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Warm-Mix Asphalt Study: Laboratory Test Results for AkzoNobel *Rediset*™ *WMX*

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Warm-Mix Asphalt

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DOCUMENT RETRIEVAL PAGE **Research Report: UCPRC-CR-2010-01**

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Abstract:
This report describes a laboratory testing study that compared the performance of a control mix, produced and compacted at conventional hot-mix asphalt temperatures, with a mix containing *Rediset*^{TM} *WMX* warm-mix additive (referred to in this report as Rediset), produced and compacted at approximately 35°C (63°F) lower than the control. Key findings from the study include:

- No problems were noted with producing and compacting the Rediset mix at the lower temperatures in the laboratory. The air-void contents of individual specimens were similar for both mixes, indicating that satisfactory laboratory-mixed and compacted specimens can be prepared with the warm mix.
- Interviews with laboratory staff revealed that no problems were experienced with preparing specimens at the lower temperatures. Improved and safer working conditions at the lower temperatures were identified as an advantage.
- The laboratory test results indicate that use of the Rediset warm-mix asphalt additive assessed in this study, produced and compacted at lower temperatures, does not significantly influence the performance of the asphalt concrete when compared to control specimens produced and compacted at conventional hot-mix asphalt temperatures. In the shear, fatigue, Hamburg Wheel Track, and Cantabro tests, the results and trends in the results indicated similar performance between the two mixes, and between the two mixes and the Control mix tested in an earlier study on warm-mix asphalt undertaken for the California Department of Transportation (Caltrans). Minor differences in the results of these tests were attributed to the inherent variability of these tests and less oxidation of the binder in the Rediset specimens due to its lower mixing temperature. In the Tensile Strength Retained Test, the Rediset mix had significantly better moisture resistance compared to the Control mix in this study as well as the Control mix in the earlier Caltrans study.

The laboratory testing completed in this study has provided no results to suggest that *Rediset* ^{TM} *WMX* warm-mix additive should not be used to produce and place asphalt concrete at lower temperatures. These results should be be verified in pilot studies on in-service pavements. The results of the Tensile Strength Retained test indicate that the use of Rediset could improve the moisture resistance of moisture sensitive mixes. This should be investigated further along with additional Hamburg Wheel Track tests on oven aged/cured samples to assess the effect of short-term curing on the results of this test.

Keywords:
Warm-mix asphalt, WMA, Rediset, accelerated pavement testing, Heavy Vehicle Simulator

Proposals for implementation:
None

Related documents:
UCPRC Warm-Mix Asphalt Work Plan (UCPRC-WP-2007-01).
WMA Study: Test Track Construction & First-Level Analysis of Phase 1 HVS & Laboratory Testing (RR-2008-11)

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PROJECT OBJECTIVES

The objective of this project is to determine whether the use of additives, in the instance AkzoNobel *Rediset* ™ WMX, to reduce the production and construction temperatures of hot-mix asphalt influences performance of the mix. This was achieved through the following tasks:

1. Preparation of an experimental design to guide the research;
2. Conducting laboratory tests to identify comparable laboratory performance measures; and
3. Preparation of a first-level analysis report detailing the experiment and the findings.

EXECUTIVE SUMMARY

A series of laboratory tests was undertaken to assess the performance of AkzoNobel's *Rediset^{TM} WMX* warm-mix against a hot-mix asphalt control. The study, based on a work plan for warm-mix asphalt research in California, and approved by the California Department of Transportation (Caltrans), included rutting and fatigue cracking performance, moisture sensitivity, and durability. Aggregates and binder were sourced from an earlier warm-mix asphalt study undertaken by the University of California Pavement Research Center (UCPRC) on behalf of Caltrans. The objective of the Caltrans study is to determine whether the use of additives to reduce the production and construction temperatures of asphalt concrete influences performance of the mix and whether warm mixes will provide equal or better performance to an equivalent hot-mix asphalt . The AkzoNobel study, like the Caltrans study, compared the performance of a control mix, produced and constructed at conventional hot-mix asphalt temperatures, with a warm-mix produced with Rediset. This warm mix was produced and compacted at approximately 35°C (63°F) lower than the control.

The same mix design (Hveem, meeting Caltrans requirements for Type A 19 mm maximum dense-graded asphalt concrete) used in the earlier Caltrans study was also used in this study. Mixes were produced using conventional laboratory procedures and then compacted into ingots using a rolling wheel compactor. Beam and core specimens were sawn from the ingots for testing.

Key findings from the study include:

- No problems were noted with producing and compacting the Rediset mix at the lower temperatures in the laboratory. The air-void contents of individual specimens were similar for both mixes, indicating that satisfactory laboratory-mixed and compacted specimens can be prepared.
- Interviews with laboratory staff revealed that no problems were experienced with preparing specimens at the lower temperatures. Improved and safer working conditions at the lower temperatures were identified as an advantage.
- The laboratory test results indicate that use of Rediset warm-mix asphalt additive assessed in this study, produced and compacted at lower temperatures, does not significantly influence the performance of the asphalt concrete when compared to control specimens produced and compacted at conventional hot-mix asphalt temperatures. In the shear, fatigue and Hamburg Wheel Track and Cantabro tests, the results and trends in the results indicated similar performance between the two mixes, and between the two mixes and the Control mix tested in the earlier Caltrans study. Any differences in the results of these tests were attributed to the inherent variability of these tests and less oxidation of the binder in the Rediset specimens due to its lower mixing temperature. In the Tensile Strength Retained Test, the Rediset mix had significantly better moisture resistance compared to the Control mix in this study as well as the Control mix in the Caltrans study.

The laboratory testing completed in this study has provided no results to suggest that *Rediset*^{TM} *WMX* warm-mix additive should not be used in the production of asphalt concrete. These results should be verified in pilot studies on in-service pavements. The results of the Tensile Strength Retained test indicate that the use of Rediset could improve the moisture resistance of moisture sensitive mixes. This should be investigated further along with additional Hamburg Wheel Track tests on oven aged/cured samples to assess the effect of short-term curing on the results of this test.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transport Officials
ASTM	American Society for Testing and Materials
Caltrans	California Department of Transportation
DGAC	Dense-graded asphalt concrete
FHWA	Federal Highway Administration
FMFC	Field-mixed, field-compacted
HMA	Hot-mix asphalt
HVS	Heavy Vehicle Simulator
LMLC	Laboratory-mixed, laboratory-compacted
RHMA-G	Gap-graded rubberized hot-mix asphalt
TSR	Tensile strength retained
UCPRC	University of California Pavement Research Center
WMA	Warm-mix asphalt

LIST OF TEST METHODS AND SPECIFICATIONS

AASHTO M-320	Standard Specification for Performance Graded Asphalt Binder
AASHTO T-166	Bulk Specific Gravity of Compacted Asphalt Mixtures
AASHTO T-209	Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
AASHTO T-245	Standard Method of Test for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus
AASHTO T-275	Standard Method of Test for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens
AASHTO T-308	Standard Method of Test for Determining the Asphalt Binder Content of Hot Mix Asphalt (HMA) by the Ignition Method
AASHTO T-320	Standard Method of Test for Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures using the Superpave Shear Tester
AASHTO T-321	Standard Method of Test for Determining the Fatigue Life of Compacted Hot-Mix Asphalt subjected to Repeated Flexural Bending
AASHTO T-324	Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)
ASTM D7064	Standard Practice for Open-Graded Friction Course (OGFC) Mix Design
CT 366	Method of Test for Stabilometer Value
CT 371	Method of Test for Resistance of Compacted Bituminous Mixture to Moisture Induced Damage

CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
Symbol	**Convert From**	**Convert To**	**Symbol**	**Conversion**
LENGTH				
mm	millimeters	inches	in	mm x 0.039
m	meters	feet	ft	m x 3.28
km	kilometers	mile	mile	km x 1.609
AREA				
mm^2	square millimeters	square inches	in^2	mm^2 x 0.0016
m^2	square meters	square feet	ft^2	m^2 x 10.764
VOLUME				
m^3	cubic meters	cubic feet	ft^3	m^3 x 35.314
kg/m^3	kilograms/cubic meter	pounds/cubic feet	lb/ft^3	kg/m^3 x 0.062
L	liters	gallons	gal	L x 0.264
L/m^2	liters/square meter	gallons/square yard	gal/yd^2	L/m^2 x 0.221
MASS				
kg	kilograms	pounds	lb	kg x 2.202
TEMPERATURE (exact degrees)				
C	Celsius	Fahrenheit	F	°C x 1.8 + 32
FORCE and PRESSURE or STRESS				
N	newtons	poundforce	lbf	N x 0.225
kPa	kilopascals	poundforce/square inch	lbf/in^2	kPa x 0.145
*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)				

1. INTRODUCTION

1.1 Background

Warm-mix asphalt is a relatively new technology. It has been developed in response to needs for reduced energy consumption and stack emissions during the production of asphalt concrete, lower placement temperatures, improved workability, and better working conditions for plant and paving crews.

Research initiatives on warm-mix asphalt are currently being conducted in most states, as well as by the Federal Highway Administration and the National Center for Asphalt Technology.

The California Department of Transportation (Caltrans) has expressed interest in warm-mix asphalt with a view to reducing stack emissions at plants, to allow longer haul distances between asphalt plants and construction projects, to improve construction quality (especially during nighttime closures), and to extend the annual period for paving. However, the use of warm-mix asphalt technology requires the addition of an additive into the mix, and/or changes in production and construction procedures, specifically related to temperature, which could influence the short- and long-term performance of the pavement. Therefore, the need for research as well as product approval testing for the various types of additives available was identified by Caltrans to address a range of concerns related to these changes before statewide implementation of the technology in California is approved.

1.2 Project Objectives

The research presented in this report was undertaken by the University of California Pavement Research Center (UCPRC) as a service to industry contract for AkzoNobel Surface Chemistry LLC. It followed the relevant parts of Partnered Pavement Research Center Strategic Plan Element 4.18 (PPRC SPE 4.18), titled "Warm-Mix Asphalt Study," undertaken for Caltrans by the UCPRC. The objective of this Caltrans project is to determine whether the use of additives intended to reduce the production and construction temperatures of asphalt concrete influence mix production processes, construction procedures, and the short-, medium-, and/or long-term performance of hot-mix asphalt. The potential benefits of using the additives will also be quantified and the findings will be used to guide the implementation of warm-mix asphalt in California *(1)*. The objective of the AkzoNobel study was to quantify the performance of *Rediset*^{TM} *WMX*, referred to as Rediset in this report, using the same testing experimental design as that followed in the Caltrans/UCPRC study described above. Where appropriate, the results of the Rediset testing (undertaken on laboratory mixed and compacted specimens) would be compared with the results obtained in the earlier Caltrans study *(2)*, undertaken on specimens sampled from a test track constructed to compare three warm-mix asphalt additives (*Advera WMA*®, *Evotherm DAT*^{TM}, and *Sasobit*®) against a hot-mix asphalt control.

1.3 Structure and Content of this Report

This report presents an overview of the Rediset laboratory testing and is organized as follows:

- Chapter 2 details the mix design, laboratory testing experimental design, and specimen preparation.
- Chapter 3 summarizes the laboratory test results, compares the performance of the Control and Rediset specimens, and where appropriate, compares the results of this study with those of the Control specimens tested in the earlier Caltrans study.
- Chapter 4 provides conclusions and preliminary recommendations.

1.4 Measurement Units

Although Caltrans has recently returned to the use of U.S. standard measurement units, metric units have always been used by the UCPRC in the design and layout of HVS test tracks, and for laboratory and field measurements and data storage. In this report, metric and English units (provided in parentheses after the metric units) are provided in general discussion. In keeping with convention, only metric units are used in laboratory data analyses and reporting. A conversion table is provided on Page xi at the beginning of this report.

1.5 Terminology

The term “asphalt concrete” is used in this report as a general descriptor for asphalt surfacings. The terms “hot-mix asphalt (HMA)” and “warm-mix asphalt (WMA)” are used as descriptors to differentiate between the two technologies discussed in this study.

2. MIX DESIGN AND EXPERIMENTAL DESIGN

2.1 Mix Design

The mix design used in the construction of the test track in the first phase of the Caltrans warm-mix asphalt study, conducted at the Graniterock Company's A.R Wilson Quarry was also used in the AkzoNobel study for all tests except the open-graded mix durability test. A standard Graniterock Company mix design that meets specifications *(3)* for "Type-A Asphalt Concrete 19 mm Coarse requirements" (similar to the example shown in Appendix A) was followed. This mix design differs slightly from the example mix designs provided by Caltrans (example also shown in Appendix A) that were included in the study work plan *(1)*. The Graniterock mix design has been extensively used on projects in the vicinity of the asphalt plant where the Caltrans study test track was constructed. The Hveem-type mix design was not adjusted for accommodation of the Rediset additive. Key parameters for the mix design are summarized in Table 2.1.

The mix design for the open-graded mix testing followed the procedures detailed in ASTM D7064 (*Standard Practice for Open-Graded Friction Course [OGFC]) Mix Design*). Key parameters for this mix design are summarized in Table 2.2.

Table 2.1: Key Mix Design Parameters for Dense-Graded Mix

Parameter		Target	Range	Actual
Grading:	1"	100	-	100
	3/4"	96	91-100	96
	1/2"	84	-	84
	3/8"	72	66-78	72
	#4	49	42-56	49
	#8	36	31-41	36
	#16	26	-	26
	#30	18	14-22	18
	#50	11	-	11
	#100	7	-	7
	#200	4	2-6	4
Asphalt concrete binder grade		PG 64-10	-	PG 64-22
Bitumen content (% by mass of aggregate)		5.2	5.1-5.4	5.2
Hveem Stability at recommended bitumen content		45	-	45
Air-void content (%)		4.5	-	See Ch 3[1]
Sand equivalent (%)		72	-	Not measured
Los Angeles Abrasion at 100 repetitions (%)		9	-	Not measured
Los Angeles Abrasion at 500 repetitions (%)		30	-	Not measured

[1] Air-void contents were measured on each specimen and are reported in Chapter 3

Table 2.2: Key Mix Design Parameters for Open-Graded Mix

Parameter		Target	Actual
Grading:	1"	0	0
	3/4"	0	0
	1/2"	5	5
	3/8"	63	63
	#4	20	20
	#8	8	8
	#30	4	4
	#200	2	2
Asphalt concrete binder grade		PG 64-10	PG 64-22
Bitumen content (% by mass of aggregate)		5.9	5.9
Air-void content (%)		18 - 22	See Ch 3[1]

[1] Air-void contents were measured on each specimen and are reported in Chapter 3

2.1.1 Aggregates

Aggregates for the base and asphalt concrete were sourced from the asphalt plant stockpiles at the Graniterock Company's A.R Wilson Quarry on the day of construction of the test track. This granitic aggregate is classified as a hornblende gabbro of the Cretaceous Age and is composed of feldspar, quartz, small quantities of mica or hornblende, minor accessory minerals and lesser amounts of dark ferromagnesium materials. It is quarried from a narrowly exposed mass of plutonic rock close to the test track. Key aggregate parameters are provided in Table 2.1.

2.1.2 Asphalt Binder

Although the Graniterock mix design lists PG 64-10 binder, the Valero Asphalt Plant in Benicia, California, from which the binder was sourced for the Caltrans study, generally only supplies PG 64-16. This binder, however, also satisfies the requirements for the PG 64-10 performance grading. A copy of the certificate of compliance for the binder delivered on the day of construction of the test track, provided by the binder supplier with the delivery, is included in Appendix B. Samples of the binder were collected in steel buckets and stored in a temperature controlled room at 15°C (59°F) at the UCPRC laboratory at the UC Berkeley Richmond Field Station.

Performance-grade testing of the asphalt binder was undertaken by the Mobile Asphalt Binder Testing Laboratory (MABTL) Program within the Federal Highway Administration (FHWA) Office of Pavement Technology after construction of the test track. Testing followed the AASHTO M-320 Table 1 (M-320) and AASHTO M-320 Table 2 (M320-T2) requirements. The M320-Continuous grading is based on the Table 1 testing requirements. Samples of the binder were collected at the asphalt plant on the day of production and then shipped to the MABTL in five-liter metal paint can style containers with friction lids. These containers were gently heated at the MABTL in order to further split the material into one-liter containers.

Key results of the binder testing are listed in Table 2.3. The base binder was graded as PG 64-22, slightly better (in terms of low-temperature cracking) than the performance grade of PG 64-16 shown on the supplier's certificate of compliance.

Table 2.3: Summary of Binder Performance-Grade Test Results

Asphalt Binder	M320	M320-T2	M320-Continuous	Critical Crack Temp. (°C)
Base	PG 64-22	PG 64-22	67.0-26.7	-24.0

2.2 Laboratory Testing Experimental Design

Laboratory testing included shear, fatigue, moisture sensitivity, and durability tests on the hot- and warm-mix specimens. Tests on mix properties were carried out on the beams and cores cut from laboratory-mixed, laboratory-compacted slabs. The experimental design used in the Caltrans warm-mix asphalt study was also followed in the AkzoNobel study to facilitate comparison of results. This experimental design is similar to other studies into the performance of hot-mix asphalt undertaken at the UCPRC. In addition to the standard testing, the durability of an open-graded friction course (OGFC) mix was also assessed, given that a considerable number of warm-mix asphalt applications in California to date have been this type of mix.

2.2.1 Shear Testing

Test Method

The AASHTO T-320 Permanent Shear Strain and Stiffness Test (*Standard Method of Test for Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures using the Superpave Shear Tester*) was followed for shear testing in this study. In the standard test methodology, cylindrical test specimens 150 mm in diameter and 50 mm thick (6.0 in. by 2.0 in.) are subjected to repeated loading in shear using a 0.1-second haversine waveform followed by a 0.6-second rest period. Three different shear stresses are 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 five 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. Shear Frequency Sweep Tests were used to establish the relationship between complex modulus and load frequency. The same loading was used at frequencies of 15, 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz.

Number of Tests

A total of 18 shear tests and nine frequency sweep tests were carried out on each mix (total of 54 tests on the two mixes) as follows:

- Standard test:
  - Two temperatures, namely 45°C and 55°C (113°F and 131°F)
  - Three stresses, namely 70 kPa, 100 kPa, and 130 kPa (10.2, 14.5, and 18.9 psi)
  - Three replicates.
- Frequency sweep test:
  - Three temperatures, namely 35°C, 45°C and 55°C (95°F, 113°F and 131°F)
  - One strain, namely 100 microstrain
  - Three replicates.

2.2.2 Fatigue Testing

Test Method

The AASHTO T-321 Flexural Controlled-Deformation Fatigue Test method (*Standard Method of Test for Determining the Fatigue Life of Compacted Hot-Mix Asphalt subjected to Repeated Flexural Bending*) was followed. In this test, three replicate beam test specimens, 50 mm thick by 63 mm wide by 380 mm long (2.0 x 2.5 x 15 in.), were subjected to four-point bending using a sinusoidal waveform at a loading frequency of 10 Hz. Testing was performed in both dry and wet condition at two different strain levels and at three different temperatures. Flexural Controlled-Deformation Frequency Sweep Tests were used to establish the relationship between complex modulus and load frequency. The same sinusoidal waveform was used in a controlled deformation mode and at frequencies of 15, 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz. The upper limit of 15 Hz is a constraint imposed by the capabilities of the test machine. To ensure that the specimen was tested in a nondestructive manner, the frequency sweep test was conducted at a small strain amplitude level (100 microstrain), proceeding from the highest frequency to the lowest in the sequence noted above.

The wet specimens used in the fatigue and frequency sweep tests were conditioned following the beam-soaking procedure described in Appendix C. The beam was first vacuum-saturated to ensure a saturation level greater than 70 percent, and then placed in a water bath at 60°C (140°F) for 24 hours, followed by a second water bath at 20°C (68°F) for two hours. The beams were then wrapped with *Parafilm*^{TM} and tested within 24 hours after soaking.

Number of Tests

A total of 36 beam fatigue tests and 12 flexural fatigue frequency sweep tests were carried out on each mix (total of 96 tests on the two mixes) as follows:

- Standard test:
  - Three temperatures, namely 10°C, 20°C and 30°C (50°F, 68°F and 86°F)
  - Two strains, namely 200 microstrain and 400 microstrain
  - Three replicates.

- Flexural frequency sweep test:
  - Three temperatures, namely 10°C, 20°C and 30°C (50°F, 68°F and 86°F)
  - One strain, namely 100 microstrain
  - Two replicates.

2.2.3 Moisture Sensitivity Testing

Test Methods

Two additional moisture sensitivity tests were conducted, namely the Hamburg Wheel-Track Test and the Tensile Strength Retained (TSR) Test.

- The AASHTO T-324 test method was followed for Hamburg Wheel-Track testing on slab specimens 320 mm long, 260 mm wide, and 120 mm thick (12.6 x 10.2 x 4.7 in.). All testing was carried out at 50°C (122°F). The Rediset specimens were not cured prior to testing. Although curing of warm-mix specimens prior to testing is practiced in a number of states to provide results more representative of evaluated field performance, the curing duration and conditions are still under investigation. The AASHTO test method followed had also not been revised, at the time or preparing this report, to include curing of warm-mix asphalt specimens.
- The Caltrans CT-371 test method (*Method of Test for Resistance of Compacted Bituminous Mixture to Moisture Induced Damage*) was followed for the Tensile Strength Retained Test on cylindrical specimens 100 mm in diameter and 63 mm thick (4.0 x 2.5 in.). This test method is similar to the AASHTO T-283 test, however, it has some modifications specific for California conditions. The Rediset specimens were not subjected to any additional curing prior to testing.

Number of Tests

Four replicates of the Hamburg Wheel-Track test and six replicates of the Tensile Strength Retained Test were tested for each mix (8 and 12 tests per method, respectively).

