Title
Development of Hot Mix Asphalt Pavement Performance Properties for Long-life Pavement Design: Caltrans District 2, Interstate 5, Red Bluff, California

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

Publication Date
2016-10-01

March 2014
Technical Memorandum: UCPRC-TM-2014-03

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

Version 1

Authors:
James 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 Districts 2 and 4, Interstate 5 Red Bluff and Weed, Interstate 80 Dixon

PREPARED FOR:

California Department of Transportation
Division of Research, Innovation and System Information
Office of Roadway Research

PREPARED BY:

University of California
Pavement Research Center
UC Davis, UC Berkeley

DOCUMENT RETRIEVAL PAGE			**UCPRC Technical Memorandum No.:** UCPRC-TM-2014-03
Title: Development of Hot Mix Asphalt Pavement Performance Properties for Long-life Pavement Design: Caltrans District 2, Interstate 5, Red Bluff, California			
Authors: J. Signore, B.-W. Tsai, and C. L. Monismith			
Caltrans Technical Lead: I. Basheer			
Prepared for: California Department of Transportation Division of Research, Innovation and System Information Office of Roadway Research	**FHWA No.:** CA152356A	**Date Work Submitted:** October 2012	**Publication Date:** October 2016

Strategic Plan Element No.: SPE 3.18.2	**Caltrans Project No.:** 2356	**Status:** Stage 6	**Version No.:** 1

Abstract:

In the period 2012 to 2014, Caltrans designed and built three long-life asphalt pavement (LLAP) rehabilitation projects. Two projects were in District 2 on Interstate 5 and one was in District 4 on Interstate 80. This technical memorandum describes the processes by which performance-related test criteria were developed for a pavement section on the project on Interstate 5 just north of Red Bluff, California. The pavement section was designed and constructed as an LLAP section consisting of the following pavement components:

- A hot mix asphalt (HMA) surface course containing a polymer-modified asphalt (PG 64-28PM), 15 percent reclaimed asphalt pavement (RAP), and a representative aggregate from the Red Bluff area treated with 1.2 percent lime (marinated)
- An HMA intermediate course containing a conventional asphalt binder (PG 64-10) and the same lime-treated aggregate as the surface course plus 25 percent RAP
- An HMA rich bottom layer containing conventional asphalt binder (PG 64-10) and the same lime-treated aggregate as the intermediate course, and containing 15 percent RAP

Representative materials were obtained by Caltrans District 2 from the Red Bluff area for the testing to develop the design and performance-related specifications for this project. During the testing of these materials some changes were made in the mix specifications regarding the asphalt binder grade and the inclusion of RAP in the surface mix and in the rich bottom mix; these are described in this memorandum. Caltrans headquarters staff from the Office of Flexible Pavement (formerly the Division of Flexible Pavement) designed the structural pavement sections using material parameters developed from AASHTO T 320 shear testing and AASHTO T 321 fatigue and stiffness testing results. To properly establish testing protocols and parameters, it was also necessary to investigate traffic loading and environmental factors as part of the study. This testing produced the performance-related testing criteria that were included in the project specifications and bid documents. In addition to the AASHTO T 320 and 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. The HWTT results were not used in the design process.

Keywords:
Long-life asphalt pavement; reclaimed asphalt pavement (RAP); hot mix asphalt (HMA), shear, fatigue, stiffness and 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; following construction, provide systematic and periodic pavement performance evaluations for at least five years, 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).
- Signore, J. M., B.W. Tsai,, C. L. Monismith. 2014. Development of Hot Mix Asphalt Pavement Performance Properties for Long-Life Pavement Design: Caltrans District 2, Interstate 5, Weed, California. (UCPRC-TM-2014-04).
- Signore, J.M., and C.L. Monismith. 2014. 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**	I. Basheer **Caltrans Technical Lead**	T. J. Holland **Caltrans Contract Manager**

DISCLAIMER STATEMENT

This document is disseminated in the interest of information exchange. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This publication does not constitute a standard, specification or regulation. This report does not constitute an endorsement by the Department of any product described herein.

For individuals with sensory disabilities, this document is available in alternate formats. For information, call (916) 654-8899, TTY 711, or write to California Department of Transportation, Division of Research, Innovation and System Information, MS-83, P.O. Box 942873, Sacramento, CA 94273-0001.

PROJECT OBJECTIVES

The objectives of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 3.18.2 were to further develop methods for the mechanistic-empirical (M-E) design of flexible pavements, to validate and improve the process of flexible pavement design and rehabilitation, and to add new information to the State Standard Materials Library available in the design software *CalME.*

The long-life asphalt pavement (LLAP) design portion of this SPE had the following objectives:

1. Identification of pilot projects to be utilized for LLAP designs
2. Obtaining representative materials and establishing performance-related test specifications (criteria) for each of the mixes in the pavement design used on each project
3. Creating asphalt concrete (AC) long-life pavement designs, utilizing M-E concepts for each project

To accomplish these objectives, three long-life pavements were designed and constructed: one on Interstate 5 near Red Bluff, one on Interstate 5 near Weed, and one on Interstate 80 near Dixon.

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
CDF	Cumulative distribution function
CT	Caltrans
GC	Clayey gravel
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
PCC	Portland cement concrete
PPRC	Partnered Pavement Research Center
RAP	Reclaimed Asphalt Pavement
RB	Rich bottom
RSCH	Repeated simple shear test at constant height
RWC	Rolling wheel compaction
SF	Shift factor
SHRP	Strategic Highway Research Program
SPE	Strategic Plan Element
SSD	Saturated Surface Dry
SSP	Standard Special Provisions
TCF	Temperature Conversion Factor
UCPRC	University of California Pavement Research Center
WIM	Weigh-in-motion

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

1.1 Background

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 in that district 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, PM 37.0 – PM 41.5 NB/SB) and the other is north of the City of Weed (Siskiyou County, PM 19.0 – PM 25.3 NB/SB). In 2012, a third LLAP project was initiated on Interstate 80 in District 4 (Solano County, PM 30.6 – PM 38.70). *(Note:* In this memorandum, these are referred to as the Red Bluff, Weed, and Solano projects, respectively.) A decision was made to conduct these projects under Caltrans/UCPRC Partnered Pavement Research Center Strategic Plan (PPRC SPE) Number 3.15, which was changed soon after to PPRC SPE 3.18.2.

This memorandum documents the collaboration between Caltrans and the UCPRC to finalize the mix designs, to perform laboratory mix testing, and to establish the performance criteria for construction of the Red Bluff section (This memo also occasionally addresses the Weed Project, which was conducted somewhat concurrently).

1.2 The Specification Development Process

Long-life pavement design in California is based on lessons learned from the construction of the state's first LLAP project, the multiphase rehabilitation of the Long Beach Freeway, I-710, in Los Angeles County, which began in 2001. Monismith et al. *(1)* summarized the lessons learned from the initial design through the performance of that project after five years of traffic.

The current process for developing a performance specification for long-life asphalt concrete (AC) mix designs requires a series of steps, including the selection of a location (including route and post mile range) and the development of a conceptual pavement design, which in this case were both accomplished by Caltrans (see Section 1.2.1).

1.2.1 Red Bluff Long-Life Asphalt Pavement Design

The Red Bluff long-life asphalt pavement (LLAP) section was selected by District 2 staff and then designed by Caltrans headquarters staff using the *California Mechanistic-Empirical Analysis and Design* software program (*CalME)* design methodology. The existing pavement primarily consisted of thick HMA above cement-treated base (CTB), with a number of areas where the HMA was stripped at different depths below the surface. The HMA had extensive alligator cracking in the wheelpaths and some cracking between the wheelpaths. The pavement design assumed that the existing HMA layers would be removed, while the CTB, which was thought to be generally intact based on coring and deflection testing, would be left in place.

Based on the availability of reclaimed asphalt pavement (RAP) materials, 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 familiarity of District 2 staff with a number of aggregate sources in the district, 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, which is the application of dry lime on damp aggregate.

After a review of as-built information and use of *CalME* mechanistic-empirical design software by staff from Caltrans headquarters and the UCPRC—and after consideration of the binder grades for the project area, the structural condition of the pavement, and other distress types, including low temperature cracking—it was decided that the pavement layers for the structural section for Red Bluff should consist of the following components:

- A hot mix (HMA) surface course containing a polymer-modified asphalt (PG 64-28PM) containing 15 percent RAP and a representative aggregate from the Red Bluff area treated with 1.2 percent lime (marinated)
- An HMA intermediate course containing a conventional asphalt binder (PG 64-10) and the same lime-treated aggregate as the surface course plus 25 percent RAP
- An HMA rich bottom layer containing conventional asphalt binder (PG 64-10) and the same lime-treated aggregate as the intermediate course containing 15 percent RAP

After Caltrans delivered this information to the UCPRC, along with aggregates and asphalt materials considered to represent those that potential bidding contractors would use to construct the Red Bluff pavement, UCPRC commenced development of the performance-based specification following the steps presented in Section 1.2.2.

1.2.2 Development of Performance-Based Specifications by UCPRC

As noted, the LLAP Technical Working Group agreed that UCPRC staff would: (1) conduct the necessary performance tests; (2) provide the required data for the structural pavement designs to Caltrans staff; and (3) provide the requisite data for the mix performance requirements based on laboratory testing and the traffic and environment (temperature) in the locations of the three long-life projects. UCPRC staff accomplished this and developed the specifications for all the asphalt concrete (AC) mixes proposed for each location by following these steps in Project SPE 3.18.2:

1. Working with local District Materials Engineer (DMEs) and the Division of Asphalt Pavement (later changed to the Office of Asphalt Pavement), the UCPRC developed mix designs from the materials identified as potential sources of aggregate and binder that local contractors might use.
2. Using site-specific temperature data (in this case, from the Red Bluff area) and corresponding traffic data provided by Caltrans, UCPRC developed the minimal performance requirements (i.e., performance specifications) for AASHTO T 320[1] (Repeated Simple Shear Constant Height, RSCH) testing, which is based on the procedure developed by UCPRC researchers and reported in SHRP-A 415 (*7*).
3. UCPRC performed RSCH testing at the climate-based temperature calculated in Step 2 to determine the Optimum Binder Content (OBC) for the mixes using the materials identified by District 2.
4. Following AASHTO T 321 (flexural fatigue and stiffness), UCPRC laboratory staff prepared specimens at the mix OBCs developed in Step 3, and then tested them. Subsequent statistical analyses of the T 321 test results were conducted and, based upon these results, flexural fatigue and stiffness specifications (i.e., performance requirements) were developed.
5. Moisture sensitivity testing was accomplished using the HWTT, which was conducted at 50°C. The test parameters (i.e., performance requirements) recommended were those included in the Caltrans standard specifications: 12.5 mm maximum rutting at 20,000 cycles.

Once this process concluded, the UCPRC provided performance-based specifications to Caltrans that were specific for the construction of the Red Bluff project. The same process was used for the Weed project using materials identified by District 2 near that site, and for the Solano project using the Red Bluff materials data and traffic and pavement temperature data specific to the Solano site.

[1] Modified according to the Lab Procedure, LLP-AC2, “Sample Preparation and Testing for Long-Life Hot Mix Asphalt Pavements,” available at *www.dot.ca.gov/hq/esc/Translab/ormt/pdf/LLP-AC2_Sample_Preparation_for_LL_HMA-Pavement.pdf*.

This technical memorandum details these steps as they were carried out for the Red Bluff Project. References *(2)* and *(3)* are technical memoranda that describe similar information for the Weed and Solano projects, respectively.

Chapter 2 of this memorandum discusses the aggregates, asphalt binder, reclaimed asphalt pavement (RAP), and lime materials used to create the Red Bluff test specimens. Chapter 3 discusses the traffic and temperature estimates used to design and to determine material testing parameters. Chapter 4 presents the results of the laboratory testing of the HMA mixes. Chapter 5 covers the development of the mix performance criteria for shear (RSCH test), fatigue, and mix stiffness. Chapter 6 presents the recommended test specifications for shear, fatigue, mix stiffness, and HWTT (the current Caltrans specification). Chapter 7 presents a project overview and a recommendation based on this work. Appendixes A through E present the detailed results of the performance-based testing.

2 MATERIALS

The asphalt mixes used to develop the structural designs were selected by District 2 to be representative of locally available materials, including the aggregate, asphalt, and RAP. These materials were used to produce the surface course, intermediate course, and rich bottom mix used in the structural cross section.

2.1 Aggregates

The materials supplied by District 2 were used to put together aggregate gradations that met Caltrans specifications. The virgin aggregate samples for the Red Bluff Project obtained by District 2 staff originated from Clear Creek near Redding. The samples included four fractions termed *dust, sand, 3/8 in.*, and *3/4 in.* Gradings from representative samples of each fraction were determined by wet sieving. The grading results were then used to prepare mixes with varied binder contents for use in mix design and performance testing. Two gradings were required for the Red Bluff Project: one with RAP (25 percent) and one without RAP. The grading results are presented in Figure 2.1. The aggregates' properties were supplied by District 2 staff and are summarized in Table 2.1.

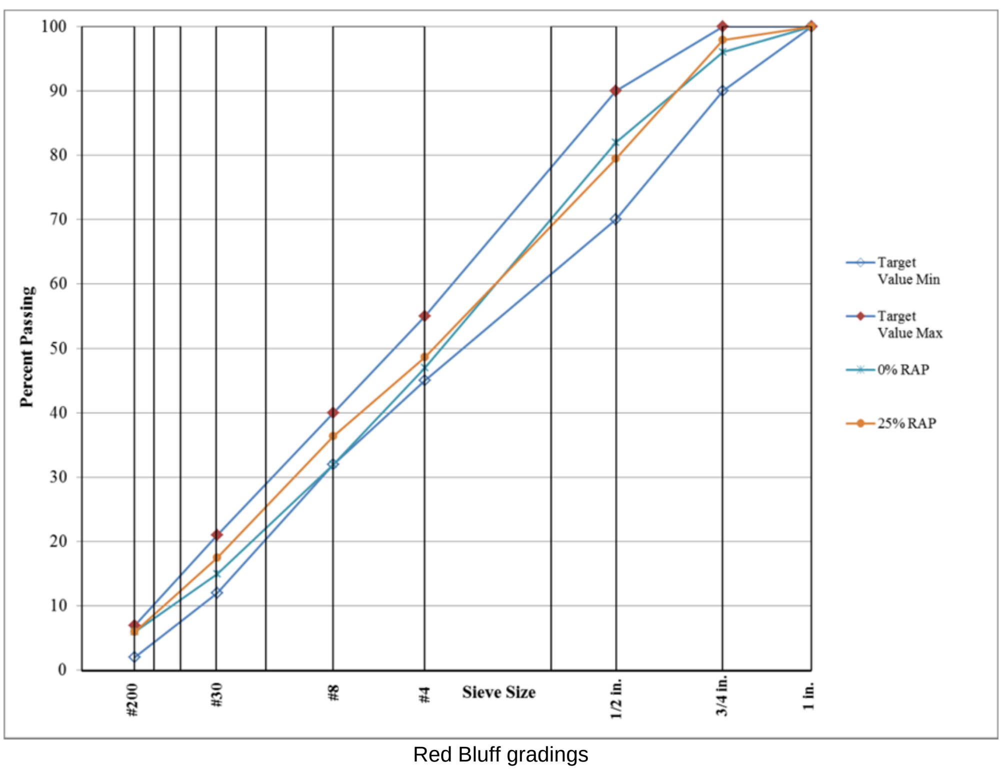


Figure 2.1: Red Bluff Project aggregate gradings with 25 percent RAP and without RAP.

At the outset of the project, it was agreed that RAP would not be used in the surface course. The performance tests (shear, fatigue, and HWTT) were performed on this mix. After the tests were completed, and just prior to construction, District 2 staff made the decision to introduce 15 percent RAP into the mix. Because the contract documents had been already prepared and there was no time to test this mix with RAP, the performance criteria in the specification were based on the mix without RAP.

Table 2.1: Aggregate Properties

		Redding Clear Creek			**Caltrans Spec.**
	Date Tested:	**6/07**	**5/08**	**7/08**	
Test Method	**Property**				
CT 205	Crushed particles, coarse aggregate Two fractured face (%)			98	98
	Crushed particles, coarse aggregate One fractured faces (%)		99	96	
	Crushed particles, fine aggregate (#4x#8) One fractured face (%)		98	97	98
CT 211	LA Rattler, loss at 100 rev. (%)	5	5	5	10
	LA Rattler, loss at 500 rev. (%)	20	22	23	25
CT 217	Sand equivalent (avg.)	52	65	64	50
AASHTO T 304 (Method A)	Fine aggregate angularity (%)			45.8	45
ASTM D4791	Flat and elongated particles % by mass @ 3:1				
	Flat and elongated particles % by mass @ 5:1			0	Report
CT 204	Plasticity index			NP	
CT 229	Fine aggregate durability index	79	77		65
	Coarse aggregate durability index	80	80		50
CT 303	K_c factor (not mandatory until further notice)				
	K_f factor (not mandatory until further notice)				
CT 206	Bulk specific gravity (oven dry), coarse aggregate	2.62	2.65	2.639	
	Absorption, coarse aggregate	1.0	1.3	1.3	
CT 207	Bulk specific gravity (SSD) of fine aggregate			2.527	
LP-2	Bulk specific gravity (oven dry) of fine aggregate			2.451	
CT 207	Absorption of fine aggregate			3.1	
CT 208/LP-2	Apparent specific gravity of supplemental fines			2.381	
LP-2	Bulk specific gravity of aggregate blend			2.575	
CT 208	Specific gravity of fines apparent	2.64			

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, which are summarized in Table 2.2, were obtained from Certificates 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 Red Bluff project specifications. While a PG 64-10 binder was called for, the PG 64-16 binder was acceptable to Caltrans since it met all of the specification requirements for the PG 64-10 binder based on a comparison 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.*

Table 2.2: Binder Properties: Red Bluff Project

Property	Caltrans Spec. PG 64-16	Test Results Red Bluff (PG 64-16)	Caltrans Spec. PG 64-28PM	Test Results Red Bluff (First Supply of PG 64-28PM	AASHTO Test Method
	Original Binder				
Flash Point, Min. C.O.C., ºC	230	296	230	276	T 48
Viscosity at 135ºC; Pa.s	3.0	0.430	3.0	0.740	T 316
Dynamic Shear: Test Temp, ºC	64	64	64	64	T 315
Min. G*/sinδ, kPa	1.0	1.61	1.0	1.64	
Solubility in TCE Percent, Min.	99	100	98.5	99.9	T 44
	RTFO Test Aged (RAP) Binder				
RTFO Test Mass Loss, Max. %	-1.0	-0.121	-1.0	-0.249	T 240
Dynamic Shear: Test Temp. ºC	64	64	64	64	T 315
Min. G*/sinδ, kPa	2.20	3.95	2.20	3.12	
Max. δ@G*sinδ = 2.2 kPa, degrees	n/a	n/a	80	64	
Min. Ductility at 25°C, cm	75	100+	n/a	n/a	T 51
Min. Elastic Recovery@25%	n/a	n/a	75	84	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	1,010	
Bending Beam Rheometer: Test Temp. °C	-6	-6	-18	-18	T 313
Max. S-Value, MPa	300	79	300	72	
Min. M-Value	0.300	0.386	0.300	0.356	

n/a, not applicable

Valero supplied PG 64-28PM twice. The first supply, taken from the last of Valero's 2010 production (from a very limited supply that they were required to keep on hand), was delivered in October 2010 and the second one was delivered in June 2011. The timing of the delivery of the first batch supplied allowed UCPRC staff to start mix performance testing early in 2011 and enabled development of the mix performance criteria in time to meet the deadline for issuance of the bid documents.

The first supply of PG 64-28PM was tested October 5, 2010, and the second on June 4, 2011, by the Valero laboratory. Test data from the first supply of PG 64-28PM binder are shown in Table 2.2. The PG 64-16 binder was tested by the Valero laboratory on December 13, 2010; these binder test data are also included in Table 2.2.

2.3 Reclaimed Asphalt Pavement Material

District 2 staff provided the UCPRC with a supply of RAP considered to be representative of the HMA in the existing pavement near the proposed Red Bluff Project rather than the actual RAP to be used for the project because the latter was unavailable in sufficient quantities at the time of mix testing. In addition to this supply of surrogate RAP for mix testing, a number of 3 inch (75 mm) diameter cores of the HMA pavement layer(s) were extracted from the existing pavement for testing. The cores and other RAP material were sent to the MACTEC Laboratory in Phoenix, Arizona so their extracted binder properties and the approximate binder contents of the RAP millings and cores could be determined along with the gradations of the extracted aggregates. The PG 64-16 binder supplied by Valero was also sent to MACTEC to determine the binder properties of blends of the new (virgin) binder and of the binders extracted from the cores from the existing pavement and the RAP millings from another source. Blends of the two extracted binders were obtained using the extracted binder contents from the cores and RAP millings, the proportion of RAP, and the estimated binder content of 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 test results on the binders extracted from the cores and RAP millings. Tests performed on blends of the PG 64-16 and the RAP-extracted and core-extracted binders were based on the following:

- Binder contents determined by extraction were 4.77 percent for the cores and 5.51 percent for the RAP millings.
- Mixes containing virgin aggregate blended with 25 percent RAP from each of the sources were assumed to have a binder content of 5.0 percent (by weight of aggregate basis).

The results of tests on blends of the PG 64-16 and the extracted binders from the cores and RAP millings are summarized in Table 2.4. It should be noted that the resulting two blends in Table 2.4 produced the same PG 70-22 grade classification although the second blend containing the millings resulted in a slightly higher

PG binder high temperature grade, 75°C versus 73°C, for the core data. These results suggest that using the binders with added RAP in the Red Bluff project should not result in a rutting problem. Fatigue performance, on the other hand, is affected by: HMA stiffness; level of tensile strain; layer thickness; and location of the layer in the pavement structure. Because of this complexity, it is not possible to make a similar statement regarding the effects of the blended binder on fatigue performance, as it is possible for rutting.

