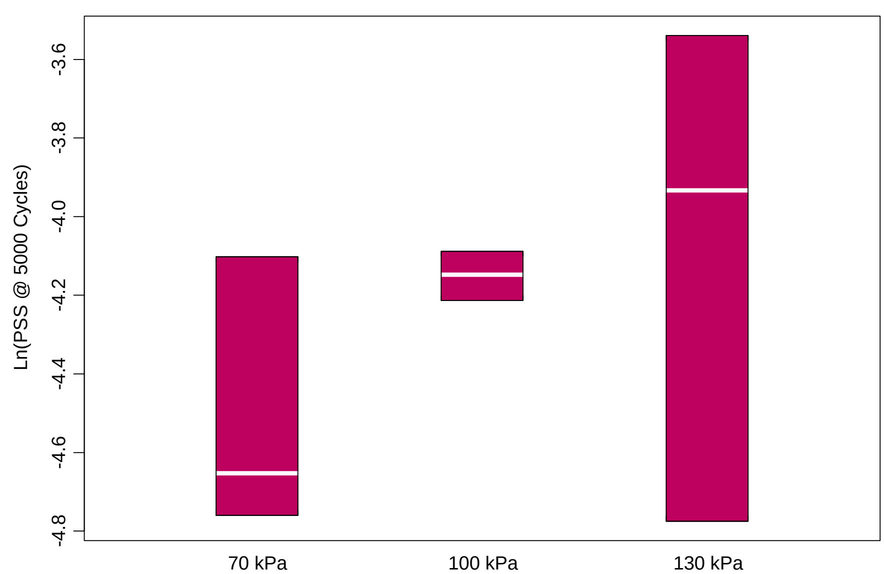


Figure A.6: Ln (γ_p@5000 Cycles) versus stress level, PG 64-28PM 15% RAP, 1.2% lime mix (ME, Weed Project, AC = 5.73%, 50°C, LMLC).

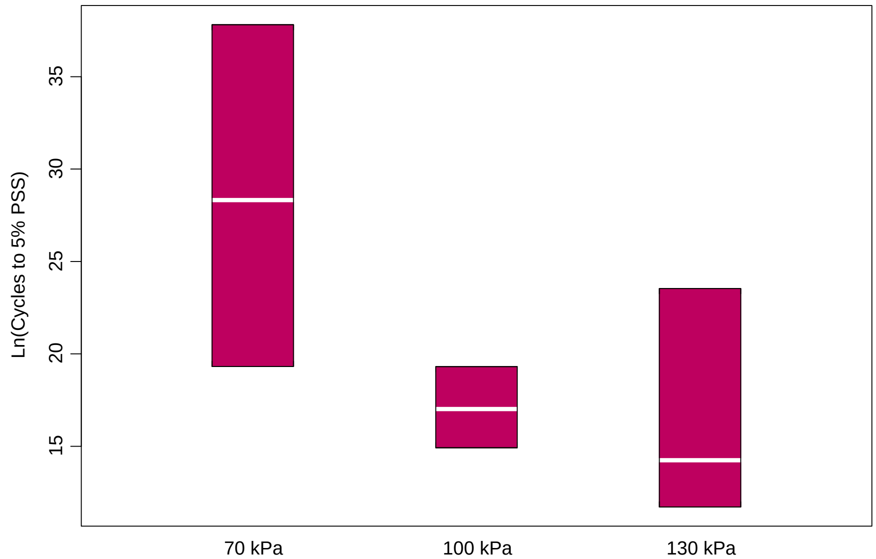


Figure A.7: Ln (load repetitions to γ_p = 5%) versus stress level, PG 64-28PM 15% RAP, 1.2% lime mix (ME, Weed Project, AC = 5.73%, 50°C, LMLC).

APPENDIX B: FATIGURE AND STIFFNESS TEST MIX RESULTS

Table B.1: Summary of Fatigue Test Results, Weed Project (20°C, LMLC, 1.2% Lime)

Mix Type	Specimen Designation	AV (%)	AC* (%)	Test Temp. (C)	Test Strain Level	Initial Phase Angle (Deg.)	Initial Stiffness (MPa)	Fatigue Life, Nf
PG 64-28PM 15% RAP, 1.2% Lime	3.15-W-PG6428PM-5.73-4B2	5.8	5.73	20.34	0.000209	32.55	3,428	3,077,533,341*
	3.15-W-PG6428PM-5.73-5A2	5.7	5.73	20.03	0.000204	31.37	3,748	71,324,267,818*
	3.15-W-PG6428PM-5.73-8B2	6.4	5.73	20.19	0.000205	31.95	3,283	17,441,256,435*
	3.15-W-PG6428PM-5.73-7A2	5.7	5.73	19.55	0.000409	29.82	3,158	465,349,381*
	3.15-W-PG6428PM-5.73-9A1	5.8	5.73	20.13	0.000409	34.20	3,125	52,589,617*
	3.15-W-PG6428PM-5.73-9A2	6.1	5.73	19.69	0.000411	30.03	3,102	272,058,498*
PG 64-16 25% RAP, 1.2% Lime	3.15-W-PG6416-5.73-2B2	6.1	5.73	19.96	0.000200	21.36	6,700	90,958,157*
	3.15-W-PG6416-5.73-3A2	5.8	5.73	20.28	0.000207	22.11	6,572	192,296,819*
	3.15-W-PG6416-5.73-7B1	6.3	5.73	19.71	0.000203	17.33	7,835	2,634,336,132*
	3.15-W-PG6416-5.73-2B1	5.8	5.73	20.08	0.000399	23.14	6,586	303,119
	3.15-W-PG6416-5.73-6A1	5.6	5.73	19.74	0.000404	17.45	7,997	335,380
	3.15-W-PG6416-5.73-7B2	5.8	5.73	19.75	0.000410	19.39	5,596	594,202

Notes:

1. RICE values: 2.5579 for PG 64-28PM R15 [15% RAP (by weight of total mix), 1.2% lime added (by weight of virgin aggregate); AC* = 5.73% (by weight of virgin aggregate plus lime)]; 2.5588 for PG 64-16 R25 [25% RAP (by weight of total mix), 1.2% lime added (by weight of virgin aggregate); AC* = 5.73% (by weight of virgin aggregate plus lime)].
2. The binder source is the Valero refinery.
3 The air-void content was measured with the parafilm method.
4 The beam specimens are laboratory-mixed, laboratory-compacted (LMLC).
5 "*" stands for "extrapolation."