2.2.4 Open-Graded Friction Course Durability Testing

Test Methods

The ASTM D7064 test method (*Standard Practice for Open-Graded Friction Course (OGFC) Mix Design*, also known as the Cantabro test) was followed for OGFC durability testing on cylindrical specimens 100 mm in diameter and 63 mm thick (4.0 in x 2.5 in.). The Rediset specimens were not cured prior to testing.

Number of Tests

Six replicates were tested for OGFC durability for each mix (total of 12 tests).

2.3 Specimen Preparation

2.3.1 Warm-Mix Additive Application Rates

The Rediset application rate was determined by AkzoNobel. A rate of 2.0 percent by mass of binder was used for all tests.

2.3.2 Mix Production and Compaction Temperatures

The same mix production temperatures used in the first phase of the Caltrans warm-mix asphalt study were used in the AkzoNobel study. These were selected based on discussions between Caltrans, Graniterock Company, and the participating warm-mix additive suppliers prior to the construction of the Caltrans study test track. Mix production temperatures were set at 155°C (310°F) for the Control mix and 120°C (250°F) for the mix with Rediset. Target compaction temperatures were therefore set at 145°C to 155°C (284°F to 310°F) for the Control mix and 110°C to 120°C (230°F to 250°F) for the Rediset mix. The study did not attempt to determine optimal or minimum temperatures at which Rediset mixes can be produced in the laboratory.

2.3.3 Mix Production and Specimen Compaction

Mix was produced according to the AASHTO PP3-94 *Standard Practice for Preparing Hot Mix Asphalt (HMA) Specimens by Means of the Rolling Wheel Compactor* test method. The addition of the Rediset additive followed guidelines provided by AkzoNobel. The prescribed amount of Rediset pellets were stirred into the binder when the required temperature had been reached. Stirring continued until there was no visible sign of the additive.

Shear, fatigue beam, and Hamburg Wheel Track specimens were prepared and compacted according to AASHTO PP3-94. Cores, beams, and slabs were cut from the prepared ingots for the respective tests.

Tensile Strength Retained test specimens were prepared and compacted according to Caltrans Test Method CT 371, *Method of Test for Resistance of Compacted Bituminous Mixture to Moisture Induced Damage*.

Specimens for durability testing were prepared according to ASTM D7064, *Standard Practice for Open-Graded Friction Course (OGFC) Mix Design*.

2.3.4 Mix Production and Specimen Compaction Observations

No problems with regard to mix production and specimen preparation were recorded by laboratory staff. Staff noted that it was easier to work with the cooler mix in terms of physical comfort, laboratory safety, and improved workability.

3. LABORATORY TEST DATA SUMMARY

3.1 Introduction

Laboratory test results for shear, beam fatigue, moisture sensitivity, and open-graded mix durability are discussed in the following sections. Detailed results are tabled in Appendix D.

3.2 Shear Testing

Shear test results for the HMA Control and Rediset specimens are listed in Table D.1 through Table D.4 in Appendix D. Key individual components of the testing are discussed in the following sections.

3.2.1 Air-Void Content

Shear specimens were cored from the compacted ingots as discussed in Chapter 2. Air-void contents were measured using the modified Parafilm method (AASHTO T-275A). Table 3.1 summarizes the air-void distribution categorized by mix type, test temperature, and test shear stress level. Summary boxplots of specimen air-void content are shown in Figure 3.1. The test track Control specimens from the earlier Caltrans study *(2)* are included for comparison. Average air-void contents for both mixes were very similar indicating that the addition of Rediset and production and compaction of the Rediset mix at lower temperatures did not influence compaction and associated air-void content. There was also very little difference in the air-void contents of individual specimens. Laboratory prepared specimens had lower air-void contents than the specimens cored from the test track.

Table 3.1: Summary of Binder and Air-Void Contents of Shear Test Specimens

Specimen			Air-void Content (%)					
			AkzoNobel Study				Test Track	
Temperature		Stress Level (kPa)	HMA Control		Rediset		HMA Control	
°C	°F		Mean	SD[1]	Mean	SD	Mean	SD
45	113	70	4.3	0.4	4.3	0.1	5.3	0.0
		100	4.8	0.2	4.4	0.5	5.3	0.0
		130	4.6	0.3	4.6	0.3	5.3	0.0
55	131	70	4.7	0.4	4.4	0.1	5.3	0.0
		100	4.5	0.5	4.4	0.1	5.3	0.0
		130	4.7	0.3	4.5	0.4	5.3	0.0
Overall			4.6	0.3	4.4	0.2	5.3	0.0
Frequency Sweep			4.4	0.4	4.1	0.1	7.1	0.7

[1] SD: Standard deviation.

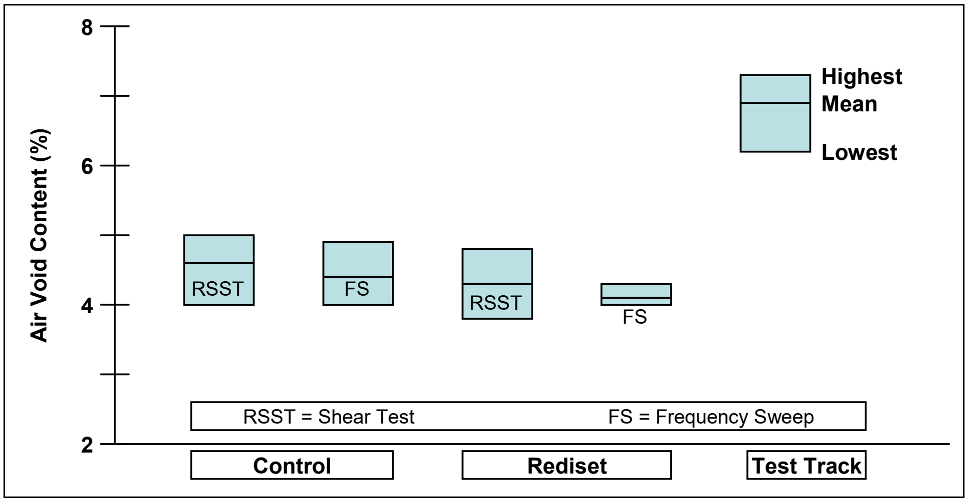


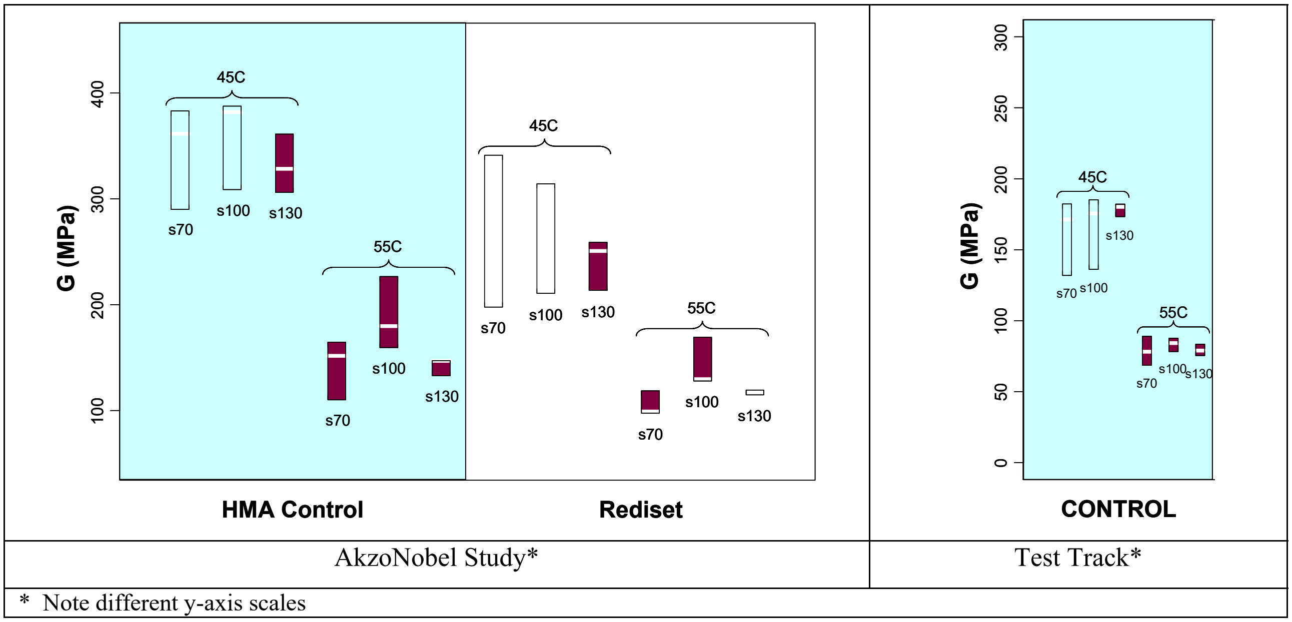
Figure 3.1: Air-void contents of shear specimens.

3.2.2 Resilient Shear Modulus (*G*)

The resilient shear modulus results for the two mixes are summarized in Figure 3.2. The resilient shear modulus was influenced by temperature, with the modulus increasing with decreasing temperature. The variation in resilient shear moduli between the replicate specimens tested at 45°C was also larger compared to the results at 55°C. The influence of different stress levels on resilient modulus was far less pronounced, especially for the 55°C tests. At 45°C, the control mix had a higher resilient shear modulus than the Rediset mix, with the difference increasing with increasing stress. The lower modulus of the Rediset specimens is likely due to less aging of the binder during mixing at lower temperatures. At 55°C, the average resilient shear moduli of both mix specimens were in a similar range, indicating that the addition of Rediset and production and compaction of the Rediset mix at lower temperatures did not significantly influence the rutting performance of the mix in this test. The resilient moduli of the laboratory-mixed specimens were considerably higher than the test track specimens, although trends between the different temperatures and stress levels were similar. This was attributed to the higher air-void contents on the test track specimens. (Note that different y-axis scales are used on the plots).

3.2.3 Cycles to Five Percent Permanent Shear Strain

The number of cycles to five percent permanent shear strain provides an indication of the rut-resistance of an asphalt mix, with higher numbers of cycles implying better rut-resistance. Figure 3.3 summarizes the shear test results in terms of the natural logarithm of this parameter. As expected, the rut-resistance capacity decreased with increasing temperature and stress level. With the exception of the Control mix at 45°C and 70 kPa stress level, and 55°C and 100 kPa stress level, there was very little difference in the average results of the Control and Rediset mixes. This indicates that the addition of Rediset and production and compaction of the Rediset mix at lower temperatures did not significantly influence the rutting performance of the mix in this test. The number of cycles to five percent permanent shear strain for the laboratory-mixed specimens was considerably higher than the test track specimens, although trends between the different temperatures and stress levels were similar. This was attributed to the higher air-void contents in the test track specimens. (Note that different y-axis scales are used on the plots).

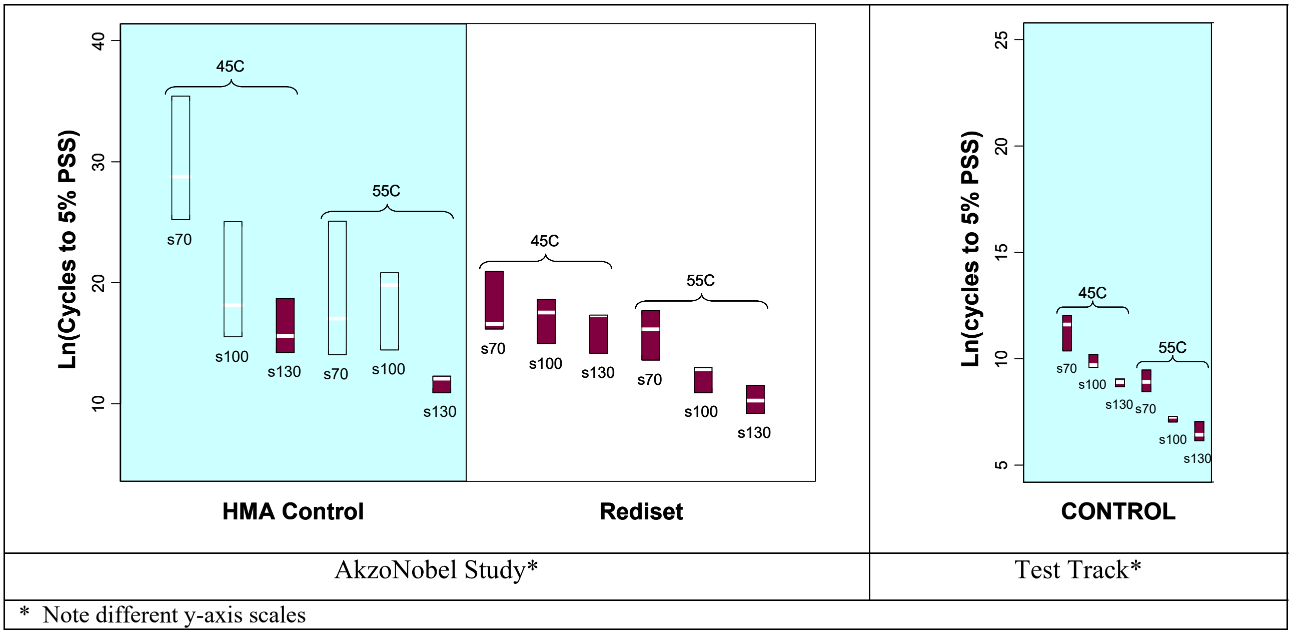


AkzoNobel Study*

Test Track*

* Note different y-axis scales

Figure 3.2: Summary boxplots of resilient shear modulus.



AkzoNobel Study*

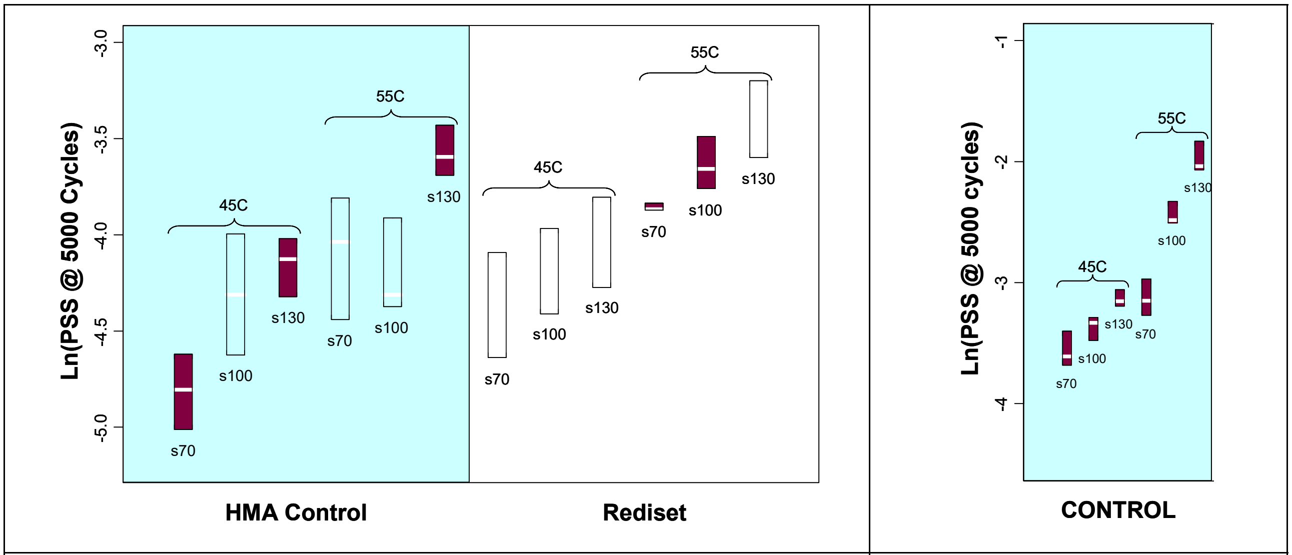
Test Track*

* Note different y-axis scales

Figure 3.3: Summary boxplots of cycles to 5% permanent shear strain.

3.2.4 Permanent Shear Strain at 5,000 Cycles

The measurement of permanent shear strain (PSS) accumulated after 5,000 cycles provides an alternative indication of the rut-resistance capacity of an asphalt mix. The smaller the permanent shear strain the better the mix's rut-resistance capacity. Figure 3.4 summarizes the rutting performance of the two mixes in terms of the natural logarithm of this parameter (i.e., increasingly negative values represent smaller cumulative permanent shear strain). At 45°C and 100 kPa and 130 kPa strain levels, and at 55°C and 70 kPa and 130 kPa strain levels, the performance of the two mixes was essentially the same. The 45°C/70 kPa and 55°C/100 kPa combinations were inconsistent. Increasing temperature and stress level resulted in larger cumulative permanent shear strain, as expected. The permanent shear strain after 5,000 cycles of the laboratory-mixed specimens was considerably higher than the test track specimens, although trends between the different temperatures and stress levels were similar. This was attributed to the higher air-void contents on the test track specimens. (Note that different y-axis scales are used on the plots).



AkzoNobel Study*	Test Track*

* Note different y-axis scales

Figure 3.4: Summary boxplots of cumulative permanent shear strain at 5,000 cycles.

3.2.5 Shear Frequency Sweep

The average shear complex moduli (G^*) of three replicates tested at the two temperatures were used to develop the shear complex modulus master curves. The reference temperature of the master curves was set at 55°C. The shifted master curves with minimized residual-sum-of-squares derived using a genetic algorithm approach was fitted with the following modified Gamma function (Equation 3.1):

$$Ln(G^*) = D + A \cdot \left(1 - \exp\left(- \frac{(x - C)}{B} \right) \cdot \sum_{m}^{n-1} \frac{(x - C)^m}{B^m m!} \right) \tag{3.1}$$

where: G^* is the flexural complex modulus (MPa),
x is the loading frequency in Hz, and
A, B, C, D, and n are the experimentally-determined parameters, and
Ln is the natural logarithm.

The experimentally-determined parameters of the modified Gamma function for the shear complex modulus curves for each mix type are listed in Table 3.2.

Table 3.2: Summary of Complex Modulus (*Ln*[*G]) Master Curves**

Mix	Master Curve					Time-Temp Relationship	
	n	**A**	**B**	**C**	**D**	**A**	**B**
Control	3	6.833574	3.705140	-6.374169	2.105417	-7.23098	34.25360
Rediset	3	4.797014	3.045149	-5.417707	2.860892	-0.46648	5.29335
Test Track Control	3	7.566435	3.344699	-3.784501	1.606332	-	-

Notes:
1. The reference temperature is 45°C.
2. Master curve Gamma-fitted equations:

If $n = 3$, $$Ln(G^*) = D + A \cdot \left(1 - \exp\left(-\frac{(x-C)}{B}\right) \cdot \left(1 + \frac{x-C}{B} + \frac{(x-C)^2}{2B^2}\right)\right),$$

If $n = 4$, $$Ln(G^*) = D + A \cdot \left(1 - \exp\left(-\frac{(x-C)}{B}\right) \cdot \left(1 + \frac{x-C}{B} + \frac{(x-C)^2}{2B^2} + \frac{(x-C)^3}{6B^3}\right)\right),$$

where $x = \ln freq + \ln aT$

Figure 3.5 shows the shifted master curves with Gamma-fitted lines for shear complex modulus for the 45°C testing (note that log scales are used on both axes). Although the two mixes followed similar (and typical) trends, the Rediset mix exhibited lower stiffness at lower frequencies (i.e. more viscous binder properties under slower moving traffic) compared to the Control mix. At higher frequencies (i.e. more elastic binder properties under faster moving traffic), the performance was similar. This was attributed to less oxidation of the binder during preparation of the specimens at the lower temperature and is typical of comparisons between aged and unaged binders and of other warm-mix asphalt tests. This behavior is unlikely to significantly affect rutting performance on in-service pavements.

Figure 3.6 shows the temperature shifting relationship for the two mixes. The temperature-shifting relationships were obtained during the construction of the complex modulus master curve and can be used to correct the temperature effect on initial stiffness. Note that a positive temperature correction value is applied when the temperature is lower than the reference temperature, while a negative temperature correction factor value is used when the temperature is higher than the reference temperature. The plot indicates that the difference in stiffness between the two mixes at lower frequencies shown in Figure 3.5 will increase with increasing temperature, while at lower temperatures, the two mixes will behave in a similar manner.

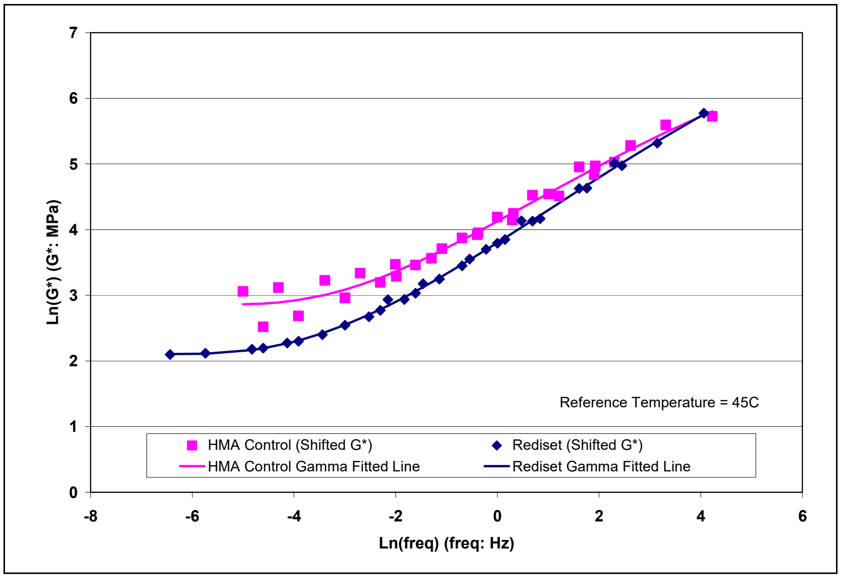


Figure 3.5: Summary of shear complex modulus master curves.