Table 2.3: Binder Properties for December 2010 Valero Binder, Binder from Cores, and Binder from RAP Determined from 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

As was noted previously, the decision to allow 15 percent RAP in the surface PG 64-28PM mix and in the PG 64-10 rich bottom mix was made after all testing discussed in this report was concluded. The results shown in this technical memorandum for those mixes are for specimens made without RAP.

Table 2.4: Binder Properties for December 2010 Valero Binder and for Blends of Valero Binder and Extracted Binders Determined from MACTEC Tests

Property	Caltrans Spec.	Test Results Valero PG 64-16 (12/13/10) Sample	Test Results, Blend of Valero Binder and Extracted Binders		AASHTO Test Method
			From Core Samples	From RAP Millings	
	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 and that lime treatment should follow the process of marination rather than be added as dry lime on damp aggregate. Caltrans Laboratory Procedure LP-7 *(4)* was followed to marinate the aggregate for the preparation of the performance test specimens. It should be noted however that because of the necessity to complete the mix performance tests in time to meet the deadline for the SSP for the bid document, shear tests on the mix with PG 64-28PM binder were completed before a decision was made by District 2 Staff to include lime in this mix.

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

Traffic data were obtained from recorded Caltrans weigh-in-motion (WIM) data within the area of the Red Bluff Project (WIM stations, WIM812 and WIM846). Following the model established in the I-710 Phase 1 LLAP Project *(1),* traffic estimates were based on the first five years after opening of the rehabilitated sections to traffic: 12.6 x 10^6 ESALs based on a 3 percent linear annual growth rate. To be conservative, this value was increased to 15.0 x 10^6 ESALs.

These estimates were used to determine the requirements for the shear test results based on the premise (and experience) that as long as the mix is properly designed and constructed, the majority of rutting in the HMA layer will occur during the first five years *(1, 5, 7).*

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

3.2 Pavement Temperatures for Shear Testing

Temperature data covering a period of years for the Red Bluff Project were obtained from the UCPRC pavement temperature database, the National Climate Data Center (NCDC), and the UCPRC weather station database. This temperature information was then used to determine the temperature for shear testing of the HMA. Test temperature selection was based on estimation of pavement temperatures at a 2 in. (50 mm) depth in the HMA. Selection of this depth was based on analyses that suggest that the maximum shear stress from tires that leads to rutting occurs at the edge of the tire at about this depth *(1).* The appropriate test temperature was determined using the following process:

- The seven-day moving average pavement temperature at the nearest major weather station to Red Bluff in the UCPRC pavement temperature database, which was Sacramento, is shown in Figure 3.1. 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 for a period of thirty years were used (01/01/1961 to 12/31/1990). Although this data is from a prior period, the changes in peak air temperatures have not changed enough since then to warrant recalculation of the pavement temperature database. Assumptions for this computation included an albedo of 0.95, 10 inch (254 mm) thick asphalt, and constant temperature of 4°C (9°F) at depth of about160 inches (4 m).

- Air temperature data for Sacramento, Red Bluff, Redding, and Cottonwood, shown in Figure 3.2, were used to adjust the pavement temperature at 2 inches depth for Red Bluff (the three sites on Interstate 5 provided a satisfactory measure for air temperature for the project site). The data for Redding, Red Bluff, and Sacramento come from the NCDC database for the ten-year period of 2001 to 2010, and the Cottonwood data come from a database of temperatures taken by UCPRC at the Cottonwood Highway Patrol load control station for the period from November 2002 to August 2006. The air temperature data indicate that pavement temperatures at Red Bluff, Redding, and Cottonwood at the 95th percentile are about 5°C (2.7°F) higher than at Sacramento, hence a temperature of 55°C (131°F) was selected for shear testing at the Red Bluff Project.

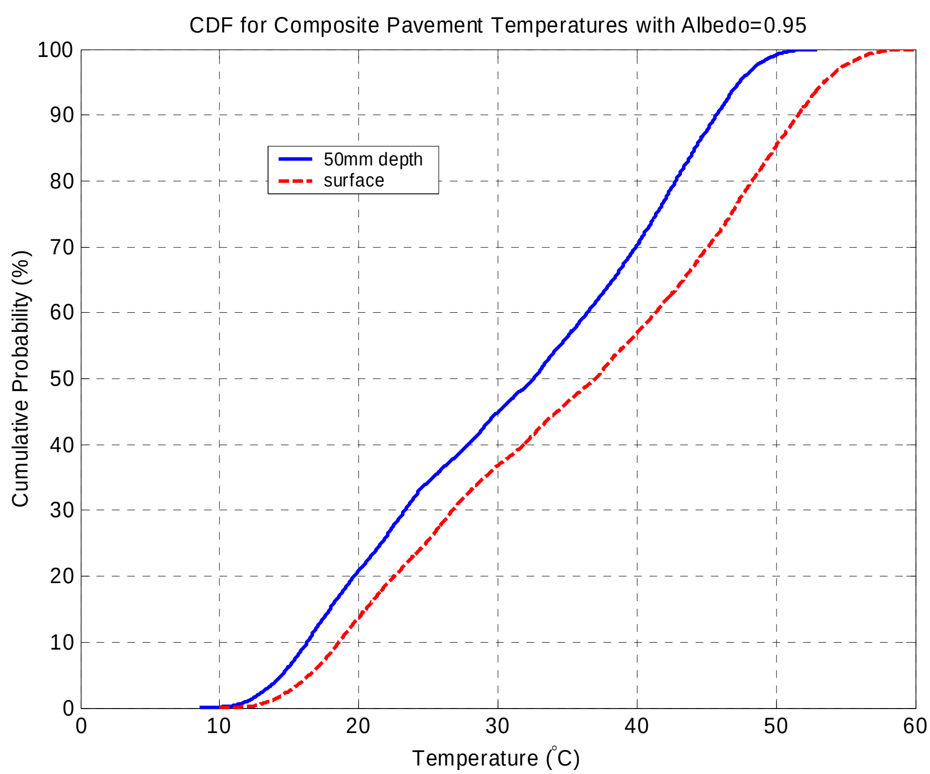


Figure 3.1: Seven-day moving average of maximum daily surface temperatures and temperatures at a 2 inch depth for Sacramento based on an analysis using the ICM.

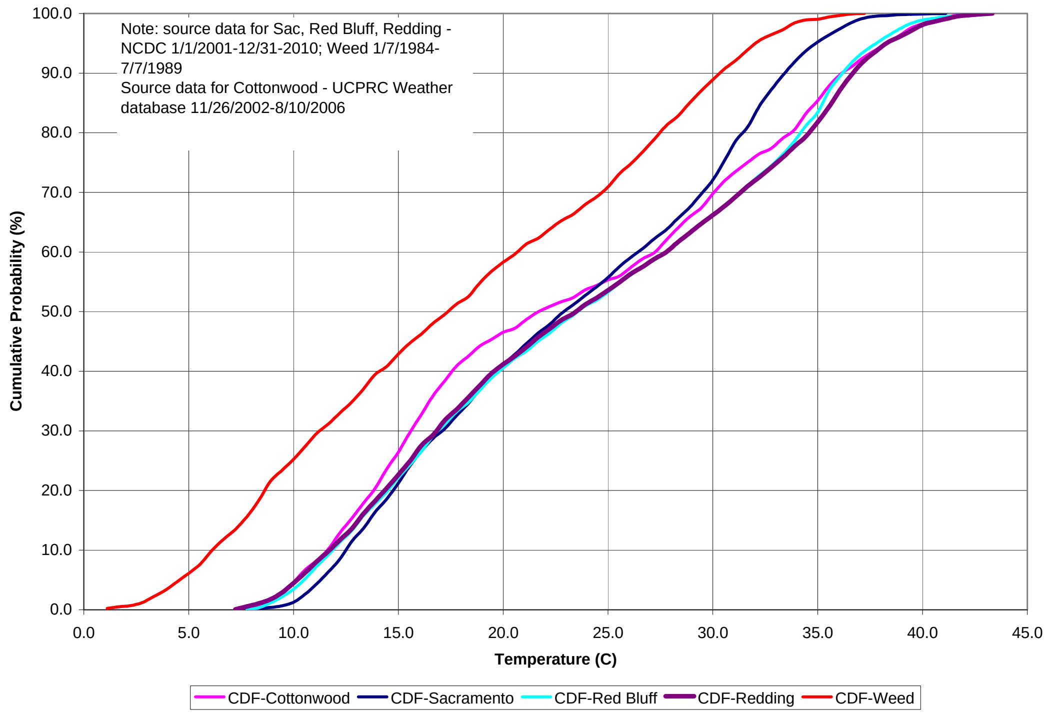


Figure 3.2: Seven-day moving average of maximum daily air temperatures for Cottonwood, Sacramento, Red Bluff, Redding, and Weed.
(Note: CDF = cumulative distribution function)

4 MIX TESTING

The UCPRC subjected samples of the proposed Red Bluff 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 Red Bluff Project.
- AASHTO T 321 (ASTM D7460), the flexural fatigue and frequency sweep test, was used to determine mix fatigue response and stiffness 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. This compaction method was used because the aggregate structure prepared by this method is similar to that obtained in mixes during pavement construction *(5).* Rolling wheel compaction, which was used for a number of years by organizations in Europe (e.g., Royal Dutch Shell and the French LCPC), was developed during the Strategic Highway Research Program and published as AASHTO PP3-94. The HWTT specimens were prepared by Superpave Gyratory Compaction because this is the current requirement in AASHTO T 324.

To define the performance requirements, the UCPRC modified the AASHTO procedures and those modifications have been reflected in the Caltrans Flexible Pavement Test Method LLP-AC2 *(6).* The modifications are detailed in the footnotes to Table 6.1, which shows the HMA performance requirements for the Red Bluff 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. Based on the testing regime described in Section 3.2, a shear testing temperature of 55ºC was selected to determine the shear test results to select the design binder content for the project's performance test specifications. Table A.1 through Table A.4 in Appendix A summarize the complete shear test data.

Initially it was agreed that no lime would be used in the mixes for this project. However, after the initial testing was completed with the PG 64-28PM mix, Caltrans made a decision to add 1.2 percent lime to the three mix types. Because of time constraints, selection of the design binder content for the PG 64-28PM was based on the results of tests without lime. Subsequent testing (shear, stiffness and fatigue, moisture susceptibility) was conducted on lime-treated mix for all mixes. These data are summarized in Table A.1.

Figure 4.1 illustrates 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, in this case for the PG 64-28PM mix. In terms of the numerical value of repetitions, the median values at 5.0 and 5.5 percent were approximately 2 x 10^9 and 9 x 10^6, respectively, a significant reduction in cycles with binder content increase from 5.0 to 5.5 percent. Based on the shear testing data, and following the SHRP-A-415 design process, a design binder content of 5.2 percent (by weight of aggregate) was selected for the PG 64-28PM mix since the mix appeared to be a critical mix, in that small changes to binder content resulted in large differences in shear testing performance. A comparable process was followed for the PG 64-10 25 percent RAP mix; detailed test results are presented in Appendix A.

Because the decision to add 1.2 percent lime was made after these data were obtained and because of time constraints, this information served as the basis for the mix testing for the PG 64-28PM mix containing 1.2 percent lime and the PG 64-10 mix with 25 percent RAP and 1.2 percent lime. Table A.2 and Table A.3 present these test data.

It should also be noted that no shear tests were required for the rich bottom mix since it is located at a depth where the shear stresses from tires would not have a significant effect on rutting, and the pavement temperature would be less than the upper part of the pavement section.

In the Special Provisions for the Red Bluff Contract (No. 02-3E8104), dated September 19, 2011, performance requirements for the PG 64-28PM mix with lime include 15 percent RAP. It must be emphasized that the performance requirements sent to Caltrans presented in this tech memo for the PG 64-28PM mix with lime are based on tests without RAP.

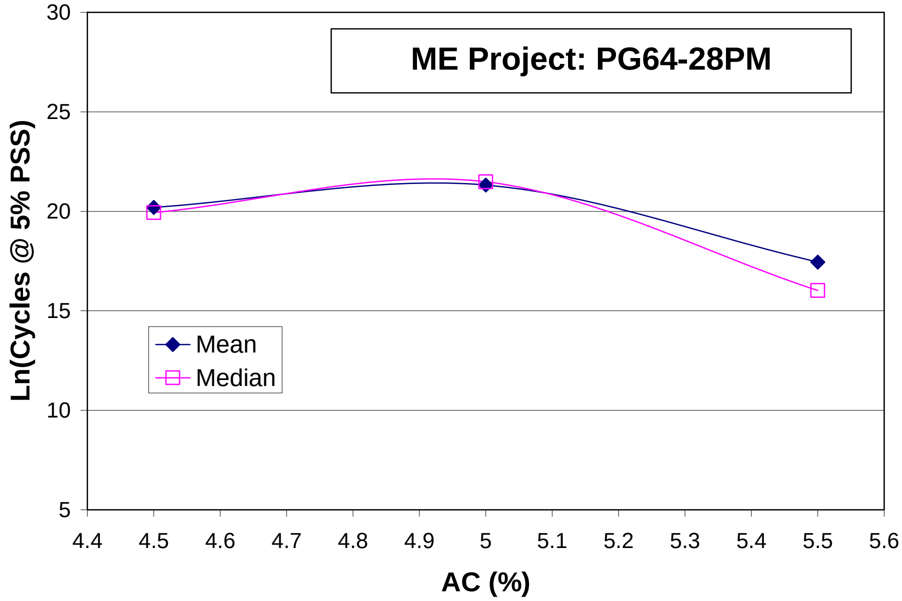


Figure 4.1: Ln (repetitions to 5 percent γ_p) versus binder content at 55ºC for Red Bluff PG 64-28PM mix (without lime).

4.3 Fatigue and Stiffness Test Results

After the optimum binder contents of the project mixes were determined, fatigue testing was conducted to determine the cracking performance and bending stiffness requirements for the specification. Fatigue test data were obtained at 10ºC, 20ºC, and 30ºC. Frequency sweep test data were obtained at the same three temperatures for a range in frequencies from 0.01 Hz to 15.2 Hz (Table B.2 through Table B.4 present the flexural stiffness measurements on beam test specimens). Master curves of stiffness versus frequency were developed from the data contained in Table B.2 through Table B.4. Table B.5 presents the coefficients for these curves, the equations for which are shown in the table footnotes. These equations 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 the ln(strain) versus ln(Nf) based on the Red Bluff project mix test data. Figure 4.3 contains the plots of the stiffness master curves (defined as E*) shifted to 20ºC as a function of frequency for the Red Bluff Project. Figure 4.4 summarizes the shift factor, a_T, as a function of temperature.

It is important to note that the frequency sweep data (shown in Table B.2 through Table B.5) and the resulting stiffness master curves were required for the design of the structural pavement sections using the *CalME* design methodology and were not required for the mix performance specifications. Stiffness data for the specifications were taken from the initial stiffness in the flexural fatigue test data.

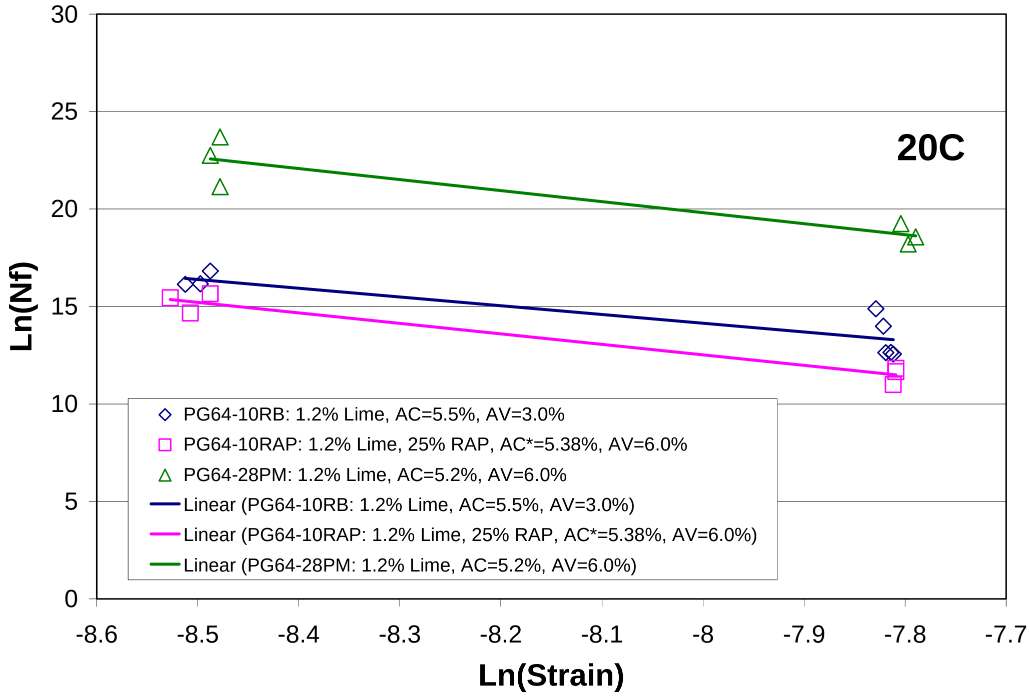


Figure 4.2: Fatigue test summary for the Red Bluff project.

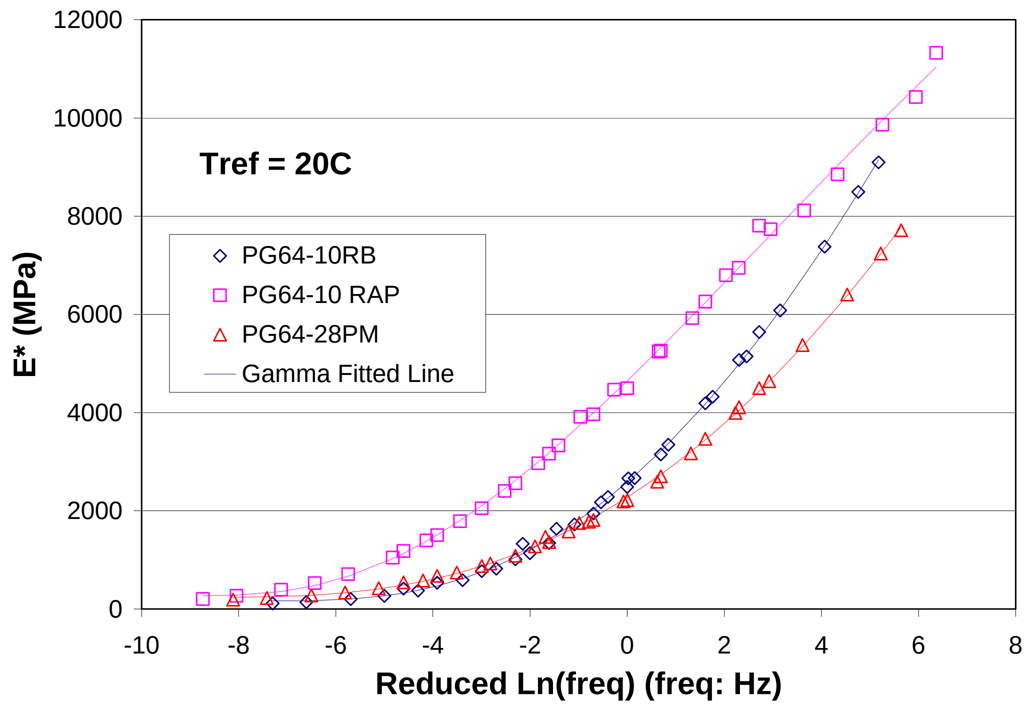


Figure 4.3: Summary of stiffness (E*) master curves, Red Bluff project.

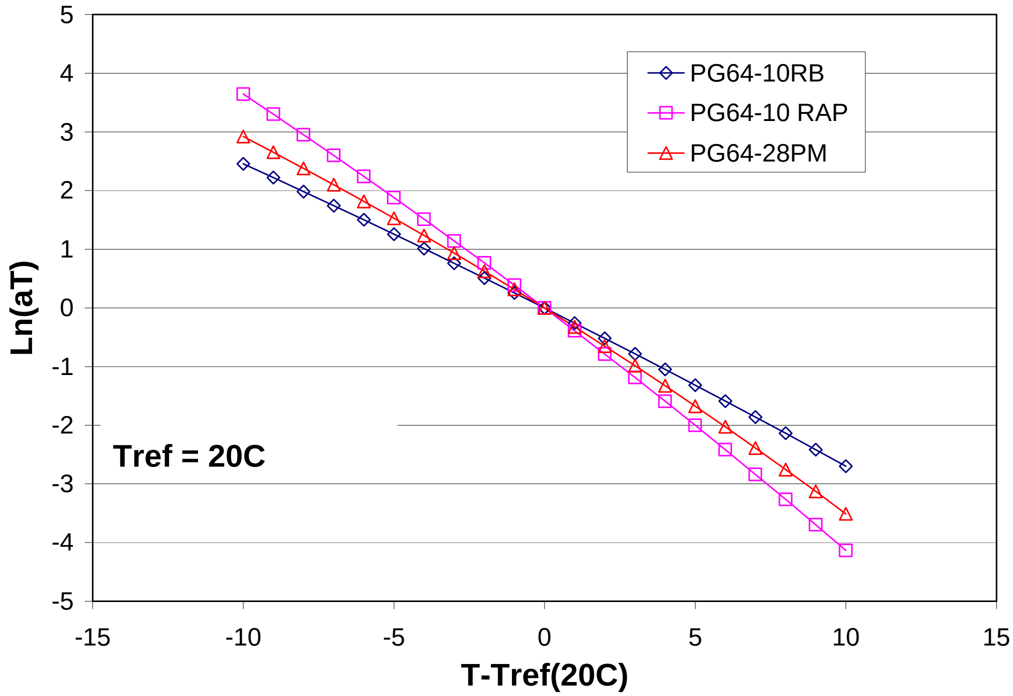


Figure 4.4: Summary of temperature-shifting relationship (ln a_T), Red Bluff project.

