September 2007
Research Report: UCPRC-RR-2006-11

Reflective Cracking Study: First-Level Report on Laboratory Shear Testing

Authors:
I. Guada, J. Signore, B. Tsai, D. Jones, J. Harvey, and C. Monismith

Partnered Pavement Research Program (PPRC) Contract Strategic Plan Element 4.10:
Development of Improved Rehabilitation Designs for Reflective Cracking

PREPARED FOR:

California Department of Transportation
Division of Research and Innovation
Office of Roadway Research

PREPARED BY:

University of California
Pavement Research Center
UC Davis, UC Berkeley

DOCUMENT RETRIEVAL PAGE **Research Report: UCPRC-RR-2006-11**

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Prepared for: Caltrans	**FHWA No:** CA091073L	**Date:** September 2007
Contract No: 65A0172	**Client Reference No:** SPE 4.10	**Status:** Stage 6, Approved Version

Abstract:
This report contains a summary of the laboratory repeated load shear tests on mixes used as overlays on the Reflective Cracking Study Test Track at the Richmond Field Station. Evaluation of the results of the laboratory study on shear response of the overlay mixes reported herein included the effects of mix temperatures, air-void content, aging, mixing and compaction conditions, aggregate gradation, and shear stress level. Shear testing was performed to assess expected rutting performance at high temperatures. Mixes with five binders were tested, namely AR4000, asphalt rubber, and three modified binders termed MB4 (meeting the Caltrans MB4 specification [2003]), MB15 (meeting the MB4 specification and containing 15 percent recycled tire rubber, referred to as MAC15), and MAC15TR (Southern California GreenBook specification, containing 15 percent recycled tire rubber, referred to as MAC15). A full factorial considering all the variables required a total of 2,880 tests. This was reduced to 186 tests to accommodate time and fund constraints. Based on the shear test results for the mixes used in the overlay experiment, mix rankings for Cycles to 5 Percent Permanent Shear Strain, Permanent Shear Strain at 5,000 Cycles, and Resilient Shear Modulus (*G**) were:

- Permanent Shear Strain at 5,000 Cycles (best performance to worst): AR4000-D; MAC15-G; RAC-G; MB4-G; MB15-G.
- Cycles to 5 Percent Permanent Shear Strain (best performance to worst): AR4000-D; MAC15-G; RAC-G; MB4-G; MB15-G.
- Resilient Shear Modulus (*G**) (stiffest to least stiff): AR4000-D; RAC-G; MAC15-G; MB4-G; MB15-G

The results show that the rankings of different mixes for expected rutting performance are the same for the two permanent deformation parameters calculated from Repeated Simple Shear Test (RSST) results: Permanent Shear Strain at 5,000 Cycles and Cycles to 5 Percent Permanent Shear Strain. The RSST demonstrated that the dense-graded mix with unmodified AR-4000 asphalt performed better than the gap-graded mixes with modified binders. Of the three gap-graded mixes with modified binders, the MAC15 mix exhibited the highest resistance to shear deformation while the MB15 mix exhibited the lowest. Dense-graded mixes with the modified binders (MB4, MB15, MAC15) generally showed an increase in permanent shear deformation resistance and shear stiffness compared to gap-graded mixes with the same binders. Until a range of pavement types and environments are evaluated in the second level analysis, these results provide only a general indication of the relative performance of the modified binders with respect to rutting performance.

Keywords:
Shear testing, rutting, overlay, modified binder, HVS test, MB Road

Proposals for implementation: Implementation recommendations will be made after completion of other testing and analyses**.**

Related documents:
UCPRC-RR-2005-03, UCPRC-RR-2006-08

Signatures:

I. Guada 1st Author	C Monismith Technical Review	D. Spinner Editor	J. Harvey Principal Investigator	M Samadian Caltrans Contract Manager

DISCLAIMER

PROJECT OBJECTIVES

The objective of this project is to develop improved rehabilitation designs for reflective cracking for California.

This objective will be met after completion of four tasks identified by the Caltrans/Industry Rubber Asphalt Concrete Task Group (RACTG):

1. Develop improved mechanistic models of reflective cracking in California,
2. Calibrate and verify these models using laboratory and HVS testing,
3. Evaluate the most effective strategies for reflective cracking, and
4. Provide recommendations for reflective cracking strategies

This document is one of a series addressing Tasks 2 and 3.

ACKNOWLEDGEMENTS

The University of California Pavement Research Center acknowledges the assistance of the Rubber Pavements Association, Valero Energy Corporation, and Paramount Petroleum which contributed funds and asphalt binders for the construction of the Heavy Vehicle Simulator test track discussed in this study.

REFLECTIVE CRACKING STUDY REPORTS

The reports prepared during the reflective cracking study document data from construction, Heavy Vehicle Simulator (HVS) tests, laboratory tests, and subsequent analyses. These include a series of first- and second-level analysis reports and two summary reports. On completion of the study this suite of documents will include:

1. Reflective Cracking Study: Summary of Construction Activities, Phase 1 HVS testing and Overlay Construction (UCPRC-RR-2005-03).
2. Reflective Cracking Study: First-level Report on the HVS Rutting Experiment (UCPRC-RR-2007-06).
3. Reflective Cracking Study: First-level Report on HVS Testing on Section 590RF — 90 mm MB4-G Overlay (UCPRC-RR-2006-04).
4. Reflective Cracking Study: First-level Report on HVS Testing on Section 589RF — 45 mm MB4-G Overlay (UCPRC-RR-2006-05).
5. Reflective Cracking Study: First-level Report on HVS Testing on Section 587RF — 45 mm RAC-G Overlay (UCPRC-RR-2006-06).
6. Reflective Cracking Study: First-level Report on HVS Testing on Section 588RF — 90 mm AR4000-D Overlay (UCPRC-RR-2006-07).
7. Reflective Cracking Study: First-level Report on HVS Testing on Section 586RF — 45 mm MB15 Overlay (UCPRC-RR-2006-12).
8. Reflective Cracking Study: First-level Report on HVS Testing on Section 591RF — 45 mm MAC15TR-G Overlay (UCPRC-RR-2007-04).
9. Reflective Cracking Study: HVS Test Section Forensic Report (UCPRC-RR-2007-05).
10. Reflective Cracking Study: First-level Report on Laboratory Fatigue Testing (UCPRC-RR-2006-08).
11. Reflective Cracking Study: First-level Report on Laboratory Shear Testing (UCPRC-RR-2006-11).
12. Reflective Cracking Study: Back Calculation of FWD Data from HVS Test Sections (UCPRC-RR-2007-08).
13. Reflective Cracking Study: Second-Level Analysis Report (UCPRC-RR-2007-09).
14. Reflective Cracking Study: Summary Report (UCPRC-SR-2007-01). Detailed summary report.
15. Reflective Cracking Study: Summary Report (UCPRC-SR-2007-03). Four page summary report.

CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m2
VOLUME				
ft^3	cubic feet	0.028	cubic meters	m^3
MASS				
lb	pounds	0.454	kilograms	kg
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	C
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce/square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
VOLUME				
m^3	cubic meters	35.314	cubic feet	ft^3
MASS				
kg	kilograms	2.202	pounds	lb
TEMPERATURE (exact degrees)				
C	Celsius	1.8C+32	Fahrenheit	F
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce/square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

GLOSSARY OF TERMS

av	Percent air-void content
binder	Binder types including AR4000, ARB, MB4, MB15, and MAC15
comp	Compaction including FMFC, FMLC, and LMLC
cond	Conditioning, either aging or non-aging
grad	Gradation
FMFC	Field-mixed field-compacted
FMLC	Field-mixed laboratory-compacted
LMLC	Laboratory-mixed laboratory-compacted
G^*	Resilient shear modulus
$\ln\alpha_1$ and β_1	Intercept and slope of Stage I of a three-stage fatigue/shear Weibull curve
$\ln\alpha_2$ and β_2	Intercept and slope of Stage II of a three-stage fatigue/shear Weibull curve
$\ln\alpha_3$ and β_3	Intercept and slope of Stage III of a three-stage fatigue/shear Weibull curve
ln*G*	Initial resilient shear modulus (MPa) in natural logarithm
ln*kcy5*	Permanent shear strain after 5,000 loading cycles
$\ln n_1$	Separation point between Stage I and Stage II of a three-stage fatigue/shear Weibull curve
$\ln n_2$	Separation point between Stage II and Stage III of a three-stage fatigue/shear Weibull curve
ln*Nf*	Traditional fatigue life (repetitions at 50 percent loss of initial stiffness) in natural logarithm
ln*pct5*	Cycles to 5 percent permanent shear strain (in natural logarithm)
ln*stif*	Initial stiffness (MPa) in natural logarithm
lnstn	Strain level in natural logarithm
lnsts	Stress level (kPa) in natural logarithm
pa	Phase angle
PSS	Permanent shear strain
RSS	Residual sum of squares
SR	Stiffness ratio
srn_1	Stage I stiffness ratio in a three-stage fatigue Weibull curve
srn_2	Stage II stiffness ratio in a three-stage fatigue Weibull curve
temp	Temperature in °C
γ_1	Parameter that determines the degree of slope change from Stage I to Stage II of a three-stage fatigue/shear Weibull curve
γ_2	Parameter that determines the degree of slope change from Stage II to Stage III of a three-stage fatigue/shear Weibull curve

EXECUTIVE SUMMARY

This report is one in a series of first-level analysis reports that describe the results of HVS and laboratory testing on a full-scale experiment being performed at the Richmond Field Station (RFS) to validate Caltrans overlay strategies for the rehabilitation of cracked asphalt concrete. It describes the results of the laboratory shear tests on mixes used as overlays in the experiment. The testing forms part of Partnered Pavement Research Center Strategic Plan Element 4.10: "Development of Improved Rehabilitation Designs for Reflective Cracking."

The objective of this project is to develop improved rehabilitation designs for reflective cracking for California. This objective will be met after completion of the following four tasks:

1. Develop improved mechanistic models of reflective cracking in California
2. Calibrate and verify these models using laboratory and HVS testing
3. Evaluate the most effective strategies for reflective cracking
4. Provide recommendations for reflective cracking strategies

This report is one of a series addressing Tasks 2 and 3. It consists of three main chapters. Chapter 2 provides an overview of the experimental design. Chapter 3 summarizes the results on binder tests, conducted by the Federal Highways Administration. Chapter 4 details the shear testing exercise and includes, temperature, air-void content, aging, mixing and compaction, and gradation effects, as well the analysis procedures followed and the results obtained. Comparison of the laboratory and test section performance, including the results of a forensic investigation to be conducted when testing is complete, will be discussed in second-level reports once the data from all of the studies has been collected. It must be emphasized that the study was focused on the use of modified binders in thin overlays on existing cracked asphalt surfaces and not in structural layers. The use of modified binders in thick overlays or as structural layers is currently not recommended.

Five binders were included in this study: AR4000 asphalt cement, asphalt rubber, and three modified binders termed MB4, MB15, and MAC15. The MB4 binder meets the Caltrans MB4 specification, as of 2003. The binder referred to as MB15 also meets the MB4 specification and contains 15 percent recycled rubber. The binder referred to as MAC15 meets the Southern California Greenbook specification (2003) for MAC15TR. The modified binders were blended at the terminal.

All mixes used the same aggregate source, and common aggregate gradations were used for all dense-graded mixes and all gap-graded mixes. The AR4000 binder was used in a dense-graded asphalt concrete (DGAC) mix, and the asphalt rubber binder was used in a gap-graded rubber asphalt concrete (RAC-G) mix. In most of the experiments included in this laboratory study the modified binders were used in gap-graded mixes. These mixes were the same as those placed for accelerated pavement testing using the Heavy Vehicle Simulator (HVS). Samples of the five mixes were prepared from loose mix samples obtained at the time of the overlay construction and stored in sealed containers until ready for compaction and testing. These resulting specimens have been designated in the report as field-mixed, laboratory-compacted (FMLC). The majority of the shear test results presented in this report are from FMLC specimens. A comparison was also made between dense-graded mixes with the three modified binders and the RAC-G and DGAC mixes because of the potential for using the modified binders in dense-graded as well as in gap-graded mixes. For this comparison, raw binder and aggregate samples retained since construction were used to mix and compact specimens. These specimens were referred to as laboratory-mixed, laboratory-compacted (LMLC).

A comprehensive experimental design was prepared for the study. To test a full factorial considering all the variables over 2,800 tests would have been required. Because of time and fund constraints, a partial factorial experiment was completed with 186 tests.

As-built binder contents of the field mixes were determined from ignition oven tests, after calibration using raw aggregate samples. The design binder contents for the DGAC and RAC-G mixes are based on Caltrans mix design requirements (Section 39 of the Standard Specifications for the DGAC and Section 39-10 of the Standard Special Provisions for the RAC-G). Design binder contents for the gap-graded mixes with the MB4, MB15, and MAC15 binders were selected based on Caltrans mix design requirements. For the LMLC dense-graded mixes containing the modified binders, the standard California procedure for mix design was followed to define the binder contents used for the test specimens.

Binder tests were performed for four of the binders (AR4000, MB4, MB15, and MAC15) by the Federal Highway Administration using the Bending Beam Rheometer (BBR) and the Dynamic Shear Rheometer (DSR) over a range of loading times for the BBR and frequencies for the DSR. Specimens were tested in their original condition, after short-term aging using the Rolling Thin Film Oven (RTFO) Test, and after long-term aging using the Pressure Aging Vessel (PAV) Test. Based on the current specification requirements, binder rankings considering low-temperature cracking, fatigue, and rutting are as follows, ranked from least to highest susceptibility:

Low Temperature Cracking	Fatigue	Permanent Deformation
MB4	MB4	AR4000
MB15	MB15	MB4 and MB15
MAC15	MAC15	MAC15
AR4000	AR4000	

Significant factors affecting shear response have been identified using:

- A correlation matrix,
- Analysis of variance (ANOVA),
- Design plots, and
- Pairs diagrams.

This approach was deemed essential since a partial factor experiment (186 tests) rather than a full factorial (2,880 tests) was conducted. By using this approach, there is greater confidence that the major effects are included in any performance equation resulting from the experiment to predict the performance of a mix containing a specific binder in pavement structures subjected to different traffic and climate conditions.

Regression models are presented for Cycles to 5 Percent Permanent Shear Strain (PSS), Permanent Shear Strain (PSS) at 5,000 Cycles, and resilient shear modulus (G^*) for the various mixes tested. Results predicted by the regression equations are presented for different values of the input variables (stress, temperature, etc.). It must be emphasized that when these regression equations are used for pavement performance analyses, mixes similar to those used in this investigation and within the range of the variables used to calibrate the equations should be used in order to obtain reasonable estimates of the effects of the various binders on pavement performance.

Based on the shear test results for FMLC specimens from the mixes used in the overlay experiment, mix rankings for Cycles to 5 percent PSS, PSS at 5,000 Cycles, and $G^*$are as follows, from best expected rutting performance to worst:

PSS 5,000 Cycles	Cycles to 5 Percent PSS	Resilient Shear Modulus (G^*)
AR4000-D	AR4000-D	AR4000-D
MAC15-G	MAC15-G	RAC-G
RAC-G	RAC-G	MAC15-G
MB4-G	MB4-G	MB4-G
MB15-G	MB15-G	MB15-G

While the shear tests on the laboratory mixed, laboratory-compacted dense-graded mixes containing the three modified binders were limited, the performance of these three dense-graded mixes was generally better than those of the corresponding gap-graded mixes. The results for the dense-graded AR4000 mix in the gradation study were not consistent relative to those of the RAC-G mix. The difference may be due to differences in aging between FMLC and LMLC specimens resulting from reheating for compaction of the field-mix for the FMLC specimens.

In conclusion, it must be emphasized that until a range of pavement types and environments are evaluated in the second-level analysis, only a general indication of the expected relative rutting performance of the modified binders can be deduced. It would appear that the MB4 and MB15 binders used in gap-graded mixes have a somewhat greater risk of rutting at high temperatures compared to RAC-G mixes, while gap-graded mixes with MAC15 binder had results similar to those of RAC-G. Recommendations for the use of MB4 and MB15 materials in thicker layers and as dense-graded mixes await further test results and pavement performance analyses.

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1. INTRODUCTION

1.1. Objectives

The first-level analysis presented in this report is part of Partnered Pavement Research Center Strategic Plan Element 4.10 (PPRC SPE 4.10) being undertaken for the California Department of Transportation (Caltrans) by the University of California Pavement Research Center (UCPRC). The objective of the study is to evaluate the reflective cracking performance of asphalt binder mixes used in overlays for rehabilitating cracked asphalt concrete pavements in California. The study includes mixes modified with rubber and polymers, and it will develop tests, analysis methods, and design procedures for mitigating reflective cracking in overlays. This work is part of a larger study on modified binder (MB) mixes being carried out under the guidance of the Caltrans Pavement Standards Team (PST) (1), which includes laboratory and accelerated pavement testing using the Heavy Vehicle Simulator (carried out by the UCPRC), and the construction and monitoring of field test sections (carried out by Caltrans).

1.2. Overall Project Organization and Deliverables

This UCPRC project is a comprehensive study, carried out in three phases, involving the following primary elements (2):

- Phase 1
    - The construction of a test pavement and subsequent overlays;
    - Six separate Heavy Vehicle Simulator (HVS) tests to crack the pavement structure;
    - Placing of six different overlays on the cracked pavement;
- Phase 2
    - Six HVS tests to assess the susceptibility of the overlays to high-temperature rutting (Phase 2a);
    - Six HVS tests to determine the low-temperature reflective cracking performance of the overlays (Phase 2b);
    - Laboratory shear and fatigue testing of the various hot-mix asphalts (Phase 2c);
    - Falling Weight Deflectometer (FWD) testing of the test pavement before and after construction and before and after each HVS test;
    - Forensic evaluation of each HVS test section;
- Phase 3
    - Performance modeling and simulation of the various mixes using models calibrated with data from the primary elements listed above.

Phase 1

In this phase, a conventional dense-graded asphalt concrete (DGAC) test pavement was constructed at the Richmond Field Station (RFS) in the summer of 2001. The pavement was divided into six cells, and within each cell a section of the pavement was trafficked with the HVS until the pavement failed by either fatigue (2.5 m/m^2 [0.76 ft/ft^2]) or rutting (12.5 mm [0.5 in]). This period of testing began in the fall of 2002 and was concluded in the spring of 2003. In June 2003 each test cell was overlaid with either conventional DGAC or asphalt concrete with modified binders as follows:

- Full-thickness (90 mm) AR4000-D overlay, included as a control for performance comparison purposes;
- Full-thickness (90 mm) MB4 gap-graded overlay;
- Half-thickness (45 mm) rubberized asphalt concrete gap-graded overlay (RAC-G), included as a control for performance comparison purposes;
- Half-thickness (45 mm) MB4 gap-graded overlay;
- Half-thickness (45 mm) MB4 gap-graded overlay with minimum 15 percent recycled tire rubber, and
- Half-thickness (45 mm) MAC15TR gap-graded overlay with minimum 15 percent recycled tire rubber.

The conventional overlay was designed using the current (2003) Caltrans overlay design process. The various modified overlays were either full (90 mm) or half thickness (45 mm). Mixes were designed by Caltrans. The overlays were constructed in one day.

Phase 2

Phase 2 included high-temperature rutting and low-temperature fatigue testing with the HVS as well as laboratory shear and fatigue testing. The rutting tests were started and completed in the fall of 2003. For these tests, the HVS was placed above a section of the underlying pavement that had not been trafficked during Phase 1. A low-temperature fatigue test was next conducted on each overlay from the winter of 2003-2004 to the summer of 2007. For these tests, the HVS was positioned precisely on top of the sections of failed pavement from the Phase 1 HVS tests to investigate the extent and rate of crack propagation through the overlay.

In conjunction with Phase 2 HVS testing, a full suite of laboratory testing, including shear and fatigue testing, was carried out on field-mixed/field-compacted, field-mixed/laboratory-compacted, and laboratory-mixed/laboratory-compacted specimens.

Phase 3

Phase 3 entailed a second-level analysis carried out on completion of HVS and laboratory testing. This included extensive analysis and characterization of the mix fatigue and mix shear data, backcalculation of the FWD data, performance modeling of each HVS test, and a detailed series of pavement simulations carried out using the combined data.

An overview of the project timeline is shown in Figure 1.1.

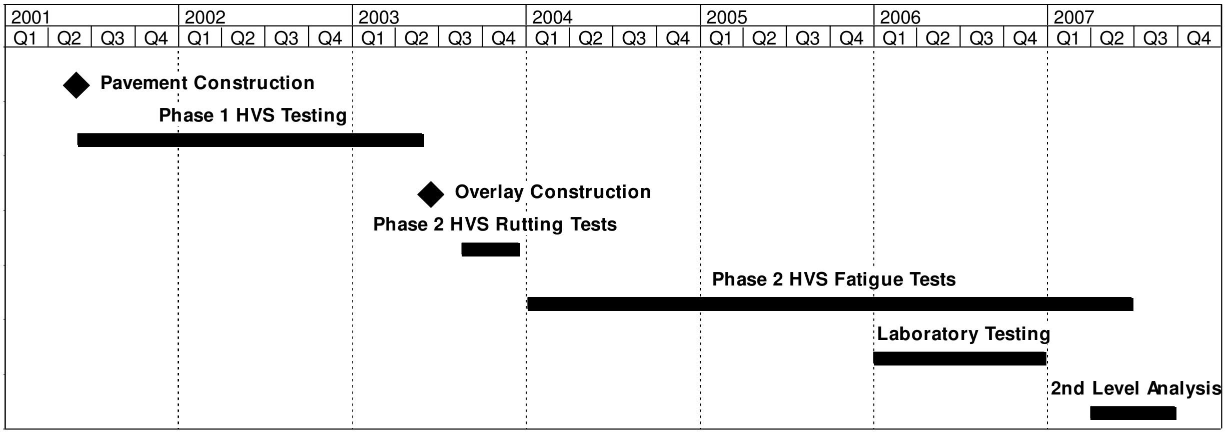


Figure 1.1: Timeline for the Reflective Cracking Study.

The reports prepared during the reflective cracking study document data from construction, HVS tests, laboratory tests, and subsequent analyses. These include a series of first- and second-level analysis reports and two summary reports. On completion of the study this suite of documents will include:

- One first-level report covering the initial pavement construction, the six initial HVS tests, and the overlay construction (Phase 1);
- One first-level report covering the six Phase 2 rutting tests. This report offers no detailed explanations or conclusions on the performance of the pavements;
- Six first-level reports, each covering a single Phase 2 fatigue test. These reports contain summaries and trends of the measured environmental conditions, pavement responses, and pavement performance. They offer no detailed explanations or conclusions on the performance of the pavement.
- One first-level report covering laboratory shear testing;
- One first-level report covering laboratory fatigue testing;
- One report summarizing the HVS test section forensic investigation;
- One report detailing Falling Weight Deflectometer (FWD) results and analysis;

- One second-level analysis report detailing characterization of laboratory fatigue and shear data, pavement modeling analysis, comparisons of the various overlays, and simulations using various scenarios (Phase 3), and
- A four-page summary report capturing the conclusions of the experiment and a longer, more detailed summary report that covers the findings and conclusions from the research conducted by the UCPRC.

Reports are prepared as soon as a specific HVS or laboratory test is complete. Additional findings from forensic investigations and later analysis are covered in the forensic, second-level analysis, and summary reports.

1.3. Content and Structure of this Report

This report presents a summary of the results of the laboratory shear test program, detailed results of which are available in the UCPRC relational database. The report is organized as follows:

- Chapter 2 details the test plan and describes specimen preparation and conditioning.
- Chapter 3 provides information on the binders used in the study.
- Chapter 4 presents and discusses the results of shear testing in terms of the variables listed above.
- Chapter 5 provides conclusions.
- Appendix A contains summary tables of test results.
- Appendix B contains mix design summary data.

1.4. Measurement Units

Metric units have always been used in the design and layout of HVS test tracks, all the measurements and data storage, and all associated laboratory testing at the eight HVS facilities worldwide (as well as all other international accelerated pavement testing facilities). Use of the metric system facilitates consistency in analysis, reporting, and data sharing.

In this report, metric and English units (provided in parentheses after the metric units) are used in the Executive Summary, Chapter 1 and 2, and the Conclusion. In keeping with convention, only metric units are used in Chapters 3, 4, and 5. A conversion table is provided on Page iv at the beginning of this report.

2. EXPERIMENT DESIGN

2.1. Introduction

The laboratory program included shear tests on mixes used in the following accelerated pavement testing sections:

1. Full-thickness (90 mm [3.5 in]) dense-graded asphalt concrete (DGAC) with AR-4000 binder, included as a control for performance comparison purposes
2. Half-thickness (45 mm [1.7 in]) rubberized asphalt concrete gap-graded (RAC-G) overlay, included as a control for performance comparison purposes
3. Full-thickness (90 mm) MB4 gap-graded overlay
4. Half-thickness (45 mm) MB4 gap-graded overlay
5. Half-thickness (45 mm) MB4 gap-graded overlay with minimum 15 percent recycled tire rubber (referred to as "MB15" in this report)
6 Half-thickness (45 mm) MAC15TR gap-graded overlay with minimum 15 percent recycled tire rubber (referred to as "MAC15" in this report)

Samples of loose asphalt mix were collected from the HVS test site during construction of the test sections. Specimens compacted in the laboratory using this material are referred to as field-mixed, laboratory-compacted (FMLC) specimens. Samples of the asphalt binders and aggregates were obtained at the hot-mix plant during construction. These materials were used to prepare laboratory-mixed, laboratory-compacted (LMLC) specimens. Cores were also cut from the pavement section for testing, and are referred to as field-mixed, field-compacted (FMFC) specimens. The resulting specimens were used to evaluate the influence of binder type, applied shear stress, temperature, degree of compaction (air-void content), aging, and aggregate gradation on permanent deformation performance.

Summaries of the test procedures, experiment design, and specimen preparation are included in this chapter.

2.2. Test Procedure

The laboratory shear test used in this study was AASHTO T320, "Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST), Procedure C, Repeated

Shear Test at Constant Height (RSST-CH)." This test procedure was originally developed as part of the Strategic Highway Research Program (SHRP). An ASTM version of the test has recently been approved.

In this report, the test is referred to as the RSST (Repeated Simple Shear Test).

In the standard test methodology, cylindrical test specimens 50 mm (2 in) thick by 150 mm (6 in) in diameter are subjected to repeated loading in shear using a 0.1-second haversine waveform followed by a 0.6-second rest period. A shear stress equaling 70 kPa (10 psi) is applied while the permanent (unrecoverable) and recoverable shear strains are measured. The permanent shear strain versus applied repetitions is normally recorded up to a value of 5 percent although 5,000 repetitions are called for in the AASHTO procedure. A constant temperature is maintained during the test (termed the *critical temperature)* representative of the local environment, generally in the temperature range of 40°C to 60°C (104°F to 140°F).

For this study, the test was also performed at two stresses greater than that used in the standard test and at two temperatures. Since tests run to 5,000 repetitions (as in the AASHTO procedure) may not produce significant permanent shear deformation, tests were run up to 30,000 repetitions or until 5 percent permanent shear strain was achieved. When specimens did not reach 5 percent permanent shear strain within 30,000 repetitions, results were extrapolated to this strain level. The purpose of the additional stress levels and temperatures, and the extended tests, was to obtain more a comprehensive data set for later analysis and simulation of the permanent deformation performance of the mixes.

2.3. Experiment Design

The experiment design was formulated to quantify the effects of:

- Applied shear stress,
- Temperature,
- Degree of compaction (air voids),
- Mix aging,
- Mixing and compaction method, and
- Aggregate gradation.

Table 2.1 presents an overview of the shear experiment design. Table 2.2 provides the detailed experiment designs for the study. The following sections briefly discuss the effects mentioned, and the motivation for and application of the study. With each effect, the type of specimen tested (laboratory-mixed, laboratory-compacted [LMLC]; field-mixed, laboratory-compacted [FMLC]; or field-mixed, field-compacted [FMFC]) is noted in parentheses. LMLC specimens were prepared from aggregate and asphalt samples taken at the plant and refinery during construction, and later mixed and compacted in the laboratory. FMLC specimens were compacted in the laboratory using mix collected from the plant during construction of the HVS test section overlays. FMFC specimens, field cores, were obtained from cores extracted from the pavement section after construction of the HVS test section overlays.

Table 2.1: Overall Laboratory Shear Testing Test Plan

Mix/ Compaction	AV*	AC**	Grad.	Test Type	Variables	Total Tests
FMLC (Temperature Susceptibility)	Design AV (6±0.5%)	Field AC	Gap-graded /Dense-graded	RSST	2 temperatures (45, 55°C) 3 stress levels (70, 100, 130 kPa) 3 replicates	18
	Field AV (9±1%)	Field AC	Gap-graded /Dense-graded	RSST	2 temperature (45, 55°C) 1 stress levels (70 kPa) 2 replicates	4
FMLC (Aging)	Design AV (6±0.5%)	Field AC	Gap-graded /Dense-graded	RSST	2 temperature (45,55°C) LTOA (6 days) 1 stress level (70 kPa) 2 replicates	4
					1 temperature (45°C) LTOA (6 days) 2 stress levels (100, 130 kPa) 2 replicates	4
LMLC	Design AV (6±0.5%)	Design AC	Gap-graded	RSST	1 temperature (45°C) 1 stress level (70 kPa) 2 replicates	2
LMLC	Design AV (6±0.5%)	Design AC (TBD)	Dense-graded	RSST	1 temperature (45°C) 1 strain levels (70 kPa) 2 replicates	2
					Total tests per mix type	39 (45)
					5 mixes	197* (227)
*AV - Air void **AC - Asphalt content (percent by mass of aggregate)						

In order to test a full factorial, a total of 2,880 tests (three replicates of five binder types, two mix types, two compaction types, two condition types, two gradations, two air-void contents, two temperatures, and three stress levels) would be required. This number of tests was unrealistic in terms of both time and resources. A partial factorial was therefore tested and where possible the same tests to evaluate different effects were not repeated. As noted, results were extrapolated when required.

Table 2.2: Experimental Design for Laboratory Shear Testing

Type of Shear Study	Test Type	Compaction	Condition	Binder Type	Gradation	Design Asphalt Content (%)*	Air-Void Content (%)	Temp. (°C)	Stress (kPa)	Replicates	Total Tests
Temperature Effect (90)	RSST-CH	FMLC	none	AR4000	DG	5.0	6 ± 0.5	45, 55	70,100, 130	3	2 x 3 x 3 = 18
				RAC	GG	8.0					2 x 3 x 3 = 18
				MAC15		7.4					2 x 3 x 3 = 18
				MB15		7.1					2 x 3 x 3 = 18
				MB4		7.2					2 x 3 x 3 = 18
Air-Void Content Effect (20) (Compared to Temp Effect Specimens at 6%)	RSST-CH	FMLC	none	AR4000	DG	5.0	9 ± 1	45, 55	70	2	2 x 1 x 2 = 4
				RAC	GG	8.0					2 x 1 x 2 = 4
				MAC15		7.4					2 x 1 x 2 = 4
				MB15		7.1					2 x 1 x 2 = 4
				MB4		7.2					2 x 1 x 2 = 4
Aging Effect (20) (Compared to Temp Effect Specimens at 6%)	RSST-CH	FMLC	aging	AR4000	DG	5.0	6 ± 0.5	45, 55	70	2	2 x 1 x 2 = 4
				RAC	GG	8.0					2 x 1 x 2 = 4
				MAC15		7.4					2 x 1 x 2 = 4
				MB15		7.1					2 x 1 x 2 = 4
				MB4		7.2					2 x 1 x 2 = 4

* Design Asphalt Contents are percent by mass of aggregate

Table 2.2: Experimental Design for Laboratory Shear Testing *(cont.)*

Type of Shear Study	**Test Type**	**Compaction**	**Condition**	**Binder Type**	**Gradation**	**Design Asphalt Content** (%)	**Air-Void Content** (%)	**Temp.** (°C)	**Stress** (kPa)	**Replicates**	**Total Runs**
Compaction Effect (26) (Compared to Temp Effect Specimens at 6%)	RSST-CH	FMFC	Field Aged and Trafficked	MB4	GG	7.2	6 ± 0.5	45	70	3	1 x 1 x 3 = 3
				AR4000	DG	5.0					1 x 1 x 3 = 3
		LMLC	none	AR4000	DG	5.0	6 ± 0.5	45	70	3	1 x 1 x 3 = 3
				MB4	GG	7.2					1 x 1 x 3 = 3
				RAC		8.0					1 x 1 x 3 = 3
				MAC15		7.4					1 x 1 x 3 = 3
				MB15		7.1					1 x 1 x 3 = 3
Gradation Effect (24) (Compared to compaction effect LMLC specimens)	RSST-CH	LMLC	none	MB4	DG	7.2	6 ± 0.5	45	70	3	1 x 1 x 3 = 3
				MB15		7.1					1 x 1 x 3 = 3
				MAC15		7.4					1 x 1 x 3 = 3

2.3.1 Temperature and Shear Stress Effects (FMLC)

This part of the experiment evaluated the temperature and stress effects on field-mixed, laboratory-compacted (FMLC) specimens. Three replicates at two temperatures (45°C and 55°C [113°F and 131°F]) and three stress levels (70 kPa, 100 kPa and 130 kPa [10 psi, 14.5 psi and 18.8 psi]) were used.

2.3.2 Air-Void Content Effect (FMLC)

The effect of construction quality in terms of compaction on pavement performance was considered by conducting tests on specimens at two different air-void contents, 6.0 ± 0.5 percent and 9.0 ± 1.0 percent. Three replicates at two temperatures (45 C and 55°C) and one stress level (70 kPa) were tested.

2.3.3 Aging Effect (FMLC)

The aging effect simulates extended environmental exposure, generally resulting in stiffening of the binder. For conventional asphalt binders (unmodified), rutting resistance is generally increased as the binder stiffness is increased. In the AASHTO PP2-94 mix aging test, a compacted specimen is conditioned for five days at 85°C (185°F). This period is considered to represent longer term aging in the field. Results from the SHRP program suggest that long-term oven aging at 85°C in a forced draft oven for eight days represents (conservatively) approximate aging at sites nine years or older in the dry-freeze zone, and eighteen years or older in the wet no-freeze zone (4). For this experiment, the aging period was modified to six days at 85°C, based on previous experience (5). After six days of aging in the forced-draft oven, specimens were allowed to cool to room temperature, then conditioned at the shear test temperature for two hours prior to testing.

To evaluate the aging effect of the asphalt binder on permanent deformation, the experiment compared four aged specimens (two temperatures, two replicates) with six non-aged specimens (two temperatures, three replicates), with all of the specimens tested at one air-void content (6 percent) and one test stress (70 kPa). Tests on field cores (field aged and trafficked) were run at a single temperature (45°C) and stress (70 kPa).

2.3.4 Mixing and Compaction Effect (FMLC, LMLC, and FMFC)

In this series the performance of LMLC cores (three replicates of five binder types), FMLC cores (three replicates of five binder types) and FMFC cores (three replicates of two binder types) were compared. One air-void content (6 percent), one applied shear stress (70 kPa), and one test temperature (45°C) were used.

2.3.5 Gradation Effect (LMLC)

HVS testing was conducted only on gap-graded mixes containing the MAC15, MB15 and MB4 binders. The laboratory shear test program was intended to provide information for assessing the use of these modified binders in dense-graded mixes. Mix designs were performed by UCPRC staff according to the CTM 304, 366, and 367 procedures for dense-graded mixes containing the MB4, MB15, and MAC15 binders. Performance of these mixes was compared with that of the dense-graded mix containing the AR4000 binder (DGAC) and the gap-graded mix with the rubber asphalt binder (ARB). One air-void content (6 percent), one applied shear stress (70 kPa), and one test temperature (45°C) were used.

2.4. Specimen Preparation

2.4.1 Laboratory-Mixed, Laboratory-Compacted Specimens

Gradation and Binder Contents

Laboratory mix aggregate gradations and binder contents are shown in Table 2.3 and Table 2.4, respectively, and in Figure 2.1 and Figure 2.2. The aggregate gradations conform to the requirements specified by Caltrans Standard Specifications, Section 39. The dense gradation meets standard specification for 19 mm (0.75 in) Type A coarse asphalt concrete (as of 2003) and the gap gradation conforms to the special provisions for Type G-MB. The target dense gradation was determined from field samples for the AR 4000 DGAC mix collected and tested by Caltrans during overlay construction. For the gap gradation, several different field samples from different mixes were tested and the average gradation was calculated and set as the laboratory target.