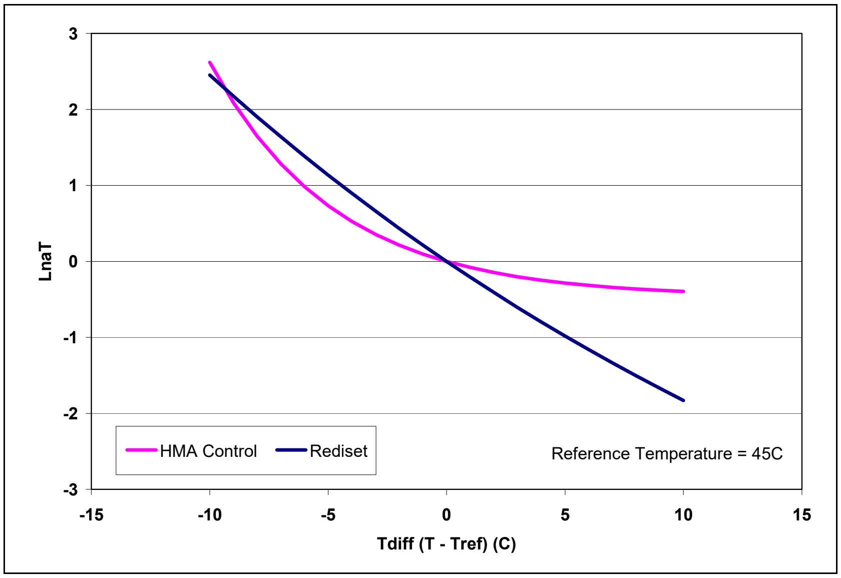


Figure 3.6: Shear frequency sweep temperature-shifting relationship.

3.3 Fatigue Beam Testing

Fatigue beam test results for the HMA Control and Rediset specimens are listed in Table D.5 through Table D.12 in Appendix D. Key individual components of the testing are discussed in the following sections.

3.3.1 Air-Void Content

Fatigue beams were saw-cut from the ingots produced in the laboratory, as discussed in Chapter 2. Air-void contents were measured using the modified Parafilm method (AASHTO T-275A). Table 3.3 and Table 3.4 summarize the air-void distribution categorized by mix type, test temperature, and test tensile strain level for the fatigue beam and frequency sweep specimens, respectively. The test track Control specimens from the earlier Caltrans study *(2)* are included for comparison. Figure 3.7 shows summary boxplots of air-void content for the wet and dry fatigue beam and flexural frequency sweep specimens, respectively. There was no significant difference in air-void content between the mixes or between the dry and wet specimens. Laboratory prepared specimens had lower air-void contents than the test track specimens.

Table 3.3: Summary of Air-Void Contents of Beam Fatigue Specimens

Specimen				**AkzoNobel Study**				**Test Track**	
Condition	**Strain (µstrain)**	**Temperature**		**HMA Control**		**Rediset**		**HMA Control**	
		°C	**°F**	**Mean**	**SD[1]**	**Mean**	**SD**	**Mean**	**SD**
Dry	200	10	50	4.2	0.3	4.3	0.5	7.3	1.0
		20	68	4.6	0.4	4.6	0.4	6.9	0.6
		30	86	4.9	0.1	4.5	0.5	7.3	0.7
	400	10	50	4.7	0.3	4.7	0.2	7.0	0.6
		20	68	4.7	0.3	4.6	0.6	7.4	0.8
		30	86	4.5	0.4	4.3	0.3	6.7	0.4
			Overall	4.6	0.4	4.5	0.4	7.1	0.6
Wet	200	10	50	4.3	0.3	4.7	0.4	8.0	0.5
		20	68	4.5	0.1	4.5	0.4	6.8	0.4
		30	86	4.5	0.3	4.6	0.2	6.9	1.2
	400	10	50	4.9	0.1	4.5	0.2	6.9	0.5
		20	68	4.6	0.2	4.6	0.3	7.0	0.3
		30	86	4.8	0.2	4.4	0.5	7.2	0.4
			Overall	4.6	0.3	4.6	0.3	7.1	0.7

[1] SD: Standard deviation.

Table 3.4: Summary of Air-Void Contents of Flexural Frequency Sweep Specimens

Specimen	**AkzoNobel Study**				**Test Track**	
Condition	**HMA Control**		**Rediset**		**HMA Control**	
	Mean	**SD[1]**	**Mean**	**SD**	**Mean**	**SD**
Dry	4.6	0.4	4.5	0.4	7.0	0.5
Wet	4.5	0.4	4.6	0.3	6.8	0.7

[1] SD: Standard deviation.

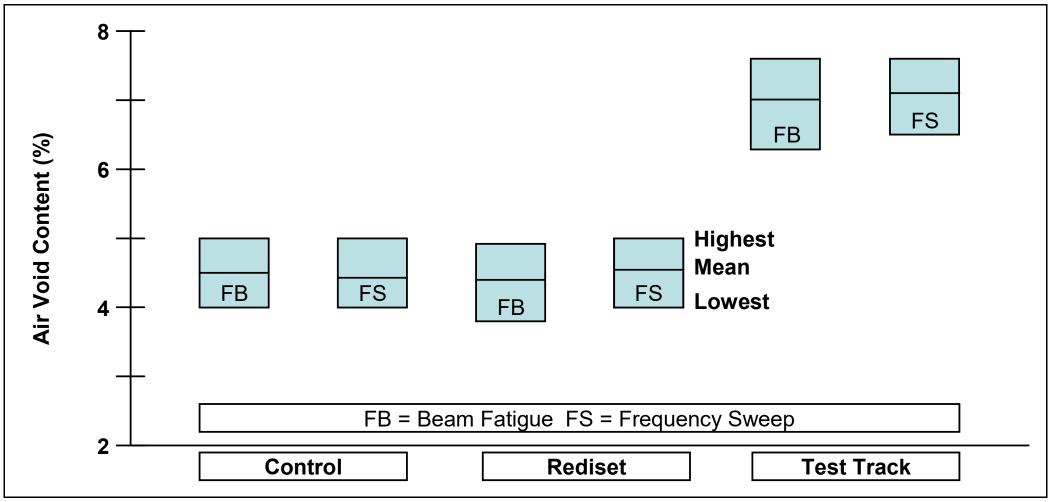


Figure 3.7: Air-void contents of fatigue beam and frequency sweep specimens.

3.3.2 Initial Stiffness

Figure 3.8 illustrates the initial stiffness comparison at various strain levels, temperatures, and conditioning for the different mix types. The following observations were made:

- Initial stiffness was generally strain-independent for both the dry and wet tests.
- There was no significant difference between the two mixes in terms of initial stiffness in the dry condition, indicating that the use of Rediset and lower production and compaction temperatures did not significantly influence the performance of the mix in this test.
- The reduction of initial stiffness due to soaking was notably more apparent in the Control mix when compared to the Rediset mix at the same temperature. These results indicate a potential reduction in moisture sensitivity with the use of Rediset.
- Temperature had a significant effect on both the dry and wet tests, as expected. The reduction in initial stiffness increased with increasing temperature, as expected, indicating a potential reduction in fatigue-resistance at higher temperatures. The results are consistent with initial stiffness test results from other studies *(2)*.
- Test results from the AkzoNobel study were comparable to the earlier Caltrans study *(2)*.

3.3.3 Initial Phase Angle

The initial phase angle can be used as an index of mix viscosity properties, with higher phase angles corresponding to more viscous and less elastic properties. Figure 3.9 illustrates the side-by-side phase angle comparison of dry and wet tests for the two mixes. The following observations were made:

- The initial phase angle appeared to be strain-independent.
- There was no significant difference between the two mixes in terms of initial phase angle indicating that the addition of Rediset and lower production and compaction temperatures did not significantly influence the performance of the mix in this test.
- The initial phase angle increased with increasing temperature, as expected.
- Soaking did not have any significant influence on the phase angle in either of the mixes.

- The initial phase angle was highly negative-correlated with the initial stiffness.
- Phase angles in the laboratory prepared specimens were similar to those removed from the test track.

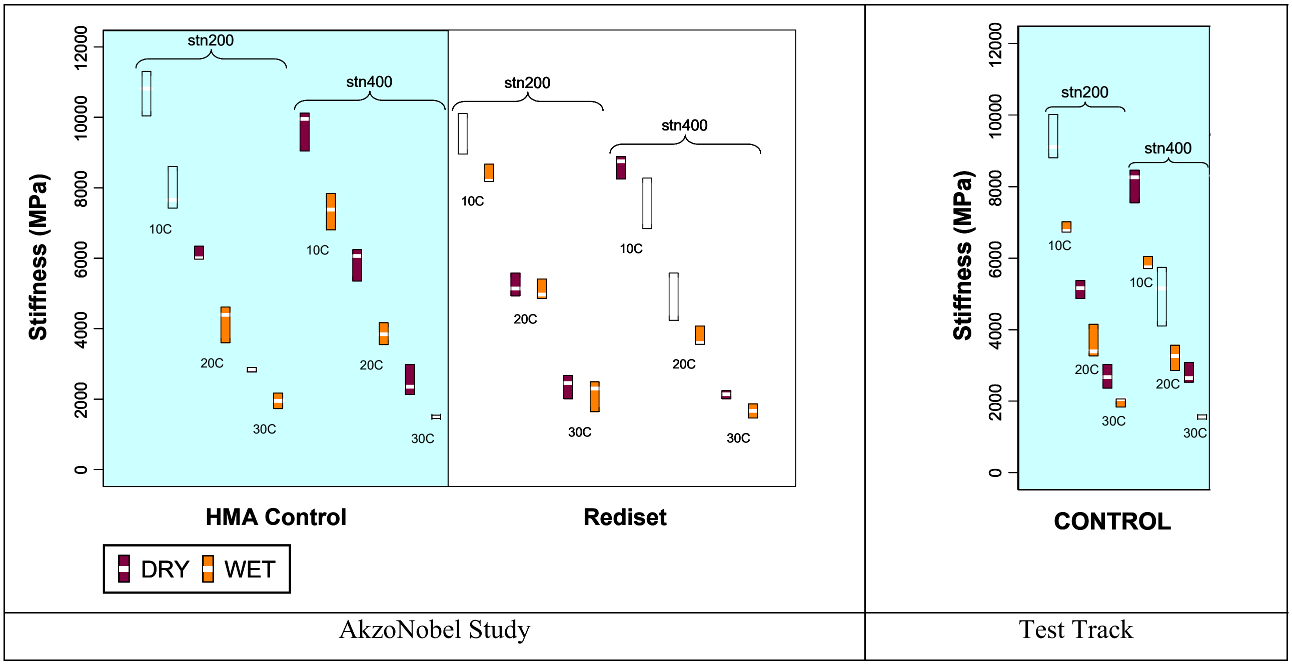
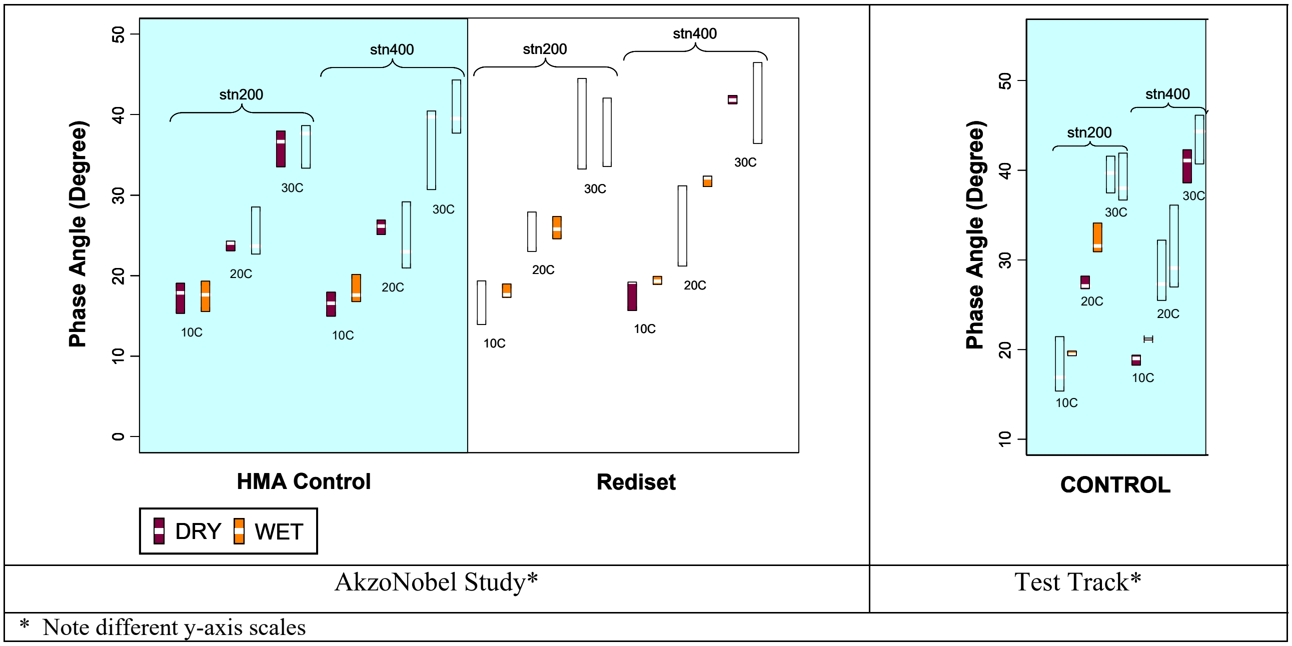


Figure 3.8: Summary boxplots of initial stiffness.



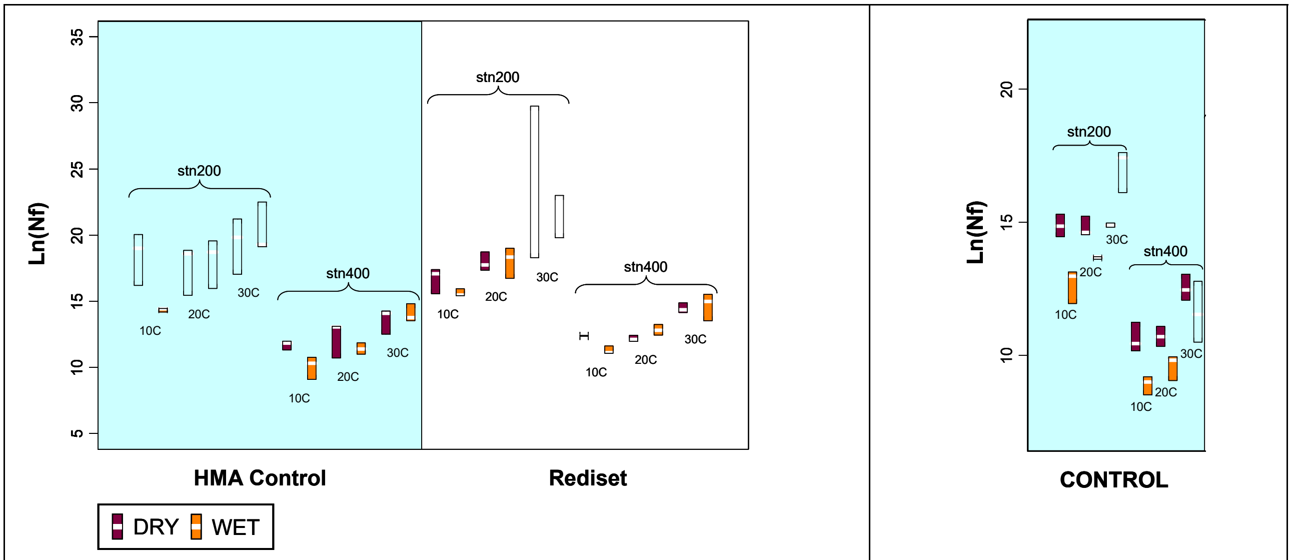
* Note different y-axis scales

Figure 3.9: Summary boxplots of initial phase angle.

3.3.4 Fatigue Life at 50 Percent Stiffness Reduction

Mix stiffness will decrease with increasing test-load repetitions. Conventional fatigue life is defined as the number of load repetitions when 50 percent stiffness reduction has been reached. A high fatigue life implies a slow fatigue damage rate and consequently higher fatigue-resistance for a given tensile strain. The side-by-side fatigue life comparison of dry and wet tests is plotted in Figure 3.10. The following observations were made:

- Fatigue life was both strain- and temperature-dependent. In general, lower strains and higher temperatures will result in higher fatigue life and vice versa.
- Water soaking had no significant effect on fatigue life in this study. The results of initial stiffness testing implied that a shorter fatigue life in the Control specimens was expected.
- There was no significant difference between the two mixes in terms of fatigue life at 50 percent stiffness reduction indicating that the addition of Rediset and lower production and compaction temperatures did not significantly influence the performance of the mix in this test.
- Fatigue life in the laboratory prepared specimens was similar to that in the specimens removed from the test track.



AkzoNobel Study*

Test Track*

* Note different y-axis scales

Figure 3.10: Summary boxplots of fatigue life.

3.3.5 Flexural Frequency Sweep

The average stiffness values of the two replicates tested at the three temperatures were used to develop the flexural complex modulus (E^*) master curve. This is considered a useful tool for characterizing the effects of loading frequency (or vehicle speed) and temperature on the initial stiffness of an asphalt mix (i.e., before any fatigue damage has occurred). The shifted master curve with minimized residual-sum-of-squares derived using a genetic algorithm approach can be appropriately fitted with the following modified Gamma function (Equation 3.3):

$$E^* = D + A \cdot \left(1 - \exp\left(-\frac{(x-C)}{B} \right) \cdot \sum_{m}^{n-1} \frac{(x-C)^m}{B^m m!} \right) \qquad \textbf{(3.3)}$$

where: E^* = flexural complex modulus (MPa);
$x = \ln freq + \ln aT$ = is the loading frequency in Hz and $\ln aT$ can be obtained from the temperature-shifting relationship (Equation 3.4);
A, B, C, D, and n are the experimentally-determined parameters.

$$\ln aT = A \cdot \left(1 - \exp\left(-\frac{T - Tref}{B} \right) \right) \qquad \textbf{(3.4)}$$

where: *lnaT* = is a horizontal shift to correct the temperature effect with the same unit as ln *freq*,
T = is the temperature in °C,
Tref = is the reference temperature, in this case, *Tref* = 20°C
A and *B* are the experimentally-determined parameters.

The experimentally-determined parameters of the modified Gamma function for each mix type are listed in Table 3.5, together with the parameters in the temperature-shifting relationship.

Table 3.5: Summary of Master Curves and Time-Temperature Relationships

Mix	Conditioning	Master Curve					Time-Temperature Relationship	
		N	A	B	C	D	A	B
Control	Dry	3	32,443.19	6.893,063	-8.287,896	288.375,3	11.464,0	-34.743,6
Rediset		3	38,681.50	7.815,284	-7.757,588	232.400,6	-16.056,4	-56.745,8
Test Track Control		3	36,709.04	6.776351	-6.193,638	287.721,8	-2.598,7	13.977,4
Control	Wet	3	3,575,422.00	58.034,36	-10.745,750	190.097,6	1.456,68	-7.685,26
Rediset		3	36,070.81	8.046,71	-7.211,638	252.660,9	-10.015,00	30.754,10
Test Track Control		3	91,682.18	11.873,93	-6.408,145	174.755,4	-3.973,13	14.364,80

Notes:

1. The reference temperature is 20°C.
2. The wet test specimens were soaked at 60°C.
3. Master curve Gamma-fitted equations:

If $n = 3$, $E^{*}=D+A\cdot\left(1-\exp\left(-\frac{(x-C)}{B}\right)\cdot\left(1+\frac{x-C}{B}+\frac{(x-C)^{2}}{2B^{2}}\right)\right)$,

If $n = 4$, $E^{*}=D+A\cdot\left(1-\exp\left(-\frac{(x-C)}{B}\right)\cdot\left(1+\frac{x-C}{B}+\frac{(x-C)^{2}}{2B^{2}}+\frac{(x-C)^{3}}{6B^{3}}\right)\right)$,

where $x=\ln freq+\ln aT$

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

Figure 3.11 and Figure 3.12 show the shifted master curves with Gamma-fitted lines and the temperature-shifting relationships, respectively, for the dry and wet beam fatigue frequency sweep tests. The temperature-shifting relationships were obtained during the construction of the complex modulus master curve and can be used to correct the temperature effect on initial stiffness. Note that a positive temperature correction value is applied when the temperature is lower than the reference temperature, while a negative temperature correction factor value is used when the temperature is higher than the reference temperature.