Table B.2: Summary of Frequency Sweep Test Results Weed Project PG 64-28PM (15% RAP with 1.2% Lime Added, AC* = 5.73% [Virgin Aggregate Plus Lime], AV = 6.0%)

3.15-W-PG6428PM-5.73-4B1 (AV= 5.7%; 10°C)						3.15-W-PG6428PM-5.73-10B1 (AV= 6.2%; 10°C)					
Freq. (Hz)	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)	Freq. (Hz)	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)
15.17	0.654814	0.000094	6960	20.64	9.67	15.16	0.601919	0.000090	6652	19.90	10.57
9.99	0.693594	0.000104	6668	19.03	9.72	10.01	0.638756	0.000103	6206	19.35	10.54
5.00	0.632204	0.000104	6077	18.93	9.78	5.00	0.562558	0.000105	5377	18.83	10.48
1.99	0.500937	0.000099	5085	19.69	9.76	1.99	0.407799	0.000092	4410	20.39	10.46
1.00	0.421738	0.000095	4439	21.39	9.70	1.00	0.376214	0.000096	3921	20.50	10.40
0.50	0.377311	0.000100	3755	23.92	9.67	0.50	0.326455	0.000097	3373	23.37	10.39
0.20	0.295414	0.000100	2960	25.54	9.62	0.20	0.259265	0.000098	2651	25.02	10.34
0.10	0.242309	0.000099	2442	26.12	9.57	0.10	0.194513	0.000096	2029	25.79	10.29
0.05	0.196119	0.000097	2012	28.17	9.75	0.05	0.176153	0.000096	1837	29.09	10.21
0.02	0.152253	0.000098	1551	29.69	9.58	0.02	0.134294	0.000094	1433	29.85	10.06
0.01	0.122761	0.000095	1290	30.58	9.68	0.01	0.111052	0.000093	1189	31.24	9.80

3.15-W-PG6428PM-5.73-5A1 (AV= 5.5%; 20°C)						3.15-W-PG6428PM-5.73-6B2 (AV= 6.4%; 20°C)					
Freq. (Hz)	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)	Freq. (Hz)	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)
15.15	0.449084	0.000102	4382	24.51	20.01	15.13	0.429492	0.000113	3805	28.90	19.84
10.00	0.431361	0.000106	4054	25.08	20.05	10.00	0.401307	0.000105	3836	27.10	19.77
4.99	0.358646	0.000105	3417	26.02	19.92	5.00	0.330784	0.000105	3145	28.13	19.80
1.99	0.252225	0.000093	2710	27.24	19.77	2.00	0.234618	0.000097	2413	29.81	19.76
1.00	0.217046	0.000098	2221	28.33	19.74	1.00	0.185741	0.000095	1962	29.66	19.74
0.50	0.181515	0.000101	1795	31.85	19.65	0.50	0.153945	0.000096	1602	32.37	19.68
0.20	0.132400	0.000099	1340	31.86	19.80	0.20	0.114980	0.000097	1183	31.78	19.59
0.10	0.105045	0.000096	1089	30.53	19.69	0.10	0.088023	0.000095	930	32.02	19.61
0.05	0.083980	0.000094	891	31.64	19.67	0.05	0.068615	0.000093	735	33.98	19.72
0.02	0.062370	0.000093	668	30.71	19.67	0.02	0.049510	0.000091	544	33.07	19.68
0.01	0.050924	0.000093	549	31.65	19.70	0.01	0.039953	0.000091	440	34.27	19.70

3.15-W-PG6428PM-5.73-1A2 (AV= 5.8%; 30°C)						3.15-W-PG6428PM-5.73-10B2 (AV= 6.3%; 30°C)					
Freq. (Hz)	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)	Freq. (Hz)	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)
15.22	0.168644	0.000101	1675	36.48	29.94	15.15	0.259693	0.000208	1246	43.51	29.76
10.01	0.161903	0.000107	1514	35.97	29.81	10.00	0.226902	0.000208	1092	41.96	29.74
4.98	0.127771	0.000105	1215	36.84	29.78	5.00	0.176085	0.000209	841	41.53	29.68
1.99	0.083369	0.000094	885	35.68	29.77	2.00	0.122567	0.000208	590	41.37	29.71
1.00	0.068284	0.000097	707	34.51	29.68	1.00	0.092849	0.000200	463	40.94	29.67
0.50	0.053133	0.000096	551	35.10	29.70	0.50	0.067359	0.000194	348	40.83	29.75
0.20	0.039629	0.000097	407	35.57	29.66	0.20	0.049263	0.000200	246	43.39	29.68
0.10	0.031701	0.000096	331	35.93	29.67	0.10	0.037640	0.000199	189	41.11	29.70
0.05	0.025811	0.000095	272	27.45	29.65	0.05	0.030182	0.000197	153	40.95	29.67
0.02	0.021584	0.000093	231	32.80	29.70	0.02	0.024631	0.000196	125	38.52	29.73
0.01	0.019669	0.000093	212	37.60	29.72	0.01	0.021930	0.000197	111	33.88	29.72

Table B.3: Summary of Frequency Sweep Test Results, Weed Project, PG 64-16 (25% RAP, 1.2% Lime, AC* = 5.73% [Virgin Aggregate Plus Lime Basis], AV = 6.0%)

3.15-W-PG6416-5.73-4B1 (AV= 6.4%; 10°C)						3.15-W-PG6416-5.73-5B1 (AV= 6.2%; 10°C)					
Freq. (Hz)	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)	Freq. (Hz)	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)
15.15	0.440800	0.000041	10746	15.65	10.15	15.15	0.382804	0.000033	11697	15.92	10.04
9.99	1.099945	0.000102	10774	2.49	10.13	10.00	1.143222	0.000101	11331	13.34	10.03
5.00	1.049077	0.000106	9897	11.52	10.13	5.01	1.032648	0.000102	10168	12.95	10.03
1.99	0.678555	0.000081	8373	12.93	10.12	2.00	0.849778	0.000096	8844	14.68	10.02
1.00	0.724664	0.000094	7696	11.80	10.11	1.00	0.735876	0.000094	7804	15.61	10.01
0.50	0.632674	0.000090	6993	13.05	10.12	0.50	0.607657	0.000089	6795	16.42	10.00
0.20	0.590248	0.000099	5990	15.70	10.11	0.20	0.553028	0.000099	5575	16.23	10.00
0.10	0.511202	0.000098	5198	16.06	10.10	0.10	0.476948	0.000099	4797	18.84	9.99
0.05	0.435098	0.000096	4510	19.77	10.08	0.05	0.402855	0.000098	4105	20.82	9.97
0.02	0.379808	0.000096	3943	22.31	10.05	0.02	0.320122	0.000095	3356	23.41	9.94
0.01	0.335736	0.000098	3413	23.25	9.97	0.01	0.278778	0.000098	2839	24.22	9.86