Table 2.3: Summary of Gradation Curves

Sieve Size (mm)	Gap-Graded (% passing)			Dense-Graded (% passing)		
	Design (Caltrans)	Field (Caltrans)	LMLC (UCB)	Design (Caltrans)	Field (Caltrans)	LMLC (UCB)
25.4	100.0	100.0	100.0	100.0	100.0	100.0
19.0	98.0	96.3	96.7	98.0	93.0	91.5
12.7	82.0	78.2	78.2	85.0	72.0	72.4
9.5	69.0	64.8	64.6	79.0	63.0	63.8
4.75	36.0	32.3	32.5	49.0	44.0	41.4
2.38	21.0	20.5	20.2	35.0	31.5	28.8
1.19	13.0	15.7	15.8	23.0	24.0	23.7
0.59	10.0	12.3	12.6	16.0	19.0	19.2
0.23	7.0	9.2	9.2	11.0	13.0	13.4
0.15	5.0	5.0	5.5	6.0	6.0	6.4
0.075	3.1	3.6	3.8	4.0	3.7	4.3

Table 2.4: Design Binder Contents of Laboratory Mixes

Gap-Graded[1]		Dense-Graded[2]	
Binder	**Binder Content[3]**	**Binder**	**Binder Content[3]**
ARB	8.0	AR4000	5.0
MAC15	7.4	MAC15	6.3
MB15	7.1	MB15	6.2
MB4	7.2	MB4	6.4

1. Gap-graded mix designs determined by Caltrans.
2. Dense-graded mix designs for MAC15, MB15, and MB4 binders determined by UC Pavement Research Center, mix design for DGAC determined by Caltrans.
3. Percent by mass of aggregate

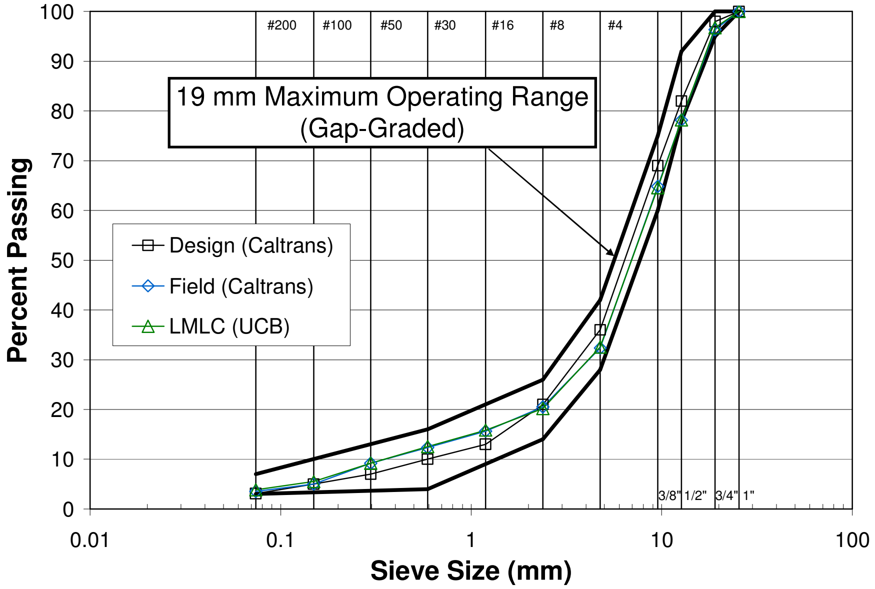


Figure 2.1: Gradation curves for gap-graded mixes.

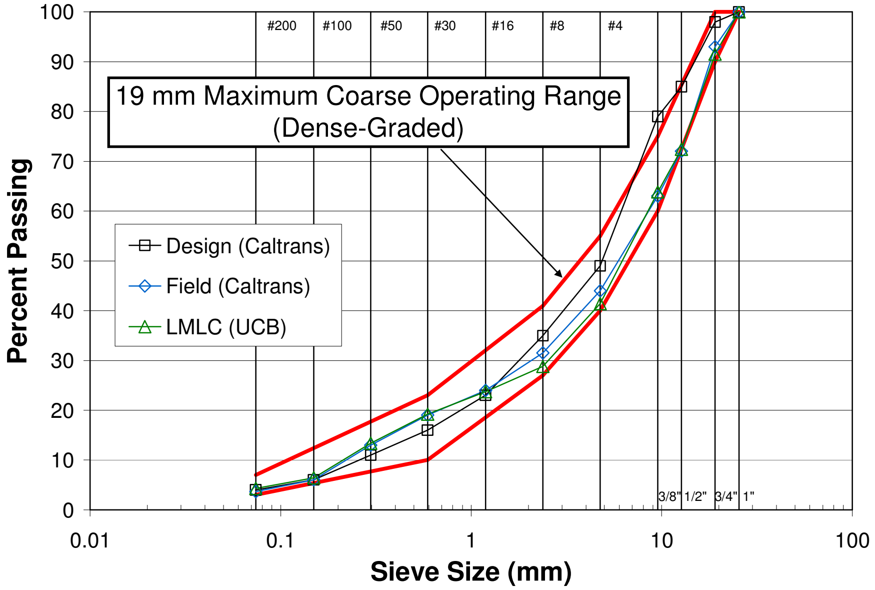


Figure 2.2: Gradation curves for dense-graded mixes.

Specimen Preparation

Specimens were prepared from raw materials supplied by the contractor constructing the Test Track, Syar Industries, Inc. The aggregate, a basalt, was obtained from Syar's Lake Herman quarry, located near Vallejo, CA. The aggregate blend was obtained from four bins with size ranges as follows: 19 mm x 12.5 mm, 12.5 mm x 9.5 mm, 9.5 mm x dust, and 4.75 mm x dust. Binders used for the test track were obtained from two California refineries, Paramount Petroleum (MAC15) and Valero (all other binders).

The production of shear cores involved:

- Checking the aggregate gradings using AASHTO T11 (wet sieving, passing the 0.075 mm [No 200] sieve) and AASHTO T27 (dry sieving of fine and coarse aggregate)
- Batching of aggregates and mixing with binder
- Short-term oven aging (AASHTO PP2-94)
- Specific gravity testing (AASHTO T209)
- Rolling wheel compaction to produce slabs (PP3-94)
- Coring and sawing to size of cores for shear tests
- Measuring air-void content (AASHTO T275 [Caltrans CTM 308])

In the batching and mixing processes, 7 kg (15.4 lb) batches were heated to the binder-specific mixing temperature (Table 2.5) for at least two hours before mixing. Asphalt binder was heated to the same temperature for approximately one hour, or until it was consistently pourable, then mixed with the aggregate until the aggregates were fully coated (typically in about five minutes). Mixing bowl and blades were preheated to prevent adhesion of the binder.

Table 2.5: LMLC Binder Mixing Temperatures

Mix	Binder Mix Temperatures (°C)	Temperature Specification Range (°C)
MB4	163[1]	150–163[3]
MB15	163	150–163
MAC15	163	150–163
RAC	163	150–163
AR4000	145[2]	–

Note: Temperatures for MB mixes are from Caltrans Type D-MB specification.

[1] 325°F [2] 295°F [3] 302-325°F

The short-term oven aging procedure used in this investigation (AASHTO PP2-94) attempts to replicate aging that occurs in the mixing and compaction process, and perhaps some early in-situ aging. In this procedure, oven-aging involves conditioning the loose mix at 145°C (295°F) for four hours with periodic stirring. Following the short-term oven-aging procedure, compaction of the LMLC and FMLC mixes were performed at the temperatures shown in Table 2.6.

Table 2.6: Compaction Temperatures for LMLC and FMLC

Mix	Compaction Temperature (°C)	Temperature Specification Range (°C)
MB4	150[1]	143–150
MB15	150	143–150
MAC	150	143–150
RAC	145[2]	143–150
AR4000	145	–
Note: Temperatures for MB mixes are from Caltrans Type D-MB specification.		
[1] 293°F [2] 302°F		

2.4.2 Field-Mixed, Laboratory Compacted Specimens

The field-mixed, laboratory-compacted (FMLC) specimens were prepared using the loose mix collected during construction of the HVS test road. After construction, this material was stored in five-gallon sealed metal cans at room temperature in a warehouse without temperature control for up to several years before compaction. Some further aging may have occurred during the time between site sampling and specimen production. For specimen production, the mix was tested for its maximum specific gravity and compacted following the procedures described above.

The compaction temperatures for field-mixed, lab-compacted specimens were the same as for the LMLC mixes (Table 2.6).

2.4.3 Field-Mixed, Field-Compacted Specimens

The field-mixed, field-compacted (FMFC) specimens were obtained from full-depth cores after the section had been tested, having been subjected to traffic as well as aging. Only the full-depth (90 mm) sections with the MB4 and AR4000 binders provided the 50 mm (2 in) thick cores required for the shear test. The 50 mm test sample was removed from the upper 70 mm (2.7 in) of the full-depth core.

2.5. Ignition Oven Tests

2.5.1 Test Method

California Test CTM382 (Determination of Asphalt Binder Content of Bituminous Mixtures by the Ignition Method) was used to determine binder contents for the field mix collected during construction of the HVS test sections. The ignition oven values were corrected for ignition of the aggregate using aggregate samples also collected during construction. Mixes tested for binder content were RAC-G, MAC15-G, MB15-G, and MB4-G.

2.5.2 Results

Table 2.7 summarizes the results of the ignition oven test on the selected mixes. The results show that the mean field binder contents were approximately 0.5, 0.15, 0.4, and 0.3 percent above the design binder contents for the RAC, MAC15, MB15, and MB4 gap-graded mixes, respectively.

Table 2.7: Summary of Asphalt Contents from Binder Ignition Tests

Mix Type	Design Binder Content[1] (%)	Ignition Oven Correction Factor	Test Results of Field Mixes					Mean	Standard Error	95% Confidence Interval
			1	2	3	4	5			
RAC-G	8.0	1.86	8.79	8.35	8.54	8.26	-	8.49	0.117	(8.11, 8.86)
MAC15-G	7.4	1.86	7.64	7.42	7.65	7.48	-	7.55	0.058	(7.36, 7.73)
MB15-G	7.1	1.76	7.89	7.66	7.41	7.08	7.58	7.52	0.135	(7.15, 7.90)
MB4-G	7.2	2.15	7.84	7.84	7.62	6.71	-	7.50	0.269	(6.65, 8.36)

[1] Percent by Mass of Aggregate

3. BINDER TESTING

3.1. Introduction

Binder tests developed by SHRP were performed on the five binders used in this investigation. These tests included the Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) tests, and were conducted at the Turner-Fairbanks Highway Research Center of the Federal Highway Administration (FHWA). The tests were conducted on binders in their original condition, after Rolling Thin Film Oven (RTFO) conditioning, and after Pressure Aging Vessel (PAV) conditioning. The tests conducted by the FHWA are identified in AASTHO PG Binder Specification M320.

The AR binder could not be tested by the FHWA because of the size of the rubber particles in the binder. Therefore test results presented in this chapter are for the AR4000, MB4, MB15, and MAC15 binders.

3.2. Dynamic Shear Rheometer

3.2.1 Test Method

AASHTO T315 method was performed to measure the rutting parameter in the AASHTO binder specification ($G/sin\delta$) and the long-term fatigue performance parameter ($Gsin\delta$) for the binders.

3.2.2 Results

Rutting Criteria

AASHTO M320 defines and places requirements on a rutting parameter for binders, $G/sin\delta$, which represents a measure of the contributiuon of the binder to the temperature rutting resistance of the mix. The specification requires that $G/sin\delta$ must be a minimum of 1.0 kPa for the original asphalt binder and 2.2 kPa after RTFO aging of the binder. Dynamic shear modulus G^* at 10 rad/s versus test temperatures and the specification requirements for the binders are shown in Figure 3.1 and Figure 3.2 for these two conditions.

Fatigue Criterion

In the AASHTO M320 specification, a binder parameter has been introduced to control mix behavior in the intermediate temperature range, $Gsin\delta$, and is listed as the fatigue criterion. To mitigate fatigue cracking, the specification requires that $Gsin\delta$ have a minimum value of 5,000 kPa after PAV aging.

Figure 3.3 illustrates the dynamic shear modulus G^* at 10 rad/s versus a range of temperatures and contains the specification requirement for $Gsin\delta$.

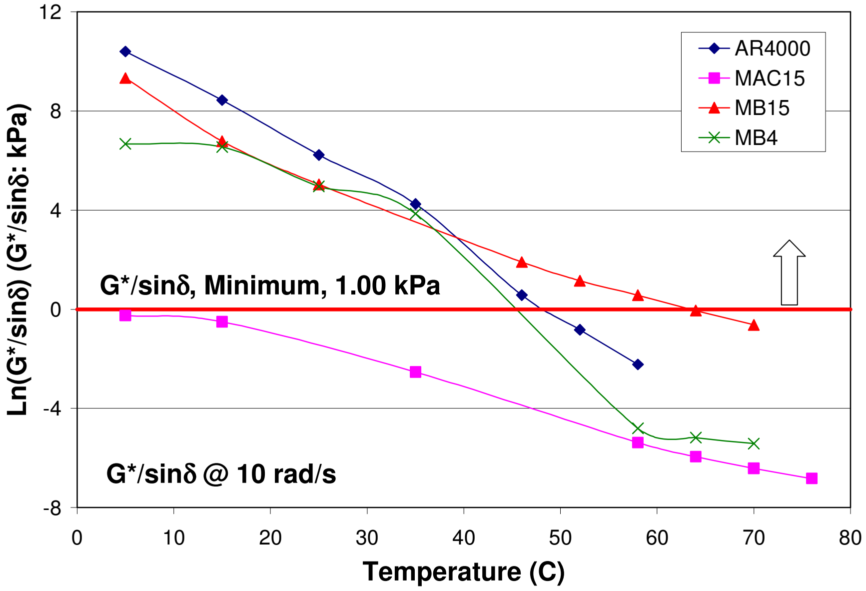


Figure 3.1: G/sinδ summary of DSR test results on original binder.

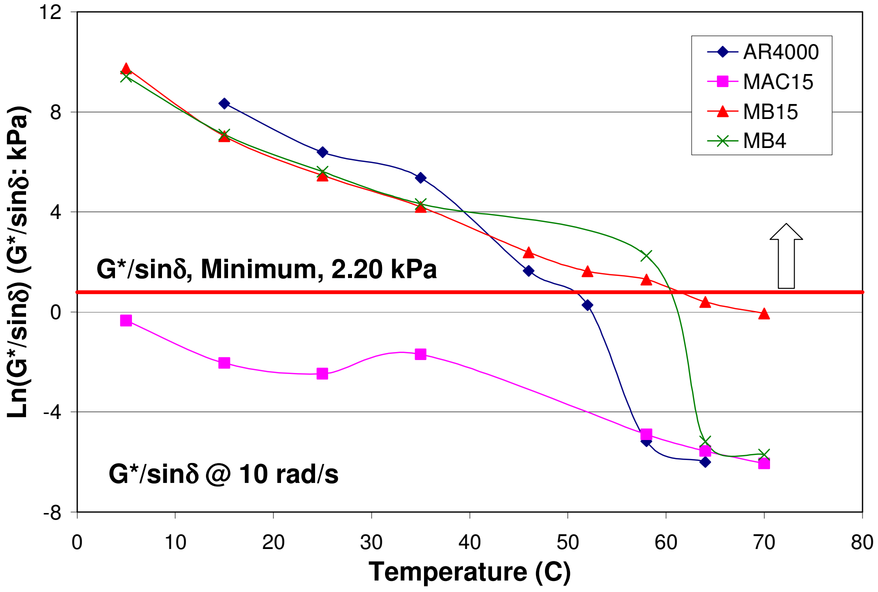


Figure 3.2: G/sinδ summary of DSR test results on RTFO aged binder.

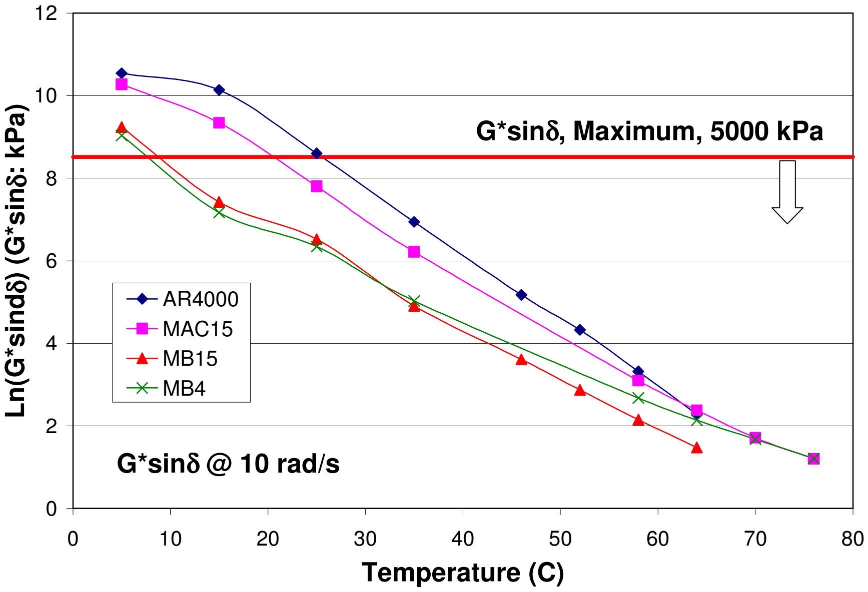


Figure 3.3: Gsinδ summary of DSR test results on PAV-aged binder.

Shear Susceptibility

The Shear Susceptibility of Viscosity (SSV) and Shear Susceptibility of Delta (SSD) are derived from DSR test results and are defined in California Test 381. Reese (5) further developed these parameters for binders used in Type G-modified binder asphalt concrete as follows:

$SSD \geq 30(0.6+SSV)^3$ for original binder @ 25°C

$SSD \geq -115(SSV) - 50.6$ for PAV-aged binder at @ 25°C

Table 3.1 summarizes the SSD and SSV values for the binders. All the binders satisfy the PAV-aged binder requirement, while only the MB4 binder satisfies the original binder requirement.

Test Summary

According to the test results, the ranking of susceptibility of the binders contributing to mix rutting is (from highest susceptibility to lowest):

1. MAC15 (binder failed to meet minimum requirements of rutting at any test temperature)
2. MB4, MB15
3. AR4000

The ranking of susceptibility of the binders contributing to mix fatigue cracking is (from highest to lowest):

1. AR4000
2. MAC15

3. MB15
4. MB4

The MB4 and MB15 binders have similar rutting (RTFO aged) and fatigue DSR test results.

Table 3.1: Summary of SSV and SSD Values from DSR Test Results

Binder	Binder Status*	SSV@25°C	SSD@25°C	Meets Specification for SSD for ORIG	Meets Specification for SSD for PAV
AR4000	ORG	-0.2085	-12.848	No	
	RTFO	-0.4264	-4.454		
	PAV	-0.2983	-11.428		Yes
MB4	ORG	-0.4523	6.388	Yes	
	RTFO	-0.4369	2.944		
	PAV	-0.3059	-2.376		Yes
MB15	ORG	-0.2201	-2.742	No	
	RTFO	-0.2742	-2.013		
	PAV	-0.2490	-5.911		Yes
MAC15	ORG	-0.2289	-0.210	No	
	RTFO	-0.2585	2.358		
	PAV	-0.2623	-6.898		Yes

* ORG: original
RTFO: rolling thin film oven
PAV: pressure aging vessel.

3.2.3 Master Curves of Shear Complex Modulus

The master curves of the binder shear complex moduli were constructed using time-temperature superposition and a genetic algorithm (3). Figure 3.4 through Figure 3.11 present the G^* master curves and temperature-shift relationships at various aging conditions for AR4000, MB4, MB15, and MAC15 binders respectively. Observations based on the results of this analysis are:

- For binders aged with the PAV procedure, the complex shear moduli increase across all frequencies for the four binders.
- The MB4 and MB15 binders show small-to-moderate changes among the various aging conditions.
- For original and RTFO aging conditions, the master curves of MAC15 binder are similar; however, the master curve after PAV aging exhibits some deviation from the other two curves. The reason is not clear.
- In general, the temperature-shift relationship does not change significantly for different aging conditions. The only exception is the MAC15 binder. Its temperature sensitivity for the PAV-aged condition increases rapidly at low temperatures and is greater than the temperature sensitivity in the original and RTFO conditions.

Figure 3.12 through Figure 3.14 compare the master curves for the original, RTFO-, and PAV-aging conditions, respectively. In the original and RTFO conditioning, the master curves of MAC15 binder are significantly lower than the master curves for the AR4000, MB4, and MB15 binders.

The ranking of the master curves from greatest to least stiffness for original binder and RTFO conditioning are the same:

1. AR4000
2. MB4
3. MB15
4. MAC15

It can be seen in the figures that this ranking is for the middle range of load frequency (also corresponding to middle values of temperature). It can also be seen that at very high and at very low frequencies the AR4000 binder is less stiff than the MB4 and MB15 binders, although it is still stiffer than the MAC15 binder.

The ranking of the master curves for PAV conditioning, from highest stiffness to lowest, is as follows,:

1. AR4000
2. MAC15
3. MB4
4. MB15

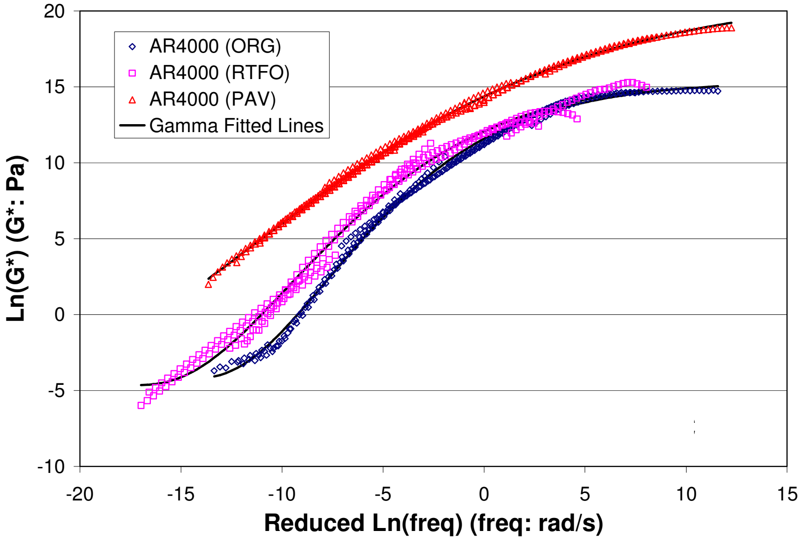


Figure 3.4: Master curves of shear complex modulus of AR4000.

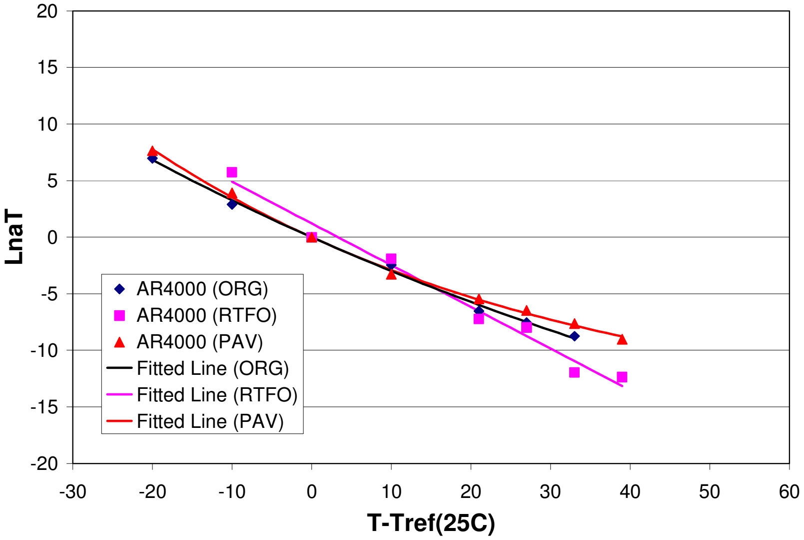


Figure 3.5: Temperature-shift relationships of AR4000.

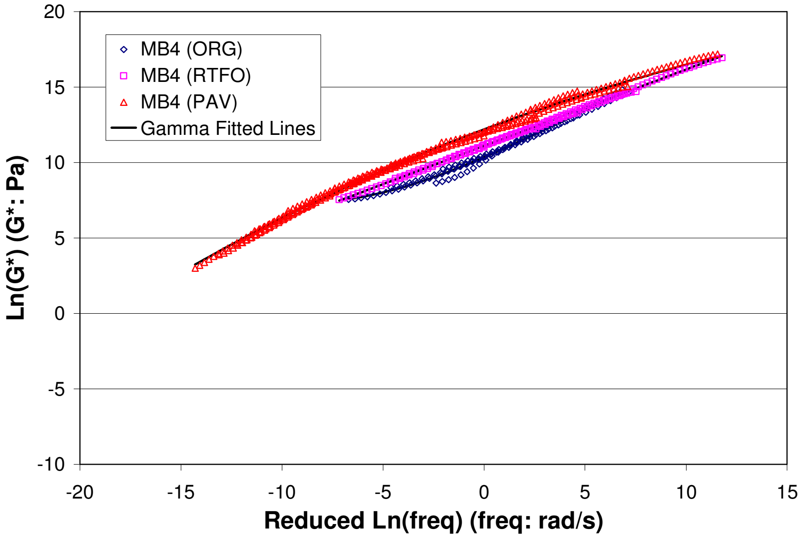


Figure 3.6: Master curves of shear complex modulus of MB4.

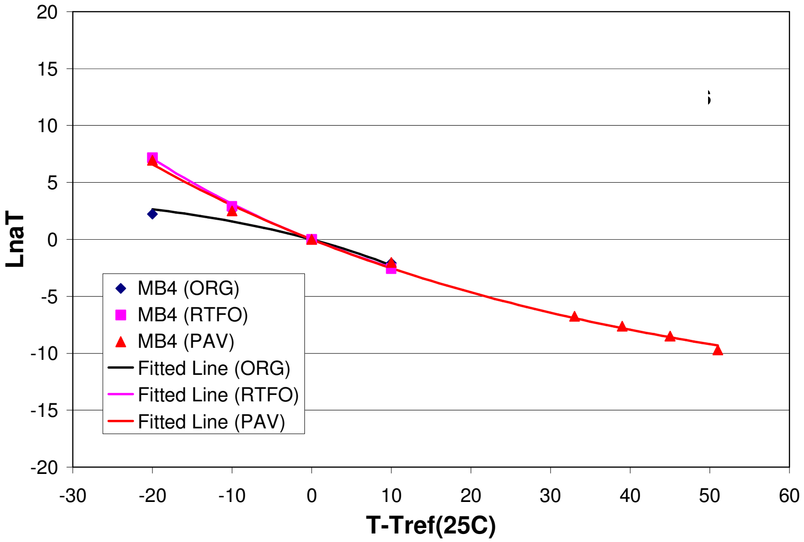
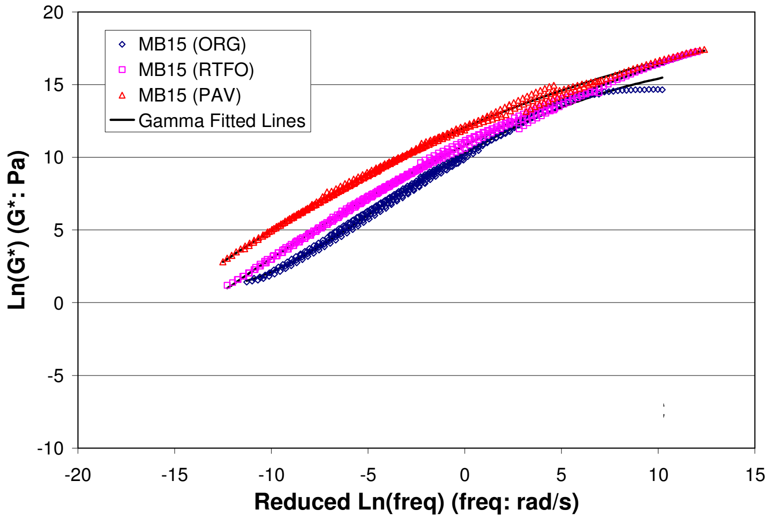


Figure 3.7: Temperature-shift relationships of MB4.



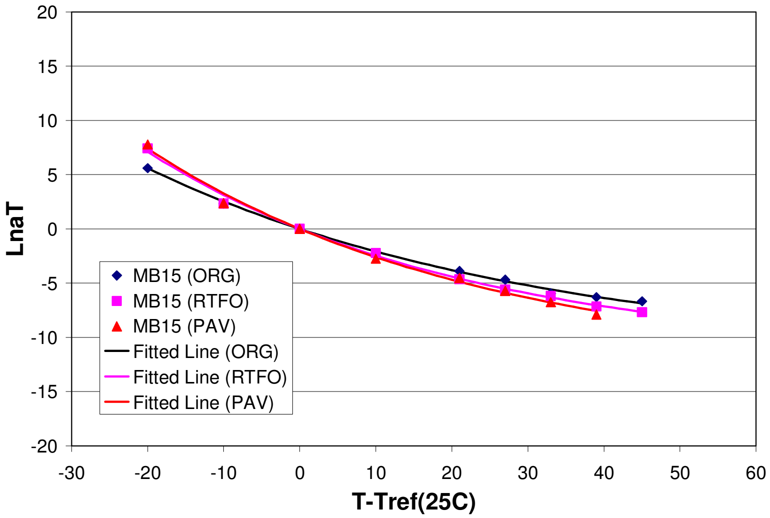
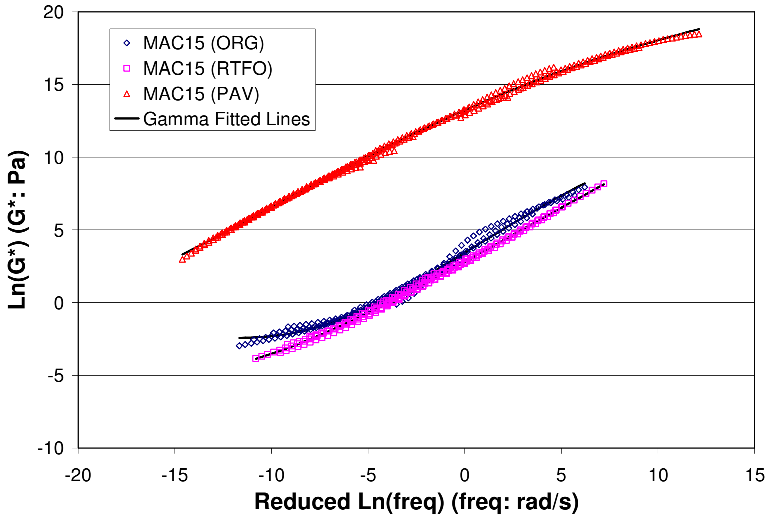


Figure 3.8: Master curves of shear complex modulus of MB15.

Figure 3.9: Temperature-shift relationships of MB15.



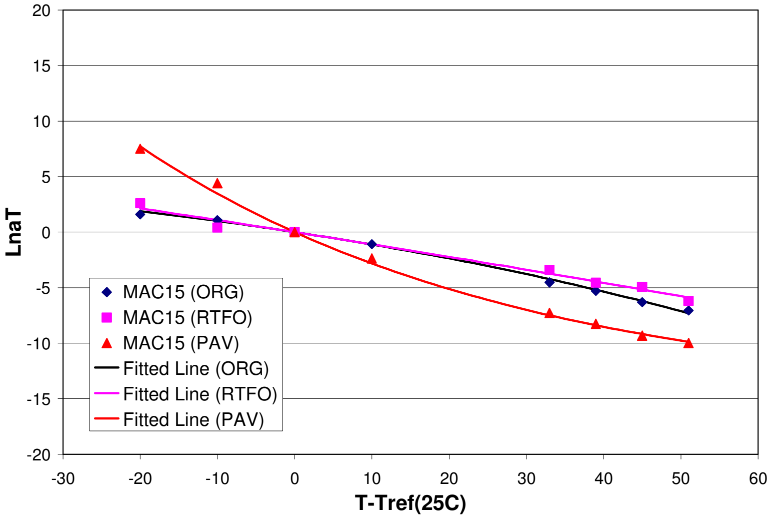


Figure 3.10: Master curves of shear complex modulus of MAC15.

Figure 3.11: Temperature-shift relationships of MAC15.

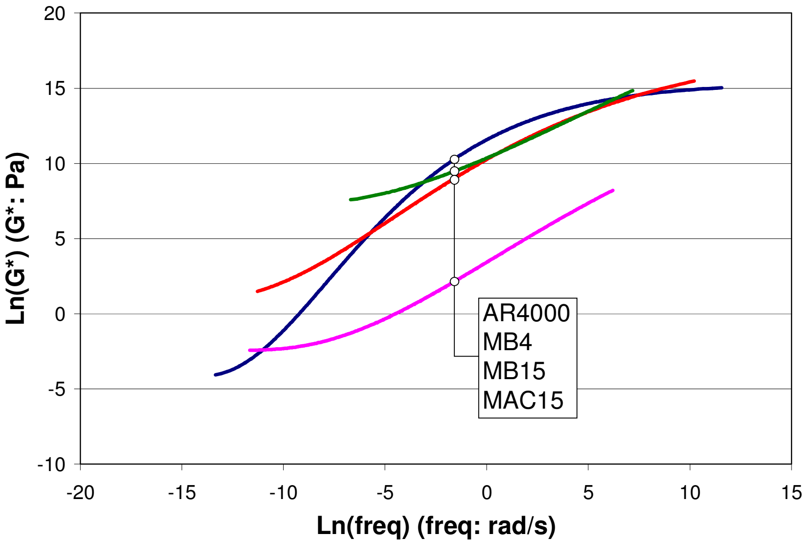


Figure 3.12: Comparison of G* Master curves (original).

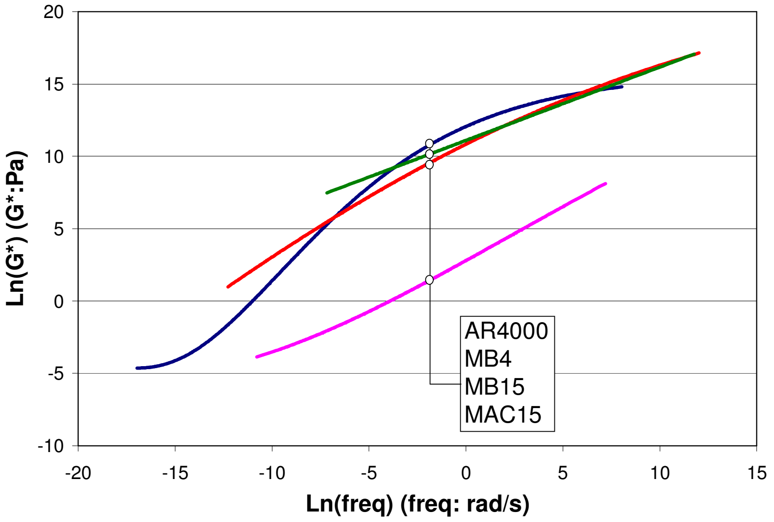


Figure 3.13: Comparison of G* Master curves (RTFO).

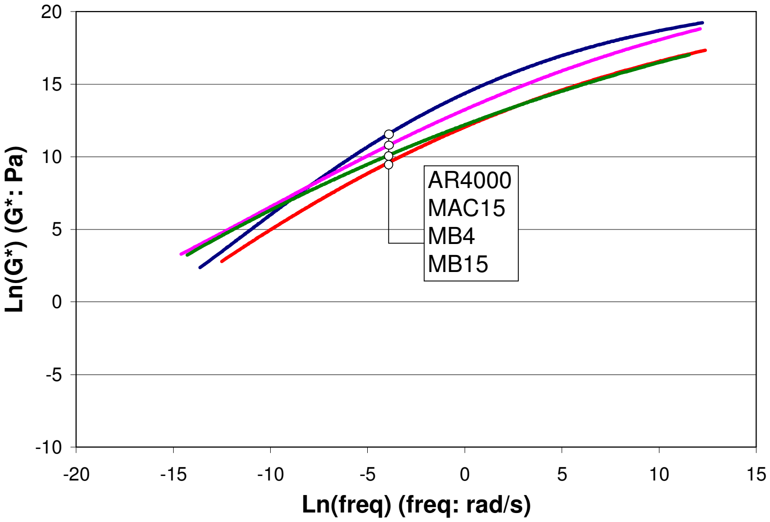


Figure 3.14: Comparison of G* Master curves (PAV).