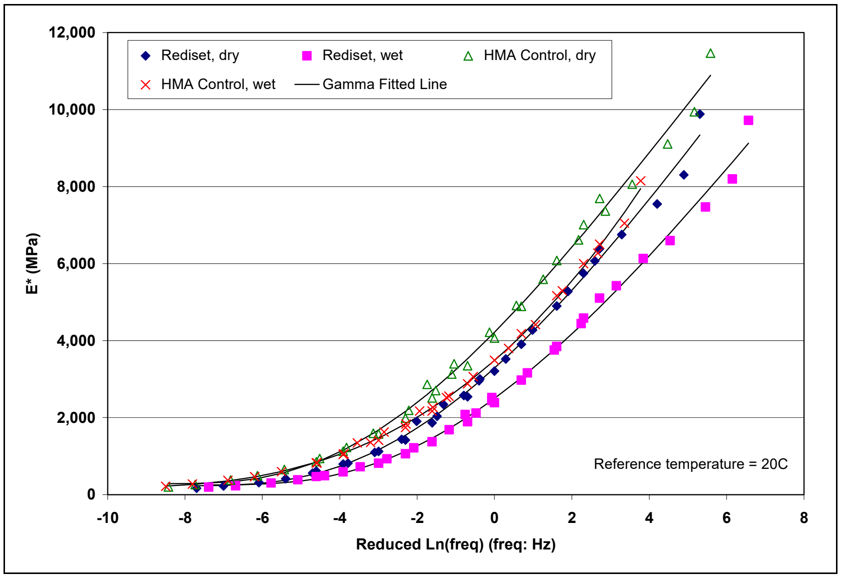


Figure 3.11: Complex modulus (*E) master curves.**

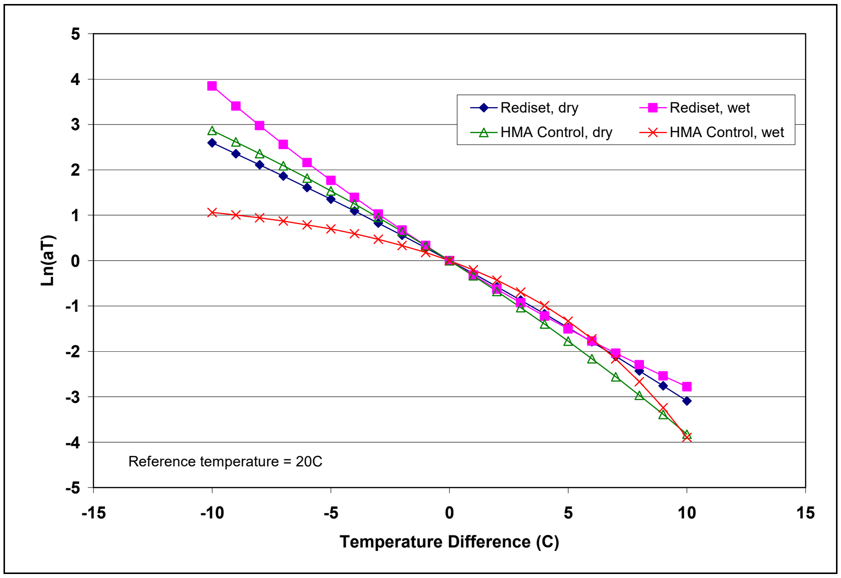


Figure 3.12: Fatigue frequency sweep temperature-shifting relationship.

The following observations were made from the frequency sweep test results:

- The results showed similar trends to those observed in the shear frequency sweep tests. The two mixes followed similar (and typical) trends, with the Rediset mix exhibiting lower stiffness at higher frequencies (i.e. more elastic binder properties under faster moving traffic) compared to the Control mix. At lower frequencies (i.e. more viscous binder properties under slower moving traffic), the performance was similar, with both mixes having very low stiffnesses, as expected. This behavior was again attributed to less oxidation of the binder during preparation of the specimens at the lower temperature and is typical of comparisons between aged and unaged binders and of other warm-mix asphalt tests. This behavior is unlikely to significantly affect fatigue performance on in-service pavements.
- A slight loss of stiffness attributed to moisture damage was apparent in both mixes, as expected.
- There were no apparent temperature-sensitivity differences between the two mixes, although the soaked Control specimens showed a different trend to the other specimens indicating that a greater loss in stiffness is likely in this mix as lower temperatures.

3.4 Moisture Sensitivity: Hamburg Wheel-Track Test

3.4.1 Air-Void Content

The air-void content of each slab specimen was calculated from the bulk specific gravity (measured in accordance with Method A of AASHTO T-166) and the theoretical maximum specific gravity (determined in accordance with ASTM D-2041). Air-void contents are listed in Table D.13 in Appendix D and summarized in Table 3.6, and include those from the test track control specimens. Air-void contents of the Rediset specimens (average 4.6 percent) were slightly lower than the Control (average 4.9 percent), while both the Control and Rediset specimens had notably lower air-void contents than the test track specimens (average 5.9 percent).

Table 3.6: Summary of Air-Void Content of Hamburg Wheel-Track Test Specimens

Mix	Bulk Specific Gravity (g/cm^3)		Max Specific Gravity (g/cm^3)		Air-Void Content (%)	
	Mean	SD[1]	Mean	SD	Mean	SD
Control	2.451	0.002	2.576	-	4.9	0.1
Rediset	2.456	0.008	2.575	-	4.6	0.3
Test Track Control	2.422	0.003	2.574	-	5.9	0.1

[1] Standard deviation

3.4.2 Test Results

The testing sequence of the specimens was randomized to avoid any potential block effect. Rut depth was recorded at 11 equally spaced points along the wheelpath on the specimen. The average of the middle seven points was then used in the analysis. This method ensures that localized distresses are smoothed and variance in the data is minimized. It should be noted that some state departments of transportation (e.g., Utah) only measure the point of maximum final rut depth, which usually results in a larger variance in the test results.

Figure 3.13 shows the rut progression curves of all specimens, in terms of both the maximum rut depth and average rut depth. As expected, the progression curves of the maximum rut depths had a larger variation. The stripping slope, stripping inflection point, and rut depths at 10,000 and 20,000 passes were calculated from the average rut progression curves, and are listed in Table D.14 in Appendix D and summarized in Table 3.7. Rut depths at 20,000 passes were linearly extrapolated for tests that terminated before the number of wheel passes reached this point.

Table 3.7: Summary of Hamburg Wheel Track Test Results (Average Rut)

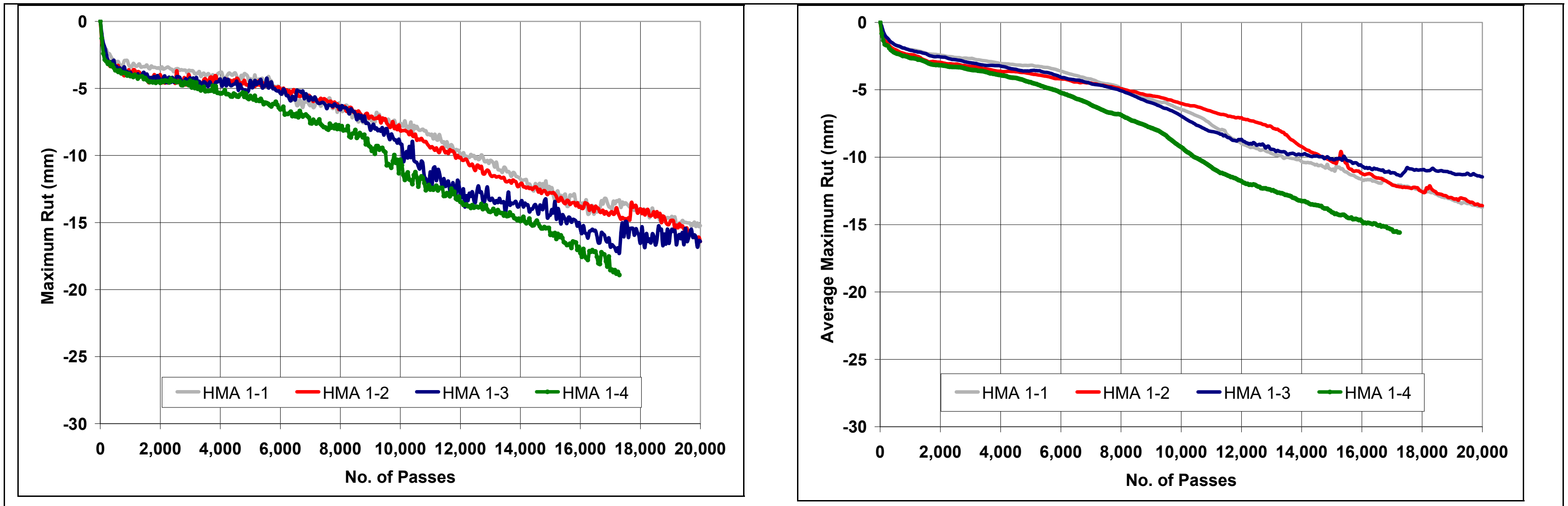
Specimen	Stripping Slope (mm/pass)		Stripping Inflection Point		Rut Depth @ 10,000 passes (mm)		Rut Depth @ 20,000 passes (mm)	
	Mean	SD[1]	Mean	SD	Mean	SD	Mean	SD
Control	-0.0009	0.0002	8,728	-	7.2	1.5	16.8	3.2
Rediset	-0.0001	0.0002	6,019	-	8.2	1.5	16.5	2.9
Test Track Control	-0.0017	0.0005	8,177	-	12.9	2.9	30.9	5.7

[1] Standard deviation

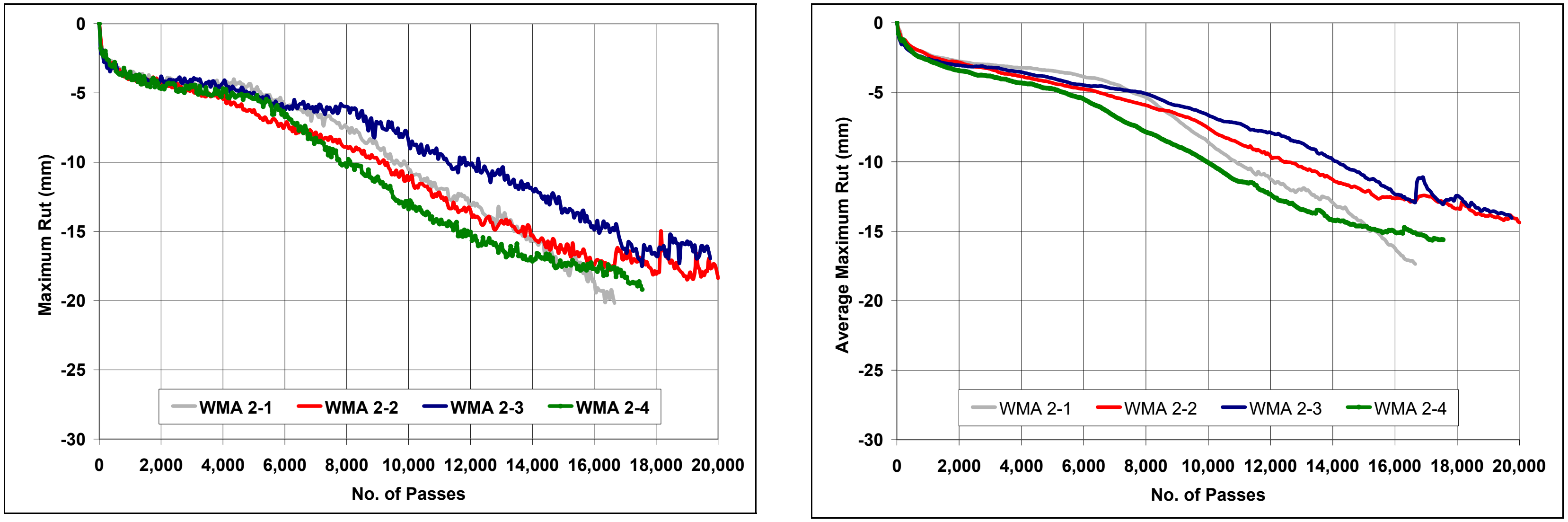
The results show similar trends for all specimens in both mixes, with average performance essentially the same between the Control and Rediset mixes after 20,000 passes. A one-way analysis of variance, using the stripping slope, stripping inflection point, and rut depth at 10,000 and 20,000 passes as the response variable, revealed no significant difference between the performances of the two mixes. This indicates that the addition of Rediset and production and compaction of the mix at lower temperatures did not influence the moisture sensitivity of the mix. It should be noted that all aggregates were oven dried (24 hours at 110°C [230°F]) before processing. No improvement in moisture resistance of the Rediset specimens was apparent from this test, as was evident in the initial stiffness tests on fatigue beams. This is consistent with other reported research in which uncured specimens were tested. A four-hour cure at 135°C (275°F) of the Rediset specimens, in line with Texas Department of Transportation recommendations is likely to result in improved moisture resistance in this test.

Both mixes out-performed the test track control mix. This was attributed to the higher air-void contents on the test track specimens.

Caltrans currently does not specify acceptance criteria for the Hamburg Wheel-Track Test, and the results can therefore not be interpreted in terms of Caltrans requirements. The current Texas Department of Transportation specifications specify a minimum number of wheel passes at 12.5 mm (0.5 in.) maximum rut depth. To accept a mix using a PG64-16 binder, a minimum of 10,000 passes before the maximum rut depth reaches 12.5 mm is required. Based on the results obtained in this study, both mixes met this requirement, although the test track Control mix did not.



Control: Maximum Rut **Control: Average Rut**



Rediset: Maximum Rut **Rediset: Average Rut**

Figure 3.13: Hamburg Wheel Track Test maximum and average rut progression curves.

3.5 Moisture Sensitivity: Tensile Strength Retained (TSR)

3.5.1 Air-Void Content

The air-void content of each Tensile Strength Retained (TSR) specimen was calculated from the bulk specific gravity (Method A of AASHTO T-166) and the theoretical maximum specific gravity (ASTM D-2041). Results are listed in Table D.15 in Appendix D and summarized in Table 3.8. The air-void contents are higher than in the other tests discussed in the report as a result of the prescribed test method followed (Caltrans CT-371), which requires higher air-void contents to allow some moisture ingress into the specimens. Test track specimens had lower air-void contents than the laboratory prepared specimens.

Table 3.8: Summary of Air-Void Content of TSR Test Specimens

Specimen	Bulk Specific Gravity (g/cm^3)		Max Specific Gravity (g/cm^3)		Air-Void Content (%)	
	Mean	SD[1]	Mean	SD	Mean	SD
Control, Dry	2.395	0.009	2.576	-	7.0	0.3
Control, Wet	2.383	0.002	2.575	-	7.5	0.1
Rediset, Dry	2.376	0.007	2.575	-	7.7	0.3
Rediset, Wet	2.388	0.008	2.575	-	7.3	0.3
Test Track Control, Dry	2.420	0.009	2.576	-	6.1	0.4
Test Track Control, Wet	2.417	0.010	2.576	-	6.2	0.4

[1] Standard deviation

3.5.2 Test Results

The Tensile Strength Retained for each mix is listed in Table D.16 in Appendix D and summarized in Table 3.9 and Figure 3.14. Note that in terms of the test method, the highest and lowest value for each set of dry and wet tests is excluded from the analysis (i.e., the results of four of the six specimens are analyzed).

Table 3.9: Summary of TSR Test Results

Specimen	Dry ITS		Wet ITS		TSR (%)	Damage[2]
	Mean	SD[1]	Mean	SD		
Control	2,487	191	613	36	25	Yes
Rediset	2,552	92	1,790	120	70	Yes
Test Track Control	905	138	564	80	62	Yes

[1] Standard deviation [2] Damage based on visual evaluation of stripping

The recorded TSR values for the laboratory and test track Control specimens were lower than the tentative criteria in the Caltrans Testing and Treatment Matrix to ensure moisture resistance (minimum 70 percent for low environmental risk regions, and minimum 75 percent for medium and high environmental risk regions). Treatment would therefore typically be required on these mixes to bring the test results up to the minimum to reduce the risk of moisture damage in the pavement. The values for the Rediset specimens were significantly higher than the control and just met the minimum 70 percent requirement for low environmental risk regions. The results indicate that the addition of Rediset reduced the moisture sensitivity of the mix.

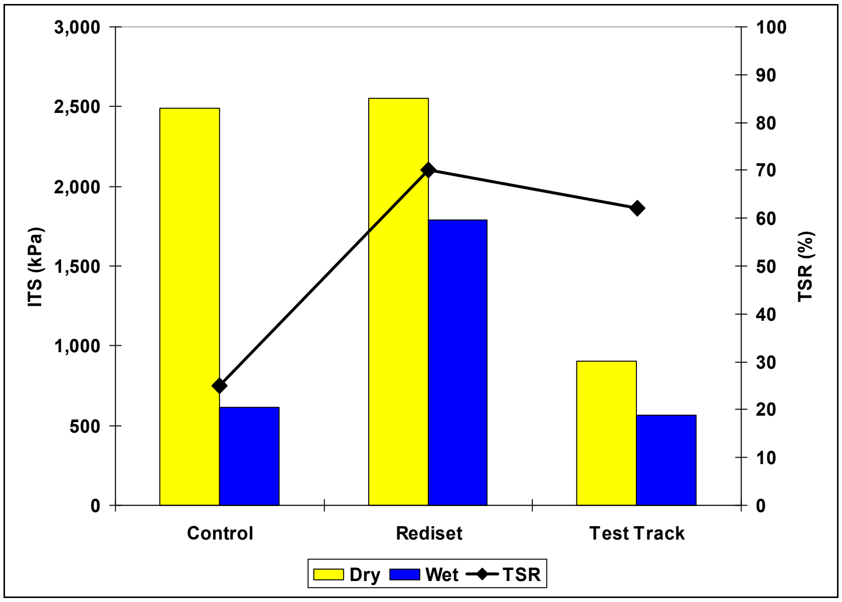


Figure 3.14: Tensile Strength Retained test results.

Observation of the split faces of the wet specimens revealed that both mixes showed some internal stripping (loss of adhesion between asphalt and aggregate evidenced by clean aggregate on the broken face) after moisture conditioning.

3.6 Durability of Open-Graded Friction Course Mixes: Cantabro Test

3.6.1 Air-Void Content

The air-void content of each Cantabro specimen was calculated from the bulk specific gravity (Method A of AASHTO T-166) and the theoretical maximum specific gravity (ASTM D-2041). Results are listed in Table D.17 in Appendix D and summarized in Table 3.10. The air-void contents were typical of laboratory compacted open-graded mix specimens and there was little difference between the Control and Rediset specimens. Note that Cantabro testing was not undertaken on the dense-graded test track materials.

Table 3.10: Summary of Air-Void Content of Cantabro Test Specimens

Specimen	Bulk Specific Gravity (g/cm^3)		Max Specific Gravity (g/cm^3)		Air-Void Content (%)	
	Mean	SD[1]	Mean	SD	Mean	SD
Control	2.112	0.005	2.576	-	18.0	0.2
Rediset	2.126	0.026	2.571	-	17.3	1.0

[1] Standard deviation

3.6.2 Test Results

The durability in terms of mass loss for each specimen in each mix is listed in Table D.18 in Appendix D and summarized in Table 3.11 and Figure 3.15.

Table 3.11: Summary of Cantabro Test Results

Specimen	Average Mass Before (g)	Average Mass After (g)	Average Mass Loss (%)	Standard Deviation
Control	1,198	1,096	8.5	1.3
Rediset	1,198	1,064	11.1	2.6
Test Track Control	Not tested	Not tested	-	-

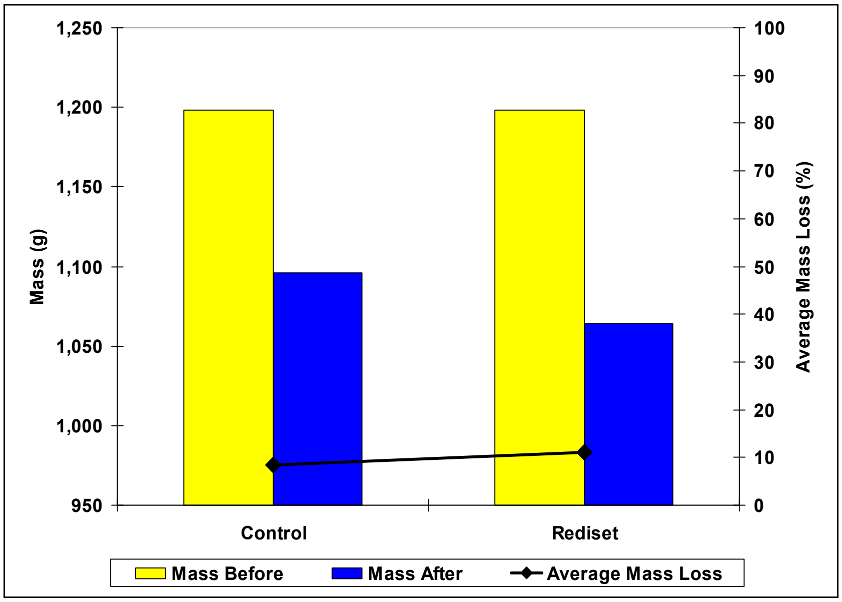


Figure 3.15: Cantabro test results.

The average mass loss was slightly higher on the Rediset specimens compared to the Control. There was also slightly higher variability in the Rediset test results. The difference between the two sets of specimens is considered to be acceptable in terms of the typical variation in Cantabro test results. This indicates that the addition of Rediset and production and compaction of the mix at lower temperatures is unlikely to influence the durability of the mix with respect to raveling.

3.7 Summary of Laboratory Testing Results

The laboratory test results discussed in the previous sections indicate that use of *Rediset^{TM} WMX* warm-mix asphalt additive assessed in this study, produced and compacted at lower temperatures, does not significantly influence the performance of asphalt concrete when compared to control specimens produced and compacted at conventional hot-mix asphalt temperatures. In the shear, fatigue, Hamburg Wheel Track and Cantabro tests, the results and trends in the results indicated similar performance between the two mixes, with minor differences attributed to the inherent variability of these tests and less oxidation of the binder in the Rediset specimens due to its lower mixing temperature. In the Tensile Strength Retained Test, the Rediset mix had significantly better moisture resistance compared to the Control mix.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This report summarizes a laboratory study to assess the performance of *Rediset*^{TM} *WMX* warm-mix additive. In this study, Rediset was used to produce a warm-mix asphalt mix, the performance of which was compared against the performance of a hot-mix asphalt control. The warm-mix asphalt was produced and compacted at 120°C (250°F) and 110°C (230°F) respectively, 35°C (63°F) lower than the Control mix, which was produced and compacted at 155°C (310°F) and 145°C (284°F) respectively.