3.15-W-PG6416-5.73-3A1 (AV= 5.7%; 20°C)						3.15-W-PG6416-5.73-4B2 (AV= 6.1%; 20°C)					
Freq. (Hz)	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)	Freq. (Hz)	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)
15.16	0.528767	0.000062	8471	16.51	19.50	15.16	0.614638	0.000095	6450	20.11	19.66
9.99	0.731116	0.000104	7047	17.96	19.59	10.00	0.622690	0.000104	5969	19.98	19.65
5.00	0.662258	0.000106	6255	17.45	19.56	5.00	0.562243	0.000105	5367	19.66	19.53
1.99	0.449283	0.000086	5228	18.94	19.47	1.99	0.394917	0.000088	4484	20.55	19.51
1.00	0.433686	0.000096	4518	19.27	19.54	1.00	0.371069	0.000097	3830	21.81	19.66
0.50	0.388765	0.000101	3845	21.71	19.61	0.50	0.334061	0.000101	3303	25.76	19.63
0.20	0.310730	0.000102	3055	25.09	19.67	0.20	0.259358	0.000101	2556	28.32	19.51
0.10	0.253693	0.000099	2575	27.27	19.51	0.10	0.207271	0.000099	2094	29.41	19.58
0.05	0.209211	0.000097	2155	29.98	19.63	0.05	0.164943	0.000097	1697	31.79	19.55
0.02	0.152984	0.000095	1609	30.88	19.56	0.02	0.124938	0.000096	1307	32.73	19.58
0.01	0.125459	0.000095	1321	32.43	19.57	0.01	0.102882	0.000095	1086	34.47	19.58

3.15-W-PG6416-5.73-1A1 (AV= 5.7%; 30°C)						3.15-W-PG6416-5.73-1A2 (AV= 6.2%; 30°C)					
z	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)	Freq. (Hz)	Tensile Sts. (MPa)	Tensile Stn.	Flex_E* (MPa)	Phase Angle (deg)	Avg. Temp. (C)
15.13	0.721189	0.000209	3451	30.62	29.74	15.16	0.408714	0.000107	3824	28.21	29.74
10.00	0.640369	0.000206	3112	31.68	29.79	10.01	0.360821	0.000105	3452	28.77	29.67
5.01	0.523168	0.000207	2526	31.85	29.63	5.00	0.296703	0.000105	2834	30.37	29.57
2.00	0.381995	0.000204	1870	33.76	29.68	1.99	0.195654	0.000093	2107	32.05	29.72
1.00	0.307193	0.000197	1558	34.83	29.74	1.01	0.163762	0.000098	1669	31.72	29.64
0.50	0.249629	0.000206	1213	38.72	29.67	0.50	0.127605	0.000098	1308	35.94	29.76
0.20	0.174895	0.000204	858	38.46	29.72	0.20	0.092513	0.000098	945	35.25	29.63
0.10	0.133096	0.000200	666	38.91	29.70	0.10	0.071307	0.000096	741	36.54	29.70
0.05	0.102770	0.000197	522	39.09	29.68	0.05	0.056166	0.000095	591	37.98	29.69
0.02	0.076976	0.000195	394	39.23	29.71	0.02	0.042318	0.000094	449	38.17	29.65
0.01	0.064830	0.000195	332	39.60	29.72	0.01	0.037266	0.000094	396	34.06	29.71

Table B.4: Summary of Master Curves and Time-Temperature Relationships for Weed Project

Mix Type	Master Curve					Time-Temperature Relationship	
	n	A	B	C	D	A	B
PG 64-28PM R15 Lime	3	117168.5	15.94195	-8.396799	209.2237	8.22774	-25.6731
PG 64-16 R25 Lime	3	80694.11	12.40037	-10.03932	314.0559	26.9539	-81.3727

Notes:

1. The reference temperature is 20°C.
2. The flexural controlled-deformation frequency sweep tests were conducted at following testing conditions:
   frequencies: 15, 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz;
   temperatures: 10, 20, and 30°C; and
   strain level: 100/200 microstrain.
3. Master curve Gamma fitting equations:

   If $n = 3$,

   $$E^* = D + A \cdot \left(1 - \exp\left(-\frac{(x-C)}{B}\right) \cdot \left(1 + \frac{x-C}{B} + \frac{(x-C)^2}{2B^2}\right)\right)$$, where $x = \ln freq + \ln aT$