3.3. Bending Beam Rheometer

3.3.1 Test Method

AASHTO T313 was used to assess the propensity of the binders to develop thermal stresses at low pavement temperatures. The two values obtained from the Bending Beam Rheometer (BBR) are the creep stiffness and the m-value (the rate of change of the creep stiffness versus time of loading). The PG binder specification M320 includes limiting values for these two parameters associated with the low temperature of the PG binder grade. The allowable maximum creep stiffness value is 300 MPa and the minimum m-value is 0.3, both determined at a loading time of 60 seconds.

3.3.2 Results

Table 3.2 lists the temperatures at which creep stiffnesses reached 300 MPa, and m-values reached 0.3. Figure 3.15 and Figure 3.16 show the creep stiffnesses and m-values versus temperature for the un-aged condition and after RTFO and PAV aging. According to the test results and the Superpave specification for thermal cracking, the ranking of susceptibility of the binders to low-temperature thermal cracking from highest susceptibility to lowest is:

1. AR4000
2. MAC15
3. MB15
4. MB4

Table 3.2: Summary of Bending Beam Rheometer Test Results

Binder Type	Binder Status*	Temp@S=300 MPa (°C)	Temp@m=0.3 (°C)
AR4000	ORG	-11.5	-15.7
	RTFO	-11.3	-15.3
	PAV	-7.7	-11.3
MAC15	ORG	-20.5	-23.9
	RTFO	-18.8	-22.3
	PAV	-18.0	-19.3
MB15	ORG	-26.7	-28.3
	RTFO	-25.6	-26.7
	PAV	-24.0	-22.5
MB4	ORG	-31.7	-31.3
	RTFO	-28.3	-27.8
	PAV	-25.7	-22.0

* ORG: original
RTFO: rolling thin film oven
PAV: pressure aging vessel

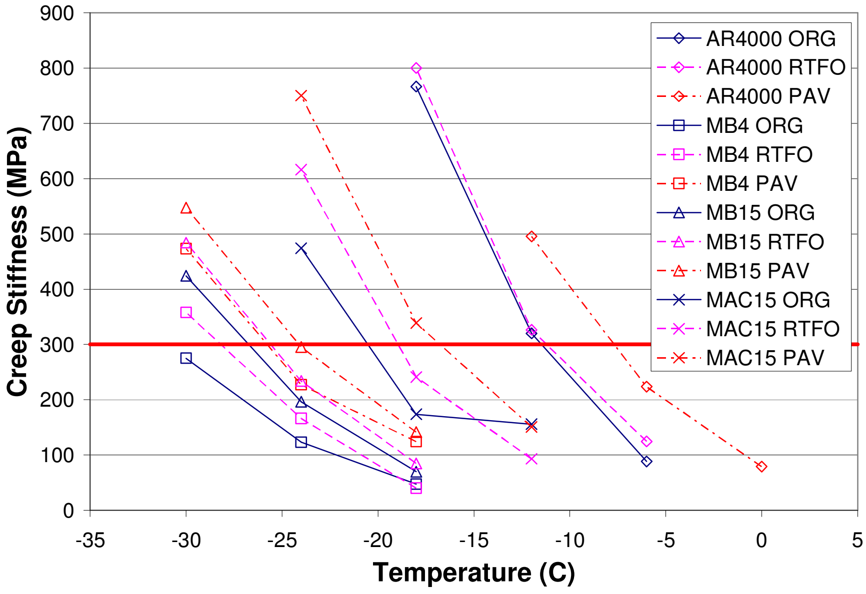


Figure 3.15: Creep stiffness summary of BBR test results.

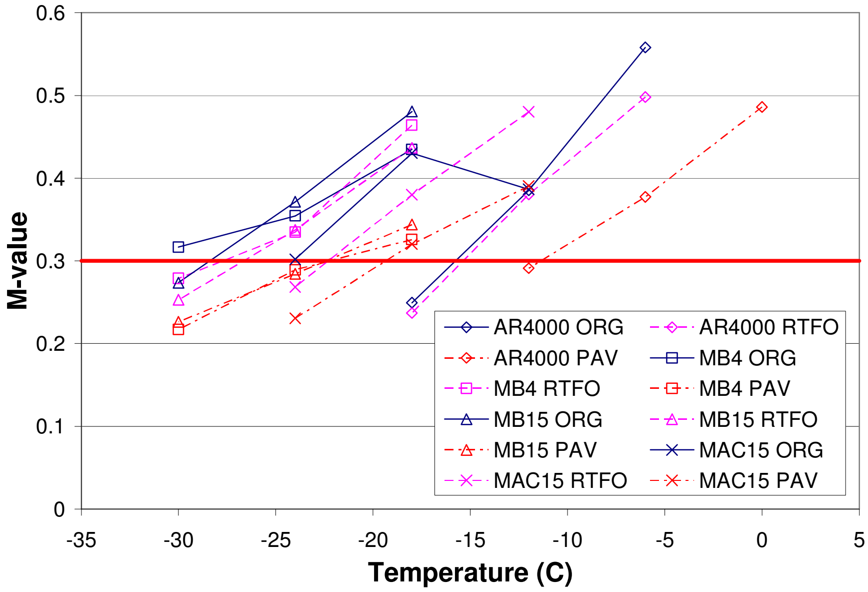


Figure 3.16: Summary of m-value results from BBR tests.

4. SHEAR TESTING

4.1. Introduction

This chapter provides a summary of the laboratory shear testing study together with the analyses and interpretation of results on field-mixed, laboratory-compacted (FMLC); laboratory-mixed, laboratory-compacted (LMLC); and field-mixed, field-compacted (FMFC) materials. Included are:

- Summary of the stress controlled-deformation Repeated Simple Shear Test (RSST) results
- Identification of the significant factors (or covariates) that affect shear performance
- Discussion of regression models for permanent shear deformation resistance and shear stiffness
- Summary of the collective dataset analysis and regression model

4.1.1 Definitions Used in Statistical Analyses

The factors investigated include:

- Temperature effect (on FMLC material)
- Air-void content effect (on FMLC material)
- Aging effect (on FMLC material)
- Compaction effect (on FMLC and FMFC material)
- Gradation effect (on LMLC material)
- Mix effect (on FMLC and LMLC material)

The response variables are:

- Number of Cycles to 5 Percent Permanent Shear Strain *(Lnpct5)*
- Permanent Shear Strain at 5,000 Cycles *(Lncyc5k)*
- Resilient Shear Modulus, G^* *(lng)*

The Resilient Shear Modulus (G^*) was obtained after 100 repetitions. At this number of repetitions the stress state and temperature, as well as the recoverable shear strain, have stabilized in the shear test specimen. The category covariates and factor levels evaluated include:

- Binder type (*binder*)
    1. AR4000 (*ar4000*)
    2. ARB (*rac*)
    3. MAC15 (*mac15*)
    4. MB15 (*mb15*)
    5. MB4 (*mb4*)

- Gradation (*grad*)
    1. Dense-graded (*dg*)
    2. Gap-graded (*gg*)
- Compaction (*comp*)
    1. Field-mixed, laboratory-compacted (*fmlc*)
    2. Laboratory-mixed, laboratory-compacted (*lmlc*)
- Conditioning (*cond*)
    1. No conditioning (*none*)
    2. Long-term oven aging for 6 days (*aging*)
- Air-void content (*av*)
    1. 6 percent air-void content (*av6*)
    2. 9 percent air-void content (*av9*)
- Test temperature (*temp*)
    1. 45°C (*45C*)
    2. 55°C (*55C*)
- Test stress levels (*sts*)
    1. 70kPa (*sts70*)
    2. 100kPa *(sts100*)
    3. 130kPa (*sts130*)

The covariate *binder* has different meanings depending on the test, as follows:

- On all effects other than gradation, *binder* implies a binder type with a specific gradation type and corresponding design binder content as used in this experiment, regardless of mixing method (FMLC or LMLC). It should be noted that AR4000-D and RAC-G are defined by specification and hence a gap-graded mix with the AR4000 binder (AR4000-G) and a dense-graded mix with the rubberized binder (RAC-D) are not included in the experiment. The interpretations of *binder* include:
    1. *ar4000:* AR4000 binder with dense-graded gradation and 5.0 percent design asphalt content
    2. *rac* : Asphalt rubber binder with gap gradation and 8.0 percent design asphalt content
    3. *mac15:* MAC15 binder with gap gradation and 7.4 percent design asphalt content
    4. *mb15:* MB15 binder with gap gradation and 7.1 percent design asphalt content
    5. *mb4:* MB4 binder with gap gradation and 7.2 percent design asphalt content
- When considering the gradation effect, *binder* implies a binder type with a specific design binder content for each gradation. In this instance, *binder* is used as follows:

1. *mac15:* MAC15 binder with 6.0 percent asphalt content if dense graded, or 7.4 percent asphalt content if gap graded.
2. *mb15:* MB15 binder with 6.0 asphalt content if dense-graded, or 7.1 percent asphalt content if gap graded.
3. *mb4:* MB4 binder with 6.3 percent asphalt content if dense graded, or 7.2 percent asphalt content if gap graded.

- When developing the comprehensive regression models with all shear tests, *binder* signifies a binder type with a specific design asphalt content associated with its gradation (dense or gap).

4.1.2 Expected Effects of Response Variables on Performance

Expected effects of the response variables from RSST tests are summarized in Table 4.1. The summary of the expected effects is a simplification of a complex distress mechanism, mixture rutting, on unmodified binders. Nonetheless, the summary provides a general guide for interpretation the results presented in this chapter.

The permanent shear strain (PSS) at 5,000 cycles, the test result typically reported from ASHTO T320, is a measure of the material's resistance to permanent shear deformation. Higher values indicate mixes that are weaker, less resistant to permanent shear deformation, and more prone to early rutting failure. Lower values are more desirable as they indicate more resistance to permanent shear deformation and mixture rutting.

The shear resistance is controlled by the entire mix (binder type and stiffness, gradation, aggregate surface texture, compaction, etc.), and not just the binder stiffness. However, for dense-graded mixes with conventional (unmodified) binders, low values are often obtained from stiffer mixes. This relationship between mix stiffness and permanent shear deformation resistance is less clear and often not true for mixes with modified binders.

The number of Cycles to 5 Percent Permanent Shear Strain (PSS) is another measurement of the material's resistance to shear deformation. Here, higher values are desirable as an indication of mixes that are less prone to rut.

The shear stiffness of the material determined after 100 shear load repetitions in the RSST is the third measure of a material's resistance to deformation. Greater shear stiffness often results in lower PSS at 5,000 Cycles and higher Cycles to 5 Percent PSS, although as mentioned previously the relationship between stiffness and permanent deformation resistance is often contradicted with mixes containing modified binders.

Table 4.1: Summary of Expected Effects of Response Variables from RSST on Performance

Shear Core Test Response Variable	Distress Mechanism in Field	Expected Effect on Field Performance
Permanent Shear Strain at 5,000 Cycles	Rutting at high temperatures	Larger shear strain indicates potential early rutting.
Cycles to 5 Percent Permanent Shear Strain	Rutting at high temperatures	Low Cycles to 5 Percent Shear Strain indicates potential early rutting.
Shear Resilient Modulus at 100th Repetition	Rutting at high temperatures	High stiffness at high temperatures expected to result in less rutting.
	Low-temperature cracking	High stiffness at low temperatures expected to increase risk of low-temperature cracking.

4.1.3 Presentation of Results

The RSST test results are organized in three sections for each effect:

- Summary boxplots of test results, where each box contains three data points (the three replicates), two of which are the top (highest) and bottom (lowest) sides of the box and one, a white line, that is the middle data point. The height of the box indicates the data variation across the three replicates.
- Identification of significant factors that affect the shear-response variables on an effect-categorized basis.
- Model selection using conventional regression analysis.

In the following discussion, brief explanations of the statistical analyses used in the chapter are provided in Section 4.2, “Temperature Effect.” A more detailed discussion of the statistical analyses performed is provided in the detailed first-level fatigue evaluation source report (3). Summary tables of the results of the RSST tests for each mix are attached to this report as Appendix A.

4.2. Temperature Effect

This dataset includes the test results of 90 field-mixed, laboratory-compacted (FMLC) cores tested with the following experiment design:

- Five binder types (AR4000, ARB, MAC15, MB15, and MB4)
- One air-void content (6.0 ± 0.5 percent)
- Two test temperatures (45°C and 55°C)
- Three stress levels (70 kPa, 100 kPa, 130 kPa)
- Three replicates

The covariates investigated were:

- Binder type (*binder*)
- Temperature (*temp*)
- Stress level (*sts*)

4.2.1 Results

Figure 4.1 through Figure 4.3 show boxplots summarizing the RSST test results of temperature effect for Cycles to 5 Percent PSS, PSS at 5,000 Cycles, and Resilient Shear Modulus *(G^*)*. The boxplots are categorized by binder/mix type, stress level, and temperature.

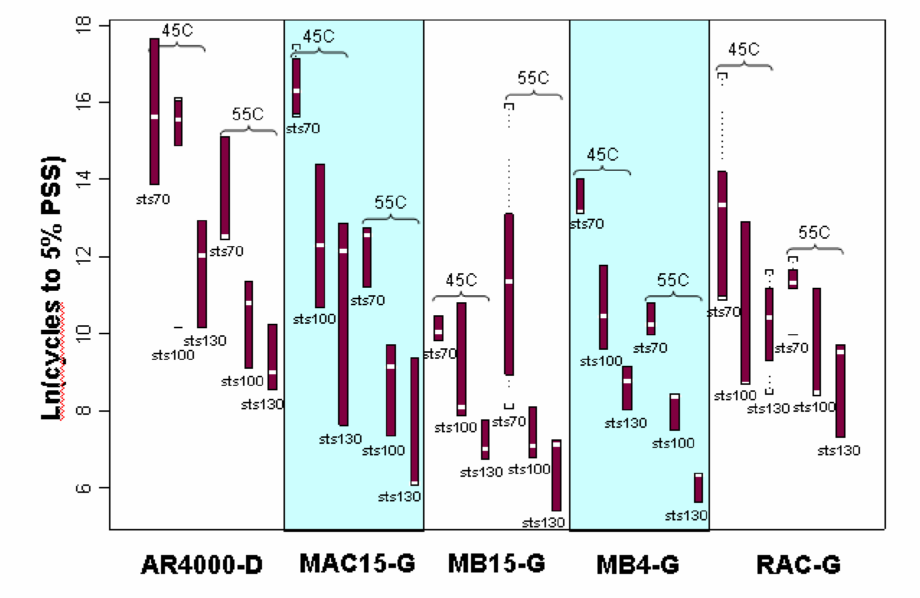


Figure 4.1: Summary plots of temperature effect and Cycles to 5 Percent PSS.

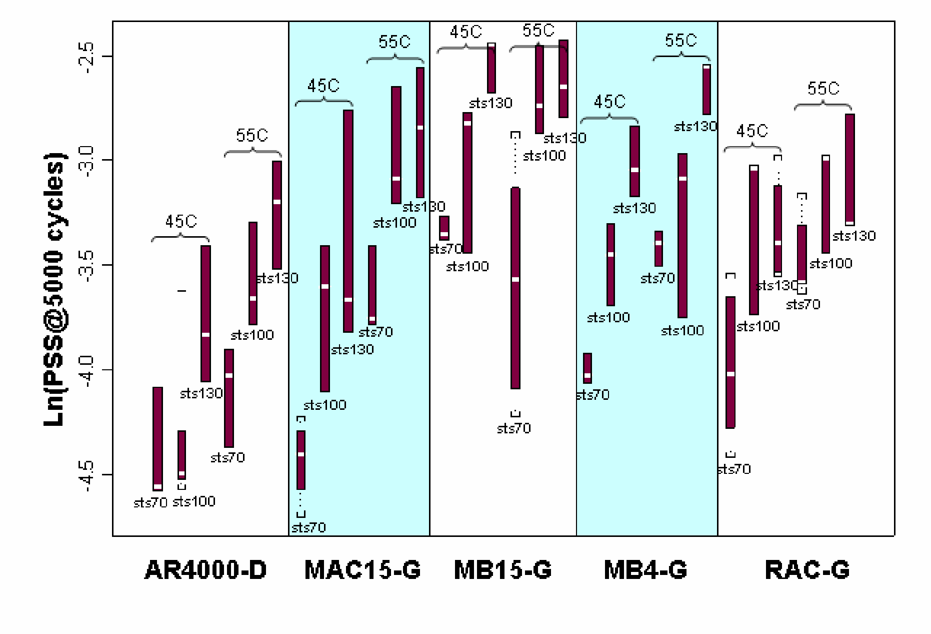


Figure 4.2: Summary plots of temperature effect and PSS at 5,000 Cycles.

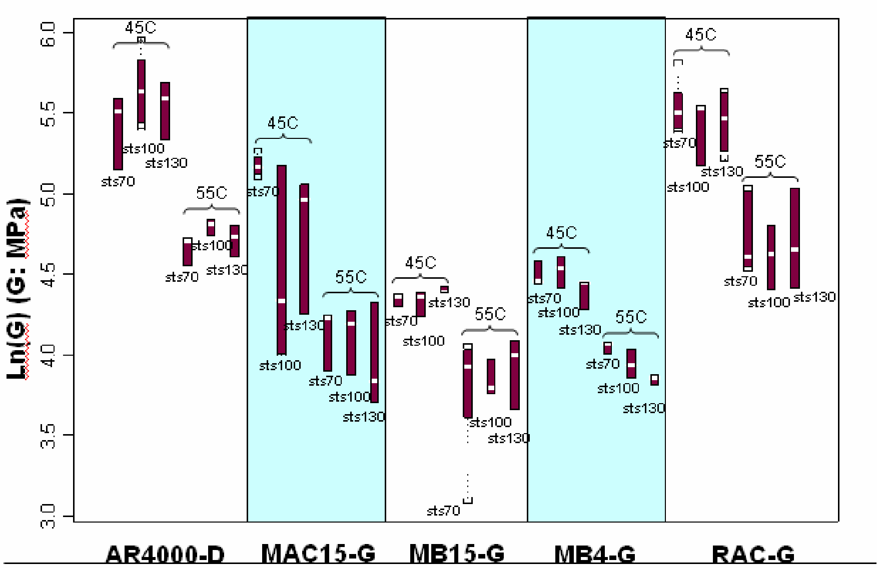


Figure 4.3: Summary plots of temperature effect and Resilient Shear Modulus, G*.

The following observations regarding performance implications were made from the plots:

- Temperature has a significant effect on performance. Specimens tested at 55°C consistently show lower Cycles to 5 Percent PSS and higher PSS at 5,000 Cycles than those tested at 45°C for a given stress level.
- There is overlap in shear performance between 45°C and 55°C in that specimens tested at 45°C/130 kPa show lower performance than those tested at 55°C and 70 kPa. There is a definite interdependence of temperature and stress levels.

- For a given temperature, Resilient Shear Modulus *(G^*)* stays relatively constant for all stress levels for a given binder type. Shear stiffness, G, at 55°C is without exception lower than G^* at 45°C for a given binder and is relatively independent of stress level.
- In general, the AR4000-D mix showed the highest resistance to permanent deformation and also had the highest shear stiffnesses. RAC-G mix consistently placed second in resistance to permanent deformation and mix stiffness. MB15-G mix showed the lowest resistance to permanent deformation and the lowest stiffness of the five mixes tested.

The following statistical observations are made from the plots:

- Temperature is highly negatively correlated with Cycles to 5 Percent PSS, particularly at lower stress levels (70 kPa). The effect of temperature diminishes with increased stress level (130 kPa).
- Temperature is highly positively correlated with PSS at 5,000 Cycles.
- Resilient Shear Modulus *(G^*)* is highly negatively correlated with temperature.
- All three response variables are significantly affected by the binder/mix types.

4.2.2 Identification of Significant Factors

Correlation Matrix

The correlation matrix (Table 4.2) shows the strength of the linear relationship between the pairs of variables and was used as a quantitative method of identifying significant factors. Correlations that are significant based on an initial threshold correlation of 0.4 are highlighted in the table. The following is observed from the correlation matrix.

- Temperature is negatively correlated with ln $G^*$and ln PSS at 5,000 Cycles. This implies that reduction in test temperature results in increased stiffness and smaller PSS at 5,000 Cycles.
- Stress (*lnsts*) is negatively correlated with PSS at 5,000 Cycles and positively correlated with Cycles to 5 Percent PSS. This implies that increased stress levels results in poorer shear performance and higher rutting potential.
- G^* is positively correlated to PSS at 5,000 Cycles and Cycles to 5 Percent PSS. This implies that increased stiffness results in increased shear performance.

Analysis of Variance (ANOVA)

The ANOVA results in Table 4.3 provide a second quantitative way to identify significant factors that affect the response variables. The criterion for assessing the importance of effect was set at a 5 percent significance level based on the p-value. Highlighted numbers in the table are considered significant.

Table 4.2: Correlation Matrix for Temperature Effect

	Binder	**Air Void**	**Temperature**	**Stress**	**ln G**	**ln Strain at 5K**	**Ln Cycles to 5%**
Binder	1.0000	0.0357	0.0072	-0.0522	-0.0338	-0.2511	0.2773
Air Void	0.057	1.0000	-0.04021	-0.0786	0.0462	-0.0174	0.0175
Temp	0.0072	-0.0402	1.0000	-0.0363	-0.6106	-0.3941	0.3525
Stress	-0.0522	-0.0786	-0.03630	1.0000	-0.0279	-0.5569	0.5364
ln G	-0.0338	0.0462	-0.6106	-0.0279	1.0000	0.5459	-0.5700
Ln Strain At 5K	-0.2511	-0.0174	-0.3941	-0.5569	0.5459	1.0000	-0.9594
Ln Cycles To 5% strain	0.2773	0.0175	0.3525	0.5364	-0.5700	-0.9594	1.0000

Table 4.3: Analysis of Variance for Temperature Effect

Covariate	**Statistic**				
	Df	**Sum of Sq**	**Mean Sq**	**F Value**	**p-value**
Percent Shear Strain at 5000 Cycles					
binder	4	178.8680	44.7170	17.3841	0.0000
temp	1	112.8799	112.8799	43.8830	0.0000
sts	1	310.7179	310.7179	120.7941	0.0000
binder:temp	4	46.6564	11.6641	4.5345	0.0023
binder:sts	4	12.1485	3.0371	1.1807	0.3249
temp:sts	1	0.0136	0.0136	0.0053	0.9421
Residuals	87	223.7896	2.5723		
Number of Cycles to 5 Percent Shear Strain					
binder	4	8.8771	2.1928	22.0115	0.0000
temp	1	3.2806	3.2806	32.9312	0.0000
sts	1	11.5121	11.5121	115.5589	0.0000
binder:temp	4	1.6123	0.4031	4.0462	0.0047
binder:sts	4	0.4153	0.1038	1.0422	0.3902
temp:sts	1	0.0362	0.0362	0.3631	0.5483
Residuals	87	8.667	0.9962		
Complex Shear Modulus G*					
binder	4	23.0896	5.7724	110.3981	0.0000
temp	1	12.2660	12.2660	234.5905	0.0000
sts	1	0.1205	0.1205	2.3040	0.1327
binder:temp	4	0.4513	0.1128	2.1579	0.0804
binder:sts	4	0.3924	0.0981	1.8761	0.1218
temp:sts	1	0.0086	0.0086	0.1650	0.6856
Residuals	87	4.5489	0.0529		

Design Plots

Design plots are a tool to qualitatively identify significant factors. A series of design plots based on the factor levels used in the study are presented in Figure 4.4 for Cycles to 5 Percent PSS, PSS at 5,000 Cycles, and Resilient Shear Modulus, G^*. It should be emphasized at the outset that identification of significance using design plots is based on subjective judgment.

The long horizontal bar through the middle of the design plot indicates the overall mean across the entire data set. The smaller horizontal bars identified for each factor level of each variable are the mean value in the data set for that factor level. A larger vertical distance between factor levels means indicates greater significance of that variable.

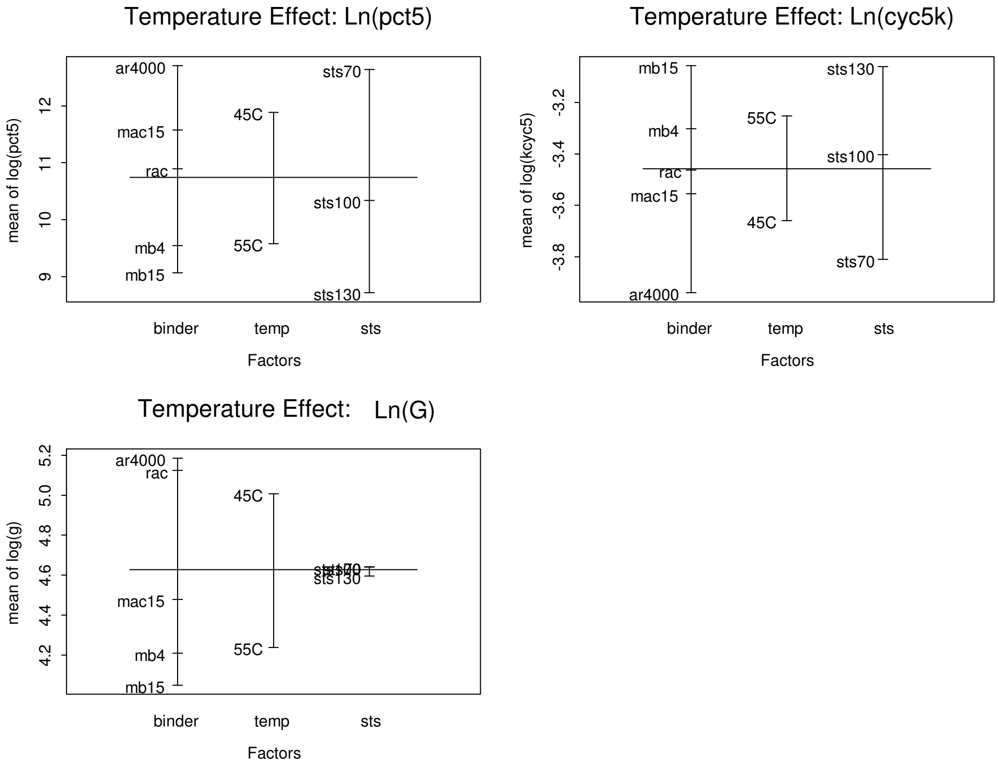


Figure 4.4: Design plots for temperature effect (6 percent AV).

The following was observed from the design plots:

- Binder type affects all three response variables.
- The difference in shear performance is evident among the various binder/mix types.
- Stress level has the largest effect on PSS at 5,000 Cycles and Cycles to 5 Percent PSS, and no effect on G.

Using the design plots, the PSS at 5,000 Cycles of the various binders is ranked best to worst as follows:

1. AR4000-D
2. MAC15-G
3. RAC-G
4. MB4-G
5. MB15-G

The ranking of Cycles to 5% PSS for the various binders from best to worst as follows:

1. AR4000-D
2. RAC-G
3. MAC15-G
4. MB4-G
5. MB15-G

The ranking of Resilient Shear Modulus *(G^*)*from stiffest to least stiff:

1. AR4000-D
2. RAC-G
3. MAC15-G
4. MB4-G
5. MB15-G

Note that the only difference in the rankings for the three performance parameters is in positions 2 and 3, RAC-G and MAC15-G, and that this change only occurs for stiffness and not for the other two parameters.

Pairs Diagram

A pairs diagram (description presented in Reference 3) was used as a second qualitative method of identifying the significance of correlation. This analysis confirmed the initial observations from the boxplots. *(N.B. An example of a pairs diagram is included subsequently in Figure 4.22.)*

Summary of Significant Factors for Temperature Effect

The significant factors were identified from the correlation matrix, analysis of variance, design plot, and other plots (e.g., pairs diagram and interception plots).

Figure 4.5 shows the summary statistics of main effects of the RSST results. If all four criteria show significance in one independent variable, then this is considered as a "very important" factor. If three criteria are check-marked, the factor is considered "important." If only one or two criteria are checked, the variable is considered "less important."

Using this approach for the temperature effect dataset, the following are noted:

- Binder is "important" to all three response variables (Cycles to 5 Percent PSS, PSS at 5,000 Cycles, and G).

- Temperature is “important” to Cycles to 5 Percent PSS and “very important” to both *G** and PSS at 5,000 Cycles.
- Applied shear stress is “very important” to PSS at 5,000 Cycles and to Cycles to 5 Percent PSS.

4.2.3 Regression Analysis

Mallows’ C_p criterion was used to identify the best subset of covariates for each regression equation, in addition to the analysis of the significance of variables described in much greater detail in Reference 3. The analysis of the significance of explanatory variables included the correlation matrix, analysis of variance, design plots, and pairs diagrams.

<u>Cycles to 5 Percent PSS</u>

Binder, temperature, and stress level were the factors most influencing Cycles to 5 Percent PSS. The final model chosen for Cycles to 5 Percent PSS is therefore:

$$\begin{aligned} E(\ln pct5) = {} & \underset{(1.7298)}{28.9019} - \underset{(0.2564)}{0.5919}\,binder1 - \underset{(0.1451)}{1.1299}\,binder2 - \underset{(0.1076)}{0.3321}\,binder3 \\ & - \underset{(0.0749)}{0.0166}\,binder4 - \underset{(0.0318)}{0.2316}\,temp - \underset{(0.0064)}{0.0680}\,sts \end{aligned} \tag{4.1}$$

$R^2 = 0.72$

where Stress *(sts)* is in kPa and temperature (*temp*) is in °C.

The term $E(\ln pct5)$ is the expected value of ln pct5 and the number in parentheses shown under each regression coefficient is the standard error of the estimate of the regression coefficient. The residual standard error is 1.6 on 95 degrees of freedom and the regression line explains as much as 72 percent of the variation in the data.

Type of Test	Response Variables	Covariates																															
		binder				*grad*				*comp*				*cond*				*ac*				*av*				*temp*				*stss*			
		C	D	F	A	C	D	F	A	C	D	F	A	C	D	F	A	C	D	F	A	C	D	F	A	C	D	F	A	C	D	F	A
Temperature Effect (FMLC)	*Lng*		√	√	√																					▨√	▨√	▨√	▨√				
	Lnpct5		√	√	√																					▨√	▨√	▨√	▨√	▨√	▨√	▨√	▨√
	Lnkcyc5		√	√	√																						√	√	√	▨√	▨√	▨√	▨√
Air-Void Content Effect (FMLC)	*Lng*		√	√	√																				√	▨√	▨√	▨√	▨√				
	Lnpct5		√	√	√																	▨√	▨√	▨√	▨√	▨√	▨√	▨√	▨√				
	Lnkcyc5		√	√	√																	▨√	▨√	▨√	▨√	▨√	▨√	▨√	▨√				
Aging Effect (FMLC)	*Lng*		√	√	√										√	√	√									▨√	▨√	▨√	▨√				
	Lnpct5		√	√	√										√	√										▨√	▨√	▨√	▨√				
	Lnkcyc5		√	√	√											√										▨√	▨√	▨√	▨√				
Compaction Effect (FMFC+ FMLC+LMLC)	*Lng*		√	√	√						√	√	√																				
	Lnpct5		√	√	√						√	√	√																				
	Lnkcyc5		√	√	√						√	√	√																				
Gradation Effect (LMLC)	*Lng*	▨√	▨√	▨√	▨√	▨√	▨√	▨√	▨√																								
	Lnpct5	▨√	▨√	▨√	▨√																												
	Lnkcyc5	▨√	▨√	▨√	▨√		√	√	√																								
Pooled Shear Tests (FMFC+ FMLC+LMLC)	*Lng*		√	√	√	▨√	▨√	▨√	▨√						√	√	√						√	√	√	▨√	▨√	▨√	▨√				
	Lnpct5		√	√	√		√	√	√		√	√	√		√	√	√						√	√	√	▨√	▨√	▨√	▨√	▨√	▨√	▨√	▨√
	Lnkcyc5		√	√	√	▨√	▨√	▨√	▨√		√	√	√		√	√	√						√	√			√	√	√	▨√	▨√	▨√	▨√

Notes:

1. *Lng*: G (MPa) in natural logarithm; *Lnpct5*: Cycles to 5 Percent PSS (Permanent Shear Strain) in natural logarithm; *Lnkcyc5*: PSS at 5,000 Cycles in natural logarithm.
2. C: correlation matrix; D: design plot; F: factor plot; A: ANOVA result.
3. The four-in-a-row diagonal shaded area means the covariate is "very important" to the corresponding response variable.

Figure 4.5: Summary statistics of main effects.

The term *binder* in the formulation is a category covariate (or factor), which needs to be coded (or parameterized) by "contrasts" for use in the linear regression equation for stiffness. To find the Cycles to 5 Percent PSS for a given mix, the appropriate set of integers shown in Table 4.4 must be used in the equation.

Table 4.4: Contrast Tables of Category Covariates Used in Regression Analyses

Factor *binder*: for all the effects equations other than gradation effect equation				
Binder	***binder1***	***binder2***	***binder3***	***binder4***
AR4000	-1	-1	-1	-1
MAC15	1	-1	-1	-1
MB15	0	2	-1	-1
MB4	0	0	3	-1
ARB	0	0	0	4
Factor *binder*: for gradation effect equation				
Binder	***binder1***	***binder2***		
MAC15	-1	-1		
MB15	1	-1		
MB4	0	2		
Factor *cond*: for aging effect equation				
Condition	***cond***			
aging	-1			
none	1			
Factor *comp*: for compaction effect equation				
Compaction	***comp1***	***comp2***		
FMFC	-1	-1		
FMLC	1	-1		
LMLC	1	2		
Factor *grad*: for gradation effect equation				
Grading	***grad***			
DG	-1			
GG	1			

Example

To determine the regression equation of Cycles to 5 Percent PSS (*ln pct5*) for MB4, the factor values should be set as follows (from Table 4.4):

$binder1 = 0$, $binder2 = 0$, $binder3 = 3$, and $binder4 = -1$.

This results in the following Cycles to 5 Percent PSS regression equation for the MB4 mixes:

$$\begin{aligned} E(\ln pct5) &= 28.9019- 0.3321*3-0.0166*(-1)-0.0.2316 temp-0.0680 sts \qquad \textbf{(4.2)} \\ &= 27.9222-0.2316 temp-0.0680 sts \end{aligned}$$

An analysis of the residuals of the fit was performed, following the procedure described in detail in Reference 3. The results of the analysis showed that there was a slight parabolic trend in the residuals. Inclusion of the interaction term *binder*temp* would correct this; however, the increasing complexity of the model specification outweighs the increase of R^2. The assumption of homoscedasticity (same variance in the response variable across the range of explanatory variables) appeared reasonable. The Cook's distance accompanied with the normal probability plot, the quantile-quantile plot (QQ plot), and the histogram of residuals was used to identify the influential points and possible outliers. The distribution of estimated residuals was found to be close to a normal distribution, which is an assumption of the regression equation. See Figures 4.26 through 4.28 for further details.

PSS at 5,000 Cycles

In evaluating the significance of variables affecting the PSS at 5,000 Cycles, stress was identified as "very important," while temperature and binder were identified as "important" in terms of influencing fatigue life. Using Mallows' C_p criterion, the same factors were identified as the best subset of covariates.

The final model chosen for PSS at 5,000 Cycles is:

$$\begin{aligned} E(\ln kcyc5) = & -\underset{(0.3306)}{6.7512} + \underset{(0.0490)}{0.1971}\, binder1 + \underset{(0.0281)}{0.2637}\, binder2 + \underset{(0.0206)}{0.0389}\, binder3 \\ & + \underset{(0.0143)}{0.0075}\, binder4 + \underset{(0.0061)}{0.0413}\, temp + \underset{(0.0012)}{0.0128}\, sts \end{aligned} \qquad \textbf{(4.3)}$$

$R^2 = 0.74$

The residual standard error of the fit is 0.31 on 94 degrees of freedom. The residuals analysis of the PSS at 5,000 Cycles fit showed no significant patterns, indicating that the suggested model is appropriate. And the QQ plot and the histogram both support the methodology as acceptable.