Key findings from the study include:

- No problems were noted with producing and compacting the Rediset mix at the lower temperatures in the laboratory. The air-void contents of individual specimens were similar for both mixes, indicating that satisfactory laboratory-mixed and compacted specimens can be prepared with the warm mix.
- Interviews with laboratory staff revealed that no problems were experienced with preparing specimens at the lower temperatures. Improved and safer working conditions at the lower temperatures were identified as an advantage.
- The laboratory test results indicate that use of the Rediset warm-mix asphalt additive assessed in this study, produced and compacted at lower temperatures, does not significantly influence the performance of the asphalt concrete when compared to control specimens produced and compacted at conventional hot-mix asphalt temperatures. In the shear, fatigue, Hamburg Wheel Track, and Cantabro tests, the results and trends in the results indicated similar performance between the two mixes, and between the two mixes and the Control mix tested in an earlier Caltrans study. Minor differences in the results of these tests were attributed to the inherent variability of these tests and less oxidation of the binder in the Rediset specimens due to its lower mixing temperature. In the Tensile Strength Retained Test, the Rediset mix had significantly better moisture resistance compared to the Control mix in this study as well as the Control mix in the earlier Caltrans study.

4.2 Recommendations

The laboratory testing completed in this study has provided no results to suggest that *Rediset* ^{TM} *WMX* warm-mix additive should not be used to produce and place asphalt concrete at lower temperatures. These results should be verified in pilot studies on in-service pavements. The results of the Tensile Strength Retained test indicate that the use of Rediset could improve the moisture resistance of moisture sensitive mixes. This should be investigated further along with additional Hamburg Wheel Track tests on oven aged/cured samples to assess the effect of short-term curing on the results of this test.

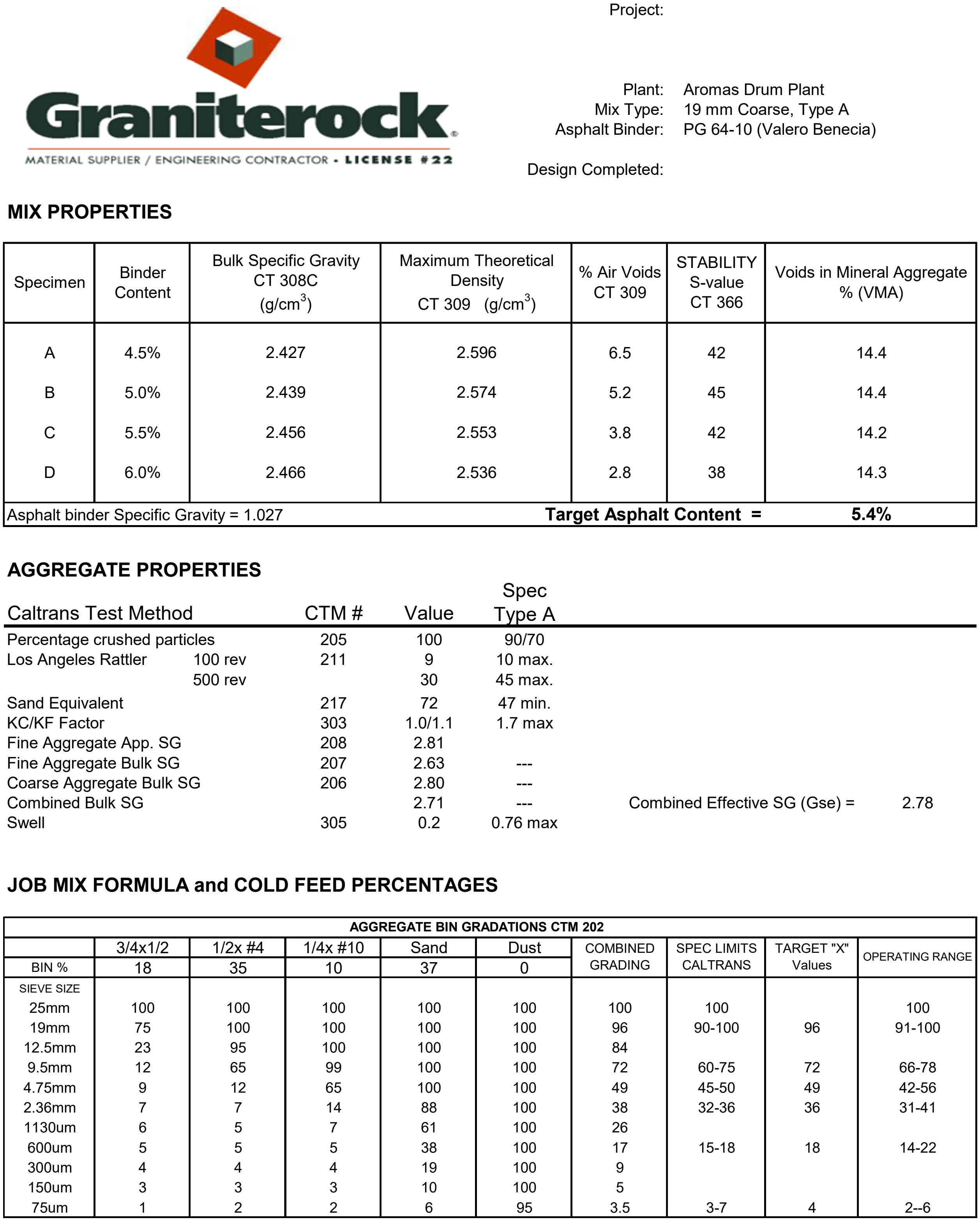
5. REFERENCES

1. JONES, D. and Harvey, J. 2007. **Warm-Mix Asphalt Study: Workplan for Comparison of Conventional and Warm-Mix Asphalt Performance using HVS and Laboratory Testing.** Davis and Berkeley, CA: University of California Pavement Research Center. (WP-2007-01).
2. JONES, D. Wu, R. Tsai, B. Lu, Q. and Harvey, J. 2008. **Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 1 HVS and Laboratory Testing.** Davis and Berkeley, CA: University of California Pavement Research Center. (RR-2008-11).
3. **Standard Specifications.** 2006. Sacramento, CA: State of California Department of Transportation.

APPENDIX A: MIX DESIGN EXAMPLES

A.1 Mix Design

Examples of Graniterock Company and Caltrans mix designs used for the production of asphalt concrete at the Graniterock Company's A.R. Wilson Asphalt Plant for earlier Caltrans projects are provided in Figure A.1 and Figure A.2. The Graniterock Company mix design was used in this study.



Project:

Plant: Aromas Drum Plant
Mix Type: 19 mm Coarse, Type A
Asphalt Binder: PG 64-10 (Valero Benecia)

Design Completed:

MIX PROPERTIES

Specimen	Binder Content	Bulk Specific Gravity CT 308C (g/cm^3)	Maximum Theoretical Density CT 309 (g/cm^3)	% Air Voids CT 309	STABILITY S-value CT 366	Voids in Mineral Aggregate % (VMA)
A	4.5%	2.427	2.596	6.5	42	14.4
B	5.0%	2.439	2.574	5.2	45	14.4
C	5.5%	2.456	2.553	3.8	42	14.2
D	6.0%	2.466	2.536	2.8	38	14.3
Asphalt binder Specific Gravity = 1.027				**Target Asphalt Content =**		**5.4%**

AGGREGATE PROPERTIES

Caltrans Test Method		CTM #	Value	Spec Type A
Percentage crushed particles		205	100	90/70
Los Angeles Rattler	100 rev	211	9	10 max.
	500 rev		30	45 max.
Sand Equivalent		217	72	47 min.
KC/KF Factor		303	1.0/1.1	1.7 max
Fine Aggregate App. SG		208	2.81	
Fine Aggregate Bulk SG		207	2.63	---
Coarse Aggregate Bulk SG		206	2.80	---
Combined Bulk SG			2.71	---
Swell		305	0.2	0.76 max

Combined Effective SG (Gse) = 2.78

JOB MIX FORMULA and COLD FEED PERCENTAGES

AGGREGATE BIN GRADATIONS CTM 202

	3/4x1/2	1/2x #4	1/4x #10	Sand	Dust	COMBINED GRADING	SPEC LIMITS CALTRANS	TARGET "X" Values	OPERATING RANGE
BIN %	18	35	10	37	0				
SIEVE SIZE									
25mm	100	100	100	100	100	100	100		100
19mm	75	100	100	100	100	96	90-100	96	91-100
12.5mm	23	95	100	100	100	84			
9.5mm	12	65	99	100	100	72	60-75	72	66-78
4.75mm	9	12	65	100	100	49	45-50	49	42-56
2.36mm	7	7	14	88	100	38	32-36	36	31-41
1130um	6	5	7	61	100	26			
600um	5	5	5	38	100	17	15-18	18	14-22
300um	4	4	4	19	100	9			
150um	3	3	3	10	100	5			
75um	1	2	2	6	95	3.5	3-7	4	2--6

Figure A.1: Example Graniterock Company mix design.

Graniterock
MATERIAL SUPPLIER / ENGINEERING CONTRACTOR • LICENSE #22

Project:

Plant: Aromas Drum Plant
Mix Type: 19 mm Coarse, Type A
Asphalt Binder: PG 64-10 (Valero Benecia)

Design Completed: January 0, 1900

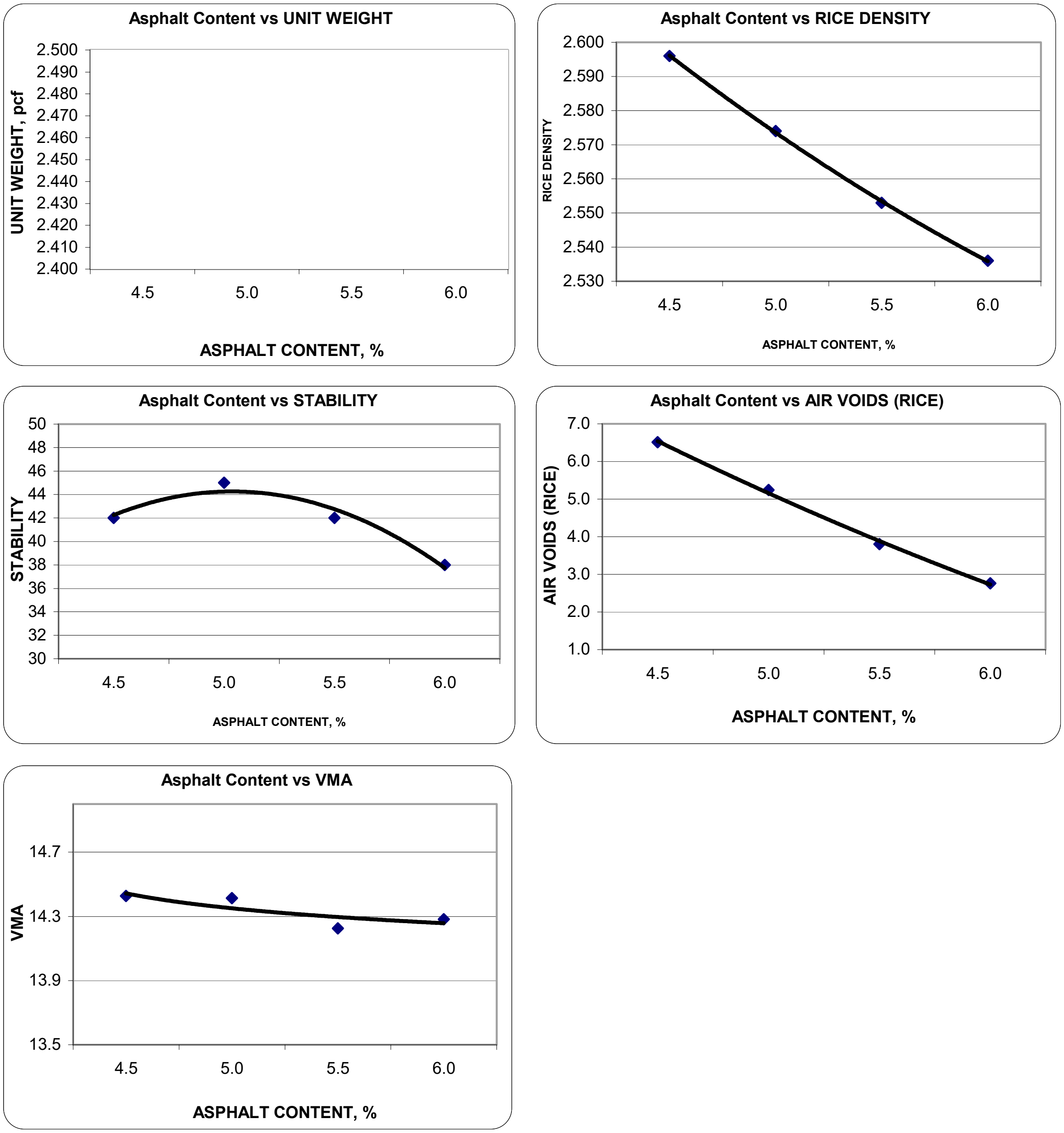


Figure A.1: Example Graniterock Company mix design (*continued*).

19mm Max Coarse, Type A
JOB MIX FORMULA

PERCENT PASSING

SIEVE SIZE (mm, um)		25	19	12.5	9.5	4.75	2.36	1130	600	300	150	75
UPPER SPECIFIED LIMIT		100	100	90	78	56	41	30	22	15	8.0	6.0
LOWER SPECIFIED LIMIT		100	91	78	66	42	31	22	14	7.0	4.0	2.0
JOB MIX FORMULA		**100**	**96**	**84**	**72**	**49**	**36**	**24**	**18**	**10**	**6.0**	**4.0**

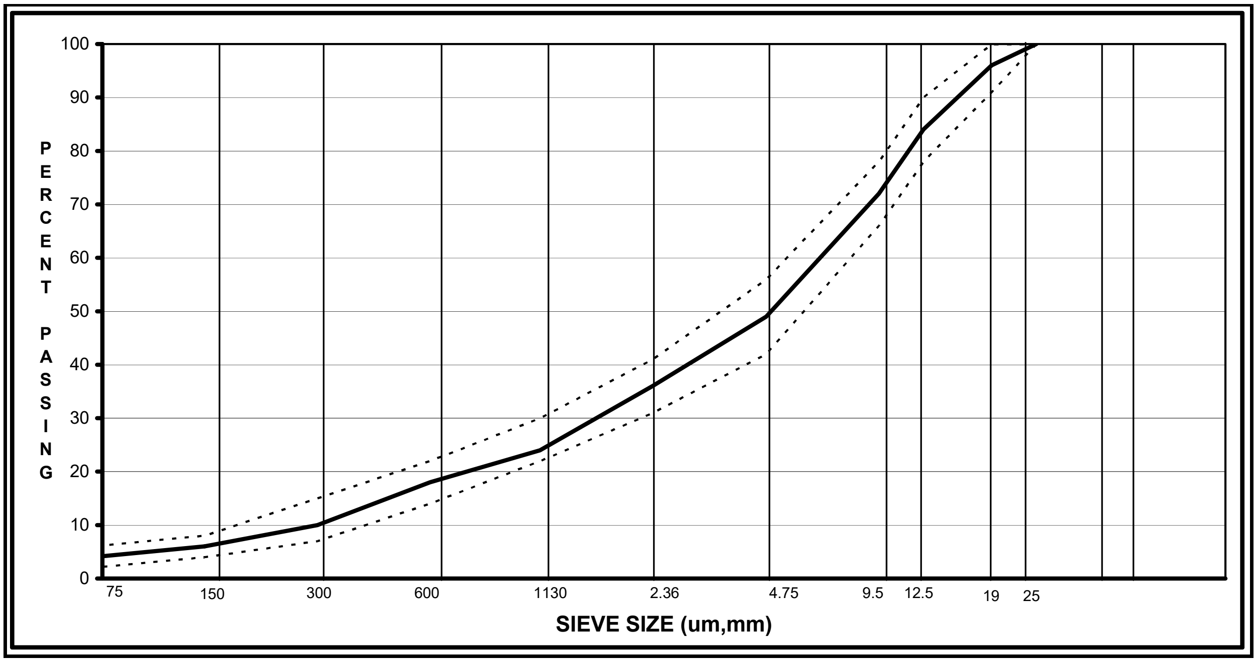
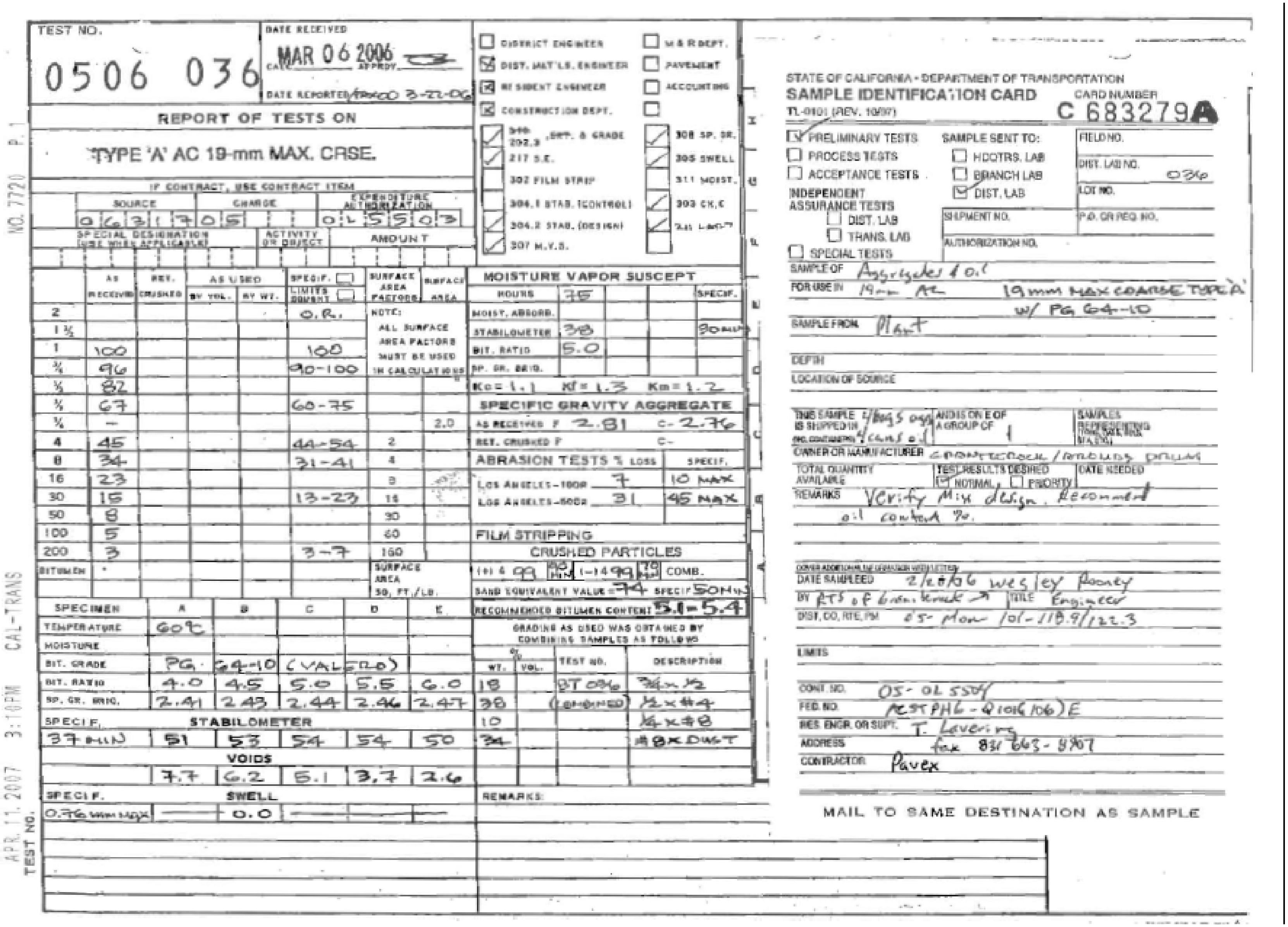


Figure A.1: Example Graniterock Company mix design (*continued*).



APR. 11. 2007 3:10PM CAL-TRANS NO. 7720 P. 1

TEST NO.

TEST NO. 0506 036

DATE RECEIVED MAR 06 2006

CALC. ____ APPRDY. ____

DATE REPORTED 3-22-06

☐ DISTRICT ENGINEER ☐ M & R DEPT.
☒ DIST. MAT'LS. ENGINEER ☐ PAVEMENT
☒ RESIDENT ENGINEER ☐ ACCOUNTING
☒ CONSTRUCTION DEPT. ☐

☑ ~~310~~ 202.3 ,SEP. & 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) ☑ 211 L.A.R.
☑ 307 M.V.S. ☐

REPORT OF TESTS ON

TYPE 'A' AC 19-mm MAX. CRSE.

IF CONTRACT, USE CONTRACT ITEM

SOURCE	CHARGE	EXPENDITURE AUTHORIZATION
0 6 3 1 7 0 5		0 L 5 5 0 3

SPECIAL DESIGNATION (USE WHEN APPLICABLE)	ACTIVITY OR OBJECT	AMOUNT

	AS RECEIVED	RET. CRUSHED	AS USED BY VOL.	AS USED BY WT.	SPECIF. ☐ LIMITS ☐ ORIGINAL ☐	SURFACE AREA FACTORS	SURFACE AREA
2					O.R.	NOTE: ALL SURFACE AREA FACTORS MUST BE USED IN CALCULATIONS	
1½							
1	100				100		
¾	96				90-100		
½	82						
⅜	67				60-75		
¼	—						2.0
4	45				44-54	2	
8	34				31-41	4	
16	23					8	
30	15				13-23	14	
50	8					30	
100	5					60	
200	3				3-7	160	
BITUMEN						SURFACE AREA SQ. FT./LB.	