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, data are based on the frequency sweep test at 10 Hz. (*It should be emphasized that frequency sweep tests are only required for the 30°C stiffness values and that it is only necessary to perform the frequency sweep test at one frequency.)*
- 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 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 *(6)*. The modifications are detailed in the footnotes to Table 6.1, which shows the HMA performance requirements for the Weed project.

4.4 Hamburg Wheel-Track Testing Results

Hamburg Wheel-Track Testing (HWTT) was conducted to determine the moisture sensitivity performance requirements for the mixes in this project. HWTT data are included in Figure 4.5 through Figure 4.7 (Appendix C contains a summary of the individual test results.) The rut depth data shown in Figure 4.5 through Figure 4.7 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. 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 as well as the smoothed "Number of Passes."

Appendix D also contains data from the CT 371 tests performed on the various mixes for the Red Bluff project.

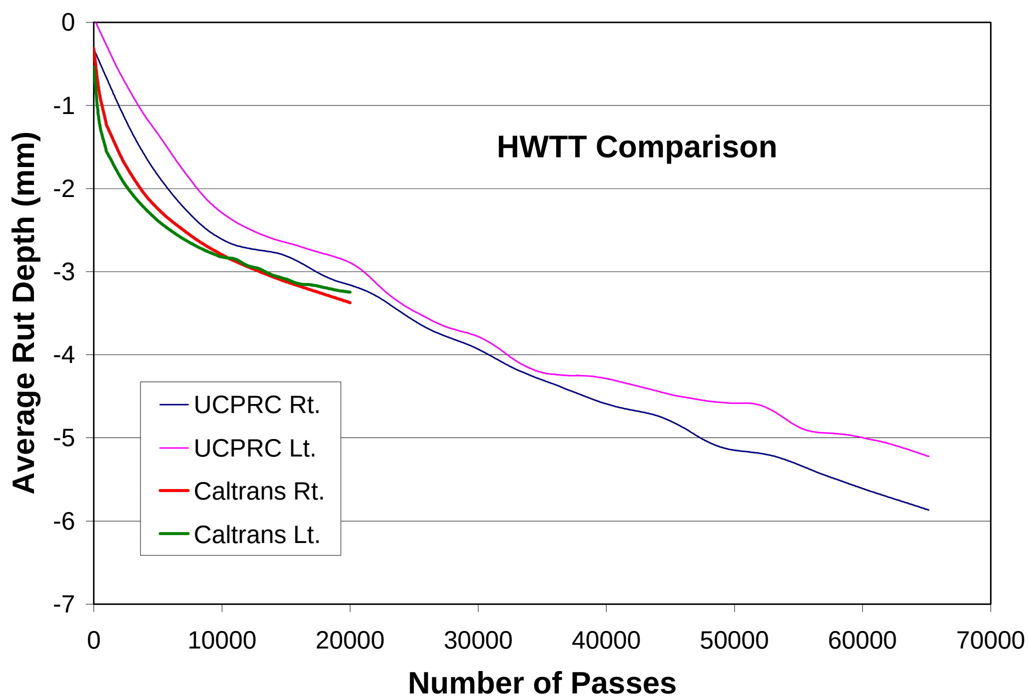


Figure 4.5: Summary of average rut depths (PG 64-10 RAP with lime), Red Bluff Project.

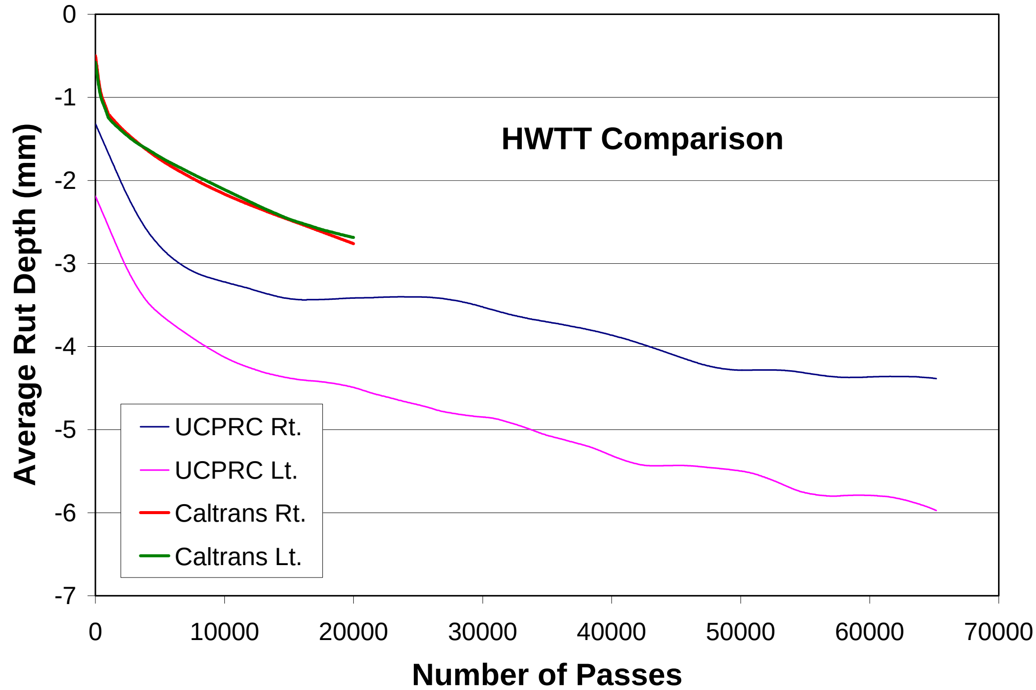


Figure 4.6: Summary of average rut depths (PG 64-10 RB with lime), Red Bluff Project.

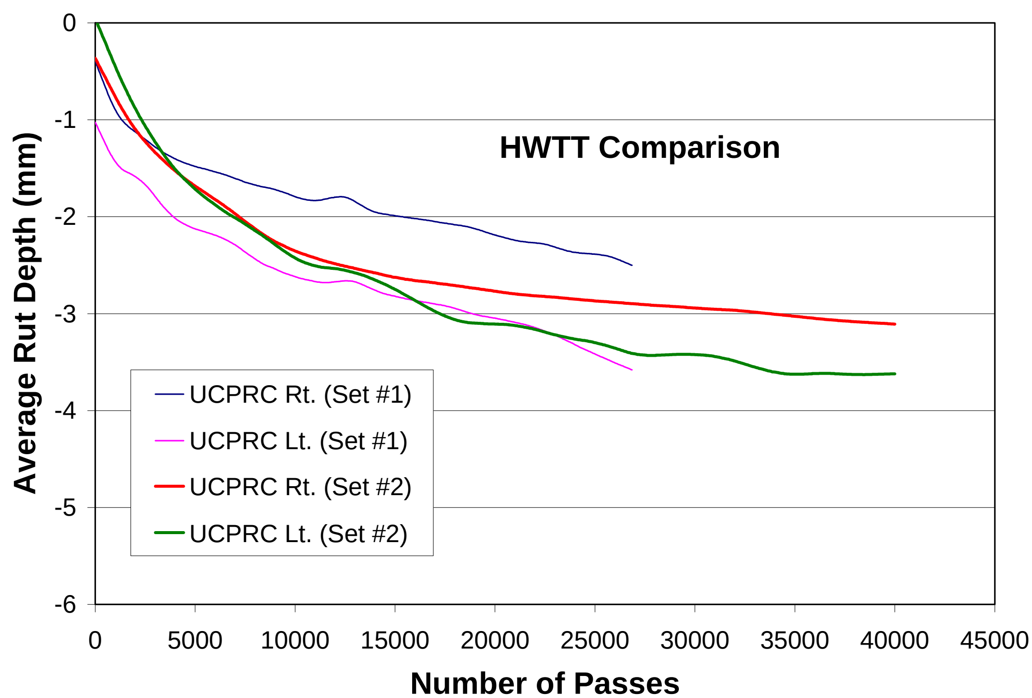


Figure 4.7: Summary of average rut depths (PG 64-28PM with lime), Red Bluff Project.

5 DEVELOPMENT OF FATIGUE AND SHEAR 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 *(7)*. 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. An example of this is shown in Figure 5.1 for the PG 64-10, 15 percent RAP, rich bottom (RB) mix. The lower bound represents the lower 95 percent confidence interval. This lower value is recommended for specification purposes.

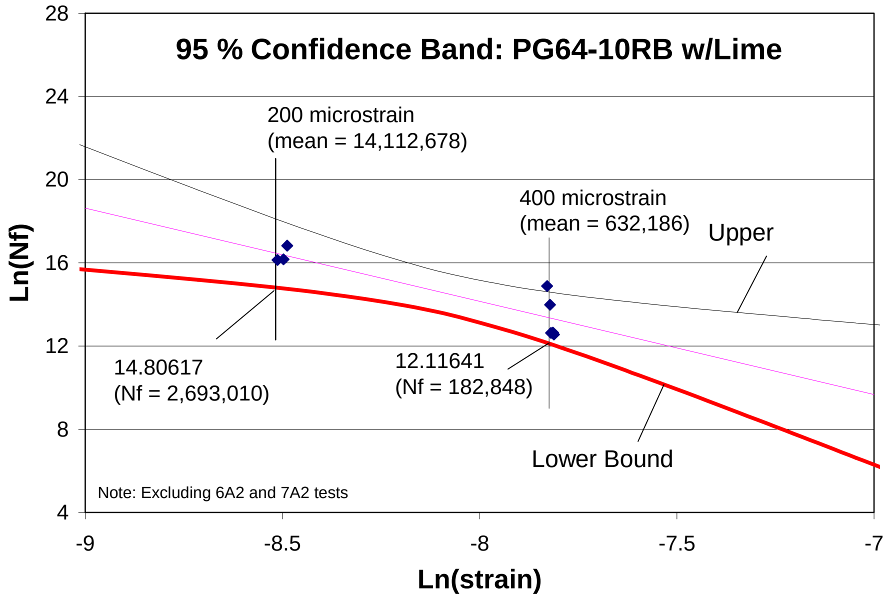


Figure 5.1: Fatigue 95% confidence bands (PG 64-10 15% RAP RB with 1.2% lime, AC = 5.5%, AV = 3%; [excluding 6A2 and 7A2 tests]).

5.3 RSCH Specification Development

As with the I-710 freeway *(1)* project, the criteria for the Red Bluff mix designs were selected to accommodate the traffic estimated for its first five years of operation. Based on the available traffic data, the design value for this five-year period was 15 x 10^6 ESALs. After this value was determined, the RSCH criteria listed in Table 6.1 were then developed according to the following equations:

$$(N_{supply}) \geq M \cdot (N_{demand}) \quad \textbf{(5.1)}$$

N_{demand} was determined as follows:

$$N_{demand} = \text{Design ESALs} \cdot TCF \cdot SF \quad \textbf{(5.2)}$$

where:

TCF = temperature conversion factor; estimated to be 0.12 for California as shown in *(7)*
SF = shift factor, value of 0.04 was used as developed in *(7)*

The development of the parameters for $N_{demand,}$ TCF and SF is documented in the SHRP-A-415 research report *(7)*. 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 *(7)*, was used based on RSCH test variance *(7)* and an estimate in the variance in ln (ESALs). This value was also taken from a table in Chapter 15 of A-415 *(7)*. For the Red Bluff Project, with its estimated traffic of 15×10^6 and the factors shown in Equations (5.1) and (5.2), N_{supply} was estimated to be 360,000 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 by a significant amount for the Red Bluff Project. Consequently, the analyses described in Chapter 4 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. 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 data used to develop the 95 percent confidence bands shown in Figure 5.1 are included in Appendix E, Table E.1. In this figure, the 95 percent confidence bands are based on eight of ten fatigue test results (three at 200 x 10^{-6} strain and five at 400 x 10^{-6} strain) for the mixes included in Table B.1. The suggested specification requirements for this mix are shown in Table 5.1. In Appendix E, Figure E.1 through Figure E.6 contain the results of the other analyses for all three mixes. The recommendations in Table 5.1 for the PG 64-10 RAP mix are based on the analysis shown in Figure E.2, and the specifications for the PG 64-28PM mix are based on the analyses shown in Figure E.5.

A similar approach was used to develop the stiffness requirements shown in Table 5.2.

Table 5.1: Suggested Fatigue Performance Requirements at 200 x 10^{-6} and 400 x 10^{-6} Strain

Mix Type	Min. Requirements for Fatigue Life Repetitions at at 20°C		Regression Line Requirement
	200 microstrain	400 microstrain	
PG 64-10 15% RAP RB with 1.2% lime	2,693,010	182,848	Regression line has to be above the lower bound
Suggested	2,700,000	182,000	
PG 64-10 25% RAP with 1.2% lime	935,232	24,933	Regression line has to be above the lower bound
Suggested	950,000	25,000	
PG 64-28 PM 15% RAP with 1.2% lime	345,053,136	23,123,732	Regression line has to be above the lower bound
Suggested	345,000,000	23,000,000	

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 64-10 RB 15% RAP with 1.2 lime was based on Figure 5.1 (excluding 6A2 and 7A2 tests).
3. The lower bound of PG 64-10 25% RAP with 1.2% lime was based on Figure E.2 (using all seven data points).
4. The lower bound of PG 64-28PM 15% RAP with 1.2% lime was based on Figure E.5 (excluding 1D2 test).

Table 5.2: Suggested Flexural Stiffness Performance Mixes

Mix Type	Flexural Stiffness at 20°C (10Hz) 95% Confidence Interval		Flexural Stiffness at 30°C (10Hz) 95% Confidence Interval	
	Lower Bound MPa (psi)	Upper Bound MPa (psi)	Lower Bound MPa (psi)	Upper Bound MPa (psi)
PG 64-10 RB with 1.2% lime	5,362 (777,692)	7,008 (1,016,425)		4,760 (690,380)
Suggested (psi)	790,000	1,000,000	220,000	No limit recommended
PG 64-10 RAP with 1.2% lime	5,997 (869,791)	6,965 (1,010,188)	801 (116,175)	5,134 (744,624)
Suggested (psi)	870,000	1,000,000	No limit recommended	No limit recommended
PG 64-28PM with 1.25 lime	2,822 (409,297)	3,354 (486,457)	1,497 (217,122)	1,662 (241,053)
Suggested (psi)	415,000	486,000	No limit recommended	No limit recommended

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 RECOMMENDED MIX PERFORMANCE SPECIFICATIONS FOR RED BLUFF

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: Recommended HMA Mix Performance Requirements for Red Bluff Project

Design Parameters	Test Method	Requirement
Permanent deformation (minimum): PG 64-28PM (with lime)[2a] PG 64-10 (with RAP and lime)[2b]	AASHTO T 320 Modified[1]	 360,000 stress repetitions[3,4] 360,000 stress repetitions[3,4]
Fatigue (minimum): PG 64-28PM (with lime)[5a,6] PG 64-10 (with RAP and lime)[5b,7a] PG 64-10 RB[11] (with lime)[5c,7b]	AASHTO T 321 Modified[1]	 23,000,000 repetitions[4,8] 345,000,000 repetitions[4,9] 25,000 repetitions[4,8] 950,000 repetitions[4,9] 182,000 repetitions[4,8] 2,700,000 repetitions[4,9]
Moisture sensitivity (minimum): PG 64-28PM (with lime) PG 64-10 (with RAP and lime) PG 64-10 RB (with lime)	AASHTO T 324 Modified[1]	 20,000 repetitions[10] 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 Pavements" *(1)*

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

2b. At proposed asphalt binder content (mix containing 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 55°C at 100 kPa.

4. Minimum test value measured from tests on three specimens.

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

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

5c. At proposed asphalt binder content (mix containing 1.2% lime) and with mix compacted to 3%+/-0.3% air voids (determined using AASHTO 209 [Method A])

6. At proposed asphalt binder content, the average mix stiffness at 20°C and a 10 Hz load frequency must be in the range 415,000 to 486,000 psi. At proposed asphalt binder content, the minimum stiffness at 30°C and a 10 Hz load frequency must be equal to or greater than 220,000 psi.

7a. At proposed asphalt binder content (mix containing RAP and 1.2% lime), average stiffness at 20°C and a 10 Hz load frequency must be in the range 870,000 to 1,000,000 psi.

7b. At proposed asphalt binder content (with 1.2% lime), average stiffness at 20°C and a 10 Hz load frequency must be in the range 790,000 to 1,000,000 psi.

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).

11. The rich bottom (RB) mix contains the same binder as the mix with RAP, i.e., the PG 64-10; the binder content of this mix is increased 0.5% (mix basis) above the binder content used for the mix containing RAP.

7 SUMMARY 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 Red Bluff. Materials were obtained and tested, and traffic and environmental conditions were considered by the UCPRC. The test data developed in this investigation were provided to Caltrans in October 2011 *(8)* for possible distribution to potential bidders at a pre-bid meeting on the contract and were used by Caltrans HQ staff for the design of the pavement section using *CalME* flexible pavement design methodology. Due to time constraints some of these test data were developed using HMA specimens that were produced without lime, while the contract required the use of lime for plant mix.

UCPRC staff performed this investigation beginning with the understanding that Caltrans wanted to include a higher RAP content (in this case 25 percent) than was typically allowed under the specifications that were current at that time. However, since these projects were to be designed as long-life pavements, a 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

Although it is not a part of this investigation, it is strongly recommended that after the Red Bluff Project is constructed, there should be systematic and regular pavement performance evaluations conducted for at least five years, and preferably longer, following an approach like that used on the I-710 Phase 1 Project (*1*). This follow up is especially important since this project is the first to use a higher percentage of RAP in HMA mixes for LLAPs.

REFERENCES

1. 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.
2. Signore, J.M., B.-W. Tsai, and C.L. Monismith. 2014. *Development of Hot Mix Asphalt Pavement Performance Properties for Long-Life Pavement Design: Caltrans District 2, Interstate 5, Weed, California.* (UCPRC-TM-2014-04)
3. Signore, J.M., and C.L. Monismith. 2014. *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)
4. State of California Department of Transportation Lab Procedure, LP-7, "Laboratory Procedure for Treating Aggregate with Lime Slurry," May 27, 2004, available at: *www.dot.ca.gov/hq/esc/Translab/ ormt/pdf/LP_7.pdf.*
5. 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.
6. State of California Department of Transportation Lab Procedure, LLP-AC2, "Sample Preparation and Testing for Long-Life Hot Mix Asphalt Pavements," August 4, 2012, available at: *www.dot.ca.gov/hq/esc/Translab/ormt/pdf/LLP-AC2_Sample_Preparation_for_LL_HMA-Pavement.pdf.*
7. 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.
8. 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

Appendix A contains: (1) three boxplots for the PG 64-28PM mix without lime for binder content versus Ln (G*), Ln (permanent shear strain, γ_p, at 5,000 load repetitions), and Ln (load repetitions at $\gamma_p = 5\%$ shear strain) (Figure A.1 through Figure A.3); (2) Ln (γ_p) versus Ln (load repetitions) for the PG 64-28PM with lime, at two temperatures and three stress levels (Figure A.4 and Figure A.5); (3) Ln (γ_p) versus Ln (load repetitions) for the PG 64-10 with RAP and lime, at two temperatures and three stress levels (Figure A.6); and (4) two boxplots for the PG 64-28PM mix with lime and the PG 64-10/16 mix with RAP and lime at two temperatures and three stress levels versus Ln (γ_p, at 5,000 load cycles) and L(G) (Figure A.7 and Figure A.8).

Table A.1: Summary of Shear Test Results at 55°C for the Red Bluff PG 64-28PM Mix Design (LMLC Without Lime)

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-ME-PG6428PM-45-1-1A-7055	Unknown	3.3	4.5	54.96	72.33	105.59	0.017660	13,995,311*
315-ME-PG6428PM-45-1-2A-7055	Unknown	3.1	4.5	54.96	72.51	102.84	0.015329	32,505,207,041*
315-ME-PG6428PM-45-1-3A-7055	Unknown	3.3	4.5	54.84	71.21	111.69	0.019863	455,594,635*
315-ME-PG6428PM-5-1-1A-7055	Unknown	2.7	5.0	55.10	72.37	84.12	0.023647	24,644,297*
315-ME-PG6428PM-5-1-2A-7055	Unknown	2.7	5.0	55.05	71.13	87.03	0.022686	922,516,778*
315-ME-PG6428PM-5-1-3A-7055	Unknown	2.8	5.0	54.80	71.61	99.85	0.011730	2,152,637,067*
315-ME-PG6428PM-5-2-1B-7055	Unknown	2.0	5.0	54.60	72.63	121.46	0.009092	61,886,570,358*
315-ME-PG6428PM-5-2-3B-7055	Unknown	2.1	5.0	54.52	70.69	106.48	0.013959	6,751,153,484*
315-ME-PG6428PM-55-3-2B-7055	Unknown	2.8	5.5	54.89	73.16	87.11	0.013958	7,035,074,769*
315-ME-PG6428PM-55-3-3B-7055	Unknown	3.1	5.5	54.89	71.60	89.54	0.012185	11,658,996*
315-ME-PG6428PM-55-4-1A-7055	Unknown	3.2	5.5	54.58	70.03	106.56	0.014326	7,105,859*
315-ME-PG6428PM-55-4-2A-7055	Unknown	3.0	5.5	54.57	67.05	71.67	0.023484	3,591,711*

Notes:

1. "*": extrapolation
2. RICE value: 2.5160 for AC 4.5%; 2.4924 for AC 5.0%; 2.4837 for AC 5.5% (percent AC was calculated by weight of aggregate).
3. All specimens were laboratory-mixed, laboratory-compacted (LMLC) without lime.