As with the regression equation for Cycles to 5 Percent PSS, the contrast scheme in Table 4.4 should be followed when using the regression equation.

Resilient Shear Modulus *(G^*)*

In evaluating the significance of variables affecting G, temperature was identified as "very important," while binder was identified as "important." Stress level had minimal effect. Using Mallows' C_p criterion, the same factors were identified as the best subset of covariates.

The final model chosen for G^* is:

$$\begin{aligned} E(\ln G) = & \underset{(0.2072)}{8.1841} - \underset{(0.0339)}{0.3045}\, binder1 - \underset{(0.0187)}{0.2330}\, binder2 - \underset{(0.0139)}{0.1009}\, binder3 \\ & + \underset{(0.0096)}{0.1167}\, binder4 - \underset{(0.0041)}{0.0711}\, temp \end{aligned} \qquad \textbf{(4.4)}$$

$R^2 = 0.90$

The residual standard error of the fit is 0.21 on 94 degrees of freedom. The residuals analysis of the *G** fit showed no significant patterns, indicating that the suggested model is appropriate. The QQ plot and the histogram both support the methodology as acceptable.

Analysis procedures similar to those described above are followed in Sections 4.3 through 4.6, and only the results are presented.

4.3. Air-Void Content Effect

This test investigated the effect of degree of compaction (the air-void content effect) on shear performance at 45°C and 55°C for various mixes. The experiment design contained a total of 110 tests comprising:

- Five binder types (AR4000, ARB, MAC15, MB15, and MB4),
- Two air-void contents (6.0 ± 0.5 percent and 9.0 ± 1.0 percent),
    1. At 6.0 ± 0.5 percent (90 tests)
        - Three stress levels (70, 100, and 130 kPa), and
        - Three replicates
    2. At 9.0 ± 1.0 percent (20 tests)
        - One stress level (70 kPa), and
        - Two replicates

As stated above, the results of 90 tests from the temperature effect study were included in this experiment.

The covariates investigated were primarily:

- Binder type (*binder*)
- Air-void content (*av*)
- Temperature (temp)

Example summary boxplots and design plots are shown in Figure 4.6 through Figure 4.9. The correlation matrices, analyses of variance, and other plots confirm the importance of the listed covariates.

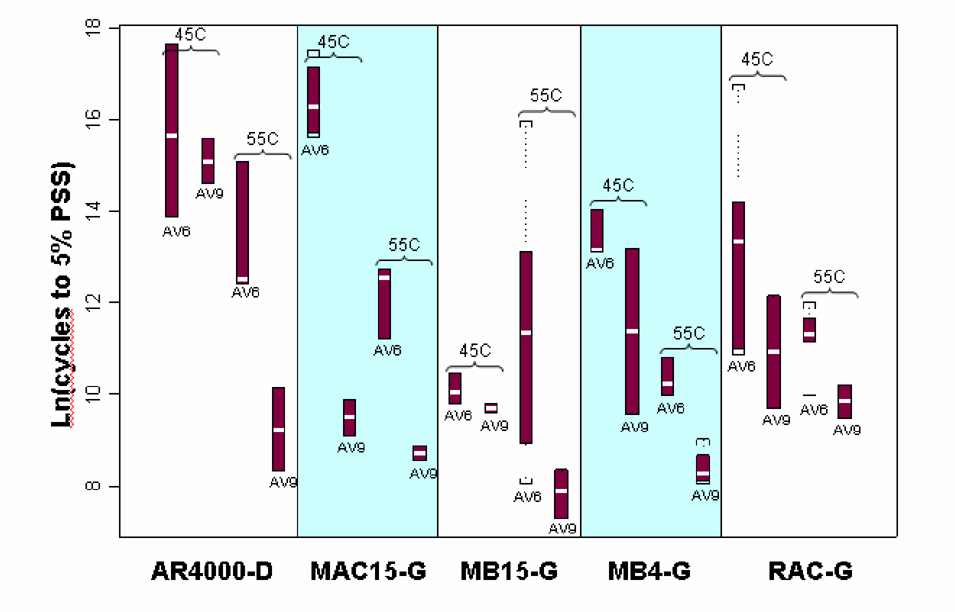


Figure 4.6: Summary boxplots of air-void content effect and Cycles to 5 Percent PSS. (AV6=6 % air-void content; AV9=9% air-void content)

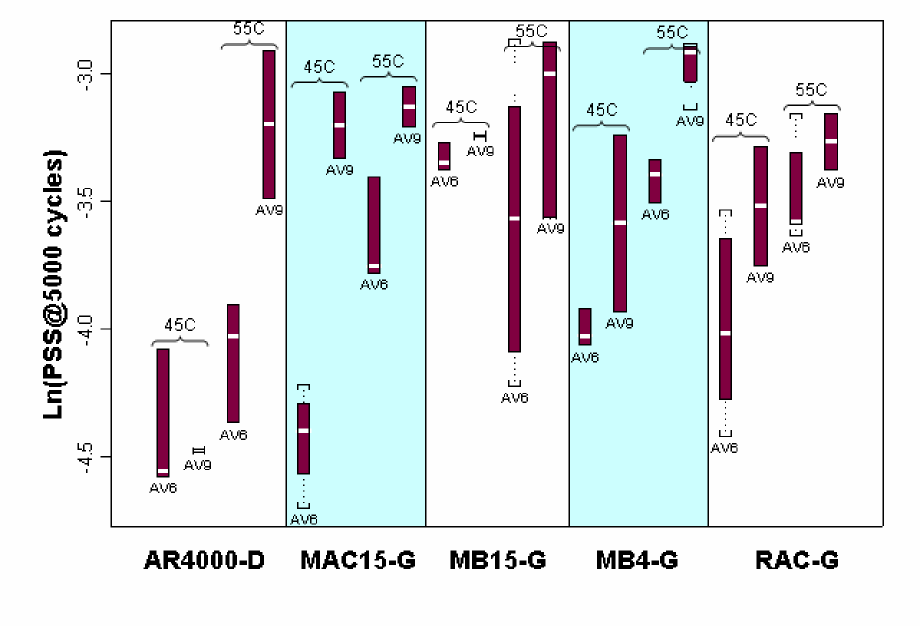


Figure 4.7: Summary boxplots of air-void content and PSS at 5,000 Cycles. (AV6=6 % air-void content; AV9=9% air-void content)

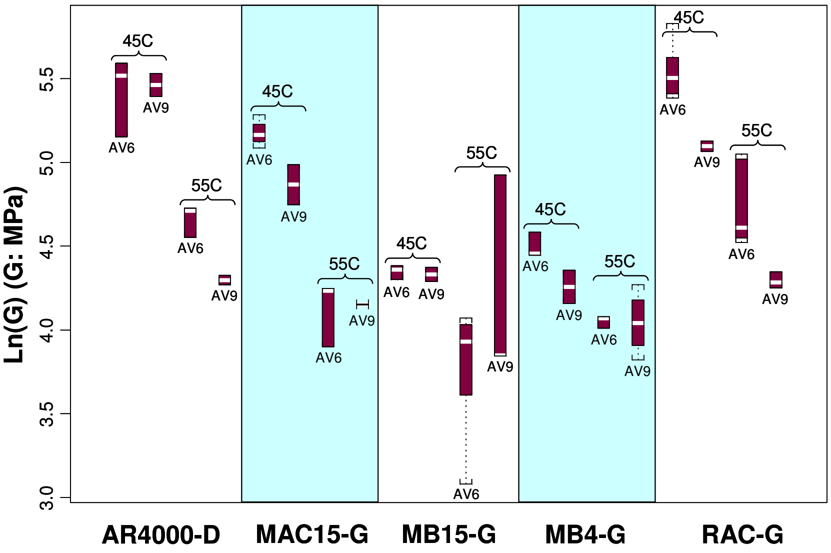


Figure 4.8: Summary boxplots of air-void content and Resilient Shear Modulus (G*). (AV6=6 % air-void content; AV9=9% air-void content)

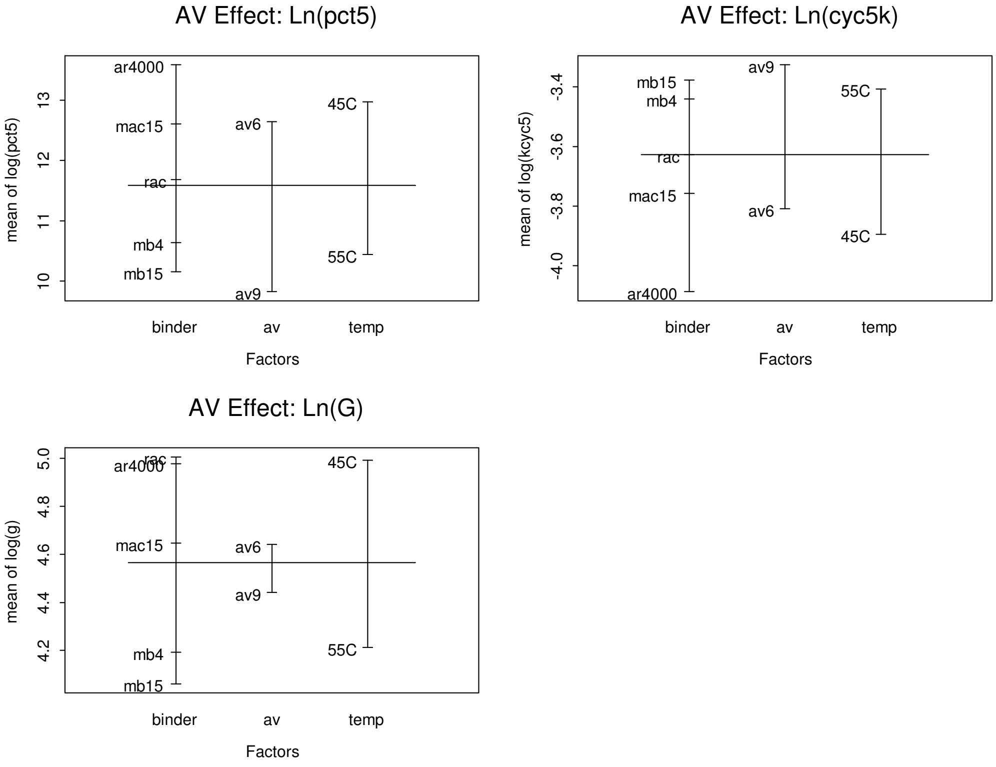


Figure 4.9: Design plots of air-void content effect. (AV6=6 % air-void content; AV9=9% air-void content)

A review of the data leads to the following observations:

- Increased air voids yield poorer performance: higher PSS at 5,000 Cycles and lower Cycles to 5 Percent PSS.
- The AR4000 at 55ºC and the MAC15-G at 45ºC are most effected by changes in air voids, for both PSS at 5,000 Cycles and Cycles to 5 Percent PSS.
- The Resilient Shear Modulus *(G^*)* generally decreases with increasing air voids, especially for the RAC-G mix, although not for all mixes or testing conditions.
- For some conditions, resilient modulus remained unchanged.

The final regression models after the identification of significant factors and the iterative procedure of model building are:

$$\begin{aligned} E(\ln pct5) = {} & \underset{(2.3049)}{29.8023} - \underset{(0.3538)}{0.7143}\, binder1 - \underset{(0.1871)}{0.9716}\, binder2 - \underset{(0.1357)}{0.2487}\, binder3 \\ & - \underset{(0.0938)}{0.0459}\, binder4 - \underset{(0.1409)}{0.8506}\, av - \underset{(0.0412)}{0.2387}\, temp \end{aligned} \tag{4.5}$$

$R^2 = 0.67$

$$\begin{aligned} E(\ln kcyc5) = {} & -\underset{(0.4458)}{6.8575} + \underset{(0.0705)}{0.2029}\, binder1 + \underset{(0.0363)}{0.1967}\, binder2 + \underset{(0.0261)}{0.0688}\, binder3 \\ & + \underset{(0.0179)}{0.0211}\, binder4 + \underset{(0.0278)}{0.1226}\, av + \underset{(0.0079)}{0.0456}\, temp \end{aligned} \tag{4.6}$$

$R^2 = 0.67$

$$\begin{aligned} E(\ln G) = {} & \underset{(0.3047)}{8.5547} - \underset{(0.0462)}{0.1935}\, binder1 - \underset{(0.0249)}{0.2171}\, binder2 - \underset{(0.0178)}{0.0774}\, binder3 \\ & + \underset{(0.0123)}{0.0993}\, binder4 - \underset{(0.0187)}{0.0632}\, av - \underset{(0.0054)}{0.0700}\, temp \end{aligned} \tag{4.7}$$

$R^2 = 0.89$

4.4. Aging Effect

This experiment investigated the effect of long-term oven aging (six days at 85°C) on shear performance for the various mixes. The experimental design for the aging tests included:

- Five binder types (AR4000, ARB, MAC15, MB15, and MB4),
- Two temperatures (45°C and 55°C),
- One stress level (70 kPa), and
- Two replicates for a total of four specimens for each mix.

The compacted specimens were conditioned in a forced draft oven for six days at 85°C.

The covariates investigated were:

- Binder type (*binder*)
- Conditioning (*cond*)
- Temperature (*tmp*)

Summary boxplots and design plots are shown in Figure 4.10 through Figure 4.13.

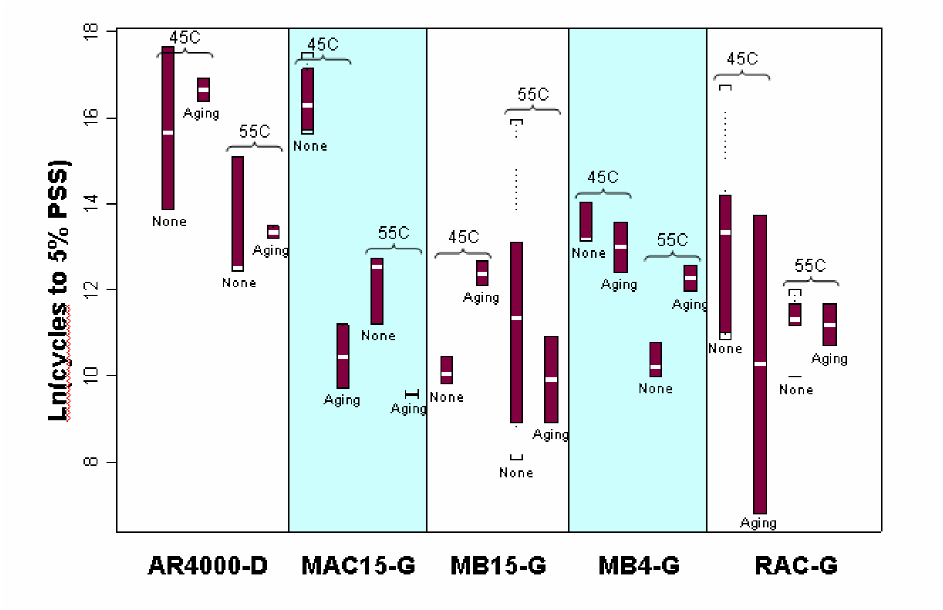


Figure 4.10: Summary boxplots of aging effect and Cycles to 5 Percent PSS. (None=no long-term aging; Aging=6 days long-term oven aging; all specimens at 6% air-voids)

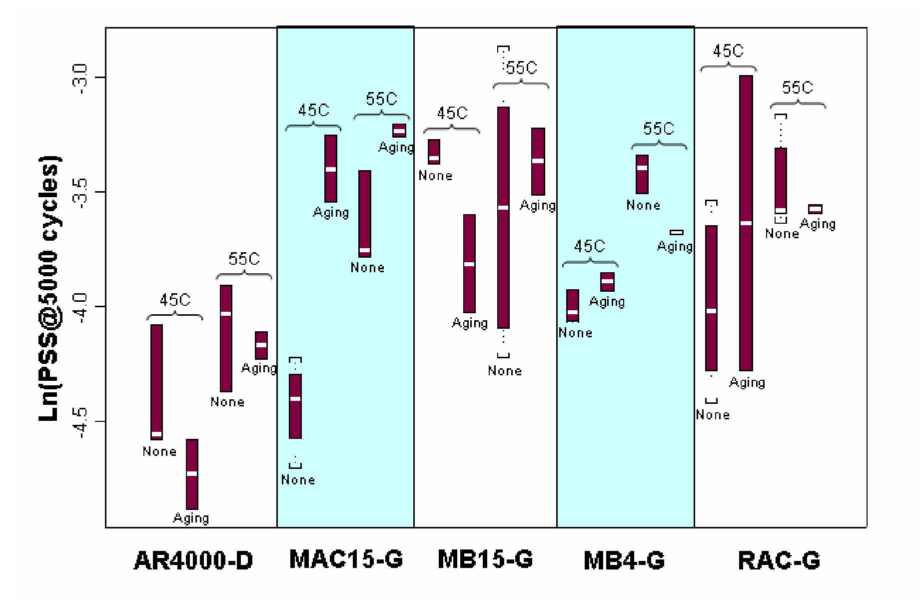


Figure 4.11: Summary boxplots aging effect and PSS at 5,000 Cycles. (None=no long-term aging; Aging=6 days long-term oven aging; all specimens at 6% air-voids)

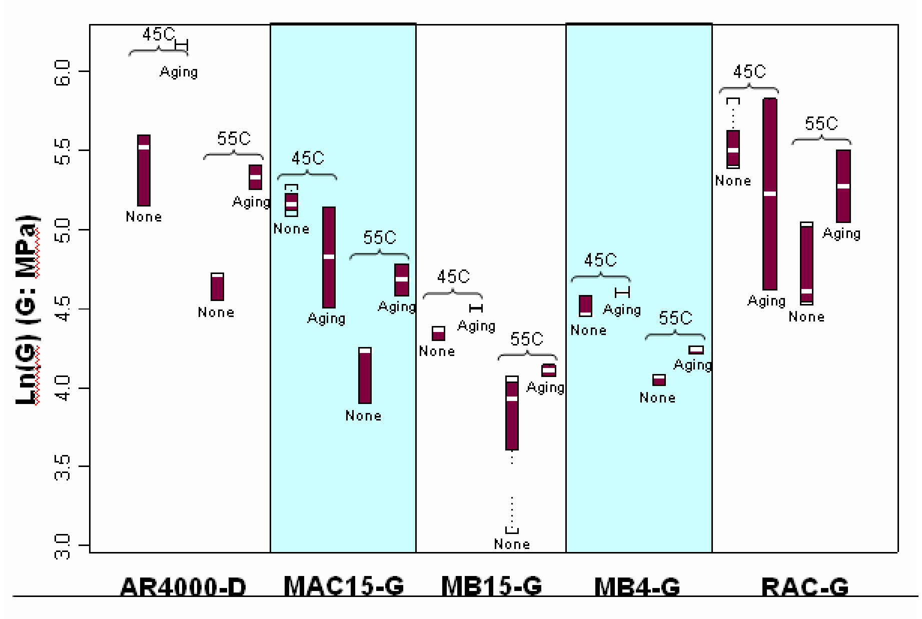
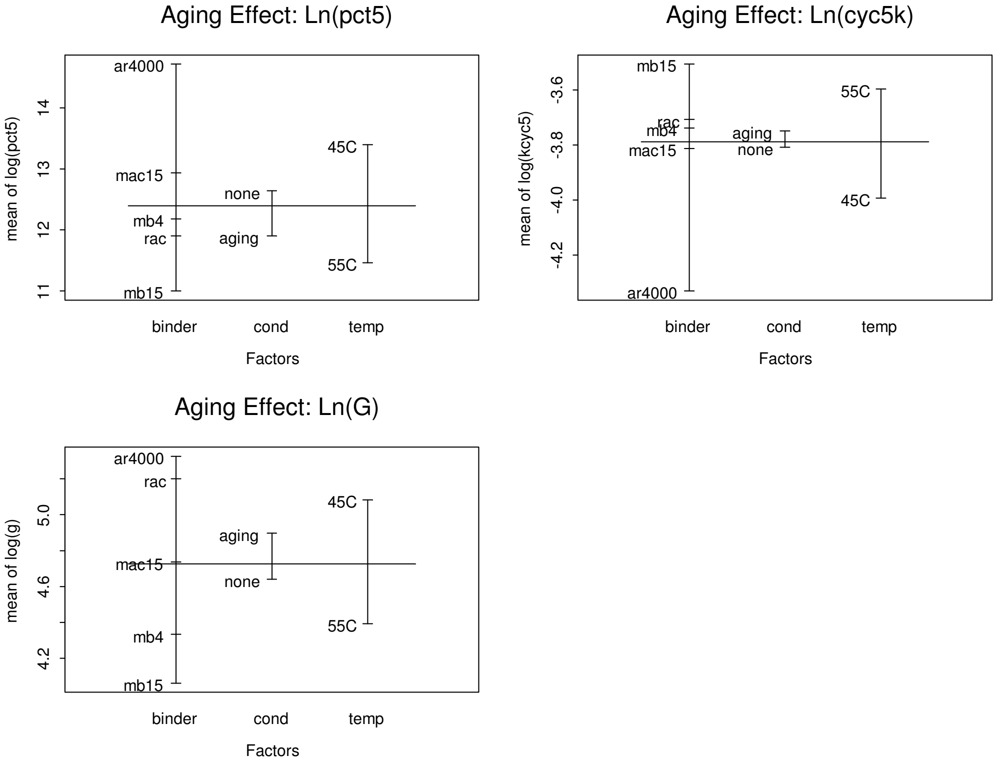


Figure 4.12: Summary boxplots of aging effect and Resilient Shear Modulus (G*.)
(None=no long-term aging; Aging=6 days long-term oven aging; all specimens at 6% air-voids)


Aging Effect: Ln(pct5)

Aging Effect: Ln(cyc5k)

Aging Effect: Ln(G)

Figure 4.13: Design plots for aging effect.
(None=no long-term aging; Aging=6 days long-term oven aging; all specimens at, 6% air-voids)

A review of the data led to the following observations regarding performance and the identification of statistically significant explanatory variables.

- From the summary boxplots, it is apparent that aging results vary widely according to binder/mix type and temperature. The results were inconsistent and appeared unreasonable at times.
    1. For AR4000, aging increased the Cycles to 5 Percent PSS and decreased the PSS at 5,000 Cycles, as expected.
    2. For the RAC-G and MAC15-G, aging unexpectedly resulted in reduced Cycles to 5 Percent PSS and higher PSS at 5,000 Cycles at both temperatures. At 55°C, aging had little to no effect on Cycles to 5 Percent PSS or PSS at 5,000 Cycles.
    3. For MB15-G and MB4-G, the performance showed opposing effects of aging. At 45°C, aging resulted in better performance (more Cycles to 5 Percent PSS and less PSS at 5,000 Cycles) for MB15-G, and the opposite for MB4-G; at 55°C aging resulted in worse performance for MB15-G and better performance for MB4-G. .
- From the design plots, it appears that aging is "important" to PSS at 5,000 Cycles and G, and has minimal effect on Cycles to 5 Percent PSS.
- The ranking of the mixes for Cycles to 5 Percent PSS, PSS at 5,000 Cycles, and *G** for aged and un-aged tests shows AR4000-D highest and MB15-G lowest, with the other three mixes in various positions in the middle rankings.
- Temperature is very important to the all three measured parameters.

The final regression models after the identification of significant factors and the iterative procedure of model building are:

$$\begin{aligned} E(\ln pct5) = {} & \underset{(2.2149)}{22.5692} - \underset{(0.3593)}{0.9385}\, binder1 - \underset{(0.1946)}{0.9770}\, binder2 - \underset{(0.1481)}{0.1556}\, binder3 \\ & - \underset{(0.1040)}{0.1307}\, binder4 - \underset{(0.0439)}{0.2010}\, temp \end{aligned} \tag{4.8}$$

$R^2 = 0.53$

$$\begin{aligned} E(\ln kcyc5) = {} & -\underset{(0.4226)}{5.9345} + \underset{(0.0693)}{0.2690}\, binder1 + \underset{(0.0375)}{0.1877}\, binder2 + \underset{(0.0286)}{0.0339}\, binder3 \\ & + \underset{(0.0195)}{0.0165}\, binder4 + \underset{(0.0084)}{0.0422}\, temp \end{aligned} \tag{4.9}$$

$R^2 = 0.57$

$$\begin{aligned} E(\ln G) = {} & \underset{(0.2835)}{8.0273} - \underset{(0.0471)}{0.2669}\, binder1 - \underset{(0.0251)}{0.2726}\, binder2 - \underset{(0.0190)}{0.1133}\, binder3 \\ & + \underset{(0.0131)}{0.1260}\, binder4 - \underset{(0.0303)}{0.1648}\, cond - \underset{(0.0056)}{0.0639}\, temp \end{aligned} \tag{4.10}$$

$R^2 = 0.90$

4.5. Mixing and Compaction Effect

This experiment investigated the effect of mixing and compaction methods on shear performance. The relative experiment design contained a total 118 tests. This experiment used results from tests on field-mixed, laboratory-compacted specimens (FMLC, 90 specimens); laboratory mixed, laboratory-compacted specimens (LMLC, 20 specimens); and field-mixed, field-compacted specimens from the full-depth (90 mm) AR4000 and MB4 sections (FMFC, 6 specimens). Comparisons can only be made for tests with the same testing conditions (45°C and 70 kPa). This resulted in 30 FMLC specimens being included in the experiment. Note that the objective of analysis of the results of this experiment is not mix ranking, but rather to investigate the use of laboratory mixed and compacted materials as opposed to field cores to simulate field performance. The variables in the experiment were:

- Five binder types (AR4000-D, RAC-G, MAC15-G, MB15-G, and MB4-G)
- One temperature (45°C)
- One stress level (70 kPa)
- Two and three replicates.

The covariates investigated were primarily:

- Binder type (*binder*)
- Mix and Compaction method (*comp*)

Summary boxplots and design plots are shown in Figure 4.14 through Figure 4.17.

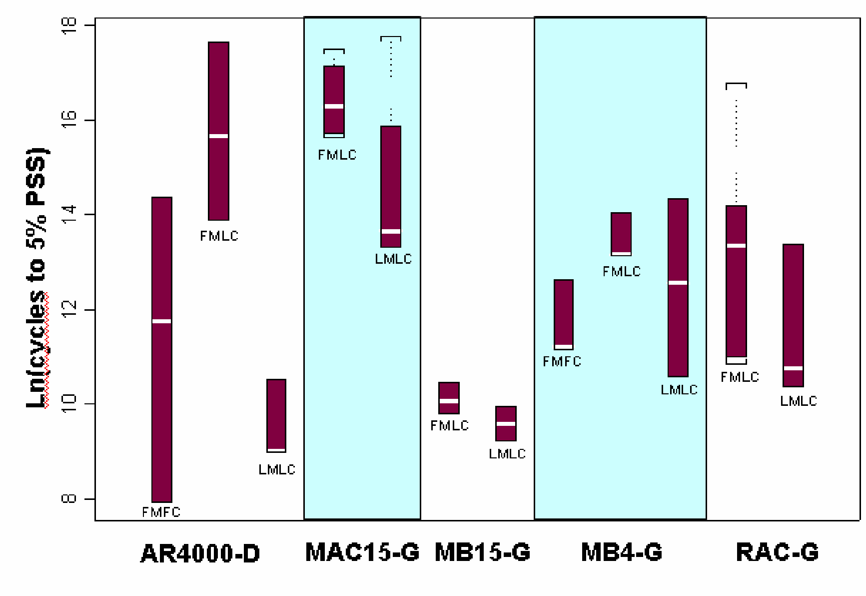


Figure 4.14: Summary boxplots of compaction effect and Cycles to 5 Percent PSS. (6% AV)

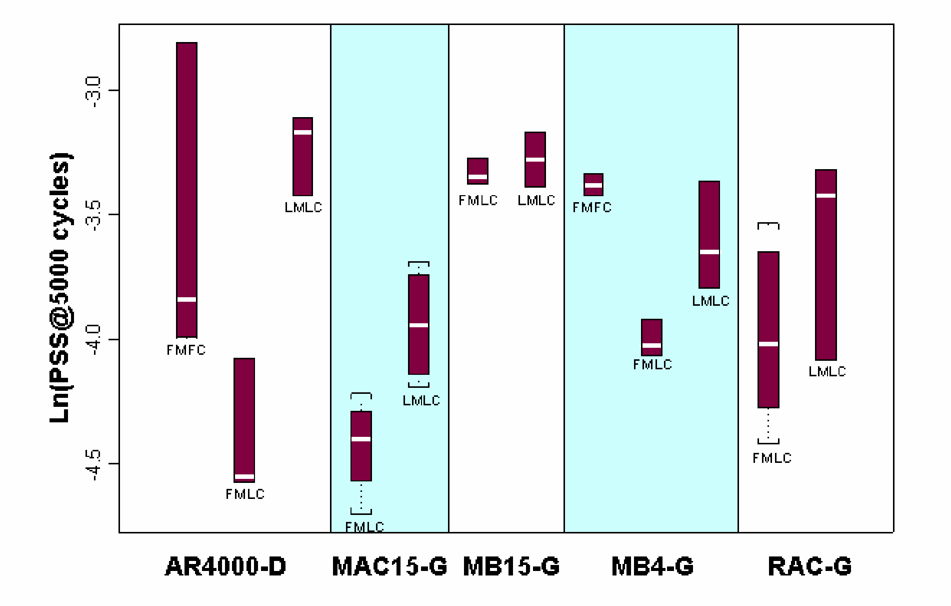


Figure 4.15: Summary boxplots of compaction effect and PSS at 5,000 Cycles. (6% AV)

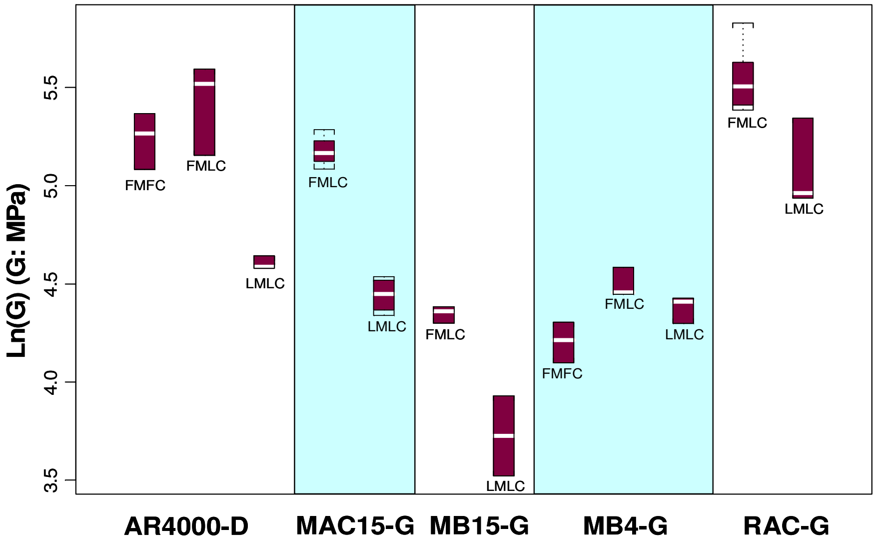


Figure 4.16: Summary boxplots of compaction effect and Resilient Shear Modulus (G*). (6% AV)

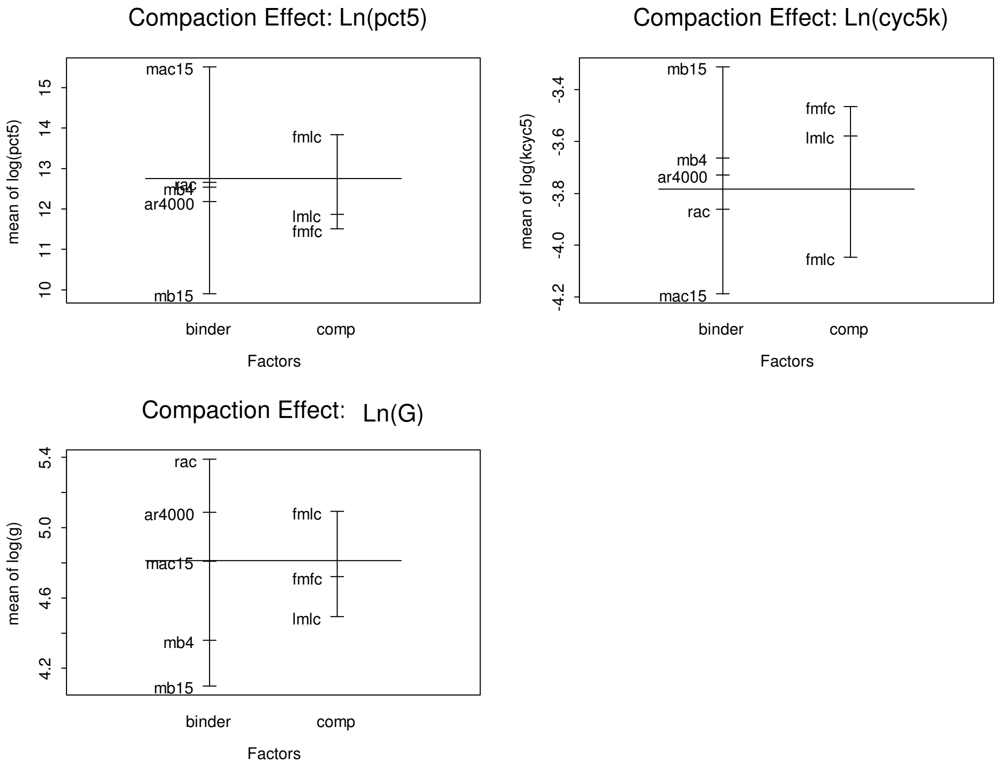


Figure 4.17: Design plots for compaction effect.
(6% AV)

A review of the data led to the following observations regarding performance and statistical significance:

- The LMLC specimens had greater PSS at 5,000 Cycles and lower Cycles to 5 Percent PSS than the FMLC.
- The FMFC results were comparable to the LMLC specimens for PSS at 5,000 Cycles and Cycles to 5 Percent PSS.
- The two previous observations indicate that the aging procedures used for the LMLC specimens do a fairly good job of replicating the mixing, aging and compaction of the FMFC specimens, and that the FMLC specimens have more aging than the LMLC and FMFC specimens. This might be expected considering that the FMLC mixes were mixed in the plant, stored in sealed buckets at relatively constant temperature (about 20°C), and then reheated for laboratory compaction, while the LMLC specimens were mixed from binder that had been stored in sealed containers, short-term oven aged, then immediately compacted.
- The effect of mix and compaction methods was not consistent on the Resilient Shear Modulus *(G^*)*. RAC-G is shown to be the stiffest and MB15-G the least stiff.

The final regression models after the identification of significant factors and the iterative procedure of model-building follow. The covariates for both binder type and compaction method are in Table 4.4.

$$\begin{aligned} E(\ln pct5) = {} & \underset{(0.3330)}{12.3973} + \underset{(0.4465)}{1.6453}\, binder1 - \underset{(0.2888)}{1.3880}\, binder2 + \underset{(0.1749)}{0.0328}\, binder3 \\ & - \underset{(0.1311)}{0.0366}\, binder4 + \underset{(0.4773)}{0.6144}\, comp1 - \underset{(0.2060)}{0.4584}\, comp2 \end{aligned} \qquad \textbf{(4.11)}$$

$R^2 = 0.62$

$$\begin{aligned} E(\ln kcyc5) = {} & -\underset{(0.0609)}{3.7031} - \underset{(0.0782)}{0.1471}\, binder1 + \underset{(0.0522)}{0.2596}\, binder2 + \underset{(0.0320)}{0.0126}\, binder3 \\ & - \underset{(0.0238)}{0.0017}\, binder4 - \underset{(0.0850)}{0.2266}\, comp1 + \underset{(0.0377)}{0.0934}\, comp2 \end{aligned} \qquad \textbf{(4.12)}$$

$R^2 = 0.62$

$$\begin{aligned} E(\ln G) = {} & \underset{(0.0375)}{4.7188} - \underset{(0.0502)}{0.1396}\, binder1 - \underset{(0.0337)}{0.3015}\, binder2 - \underset{(0.0203)}{0.0717}\, binder3 \\ & + \underset{(0.0154)}{0.1443}\, binder4 + \underset{(0.0518)}{0.1397}\, comp1 - \underset{(0.0236)}{0.1380}\, comp2 \end{aligned} \qquad \textbf{(4.13)}$$

$R^2 = 0.89$

4.6. Gradation Effect

This experiment investigated the effect of dense- and gap-gradations on Cycles to 5 Percent PSS, PSS at 5,000 Cycles, and G. The experiment design contained a total of twenty-four tests on laboratory-mixed, laboratory compacted cores as follows:

- Three binder types (MAC15, MB15, and MB4),
- Two gradations (dense- and gap-),
- One stress level (70 kPa),
- Two temperatures (45°C and 55°C), and
- One air-void content (6 percent).