4. Time-temperature relationship:

   $$\ln(aT) = A \cdot \left(1 - \exp\left(-\frac{T - Tref}{B}\right)\right)$$

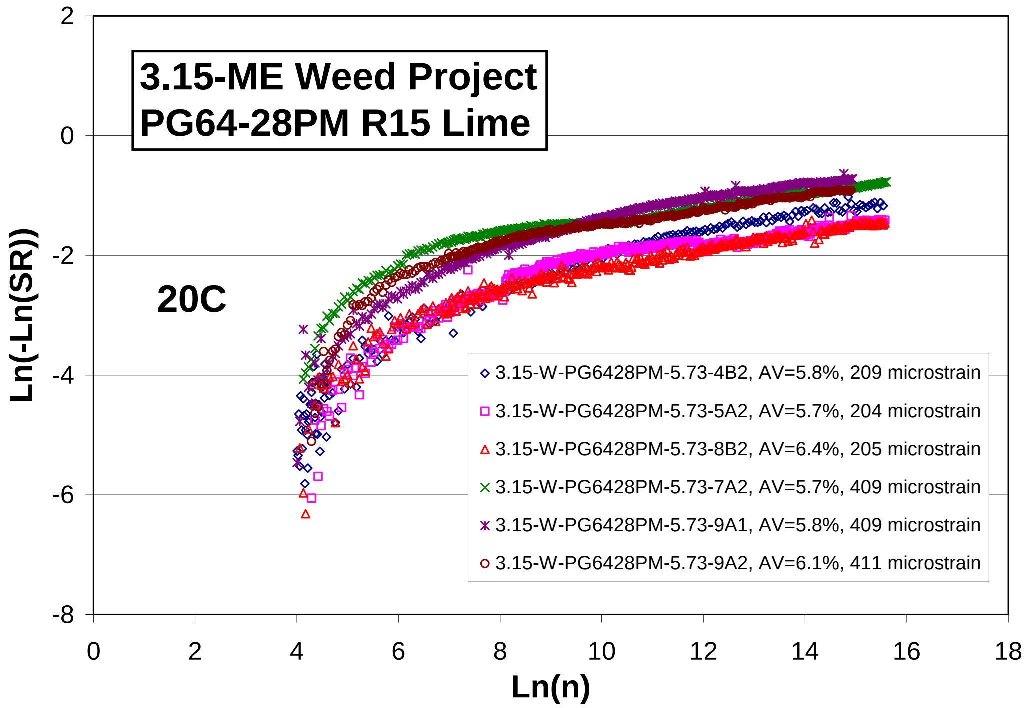


Figure B.1: Summary of fatigue test results, (PG 64-28PM, 15% RAP, 1.2% lime, AC* = 5.73% [(by weight of virgin aggregate plus lime], AV = 6.0%].

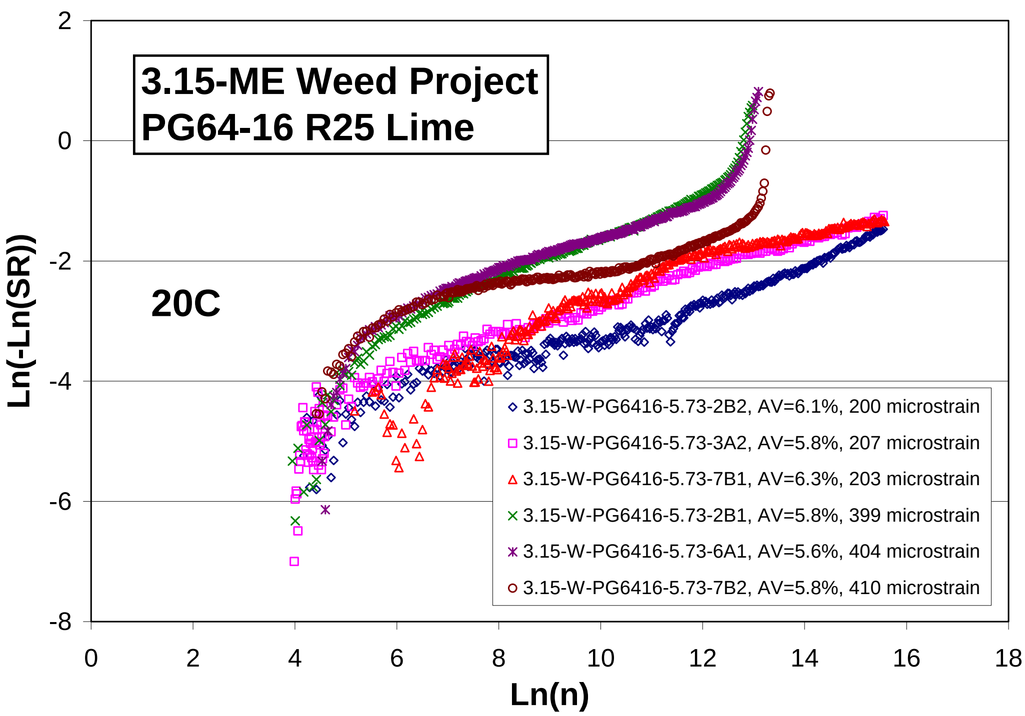


Figure B.2: Summary of fatigue test results (PG 64-16, 25% RAP, 1.2% lime, AC* = 5.73% [by weight of virgin aggregate plus lime], AV = 6.0%).

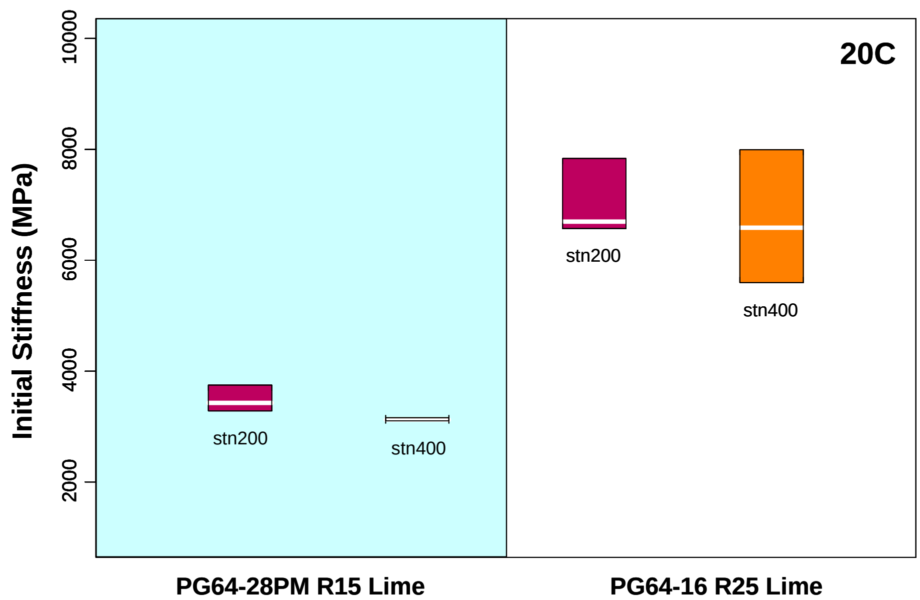


Figure B.3: Boxplot summary of initial stiffness moduli, Weed Project.