SPECIMEN	A	B	C	D	E
TEMPERATURE	60°C				
MOISTURE					
BIT. GRADE	PG 64-10 (VALERO)				
BIT. RATIO	4.0	4.5	5.0	5.5	6.0
SP. GR. BRIQ.	2.41	2.43	2.44	2.46	2.47
SPECIF.	STABILOMETER				
37 min	51	53	54	54	50
	VOIDS				
	7.7	6.2	5.1	3.7	2.6
SPECIF.	SWELL				
0.76 mm max	—	0.0	—	—	—

MOISTURE VAPOR SUSCEPT

HOURS	75			SPECIF.
MOIST. ABSORB.				
STABILOMETER	38			30 min
BIT. RATIO	5.0			
SP. GR. BRIQ.				

Kc = 1.1 Kf = 1.3 Km = 1.2

SPECIFIC GRAVITY AGGREGATE

AS RECEIVED F 2.81 C- 2.76

RET. CRUSHED F C-

ABRASION TESTS % LOSS		SPECIF.
LOS ANGELES-100R	7	10 MAX
LOS ANGELES-500R	31	45 MAX

FILM STRIPPING

CRUSHED PARTICLES

(+) 4 99 90 min (-)4 99 70 min COMB.

SAND EQUIVALENT VALUE = 74 SPECIF 50 min

RECOMMENDED BITUMEN CONTENT 5.1-5.4

GRADING AS USED WAS OBTAINED BY COMBINING SAMPLES AS FOLLOWS

% WT.	% VOL.	TEST NO.	DESCRIPTION
18		BT 036 (COMBINED)	¾ x ½
38			½ x #4
10			¼ x #8
34			#8 x DUST

REMARKS:

STATE OF CALIFORNIA - DEPARTMENT OF TRANSPORTATION
SAMPLE IDENTIFICATION CARD
TL-0101 (REV. 10/97)

CARD NUMBER C 683279A

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

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

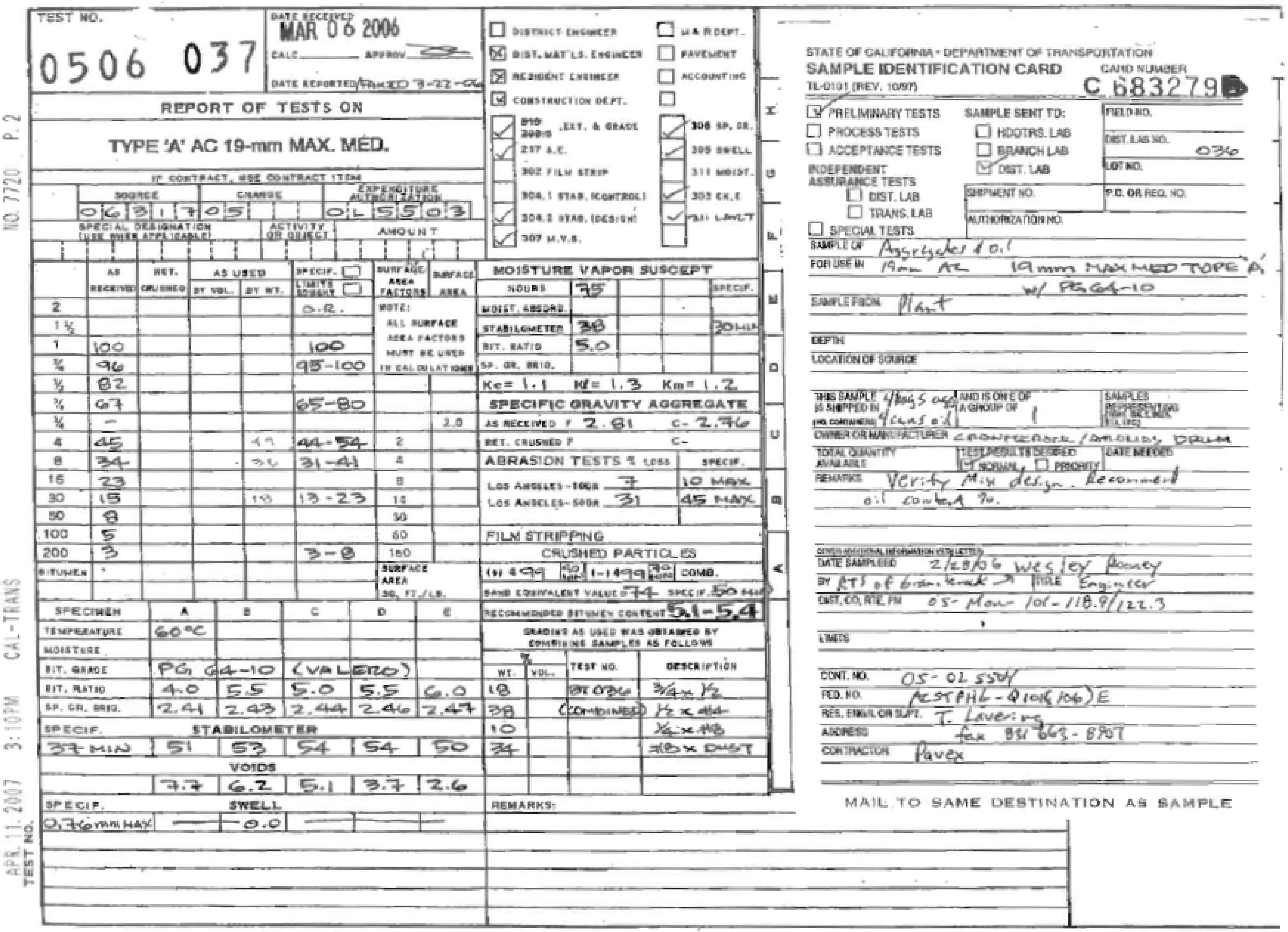
FIELD NO.
DIST. LAB NO. 036
LOT NO.
SHIPMENT NO.
P.O. OR REQ. NO.
AUTHORIZATION NO.

SAMPLE OF Aggregates & oil
FOR USE IN 19mm AC 19mm MAX COARSE TYPE 'A' w/ PG 64-10
SAMPLE FROM Plant
DEPTH
LOCATION OF SOURCE
THIS SAMPLE IS SHIPPED IN (NO. CONTAINERS) 5 bags agg 4 cans oil
AND IS ONE OF A GROUP OF 1
SAMPLES REPRESENTING (TONS, CWT, BBL, M.A.T.S.)
OWNER OR MANUFACTURER Granite Rock / Arroyos Drive
TOTAL QUANTITY AVAILABLE
TEST RESULTS DESIRED ☑ NORMAL ☐ PRIORITY
DATE NEEDED
REMARKS Verify Mix design. Recommend oil content %.

DATE SAMPLED 2/28/06 Wesley Rooney
BY RTS of Granite Rock → TITLE Engineer
DIST, CO, RTE, PM 05-Mon-101-118.9/122.3
LIMITS
CONT. NO. 05-0L5504
FED. NO. ACSTPHG-Q101(106)E
RES. ENGR. OR SUPT. T. Levering
ADDRESS fax 831 663-8707
CONTRACTOR Pavex

MAIL TO SAME DESTINATION AS SAMPLE

Figure A.2: Example Caltrans mix design.



NO. 7720 P. 2

APR. 11. 2007 3:10PM CAL-TRANS

TEST NO.

TEST NO. 0506 037

DATE RECEIVED MAR 06 2006

CALC. ______ APPROV.

DATE REPORTED FAXED 3-22-06

☐ DISTRICT ENGINEER
☒ DIST. MAT'LS. ENGINEER
☒ RESIDENT ENGINEER
☒ CONSTRUCTION DEPT.
☐ M & R DEPT.
☐ PAVEMENT
☐ ACCOUNTING
☐

☑ 210 202-B , EXT. & GRADE
☑ 217 A.C.
☐ 302 FILM STRIP
☐ 304.1 STAB. (CONTROL)
☑ 304.2 STAB. (DESIGN)
☑ 307 M.V.S.
☑ 306 SP. GR.
☑ 305 SWELL
☐ 311 MOIST.
☑ 303 CK.E
☑ 211 LAVLT
☐

REPORT OF TESTS ON

TYPE 'A' AC 19-mm MAX. MED.

IF CONTRACT, USE CONTRACT ITEM

SOURCE	CHARGE	EXPENDITURE AUTHORIZATION
0 6 3 1 7 0 5		0 L 5 5 0 3

SPECIAL DESIGNATION (USE WHEN APPLICABLE)	ACTIVITY OR OBJECT	AMOUNT

	AS RECEIVED	RET. CRUSHED	AS USED BY VOL.	AS USED BY WT.	SPECIF. ☐ LIMITS SOUGHT ☐	SURFACE AREA FACTORS	SURFACE AREA
2					O.R.	NOTE: ALL SURFACE AREA FACTORS MUST BE USED IN CALCULATIONS	
1½							
1	100				100		
¾	96				95-100		
½	82						
⅜	67				65-80		
¼	–						2.0
4	45			47	44-54	2	
8	34			36	31-41	4	
16	23					8	
30	15			18	13-23	14	
50	8					30	
100	5					60	
200	3				3-8	160	
BITUMEN						SURFACE AREA SQ. FT./LB.	

SPECIMEN	A	B	C	D	E
TEMPERATURE	60°C				
MOISTURE					
BIT. GRADE	PG 64-10 (VALERO)				
BIT. RATIO	4.0	5.5	5.0	5.5	6.0
SP. GR. BRIQ.	2.41	2.43	2.44	2.46	2.47
SPECIF.	STABILOMETER				
37 MIN	51	53	54	54	50
	VOIDS				
	7.7	6.2	5.1	3.7	2.6
SPECIF.	SWELL				
0.76 mm MAX	—	0.0	—	—	—

MOISTURE VAPOR SUSCEPT

HOURS	75			SPECIF.
MOIST. ABSORB.				
STABILOMETER	38			30 MIN
BIT. RATIO	5.0			
SP. GR. BRIQ.				

Kc= 1.1 Kf= 1.3 Km= 1.2

SPECIFIC GRAVITY AGGREGATE

AS RECEIVED F 2.81 C- 2.76

RET. CRUSHED F C-

ABRASION TESTS % LOSS	SPECIF.
LOS ANGELES-100R 7	10 MAX
LOS ANGELES-500R 31	45 MAX

FILM STRIPPING

CRUSHED PARTICLES

(+) 4 90 MIN | 1-149 90 MIN | COMB.

SAND EQUIVALENT VALUE 74 SPECIF. 50 MIN

RECOMMENDED BITUMEN CONTENT 5.1-5.4

GRADING AS USED WAS OBTAINED BY COMBINING SAMPLES AS FOLLOWS

% WT.	% VOL.	TEST NO.	DESCRIPTION
18		BT 036 (COMBINED)	¾ x ½
38			½ x #4
10			¼ x #8
34			#8 x DUST

REMARKS:

STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION
SAMPLE IDENTIFICATION CARD
TL-0101 (REV. 10/97)

CARD NUMBER C 683279

☑ 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. 036
LOT NO.
SHIPMENT NO.
P.O. OR REQ. NO.
AUTHORIZATION NO.

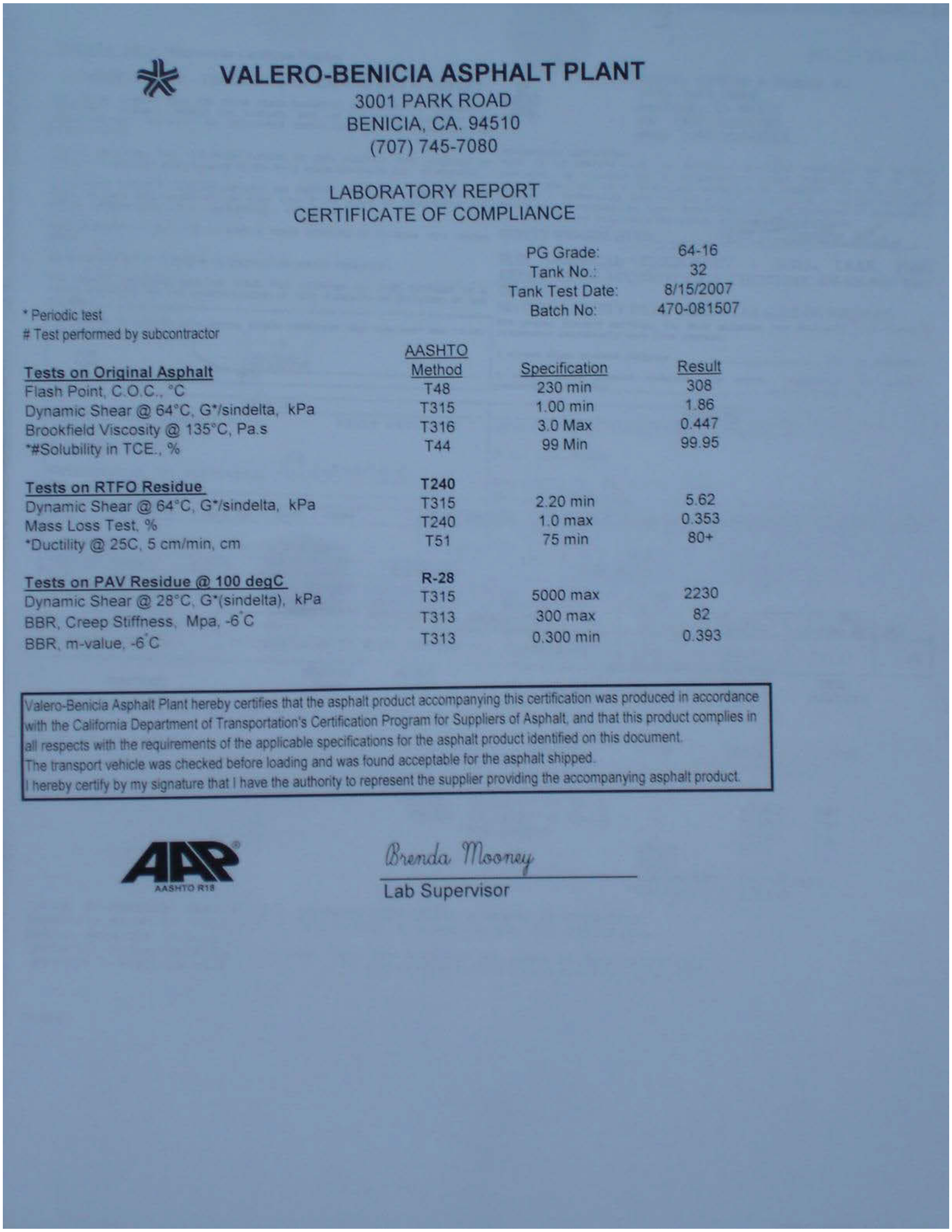
SAMPLE OF Aggregates & oil
FOR USE IN 19mm AC 19mm MAX MED TYPE 'A' w/ PG64-10
SAMPLE FROM Plant
DEPTH
LOCATION OF SOURCE
THIS SAMPLE IS SHIPPED IN (NO. CONTAINERS) 4 bags agg. 4 cans oil
AND IS ONE OF A GROUP OF 1
SAMPLES REPRESENTING
OWNER OR MANUFACTURER Granite Rock / Aromas Drum
TOTAL QUANTITY AVAILABLE
TEST RESULTS DESIRED ☑ NORMAL ☐ PRIORITY
DATE NEEDED
REMARKS Verify Mix design. Recommend oil content %.

OTHER ADDITIONAL INFORMATION (IF SELECTED)
DATE SAMPLED 2/28/06 Wesley Rooney
BY RTS of Granite Rock → TITLE Engineer
DIST, CO, RTE, PM 05- Mon 101- 118.9/122.3
LIMITS
CONT. NO. 05-0L5504
FED. NO. ACSTPHL-Q101(106)E
RES. ENGR. OR SUPT. T. Lavering
ADDRESS fax 831 663-8707
CONTRACTOR Pavex

MAIL TO SAME DESTINATION AS SAMPLE

Figure A.2: Example Caltrans mix design (*continued*).

APPENDIX B: BINDER COMPLIANCE CERTIFICATE



VALERO-BENICIA ASPHALT PLANT
3001 PARK ROAD
BENICIA, CA. 94510
(707) 745-7080

LABORATORY REPORT
CERTIFICATE OF COMPLIANCE

PG Grade: 64-16
Tank No.: 32
Tank Test Date: 8/15/2007
Batch No: 470-081507

* Periodic test
\# Test performed by subcontractor

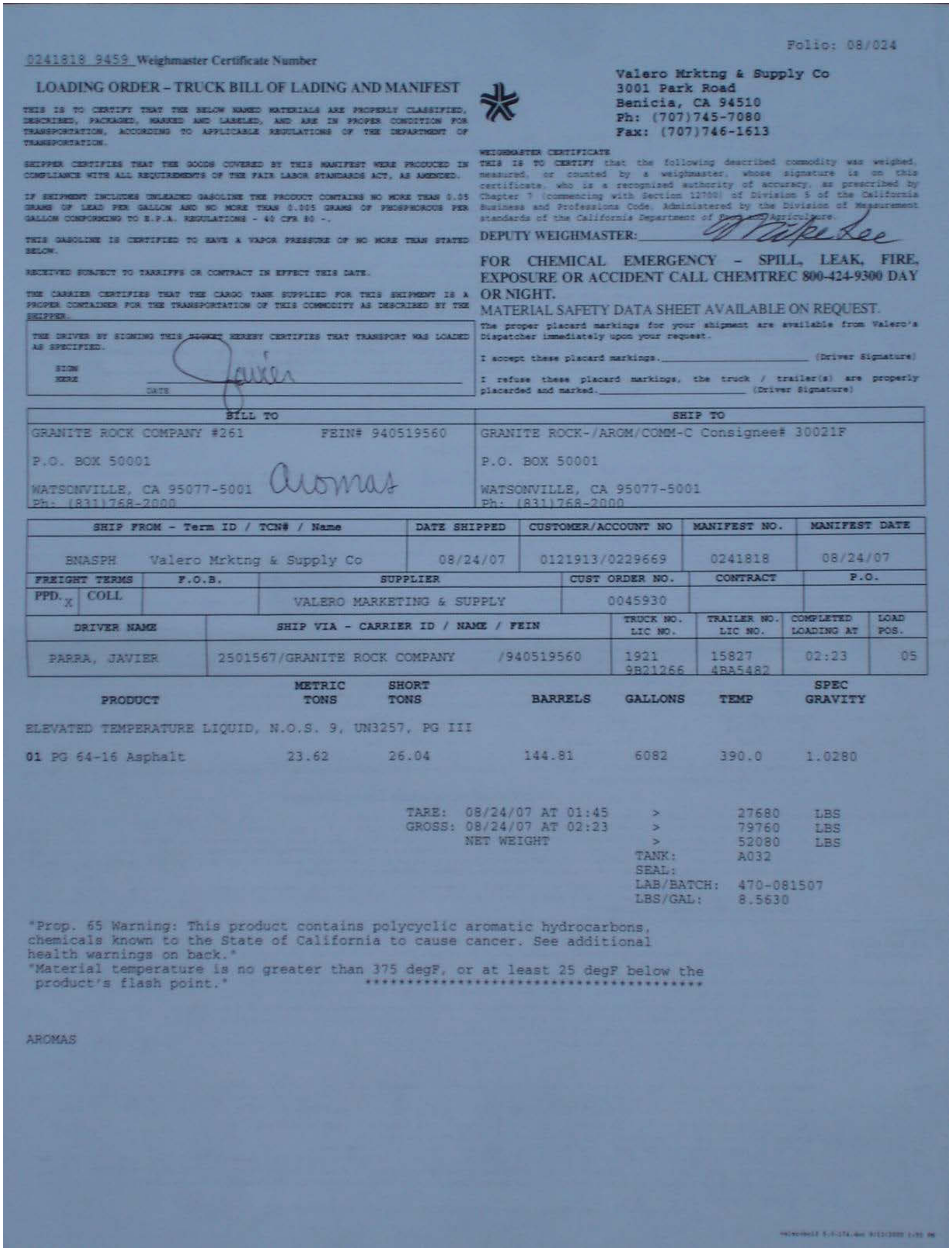
	AASHTO Method	Specification	Result
Tests on Original Asphalt			
Flash Point, C.O.C., °C	T48	230 min	308
Dynamic Shear @ 64°C, G*/sindelta, kPa	T315	1.00 min	1.86
Brookfield Viscosity @ 135°C, Pa.s	T316	3.0 Max	0.447
*#Solubility in TCE., %	T44	99 Min	99.95
Tests on RTFO Residue	**T240**		
Dynamic Shear @ 64°C, G*/sindelta, kPa	T315	2.20 min	5.62
Mass Loss Test, %	T240	1.0 max	0.353
*Ductility @ 25C, 5 cm/min, cm	T51	75 min	80+
Tests on PAV Residue @ 100 degC	**R-28**		
Dynamic Shear @ 28°C, G*(sindelta), kPa	T315	5000 max	2230
BBR, Creep Stiffness, Mpa, -6°C	T313	300 max	82
BBR, m-value, -6°C	T313	0.300 min	0.393

Valero-Benicia Asphalt Plant hereby certifies that the asphalt product accompanying this certification was produced in accordance with the California Department of Transportation's Certification Program for Suppliers of Asphalt, and that this product complies in all respects with the requirements of the applicable specifications for the asphalt product identified on this document.
The transport vehicle was checked before loading and was found acceptable for the asphalt shipped.
I hereby certify by my signature that I have the authority to represent the supplier providing the accompanying asphalt product.