Table A.2: Summary of Shear Test Results for PG 64-28PM Lime Mixes (ME, Red Bluff Project, 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-PG6428PM-52-1-1A-7045	2.7	5.2	44.58	75.77	139	0.010362	1.2910E+12*
315-PG6428PM-52-1-2B-7045	2.7	5.2	45.48	75.21	118	0.009456	7.7629E+10*
315-PG6428PM-52-2-1D-7045	2.8	5.2	44.65	78.17	161	0.005695	9.1470E+13*
315-PG6428PM-52-1-1B-10045	3.3	5.2	44.84	101.35	159	0.012871	2.3424E+09*
315-PG6428PM-52-1-2A-10045	2.8	5.2	45.41	100.68	125	0.017264	375,064,876*
315-PG6428PM-52-2-3D-10045	3.0	5.2	44.82	100.33	143	0.015439	126,397,444*
315-PG6428PM-52-1-3A-13045	3.2	5.2	44.65	132.20	136	0.013602	1.2157E+09*
315-PG6428PM-52-1-3B-13045	3.3	5.2	45.42	133.55	150	0.015065	645,444,606*
315-PG6428PM-52-2-2B-13045	3.3	5.2	44.60	133.27	148	0.016240	23,450,496*
315-PG6428PM-52-2-2D-7055	2.8	5.2	55.06	74.59	84	0.016417	603,875,381*
315-PG6428PM-52-2-3B-7055	3.5	5.2	55.07	73.40	88	0.022804	13,465,122*
315-PG6428PM-52-3-1B-7055	3.4	5.2	55.25	73.59	103	0.019915	13,413,741*
315-PG6428PM-52-2-3A-10055	3.5	5.2	55.14	100.08	88	0.010583	3.3163E+09*
315-PG6428PM-52-4-1D-10055	3.3	5.2	55.09	100.10	104	0.017181	18,933,919*
315-PG6428PM-52-4-3D-10055	2.9	5.2	55.20	98.07	86	0.021969	10,914,381*
315-PG6428PM-52-3-2B-13055	3.3	5.2	55.16	133.46	121	0.027806	136,871*
315-PG6428PM-52-3-3B-13055	3.5	5.2	55.00	131.59	101	0.031214	364,808*
315-PG6428PM-52-4-2D-13055	2.9	5.2	55.02	133.88	74	0.034528	110,012*

Notes:

1. “*”: extrapolation
2. RICE value: 2.4890 for PG 64-28PM lime [1.2% lime added (by weight of aggregate); AC = 5.2% (by weight of aggregate plus lime)]
3. Percent air-void content was measured using parafilm method.
4. All specimens were laboratory-mixed, laboratory-compacted (LMLC).

Table A.3: Summary of Shear Test Results for PG 64-10, R25, Lime Mixes (ME, Red Bluff Project, 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
3.15-ME-RAP6410-538-2-3B-7045	2.8	5.38	44.59	75.43	265	0.006882	3.8189E+09*
3.15-ME-RAP6410-538-4-1B-7045	2.8	5.38	44.52	81.44	414	0.008276	9.8705E+11*
3.15-ME-RAP6410-538-5-3A-7045	2.7	5.38	44.52	75.70	403	0.006433	9.4378E+12*
3.15-ME-RAP6410-538-3-1A-10045	2.7	5.38	44.88	104.37	422	0.005919	3.4102E+12*
3.15-ME-RAP6410-538-3-2A-10045	3.0	5.38	44.54	105.19	358	0.004019	1.4798E+13*
3.15-ME-RAP6410-538-5-3B-10045	2.7	5.38	45.23	108.13	482	0.008137	3.5822E+09*
3.15-ME-RAP6410-538-3-3B-13045	2.7	5.38	44.88	140.35	573	0.011637	2.2743E+10*
3.15-ME-RAP6410-538-4-2B-13045	2.7	5.38	44.58	140.74	415	0.010443	4.3852E+09*
3.15-ME-RAP6410-538-5-1B-13045	3.1	5.38	45.25	140.41	400	0.016747	5,164,249*
3.15-ME-RAP6410-538-1-2A-7055	2.9	5.38	55.08	74.10	236	0.007793	1.2145E+12*
3.15-ME-RAP6410-538-2-1A-7055	2.8	5.38	54.95	71.50	137	0.010686	3.2872E+10*
3.15-ME-RAP6410-538-2-2A-7055	2.7	5.38	55.08	73.98	143	0.011648	6.2681E+10*
3.15-ME-RAP6410-538-1-3A-10055	3.1	5.38	55.03	101.68	242	0.007644	2.8027E+10*
3.15-ME-RAP6410-538-2-1B-10055	2.7	5.38	55.43	97.86	136	0.020728	5,858,407*
3.15-ME-RAP6410-538-3-3A-10055	3.1	5.38	55.06	102.12	211	0.008996	4.8536E+10*
3.15-ME-RAP6410-538-1-1A-13055	2.8	5.38	55.15	133.81	271	0.013382	73,185,861*
3.15-ME-RAP6410-538-2-2B-13055	2.9	5.38	55.18	132.38	123	0.027515	583,819*
3.15-ME-RAP6410-538-2-3A-13055	2.9	5.38	55.18	130.87	127	0.015321	149,427,845*

Note:

1. "*": extrapolation
2. PG 64-10 R25 Lime: PG 64-10 binder with AC* = 5.38% (by weight of virgin aggregate plus line); 25% RAP (by weight of total mix); 1.2% lime added (by weight of virgin aggregate). Actual binder tested was PG 64-16.
3. RICE value: 2.4578 for PG 64-10 R25 Lime
4. Percent air-void content was measured using parafilm method.
5. All specimens were laboratory-mixed, laboratory-compacted (LMLC).

Table A.4: Summary of Shear Test Results for PG 64-10 Mix Design (LMLC) Without Lime

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-ME-PG6410-45-2-1A-7055	Unknown	3.3	4.5	55.4	70.71	94.92	0.018103	57,893,064*
315-ME-PG6410-45-2-2A-7055	Unknown	3.3	4.5	54.6	70.07	102.73	0.021584	63,603,420*
315-ME-PG6410-45-2-3A-7055	Unknown	3.0	4.5	54.8	70.91	120.14	0.019605	178,072,453*
315-ME-PG6410-50-1-1A-7055	Unknown	3.2	5.0	54.5	72.91	83.11	0.020281	328,133,975*
315-ME-PG6410-50-1-2A-7055	Unknown	2.8	5.0	54.9	72.12	86.54	0.022787	2,679,274*
315-ME-PG6410-50-1-3A-7055	Unknown	2.7	5.0	54.7	71.70	99.36	0.016721	217,683,187*
315-ME-PG6410-55-1-1A-7055	Unknown	2.7	5.5	54.5	70.56	108.50	0.024351	641,786*
315-ME-PG6410-55-2-1A-7055	Unknown	3.2	5.5	55.4	71.02	94.44	0.030893	273,488*
315-ME-PG6410-55-2-3A-7055	Unknown	2.8	5.5	54.9	70.98	117.20	0.034305	59,953*

Note:

1. "*": extrapolation
2. RICE value: 2.5122 for AC 4.5%; 2.4935 for AC 5.0%; 2.4756 for AC 5.5% (percent AC was calculated by weight of aggregate).
3. All specimens were laboratory-mixed, laboratory-compacted. Actual binder tested was PG 64-16.

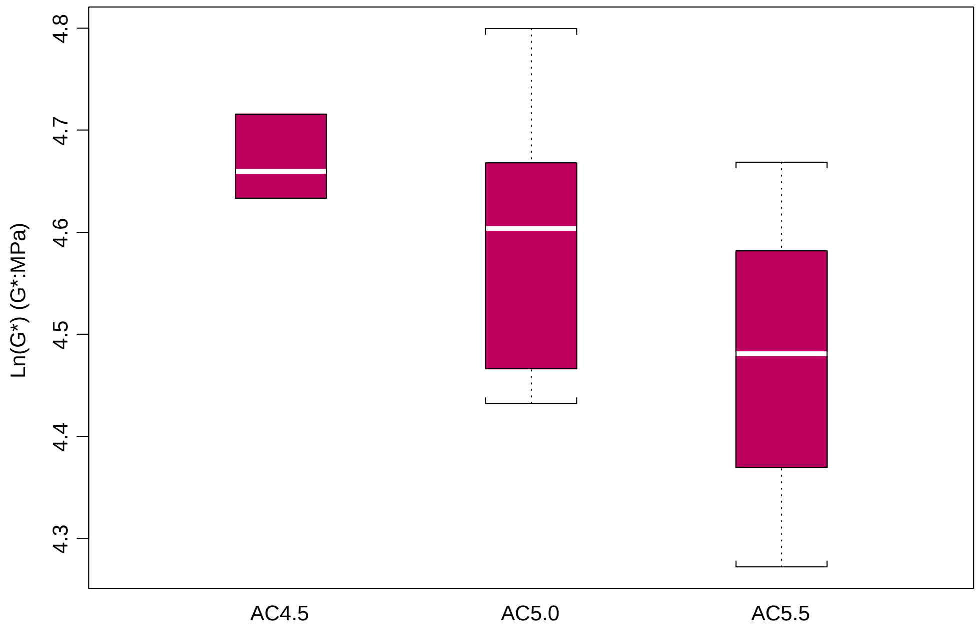


Figure A.1: Ln (shear modulus, G) versus binder content for Red Bluff PG 64-28PM mix (55°C, 70 kPa shear stress, without lime).

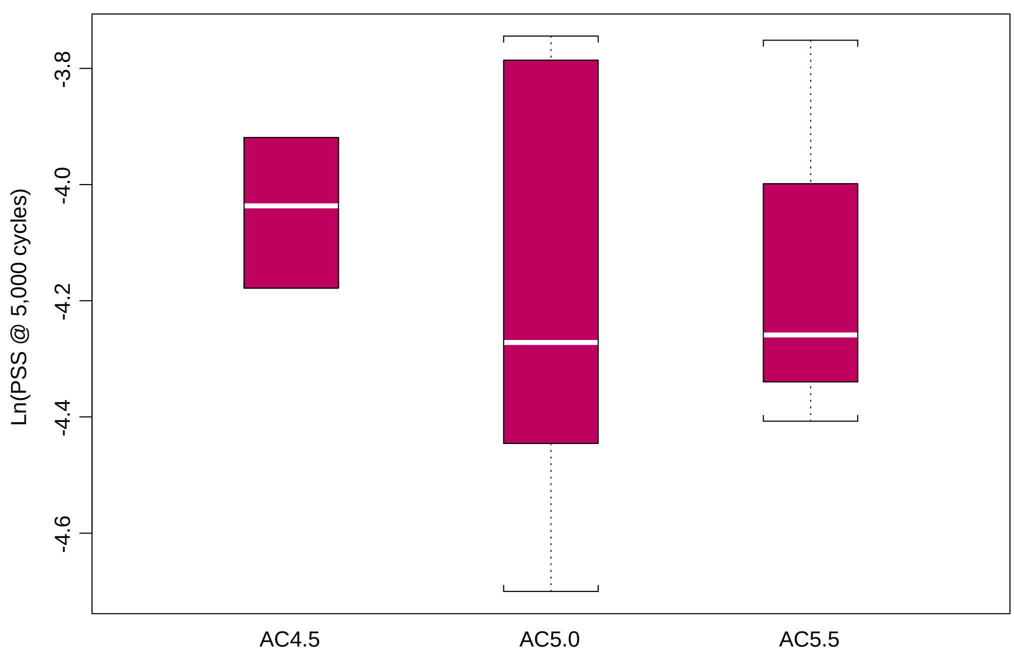


Figure A.2: Ln (permanent shear strain, γ_p after 5,000 load repetitions) versus binder content for Red Bluff PG 64-28PM mix (55°C, 70 kPa shear stress, without lime).

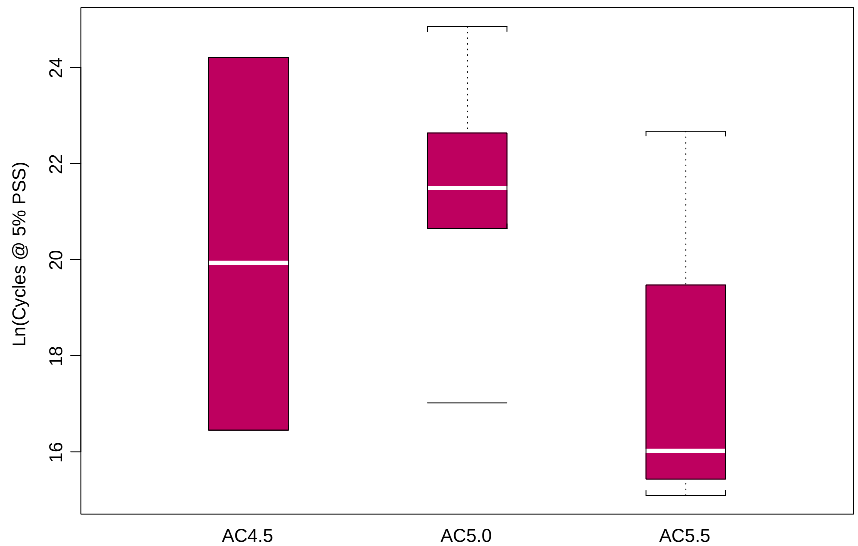


Figure A.3: Ln (load for repetitions at γ_p= 5%) versus binder content for Red Bluff PG 64-28PM mix (55°C, 70 kPa shear stress, without lime).

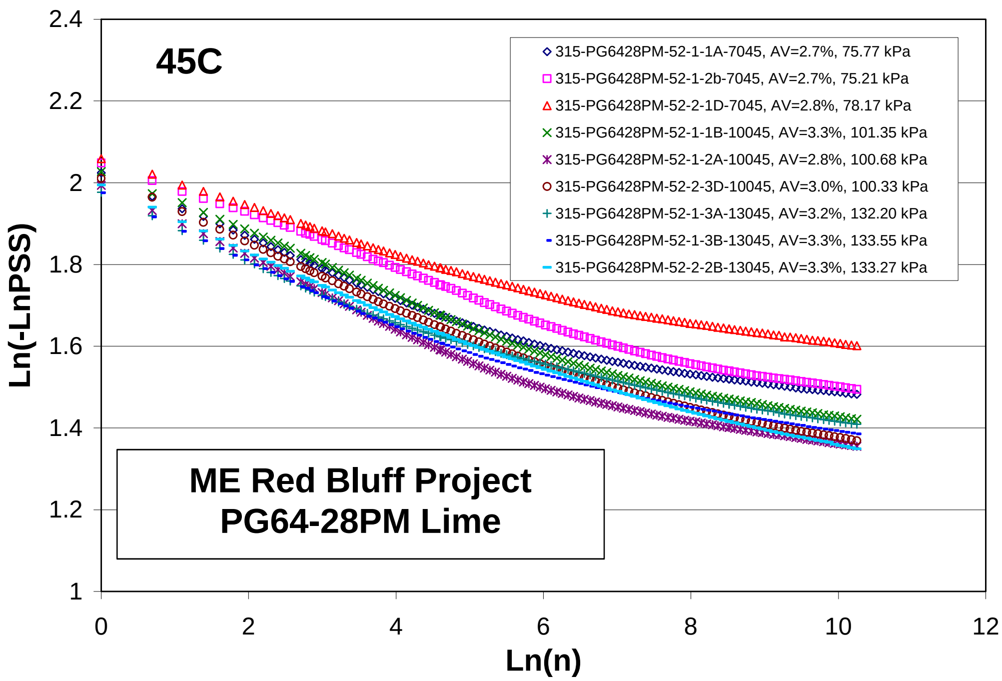


Figure A.4: Summary of shear test results at 45ºC, Ln (Ln(γ_p)) versus Ln (load repetitions), PG 64-28PM mix (ME, Red Bluff Project, AC = 5.2% [by weight of aggregate plus lime], 1.2% lime, AV = 3.0%, LMLC).

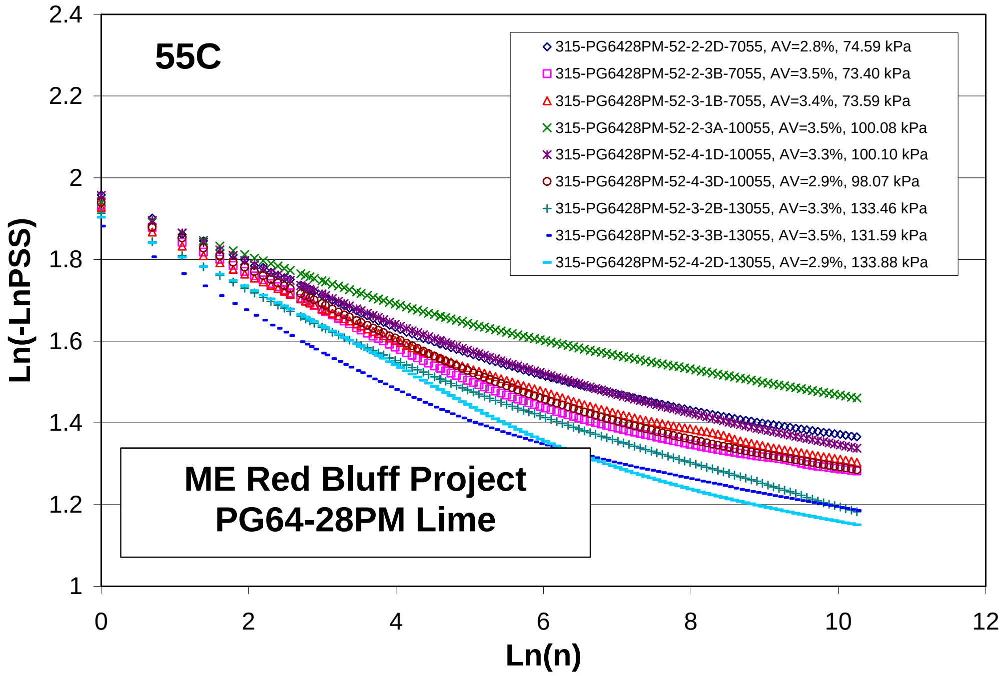


Figure A.5: Summary of shear test results at 55ºC, Ln (Lnγ_p) versus Ln (load repetitions), PG 64-28PM mix, (ME, Red Bluff Project, AC = 5.2% [by weight of virgin aggregate plus lime], AV = 3.0%, LMLC).

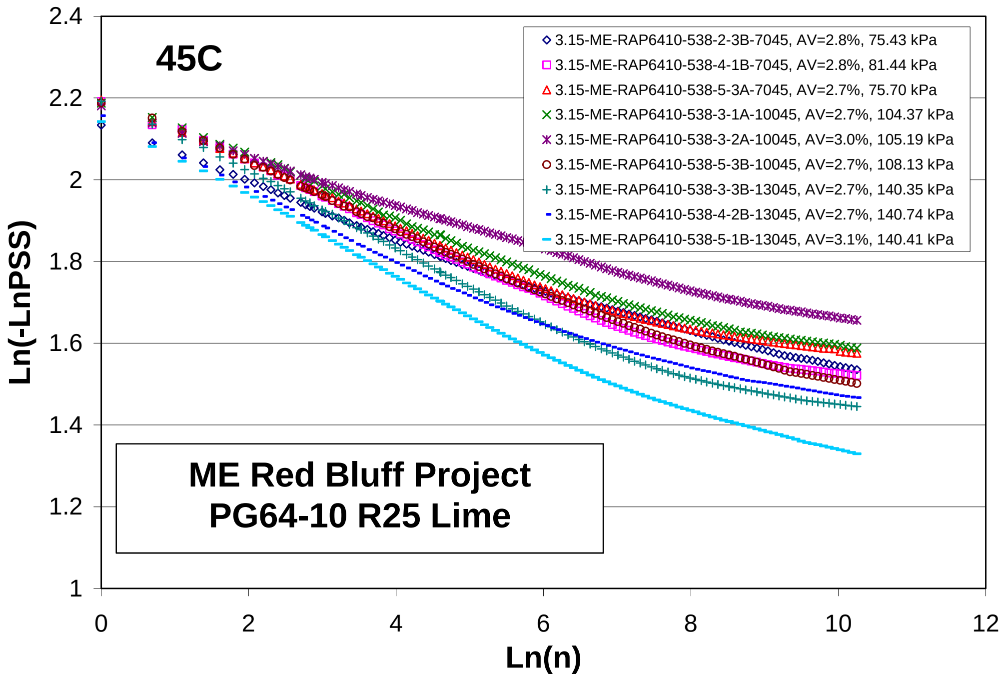


Figure A.6: Summary of shear test results at 45ºC, Ln (Lnγ_p) versus Ln (load repetitions), PG 64-10 mix (ME, Red Bluff Project, AC = 5.38% [by weight of virgin aggregate plus lime], 25% RAP, 1.2% lime, AV = 3.0%, LMLC).