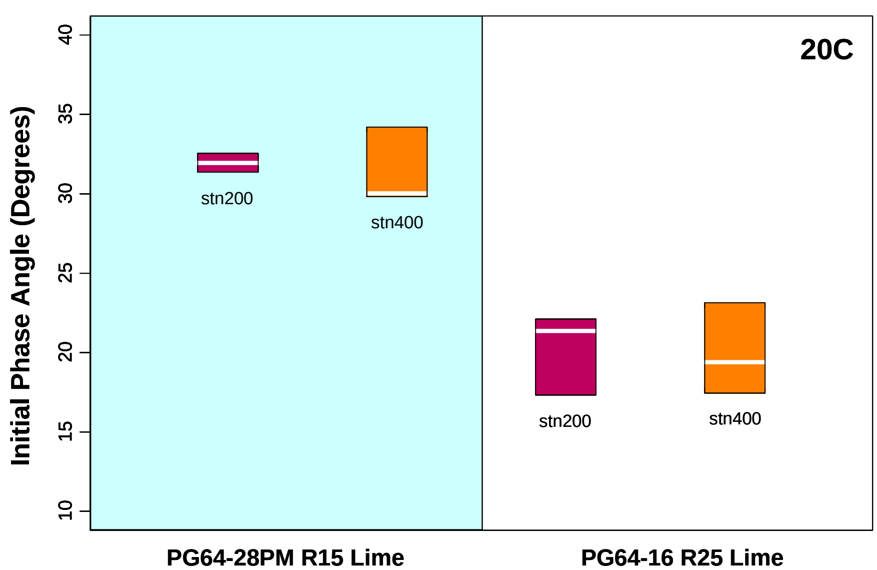


Figure B.4: Boxplot summary of initial phase angle values, Weed Project.

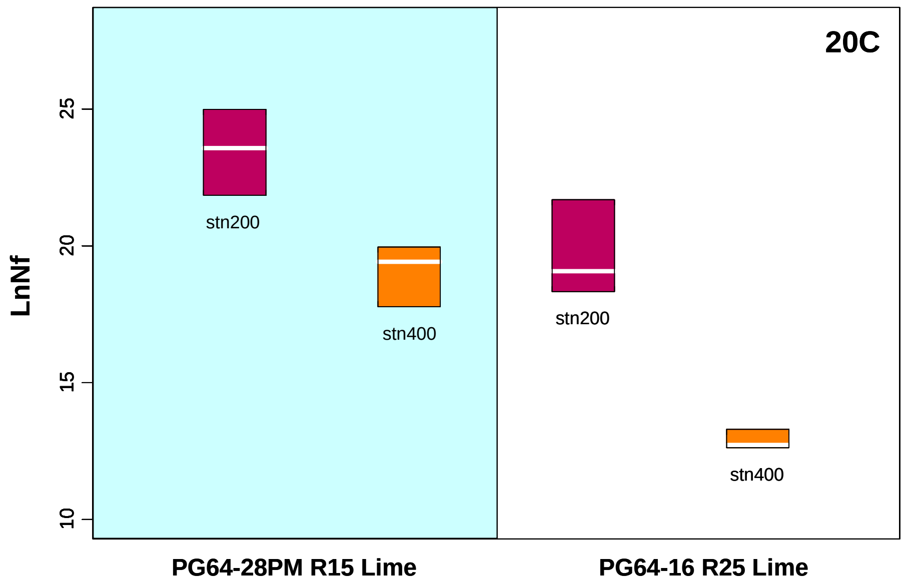


Figure B.5: Boxplot summary of cycles to failure at strains of 200 x 10^{-6} strain and 400 x 10^{-6} strain, Weed Project.

APPENDIX C: HAMBURG WHEEL-TRACK TESTING RESULTS

Table C.1: Summary of HWTT Results for Weed Project

Mix Type	Set	Position	Specimen Name	% AV (SSD)	Average Rut Depth (mm)	
					10k Passes	20k Passes
PG 64-28PM 15% RAP, 1.2% Lime	1	Rt.	3.15-W-PG6428PM-5.73-4	6.9	2.05	2.41
			3.15-W-PG6428PM-5.73-6	6.9		
		Lt.	3.15-W-PG6428PM-5.73-2580	5.8	1.08	1.49
			3.15-W-PG6428PM-5.73-5	6.6		
	2	Rt.	3.15-W-PG6428PM-5.73-3	6.8	1.73	2.21
			3.15-W-PG6428PM-5.73-1	6.6		
		Lt.	3.15-W-PG6428PM-5.73-2560	6.1	1.34	1.67
			3.15-W-PG6428PM-5.73-2570	6.1		
PG 64-16 25% RAP, 1.2% Lime	1	Rt.	3.15-W-PG6416-5.73-D	6.6	2.46	2.70
			3.15-W-PG6416-5.73-3	6.6		
		Lt.	3.15-W-PG6416-5.73-4	6.0	1.94	2.41
			3.15-W-PG6416-5.73-2	6.2		
	2	Rt.	3.15-W-PG6416-5.73-1	6.9	2.27	2.76
			3.15-W-PG6416-5.73-9	6.8		
		Lt.	3.15-W-PG6416-5.73-7	6.4	1.61	1.94
			3.15-W-PG6416-5.73-10	6.3		

Note:

1. All the specimens were prepared using Superpave gyratory compaction.
2. Average rut depth was defined as the average of ruts of three middle profile positions from the smoothed plot.

Figure C.1: HWTT result for PG 64-28PM 15% RAP, 1.2% lime (set #1, rt.) after 40,000 passes.

Figure C.2: HWTT result for PG 64-28PM 15% RAP, 1.2% lime (set #1, lt.) after 40,000 passes.

Figure C.3: HWTT result for PG 64-28PM 15% RAP, 1.2% lime (set #2, rt.) after 22,950 passes.