AASHTO R18

Brenda Mooney
Lab Supervisor

Figure B.1: Binder compliance certificate.



Folio: 08/024

0241818 9459 Weighmaster Certificate Number

LOADING ORDER – TRUCK BILL OF LADING AND MANIFEST

THIS IS TO CERTIFY THAT THE BELOW NAMED MATERIALS ARE PROPERLY CLASSIFIED, DESCRIBED, PACKAGED, MARKED AND LABELED, AND ARE IN PROPER CONDITION FOR TRANSPORTATION, ACCORDING TO APPLICABLE REGULATIONS OF THE DEPARTMENT OF TRANSPORTATION.

SHIPPER CERTIFIES THAT THE GOODS COVERED BY THIS MANIFEST WERE PRODUCED IN COMPLIANCE WITH ALL REQUIREMENTS OF THE FAIR LABOR STANDARDS ACT, AS AMENDED.

IF SHIPMENT INCLUDES UNLEADED GASOLINE THE PRODUCT CONTAINS NO MORE THAN 0.05 GRAMS OF LEAD PER GALLON AND NO MORE THAN 0.005 GRAMS OF PHOSPHOROUS PER GALLON CONFORMING TO E.P.A. REGULATIONS - 40 CFR 80 -.

THIS GASOLINE IS CERTIFIED TO HAVE A VAPOR PRESSURE OF NO MORE THAN STATED BELOW.

RECEIVED SUBJECT TO TARRIFFS OR CONTRACT IN EFFECT THIS DATE.

THE CARRIER CERTIFIES THAT THE CARGO TANK SUPPLIED FOR THIS SHIPMENT IS A PROPER CONTAINER FOR THE TRANSPORTATION OF THIS COMMODITY AS DESCRIBED BY THE SHIPPER.

THE DRIVER BY SIGNING THIS TICKET HEREBY CERTIFIES THAT TRANSPORT WAS LOADED AS SPECIFIED.

SIGN HERE Javier

DATE

Valero Mrktng & Supply Co
3001 Park Road
Benicia, CA 94510
Ph: (707)745-7080
Fax: (707)746-1613

WEIGHMASTER CERTIFICATE
THIS IS TO CERTIFY that the following described commodity was weighed, measured, or counted by a weighmaster, whose signature is on this certificate, who is a recognized authority of accuracy, as prescribed by Chapter 7 (commencing with Section 12700) of Division 5 of the California Business and Professions Code. Administered by the Division of Measurement standards of the California Department of Food and Agriculture.

DEPUTY WEIGHMASTER:

FOR CHEMICAL EMERGENCY – SPILL, LEAK, FIRE, EXPOSURE OR ACCIDENT CALL CHEMTREC 800-424-9300 DAY OR NIGHT.

MATERIAL SAFETY DATA SHEET AVAILABLE ON REQUEST.

The proper placard markings for your shipment are available from Valero's Dispatcher immediately upon your request.

I accept these placard markings.________________ (Driver Signature)

I refuse these placard markings, the truck / trailer(s) are properly placarded and marked.________________ (Driver Signature)

BILL TO	SHIP TO
GRANITE ROCK COMPANY #261 FEIN# 940519560 P.O. BOX 50001 WATSONVILLE, CA 95077-5001 aromas Ph: (831)768-2000	GRANITE ROCK-/AROM/COMM-C Consignee# 30021F P.O. BOX 50001 WATSONVILLE, CA 95077-5001 Ph: (831)768-2000

SHIP FROM - Term ID / TCN# / Name	DATE SHIPPED	CUSTOMER/ACCOUNT NO	MANIFEST NO.	MANIFEST DATE
BNASPH Valero Mrktng & Supply Co	08/24/07	0121913/0229669	0241818	08/24/07

FREIGHT TERMS		F.O.B.	SUPPLIER	CUST ORDER NO.	CONTRACT	P.O.
PPD. X	COLL		VALERO MARKETING & SUPPLY	0045930		

DRIVER NAME	SHIP VIA - CARRIER ID / NAME / FEIN	TRUCK NO. LIC NO.	TRAILER NO. LIC NO.	COMPLETED LOADING AT	LOAD POS.
PARRA, JAVIER	2501567/GRANITE ROCK COMPANY /940519560	1921 9B21266	15827 4BA5482	02:23	05

PRODUCT	METRIC TONS	SHORT TONS	BARRELS	GALLONS	TEMP	SPEC GRAVITY
ELEVATED TEMPERATURE LIQUID, N.O.S. 9, UN3257, PG III						
01 PG 64-16 Asphalt	23.62	26.04	144.81	6082	390.0	1.0280

```
TARE:  08/24/07 AT 01:45     >         27680    LBS
GROSS: 08/24/07 AT 02:23     >         79760    LBS
       NET WEIGHT            >         52080    LBS
                         TANK:         A032
                         SEAL:
                         LAB/BATCH:    470-081507
                         LBS/GAL:      8.5630
```

"Prop. 65 Warning: This product contains polycyclic aromatic hydrocarbons, chemicals known to the State of California to cause cancer. See additional health warnings on back."
"Material temperature is no greater than 375 degF, or at least 25 degF below the product's flash point." **************************************

AROMAS

Figure B.1: Binder compliance certificate (*continued*).

APPENDIX C: FATIGUE BEAM SOAKING PROCEDURE

C.1 Preparation of Specimens

Specimens are prepared as follows:

1. The bulk specific gravity, width, and height of each beam shall first be measured and recorded.
2. Each beam is dried at room temperature (around 30°C) in a forced draft oven or in a concrete conditioning room to constant mass (defined as the mass at which further drying does not alter the mass by more than 0.05 percent at two-hour drying intervals). The final dry mass should be recorded. Note: Beams should be placed on a rigid and flat surface during drying.
3. A nut used for supporting the LVDT is bonded to the beam using epoxy resin. The mass of the beam with the nut should be recorded.

C.2 Conditioning of Specimens

1. Place the beam in the vacuum container supported above the container bottom by a spacer. Fill the container with water so that the beam is totally submerged in the water. Apply a vacuum of 635 mm (25 in.) of mercury for 30 minutes. Remove the vacuum and determine the saturated surface dry mass according to AASHTO T-166. Calculate the volume of absorbed water and determine the degree of saturation. If the saturation level is less than 70 percent, vacuum saturate the beam for a longer time and determine the saturated surface dry mass again.
2. Place the vacuum-saturated beam in a water bath with the water temperature pre-set at 60°C. The beam should be supported on a rigid, flat (steel or wood) plate to prevent deformation of the beam during conditioning. The top surface of the beam should be about 25 mm below the water surface.
3. After 24 hours, drain the water bath and refill it with cold tap water. Set the water bath temperature to 20°C. Wait for 2 hours for temperature equilibrium.
4. Remove the beam from the water bath, and determine its saturated surface dry mass.
5. Wrap the beam with Parafilm to ensure no water leakage.
6. Check the bonded nut. If it becomes loose, remove it and rebond it with epoxy resin.
7. Apply a layer of scotch tape to the areas where the beam contacts the clamps of the fatigue machine. This will prevent adhesion between the Parafilm and the clamps.
8. Start the fatigue test of the conditioned beam within 24 hours.

APPENDIX D: TEST RESULTS

Table D.1: Shear Test Results: Control

Specimen Designation	AV[1] (%)	AC[2] (%)	Temp[3] (°C)	Shear Stress (kPa)	*G*[4] (MPa)	PSS[5] at 5,000 cycles	Cycles to 5% PSS[6]
CL-3-1A-7045	4.0	5.3	45.0	75.4	290.0	0.006663	2.374832E+15
CL-6-1B-7045	4.1	5.3	45.2	79.4	383.1	0.008191	3.120690E+12
CL-7-3A-7045	4.7	5.3	45.0	84.0	361.6	0.009852	9.028634E+10
CL-1-1A-10045	4.7	5.3	45.6	106.0	387.6	0.009806	7.569411E+10
CL-2-1B-10045	4.8	5.3	45.1	102.5	381.9	0.018421	5,593,668
CL-5-2A-10045	5.0	5.3	44.9	108.5	308.7	0.013424	75,735,391
CL-4-3B-13045	4.5	5.3	45.0	136.9	328.4	0.017948	1,525,527
CL-5-3A-13045	4.9	5.3	45.0	132.5	361.2	0.016156	6,060,987
CL-9-2A-13045	4.3	5.3	44.9	137.2	306.2	0.01327	131,428,782
CL-5-1A-7055	5.0	5.3	54.8	71.8	110.3	0.017655	25,387,372
CL-6-3B-7055	4.2	5.3	54.9	74.8	164.5	0.011791	77,958,903,446
CL-10-2B-7055	4.9	5.3	54.9	74.0	151.6	0.022169	1,280,591
CL-1-2A-10055	4.5	5.3	54.9	103.8	179.7	0.013414	394,417,775
CL-2-3B-10055	5.0	5.3	54.9	102.8	159.4	0.020001	1,884,150
CL-3-3A-10055	4.1	5.3	54.9	104.1	226.6	0.012614	1,103,540,372
CL-7-2A-13055	5.0	5.3	54.9	132.1	147.0	0.024971	219,234
CL-10-1B-13055	4.4	5.3	55.0	131.4	133.0	0.027456	175,392
CL-10-3B-13055	4.7	5.3	54.7	132.7	146.9	0.032392	54,864

[1] Air-void content
[2] Binder content
[3] Temperature
[2] Initial resilient shear modulus
[4] Permanent shear strain
[5] Extrapolated values

Table D.2: Shear Test Results: Rediset

Specimen Designation	AV[1] (%)	AC[2] (%)	Temp[3] (°C)	Shear Stress (kPa)	*G*[4] (MPa)	PSS[5] at 5,000 cycles	Cycles to 5% PSS[6]
AN-2-1B-7045	4.4	5.3	44.9	77.4	341.3	0.009685	1,244,417,062
AN-8-2B-7045	4.3	5.3	45.0	77.3	197.7	0.016707	10,754,354
AN-9-1A-7045	4.2	5.3	44.9	79.6	320.7	0.013912	16,030,687
AN-1-2A-10045	3.8	5.3	44.9	103.0	210.7	0.015462	123,550,930
AN-1-3A-10045	4.6	5.3	45.1	103.7	314.4	0.012149	41,798,862
AN-4-2B-10045	4.8	5.3	45.2	103.9	251.9	0.018938	3,216,499
AN-2-3B-13045	4.3	5.3	45.0	138.7	258.9	0.013932	34,062,156
AN-6-1B-13045	4.5	5.3	45.0	134.9	250.8	0.017908	33,140,885
AN-8-3B-13045	4.9	5.3	45.0	134.5	213.8	0.022280	1,446,160
AN-4-3B-7055	4.4	5.3	54.9	76.0	99.0	0.020923	10,444,554
AN-5-1A-7055	4.4	5.3	55.0	77.0	118.5	0.021598	48,722,469
AN-8-1B-7055	4.5	5.3	55.0	84.6	97.6	0.020814	824,426
AN-4-1B-10055	4.5	5.3	55.2	102.6	127.9	0.025808	444,862
AN-7-1A-10055	4.5	5.3	54.8	97.0	129.5	0.030551	55,482
AN-10-2B-10055	4.3	5.3	55.0	104.6	169.2	0.023302	379,673
AN-1-1A-13055	4.7	5.3	54.9	130.5	116.7	0.027924	28,936
AN-5-2A-13055	4.1	5.3	54.9	130.1	119.4	0.027365	101,700
AN-9-2A-13055	4.8	5.3	54.9	131.4	114.7	0.040790	10,069

[1] Air-void content
[2] Binder content
[3] Temperature
[2] Initial resilient shear modulus
[4] Permanent shear strain
[5] Extrapolated values

Table D.3: Shear Frequency Sweep Test Results: Control

CL-1-3A-FS @ 35°C (AV = 4.3%)						CL-4-1B-FS @ 35°C (AV = 4.9%)						Avg. G* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degrees)	Modulus (G*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degrees)	Modulus (G*) (MPa)	
5.00	0.322124	0.001001	35.10	57.57	321.91	5.00	0.287183	0.000990	35.15	50.38	289.96	305.94
2.00	0.288145	0.000992	35.18	43.20	290.55	2.00	0.245345	0.000994	35.07	50.39	246.88	268.71
1.00	0.206768	0.000975	35.15	43.18	212.02	1.00	0.177884	0.000982	35.07	50.38	181.19	196.60
0.50	0.151229	0.000974	35.18	50.39	155.27	0.50	0.131234	0.000987	35.02	50.39	132.97	144.12
0.20	0.099861	0.000991	35.15	50.40	100.76	0.20	0.085779	0.000989	35.11	50.40	86.74	93.75
0.10	0.074607	0.000996	35.12	50.40	74.93	0.10	0.064472	0.000996	35.13	50.40	64.73	69.83
0.05	0.055070	0.000987	35.14	50.41	55.79	0.05	0.047660	0.000988	35.10	50.40	48.26	52.02
0.02	0.036750	0.000978	35.12	50.41	37.59	0.02	0.032513	0.000988	35.11	50.41	32.90	35.25
0.01	0.027752	0.000977	35.13	50.40	28.40	0.01	0.024576	0.000976	35.10	50.40	25.17	26.79

CL-4-2B-FS @ 45°C (AV = 4.8%)						CL-9-1A-FS @ 45°C (AV = 4.4%)						Avg. G* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degrees)	Modulus (G*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degrees)	Modulus (G*) (MPa)	
10.00	0.161399	0.001002	45.57	57.58	161.14	10.00	0.145761	0.001015	45.60	50.38	143.62	152.38
5.00	0.160010	0.001026	45.66	50.42	155.95	5.00	0.132347	0.001037	45.67	50.42	127.63	141.79
2.00	0.104770	0.001043	45.76	50.36	100.46	2.00	0.089285	0.001064	45.66	50.34	83.89	92.17
1.00	0.072135	0.001011	45.71	50.40	71.36	1.00	0.062039	0.001024	45.57	43.20	60.57	65.97
0.50	0.050802	0.000999	45.67	50.40	50.84	0.50	0.045649	0.001010	45.59	43.22	45.20	48.02
0.20	0.032357	0.000994	45.67	50.40	32.56	0.20	0.031114	0.001000	45.51	43.20	31.11	31.83
0.10	0.023801	0.000993	45.72	50.42	23.97	0.10	0.024675	0.000992	45.49	43.22	24.88	24.42
0.05	0.017848	0.000988	45.73	50.41	18.06	0.05	0.020363	0.000991	45.54	43.22	20.56	19.31
0.02	0.012602	0.000988	45.88	43.21	12.75	0.02	0.016368	0.000988	45.43	36.03	16.58	14.66
0.01	0.010033	0.000988	45.94	43.21	10.15	0.01	0.014496	0.000987	45.41	36.02	14.69	12.42

CL-3-2A @ 55°C (AV = 4.1%)						CL-6-2B-FS @ 55°C (AV = 4.0%)						Avg. G* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degrees)	Modulus (G*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degrees)	Modulus (G*) (MPa)	
10.00	0.124659	0.001042	55.08	57.59	119.66	10.00	0.138919	0.001047	54.31	50.38	132.64	126.15
5.00	0.086582	0.001058	54.49	57.63	81.82	5.00	0.105728	0.001054	54.70	43.22	100.36	91.09
2.00	0.057657	0.001075	54.65	50.35	53.61	2.00	0.078261	0.001076	54.74	43.15	72.71	63.16
1.00	0.041950	0.001031	55.00	50.41	40.69	1.00	0.061660	0.001021	54.04	36.00	60.38	50.54
0.50	0.031705	0.001014	54.93	43.22	31.26	0.50	0.050711	0.001007	54.25	36.01	50.35	40.81
0.20	0.023060	0.000996	54.85	43.21	23.15	0.20	0.040804	0.000991	54.43	36.01	41.16	32.16
0.10	0.019514	0.000998	54.83	43.22	19.55	0.10	0.036444	0.000994	54.64	36.01	36.67	28.11
0.05	0.016837	0.000989	54.63	36.03	17.02	0.05	0.032979	0.000991	54.67	36.02	33.29	25.15
0.02	0.014697	0.000990	54.82	36.03	14.85	0.02	0.029873	0.000986	54.56	28.81	30.29	22.57
0.01	0.013584	0.000978	54.82	36.02	13.89	0.01	0.028053	0.000978	54.62	28.81	28.67	21.28

Table D.4: Shear Frequency Sweep Test Results: Rediset

AN-3-1A-FS @ 35°C (AV = 4.2%)						AN-7-3A-FS @ 35°C (AV = 4.1%)						Avg. G* (MPa)
Freq. (Hz)	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degrees)**	**Modulus (G*) (MPa)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degrees)**	**Modulus (G*) (MPa)**	
5.00	0.323204	0.001001	35.09	51.42	322.88	5.00	0.316705	0.000991	35.07	50.41	319.72	321.30
2.00	0.203487	0.000998	35.26	57.58	203.84	2.00	0.204487	0.001004	35.04	57.59	203.59	203.72
1.00	0.143510	0.000986	35.17	57.59	145.52	1.00	0.141696	0.000988	35.05	57.59	143.45	144.49
0.50	0.102669	0.000988	35.15	50.42	103.91	0.50	0.100267	0.000989	35.00	50.40	101.39	102.65
0.20	0.064109	0.000984	35.26	50.42	65.15	0.20	0.063178	0.000994	35.08	50.41	63.57	64.36
0.10	0.046762	0.000987	35.22	50.41	47.36	0.10	0.046399	0.000998	35.09	50.40	46.51	46.94
0.05	0.034555	0.000990	35.24	50.43	34.91	0.05	0.034634	0.000996	35.09	50.42	34.77	34.84
0.02	0.023573	0.000989	35.25	50.42	23.85	0.02	0.023794	0.000989	35.08	50.43	24.05	23.95
0.01	0.018003	0.000982	35.28	50.43	18.33	0.01	0.018991	0.000988	35.08	50.43	19.21	18.77
AN-2-2B-FS @ 45°C (AV = 4.0%)						**AN-2-3B-FS @ 45°C (AV = 4.3%)**						**Avg. G* (MPa)**
Freq. (Hz)	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degrees)**	**Modulus (G*) (MPa)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degrees)**	**Modulus (G*) (MPa)**	
10.00	0.155395	0.001019	45.20	57.58	152.57	10.00	0.149881	0.001012	44.92	50.38	148.17	150.37
5.00	0.112609	0.001043	45.26	57.62	107.92	5.00	0.100301	0.001042	45.00	50.41	96.22	102.07
2.00	0.069946	0.001065	45.22	50.35	65.66	2.00	0.062467	0.001068	44.99	50.35	58.48	62.07
1.00	0.047862	0.001032	45.23	50.41	46.39	1.00	0.043481	0.001031	45.04	50.42	42.19	44.29
0.50	0.033281	0.001015	45.20	50.42	32.78	0.50	0.030599	0.001016	45.02	43.23	30.13	31.46
0.20	0.021279	0.000995	45.26	50.40	21.38	0.20	0.019981	0.000995	45.02	43.22	20.08	20.73
0.10	0.016265	0.000994	45.24	50.43	16.36	0.10	0.015522	0.000994	45.00	43.23	15.62	15.99
0.05	0.012797	0.000989	45.22	43.23	12.95	0.05	0.012332	0.000988	45.03	43.22	12.48	12.71
0.02	0.010008	0.000989	45.24	43.24	10.12	0.02	0.009719	0.000988	45.11	36.02	9.83	9.98
0.01	0.008731	0.000981	45.27	36.02	8.90	0.01	0.008917	0.000987	45.11	28.81	9.03	8.97
AN-3-2A-FS @ 55°C (AV = 4.1%)						**AN-6-3B-FS @ 55°C (AV = 4.1%)**						**Avg. G* (MPa)**
Freq. (Hz)	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degrees)**	**Modulus (G*) (MPa)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degrees)**	**Modulus (G*) (MPa)**	
10.01	0.065727	0.001062	55.53	57.65	61.90	10.00	0.066701	0.001061	55.04	57.62	62.86	62.38
5.00	0.043670	0.001092	55.37	57.59	40.00	5.00	0.044537	0.001086	55.28	57.59	40.99	40.49
2.00	0.027095	0.001077	55.26	57.52	25.17	2.00	0.028175	0.001077	55.61	50.32	26.15	25.66
1.00	0.018931	0.001022	55.24	50.41	18.52	1.00	0.019594	0.001021	55.54	50.41	19.18	18.85
0.50	0.014405	0.001016	55.17	43.22	14.18	0.50	0.014970	0.001012	55.49	43.22	14.80	14.49
0.20	0.010733	0.000993	55.38	43.20	10.81	0.20	0.011199	0.000997	55.58	36.02	11.23	11.02
0.10	0.009582	0.000999	55.16	36.02	9.59	0.10	0.009742	0.000988	55.39	36.03	9.86	9.73
0.05	0.008561	0.000990	55.20	36.03	8.65	0.05	0.008940	0.000990	55.34	36.03	9.03	8.84
0.02	0.008028	0.000985	55.27	36.03	8.15	0.02	0.008381	0.000989	55.22	28.82	8.47	8.31
0.01	0.007907	0.000981	55.20	36.02	8.06	0.01	0.008064	0.000981	54.97	28.81	8.22	8.14

Table D.5: Fatigue Beam Test Results: Control (Dry)