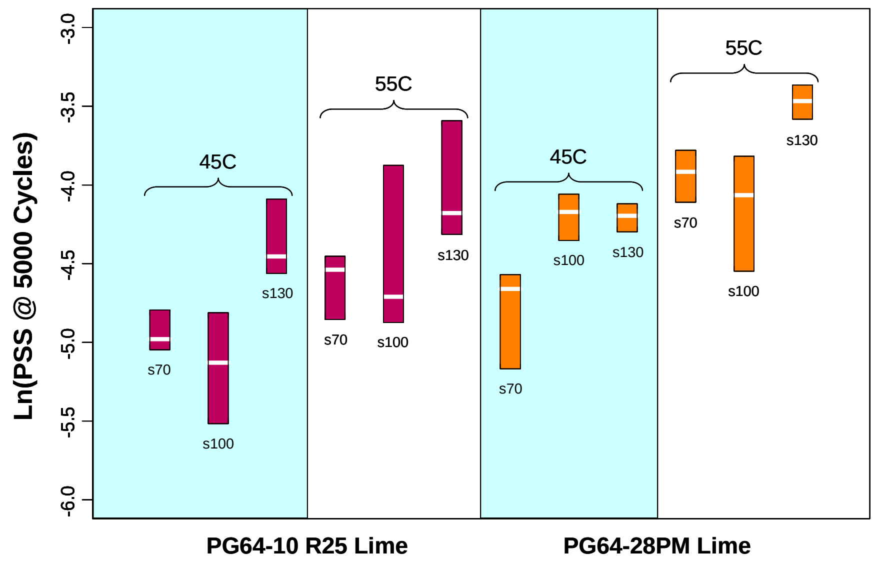


Figure A.7: Ln (γ_p at 5,000 load repetitions) at three shear stress levels and at 45ºC and 55ºC; Red Bluff Project (PG 64-28PM and PG 64-10 mixes).

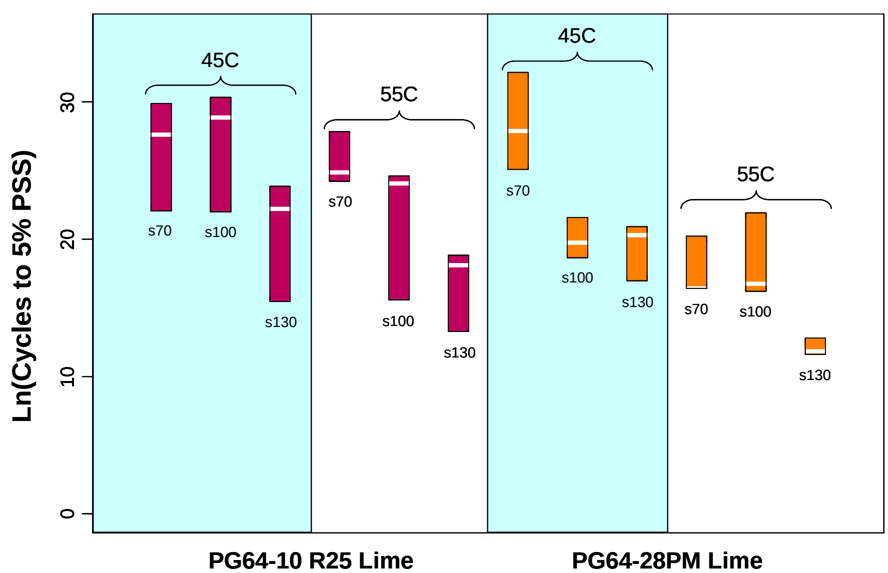


Figure A.8: Ln (G) at three shear stress levels and at 45ºC and 55ºC; Red Bluff Project (PG 64-28PM and PG 64-10 mixes).

APPENDIX B: FATIGUE AND STIFFNESS TEST MIX RESULTS

Table B.1: Summary of Fatigue Test Results, Red Bluff 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 64-10 RB	ME-64-10-RB-5.5-6A2	2.5	5.5	19.95	0.000201	30.15	5,664	1,265,096,581*
	ME-64-10-RB-5.5-6B1	2.8	5.5	20.02	0.000206	28.72	6,683	20,206,253*
	ME-64-10-RB-5.5-7A1	3.2	5.5	19.84	0.000204	18.89	6,282	10,473,690*
	ME-64-10-RB-5.5-7A2	3.0	5.5	20.10	0.000202	25.85	7,118	4,953,708
	ME-64-10-RB-5.5-8A2	2.3	5.5	19.94	0.000201	23.22	7,959	10,175,552*
	ME-64-10-RB-5.5-1A1	2.8	5.5	20.14	0.000401	31.99	5,017	1,187,203
	ME-64-10-RB-5.5-1B1	2.8	5.5	21.65	0.000398	38.14	4,117	2,910,710
	ME-64-10-RB-5.5-7B1	3.0	5.5	19.92	0.000402	20.17	6,736	306,147
	ME-64-10-RB-5.5-7B2	3.3	5.5	19.87	0.000405	21.76	6,582	282,834
	ME-64-10-RB-5.5-8A1	3.3	5.5	20.16	0.000404	28.02	5,692	309,726
PG 64-10 RAP	3.15-RAP-6410-5.38-1A1	5.5	5.38	20.14	0.000206	23.78	6,169	6,291,065*
	3.15-RAP-6410-5.38-1C1	6.2	5.38	20.10	0.000207	23.52	6,669	965,516
	3.15-RAP-6410-5.38-2C2	6.2	5.38	21.76	0.000202	23.67	6,120	2,325,347
	3.15-RAP-6410-5.38-3C2	5.9	5.38	21.50	0.000198	21.67	7,247	5,097,139
	3.15-RAP-6410-5.38-1C2	5.9	5.38	19.89	0.000405	18.79	6,009	58,898
	3.15-RAP-6410-5.38-2A1	5.7	5.38	19.78	0.000406	19.60	6,052	137,267
	3.15-RAP-6410-5.38-3C1	6.1	5.38	19.87	0.000406	18.78	7,102	114,469
PG 64-28PM	3.15-ME-6428PM-5.2-1D2	5.8	5.2	20.02	0.000204	32.56	3,445	3,693,146,879,174*
	3.15-ME-6428PM-5.2-4A1	5.6	5.2	20.14	0.000206	33.65	3,102	7,616,558,415*
	3.15-ME-6428PM-5.2-4A2	5.5	5.2	20.14	0.000208	34.15	3,120	1,532,850,140*
	3.15-MEP6428PM-5.2-5B1	5.8	5.2	19.87	0.000208	26.06	3,253	19,490,531,682*
	3.15-ME-6428PM-5.2-3D1	5.8	5.2	19.96	0.000411	28.76	3,215	80,792,211*
	3.15-ME-6428PM-5.2-4B1	5.5	5.2	19.83	0.000414	31.60	2,688	115,626,722*
	3.15-ME-6428PM-5.2-5B2	5.7	5.2	19.84	0.000408	27.26	2,960	229,697,271*

Notes:

1. RICE values: 2.4704 for PG 64-10 RB (with lime added; AC = 5.5%); 2.4578 for PG 64-10 RAP (with lime added; AC = 5.38% by weight of virgin aggregate); 2.4890 for PG 64-28PM (with lime added; AC = 5.2%)
2. 25% RAP (by weight of virgin aggregate) was added to PG 64-10 RAP mix.
3. 1.2% of lime (by weight of virgin aggregate) was added to PG 64-10 RAP mix; 1.2% of lime (by weight of aggregate) was added to both PG 64-10 RB and PG 64-28PM mixes.
4. The source of aggregate is Red Bluff (District 2).
5. The binder source is the Valero refinery.
6. The air-void content was measured with the parafilm method.
7. The beam specimens are laboratory-mixed, laboratory-compacted (LMLC).
8. "*" stands for "extrapolation."
9. Data shaded yellow might be considered outliers.

Table B.2: Summary of Frequency Sweep Test Results, Red Bluff Project, PG 64-10 RB Mix (1.2% Lime, AC = 5.5%, AV = 3%)

ME-64-10-RB-5.5-1A2 (AV= 3.0%; 10°C)						ME-64-10-RB-5.5-1B2 (AV= 3.3%; 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)
15.16	0.815218	0.000094	8657	17.97	9.76	15.16	0.744428	0.000078	9542	17.24	9.95
10.00	0.831589	0.000104	8027	18.70	9.73	10.00	0.944201	0.0000105	8958	18.29	9.96
5.01	0.723290	0.000103	7018	19.81	9.69	5.00	0.810441	0.000105	7741	19.27	9.93
2.00	0.587679	0.000102	5766	21.64	9.66	2.00	0.639349	0.000100	6396	21.30	9.92
1.00	0.475488	0.000097	4882	22.50	9.78	1.00	0.517152	0.000096	5410	22.55	9.88
0.50	0.390648	0.000095	4101	25.07	9.85	0.50	0.442861	0.000097	4542	25.56	9.88
0.20	0.314942	0.000099	3181	27.79	9.89	0.20	0.351082	0.000100	3512	27.98	9.85
0.10	0.250108	0.000099	2535	27.74	9.84	0.10	0.274144	0.000098	2800	28.46	9.82
0.05	0.198702	0.000096	2069	30.27	9.73	0.05	0.218798	0.000096	2276	31.27	9.77
0.02	0.149242	0.000095	1563	31.51	9.79	0.02	0.161190	0.000095	1704	33.29	9.83
0.01	0.121558	0.000095	1277	33.38	9.77	0.01	0.129161	0.000094	1379	33.95	9.77
ME-64-10-RB-5.5-2A1 (AV= 3.3%; 20°C)						**ME-64-10-RB-5.5-6B1 (AV= 2.8%; 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)**
15.17	0.431772	0.000101	4285	26.88	19.56	15.16	0.692986	0.000099	6995	24.22	19.73
10.01	0.401131	0.000104	3860	27.63	19.64	10.01	0.634818	0.000101	6287	25.13	19.65
5.01	0.335121	0.000106	3176	28.97	19.62	5.00	0.534822	0.000103	5207	27.60	19.51
2.00	0.245356	0.000102	2396	30.42	19.55	2.00	0.400920	0.000103	3896	31.71	19.53
1.00	0.190235	0.000100	1905	31.67	19.61	1.00	0.298153	0.000097	3066	33.61	19.64
0.50	0.141209	0.000092	1537	33.85	19.68	0.50	0.230482	0.000098	2348	38.41	19.59
0.20	0.108011	0.000099	1096	35.04	19.67	0.20	0.160854	0.000101	1591	41.35	19.51
0.10	0.084672	0.000099	857	35.94	19.55	0.10	0.113279	0.000097	1164	42.56	19.60
0.05	0.065576	0.000097	676	36.26	19.62	0.05	0.084531	0.000097	870	46.06	19.63
0.02	0.047610	0.000097	493	35.62	19.66	0.02	0.055570	0.000096	579	45.47	19.63
0.01	0.039334	0.000096	410	32.84	19.61	0.01	0.039920	0.000095	420	47.07	19.63
ME-64-10-RB-5.5-6A1 (AV= 2.5%; 30°C)						**ME-64-10-RB-5.5-6B2 (AV= 2.3%; 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)**
15.14	0.504929	0.000207	2437	41.26	29.93	15.16	0.584690	0.000203	2885	38.85	30.04
10.00	0.422313	0.000202	2088	42.35	29.97	10.00	0.504513	0.000204	2478	40.32	29.87
5.00	0.318595	0.000204	1559	43.83	29.95	5.00	0.386153	0.000205	1885	42.35	29.78
2.00	0.205569	0.000200	1029	46.41	29.83	2.00	0.248202	0.000199	1248	45.09	29.80
1.00	0.149544	0.000202	742	47.07	29.78	1.00	0.181138	0.000201	903	47.55	29.84
0.50	0.106950	0.000201	532	47.59	29.86	0.50	0.130343	0.000201	648	47.94	29.89
0.20	0.069155	0.000199	348	45.84	29.84	0.20	0.080038	0.000198	404	49.75	29.89
0.10	0.049334	0.000200	247	45.12	29.81	0.10	0.057520	0.000198	290	48.10	29.86
0.05	0.037210	0.000198	188	45.13	29.79	0.05	0.042576	0.000197	216	47.17	29.89
0.02	0.027498	0.000198	139	40.70	29.79	0.02	0.028343	0.000197	144	47.52	29.87
0.01	0.022170	0.000197	112	33.34	29.78	0.01	0.022641	0.000196	115	52.49	29.88

Table B.3: Summary of Frequency Sweep Test Results, Red Bluff Project, PG 64-10 (25% RAP, 1.2% Lime, AC = 5.38% [Virgin Aggregate Basis], AV = 6.0%)

3.15-RAP-6410-5.38-3A1 (AV= 6.2%; 10°C)						3.15-RAP-6410-5.38-3A2 (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)
15.16	0.803457	0.000080	10064	12.26	9.82	15.17	0.648455	0.000052	12588	12.57	9.83
9.99	1.017310	0.000105	9730	11.12	9.73	9.99	1.132050	0.000102	11124	11.56	9.76
5.01	0.963997	0.000104	9239	11.08	9.73	5.01	1.094216	0.000104	10486	10.55	9.79
2.00	0.767282	0.000092	8305	11.57	9.81	1.99	0.719447	0.000077	9398	11.91	9.78
1.00	0.734348	0.000096	7615	11.28	9.79	1.00	0.818730	0.000095	8615	10.73	9.74
0.50	0.685289	0.000096	7107	11.97	9.73	0.50	0.809139	0.000097	8364	12.74	9.81
0.20	0.625003	0.000100	6248	13.09	9.69	0.20	0.735103	0.000100	7343	14.42	9.81
0.10	0.547926	0.000100	5475	15.12	9.83	0.10	0.634387	0.000100	6372	14.96	9.68
0.05	0.481642	0.000099	4875	16.64	9.78	0.05	0.542073	0.000097	5609	18.24	9.71
0.02	0.403610	0.000097	4143	19.07	9.74	0.02	0.456908	0.000095	4788	20.28	9.74
0.01	0.348758	0.000097	3601	22.05	9.77	0.01	0.400954	0.000095	4220	22.48	9.76
3.15-RAP-6410-5.38-2D1 (AV= 5.6%; 20°C)						**3.15-RAP-6410-5.38-3B2 (AV= 5.5%; 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)**
15.14	0.746613	0.000103	7239	18.32	19.89	15.18	0.608980	0.000073	8375	14.95	19.91
9.97	0.706227	0.000105	6744	17.77	19.99	10.00	0.731474	0.000102	7152	16.87	19.85
5.01	0.636018	0.000105	6045	18.33	20.01	5.01	0.681639	0.000105	6471	17.65	19.93
2.00	0.513747	0.000102	5050	20.70	19.85	2.00	0.529491	0.000097	5467	18.73	19.79
1.00	0.414417	0.000098	4250	20.19	19.80	1.00	0.460262	0.000097	4737	18.83	19.80
0.50	0.383721	0.000103	3709	24.45	19.98	0.50	0.424113	0.000101	4219	22.07	19.89
0.20	0.303372	0.000102	2980	28.59	19.91	0.20	0.333177	0.000100	3346	25.31	19.80
0.10	0.234456	0.000099	2372	30.66	19.90	0.10	0.272468	0.000099	2747	26.89	19.83
0.05	0.181199	0.000097	1875	33.77	19.94	0.05	0.212951	0.000096	2226	30.76	19.84
0.02	0.128708	0.000095	1352	34.77	19.90	0.02	0.156485	0.000095	1654	33.39	19.86
0.01	0.098509	0.000095	1042	39.10	19.92	0.01	0.125158	0.000095	1322	35.85	19.87
3.15-RAP-6410-5.38-2A2 (AV= 5.9%; 30°C)						**3.15-RAP-6410-5.38-2C1 (AV= 5.9 %; 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)**
15.16	0.667729	0.000212	3147	31.79	29.74	15.14	0.754364	0.000215	3515	28.72	30.02
10.00	0.590212	0.000211	2797	32.62	29.90	10.00	0.652163	0.000208	3138	29.79	29.90
5.00	0.466812	0.000206	2264	34.85	29.87	5.00	0.518391	0.000204	2540	31.02	30.02
2.00	0.336119	0.000203	1656	37.75	29.90	2.00	0.388100	0.000202	1920	34.59	29.92
1.00	0.251373	0.000201	1250	39.55	29.94	1.00	0.309312	0.000200	1547	36.71	29.97
0.50	0.183567	0.000197	932	41.96	29.85	0.50	0.241777	0.000208	1165	40.15	29.90
0.20	0.125193	0.000202	620	43.41	29.85	0.20	0.163669	0.000205	797	41.41	29.96
0.10	0.091882	0.000199	461	44.22	29.90	0.10	0.119527	0.000201	595	42.39	29.93
0.05	0.066158	0.000197	335	42.29	29.86	0.05	0.089291	0.000199	448	41.91	29.94
0.02	0.045793	0.000196	233	42.69	29.84	0.02	0.060209	0.000197	305	42.48	29.90
0.01	0.033585	0.000195	172	41.00	29.88	0.01	0.045086	0.000197	229	43.74	29.88

Table B.4: Summary of Frequency Sweep Test Results Red Bluff Project, PG 64-28PM (1.2% Lime, AC = 5.0%, AV = 6.0%)

3.15-ME-6428PM-5.2-3A2 (AV= 6.2%; 10°C)						3.15-ME-6428PM-5.2-3B2 (AV= 5.8%; 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	0.796199	0.000102	7770	16.25	9.86	15.16	0.713504	0.000093	7660	18.98	9.79
10.00	0.748072	0.000103	7260	17.02	9.81	10.00	0.750059	0.000104	7220	18.80	9.74
5.00	0.664736	0.000104	6421	17.99	9.70	5.00	0.656480	0.000103	6390	19.47	9.69
2.00	0.527309	0.000097	5430	19.02	9.68	2.00	0.540756	0.000102	5325	20.57	9.75
1.00	0.458779	0.000098	4678	19.48	9.78	1.00	0.451942	0.000098	4601	20.51	9.70
0.50	0.408513	0.000100	4075	22.22	9.78	0.50	0.384452	0.000098	3912	23.63	9.66
0.20	0.336669	0.000104	3237	23.05	9.69	0.20	0.310748	0.000100	3104	24.35	9.75
0.10	0.267564	0.000101	2655	23.24	9.71	0.10	0.250702	0.000099	2530	25.92	9.79
0.05	0.217317	0.000098	2222	26.10	9.76	0.05	0.209199	0.000097	2161	27.56	9.74
0.02	0.172504	0.000096	1792	26.42	9.79	0.02	0.162095	0.000094	1718	28.10	9.71
0.01	0.143662	0.000096	1496	27.64	9.75	0.01	0.136264	0.000095	1442	28.66	9.76
3.15-ME-6428PM-5.2-3A1 (AV= 5.9%; 20°C)						**3.15-ME-6428PM-5.2-3D1 (AV= 5.8%; 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	0.492444	0.000106	4635	23.54	20.06	15.14	0.463054	0.000106	4362	25.15	19.99
10.00	0.441040	0.000104	4255	23.60	19.96	10.00	0.418168	0.000106	3962	25.52	20.12
5.00	0.384898	0.000107	3605	24.61	20.02	5.01	0.351936	0.000106	3327	26.40	19.90
2.00	0.298358	0.000105	2841	25.95	19.91	2.00	0.262781	0.000102	2569	28.46	19.99
1.00	0.230329	0.000098	2349	25.56	19.87	1.00	0.206629	0.000099	2091	27.59	20.00
0.50	0.198562	0.000102	1949	27.40	19.88	0.50	0.169748	0.000101	1682	30.18	19.88
0.20	0.148925	0.000101	1481	29.18	19.85	0.20	0.125064	0.000100	1247	32.36	19.95
0.10	0.116680	0.000099	1181	29.95	19.88	0.10	0.096680	0.000098	991	31.17	19.90
0.05	0.094128	0.000097	967	29.95	19.90	0.05	0.076256	0.000097	786	32.18	19.84
0.02	0.071701	0.000095	754	29.50	19.87	0.02	0.057206	0.000096	598	31.60	19.88
0.01	0.057977	0.000095	611	30.09	19.91	0.01	0.045210	0.000095	475	31.31	19.88
3.15-ME-6428PM-5.2-1D1(AV= 5.7%; 30°C)						**3.15-ME-6428PM-5.2-3D2 (AV= 5.5%; 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)
15.17	0.189574	0.000106	1783	36.56	30.06	15.15	0.188199	0.000106	1777	36.20	30.32
10.02	0.168260	0.000106	1586	34.82	30.02	9.99	0.166453	0.000106	1573	35.02	30.14
5.00	0.134337	0.000105	1282	34.36	29.92	5.00	0.135708	0.000107	1266	34.64	30.03
2.00	0.095200	0.000103	925	34.31	29.99	2.00	0.096602	0.000104	929	34.86	30.06
1.00	0.072932	0.000098	745	32.41	29.83	1.00	0.073552	0.000100	737	33.24	29.86
0.50	0.055168	0.000094	589	32.53	29.95	0.50	0.051392	0.000090	572	35.69	29.93
0.20	0.042091	0.000098	429	34.00	29.88	0.20	0.041263	0.000099	418	31.99	29.88
0.10	0.033404	0.000097	345	32.35	29.91	0.10	0.031849	0.000098	326	32.64	29.90
0.05	0.025839	0.000096	270	29.69	29.91	0.05	0.026956	0.000097	278	36.52	29.90
0.02	0.020609	0.000093	221	34.90	29.89	0.02	0.021818	0.000096	228	33.44	29.86
0.01	0.018346	0.000095	193	27.65	29.85	0.01	0.018326	0.000095	193	34.28	29.86

Table B.5: Summary of Master Curves and Time-Temperature Relationships for Red Bluff Project

Mix Type	Master Curve					Time-Temperature Relationship	
	n	A	B	C	D	A	B
PG 64-10 RB	3	114568.0	12.61107	-7.303561	166.3143	27.5974	-107.257
PG 64-10 RAP	3	22396.7	5.891316	-8.935554	270.8734	30.9132	-79.6985
PG 64-28PM	3	259843.6	21.87722	-8.710714	238.5238	17.4683	-54.6339

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

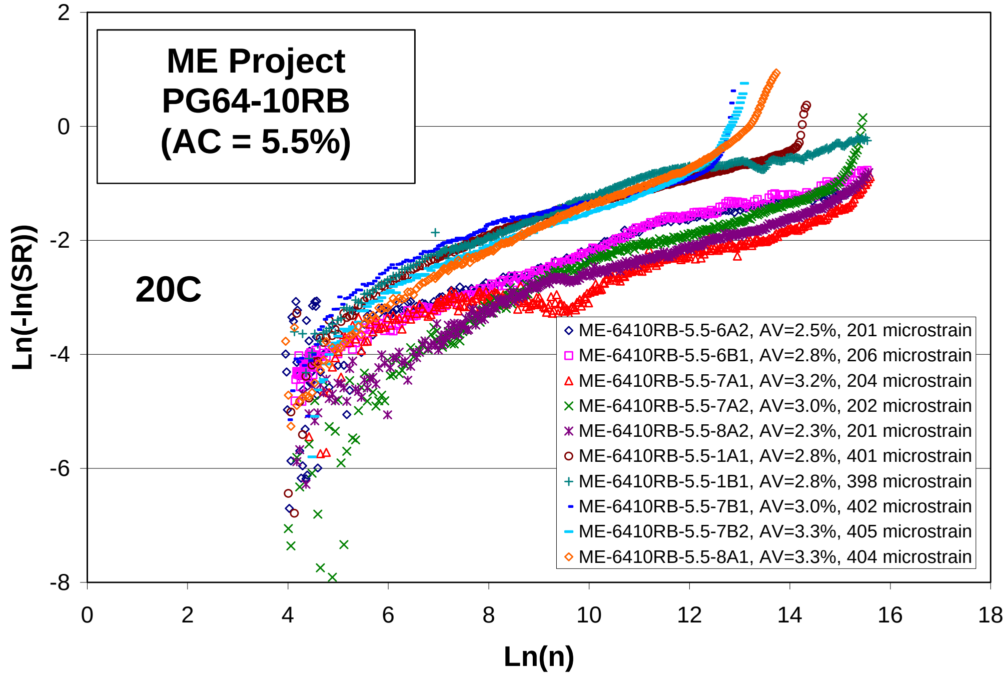


Figure B.1: Summary of fatigue test results, Red Bluff (PG 64-10 RB with 1.2% lime, AC = 5.5%, AV = 3.0%).