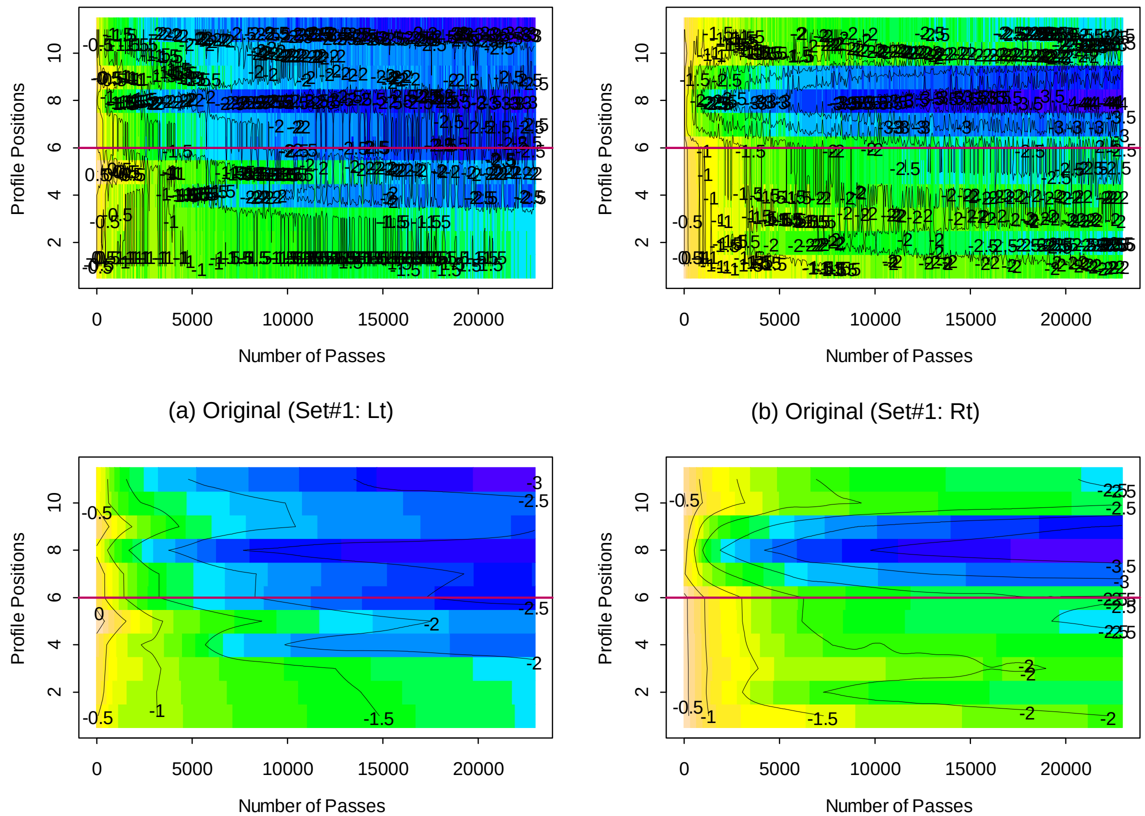
Figure C.4: HWTT result for PG 64-28PM 15% RAP, 1.2% lime (set #2, lt.) after 22,950 passes.

Figure C.5: HWTT result for PG 64-16 25% RAP, 1.2% lime (set #1 rt.) after 40,000 passes.

Figure C.6: HWTT result for PG 64-16 25% RAP, 1.2% lime (set #1 lt.) after 40,000 passes.

Figure C.7: HWTT result for PG 64-16 25% RAP, 1.2% lime (set #2, rt.) after 40,000 passes.

Figure C.8: HWTT result for PG 64-16 25% RAP, 1.2% lime (set #2, lt.) after 40,000 passes.



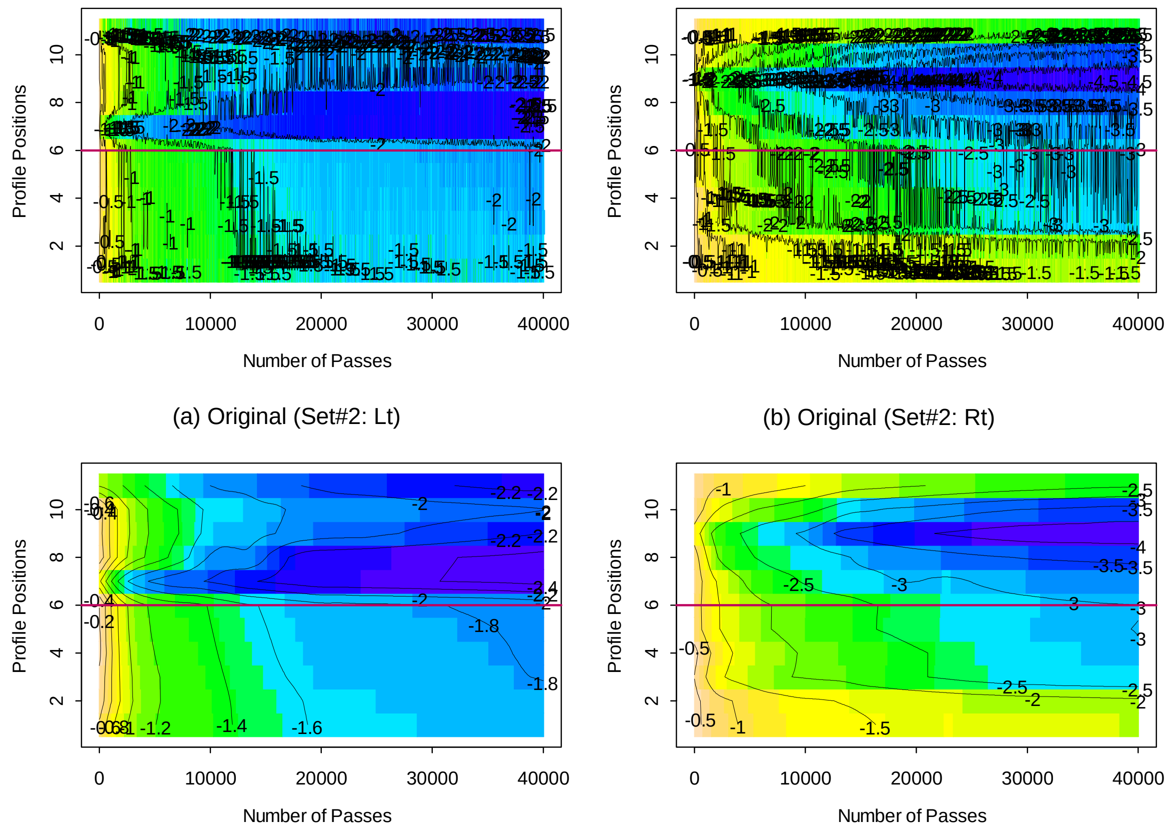
(a) Original (Set#1: Lt)

(b) Original (Set#1: Rt)

(c) Smoothed in "Number of Passes" (Set#1: Lt)

(d) Smoothed in "Number of Passes" (Set#1: Rt)

Figure C.9: Rutting evolution image and contour plots for PG 64-28PM 15% RAP, 1.2% lime mix, set #1 (a) original data (lt.), (b) original data (rt.), (c) smoothed in "number of passes" direction (lt.), and (d) smoothed in "number of passes" direction (rt.). (HWTT set #1 rt.; 3.15-W-PG6428PM-5.73, specimen 4 and specimen 6; set #1 lt.: 3.15-W-PG6428PM-5.73, specimen 2580 and specimen 5).