There were two replicates for each combination of variables. In addition to these twenty-four cores, four AR4000-D (LMLC) and four RAC-G (LMLC) cores were tested for comparison.

The covariates investigated were primarily:

- Binder type (*binder*)
- Gradation (*grad*)

Summary boxplots and design plots are shown in Figure 4.18 through Figure 4.21.

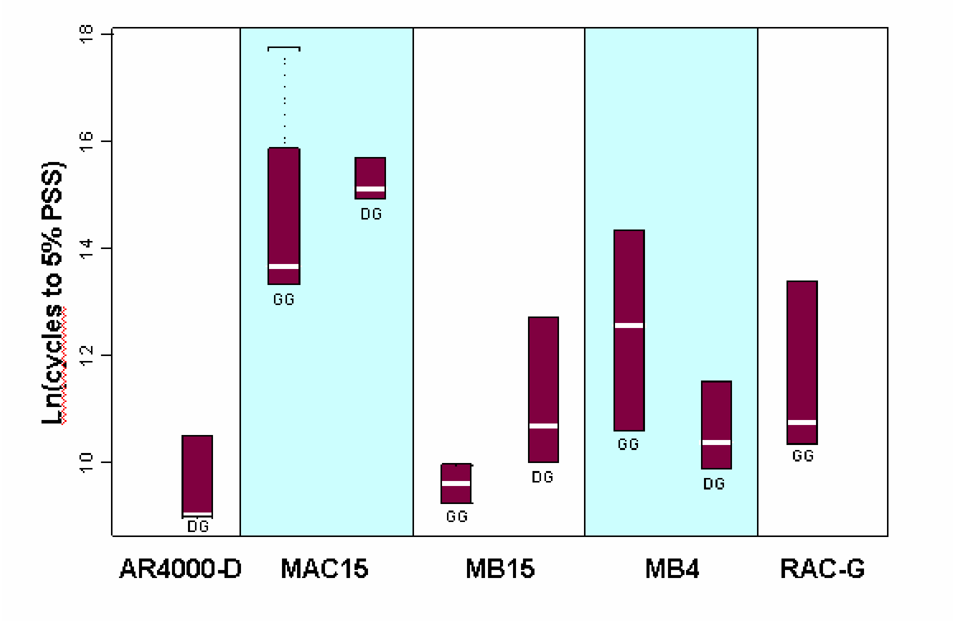


Figure 4.18: Summary boxplots of gradation effect and Cycles to 5 Percent PSS. (6% AV)

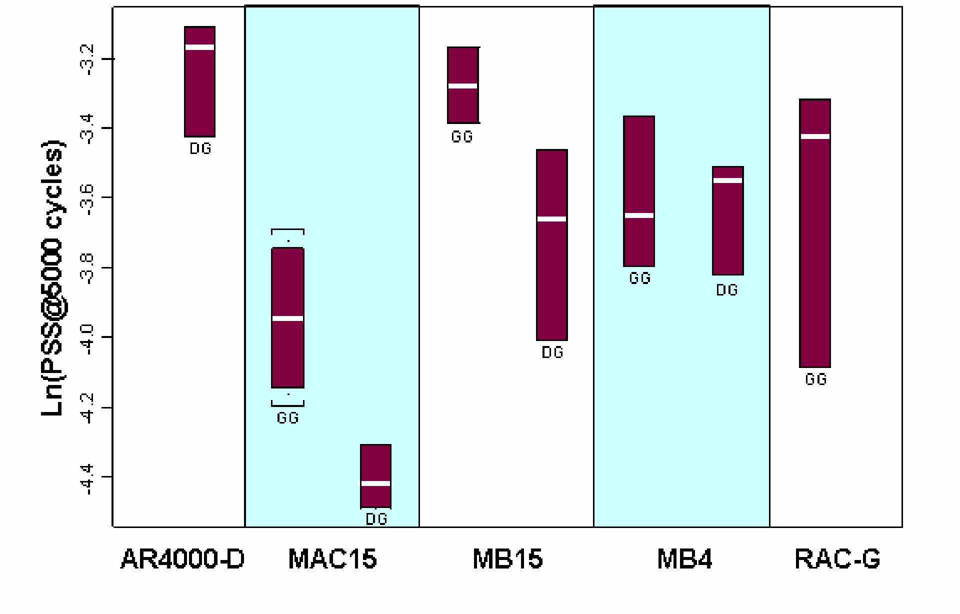


Figure 4.19: Summary boxplots of gradation effect and PSS at 5,000 Cycles. (6% AV)

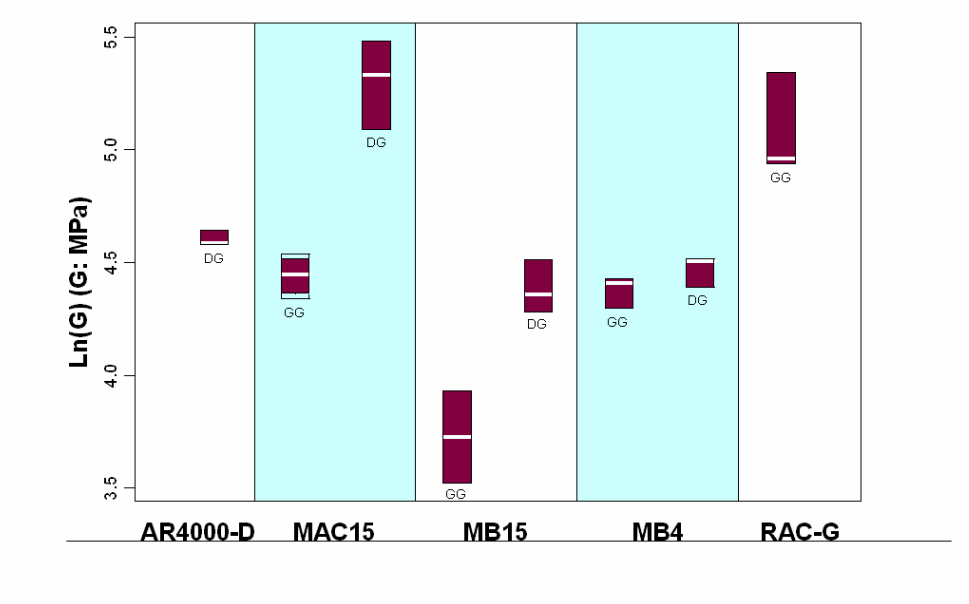
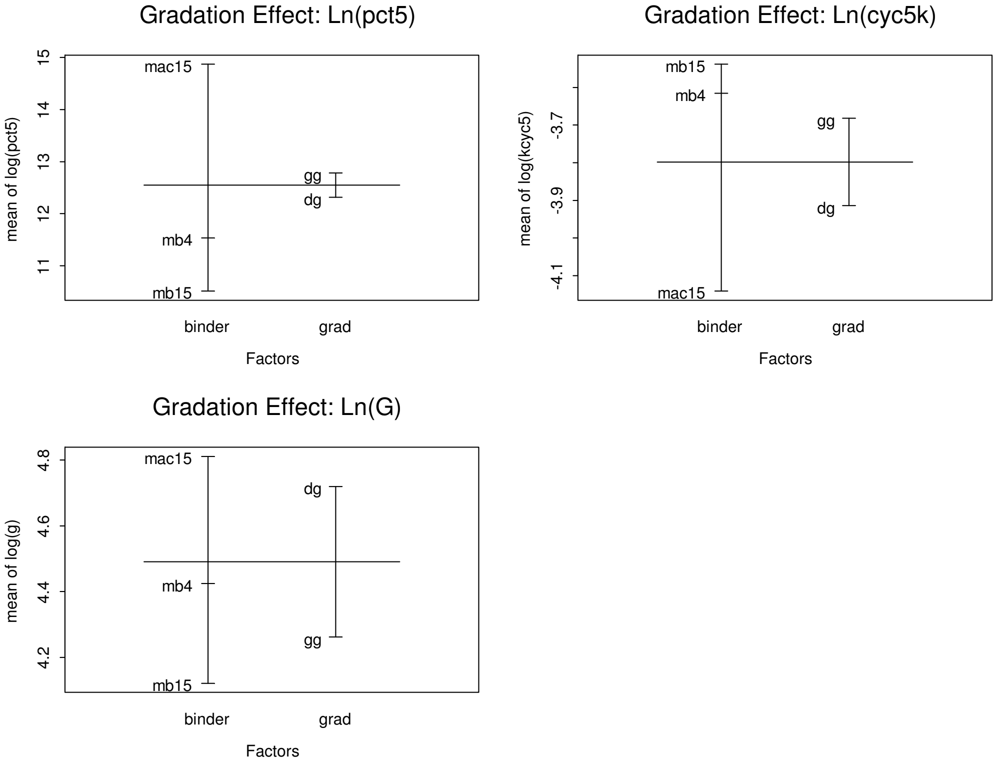


Figure 4.20: Summary boxplots of gradation effect and Resilient Shear Modulus (G*). (6% AV)


Gradation Effect: Ln(pct5)

Gradation Effect: Ln(cyc5k)

Gradation Effect: Ln(G)

Figure 4.21: Design plots for gradation effect. (6% AV)

A review of the data and box and design plots leads to the following statistical observations:

- From the design plots, gradation has an apparent effect on G, less of an influence on PSS at 5,000 Cycles and little effect on Cycles to 5 Percent PSS.
- For the MAC15 and MB15 binders, the dense gradation resulted in increased Cycles to 5 Percent PSS and higher stiffnesses relative to the gap gradation.
- While dense-graded MB4 mix showed an opposite response with lower Cycles to 5 Percent PSS and higher PSS at 5,000 Cycles, the Resilient Shear Modulus *(G^*)* did increase over the gap-gradation.
- MAC15 binder consistently shows the best performance the three modified binders studied, followed by MB4 and MB15.
- In general, these dense-graded mixes are likely to have greater rutting resistance (indicated by PSS results) and reduced risk of rutting of the unbound layers (indicated by greater stiffness), compared to using the same binder in gap-graded mixes.
- The reason for the poor results for the AR4000 relative to the other mixes in the gradation study is not certain, considering that it had the best results for the field–mixed, laboratory-compacted specimens. The difference may be due to differences in aging in the laboratory compared to the plant during mixing.

The final regression models after the identification of significant factors and the iterative procedure of model building follow. The covariates for both binder type and compaction method are in Table 4.4.

$$E(\ln pct5) = \underset{(0.2410)}{11.7599} - \underset{(0.2965)}{2.2128}\, binder1 - \underset{(0.1696)}{0.4199}\, binder2 - \underset{(0.2388)}{0.2848}\, grad \tag{4.14}$$

$R^2 = 0.83$

$$E(\ln kcyc5) = -\underset{(0.0476)}{3.7107} + \underset{(0.0582)}{0.3713}\, binder1 + \underset{(0.0340)}{0.0812}\, binder2 + \underset{(0.0468)}{0.1556}\, grad \tag{4.15}$$

$R^2 = 0.86$

$$E(\ln G) = \underset{(0.0505)}{4.4254} - \underset{(0.0643)}{0.3533}\, binder1 - \underset{(0.0352)}{0.0007}\, binder2 - \underset{(0.0516)}{0.2422}\, grad \tag{4.16}$$

$R2 = 0.77$

4.7. Pooled Shear Tests

Analyses of grouped results were undertaken to develop comprehensive models that better describe the rutting performance of the materials tested. The dataset used consisted of all shear tests. The covariates inspected were:

- Binder type *(binder)*
- Gradation *(grad)*
- Compaction *(comp)*
- Aging *(cond)*
- Air-void content *(av)*
- Temperature *(temp)*
- Stress (*sts*)

Figure 4.22 presents the pairs diagram showing the relationships between variables. Summary boxplots and design plots are shown in Figure 4.23 through Figure 4.25.

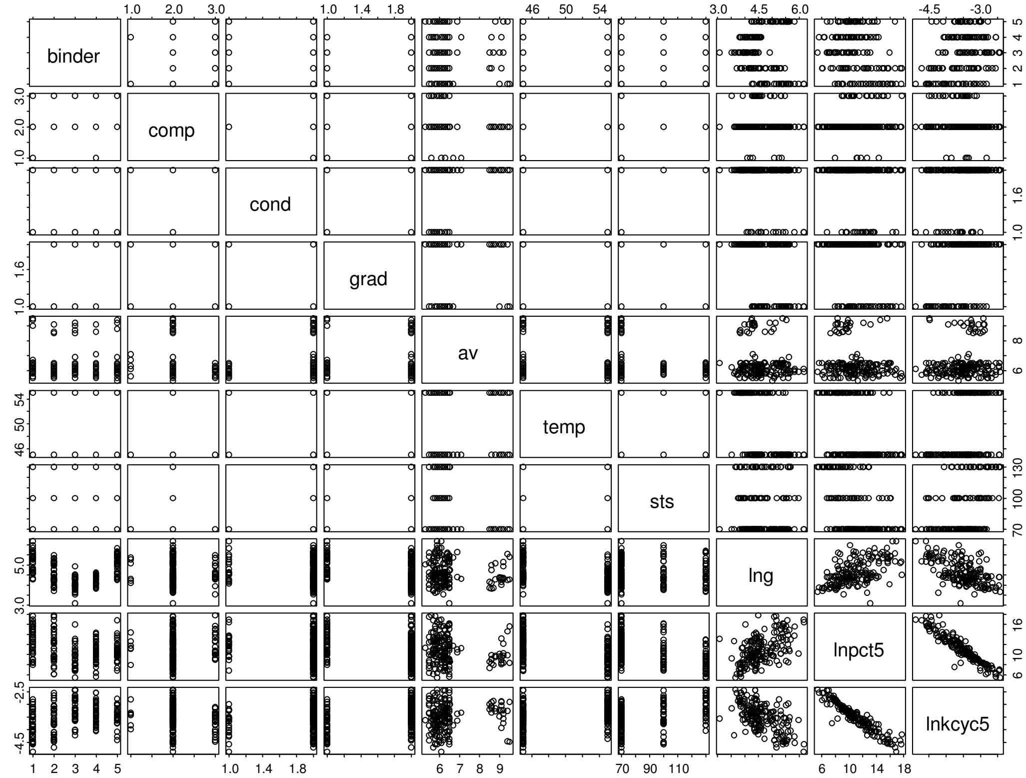


Figure 4.22: Pairs diagram showing relationships among variables.

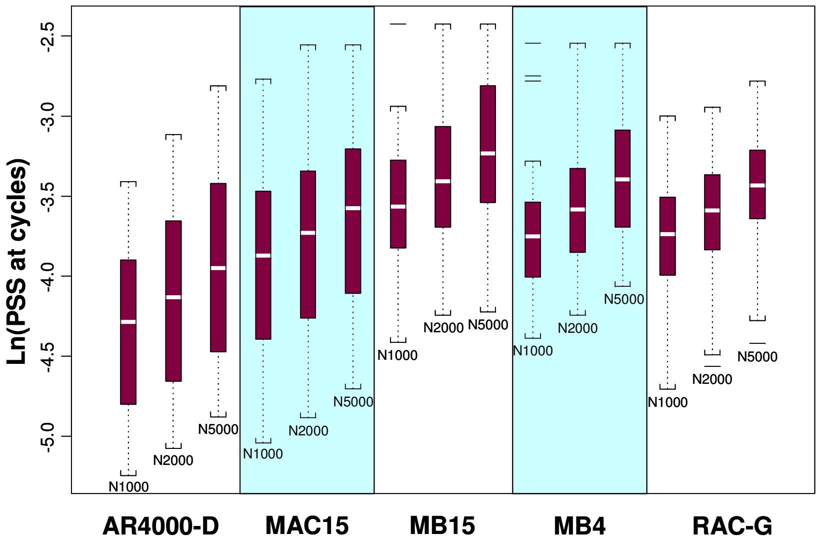


Figure 4.23: Summary boxplots of pooled shear testing for permanent shear strain at cycles. (6% AV)

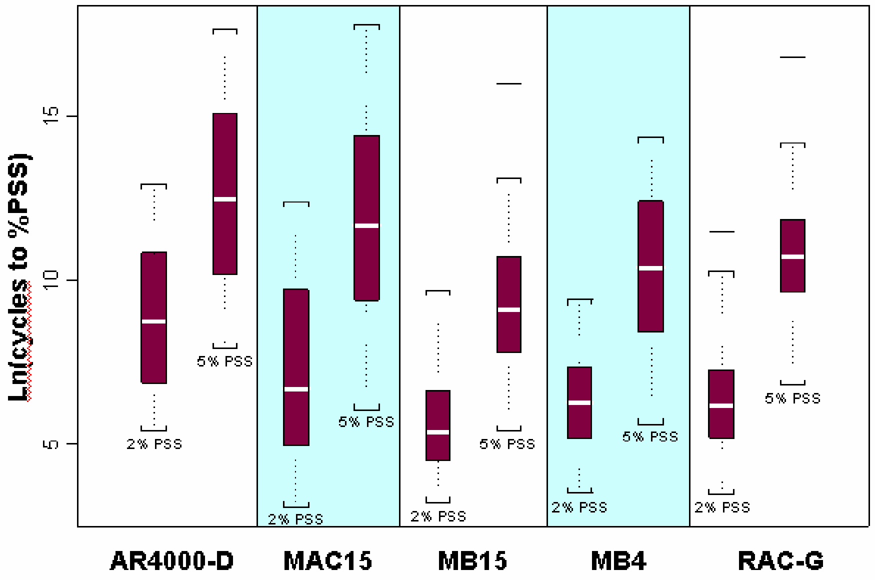


Figure 4.24: Summary boxplots of pooled shear testing for Cycles to 5 Percent PSS. (6% AV)

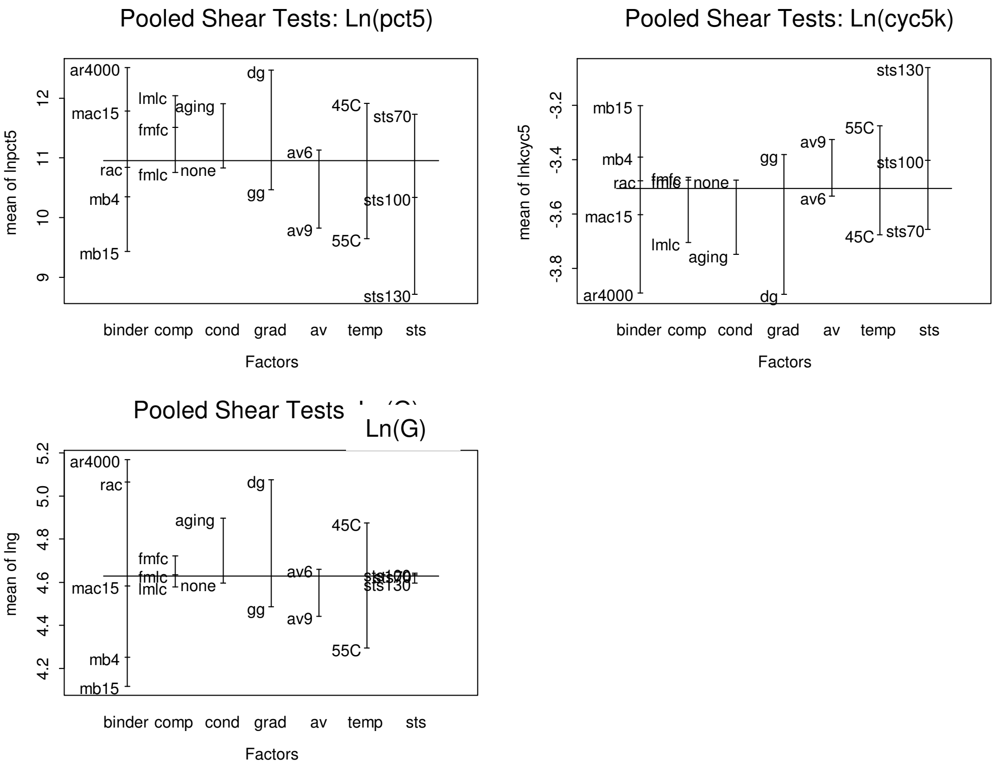


Figure 4.25: Example design plots for pooled shear tests.

A review of the data and charts led to the following observations:

- All five binders show consistent performance for cycles to 2 and 5 percent PSS and PSS at 1,000, 2,000, and 5,000 cycles.
- AR4000-D consistently shows the best rutting performance in these tests.
- MB15 consistently showed the poorest rutting performance.
- Stress level, temperature, and gradation are "very important" to Cycles to 5 Percent PSS, PSS at 5,000 Cycles, and G.
- Air-void content, aging, and compaction method are less important to these same parameters.
- Both the degree of compaction and the applied stress level have little influence on Resilient Shear Modulus *(G^*)*.

The final regression models for grouped shear testing after the identification of significant factors and the iterative procedure of model building are:

$$\begin{aligned} E(\ln pct5) = {} & \underset{(1.6884)}{32.6002} + \underset{(0.3948)}{0.2724}\,binder1 - \underset{(0.1597)}{0.6457}\,binder2 - \underset{(0.0987)}{0.0650}\,binder3 \\ & + \underset{(0.0755)}{0.1139}\,binder4 + \underset{(0.3965)}{0.7332}\,comp1 - \underset{(0.1989)}{0.5516}\,comp2 - \underset{(0.3576)}{0.9076}\,grad \\ & - \underset{(0.1280)}{0.7721}\,av - \underset{(0.0275)}{0.2321}\,temp - \underset{(0.0060)}{0.0658}\,sts \end{aligned} \qquad \textbf{(4.17)}$$

$R^2 = 0.64$

$$
\begin{aligned}
E(\ln kcyc5) = & -\underset{(0.3353)}{7.4491} - \underset{(0.1121)}{0.4308}\,binder1 - \underset{(0.0417)}{0.0218}\,binder2 - \underset{(0.0238)}{0.0574}\,binder3 \\
& - \underset{(0.0169)}{0.0562}\,binder4 - \underset{(0.0804)}{0.2470}\,comp1 + \underset{(0.0446)}{0.1725}\,comp2 + \underset{(0.1000)}{0.4810}\,grad \\
& + \underset{(0.0255)}{0.1365}\,av + \underset{(0.0055)}{0.0384}\,temp + \underset{(0.0012)}{0.0130}\,sts + \underset{(0.0781)}{0.0477}\,comp1 \cdot grad \\
& - \underset{(0.0440)}{0.1513}\,comp2 \cdot grad
\end{aligned} \qquad \textbf{(4.18)}
$$

$R^2 = 0.65$

$$
\begin{aligned}
E(\ln G) = & \underset{(0.2272)}{8.2761} - \underset{(0.0592)}{0.0047}\,binder1 - \underset{(0.0237)}{0.1508}\,binder2 - \underset{(0.0147)}{0.0391}\,binder3 \\
& + \underset{(0.0113)}{0.1483}\,binder4 + \underset{(0.0544)}{0.1365}\,comp1 - \underset{(0.0283)}{0.1150}\,comp2 - \underset{(0.0311)}{0.1706}\,cond \\
& - \underset{(0.0531)}{0.3011}\,grad - \underset{(0.0187)}{0.0490}\,av - \underset{(0.0041)}{0.0654}\,temp
\end{aligned} \qquad \textbf{(4.19)}
$$

$R^2 = 0.84$

Figure 4.26 through Figure 4.28 present the residual plots for the regression analysis of pooled shear tests.

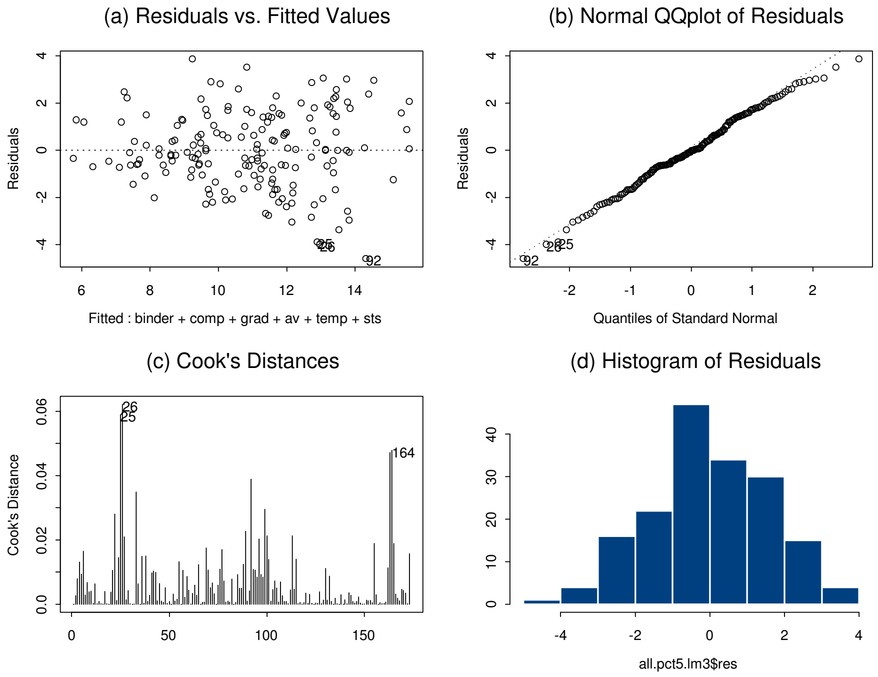


Figure 4.26: Residual plots of Ln(pct5). (Pooled Shear Tests)

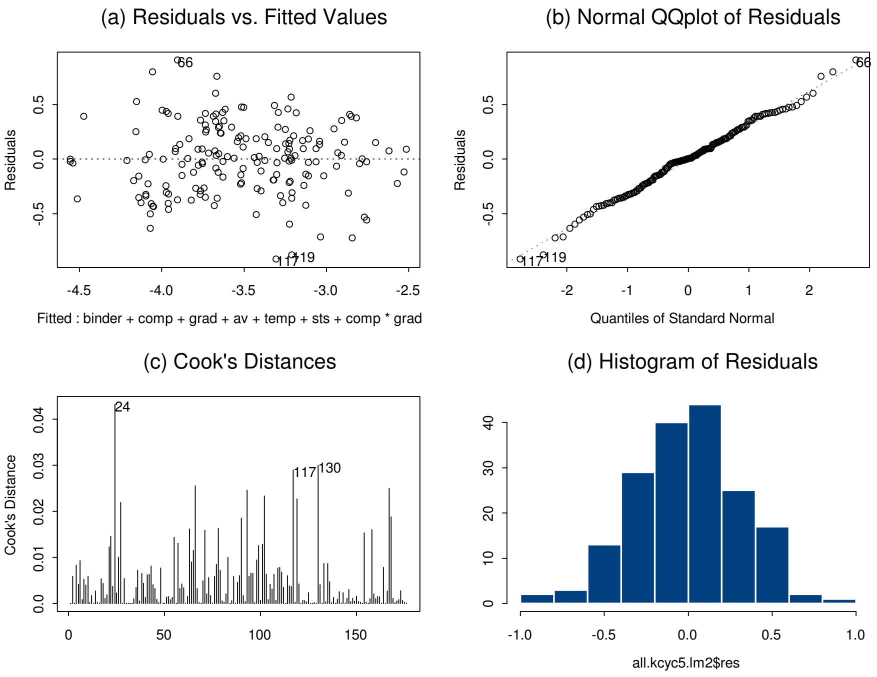


Figure 4.27: Residual plots of Ln(kcyc5) (Pooled Shear Tests).

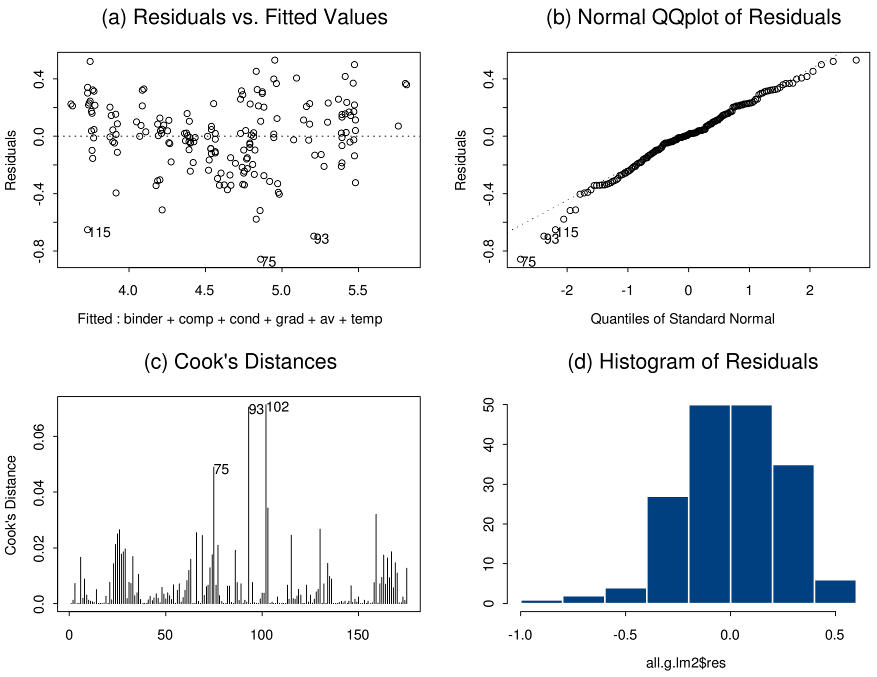


Figure 4.28: Residual plots of LnG. (Pooled Shear Tests).

4.8. Summary of Factor Identification

A main-effect summary table (Figure 4.5) was developed based on quantitative and qualitative analyses to identify the significant factors of the study. This table describes the four analyses performed in this study.

In the table, the more blocks checked and cross-hatched for a variable, the more important or significant it is. Although this process is somewhat subjective, the factors identified as significant closely match the covariates selected for regression analysis using Mallow's C_p criterion. A summary of the factor identification process includes:

- The temperature effect on shear performance is apparent and very important to all three response variables: Cycles to 5 Percent PSS, PSS at 5,000 Cycles, and G.
- The air-void content effect is most significant for Cycles to 5 Percent PSS and PSS at 5,000 Cycles.
- The aging effect is important for G^* and only somewhat important for Cycles to 5 Percent PSS.
- The compaction method is somewhat important for all the response variables.
- The gradation effect is significant for mix stiffness G. Dense-graded mixes showed higher stiffnesses than the gap-graded mixes.
- Binder type has a distinct effect on all the response variables.

4.9. Summary of Regression Analysis

The regression models are summarized in Tables 4.5 through 4.7. Given that a partial factorial experimental design was followed, extrapolations or inferences of model predictions beyond the data range should be undertaken with caution.