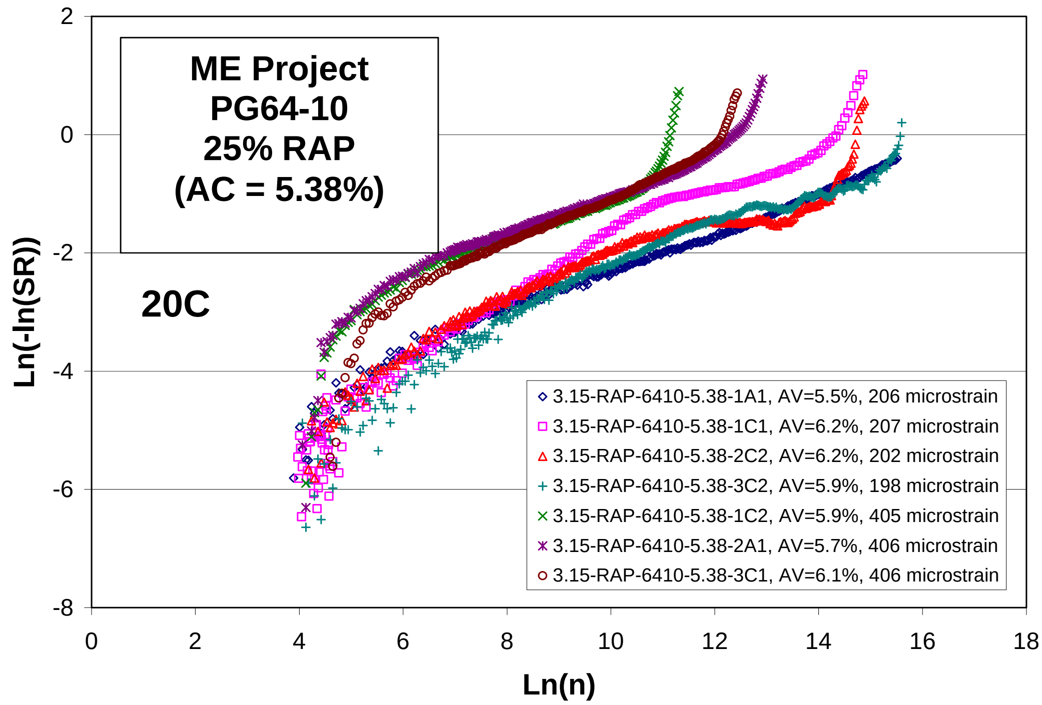


Figure B.2: Summary of fatigue test results, Red Bluff (PG 64-10 25% RAP, 1.2% lime, AC* = 5.38% [by weight of virgin aggregate]).

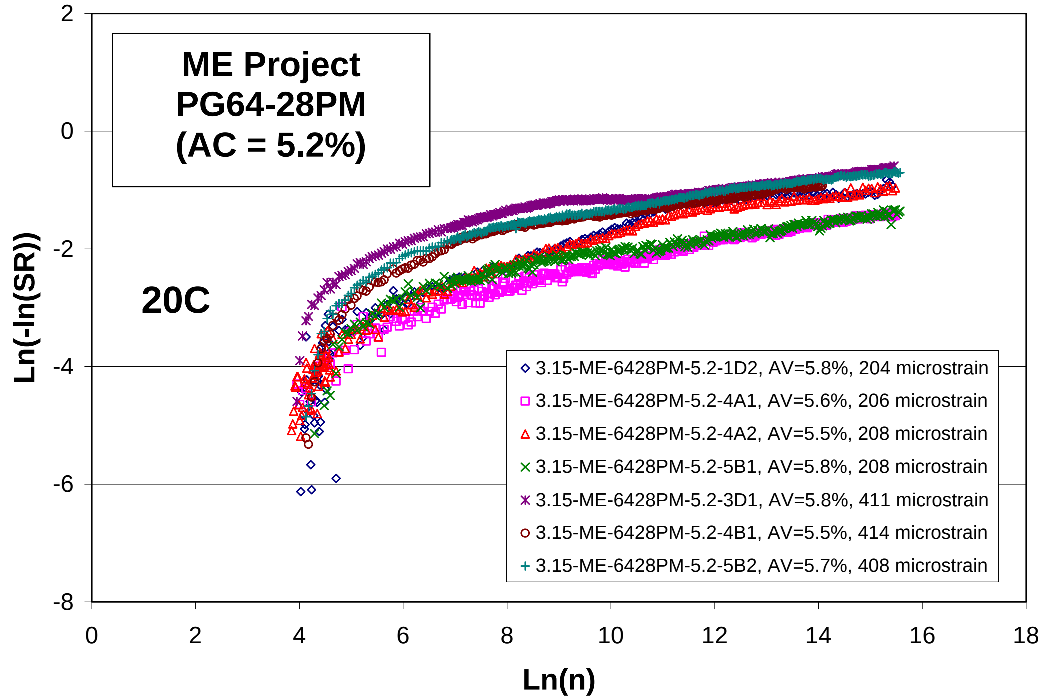


Figure B.3: Summary of fatigue test results, Red Bluff (PG 64-28PM, 1.2%, AC = 5.2%, AV = 6%).

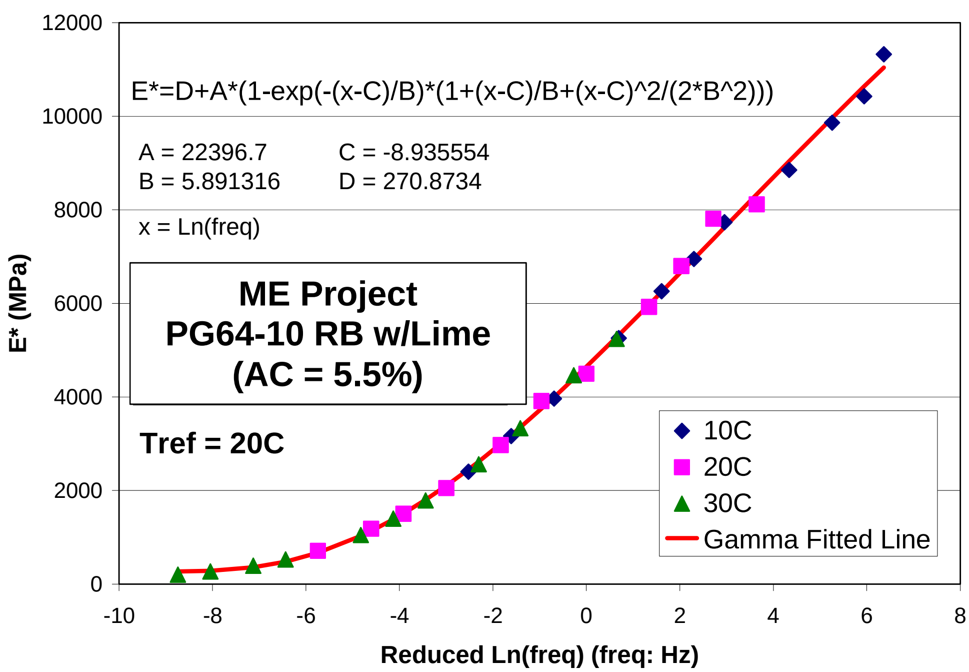


Figure B.4: E* master curve, Red Bluff Project (PG 64-10 RB, 1.2% lime, AC = 5.5%, AV =3%).

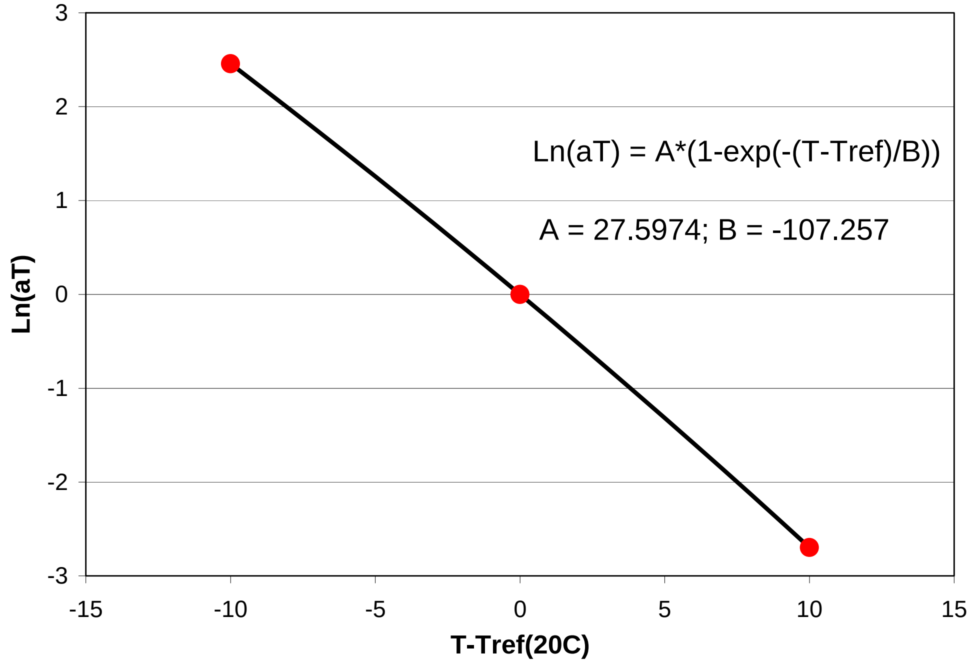


Figure B.5: Temperature-shifting relationship, Red Bluff Project (PG 64-10 RB, 1.2% lime, AC = 5.5%, AV = 3%).

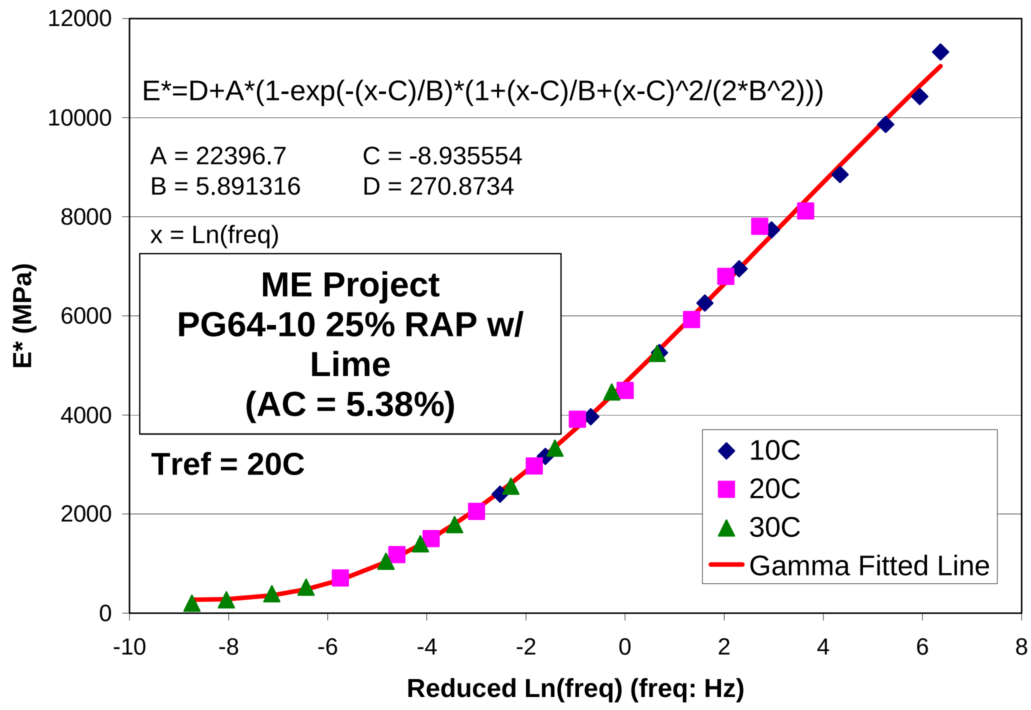


Figure B.6: E* master curve, Red Bluff Project (PG 64-10 25% RAP, 1.2% lime, AC* = 5.38% [by weight of virgin aggregate], AV = 6.0%).

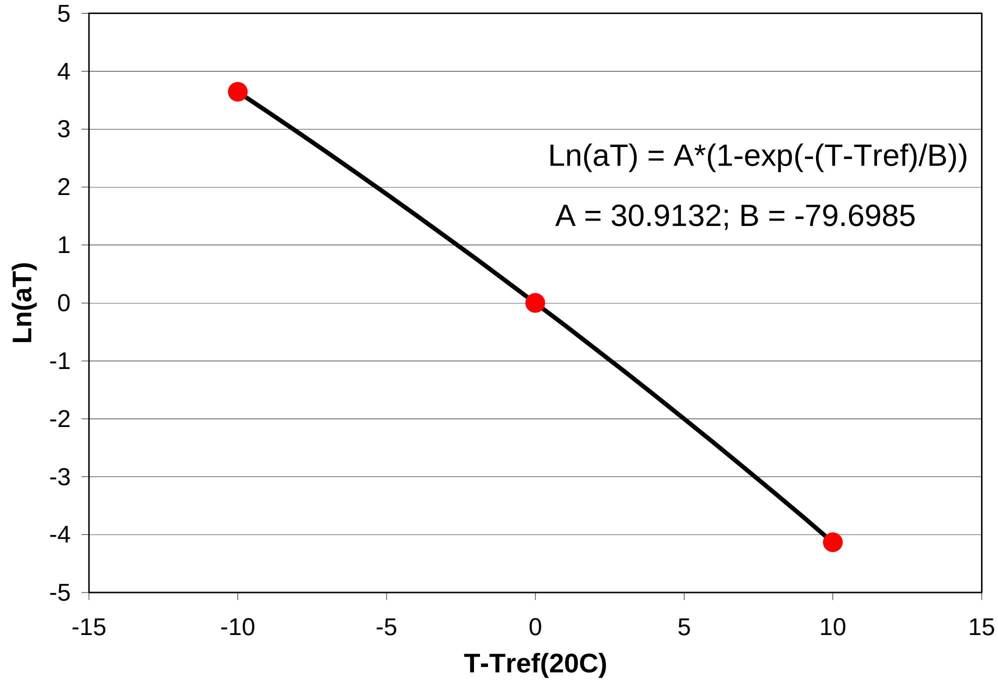


Figure B.7: Temperature-shifting relationship, Red Bluff Project (PG 64-10 25% RAP, 1.2% lime, AC* = 5.38% [by weight of virgin aggregate], AV = 6.0%).

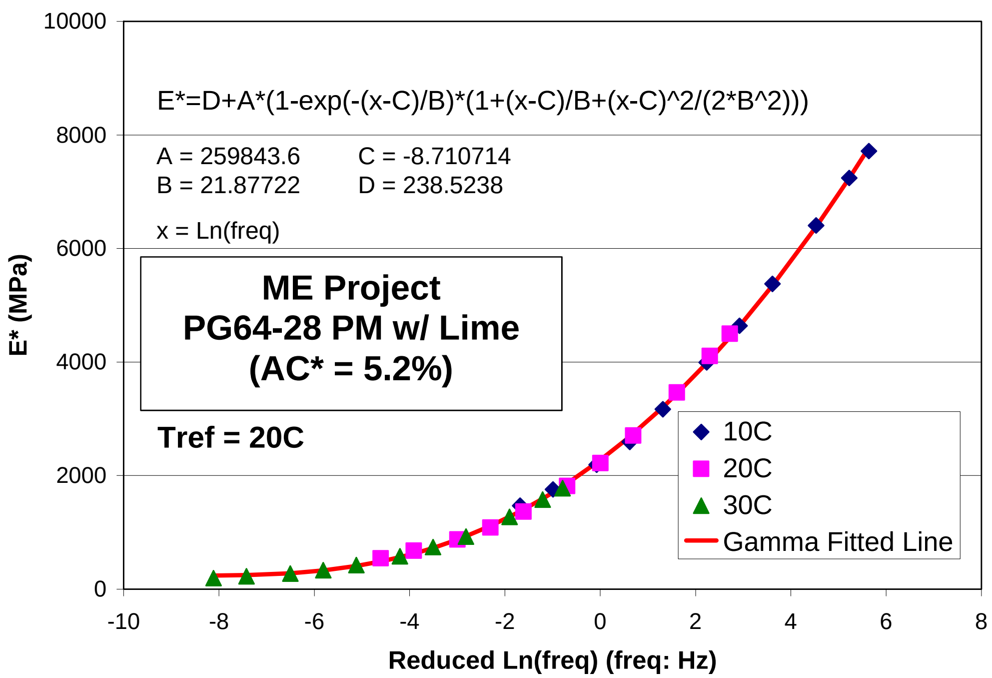


Figure B.8: E* master curve, Red Bluff Project (PG 64-28PM, 1.2% lime, AC = 5.2%,AV = 6.0%).

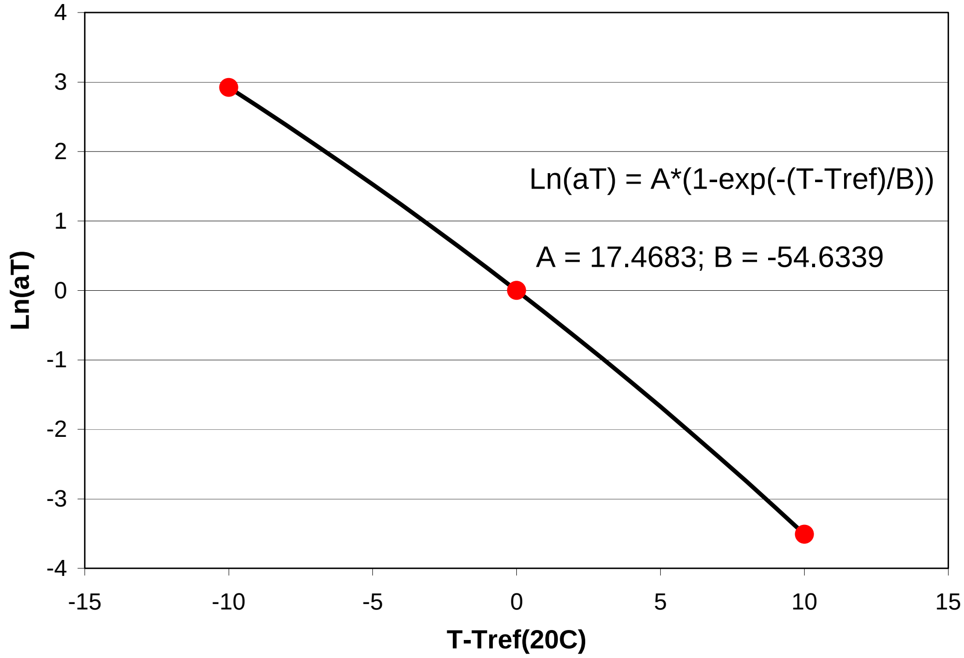


Figure B.9: Temperature-shifting relationship, Red Bluff Project (PG 64-28PM, 1.2% lime, AC = 5.2%, AV = 6.0%).