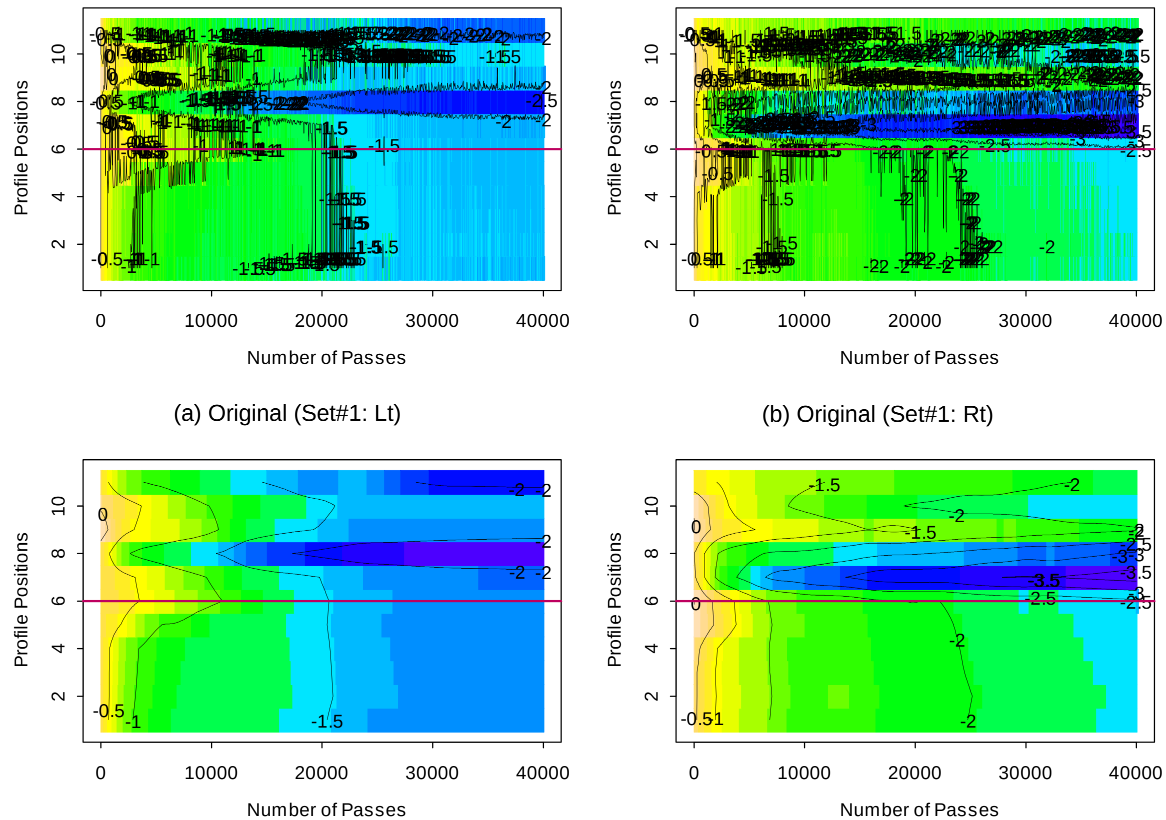
(a) Original (Set#2: Lt)

(b) Original (Set#2: Rt)

(c) Smoothed in “Number of Passes” (Set#2: Lt)

(d) Smoothed in “Number of Passes” (Set#2: Rt)

Figure C.10: Rutting evolution image and contour plots for PG 64-28PM 15% RAP, 1.2% lime mix set #2 (a) original data (lt.), (b) original data (rt.), (c) smoothed in “number of passes” direction (lt.), and (d) smoothed in “number of passes” direction (rt.). (HWTT set #2 rt.; 3.15-W-PG6428PM-5.73, specimen 3 and specimen 1; set #2 lt: 3.15-W-PG6428PM-5.73, specimen 2560 and specimen 2570).



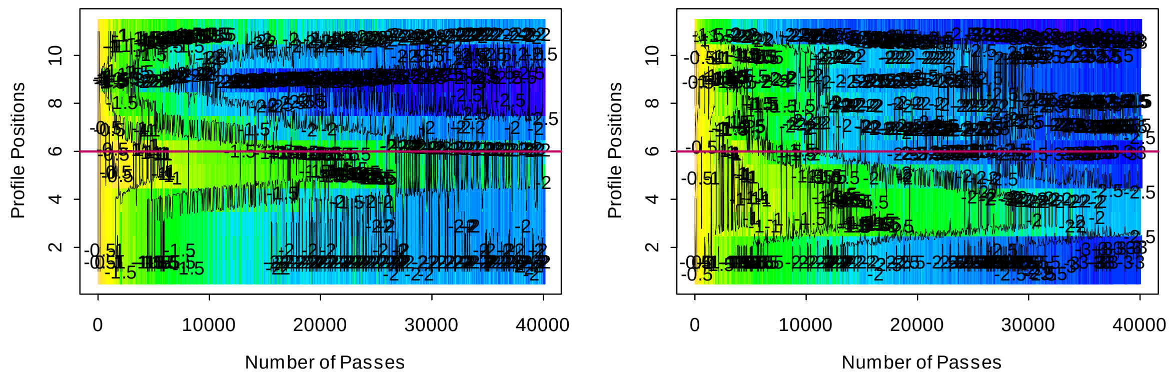
(a) Original (Set#1: Lt)

(b) Original (Set#1: Rt)