Table 4.5: Regression Models for ln Cycles to 5 Percent Permanent Shear Strain

Test	Regression Model	R^2
Temperature Effect (FMLC)	$E(\ln pct5) = \underset{(1.7298)}{28.9019} - \underset{(0.2564)}{0.5919}\, binder1 - \underset{(0.1451)}{1.1299}\, binder2 - \underset{(0.1076)}{0.3321}\, binder3$ $- \underset{(0.0749)}{0.0166}\, binder4 - \underset{(0.0318)}{0.2316}\, temp - \underset{(0.0064)}{0.0680}\, sts$	0.72
Air-void Content Effect (FMLC)	$E(\ln pct5) = \underset{(2.3049)}{29.8023} - \underset{(0.3538)}{0.7143}\, binder1 - \underset{(0.1871)}{0.9716}\, binder2 - \underset{(0.1357)}{0.2487}\, binder3$ $- \underset{(0.0938)}{0.0459}\, binder4 - \underset{(0.1409)}{0.8506}\, av - \underset{(0.0412)}{0.2387}\, temp$	0.67
Aging Effect (FMLC)	$E(\ln pct5) = \underset{(2.2149)}{22.5692} - \underset{(0.3593)}{0.9385}\, binder1 - \underset{(0.1946)}{0.9770}\, binder2 - \underset{(0.1481)}{0.1556}\, binder3$ $- \underset{(0.1040)}{0.1307}\, binder4 - \underset{(0.0439)}{0.2010}\, temp$	0.53
Compaction Effect (FMFC+FMLC+ LMLC)	$E(\ln pct5) = \underset{(0.3330)}{12.3973} + \underset{(0.4465)}{1.6453}\, binder1 - \underset{(0.2888)}{1.3880}\, binder2 + \underset{(0.1749)}{0.0328}\, binder3$ $- \underset{(0.1311)}{0.0366}\, binder4 + \underset{(0.4773)}{0.6144}\, comp1 - \underset{(0.2060)}{0.4584}\, comp2$	0.62
Gradation Effect (LMLC)	$E(\ln pct5) = \underset{(0.2410)}{11.7599} - \underset{(0.2965)}{2.2128}\, binder1 - \underset{(0.1696)}{0.4199}\, binder2 - \underset{(0.2388)}{0.2848}\, grad$	0.86
Pooled Shear Tests (FMFC+FMLC+ LMLC)	$E(\ln pct5) = \underset{(1.6884)}{32.6002} + \underset{(0.3948)}{0.2724}\, binder1 - \underset{(0.1597)}{0.6457}\, binder2 - \underset{(0.0987)}{0.0650}\, binder3$ $+ \underset{(0.0755)}{0.1139}\, binder4 + \underset{(0.3965)}{0.7332}\, comp1 - \underset{(0.1989)}{0.5516}\, comp2 - \underset{(0.3576)}{0.9076}\, grad$ $- \underset{(0.1280)}{0.7721}\, av - \underset{(0.0275)}{0.2321}\, temp - \underset{(0.0060)}{0.0658}\, sts$	0.64

Table 4.6: Regression Models for ln Permanent Shear Strain at 5,000 Cycles

Test	Regression Model	R^2
Temperature Effect (FMLC)	$E(\ln kcyc5) = -\underset{(0.3306)}{6.7512} + \underset{(0.0490)}{0.1971}\,binder1 + \underset{(0.0281)}{0.2637}\,binder2 + \underset{(0.0206)}{0.0389}\,binder3$ $+\underset{(0.0143)}{0.0075}\,binder4 + \underset{(0.0061)}{0.0413}\,temp + \underset{(0.0012)}{0.0128}\,sts$	0.74
Air-void Content Effect (FMLC)	$E(\ln kcyc5) = -\underset{(0.4458)}{6.8575} + \underset{(0.0705)}{0.2029}\,binder1 + \underset{(0.0363)}{0.1967}\,binder2 + \underset{(0.0261)}{0.0688}\,binder3$ $+\underset{(0.0179)}{0.0211}\,binder4 + \underset{(0.0278)}{0.1226}\,av + \underset{(0.0079)}{0.0456}\,temp$	0.67
Aging Effect (FMLC)	$E(\ln kcyc5) = -\underset{(0.4226)}{5.9345} + \underset{(0.0693)}{0.2690}\,binder1 + \underset{(0.0375)}{0.1877}\,binder2 + \underset{(0.0286)}{0.0339}\,binder3$ $+\underset{(0.0195)}{0.0165}\,binder4 + \underset{(0.0084)}{0.0422}\,temp$	0.57
Compaction Effect (FMFC+FMLC+ LMLC)	$E(\ln kcyc5) = -\underset{(0.0609)}{3.7031} - \underset{(0.0782)}{0.1471}\,binder1 + \underset{(0.0522)}{0.2596}\,binder2 + \underset{(0.0320)}{0.0126}\,binder3$ $-\underset{(0.0238)}{0.0017}\,binder4 - \underset{(0.0850)}{0.2266}\,comp1 + \underset{(0.0377)}{0.0934}\,comp2$	0.62
Gradation Effect (LMLC)	$E(\ln kcyc5) = -\underset{(0.0476)}{3.7107} + \underset{(0.0582)}{0.3713}\,binder1 + \underset{(0.0340)}{0.0812}\,binder2 + \underset{(0.0468)}{0.1556}\,grad$	0.83
Pooled Shear Tests (FMFC+FMLC+ LMLC)	$E(\ln kcyc5) = -\underset{(0.3353)}{7.4491} - \underset{(0.1121)}{0.4308}\,binder1 - \underset{(0.0417)}{0.0218}\,binder2 - \underset{(0.0238)}{0.0574}\,binder3$ $-\underset{(0.0169)}{0.0562}\,binder4 - \underset{(0.0804)}{0.2470}\,comp1 + \underset{(0.0446)}{0.1725}\,comp2 + \underset{(0.1000)}{0.4810}\,grad$ $+\underset{(0.0255)}{0.1365}\,av + \underset{(0.0055)}{0.0384}\,temp + \underset{(0.0012)}{0.0130}\,sts + \underset{(0.0781)}{0.0477}\,comp1 \cdot grad$ $-\underset{(0.0440)}{0.1513}\,comp2 \cdot grad$	0.65

Table 4.7: Regression Models for Resilient Shear Modulus (G*)

Test	Regression Model	R^2
Temperature Effect (FMLC)	$E(\ln G) = \underset{(0.2072)}{8.1841} - \underset{(0.0339)}{0.3045}\,binder1 - \underset{(0.0187)}{0.2330}\,binder2 - \underset{(0.0139)}{0.1009}\,binder3$ $+\underset{(0.0096)}{0.1167}\,binder4 - \underset{(0.0041)}{0.0711}\,temp$	0.90
Air-void Content Effect (FMLC)	$E(\ln G) = \underset{(0.3047)}{8.5547} - \underset{(0.0462)}{0.1935}\,binder1 - \underset{(0.0249)}{0.2171}\,binder2 - \underset{(0.0178)}{0.0774}\,binder3$ $+\underset{(0.0123)}{0.0993}\,binder4 - \underset{(0.0187)}{0.0632}\,av - \underset{(0.0054)}{0.0700}\,temp$	0.89
Aging Effect (FMLC)	$E(\ln G) = \underset{(0.2835)}{8.0273} - \underset{(0.0471)}{0.2669}\,binder1 - \underset{(0.0251)}{0.2726}\,binder2 - \underset{(0.0190)}{0.1133}\,binder3$ $+\underset{(0.0131)}{0.1260}\,binder4 - \underset{(0.0303)}{0.1648}\,cond - \underset{(0.0056)}{0.0639}\,temp$	0.90
Compaction Effect (FMFC+FMLC+ LMLC)	$E(\ln G) = \underset{(0.0375)}{4.7188} - \underset{(0.0502)}{0.1396}\,binder1 - \underset{(0.0337)}{0.3015}\,binder2 - \underset{(0.0203)}{0.0717}\,binder3$ $+\underset{(0.0154)}{0.1443}\,binder4 + \underset{(0.0518)}{0.1397}\,comp1 - \underset{(0.0236)}{0.1380}\,comp2$	0.89
Gradation Effect (LMLC)	$E(\ln G) = \underset{(0.0505)}{4.4254} - \underset{(0.0643)}{0.3533}\,binder1 - \underset{(0.0352)}{0.0007}\,binder2 - \underset{(0.0516)}{0.2422}\,grad$	0.77
Pooled Shear Tests (FMFC+FMLC+ LMLC)	$E(\ln G) = \underset{(0.2272)}{8.2761} - \underset{(0.0592)}{0.0047}\,binder1 - \underset{(0.0237)}{0.1508}\,binder2 - \underset{(0.0147)}{0.0391}\,binder3$ $+\underset{(0.0113)}{0.1483}\,binder4 + \underset{(0.0544)}{0.1365}\,comp1 - \underset{(0.0283)}{0.1150}\,comp2 - \underset{(0.0311)}{0.1706}\,cond$ $-\underset{(0.0531)}{0.3011}\,grad - \underset{(0.0187)}{0.0490}\,av - \underset{(0.0041)}{0.0654}\,temp$	0.84

4.9.1 Cycles to 5 Percent Permanent Shear Strain

Figure 4.29 and Figure 4.30 schematically summarize the regression models listed in Table 4.5. Evaluations of these data indicate the following:

- The ranking of Cycles to 5 Percent PSS of the binders from best performance to poorest under all effects (except compaction) is in the order listed below for the FMLC specimens.
  1. AR4000-D
  2. MAC15-G
  3. RAC-G
  4. MB4-G
  5. MB15-G
- This order changes only for compaction effect as follows:
  1. MAC15-G
  2. MB4-G
  3. AR4000-D
  4. RAC-G
  5. MB15-G

4.9.2 PSS at 5,000 Cycles

Figure 4.31 and Figure 4.32 schematically summarize the regression models for PSS at 5,000 Cycles using the regression equations shown in Table 4.6. The following are observed, which is consistent with Cycles to 5 Percent PSS:

- The ranking of PSS at 5,000 Cycles for the binders from best performance to worst under all effects (except compaction) is in the order listed below for the FMLC specimens.
  1. AR4000-D
  2. MAC15-G
  3. RAC-G
  4. MB4-G
  5. MB15-G
- This order changes only for compaction effect as follows:
  1. MAC15-G
  2. AR4000-D
  3. RAC-G
  4. MB4-G
  5. MB15-G

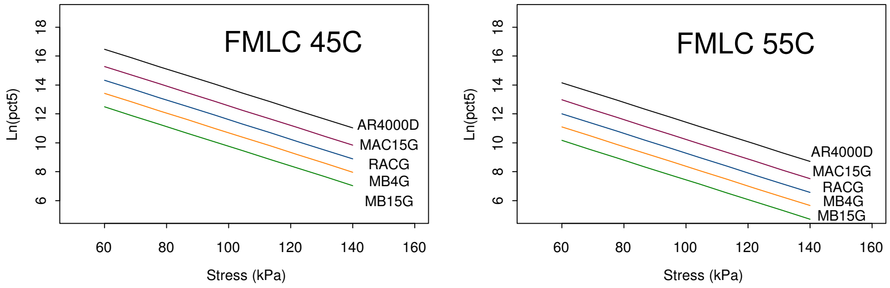
4.9.3 Resilient Shear Modulus *(G^*)*

Figure 4.33 and Figure 4.34 schematically summarize the regression models for Resilient Shear Modulus *(G^*)* as in Table 4.7. The following are observed:

- The ranking of G^* for the binders from stiffest to least stiff under all effects (except compaction) is in the order listed below for the FMLC specimens.
    1. AR4000-D
    2. RAC-G
    3. MAC15-G
    4. MB4-G
    5. MB15-G
- This order changes only for compaction effect as follows:
    1. RAC-G
    2. AR4000-D
    3. MAC15-G
    4. MB4-G
    5. MB15-G

(a) Temperature Effect

(b) Temperature Effect



(c) Air-Void Content Effect

(d) Air-Void Content Effect

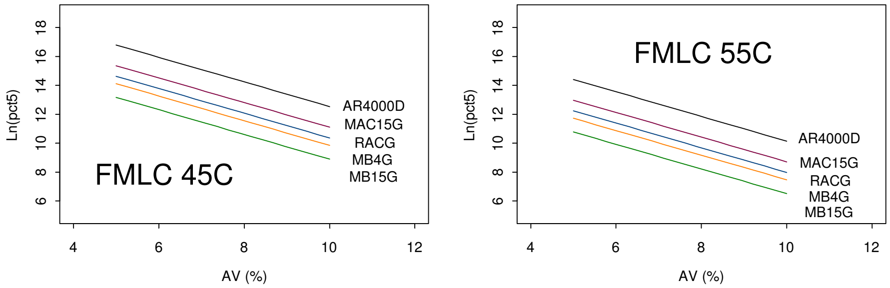


Figure 4.29: Schematic summary of Cycles to 5 Percent PSS regression models – Part A.

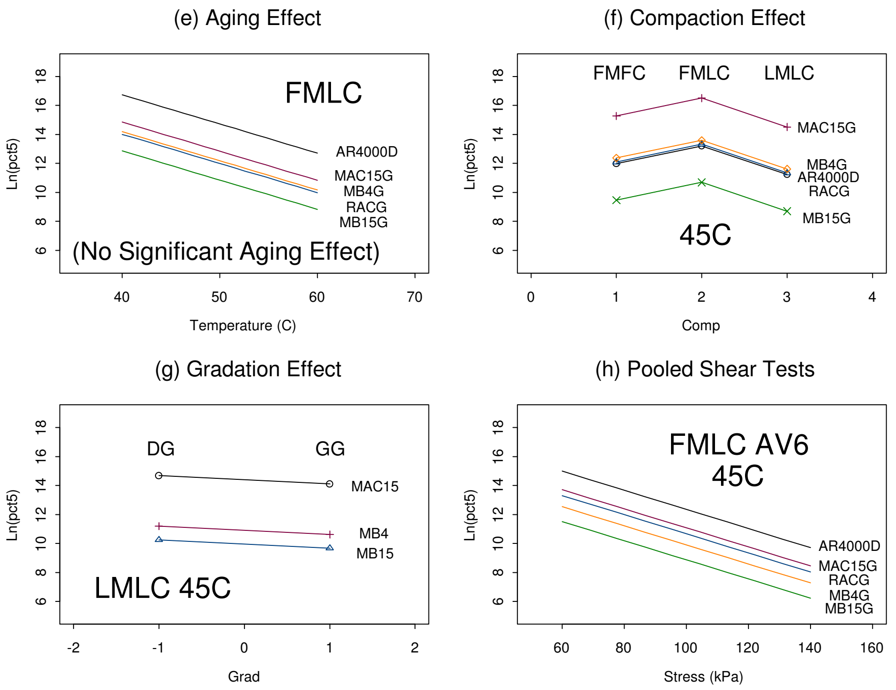


Figure 4.30: Schematic summary of Cycles to 5 Percent PSS regression models – Part B.

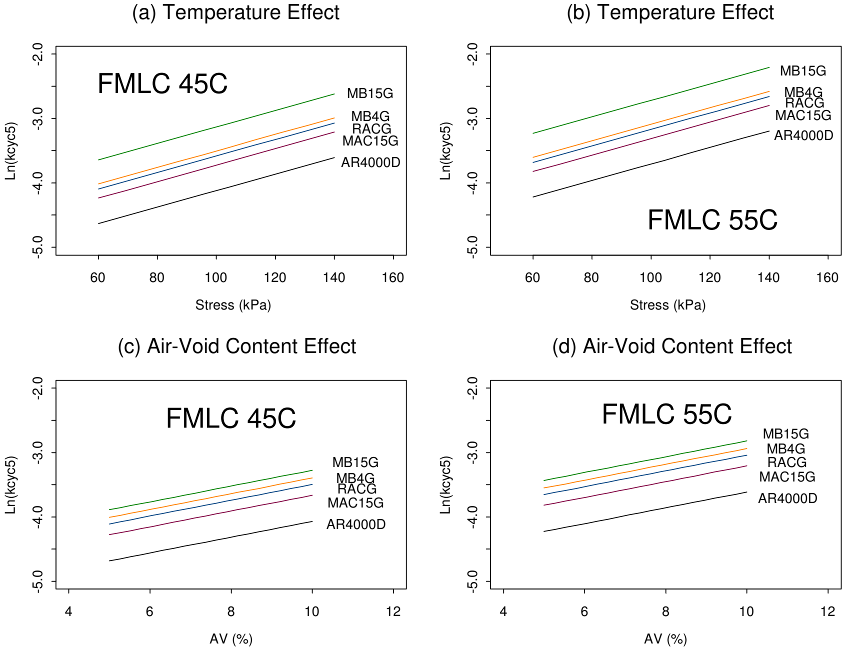
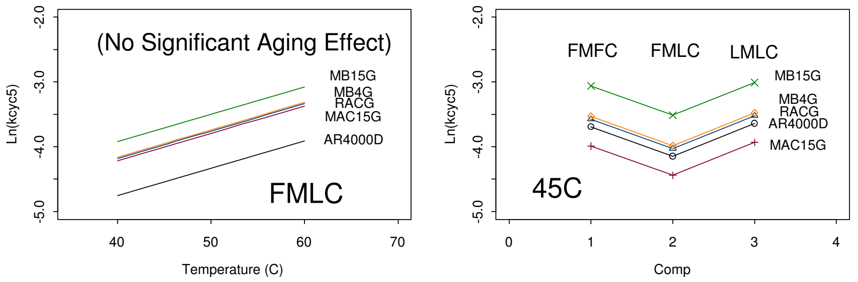
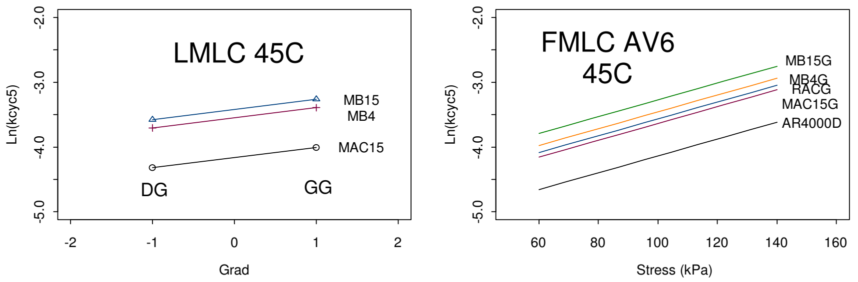


Figure 4.31: Schematic summary of PSS at 5,000 Cycles regression models – Part A.



(e) Aging Effect

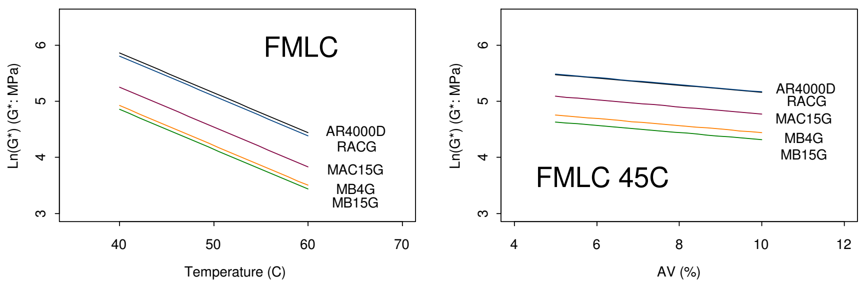
(f) Compaction Effect



(g) Gradation Effect

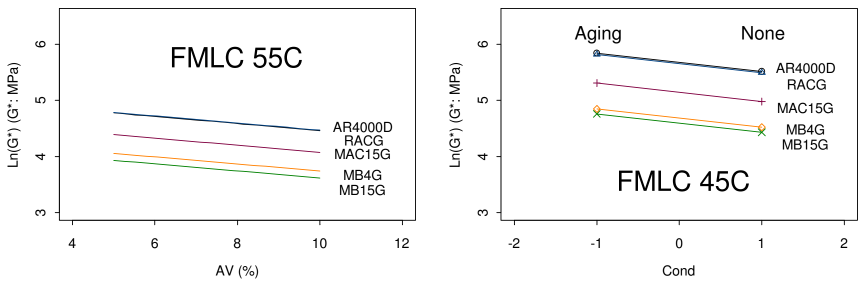
(h) Pooled Shear Tests

Figure 4.32: Schematic summary of PSS at 5,000 Cycles regression models – Part B.



(a) Temperature Effect

(b) Air-Void Content Effect



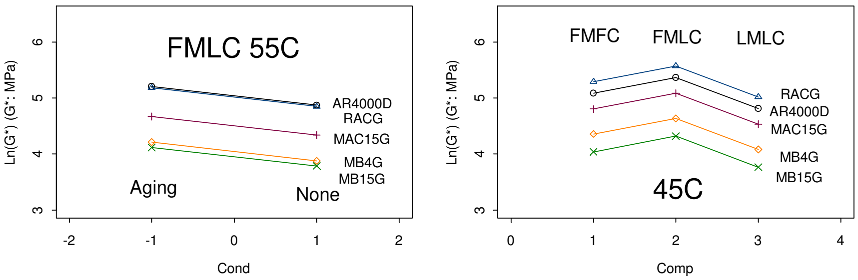
(c) Air-Void Content Effect

(d) Aging Effect

Figure 4.33: Schematic summary of Resilient Shear Modulus (G*) regression models – Part A.

(e) Aging Effect

(f) Compaction Effect



(g) Gradation Effect

(h) Pooled Shear Tests

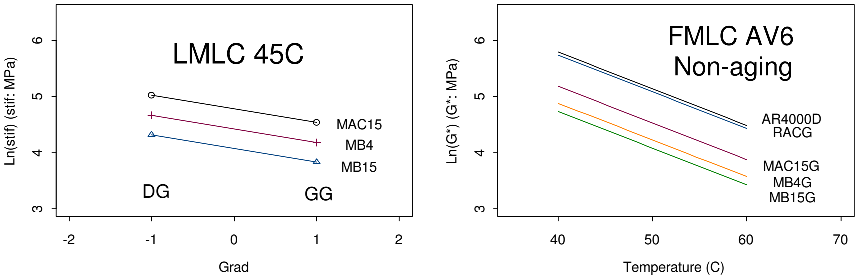


Figure 4.34: Schematic summary of Resilient Shear Modulus (G*) regression models – Part B.

In Figure 4.29 through Figure 4.34 (a) through (f) results were calculated using the regression equation from the associated experiment, as shown in Table 4.5 through Table 4.7, and (g) and (h) results were calculated using the pooled shear test results equations in the tables.

4.10. Weibull Analysis

Two-stage Weibull analysis was briefly studied on selected shear test results. The data can be plotted in terms of the double natural logarithm ln (ln taken twice) of the PSS versus the number of shear repetitions in the test. A more detailed analysis of the Weibull parameters for all of the core test results will be included in the second-level analysis report to follow. Potentially, a three-stage Weibull model may be discussed.

When plotted as a double log of PSS at 5,000 Cycles versus log of Cycles to 5 Percent PSS, the deformation curve for a shear permanent deformation test (RSST) typically consists of two (Figure 4.35 and Figure 4.36) or three stages (to be discussed in the second-level report), namely:

1. Stage I, an initial stage;
2. Stage II, deformation, during which there is a steady rate of shear deformation versus repetitions; and

3. Stage III, potential tertiary flow, during which the rate of shear deformation versus repetitions is greater than in Stage II.

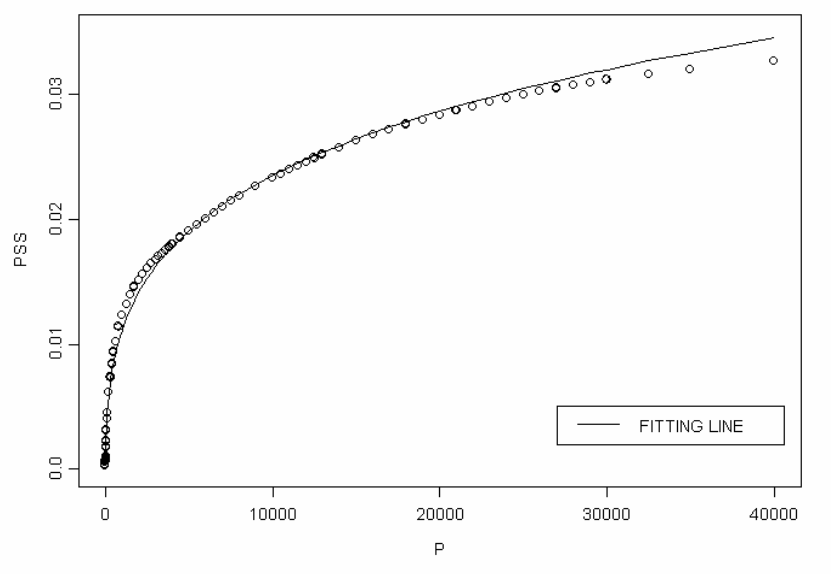


Figure 4.35: Two-Stage Weibull fitting for RSST-CH test result.

These three stages can be analyzed using a three-stage Weibull equation (3, 5); in this study it was used to evaluate each shear test. The associated shear parameters that define the three-stage Weibull fatigue curve are:

- Six parameters taken directly from the curve: $\ln\alpha_1$, β_1, $\ln\alpha_2$, β_2, $\ln\alpha_3$, β_3; and
- Two parameters derived from the curve, i.e., the repetitions at which the transitions between Stages I and II, and Stage II and Stage III occur: n_1, n_2, respectively.

As shown in Figure 4.37, the Ln(PSS at 5,000 Cycles) and the Ln(Cycles to 5 Percent PSS) are highly negatively-correlated with correlation = -0.951. It might imply that for *ranking mix performance*, for mixes with polymer-modified binders or for mixes that take more than 5,000 cycles to reach 5 percent permanent shear strain, the RSST can be stopped at 5,000 cycles as specified in AASHTO T320.

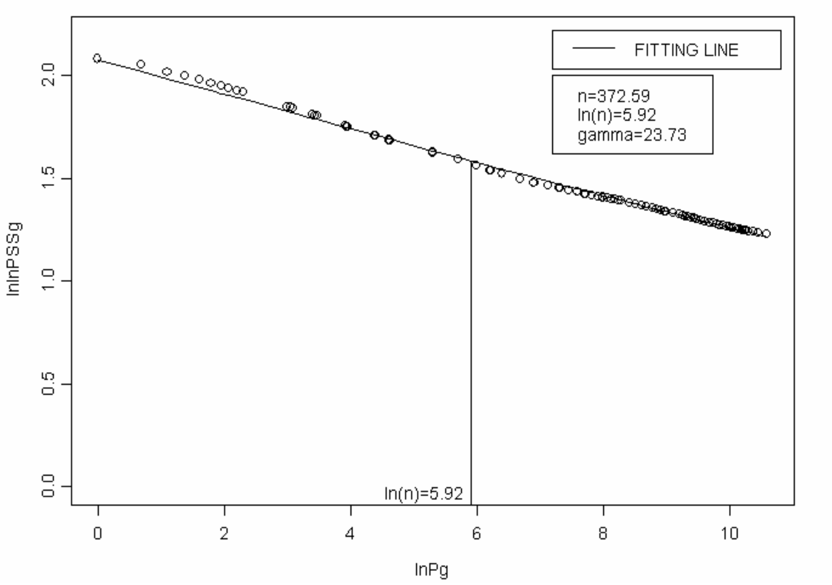


Figure 4.36: PSS Correlation.

$$\begin{cases} PSS = \exp\left(-\alpha_1 n^{\beta_1}\right) & ,0 < n \le n_0 \\ PSS = \exp\left(-\alpha_2 (n-\gamma)^{\beta_2}\right) & ,n > n_0 \end{cases} \qquad \textbf{(4.20)}$$

where *PSS* is the Permanent Shear Strain and *n* is number of loading repetitions.

Fitting results:

α_1=exp(2.075632)=7.9696

α_2=exp(2.039126)=7.6839

β_1=−0.0832

β_2=−0.0779

γ=23.73

n_0=372.59

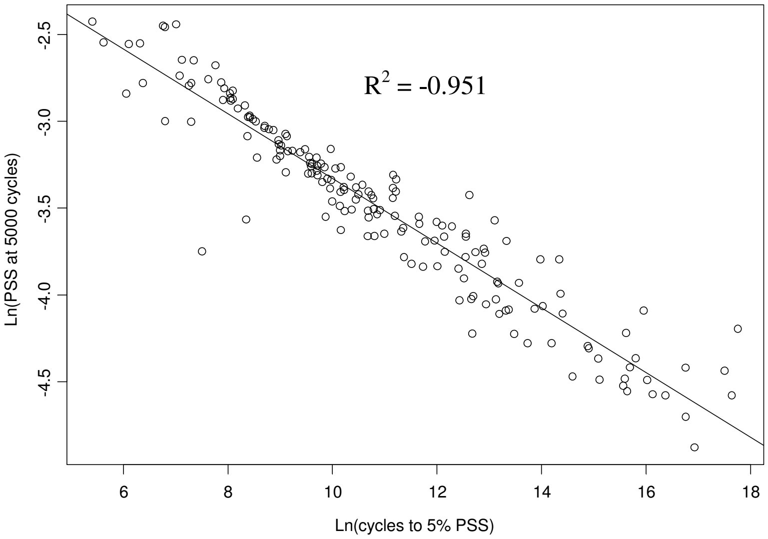


Figure 4.37: Correlation between PSS at 5,000 Cycles and Cycles to 5 Percent PSS.

4.11. Second-Level Analysis

Second-level analysis reports will be prepared on completion of HVS testing, laboratory testing, and forensic evaluations. These reports will include:

- As-built layer thicknesses of the HVS sections;
- Backcalculation of moduli from deflection measurements (RSD, MDD, and FWD);
- Verification of data collected from in-depth measurements with visual observations from test pits;
- Comparison of performance between HVS test sections;
- Comparison of performance between HVS test sections, after accounting for any differences in underlying support conditions;
- Comparisons of HVS test results with laboratory test results;
- Analysis of expected shear performance for a range of pavement structures containing dense-graded mixes with MB4, MB15, and MAC15 binders, and comparison with dense-graded mixes containing conventional and other modified binders;
- Analysis of the shear test results using a two- or three-stage Weibull analysis; and
- Final recommendations.

5. CONCLUSIONS

This summary report is one of a series of reports detailing the results of laboratory testing undertaken in conjunction with HVS testing to validate Caltrans overlay strategies for the overlay of cracked asphalt pavements. The report describes the results of the laboratory shear test study, carried out on five binders (AR4000, asphalt rubber, and three modified binders, MB4, MB4 with 15 percent recycled rubber (referred to as MB15), and MAC15TR (referred to as MAC15). The AR4000 was tested in dense-graded mixes only, and the asphalt rubber was tested only in gap-graded mixes (RAC-G). The MB4, MB15, and MAC15 were tested in both gap-graded and dense-graded mixes.

The Repeated Simple Shear Test (RSST) at Constant Height, AASHTO M320 Procedure C, was the only test used in this study. Across several experiments tests were performed at two temperatures, 45°C and 55°C (113°F and 131°F); three stress levels, two air-void contents, and with and without six days of long-term oven aging.

Test specimens were prepared from field mix compacted in the laboratory, mix prepared and compacted in the laboratory from aggregate and binder samples taken during construction of the HVS test sections, and field cores.

Binder tests were performed by the Federal Highway Administraton (FHWA).

Comparison of the laboratory and test section performance, including the results of a forensic investigation to be conducted when testing is complete, will be discussed in a second-level reports once the data from all of the studies has been collected. Findings and observations based on the laboratory shear study are discussed below. It should be noted that the study was focused on the use of modified binders in thin overlays on existing cracked asphalt surfaces, and not in structural layers.

5.1. Findings and Observations

Summary of Binder Tests

- Based on Bending Beam Rheometer (BBR) results from tests performed by the FHWA, the ranking of propensity to low temperature thermal cracking is listed below, from best to worst. Asphalt rubber binder was not tested.

    1. MB4
    2. MB15
    3. MAC15
    4. AR4000

- The order of thermal cracking potential is closely matched with the order of initial stiffness in the fatigue beam tests and flexural frequency sweep results; hence a mix with a higher initial stiffness might have a higher thermal cracking potential.
- The Dynamic Shear Rheometer (DSR) test results obtained from the FHWA indicated that:
    - MAC15 failed to meet the Superpave rutting specification.
    - MB4 and MB15 binders have better rutting resistance capacities than the AR4000 binder.
    - According to the Superpave specification, the ranking of fatigue resistance capacity is in the order listed below, from best to worst, which is the same ranking obtained for initial stiffness during laboratory mix fatigue tests, from highest to lowest stiffness.
        1. MB4
        2. MB15
        3. MAC15
        4. AR4000

Overall Summary of Repeated Simple Shear Test Results

- The binder type has an overall effect on all the response variables including permanent shear strain (PSS) at 5,000 Cycles, Cycles to 5 Percent PSS, and shear stiffness (G). As expected, the temperature effect on all three response variables is immediately apparent and significant. The other effects assessed (for comparison with HVS testing) reveal that:
    - Air-void content had a significant effect for Cycles to 5 Percent PSS and PSS at 5,000 Cycles but the effect was not significant for G.
    - Overall, the long-term aging effect is only minimally significant.
    - For MAC15, MB15, and MB4 mixes, all the response variables are significantly affected by the change from a gap gradation to a dense gradation, with expected rutting performance improved when the binders are used with the dense gradation as opposed to gap gradation.

Ranking of PSS at 5,000 Cycles, Cycles to 5 Percent PSS, and Shear Resilient modulus (G)

The ranking of these parameters under the various specimen preparation and testing conditions for RSST test used in this study is listed below from best to worst with respect to expected rutting performance.

Cycles to 5 Percent PSS	**PSS 5,000 Cycles**	**Resilient Shear Modulus *(G^*)***
1. AR4000-D	1. AR4000-D	1. AR4000-D
2. MAC15-G	2. MAC15-G	2. RAC-G
3. RAC-G	3. RAC-G	3. MAC15-G
4. MB4-G	4. MB4-G	4. MB4-G
5. MB15-G	5. MB15-G	5. MB15-G

Dense-Graded versus Gap-Graded Mixes

- The optimum binder contents used in the mix designs based on Hveem stabilometer tests for the MAC15, MB15, and MB4 dense-graded mixes (6.0, 6.0, and 6.3 percent respectively) were lower than the optimum binder contents used in the mix designs of the gap-graded mixes (7.4, 7.1, and 7.2 percent respectively), with all mix designs performed following standard Caltrans methods.
- Limited shear testing of modified binders in dense-graded mixes led to the following observation, based on testing of laboratory-mixed, laboratory-compacted specimens:
  - The PSS at 5,000 Cycles and Cycles to 5 Percent PSS results for the dense-graded mixes indicated generally better rutting performance than those of the corresponding gap-graded mixes.

5.2. Recommendations

No recommendations as to the use of modified binder mixes are made at this time. These recommendations will be included in the second-level analysis report that will be prepared and submitted on completion of all HVS and laboratory testing.

6. REFERENCES

1. **Generic Experimental Design for Product/Strategy Evaluation—Crumb Rubber Modified Materials**. 2005. State of California Department of Transportation (Caltrans), Sacramento, CA: Materials and Engineering Testing Services, Office of Flexible Pavement Materials. 55 pp.
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APPENDIX A: SUMMARY OF RESULTS

Table A.1: Summary of Shear Laboratory Test Results for AR4000 Mixes (Temperature Effect). (FMLC, AV = 6. ± 0.5%, AC=5.0%)

Specimen ID	Binder Type	Comp.	Grad.	AV (%)	AC (%)	Test Stress Level (kPa)	Test Temp. (^oC)	G (MPa)	n@5% PSS	PSS@ 5000cycles
DGAC-6-6-1-7045	AR-4000	FMLC	DG	5.8	5.0	70	45	173	46,078,399	0.010270
DGAC-6-14-3-7045	AR-4000	FMLC	DG	5.8	5.0	70	45	249	6,222,167	0.010514
DGAC-6-15-2-7045	AR-4000	FMLC	DG	6.4	5.0	70	45	268	1,058,305	0.016905
DGAC-6-10-2-7055	AR-4000	FMLC	DG	5.8	5.0	70	55	113	3,570,699	0.012686
DGAC-6-10-3-7055	AR-4000	FMLC	DG	6.5	5.0	70	55	111	251,616	0.017752
DGAC-6-11-1-7055	AR-4000	FMLC	DG	5.9	5.0	70	55	95	272,762	0.020137
DGAC-6-14-1-10045	AR-4000	FMLC	DG	6.5	5.0	100	45	222	10,110,764	0.010332
DGAC-6-14-2-10045	AR-4000	FMLC	DG	6.0	5.0	100	45	231	9,107,224	0.011206
DGAC-6-15-3-10045	AR-4000	FMLC	DG	5.9	5.0	100	45	393	25,944	0.026597
DGAC-6-16-1-10045	AR-4000	FMLC	DG	6.0	5.0	100	45	282	2,915,617	0.013628
DGAC-6-16-3-10045	AR-4000	FMLC	DG	6.1	5.0	100	45	342	5,746,161	0.010848
DGAC-6-8-1-10055	AR-4000	FMLC	DG	6.0	5.0	100	55	123	49,276	0.025691
DGAC-6-8-2-10055	AR-4000	FMLC	DG	6.0	5.0	100	55	126	86,808	0.022751
DGAC-6-8-3-10055	AR-4000	FMLC	DG	6.5	5.0	100	55	115	9,047	0.037099
DGAC-6-10-1-13045	AR-4000	FMLC	DG	5.9	5.0	130	45	296	418,300	0.017335
DGAC-6-11-2-13045	AR-4000	FMLC	DG	5.9	5.0	130	45	208	25,790	0.033128
DGAC-6-11-3-13045	AR-4000	FMLC	DG	5.8	5.0	130	45	268	164,903	0.021585
DGAC-6-4-1-13055	AR-4000	FMLC	DG	6.5	5.0	130	55	114	5,083	0.049719
DGAC-6-6-2-13055	AR-4000	FMLC	DG	6.1	5.0	130	55	101	8,105	0.040761
DGAC-6-6-3-13055	AR-4000	FMLC	DG	6.3	5.0	130	55	123	27,866	0.029691

Note:

1. FMLC: field-mixed laboratory-compacted; LMLC: laboratory-mixed laboratory compacted.
2. DG: dense-graded; GG:gap-graded.

Table A.2: Summary of Shear Laboratory Test Results for RAC Mixes (Temperature Effect).

(FMLC, AV = 6.0 ± 0.5%, AC=8%).

Specimen ID	Binder Type	Comp.	Grad.	AV (%)	AC (%)	Test Stress Level (kPa)	Test Temp. (^oC)	G (MPa)	n@5% PSS	PSS@ 5000 cycles
RACG-6-10-3-7045	ARB	FMLC	GG	6.9	8.0	70	45	278	59,533	0.026025
RACG-6-13-1-7045	ARB	FMLC	GG	6.0	8.0	70	45	340	924,374	0.013866
RACG-6-16-1-7045	ARB	FMLC	GG	6.0	8.0	70	45	262	19,000,787	0.012036
RACG-6-21-2-7045	ARB	FMLC	GG	6.5	8.0	70	45	224	408,923	0.023341
RACG-6-22-3-7045	ARB	FMLC	GG	5.9	8.0	70	45	231	51,876	0.029105
RACG-6-9-3-7045	ARB	FMLC	GG	6.4	8.0	70	45	218	1,461,806	0.013873
RACG-6-13-2-7055	ARB	FMLC	GG	6.5	8.0	70	55	156	116,446	0.027573
RACG-6-16-2-7055	ARB	FMLC	GG	5.7	8.0	70	55	95	21,369	0.042460
RACG-6-18-1-7055	ARB	FMLC	GG	5.8	8.0	70	55	100	161,947	0.027892
RACG-6-20-2-7055	ARB	FMLC	GG	5.3	8.0	70	55	151	82,473	0.026392
RACG-6-22-1-7055	ARB	FMLC	GG	6.4	8.0	70	55	92	70,552	0.036577
RACG-6-19-1-10045	ARB	FMLC	GG	6.4	8.0	100	45	256	399,546	0.023893
RACG-6-6-1-10045	ARB	FMLC	GG	6.5	8.0	100	45	177	6,043	0.048453
RACG-6-6-2-10045	ARB	FMLC	GG	6.4	8.0	100	45	251	6,000	0.047912
RACG-6-17-3-10055	ARB	FMLC	GG	5.7	8.0	100	55	102	70,057	0.031987
RACG-6-18-2-10055	ARB	FMLC	GG	6.3	8.0	100	55	82	4,392	0.051036
RACG-6-22-2-10055	ARB	FMLC	GG	5.9	8.0	100	55	122	4,804	0.050382
RACG-6-17-1-13045	ARB	FMLC	GG	6.4	8.0	130	45	183	115,428	0.028685
RACG-6-20-1-13045	ARB	FMLC	GG	5.8	8.0	130	45	287	43,624	0.029713
RACG-6-20-2-13045	ARB	FMLC	GG	5.5	8.0	130	45	272	4,546	0.050950
RACG-6-21-3-13045	ARB	FMLC	GG	6.4	8.0	130	45	206	25,913	0.038179
RACG-6-17-2-13055	ARB	FMLC	GG	6.3	8.0	130	55	153	16,605	0.036441
RACG-6-18-3-13055	ARB	FMLC	GG	6.1	8.0	130	55	83	1,482	0.061992
RACG-6-19-3-13055	ARB	FMLC	GG	6.2	8.0	130	55	105	13,842	0.036825

Note: FMLC:1. field-mixed laboratory-compacted; LMLC: laboratory-mixed laboratory compacted; 2. DG: dense-graded; GG:gap-graded.