APPENDIX C: HAMBURG WHEEL-TRACK TESTING RESULTS

Table C.1: Summary of Hamburg Wheel-Tracking Test Results, Red Bluff Project

Mix Type	Set	Position	Specimen Name	% AV (Parafilm)	Average Rut Depth (mm)	
					10k Passes	20k Passes
PG 64-10 RB with lime	1 (UCPRC)	Rt.	3.15-HAM-6410RB-5.5-3-1B	3.0	3.22	3.41
			3.15-HAM-6410RB-5.5-3-1B	3.1		
		Lt.	3.15-HAM-6410RB-5.5-3-1B	3.2	4.13	4.49
			3.15-HAM-6410RB-5.5-3-1B	3.1		
	2 (Caltrans)	Rt.	3.15-HAM-6410RB-5.5-1-3A	3.1	1.20	2.76
			3.15-HAM-6410RB-5.5-4-3A	3.2		
		Lt.	3.15-HAM-6410RB-5.5-1-2A	3.0	1.25	2.69
			3.15-HAM-6410RB-5.5-4-2A	2.9		
PG 64-10 RAP with lime	1 (UCPRC)	Rt.	3.15-HAM-RAP-6410-5.38-2-2D	6.0	2.61	3.16
			3.15-HAM-RAP-6410-5.38-1-3C	5.9		
		Lt.	3.15-HAM-RAP-6410-5.38-1-1C	5.8	2.29	2.89
			3.15-HAM-RAP-6410-5.38-2-1C	5.8		
	2 (Caltrans)	Rt.	3.15-HAM-RAP-6410-5.38-1-1D	5.2	2.80	3.37
			3.15-HAM-RAP-6410-5.38-2-3C	6.1		
		Lt.	3.15-HAM-RAP-6410-5.38-2-2C	5.8	2.82	3.25
			3.15-HAM-RAP-6410-5.38-2-3D	5.7		
PG 64-28PM with lime	1 (UCPRC)	Rt.	3.15-HAM-6428PM-5.2-1-1D	6.1	1.79	2.19
			3.15-HAM-6428PM-5.2-2-1D	6.0		
		Lt.	3.15-HAM-6428PM-5.2-2-2D	5.7	2.62	3.05
			3.15-HAM-6428PM-5.2-3-3D	5.9		
	2 (UCPRC)	Rt.	3.15-HAM-6428PM-5.2-2-2C	6.6	2.35	2.77
			3.15-HAM-6428PM-5.2-1-2C	6.8		
		Lt.	3.15-HAM-6428PM-5.2-1-3C	8.1	2.43	3.11
			3.15-HAM-6428PM-5.2-2-3C	7.7		

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

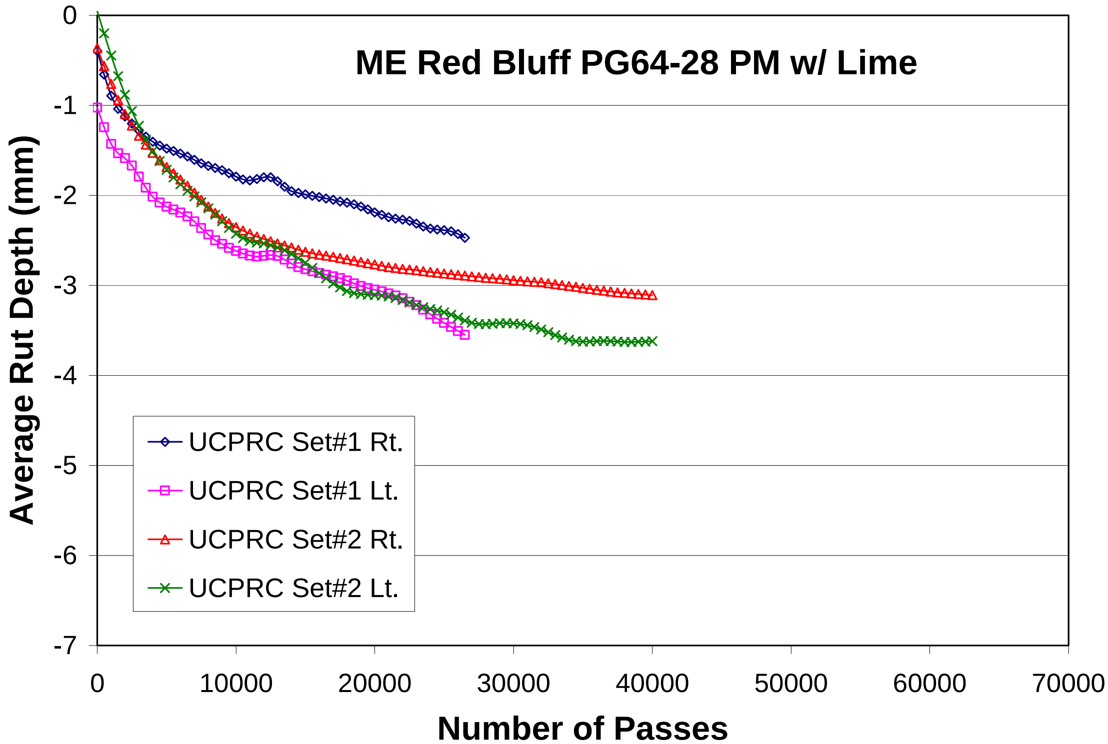
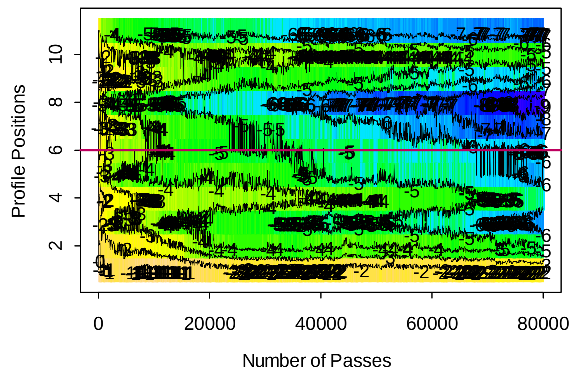
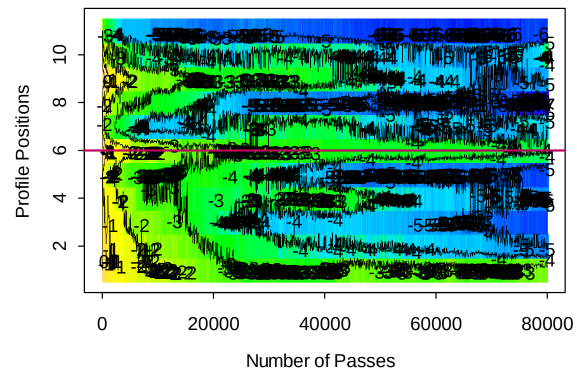


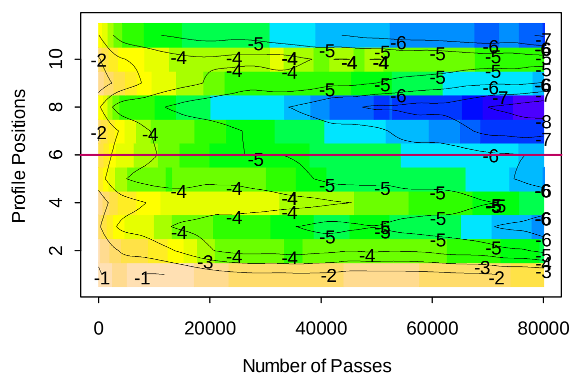
Figure C.1: HWTT summary of Red Bluff, PG 64-28PM 15% RAP with 1.2% lime.



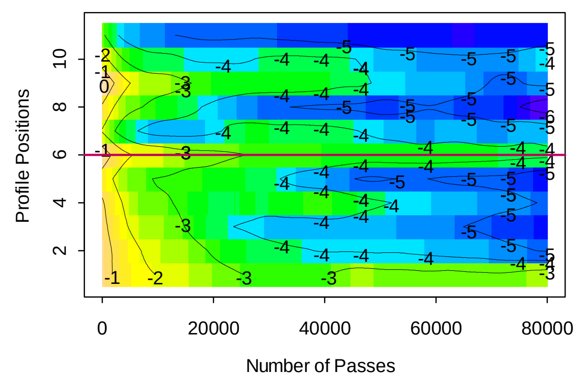
(a) Original (Set#1: Lt)



(b) Original (Set#1: Rt)

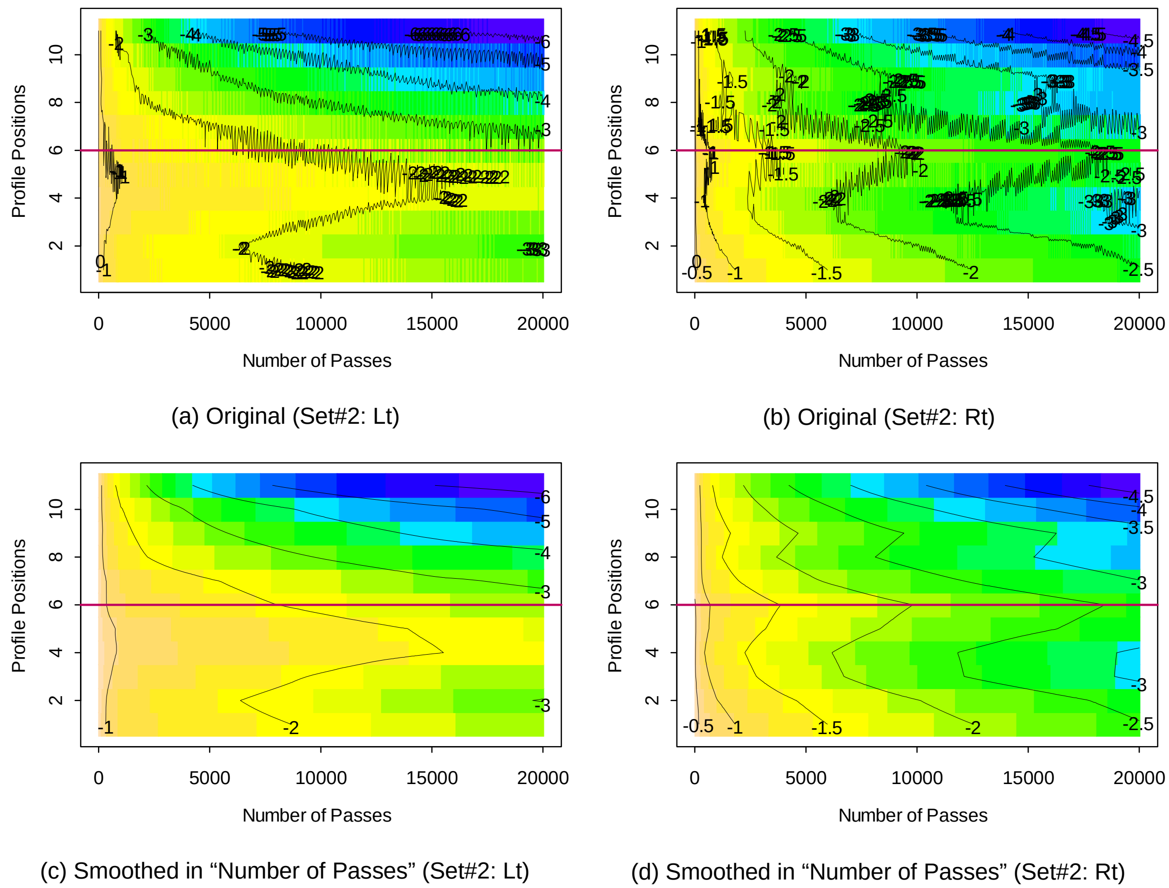


(c) Smoothed in "Number of Passes" (Set#1: Lt)



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

Figure C.2: Rutting evolution image and contour plots for PG 64-10 RB mix set #1 after 80,000 passes: (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.) *(by UCPRC).*



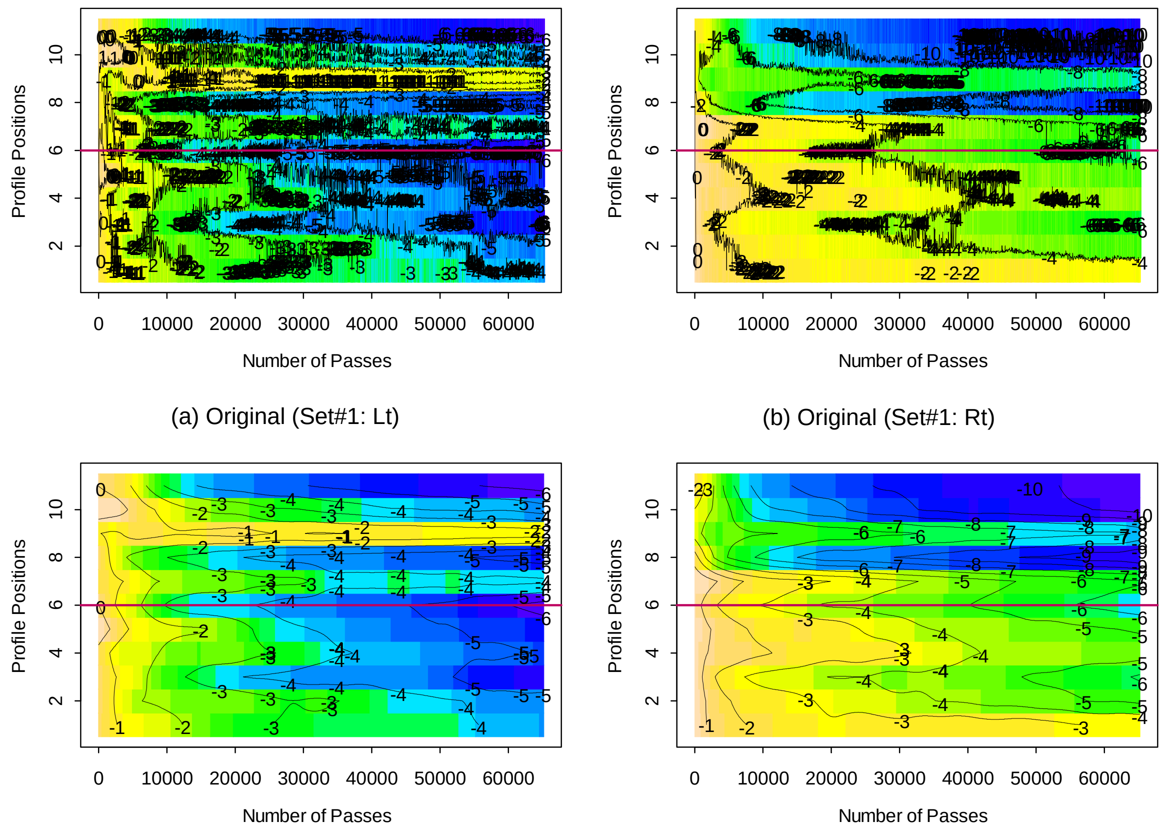
(a) Original (Set#2: Lt)

(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.3: Rutting evolution image and contour plots for PG 64-10 RB mix set #2 after 20,000 passes: (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.) *(by Caltrans).*



(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.4: Rutting evolution image and contour plots for PG 64-10 RAP with lime mix set #1 after 65,150 passes: (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.) *(by UCPRC).*

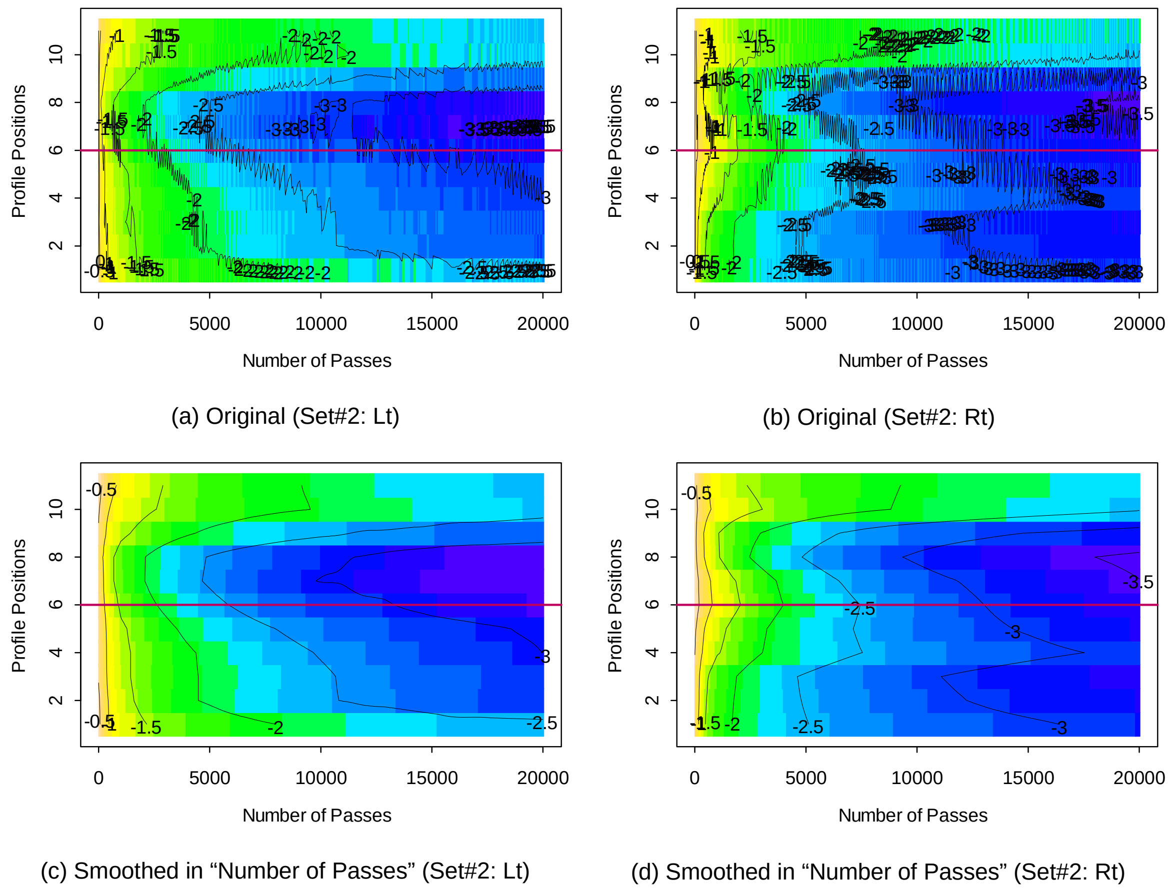
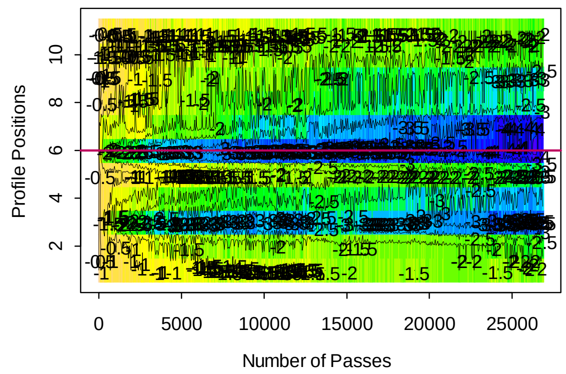
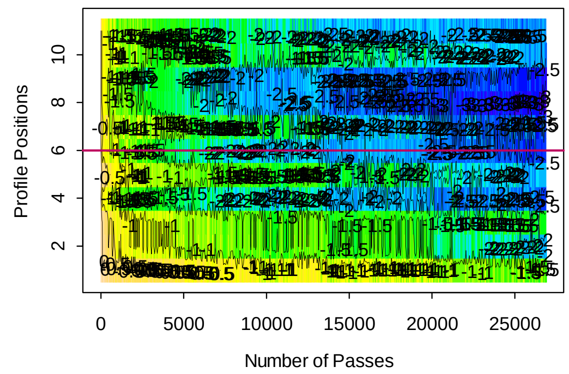


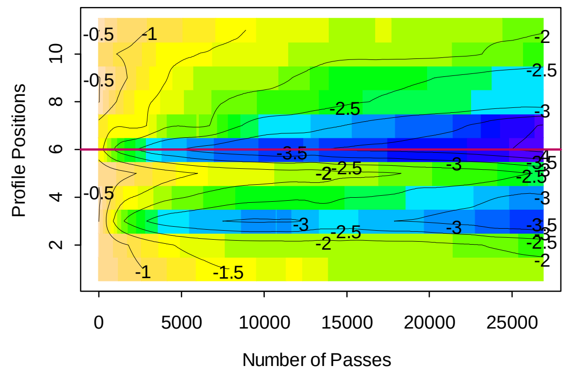
Figure C.5: Rutting evolution image and contour plots for PG 64-10 RAP with lime mix set #2 after 20,000 passes: (a) original data (lt.), (b) original data (rt.), (c) smoothed in "number of passes" direction (lt.), and (d) smoothed in "number of passes" direction (rt.) *(by Caltrans).*



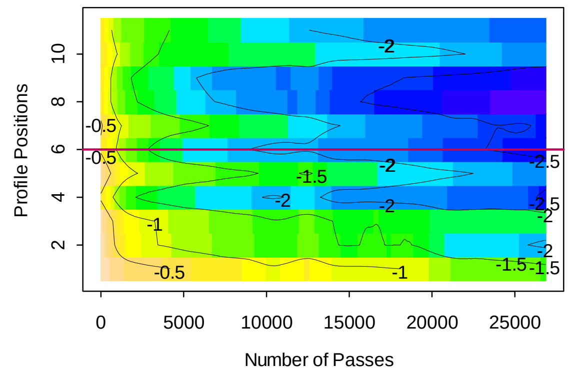
(a) Original (Set#1: Lt)



(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.6: Rutting evolution image and contour plots for PG 64-28PM 15%RAP with lime mix set #1 after 26,850 passes: (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.) *(by UCPRC).*