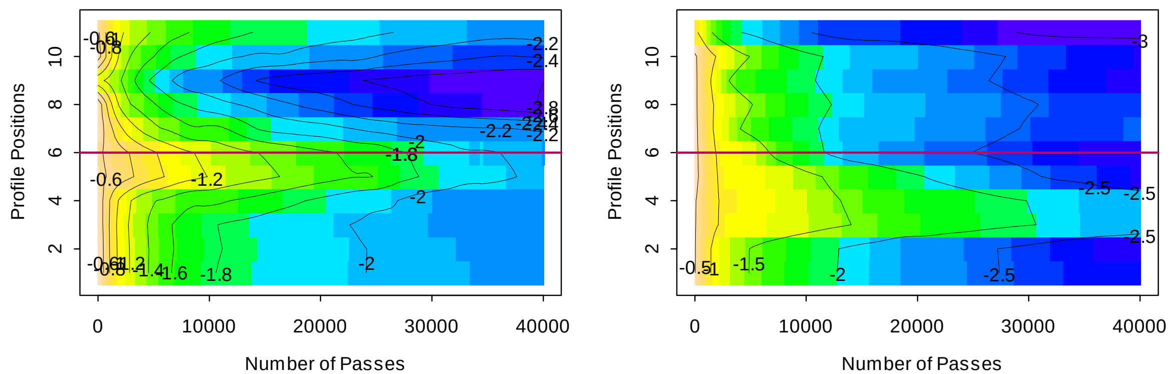
(c) Smoothed in "Number of Passes" (Set#1: Lt)

(d) Smoothed in "Number of Passes" (Set#1: Rt)

Figure C.11: Rutting evolution image and contour plots for PG 64-16 25% RAP, 1.2% lime mix, set #1 (a) original data (lt.), (b) original data (rt.), (c) smoothed in "number of passes" direction (lt.) and (d) smoothed in "number of passes" direction (rt.). (HWTT set #1 rt.; 3.15-W-PG6416-5.73, specimen D and specimen 3; set #1 lt: 3.15-W-PG6416-5.73, specimen 4 and specimen 2).



(a) Original (Set#2: Lt) (b) Original (Set#2: Rt)



(c) Smoothed in “Number of Passes” (Set#2: Lt) (d) Smoothed in “Number of Passes” (Set#2: Rt)

Figure C.12: Rutting evolution image and contour plots for PG 64-16 25% RAP, 1.2% lime mix, set #2 (a) original data (lt.), (b) original data (rt.), (c) smoothed in “number of passes” direction (lt.), and (d) smoothed in “number of passes” direction (rt.). (HWTT set #2 rt.; 3.15-W-PG6416-5.73, specimen 1 and specimen 9; set #2 lt: 3.15-W-PG6416-5.73, specimen 7 and specimen 10).

APPENDIX D: DEVELOPMENT OF FATIGURE AND STIFFNESS MIX PERFORMANCE TEST REQUIREMENTS

Table D.1: Lower Bound Construction of 95% Confidence Band for PG 64-28PM 15% RAP, 1.2% Lime and PG 64-16 25% RAP, 1.2% Lime Mixes, Weed Project

Strain	Ln(Strain)	PG 64-28PM R15 lime (lower bound) Ln(Nf)	PG 64-16 R25 lime (lower bound) Ln(Nf)
0.000100	-9.21034	21.57795	20.23469
0.000164	-8.71390	21.03811	17.97436
0.000229	-8.38366	20.34907	16.12638
0.000293	-8.13583	19.18605	14.07027
0.000357	-7.93738	17.56381	11.73948
0.000421	-7.77186	15.87054	9.47303
0.000486	-7.62989	14.29268	7.41146
0.000550	-7.50559	12.85992	5.55831
0.000614	-7.39505	11.56116	3.88705
0.000679	-7.29552	10.37846	2.36963
0.000743	-7.20501	9.29495	0.98210
0.000807	-7.12201	8.29634	
0.000871	-7.04538	7.37087	
0.000936	-6.97420	6.50889	
0.001000	-6.90776	5.70243	

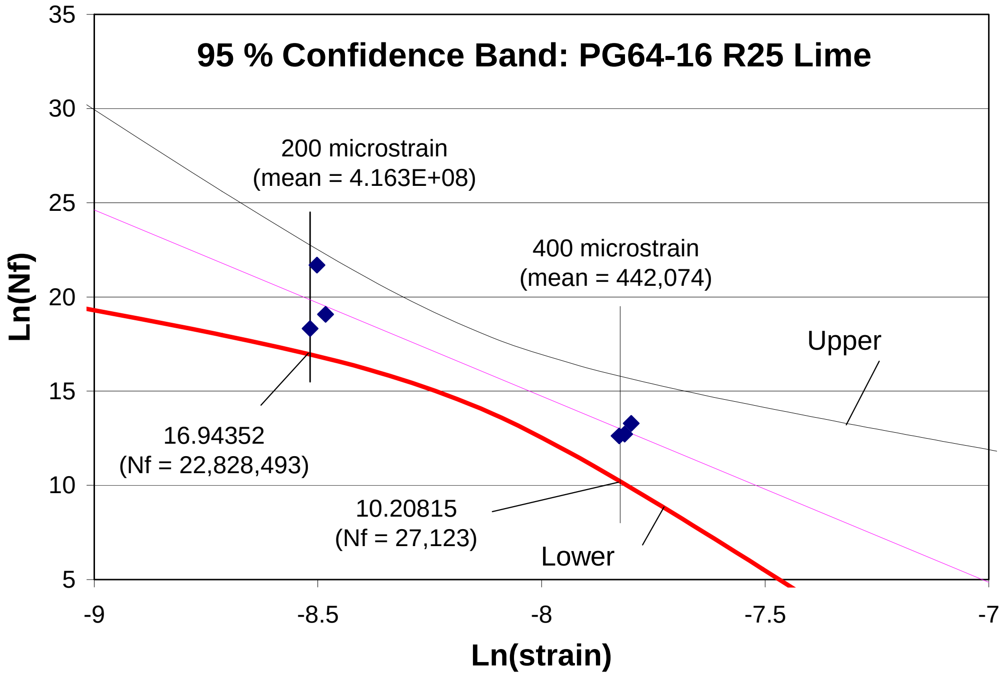


Figure D.1: Fatigue 95% confidence band, PG 64-16 25% RAP with 1.2% lime (AC* = 5.73% [by weight of virgin aggregate plus lime], AV = 6.0%), Weed Project.