Table A.3: Summary of Shear Laboratory Test Results for MAC15 Mixes (Temperature Effect).
(FMLC, AV = 6.0 ± 0.5%, AC=7.4%).

Specimen ID	Binder Type	Comp.	Grad.	AV (%)	AC (%)	Test Stress Level (kPa)	Test Temp. (^{o}C)	G (MPa)	n@5% PSS	PSS@ 5000 cycles
MAC15-6-13-3-7045	MAC15	FMLC	GG	5.5	7.4	70	45	162	40,070,646	0.011830
MAC15-6-1-3-7045	MAC15	FMLC	GG	5.7	7.4	70	45	176	19,114,642	0.009073
MAC15-6-15-3-7045	MAC15	FMLC	GG	6.4	7.4	70	45	175	6,089,300	0.014695
MAC15-6-9-3-7045	MAC15	FMLC	GG	6.5	7.4	70	45	197	7,304,479	0.012701
MAC15-6-10-1-7055	MAC15	FMLC	GG	5.9	7.4	70	55	70	282,137	0.022781
MAC15-6-10-3-7055	MAC15	FMLC	GG	5.8	7.4	70	55	69	341,817	0.023404
MAC15-6-11-2-7055	MAC15	FMLC	GG	6.0	7.4	70	55	49	74,117	0.033185
MAC15-6-11-3-10045	MAC15	FMLC	GG	6.0	7.4	100	45	77	44,152	0.033211
MAC15-6-15-2-10045	MAC15	FMLC	GG	5.9	7.4	100	45	55	217,422	0.027160
MAC15-6-9-1-10045	MAC15	FMLC	GG	5.7	7.4	100	45	178	1,807,288	0.016438
MAC15-6-2-3-10055	MAC15	FMLC	GG	6.3	7.4	100	55	48	1,546	0.070742
MAC15-6-6-3-10055	MAC15	FMLC	GG	6.3	7.4	100	55	72	16,274	0.040413
MAC15-6-7-2-10055	MAC15	FMLC	GG	6.2	7.4	100	55	66	9,225	0.045680
MAC15-6-11-1-13045	MAC15	FMLC	GG	6.5	7.4	130	45	70	2,048	0.063363
MAC15-6-8-1-13045	MAC15	FMLC	GG	6.2	7.4	130	45	157	385,830	0.021900
MAC15-6-8-3-13045	MAC15	FMLC	GG	5.9	7.4	130	45	144	187,093	0.025595
MAC15-6-1-3-13055	MAC15	FMLC	GG	5.7	7.4	130	55	41	447	0.077662
MAC15-6-2-1-13055	MAC15	FMLC	GG	6.5	7.4	130	55	46	428	0.058382
MAC15-6-7-3-13055	MAC15	FMLC	GG	6.0	7.4	130	55	76	11,883	0.041680

Note:
1. FMLC: field-mixed laboratory-compacted; LMLC: laboratory-mixed laboratory compacted.
2. DG: dense-graded; GG:gap-graded.

Table A.4: Summary of Shear Laboratory Test Results for MB15 Mixes (Temperature Effect).
(FMLC, AV = 6.0 ± 0.5%, AC=7.1%).

Specimen ID	Binder Type	Comp.	Grad.	AV (%)	AC (%)	Test Stress Level (kPa)	Test Temp. (°C)	G (MPa)	n@5% PSS	PSS@ 5000 cycles
MB15-6-6-1-7045	MB15	FMLC	GG	6.9	7.1	70	45	80	34,680	0.034050
MB15-6-6-3-7045	MB15	FMLC	GG	6.3	7.1	70	45	74	23,359	0.037937
MB15-6-9-1-7045	MB15	FMLC	GG	6.1	7.1	70	45	78	18,166	0.035066
MB15-6-2-2-7055	MB15	FMLC	GG	6.5	7.1	70	55	59	7,560	0.039938
MB15-6-10-3-7055	MB15	FMLC	GG	5.9	7.1	70	55	50	3,128	0.056893
MB15-6-2-3-7055	MB15	FMLC	GG	6.5	7.1	70	55	22	492,011	0.028120
MB15-6-3-1-7055	MB15	FMLC	GG	6.0	7.1	70	55	51	85,441	0.026907
MB15-6-4-3-7055	MB15	FMLC	GG	5.8	7.1	70	55	37	320,841	0.014645
MB15-6-5-2-7055	MB15	FMLC	GG	6.4	7.1	70	55	52	7,912	0.043635
MB15-6-7-1-7055	MB15	FMLC	GG	6.5	7.1	70	55	56	8,531,076	0.016734
MB15-6-10-1-10045	MB15	FMLC	GG	6.3	7.1	100	45	78	2,630	0.062278
MB15-6-11-1-10045	MB15	FMLC	GG	5.8	7.1	100	45	69	48,279	0.031921
MB15-6-9-3-10045	MB15	FMLC	GG	5.7	7.1	100	45	80	3,265	0.059291
MB15-6-10-2-10055	MB15	FMLC	GG	6.3	7.1	100	55	53	895	0.085694
MB15-6-11-3-10055	MB15	FMLC	GG	5.7	7.1	100	55	43	3,276	0.056567
MB15-6-8-3-10055	MB15	FMLC	GG	6.0	7.1	100	55	44	1,189	0.064759
MB15-6-2-1-13045	MB15	FMLC	GG	6.2	7.1	130	45	81	859	0.086344
MB15-6-6-2-13045	MB15	FMLC	GG	6.5	7.1	130	45	80	1,108	0.086964
MB15-6-8-2-13045	MB15	FMLC	GG	5.5	7.1	130	45	84	2,351	0.068717
MB15-6-11-2-13055	MB15	FMLC	GG	5.8	7.1	130	55	60	1,239	0.070906
MB15-6-5-3-13055	MB15	FMLC	GG	5.9	7.1	130	55	39	223	0.088387
MB15-6-7-2-13055	MB15	FMLC	GG	5.5	7.1	130	55	54	1,415	0.061114

Note:

1. FMLC: field-mixed laboratory-compacted; LMLC: laboratory-mixed laboratory compacted.
2. DG: dense-graded; GG:gap-graded.

Table A.5: Summary of Shear Laboratory Test Results for MB4 Mixes (Temperature Effect).
(FMLC, AV = 6.0 ± 0.5%, AC=7.2%).

Specimen ID	Binder Type	Comp.	Grad.	AV (%)	AC (%)	Test Stress Level (kPa)	Test Temp. (^{o}C)	G (MPa)	n@5% PSS	PSS@ 5000cycles
MB4-6-1-4-7045	MB4	FMLC	GG	5.8	7.2	70	45	98	503,010	0.017837
MB4-6-5-3-7045	MB4	FMLC	GG	6.4	7.2	70	45	85	1,238,930	0.017178
MB4-6-7-2-7045	MB4	FMLC	GG	5.8	7.2	70	45	86	518,147	0.019745
MB4-6-15-1-7055	MB4	FMLC	GG	5.7	7.2	70	55	58	27,623	0.033518
MB4-6-16-1-7055	MB4	FMLC	GG	5.5	7.2	70	55	55	21,487	0.035499
MB4-6-2-1-7055	MB4	FMLC	GG	6.5	7.2	70	55	59	48,738	0.030014
MB4-6-1-2-10045	MB4	FMLC	GG	6.3	7.2	100	45	100	129,823	0.024905
MB4-6-2-3-10045	MB4	FMLC	GG	6.3	7.2	100	45	83	34,513	0.031734
MB4-6-5-1-10045	MB4	FMLC	GG	5.8	7.2	100	45	94	14,843	0.036867
MB4-6-12-1-10055	MB4	FMLC	GG	6.1	7.2	100	55	51	4,532	0.051366
MB4-6-12-3-10055	MB4	FMLC	GG	6.1	7.2	100	55	47	4,348	0.045655
MB4-6-7-3-10055	MB4	FMLC	GG	6.3	7.2	100	55	56	1,820	0.023518
MB4-6-3-3-13045	MB4	FMLC	GG	5.8	7.2	130	45	85	3,107	0.058447
MB4-6-4-2-13045	MB4	FMLC	GG	5.5	7.2	130	45	73	6,539	0.047531
MB4-6-7-1-13045	MB4	FMLC	GG	6.4	7.2	130	45	86	9,400	0.041901
MB4-6-3-1-13055	MB4	FMLC	GG	6.5	7.2	130	55	48	276	0.078451
MB4-6-3-2-13055	MB4	FMLC	GG	5.5	7.2	130	55	45	588	0.062037
MB4-6-5-2-13055	MB4	FMLC	GG	5.9	7.2	130	55	47	556	0.077945

Note:

1. FMLC: field-mixed laboratory-compacted; LMLC: laboratory-mixed laboratory compacted.
2. DG: dense-graded; GG:gap-graded.

Table A.6: Summary of Shear Laboratory Test Results for all Mixes (Air-Void Content Effect) (FMLC, AV = 9 ± 1%).

Specimen ID	Binder Type	Comp.	Grad.	AV (%)	AC (%)	Test Stress Level (kPa)	Test Temp. (^oC)	G (MPa)	n@5% PSS	PSS@ 5000 cycles
DGAC-69-3-2-7045	AR4000	FMLC	DG	9.4	5.0	70	45	252	2,186,262	0.011442
DGAC-69-3-3-7045	AR4000	FMLC	DG	9.5	5.0	70	45	220	5,929,144	0.011293
DGAC-69-1-1-7055	AR4000	FMLC	DG	9.0	5.0	70	55	76	25,459	0.030580
DGAC-69-1-3-7055	AR4000	FMLC	DG	9.5	5.0	70	55	72	4,131	0.054568
RACG-69-1-2-7045	ARB	FMLC	GG	9.2	8.0	70	45	169	189,749	0.023460
RACG-69-2-2-7045	ARB	FMLC	GG	8.8	8.0	70	45	158	16,341	0.037432
RACG-6-1-3-7055	ARB	FMLC	GG	9.4	8.0	70	55	70	18,987	0.038197
RACG-69-1-1-7055	ARB	FMLC	GG	9.2	8.0	70	55	77	27,352	0.034081
RACG-69-2-3-7055	ARB	FMLC	GG	8.8	8.0	70	55	73	13,055	0.042373
MAC15-9-3-2-7045	MAC15	FMLC	GG	8.6	7.4	70	45	147	19,981	0.035773
MAC15-9-8-2-7045	MAC15	FMLC	GG	8.6	7.4	70	45	115	9,008	0.046281
MAC15-9-4-1-7055	MAC15	FMLC	GG	9.1	7.4	70	55	63	7,133	0.047294
MAC15-9-7-1-7055	MAC15	FMLC	GG	8.5	7.4	70	55	64	5,195	0.040399
MB15-9-15-1-7045	MB15	FMLC	GG	9.2	7.1	70	45	73	17,708	0.038993
MB15-9-15-2-7045	MB15	FMLC	GG	9.0	7.1	70	45	79	14,934	0.038910
MB15-9-13-2-7055	MB15	FMLC	GG	8.5	7.1	70	55	47	1,475	0.049630
MB15-9-13-3-7055	MB15	FMLC	GG	8.7	7.1	70	55	47	2,717	0.056306
MB15-9-14-2-7055	MB15	FMLC	GG	9.2	7.1	70	55	138	4,238	0.028272
MB4-9-19-2-7045	MB4	FMLC	GG	9.1	7.2	70	45	78	527,488	0.019540
MB4-9-20-1-7045	MB4	FMLC	GG	9.1	7.2	70	45	64	14,370	0.039149
MB4-69-1-3-7055	MB4	FMLC	GG	9.1	7.2	70	55	72	4,131	0.054568
MB4-9-17-1-7055	MB4	FMLC	GG	8.6	7.2	70	55	46	3,609	0.053601
MB4-9-18-3-7055	MB4	FMLC	GG	9.1	7.2	70	55	54	3,145	0.056091
MB4-9-19-1-7055	MB4	FMLC	GG	8.6	7.2	70	55	60	8,259	0.043312

Note:

1. FMLC: field-mixed laboratory-compacted; LMLC: laboratory-mixed laboratory compacted. 2.DG: dense-graded; GG:gap-graded

Table A.7: Summary of Shear Laboratory Test Results for all Mixes (Aging Effect).
(FMLC, AV = 6 ± 0.5%).

Specimen ID	Binder Type	Comp.	Grad.	AV (%)	AC (%)	Test Stress Level (kPa)	Test Temp. (^{o}C)	G (MPa)	n@5% PSS	PSS@ 5000 cycles
DGAC-6-21-1-LT-7045	AR4000	FMLC	DG	5.9	5.0	70	45	480	12,957,636	0.010262
DGAC-6-21-3-LT-7045	AR4000	FMLC	DG	6.1	5.0	70	45	480	22,551,627	0.007604
DGAC-6-18-3-LT-7055	AR4000	FMLC	DG	6.3	5.0	70	55	191	538,053	0.016410
DGAC-6-19-1-LT-7055	AR4000	FMLC	DG	5.5	5.0	70	55	223	715,540	0.014614
RACG-6-8-2-LT-7045	ARB	FMLC	GG	6.4	8.0	70	45	102	897	0.049862
RACG-6-13-1-LT-7045	ARB	FMLC	GG	5.9	8.0	70	45	340	924,374	0.013866
RACG-6-13-2-LT-7055	ARB	FMLC	GG	6.5	8.0	70	55	156	116,446	0.027573
RACG-6-16-3-LT-7055	ARB	FMLC	GG	6.1	8.0	70	55	245	44,248	0.028600
MAC15-6-1-2-LT-7045	MAC15	FMLC	GG	5.8	7.4	70	45	91	16,526	0.038512
MAC15-6-2-1-LT-7045	MAC15	FMLC	GG	6.5	7.4	70	45	172	72,628	0.028884
MAC15-6-5-1-LT-7055	MAC15	FMLC	GG	5.8	7.4	70	55	119	14,708	0.038381
MAC15-6-5-2-LT-7055	MAC15	FMLC	GG	6.1	7.4	70	55	98	14,152	0.040559
MB15-6-12-2-LT-7045	MB15	FMLC	GG	6.0	7.1	70	45	90	315,458	0.017876
MB15-6-12-3-LT-7045	MB15	FMLC	GG	5.9	7.1	70	45	91	180,700	0.027282
MB15-6-12-1-LT-7055	MB15	FMLC	GG	5.7	7.1	70	55	63	54,675	0.029856
MB15-6-2-2-LT-7055	MB15	FMLC	GG	6.5	7.1	70	55	59	7,560	0.039938
MB4-6-10-1-LT-7045	MB4	FMLC	GG	5.5	7.2	70	45	100	245,601	0.021296
MB4-6-9-3-LT-7045	MB4	FMLC	GG	6.3	7.2	70	45	100	781,924	0.019624
MB4-6-10-2-LT-7055	MB4	FMLC	GG	5.6	7.2	70	55	68	283,823	0.025628
MB4-6-10-3-LT-7055	MB4	FMLC	GG	6.5	7.2	70	55	71	156,258	0.025026

Note:
1. FMLC: field-mixed laboratory-compacted; LMLC: laboratory-mixed laboratory compacted.
2. DG: dense-graded; GG:gap-graded.

Table A.8: Summary of Shear Laboratory Test Results for all Mixes (Compaction Effect). (FMLC&LMLC, AV = 6 ± 0.5%).

Specimen ID	Binder Type	Comp.	Grad.	AV (%)	AC (%)	Test Stress Level (kPa)	Test Temp. (^{o}C)	G (MPa)	n@5% PSS	PSS@ 5000 cycles
DGAC-FIELD-01-TL-7045	AR4000	FMFC	DG	5.6	5.0	70	45	161	1,732,691	0.018420
DGAC-FIELD-02-TL-7045	AR4000	FMFC	DG	6.7	5.0	70	45	214	125,081	0.021524
DGAC-FIELD-05-TL-7045	AR4000	FMFC	DG	6.3	5.0	70	45	193	2,788	0.060184
DGAC-LM-6-2-1-7045	AR4000	LMLC	DG	6.2	5.0	70	45	98	8,116	0.042107
DGAC-LM-6-2-2-7045	AR4000	LMLC	DG	6.1	5.0	70	45	97	7,872	0.044650
DGAC-LM-6-2-3-7045	AR4000	LMLC	DG	6.3	5.0	70	45	104	36,311	0.032639
RAC-LM-6-1-1-7045	ARB	LMLC	GG	5.7	8.0	70	45	143	31,352	0.036181
RAC-LM-6-1-2-7045	ARB	LMLC	GG	5.7	8.0	70	45	139	46,515	0.032539
RAC-LM-6-2-3-7045	ARB	LMLC	GG	5.7	8.0	70	45	209	646,689	0.016811
MAC15-LM-6-1-1-7045	MAC15	LMLC	GG	6.1	7.4	70	45	77	1,183,841	0.022451
MAC15-LM-6-1-2-7045	MAC15	LMLC	GG	6.0	7.4	70	45	81	611,185	0.016737
MAC15-LM-6-1-3-7045	MAC15	LMLC	GG	5.6	7.4	70	45	90	51,750,300	0.015055
MAC15-LM-6-3-2-7045	MAC15	LMLC	GG	5.9	7.4	70	45	93	616,304	0.024981
MB15-LM-6-2-2-7045	MB15	LMLC	GG	6.2	7.1	70	45	34	10,236	0.042000
MB15-LM-6-2-3-7045	MB15	LMLC	GG	6.2	7.1	70	45	51	21,105	0.033786
MB4-FIELD-24-TL-7045	MB4	FMFC	GG	7.1	7.2	70	45	74	74,487	0.035622
MB4-FIELD-25-TL-7045	MB4	FMFC	GG	6.3	7.2	70	45	68	70,284	0.033886
MB4-FIELD-26-TL-7045	MB4	FMFC	GG	6.1	7.2	70	45	60	303,840	0.032545
MB4-LM-6-1-2-7045	MB4	LMLC	GG	5.5	7.2	70	45	84	39,148	0.034497
MB4-LM-6-1-3-7045	MB4	LMLC	GG	5.7	7.2	70	45	74	283,016	0.026028
MB4-LM-6-2-3-7045	MB4	LMLC	GG	5.7	7.2	70	45	82	1,696,084	0.022477

Note:

1. FMLC: field-mixed laboratory-compacted; LMLC: laboratory-mixed laboratory compacted.
2. DG: dense-graded; GG:gap-graded.
3. All FMFC specimens are in Field Aged and Trafficked condition.

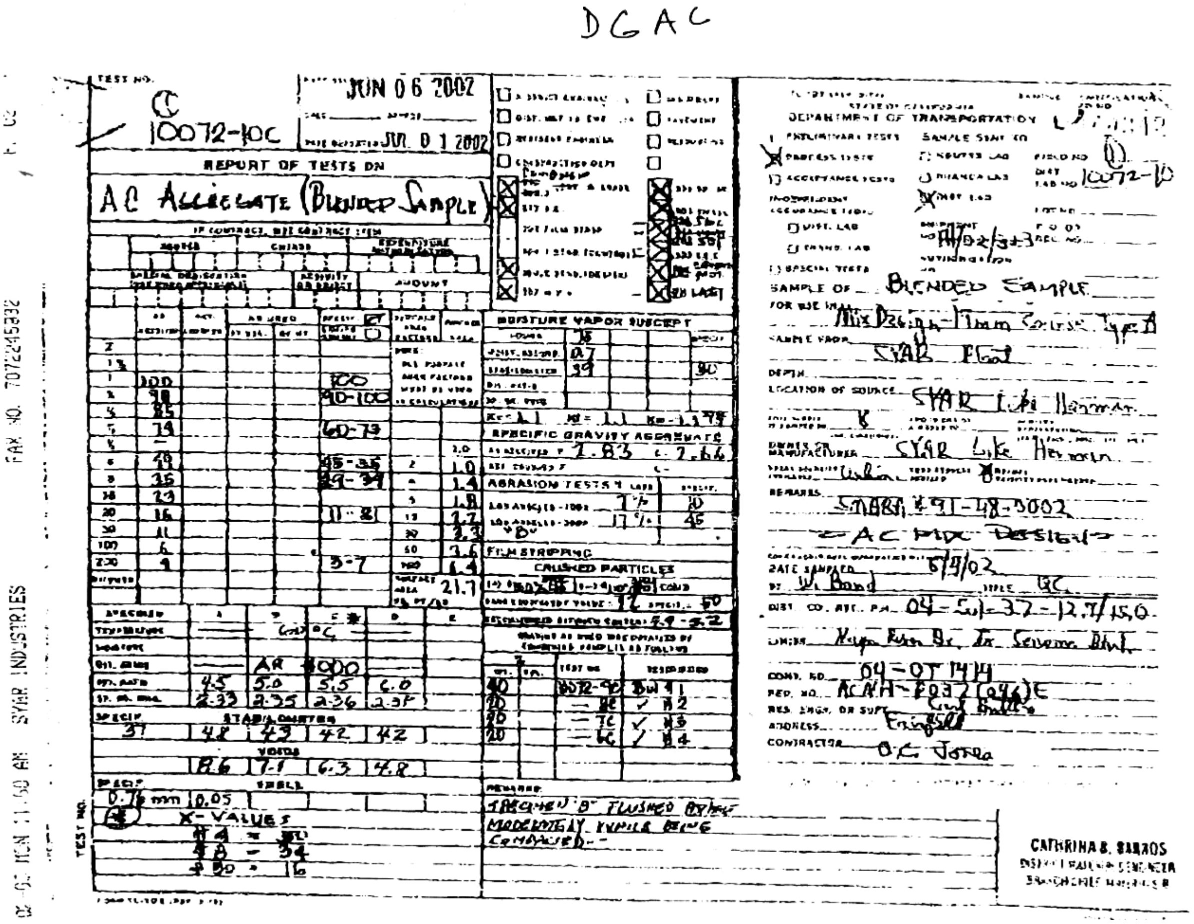
Table A.9: Summary of Shear Laboratory Test Results for all Mixes (Gradation Effect) (FMLC&LMLC, AV = 6 ± 0.5%).

Specimen ID	Binder Type	Comp.	Grad.	AV (%)	AC (%)	Test Stress Level (kPa)	Test Temp. (^{o}C)	G (MPa)	n@5% PSS	PSS@ 5000 cycles
MB4-DG-6-1-3-7045	MB4	LMLC	DG	5.6	6.3	70	45	91	19,407	0.028693
MB4-DG-6-3-1-7045	MB4	LMLC	DG	6.3	6.3	70	45	81	31,889	0.029908
MB4-DG-6-3-3-7045	MB4	LMLC	DG	6.2	6.3	70	45	91	100,053	0.021910
MB15-DG-6-1-1-7045	MB15	LMLC	DG	6.1	6.0	70	45	78	326,231	0.018156
MB15-DG-6-1-3-7045	MB15	LMLC	DG	6.3	6.0	70	45	91	43,389	0.025670
MB15-DG-6-2-1-7045	MB15	LMLC	DG	6.2	6.0	70	45	72	22,003	0.031358
MAC15-DG-6-1-1-7045	MAC15	LMLC	DG	6.2	6.0	70	45	162	6,554,338	0.012057
MAC15-DG-6-2-1-7045	MAC15	LMLC	DG	6.5	6.0	70	45	240	3,658,443	0.011243
MAC15-DG-6-2-3-7045	MAC15	LMLC	DG	6.3	6.0	70	45	207	2,983,215	0.013458

Note:

1. FMLC: field-mixed laboratory-compacted; LMLC: laboratory-mixed laboratory compacted.
2. DG: dense-graded; GG:gap-graded.

APPENDIX B: MIX DESIGN INFORMATION



DGAC

SYAR INDUSTRIES FAX NO. 7072245332 MON 11:50 AM P. 02

TEST NO. 10072-10C

JUN 06 2002

JUN 01 2002

REPORT OF TESTS ON

AC AGGREGATE (BLENDED SAMPLE)

2		
1½		
1	100	100
¾	98	90-100
½	85	
⅜	74	60-75
¼	—	
4	49	45-55
8	35	29-39
16	23	
30	16	11-21
50	11	
100	6	
200	4	3-7

SURFACE AREA 21.7

MOISTURE VAPOR SUSCEPT.

Kc = 1.1 Kf = 1.1 Km = 1.179

SPECIFIC GRAVITY AGGREGATE 2.83 2.66

ABRASION TESTS

LOS ANGELES - 100 REV. 7% 10

LOS ANGELES - 500 REV. 17% 45

"B"

FILM STRIPPING

CRUSHED PARTICLES

SAND EQUIVALENT VALUE: 72 SPECIF.: 50

RECOMMENDED BITUMEN CONTENT: 4.9 - 5.2

SPECIMEN	A	B	C*	D	E
TEST TEMP.	—	60 °C		—	
OIL GRADE	—	AR 4000			
OIL RATIO	4.5	5.0	5.5	6.0	
SP. GR.	2.33	2.35	2.36	2.38	
STABILOMETER (SPECIF. 37)	48	43	42	42	
VOIDS	8.6	7.1	6.3	4.8	
SWELL (SPECIF. 0.76 mm)	0.05				

X-VALUES

#4 = 52

#8 = 34

#200 = 16

WT.		TEST NO.	
40		10072-9C	BW #1
20		— 8C	✓ #2
20		— 7C	✓ #3
20		— 6C	✓ #4

REMARKS: SPECIMEN "B" FLUSHED ASPHALT MODERATELY WHILE BEING COMPACTED. –

STATE OF CALIFORNIA

DEPARTMENT OF TRANSPORTATION

☒ PROCESS TESTS

☐ ACCEPTANCE TESTS

☒ DIST. LAB

FIELD NO. D

DIST. LAB NO. 10072-10

SAMPLE OF BLENDED SAMPLE

FOR USE IN Mix Design - 19mm Coarse Type A

SAMPLE FROM SYAR Plant

LOCATION OF SOURCE SYAR Lake Herman

OWNER OR MANUFACTURER SYAR Lake Herman

REMARKS SMARA #91-48-0002

AC MIX DESIGN

DATE SAMPLED 5/9/02

BY W. Bond TITLE QC

DIST. CO. RTE. P.M. 04-Sol-37-12.7/15.0

LIMITS Napa River Br. to Sonoma Blvd.

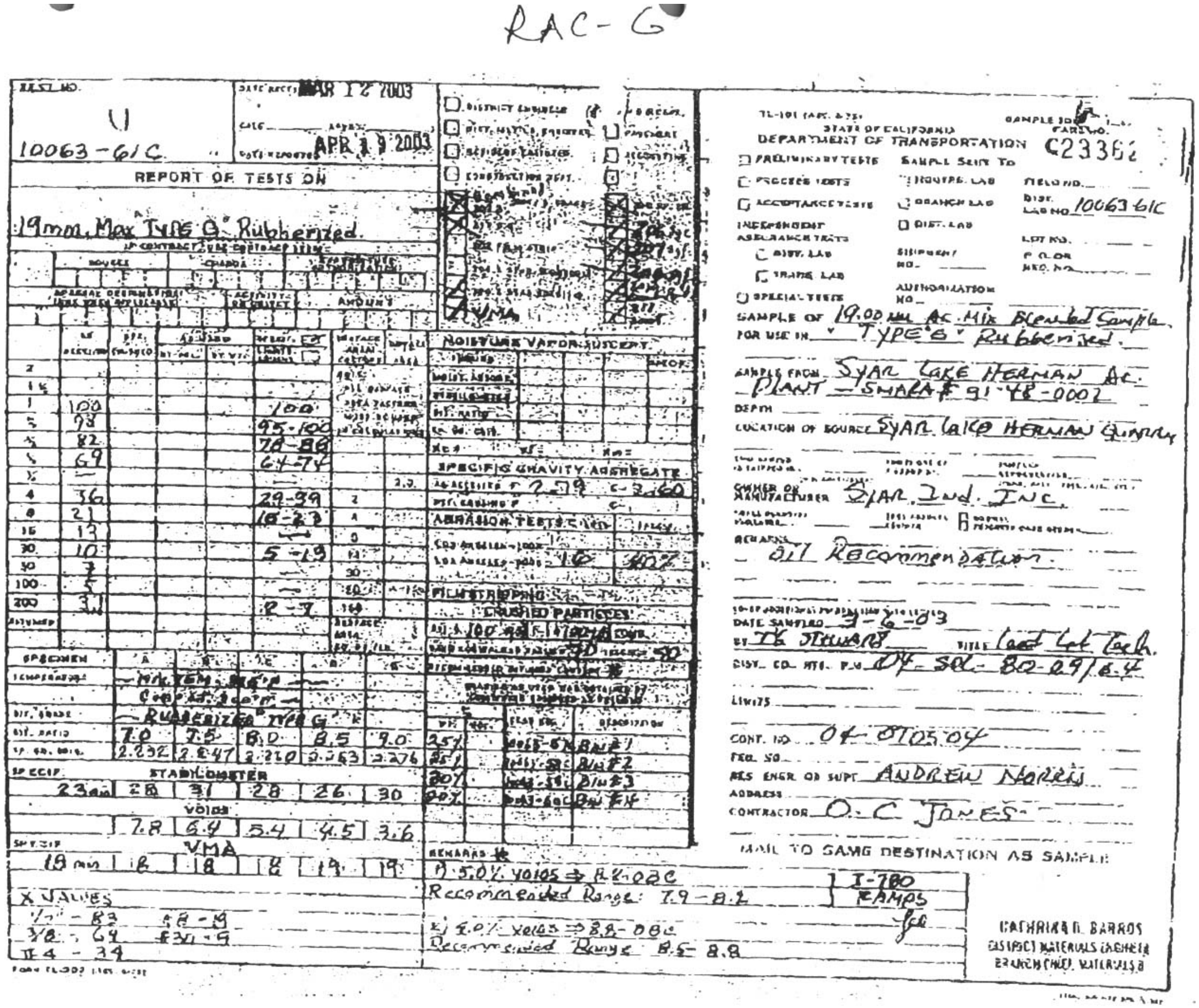
CONT. NO. 04-0T1414

FED. NO. ACNH-P037(046)E

CONTRACTOR O.C. Jones

CATHRINA B. BARROS

Figure B.1: Caltrans DGAC mix design.



RAC-G

TEST NO. 10063-61C

DATE REC'D MAR 12 2003

DATE REPORTED APR 19 2003

REPORT OF TESTS ON

19mm. Max "Type G" Rubberized.

Sieve	As received	Specs
2		
1½		
1	100	100
¾	98	95-100
½	82	78-88
⅜	69	64-74
¼	—	—
4	36	29-39
8	21	16-23
16	13	—
30	10	5-19
50	7	—
100	5	—
200	3.1	2-7

SPECIFIC GRAVITY AGGREGATE: F 2.59 C 2.60

ABRASION TESTS

CRUSHED PARTICLES: 100

SPECIMEN	A	B	C	D	E
TEMPERATURE	Mix Tem.				
	Comp. Tem.				
BIT. GRADE	Rubberized "Type G"				
BIT. RATIO	7.0	7.5	8.0	8.5	9.0
SP. GR. BRIQ.	2.232	2.247	2.260	2.263	2.276
STABILOMETER (SPECIF. 23 min)	28	31	28	26	30
VOIDS	7.8	6.4	5.4	4.5	3.6
VMA (SPECIF. 18 min)	18	18	18	19	19

%	Bin
25%	Bin #1
25%	Bin #2
20%	Bin #3
30%	Bin #4

X VALUES

½" - 83 #8 - 19

⅜ - 64 #30 - 9

#4 - 34

REMARKS

1) 5.0% voids ⇒ 8.2-OBC

Recommended Range: 7.9 - 8.2 } I-780 Ramps

2) 4.0% voids ⇒ 8.8-OBC

Recommended Range 8.5 - 8.8

TL-101

STATE OF CALIFORNIA

DEPARTMENT OF TRANSPORTATION

SAMPLE ID CARD NO. C2336[illegible]

☐ PRELIMINARY TESTS

☐ PROCESS TESTS

☐ ACCEPTANCE TESTS

INDEPENDENT ASSURANCE TESTS

☐ DIST. LAB

☐ TRANS. LAB

☐ SPECIAL TESTS

SAMPLE SENT TO

☐ HDQTRS. LAB

☐ BRANCH LAB

☐ DIST. LAB

SHIPMENT NO.

AUTHORIZATION NO.

FIELD NO.

DIST. LAB NO. 10063 61C

LOT NO.

P.O. OR REQ. NO.

SAMPLE OF 19.00 mm AC Mix Blended Sample

FOR USE IN "Type G" Rubberized.

SAMPLE FROM Syar Lake Herman AC. Plant - SMALA # 91-48-0002

DEPTH

LOCATION OF SOURCE Syar Lake Herman Quarry

OWNER OR MANUFACTURER Syar Ind. Inc.

REMARKS Oil Recommendation.

DATE SAMPLED 3-6-03

BY TK Stewart TITLE Asst Lab Tech.

DIST. CO. RTE. P.M. 04-SOL-80-09/6.4

LIMITS

CONT. NO. 04-0T0504

FED. NO.

RES. ENGR. OR SUPT. Andrew Norris

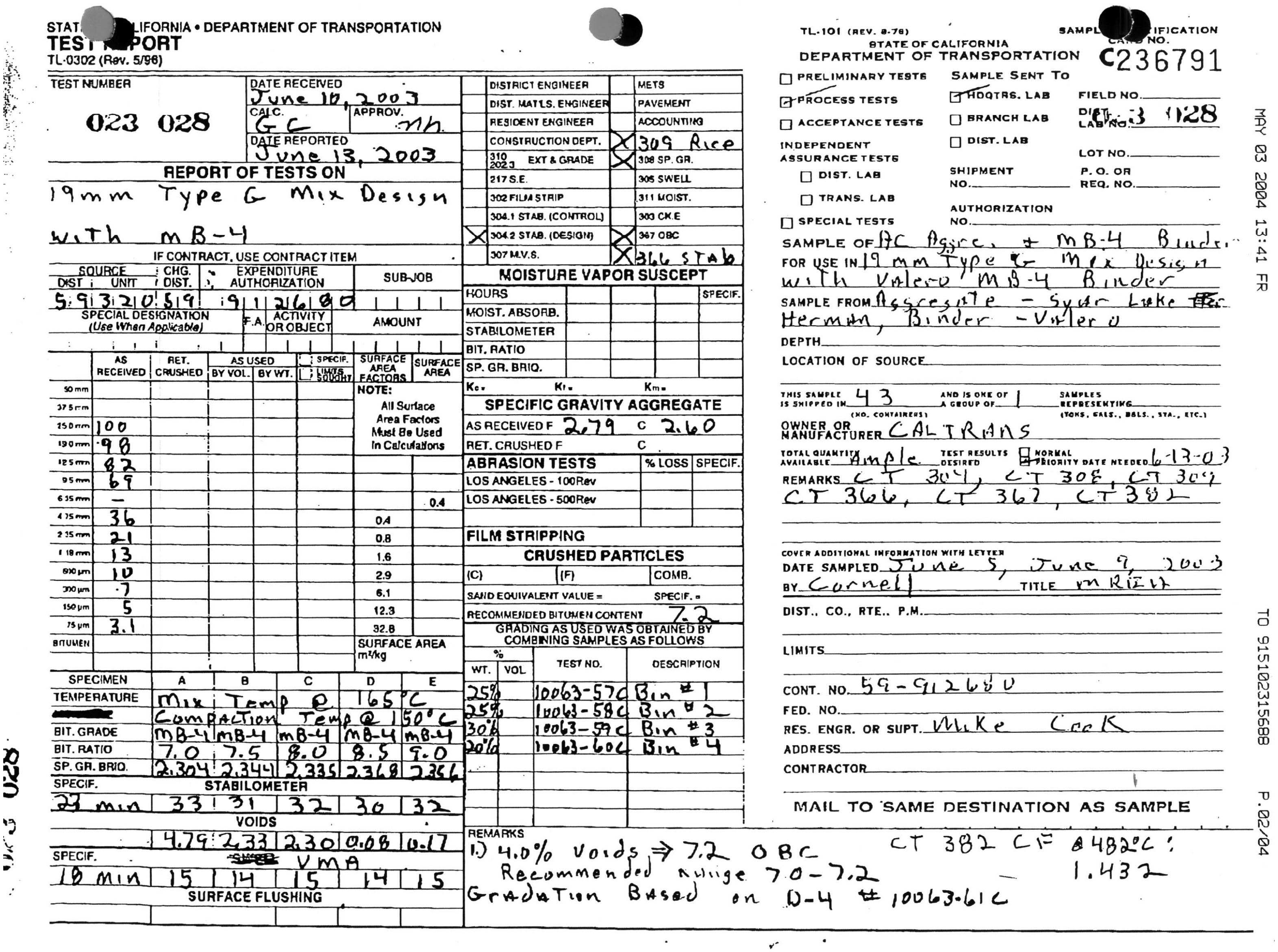
ADDRESS

CONTRACTOR O. C. Jones

MAIL TO SAME DESTINATION AS SAMPLE

CATHRINA R. BARROS
DISTRICT MATERIALS ENGINEER
BRANCH CHIEF, MATERIALS B

Figure B.2: Caltrans RAC-G mix design.



STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION
TEST REPORT
TL-0302 (Rev. 5/96)

TEST NUMBER 023 028	DATE RECEIVED June 10, 2003	
	CALC. GC	APPROV. mh
	DATE REPORTED June 13, 2003	

REPORT OF TESTS ON
19mm Type G Mix Design with MB-4

IF CONTRACT, USE CONTRACT ITEM

SOURCE DIST	UNIT	CHG. DIST.	EXPENDITURE AUTHORIZATION	SUB-JOB
59	3210	59	912680	

SPECIAL DESIGNATION (Use When Applicable)	F.A.	ACTIVITY OR OBJECT	AMOUNT

	AS RECEIVED	RET. CRUSHED	AS USED BY VOL.	AS USED BY WT.	☐ SPECIF. ☐ LIMITS SOUGHT	SURFACE AREA FACTORS	SURFACE AREA
50 mm						NOTE: All Surface Area Factors Must Be Used In Calculations	
37.5 mm							
25.0 mm	100						
19.0 mm	98						
12.5 mm	82						
9.5 mm	69						
6.35 mm	—						0.4
4.75 mm	36					0.4	
2.36 mm	21					0.8	
1.18 mm	13					1.6	
600 µm	10					2.9	
300 µm	7					6.1	
150 µm	5					12.3	
75 µm	3.1					32.8	
BITUMEN						SURFACE AREA m²/kg	

SPECIMEN	A	B	C	D	E
TEMPERATURE	Mix Temp @ 165°C				
[redacted]	Compaction Temp @ 150°C				
BIT. GRADE	MB-4	MB-4	MB-4	MB-4	MB-4
BIT. RATIO	7.0	7.5	8.0	8.5	9.0
SP. GR. BRIQ.	2.304	2.344	2.335	2.368	2.356
SPECIF.	STABILOMETER				
23 min	33	31	32	30	32
	VOIDS				
	4.79	2.33	2.30	0.08	0.17
SPECIF.	~~SWELL~~ VMA				
18 min	15	14	15	14	15
	SURFACE FLUSHING				

	DISTRICT ENGINEER		METS
	DIST. MAT'LS. ENGINEER		PAVEMENT
	RESIDENT ENGINEER		ACCOUNTING
	CONSTRUCTION DEPT.	☒	309 Rice
	310 2023 EXT & GRADE	☒	308 SP. GR.
	217 S.E.		305 SWELL
	302 FILM STRIP		311 MOIST.
	304.1 STAB. (CONTROL)		303 CK.E
☒	304.2 STAB. (DESIGN)	☒	367 OBC
	307 M.V.S.	☒	366 STAB

MOISTURE VAPOR SUSCEPT

HOURS				SPECIF.
MOIST. ABSORB.				
STABILOMETER				
BIT. RATIO				
SP. GR. BRIQ.				

Kc = Kf = Km =

SPECIFIC GRAVITY AGGREGATE
AS RECEIVED F 2.79 C 2.60
RET. CRUSHED F C

ABRASION TESTS	% LOSS	SPECIF.
LOS ANGELES - 100Rev		
LOS ANGELES - 500Rev		

FILM STRIPPING

CRUSHED PARTICLES
(C) (F) COMB.

SAND EQUIVALENT VALUE = SPECIF. =

RECOMMENDED BITUMEN CONTENT 7.2

GRADING AS USED WAS OBTAINED BY COMBINING SAMPLES AS FOLLOWS

% WT.	% VOL	TEST NO.	DESCRIPTION
25%		10063-57C	Bin #1
25%		10063-58C	Bin #2
30%		10063-59C	Bin #3
20%		10063-60C	Bin #4

REMARKS
1.) 4.0% Voids ⇒ 7.2 OBC
Recommended Range 7.0-7.2
Gradation Based on D-4 #10063-61C
CT 382 CF @ 482°C:
1.432

TL-101 (REV. 8-76)
STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
SAMPLE IDENTIFICATION CARD NO.
C236791

☐ PRELIMINARY TESTS
☑ PROCESS TESTS
☐ ACCEPTANCE TESTS
INDEPENDENT ASSURANCE TESTS
☐ DIST. LAB
☐ TRANS. LAB
☐ SPECIAL TESTS

SAMPLE SENT TO
☑ HDQTRS. LAB
☐ BRANCH LAB
☐ DIST. LAB

FIELD NO.
DIST. LAB NO. 03 1128
LOT NO.
SHIPMENT NO.
P. O. OR REQ. NO.
AUTHORIZATION NO.

SAMPLE OF AC Aggre. + MB-4 Binder
FOR USE IN 19 mm Type G Mix Design with Valero MB-4 Binder
SAMPLE FROM Aggregate - Syar Lake ~~Her~~ Herman, Binder - Valero
DEPTH
LOCATION OF SOURCE

THIS SAMPLE IS SHIPPED IN 43 (NO. CONTAINERS) AND IS ONE OF A GROUP OF 1 SAMPLES REPRESENTING (TONS, GALS., BBLS., STA., ETC.)
OWNER OR MANUFACTURER CALTRANS
TOTAL QUANTITY AVAILABLE Ample TEST RESULTS DESIRED ☐ NORMAL ☒ PRIORITY DATE NEEDED 6-13-03
REMARKS CT 304, CT 308, CT 309
CT 366, CT 367, CT 382

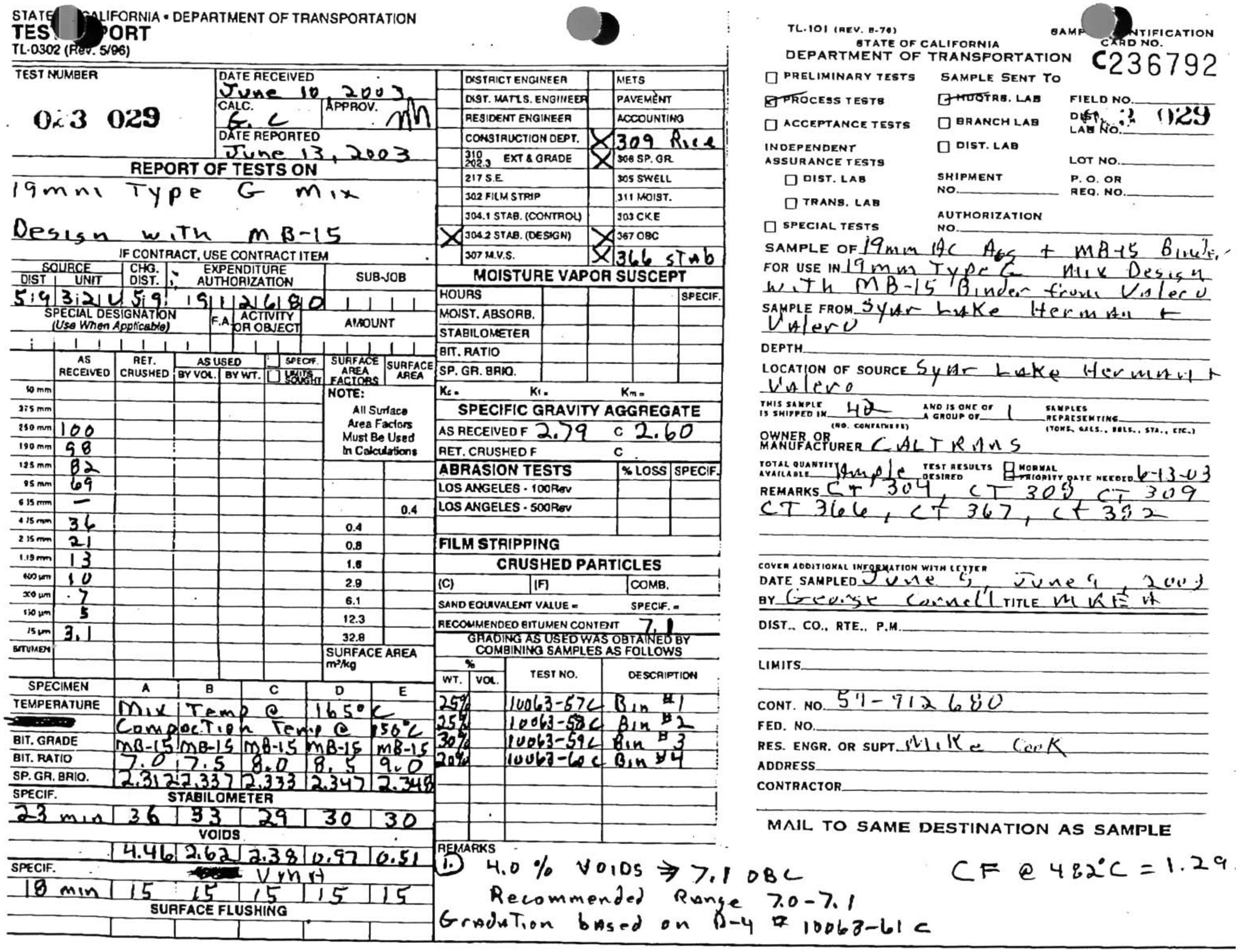
COVER ADDITIONAL INFORMATION WITH LETTER
DATE SAMPLED June 5, June 9, 2003
BY Cornell TITLE mRIEII
DIST., CO., RTE., P.M.
LIMITS
CONT. NO. 59-91268U
FED. NO.
RES. ENGR. OR SUPT. Mike Cook
ADDRESS
CONTRACTOR

MAIL TO SAME DESTINATION AS SAMPLE

MAY 03 2004 13:41 FR TO 915102315688 P.02/04

028

Figure B.3: Caltrans MB-4 mix design.



STATE [illegible] ALIFORNIA • DEPARTMENT OF TRANSPORTATION
TES[illegible]ORT
TL-0302 (Rev. 5/96)

TEST NUMBER 03 029	DATE RECEIVED June 10, 2003 CALC. G. C. — APPROV. MN DATE REPORTED June 13, 2003

REPORT OF TESTS ON

19mm Type G Mix
Design with MB-15

IF CONTRACT, USE CONTRACT ITEM

SOURCE DIST	SOURCE UNIT	CHG. DIST.	EXPENDITURE AUTHORIZATION	SUB-JOB
59	32U	59	1912680	

SPECIAL DESIGNATION (Use When Applicable)	F.A.	ACTIVITY OR OBJECT	AMOUNT

	AS RECEIVED	RET. CRUSHED	AS USED BY VOL.	AS USED BY WT.	☐ SPECIF. ☐ LIMITS SOUGHT	SURFACE AREA FACTORS	SURFACE AREA
50 mm						NOTE: All Surface Area Factors Must Be Used In Calculations	
37.5 mm							
25.0 mm	100						
19.0 mm	98						
12.5 mm	82						
9.5 mm	69						
6.35 mm	—						0.4
4.75 mm	36					0.4	
2.36 mm	21					0.8	
1.18 mm	13					1.6	
600 µm	10					2.9	
300 µm	7					6.1	
150 µm	5					12.3	
75 µm	3.1					32.8	
BITUMEN						SURFACE AREA m²/kg	

SPECIMEN	A	B	C	D	E
TEMPERATURE	Mix Temp @ 165°C				
[redacted]	Compaction Temp @ 150°C				
BIT. GRADE	MB-15	MB-15	MB-15	MB-15	MB-15
BIT. RATIO	7.0	7.5	8.0	8.5	9.0
SP. GR. BRIQ.	2.312	2.337	2.333	2.347	2.348
SPECIF.	STABILOMETER				
23 min	36	33	29	30	30
	VOIDS				
	4.46	2.62	2.38	0.97	0.51
SPECIF.	[redacted] VMA				
18 min	15	15	15	15	15
	SURFACE FLUSHING				

☐	DISTRICT ENGINEER	☐	METS
☐	DIST. MAT'LS. ENGINEER	☐	PAVEMENT
☐	RESIDENT ENGINEER	☐	ACCOUNTING
☐	CONSTRUCTION DEPT.	☒	309 Rice
☐	310 202.3 EXT & GRADE	☒	308 SP. GR.
☐	217 S.E.	☐	305 SWELL
☐	302 FILM STRIP	☐	311 MOIST.
☐	304.1 STAB. (CONTROL)	☐	303 CKE
☒	304.2 STAB. (DESIGN)	☒	367 OBC
☐	307 M.V.S.	☒	366 STab

MOISTURE VAPOR SUSCEPT

				SPECIF.
HOURS				
MOIST. ABSORB.				
STABILOMETER				
BIT. RATIO				
SP. GR. BRIQ.				

Kc = Kf = Km =

SPECIFIC GRAVITY AGGREGATE

AS RECEIVED F 2.79 C 2.60
RET. CRUSHED F C

ABRASION TESTS	% LOSS	SPECIF.
LOS ANGELES - 100Rev		
LOS ANGELES - 500Rev		

FILM STRIPPING

CRUSHED PARTICLES

(C) (F) COMB.

SAND EQUIVALENT VALUE = SPECIF. =

RECOMMENDED BITUMEN CONTENT 7.1

GRADING AS USED WAS OBTAINED BY COMBINING SAMPLES AS FOLLOWS

% WT.	% VOL.	TEST NO.	DESCRIPTION
25%		10063-57C	Bin #1
25%		10063-58C	Bin #2
30%		10063-59C	Bin #3
20%		10063-60C	Bin #4

REMARKS
① 4.0 % VOIDS ⇒ 7.1 OBC
Recommended Range 7.0-7.1
Gradation based on D-4 # 10063-61C

CF @ 482°C = 1.29

TL-101 (REV. 8-78)
STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION

SAMP[illegible]NTIFICATION CARD NO. C236792

☐ PRELIMINARY TESTS
☒ PROCESS TESTS
☐ ACCEPTANCE TESTS
INDEPENDENT ASSURANCE TESTS
☐ DIST. LAB
☐ TRANS. LAB
☐ SPECIAL TESTS

SAMPLE SENT TO
☒ HDQTRS. LAB
☐ BRANCH LAB
☐ DIST. LAB

SHIPMENT NO.
AUTHORIZATION NO.

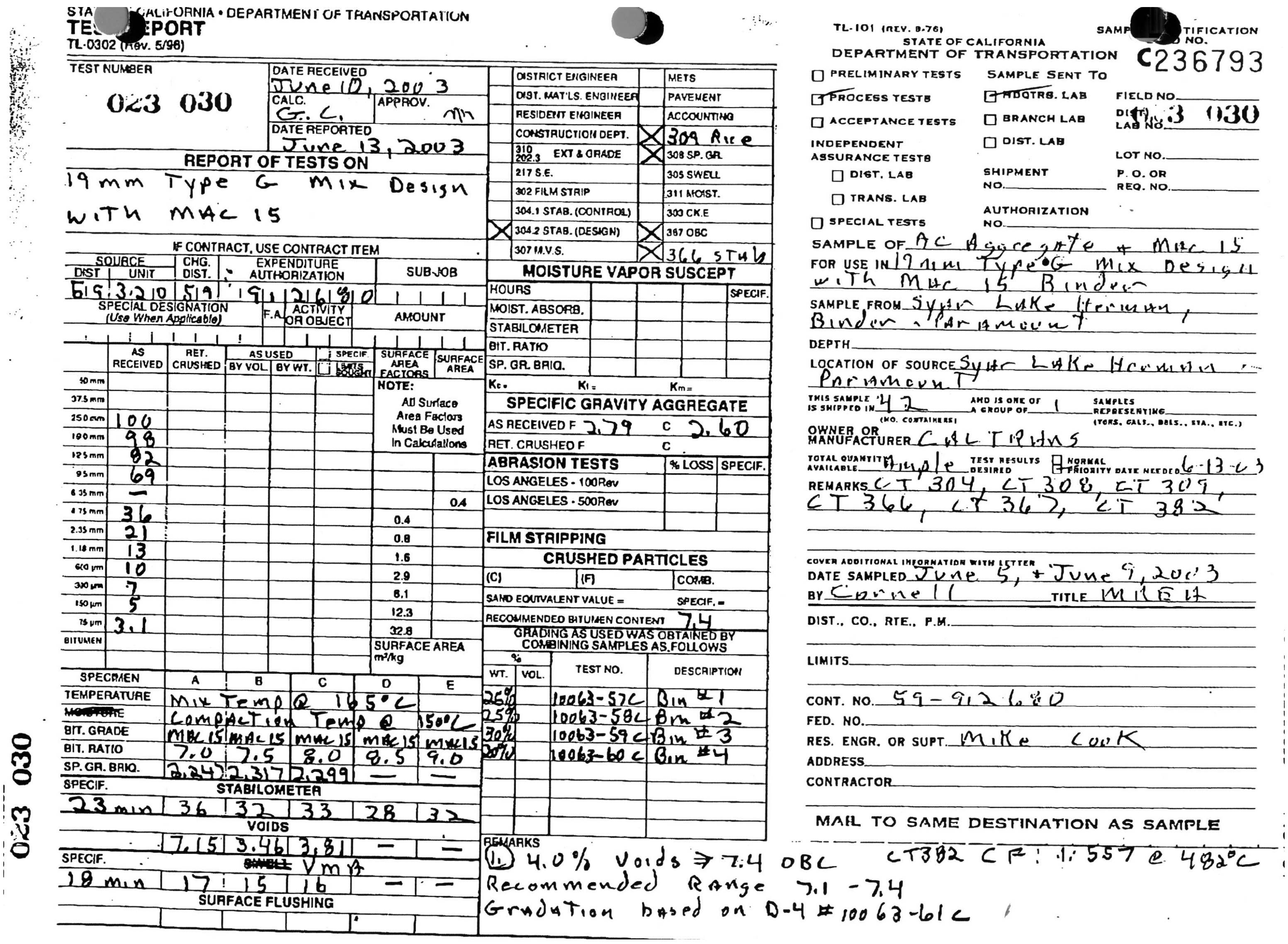
FIELD NO.
DIST. LAB NO. 03 029
LOT NO.
P. O. OR REQ. NO.

SAMPLE OF 19mm AC Agg + MB-15 Binder
FOR USE IN 19mm Type G Mix Design with MB-15 Binder from Valero
SAMPLE FROM Syar Lake Herman + Valero
DEPTH
LOCATION OF SOURCE Syar Lake Herman + Valero
THIS SAMPLE IS SHIPPED IN 42 (NO. CONTAINERS) AND IS ONE OF A GROUP OF 1 SAMPLES REPRESENTING (TONS, GALS., BBLS., STA., ETC.)
OWNER OR MANUFACTURER CALTRANS
TOTAL QUANTITY AVAILABLE Ample TEST RESULTS DESIRED ☐ NORMAL ☒ PRIORITY DATE NEEDED 6-13-03
REMARKS CT 304, CT 308, CT 309
CT 366, CT 367, CT 382

COVER ADDITIONAL INFORMATION WITH LETTER
DATE SAMPLED June 5, June 9, 2003
BY George Cornell TITLE MKE II
DIST., CO., RTE., P.M.
LIMITS
CONT. NO. 59-912680
FED. NO.
RES. ENGR. OR SUPT. Mike Cook
ADDRESS
CONTRACTOR

MAIL TO SAME DESTINATION AS SAMPLE

Figure B.4: Caltrans MB-15 mix design.



STA CALIFORNIA • DEPARTMENT OF TRANSPORTATION
TES EPORT
TL-0302 (Rev. 5/98)

TEST NUMBER 023 030	DATE RECEIVED June 10, 2003	
	CALC. G. C.	APPROV. Mh
	DATE REPORTED June 13, 2003	

REPORT OF TESTS ON
19 mm Type G Mix Design
with MAC 15

IF CONTRACT, USE CONTRACT ITEM

SOURCE DIST	SOURCE UNIT	CHG. DIST.	EXPENDITURE AUTHORIZATION	SUB-JOB
59	3210	59	912680	

SPECIAL DESIGNATION (Use When Applicable)	F.A.	ACTIVITY OR OBJECT	AMOUNT

	DISTRICT ENGINEER		METS
	DIST. MAT'LS. ENGINEER		PAVEMENT
	RESIDENT ENGINEER		ACCOUNTING
	CONSTRUCTION DEPT.	☒	309 Rice
	310 202.3 EXT & GRADE	☒	308 SP. GR.
	217 S.E.		305 SWELL
	302 FILM STRIP		311 MOIST.
	304.1 STAB. (CONTROL)		303 CK.E
☒	304.2 STAB. (DESIGN)	☒	367 OBC
	307 M.V.S.	☒	366 Stab

	AS RECEIVED	RET. CRUSHED	AS USED BY VOL.	AS USED BY WT.	☐ SPECIF. LIMITS SOUGHT	SURFACE AREA FACTORS	SURFACE AREA
50 mm						NOTE: All Surface Area Factors Must Be Used In Calculations	
37.5 mm							
25.0 mm	100						
19.0 mm	98						
12.5 mm	82						
9.5 mm	69						
6.35 mm	—						0.4
4.75 mm	36					0.4	
2.36 mm	21					0.8	
1.18 mm	13					1.6	
600 µm	10					2.9	
300 µm	7					6.1	
150 µm	5					12.3	
75 µm	3.1					32.8	
BITUMEN						SURFACE AREA m²/kg	

SPECIMEN	A	B	C	D	E
TEMPERATURE	Mix Temp @ 165°C				
~~MOISTURE~~	Compaction Temp @ 150°C				
BIT. GRADE	MAC 15	MAC 15	MAC 15	MAC 15	MAC 15
BIT. RATIO	7.0	7.5	8.0	8.5	9.0
SP. GR. BRIQ.	2.247	2.317	2.299	—	—
SPECIF.	STABILOMETER				
23 min	36	32	33	28	32
	VOIDS				
	7.15	3.46	3.81	—	—
SPECIF.	~~SWELL~~ VMA				
18 min	17	15	16	—	—
	SURFACE FLUSHING				

MOISTURE VAPOR SUSCEPT

				SPECIF.
HOURS				
MOIST. ABSORB.				
STABILOMETER				
BIT. RATIO				
SP. GR. BRIQ.				

Kc = Ki = Km =

SPECIFIC GRAVITY AGGREGATE
AS RECEIVED F 2.79 C 2.60
RET. CRUSHED F C

ABRASION TESTS	% LOSS	SPECIF.
LOS ANGELES - 100Rev		
LOS ANGELES - 500Rev		

FILM STRIPPING

CRUSHED PARTICLES
(C) (F) COMB.

SAND EQUIVALENT VALUE = SPECIF. =

RECOMMENDED BITUMEN CONTENT 7.4

GRADING AS USED WAS OBTAINED BY COMBINING SAMPLES AS FOLLOWS

% WT.	% VOL.	TEST NO.	DESCRIPTION
26%		10063-57C	Bin #1
25%		10063-58C	Bin #2
30%		10063-59C	Bin #3
20%		10063-60C	Bin #4

REMARKS
① 4.0% Voids ⇒ 7.4 OBC CT382 CF: 1.557 @ 482°C
Recommended Range 7.1 - 7.4
Gradation based on D-4 #10063-61C

023 030

TL-101 (REV. 8-76)
STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
SAMP TIFICATION NO. C236793

☐ PRELIMINARY TESTS
☑ PROCESS TESTS
☐ ACCEPTANCE TESTS
INDEPENDENT ASSURANCE TESTS
☐ DIST. LAB
☐ TRANS. LAB
☐ SPECIAL TESTS

SAMPLE SENT TO
☑ HDQTRS. LAB
☐ BRANCH LAB
☐ DIST. LAB

SHIPMENT NO.
AUTHORIZATION NO.

FIELD NO.
DIST. LAB NO. 023 030
LOT NO.
P. O. OR REQ. NO.

SAMPLE OF AC Aggregate + MAC 15
FOR USE IN 19 mm Type G Mix Design with MAC 15 Binder
SAMPLE FROM Syar Lake Herman, Binder - Paramount
DEPTH
LOCATION OF SOURCE Syar Lake Herman - Paramount
THIS SAMPLE IS SHIPPED IN 42 (NO. CONTAINERS) AND IS ONE OF A GROUP OF 1 SAMPLES REPRESENTING (TONS, GALS., BBLS., STA., ETC.)
OWNER OR MANUFACTURER CALTRANS
TOTAL QUANTITY AVAILABLE Ample TEST RESULTS DESIRED ☐ NORMAL ☑ PRIORITY DATE NEEDED 6-13-03
REMARKS CT 304, CT 308, CT 309, CT 366, CT 367, CT 382

COVER ADDITIONAL INFORMATION WITH LETTER
DATE SAMPLED June 5, + June 9, 2003
BY Connell TITLE MTE II
DIST., CO., RTE., P.M.
LIMITS
CONT. NO. 59-912680
FED. NO.
RES. ENGR. OR SUPT. Mike Cook
ADDRESS
CONTRACTOR

MAIL TO SAME DESTINATION AS SAMPLE

Figure B.5: Caltrans MAC 15 mix design.

APPENDIX C: UCPRC MB-DENSE MIX DESIGN SUMMARY

Table C.1: MB-15 Stability Values

Binder:	**MB-15**							
Aggregate:	**19 mm Max Dense Graded**							
Specimen No.		**1**	**2**	**3**	**4**	**5[a]**	**6**	**7**
% AC by Wt. Mix		4	4.5	5	5.5	6.00	6.5	7
Total Load pounds	Unit Load-P_v(psi)	Stabilometer Pressure Gauge Readings P_h Horizental Pressure						
1000	80	11	13	12	12	13	13	14
2000	160	16	20	19	18	22	20	21
3000	240	23	26	25	24	29	27	30
4000	320	30	33	32	30	35	34	40
5000	400	36	36	35	37	42	43	50
6000	480	46	43	41	45	49	52	60
Displacement Turns-D_2		3.84	3.65	3.65	3.8	3.45	3.55	3.35
Uncorrected Hveem Stabilometer Value-S		37	38	39	36	35	34	32
Ht. of Specimen mm or inches		69	69	67	68	67	68	68
Corrected Hveem Stabilometer Value-S		40	41	42	39	38	37	35

a) specimens showed slight flushing at 6.5% and moderate flushing at 7%

Table C.2: MB-15 Air Voids Analysis

Specimen Number	% Asphalt Content	Wt. in Air(A)	Wt. in Air w/ Paraffin(D)	Wt. in water w. Paraffin(E)	Wt. in water	Bulk-G_{mb} Sp. Gr. (Method A)	Max Specific Gravity(G_{mm})	Relative Density (RD)	% Air Voids
1	4	1210.4	1214.13	658.7	685.7	2.20	2.54	86.51	13.49
2	4.5	1223.2	1228.7	664.3	693	2.19	2.51	87.38	12.62
3	5	1226.2	1228.4	675.4	692	2.23	2.48	89.89	10.11
4	5.5	1237.7	1242.2	686.9	708.5	2.25	2.45	91.86	8.14
5	6	1233.2	1236.2	689.2	705.3	2.27	2.42	93.73	6.27
6	6.5	1244.7	1249.2	701.1	711.6	2.29	2.39	95.80	4.20
7	7	1255.9	1261.7	707.6	718.3	2.29	2.37	96.96	3.04

Table C.3: MB-4 Stability Values

Binder:	**MB-4**							
Aggregate:	**19 mm Max dense graded**							
Specimen No.		**1**	**2**	**3**	**4**	**5[a]**	**6**	**7**
% AC by Wt. Mix		4	4.5	5	5.5	6.00	6.5	7
Total Load pounds	Unit Load-P_v(psi)	Stabilometer Pressure Gauge Readings P_h Horizental Pressure						
1000	80	12	11	12	12	11	12	16
2000	160	17	15	17	18	17	18	24
3000	240	21	19	21	25	23	25	34
4000	320	26	22	26	31	30	34	46
5000	400	31	29	33	39	38	44	59
6000	480	38	36	41	47	47	56	76
Displacement Turns-D_2		3.5	3.94	3.72	3.25	3.25	3.32	3.16
Uncorrected Hveem Stabilometer Value-S		43	42	40	39	39	35	29
Ht. of Specimen mm or inches		67	69	69	68	69	68	68
Corrected Hveem Stabilometer Value-S		46	45	43	42	42	38	32

a) specimens showed slight flushing at 6.5% and moderate flushing at 7%

Table C.4: MB-4 Air Voids Analysis

Specimen Number	% Asphalt Content	Wt. in Air(A)	Wt. in Air w/ Paraffilm(D)	Wt. in water w. Paraffilm(E)	Wt. in water	Bulk-G_{mb} Sp. Gr. (Method A)	Max Specific Gravity(G_{mm})	Relative Density (RD)	% Air Voids
1	4	1219.1	1222.6	670.8	687.8	2.22	2.54	87.67	12.33
2	4.5	1228.6	1231.5	665	687.8	2.18	2.51	86.99	13.01
3	5	1235.9	1239.4	677.1	699.4	2.21	2.48	89.33	10.67
4	5.5	1247.4	1250.3	696.5	713.4	2.27	2.45	92.53	7.47
5	6	1249	1254.3	693.1	713	2.25	2.42	92.94	7.06
6	6.5	1251.2	1253.8	701	714.7	2.28	2.39	95.11	4.89
7	7	1252.8	1256	708.1	717.3	2.30	2.37	97.31	2.69

Table C.5: MAC-15 Stability Values

Binder: **MAC-15**
Aggregate: **19 mm Max Dense Graded**

Specimen No.		**1**	**2**	**3**	**4**	**5**[a]	**6**	**7**
% AC by Wt. Mix		4	4.5	5	5.5	6.00	6.5	7
Total Load pounds	Unit Load-P_v(psi)	Stabilometer Pressure Gauge Readings P_h Horizental Pressure						
1000	80	11	10	11	12	13	19	16
2000	160	15	14	16	15	20	27	24
3000	240	19	17	21	22	27	36	34
4000	320	23	22	28	29	35	45	44
5000	400	28	28	36	37	45	53	55
6000	480	35	34	44	46	54	64	68
Displacement Turns-D_2		3.05	3.44	3.45	3.4	3.25	3.1	3.12
Uncorrected Hveem Stabilometer Value-S		49	46	39	39	35	32	31
Ht. of Specimen mm or inches		67	69	69	68	68	67	68
Corrected Hveem Stabilometer Value-S		52	49	42	42	38	35	34

a) specimens showed slight flushing at 6.5% and moderate flushing at 7%

Table C.6: MAC-15 Air Voids Analysis

Specimen Number	% Asphalt Content	Wt. in Air(A)	Wt. in Air w/ Paraffin(D)	Wt. in water w. Paraffin(E)	Wt. in water	Bulk-G_{mb} Sp. Gr. (Method A)	Max Specific Gravity(G_{mm})	Relative Density (RD)	% Air Voids
1	4	1227.1	1232.9	673.1	694.7	2.22	2.54	87.38	12.62
2	4.5	1242	1245	684	703	2.23	2.51	88.82	11.18
3	5	1242.6	1249.9	683.8	706.3	2.23	2.48	89.88	10.12
4	5.5	1243.7	1249.4	685.2	710.1	2.23	2.45	91.05	8.95
5	6	1244.4	1253.9	700.8	714.3	2.29	2.42	94.78	5.22
6	6.5	1241.6	1246.9	697.2	710.3	2.28	2.39	95.44	4.56
7	7	1248.3	1255.8	705.5	717.9	2.30	2.37	97.39	2.61

Table C.7: OBC Summary

Aggregate:	19 mm dense-graded		
	Recommended OBC Range (%)		
Mix	Lower Limit	Upper Limit	Design
MB-4	6.3	6.6	6.3
MB-15	6.2	6.5	6.2
MAC-15	5.9	6.0	6.0

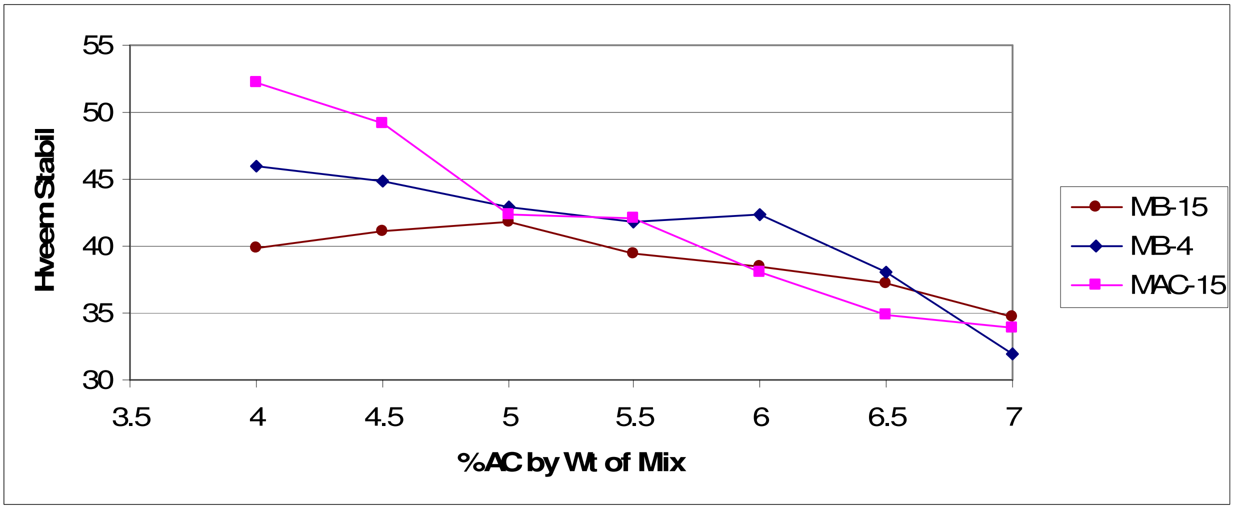


Figure C.1: Stability vs. Percent Asphalt Content

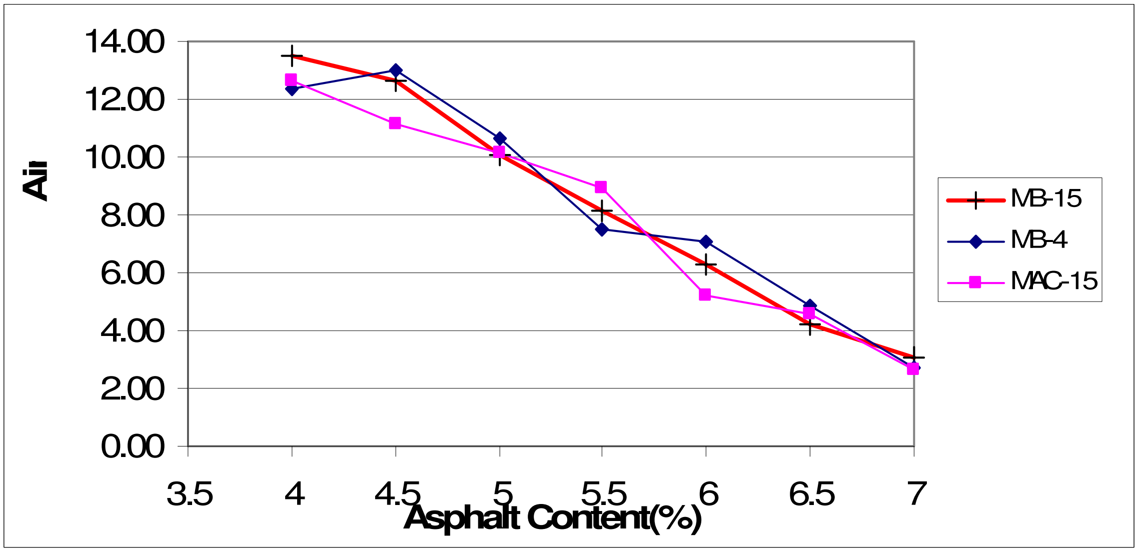


Figure C.2: Air Voids vs. Percent Asphalt Content