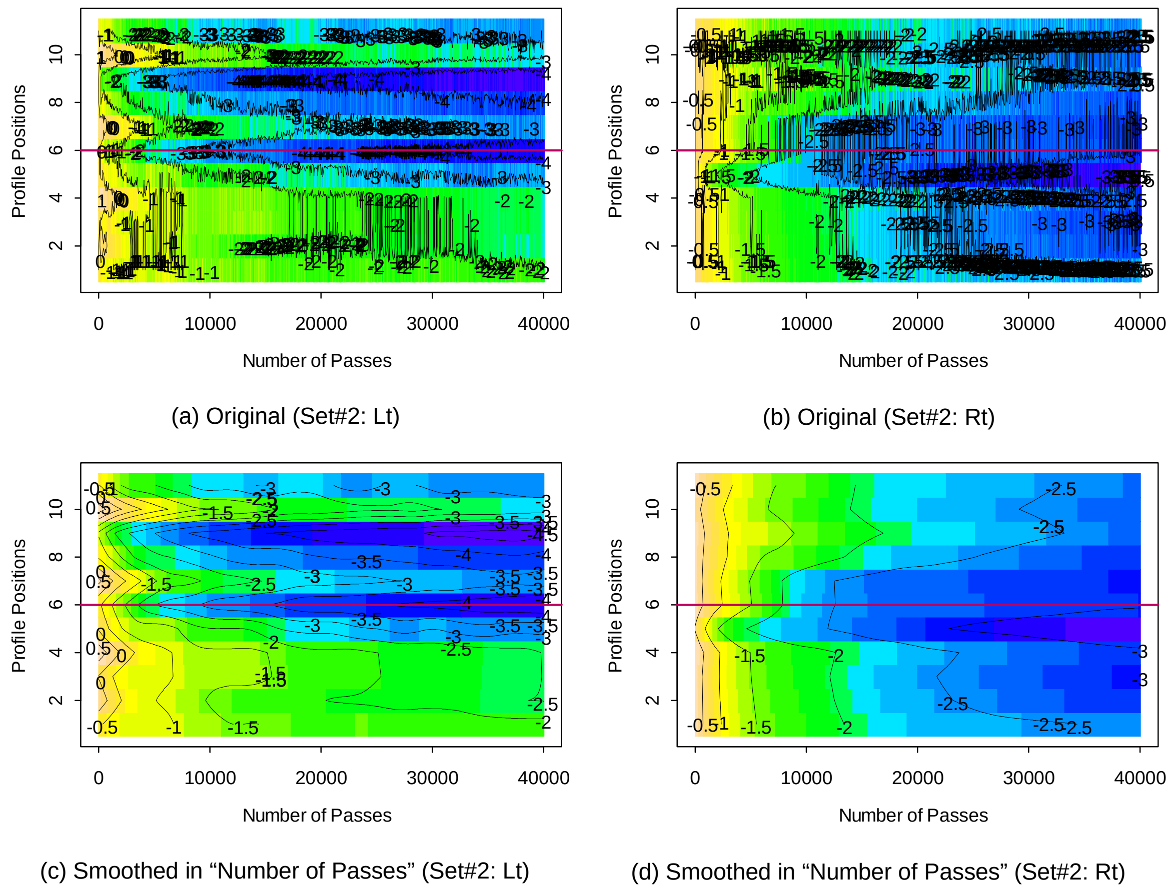


Figure C.7: Rutting evolution image and contour plots for PG 64-28PM with lime mix set #2 after 40,000 passes: (a) original data (lt.), (b) original data (rt.), (c) smoothed in "number of passes" direction (lt.), and (d) smoothed in "number of passes" direction (rt.) *(by UCPRC).*

APPENDIX D: CT 371 TEST RESULTS

Table D.1: Summary of CT 371 TSR Results of Red Bluff Project

Mix Type	Specimen Name	AV (%)	Strength (psi)	Condition	Average Strength (psi)	TSR
PG 64-10 RB 15% RAP with lime	1125-1	6.55	161.88	Dry	212.77	0.96
	1135-1	7.45	225.32			
	1135-2	7.36	220.09			
	1140-3	6.47	169.89			
	1140-4	7.49	303.62			
	1150-1	6.62	195.82			
	1140-1	7.55	134.56	Wet	189.12	
	1150-5	7.81	203.05			
	1150-4	7.71	213.60			
	1140-5	6.78	225.31			
	1140-2	6.66	215.04			
	1125-2	6.61	143.13			
PG 64-28PM 15% RAP with lime	1160-3	6.59	135.49	Dry	147.82	0.84
	1160-4	6.61	140.48			
	1160-9	6.81	197.19			
	1160-13	7.14	138.47			
	1160-15	6.70	132.17			
	1160-17	7.03	143.13			
	1160-1	7.50	102.69	Wet	118.28	
	1160-2	7.09	106.68			
	1160-6	6.77	106.08			
	1160-7	6.73	135.61			
	1160-10	7.03	117.92			
	1160-12	6.51	140.69			
PG 64-10 25% RAP with lime	1125-1	6.45	290.15	Dry	245.7	0.75
	1125-6	7.27	246.23			
	1125-7	7.50	265.38			
	1125-12	6.52	220.35			
	1125-14	7.19	234.33			
	1125-16	7.55	217.76			
	1125-2	6.77	182.36	Wet	182.22	
	1125-3	6.58	211.91			
	1125-5	6.64	188.37			
	1125-8	7.45	186.07			
	1125-9	7.21	169.90			
	1125-10	7.57	154.69			

APPENDIX E: DEVELOPMENT OF FATIGUE AND STIFFNESS MIX PERFORMANCE TEST REQUIREMENTS

Table E.1: Lower Bound Construction of 95% Confidence Band for PG 64-10 RB, 15% RAP, PG 64-10, 25% RAP, and PG 64-28PM, 15% RAP Mixes

Strain	Ln(Strain)	PG 64-10 RB with lime (lower bound) Ln(Nf)		PG 64-10 RAP with lime (lower bound) Ln(Nf)		PG 64-28PM with lime (lower bound) Ln(Nf)		
		Using all 10 data points	Excluding 6A2 and 7A2 tests	Using all 7 data points	Excluding 1C1 test	Using all 6 data points	Excluding 1D2 test (5 data points)	Excluding 1D2 test (6 data points)
0.000100	-9.21034	15.81985	16.01879	15.63268	16.58637	16.04276	20.20609	21.78165
0.000164	-8.71390	15.21146	15.18493	14.34777	14.91169	17.71877	19.86629	20.95204
0.000229	-8.38366	14.52459	14.50823	13.30796	13.66449	18.12476	19.45809	20.16316
0.000293	-8.13583	13.45893	13.74865	12.18087	12.47426	17.04798	18.78389	19.10352
0.000357	-7.93738	12.04937	12.79496	10.98033	11.26495	14.70458	17.74516	17.74487
0.000421	-7.77186	10.61595	11.782099	9.85850	10.13530	12.01503	16.56064	16.35684
0.000486	-7.62989	9.29322	10.82803	8.85378	9.12177	9.43551	15.41701	15.07220
0.000550	-7.50559	8.09695	9.95898	7.95648	8.21599	7.06540	14.36458	13.90914
0.000614	-7.39505	7.01470	9.17059	7.14983	7.40154	4.90410	13.40497	12.85651
0.000679	-7.29552	6.03023	8.45261	6.41876	6.66335	2.92906	12.52850	11.89884
0.000743	-7.20501	5.12893	7.79493	5.75100	5.98912	1.11562	11.72418	11.02204
0.000807	-7.12201	4.29864	7.18891	5.13683	5.36901		10.98212	10.21429
0.000871	-7.04538	3.52939	6.62739	4.56846	4.79517		10.29393	9.46594
0.000936	-6.97420	2.81308	6.10449	4.03966	4.26130		9.65264	8.76909
0.001000	-6.90776	2.14304	5.61535	3.54533	3.76225		9.05246	8.11725

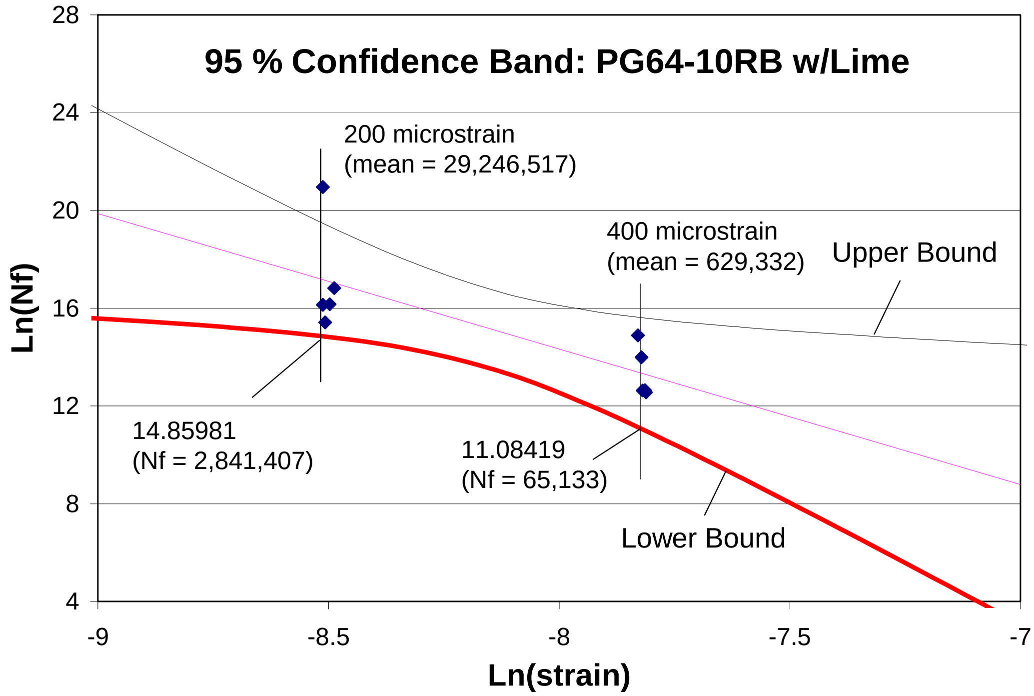


Figure E.1: Fatigue 95% confidence band, PG 64-10 RB 15% RAP with lime (AC = 5.5%, AV = 3%).

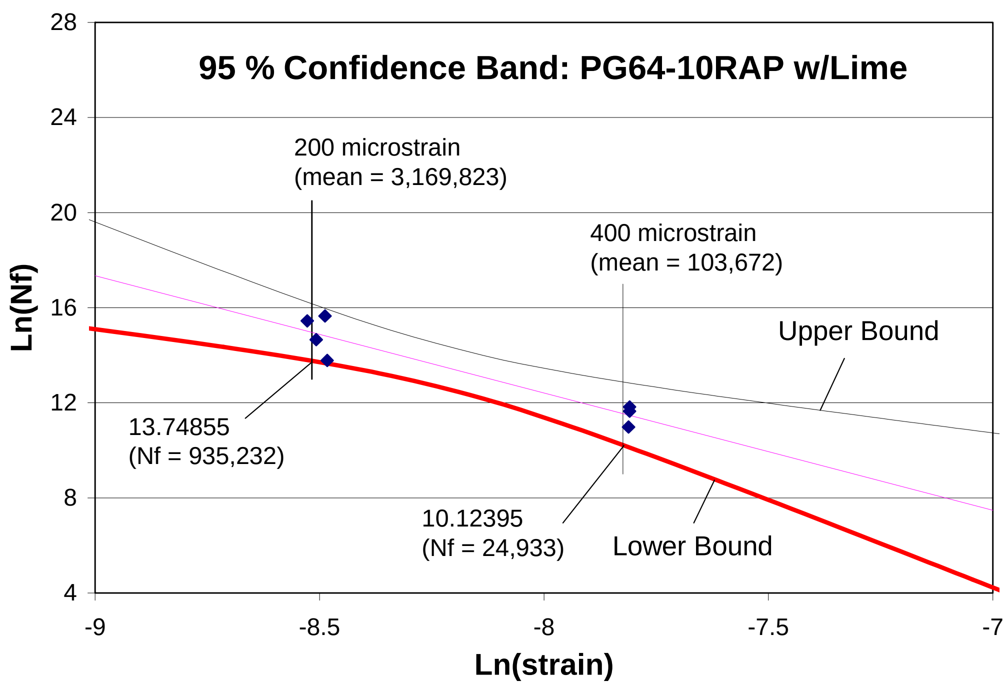


Figure E.2: Fatigue 95% confidence band, PG 64-10 25% RAP with lime (AC* = 5.38% [by weight of virgin aggregate], AV = 6.0%).

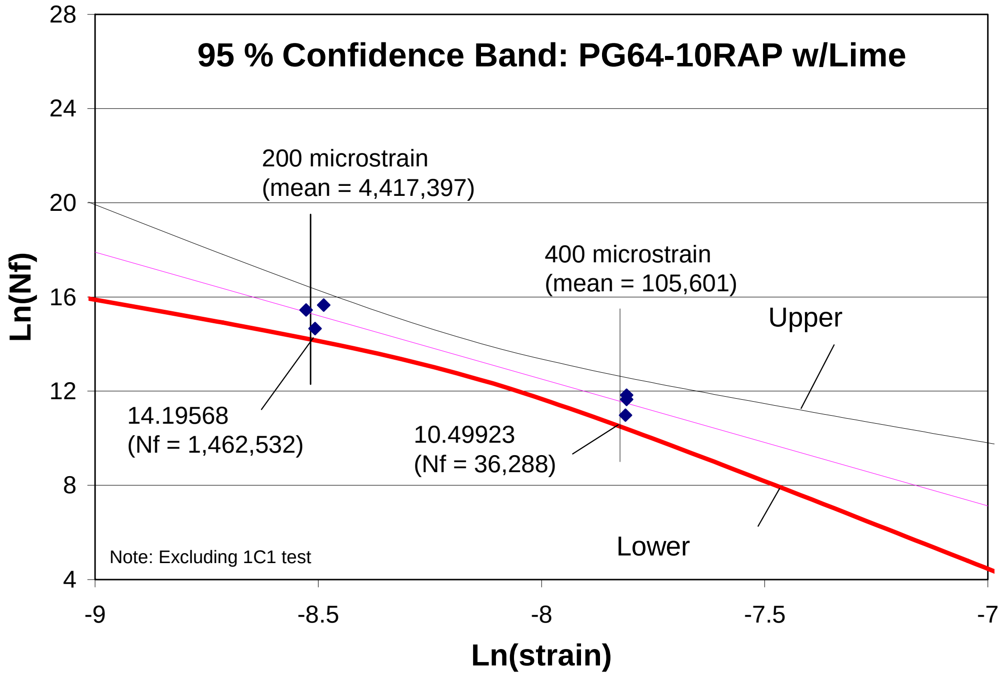


Figure E.3: Fatigue 95% confidence band, PG 64-10 25% RAP with lime (AC* = 5.38% [by weight of virgin aggregate], AV = 6.0%; excluding the 1C1 test).

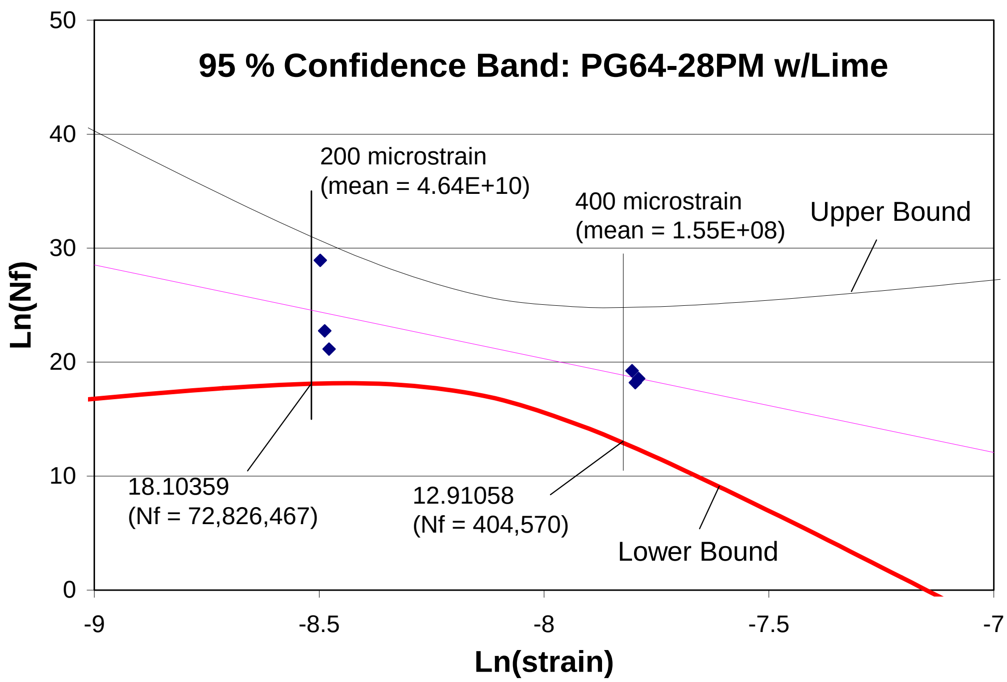


Figure E.4: Fatigue 95% confidence band, PG 64-28PM 15% RAP with lime (AC = 5.2%, AV = 6.0%).

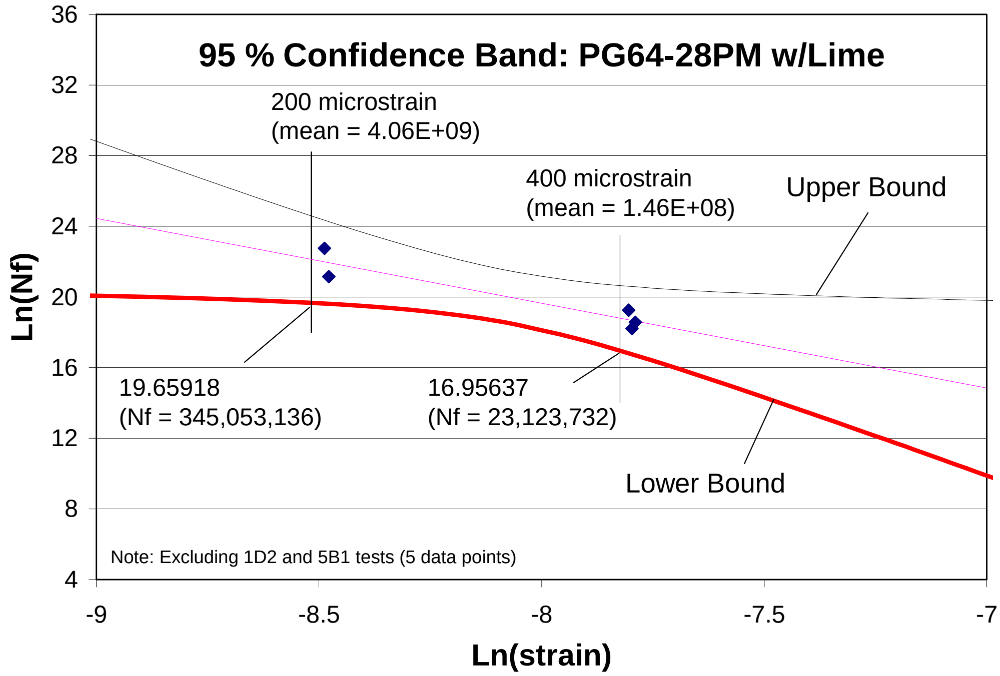


Figure E.5: Fatigue 95% confidence band, PG 64-28PM 15% RAP with lime (AC = 5.2%, AV = 6.0%; excluding the 1D2 and 5B1 tests).

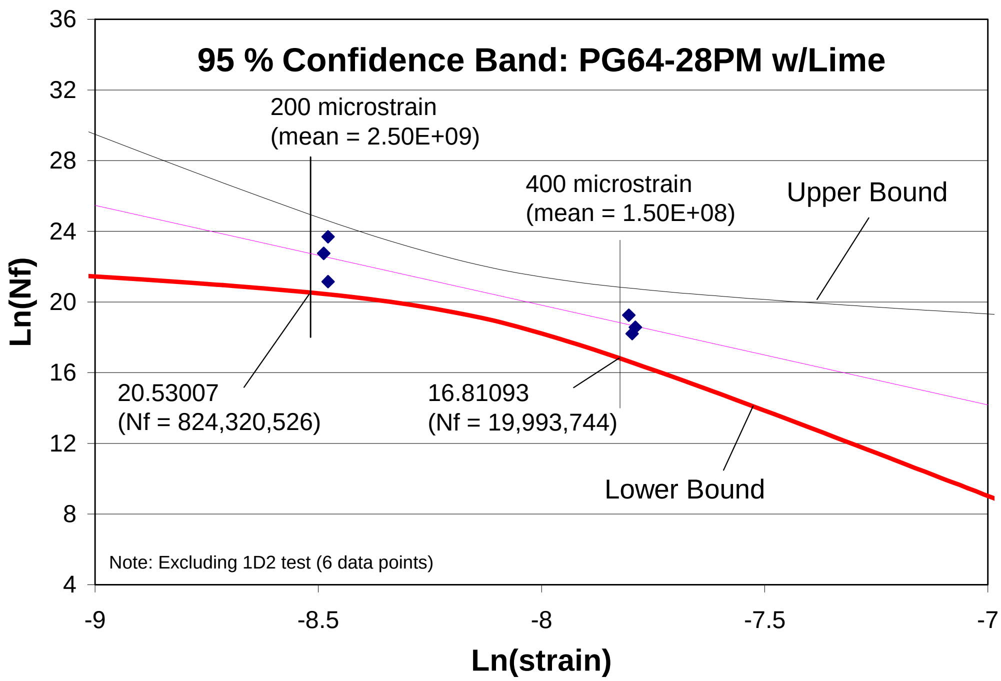


Figure E.6: Fatigue 95% confidence band, PG 64-28PM 15% RAP with lime (AC = 5.2%, AV = 6.0%; excluding the 1D2 test).