Specimen Designation	Air-void Content (%)	Binder Content (%)	Test Temp (°C)	Test Strain Level	Initial Phase Angle (Deg)	Initial Stiffness (MPa)	Fatigue Life (Nf)
CL-24B2	4.1	5.3	10.0	0.000200	19.06	10,815	509,126,752[1]
CL-26B2	4.6	5.3	9.9	0.000200	15.32	10,045	180,945,740[1]
CL-32B1	4.0	5.3	10.0	0.000200	17.86	11,308	10,814,508[1]
CL-16B1	4.7	5.3	9.9	0.000396	16.56	10,121	82,021
CL-25A1	5.0	5.3	9.9	0.000397	17.94	9,043	158,060
CL-29A1	4.2	5.3	9.8	0.000409	14.96	9,958	137,458
CL-12B2	4.8	5.3	19.6	0.000204	24.28	5,974	11,873,101[1]
CL-6B2	5.0	5.3	20.3	0.000210	24.04	6,341	5,070,594
CL-7A1	5.0	5.3	20.1	0.000200	23.09	6,000	152,983,561[1]
CL-6B1	4.6	5.3	20.0	0.000399	25.11	6,066	44,604
CL-10B2	4.4	5.3	20.1	0.000395	26.16	6,243	469,873
CL-14B2	5.0	5.3	20.4	0.000414	26.92	5,350	492,755
CL-16B2	4.7	5.3	29.7	0.000205	37.95	2,899	1,637,206,836[1]
CL-22B1	4.4	5.3	30.4	0.000205	36.65	2,845	25,188,908[1]
CL-30B2	5.0	5.3	29.8	0.000204	33.54	2,771	403,884,113[1]
CL-19A1	5.0	5.3	29.8	0.000414	39.74	2,131	1,546,350
CL-20B1	4.2	5.3	30.0	0.000404	30.69	2,979	1,310,776
CL-25A2	4.3	5.3	29.8	0.000409	40.47	2,352	272,404

[1] Extrapolated values

Table D.6: Fatigue Beam Test Results: Control (Wet)

Specimen Designation	Air-void Content (%)	Binder Content (%)	Test Temp (°C)	Test Strain Level	Initial Phase Angle (Deg)	Initial Stiffness (MPa)	Fatigue Life (Nf)
CL-21A2	4.6	5.3	9.8	0.000202	17.64	7,423	1,443,688
CL-28B2	4.0	5.3	9.9	0.000203	15.54	8,608	1,850,717
CL-30B1	4.2	5.3	9.9	0.000204	19.31	7,659	1,885,602
CL-20B2	4.5	5.3	9.8	0.000408	16.78	7,834	8,836
CL-22B2	4.6	5.3	9.8	0.000410	17.60	7,385	30,006
CL-26B1	4.5	5.3	9.9	0.000405	20.16	6,806	46,609
CL-4B2	4.9	5.3	20.1	0.000202	23.67	4,613	132,356,108[1]
CL-8B1	4.4	5.3	20.3	0.000210	28.53	4,393	8,553,362[1]
CL-14B1	4.3	5.3	19.7	0.000206	22.66	3,598	312,547,162[1]
CL-7A2	4.9	5.3	19.7	0.000405	22.97	3,840	87,366
CL-9A1	5.0	5.3	20.3	0.000423	29.18	3,546	139,568
CL-9A2	4.8	5.3	19.7	0.000403	20.96	4,173	59,935
CL-18B2	4.7	5.3	29.7	0.000205	33.34	2,171	5,975,869,294[1]
CL-21A2	4.6	5.3	30.0	0.000206	37.66	1,728	235,542,025[1]
CL-23A2	4.4	5.3	30.0	0.000212	38.63	1,949	201,894,393[1]
CL-19A2	4.5	5.3	30.0	0.000409	39.53	1,543	2,712,972
CL-27A1	4.9	5.3	30.0	0.000407	37.70	1,491	938,453
CL-31A2	4.9	5.3	29.9	0.000418	44.32	1,448	756,626

[1] Extrapolated values

Table D.7: Fatigue Beam Test Results: Rediset (Dry)

Specimen Designation	Air-void Content (%)	Binder Content (%)	Test Temp (°C)	Test Strain Level	Initial Phase Angle (Deg)	Initial Stiffness (MPa)	Fatigue Life (Nf)
AN-17A2	4.9	5.3	9.8	0.000201	16.98	8,961	26,092,686[1]
AN-28B1	4.1	5.3	10.0	0.000202	19.36	9,310	35,822,628[1]
AN-34B2	4.0	5.3	9.8	0.000202	13.94	10,111	5,788,168[1]
AN-21A2	4.9	5.3	9.9	0.000395	15.65	8,756	226,923
AN-22B2	4.1	5.3	10.0	0.000398	19.20	8,885	245,805
AN-30B1	4.7	5.3	9.9	0.000397	19.20	8,247	246,802
AN-5A2	4.7	5.3	19.8	0.000205	25.35	5,584	50,863,548[1]
AN-28B2	4.0	5.3	20.3	0.000208	27.90	4,933	34,056,589[1]
AN-36B2	4.9	5.3	20.0	0.000200	23.01	5,141	136,249,736[1]
AN-13A1	4.8	5.3	20.0	0.000394	21.17	5,584	157,172
AN-32B2	4.9	5.3	19.9	0.000397	22.57	4,852	246,490
AN-35A1	4.5	5.3	19.6	0.000402	31.18	4,238	181,977
AN-10B1	4.9	5.3	30.1	0.000202	33.24	2,456	87,366,025[1]
AN-17A1	5.0	5.3	31.2	0.000207	44.51	2,008	8,436,769,496,302[1]
AN-24B1	4.0	5.3	30.6	0.000204	39.28	2,668	338,185,551,227[1]
AN-22B1	4.1	5.3	30.4	0.000404	41.36	2,237	2,860,006
AN-30B2	4.2	5.3	29.6	0.000413	41.83	2,139	1,708,579
AN-31A2	4.7	5.3	30.3	0.000403	42.37	2,007	1,402,430

[1] Extrapolated values

Table D.8: Fatigue Beam Test Results: Rediset (Wet)

Specimen Designation	Air-void Content (%)	Binder Content (%)	Test Temp (°C)	Test Strain Level	Initial Phase Angle (Deg)	Initial Stiffness (MPa)	Fatigue Life (Nf)
AN-3A1	5.0	5.3	9.9	0.000204	17.63	8,183	4,964,879
AN-11A2	4.9	5.3	9.8	0.000200	18.97	8,196	8,380,196[1]
AN-24B2	4.3	5.3	10.0	0.000201	17.31	8,671	5,192,088
AN-12B2	4.0	5.3	9.9	0.000397	19.31	8,279	66,368
AN-23A2	4.6	5.3	9.9	0.000400	19.91	6,842	63,588
AN-32B1	4.8	5.3	10.0	0.000401	18.92	7,137	110,462
AN-5A1	4.5	5.3	19.8	0.000207	25.76	4,970	18,355,420[1]
AN-7A2	4.8	5.3	20.3	0.000209	27.36	4,860	92,016,179[1]
AN-19A1	4.5	5.3	20.1	0.000199	24.58	5,408	180,489,856[1]
AN-15A2	4.3	5.3	20.4	0.000420	31.06	3,594	360,542
AN-31A1	4.6	5.3	20.0	0.000399	32.17	4,075	565,216
AN-35A2	4.7	5.3	20.4	0.000415	32.35	3,559	253,677
AN-11A1	4.9	5.3	29.9	0.000206	42.06	1,641	396,275,616[1]
AN-16B2	4.5	5.3	30.1	0.000205	33.58	2,493	6,919,741,215[1]
AN-19A2	4.3	5.3	30.5	0.000206	38.28	2,301	9,662,636,462[1]
AN-20B1	4.0	5.3	30.0	0.000406	36.43	1,866	5,412,839
AN-33A2	4.3	5.3	29.9	0.000420	46.48	1,467	3,226,113
AN-36B1	5.0	5.3	29.9	0.000420	41.59	1,666	746,221

[1] Extrapolated values

Table D.9: Flexural Frequency Sweep Test Results: Control (Dry)

CL-15A1 @ 10°C (AV = 4.6%)						CL-4B1 @ 10°C (AV = 4.9%)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa))	
15.17	0.3219	0.000028	10.51	12.40	11,360	15.14	0.2589	0.000022	9.93	11.14	11,572	11,466
9.99	0.9649	0.000100	10.46	18.32	9,659	9.99	1.0022	0.000098	9.96	15.25	10,226	9,943
5.00	0.8809	0.000102	10.40	17.03	8,677	5.01	0.9428	0.000099	9.92	15.70	9,532	9,105
2.00	0.7458	0.000098	10.35	17.01	7,588	2.00	0.8153	0.000096	9.93	15.10	8,535	8,062
1.00	0.6645	0.000097	10.28	17.30	6,825	1.00	0.7685	0.000097	9.83	15.65	7,910	7,367
0.50	0.6091	0.000099	10.25	19.44	6,133	0.50	0.6987	0.000098	9.81	16.59	7,101	6,617
0.20	0.4997	0.000096	10.19	20.77	5,191	0.20	0.5962	0.000099	10.05	18.74	6,000	5,595
0.10	0.4495	0.000098	10.12	22.48	4,608	0.10	0.5244	0.000101	10.06	20.05	5,215	4,911
0.05	0.3863	0.000097	10.00	24.20	3,693	0.05	0.4452	0.000100	9.93	22.00	4,474	4,219
0.02	0.3086	0.000097	9.84	27.10	3,187	0.02	0.3579	0.000099	10.06	24.47	3,606	3,397
0.01	0.2630	0.000097	9.93	27.58	2,714	0.01	0.2981	0.000099	9.94	25.75	3,018	2,866
CL-12B1 @ 20°C (AV = 4.5%)						CL-3A1 @ 20°C (AV = 4.0%)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa))	
15.12	0.2784	0.000040	19.68	19.48	6,972	15.16	0.2721	0.000032	19.98	16.32	8,410	7,691
10.00	0.6395	0.000102	19.77	20.78	6,272	10.00	0.7940	0.000102	20.05	17.68	7,746	7,009
5.00	0.5326	0.000099	19.83	22.39	5,397	5.00	0.6844	0.000101	20.20	19.94	6,791	6,079
2.00	0.4276	0.000100	19.94	24.86	4,292	2.00	0.5380	0.000098	20.30	22.05	5,493	4,893
1.00	0.3438	0.000097	20.13	27.43	3,538	1.00	0.4451	0.000097	20.45	23.99	4,599	4,068
0.50	0.2924	0.000102	20.20	30.05	2,881	0.50	0.3829	0.000100	20.41	25.88	3,813	3,347
0.20	0.2079	0.000099	20.31	32.72	2,101	0.20	0.2899	0.000099	20.25	28.34	2,921	2,511
0.10	0.1613	0.000099	20.44	33.24	1,634	0.10	0.2316	0.000099	20.26	29.78	2,345	1,990
0.05	0.1247	0.000097	20.31	35.38	1,280	0.05	0.1811	0.000097	20.33	31.75	1,872	1,576
0.02	0.0871	0.000098	20.34	38.29	892	0.02	0.1329	0.000098	20.35	34.32	1,361	1,127
0.01	0.0655	0.000098	20.37	38.53	670	0.01	0.1014	0.000097	20.40	35.37	1,040	855
CL-5A1 @ 30°C (AV = 5.0%)						CL-12B2 @ 30°C (AV = 4.8%)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa))	
15.22	0.2296	0.000072	30.33	30.25	3,195	15.14	0.2279	0.000074	30.20	30.51	3,068	3,132
9.99	0.2894	0.000104	30.20	30.93	2,785	9.99	0.2796	0.000107	30.15	32.93	2,624	2,705
5.00	0.2350	0.000103	30.23	31.44	2,275	5.00	0.2150	0.000102	29.96	34.83	2,107	2,191
2.00	0.1671	0.000100	30.07	34.24	1,676	2.00	0.1505	0.000100	29.99	36.89	1,509	1,593
1.00	0.1278	0.000099	30.21	36.82	1,286	1.00	0.1145	0.000099	30.10	39.25	1,162	1,224
0.50	0.1036	0.000103	30.06	39.04	1,009	0.50	0.0886	0.000102	29.97	41.20	869	939
0.20	0.0697	0.000099	30.04	41.58	701	0.20	0.0604	0.000100	30.02	42.99	604	653
0.10	0.0529	0.000099	30.13	41.37	534	0.10	0.0446	0.000100	30.07	42.32	447	490
0.05	0.0401	0.000098	30.09	43.69	408	0.05	0.0345	0.000099	30.10	38.46	349	379
0.02	0.0284	0.000098	30.11	43.93	290	0.02	0.0231	0.000099	30.03	39.77	235	262
0.01	0.0214	0.000098	30.11	49.20	218	0.01	0.0180	0.000099	30.06	43.72	183	200

Table D.10: Flexural Frequency Sweep Test Results: Control (Wet)

CL-8B2 @ 10°C (AV = 4.5%)						CL-11A2 @ 10°C (AV = 5.0%)						Avg. E* (MPa)
Freq. (Hz)	**Stress (MPa)**	**Strain**	**Temp. (C)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain**	**Temp. (C)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa))**	
15.16	0.2519	0.000027	9.90	13.69	9,304	15.18	0.2650	0.000038	9.92	15.77	6,992	8,148
9.99	0.7782	0.000101	9.83	18.93	7,728	9.99	0.6608	0.000104	9.83	16.48	6,369	7,049
5.00	0.6904	0.000100	9.76	18.40	6,906	5.00	0.5727	0.000102	9.94	17.81	5,639	6,273
2.00	0.5685	0.000097	9.76	19.80	5,844	2.00	0.4696	0.000099	9.99	19.40	4,747	5,296
1.00	0.4668	0.000099	9.94	19.22	4,725	1.00	0.3965	0.000097	9.93	20.99	4,105	4,415
0.50	0.4143	0.000101	9.95	20.42	4,113	0.50	0.3494	0.000100	9.87	22.29	3,486	3,800
0.20	0.3327	0.000099	9.92	21.50	3,353	0.20	0.2739	0.000099	9.78	24.24	2,777	3,065
0.10	0.2700	0.000098	9.83	21.31	2,741	0.10	0.2247	0.000098	9.93	25.50	2,303	2,522
0.05	0.2398	0.000098	9.94	25.47	2,442	0.05	0.1845	0.000097	9.87	27.97	1,905	2,173
0.02	0.1758	0.000098	9.88	26.21	1,794	0.02	0.1403	0.000096	9.94	28.89	1,456	1,625
0.01	0.1460	0.000098	9.85	27.67	1,496	0.01	0.1149	0.000096	9.91	29.71	1,192	1,344

CL-1A2 @ 20°C (AV = 4.2%)						CL-10B1 @ 20°C (AV = 4.0%)						Avg. E* (MPa)
Freq. (Hz)	**Stress (MPa)**	**Strain**	**Temp. (C)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain**	**Temp. (C)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa))**	
15.14	0.2663	0.000040	19.78	18.17	6,602	15.15	0.2853	0.000045	19.56	18.86	6,406	6,504
10.00	0.6279	0.000102	19.86	18.57	6,168	10.01	0.5924	0.000102	19.67	20.01	5,828	5,998
5.00	0.5334	0.000100	20.01	19.97	5,327	5.00	0.5019	0.000100	19.82	21.92	5,006	5,166
2.00	0.4254	0.000097	20.09	22.24	4,368	2.00	0.3924	0.000098	19.92	23.75	3,992	4,180
1.00	0.3550	0.000097	20.24	23.67	3,662	1.00	0.3268	0.000098	20.06	25.08	3,320	3,491
0.50	0.3072	0.000101	20.29	25.85	3,043	0.50	0.2789	0.000103	20.11	27.43	2,711	2,877
0.20	0.2302	0.000099	20.38	28.06	2,324	0.20	0.2027	0.000100	20.20	29.46	2,020	2,172
0.10	0.1859	0.000098	20.48	27.41	1,891	0.10	0.1588	0.000099	20.30	30.01	1,600	1,746
0.05	0.1502	0.000098	20.30	31.36	1,529	0.05	0.1272	0.000098	20.46	32.39	1,294	1,412
0.02	0.1119	0.000098	20.32	32.99	1,139	0.02	0.0928	0.000098	20.36	33.35	946	1,043
0.01	0.0884	0.000098	20.37	33.54	903	0.01	0.0731	0.000098	20.35	34.47	743	823

CL-3A2 @ 30°C (AV = 4.5%)						CL-15A2 @ 30°C (AV = 4.8%)						Avg. E* (MPa)
Freq. (Hz)	**Stress (MPa)**	**Strain**	**Temp. (C)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain**	**Temp. (C)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa))**	
15.13	0.1994	0.000068	29.97	28.35	2,935	15.13	0.2214	0.000102	30.22	32.26	2,179	2,557
9.99	0.2630	0.000102	29.99	29.34	2,586	10.00	0.2005	0.000103	30.11	32.44	1,947	2,266
5.00	0.2195	0.000105	29.98	30.81	2,091	5.00	0.1643	0.000104	30.14	33.35	1,580	1,835
2.00	0.1576	0.000101	30.03	32.12	1,563	2.00	0.1138	0.000099	30.19	33.77	1,149	1,356
1.00	0.1209	0.000099	30.12	33.80	1,225	1.00	0.0893	0.000099	30.07	33.95	903	1,064
0.50	0.0955	0.000101	30.05	35.37	945	0.50	0.0704	0.000100	30.12	34.32	702	824
0.20	0.0678	0.000099	30.15	35.63	688	0.20	0.0501	0.000098	30.09	37.48	508	598
0.10	0.0520	0.000097	30.14	37.33	535	0.10	0.0384	0.000097	30.11	36.26	395	465
0.05	0.0412	0.000096	30.11	36.96	427	0.05	0.0303	0.000097	30.08	31.74	313	370
0.02	0.0294	0.000096	30.09	36.97	305	0.02	0.0239	0.000097	30.08	34.36	247	276
0.01	0.0246	0.000096	30.09	34.95	255	0.01	0.0173	0.000097	30.08	38.20	178	217

Table D.11: Flexural Frequency Sweep Test Results: Rediset (Dry)

AN-14B1 @ 10°C (AV = 4.9%)						AN-29A2 @ 10°C (AV = 4.2%)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa))	
15.11	0.2636	0.000030	9.57	15.03	8,832	15.12	0.2502	0.000023	9.87	13.01	10,928	9,880
9.99	0.7503	0.000099	9.67	20.15	7,580	9.99	0.9182	0.000102	9.78	17.59	9,029	8,304
5.00	0.6895	0.000101	9.66	19.53	6,850	5.01	0.8251	0.000100	9.85	17.80	8,244	7,547
2.00	0.6119	0.000098	9.82	19.35	6,243	2.00	0.7070	0.000097	9.97	18.48	7,266	6,755
1.00	0.5359	0.000097	9.93	20.30	5,503	1.00	0.6366	0.000096	9.94	18.92	6,635	6,069
0.50	0.4725	0.000102	9.91	23.22	4,623	0.50	0.5765	0.000097	9.89	20.63	5,933	5,278
0.20	0.3681	0.000100	9.83	26.88	3,673	0.20	0.4777	0.000098	9.78	22.86	4,874	4,274
0.10	0.2929	0.000099	9.70	24.46	2,952	0.10	0.4026	0.000098	9.83	23.42	4,088	3,520
0.05	0.2424	0.000099	9.46	32.34	2,452	0.05	0.3375	0.000097	9.93	27.33	3,462	2,957
0.02	0.1932	0.000100	9.28	33.11	1,942	0.02	0.2677	0.000098	9.90	30.25	2,742	2,342
0.01	0.1577	0.000100	9.89	34.59	1,576	0.01	0.2178	0.000098	9.87	30.80	2,228	1,902

AN-25A1 @ 20°C (AV = 4.8%)						AN-27A1 @ 20°C (AV = 4.0%)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa))	
15.12	0.2487	0.000040	19.35	19.51	6,205	15.11	0.2857	0.000044	19.27	19.11	6,560	6,383
10.00	0.5771	0.000101	19.43	21.59	5,709	10.00	0.5866	0.000101	19.36	22.46	5,780	5,745
5.00	0.4837	0.000100	19.53	22.80	4,841	5.00	0.4998	0.000101	16.45	23.74	4,960	4,901
2.00	0.3742	0.000097	19.58	25.32	3,872	2.00	0.3855	0.000098	19.53	26.40	3,940	3,906
1.00	0.3089	0.000096	19.68	27.54	3,215	1.00	0.3141	0.000098	19.64	28.74	3,205	3,210
0.50	0.2617	0.000103	19.72	31.43	2,533	0.50	0.2576	0.000101	19.67	31.79	2,549	2,541
0.20	0.1887	0.000101	19.78	34.84	1,867	0.20	0.1845	0.000099	19.74	34.75	1,860	1,863
0.10	0.1422	0.000100	19.71	32.76	1,418	0.10	0.1398	0.000099	19.78	34.76	1,417	1,418
0.05	0.1125	0.000099	19.63	38.64	1,135	0.05	0.1105	0.000099	19.72	40.24	1,114	1,124
0.02	0.0792	0.000098	19.68	40.52	806	0.02	0.0771	0.000098	19.72	40.09	782	794
0.01	0.0614	0.000100	19.67	42.29	616	0.01	0.0598	0.000098	19.67	39.85	609	612

AN-12B1 @ 30°C (AV = 4.0%)						AN-21A1 @ 30°C (AV = 4.8%)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa))	
15.14	0.2272	0.000078	30.13	31.84	2,912	15.09	0.2310	0.000075	30.17	30.27	3,093	3,002
10.01	0.2524	0.000102	30.14	33.76	2,478	10.00	0.2692	0.000101	30.16	32.61	2,675	2,576
5.01	0.2009	0.000103	30.08	35.48	1,953	5.00	0.2160	0.000102	30.16	33.42	2,114	2,034
2.00	0.1371	0.000100	30.13	38.53	1,375	2.00	0.1488	0.000099	30.14	36.13	1,502	1,438
1.00	0.1030	0.000099	30.07	40.89	1,041	1.00	0.1128	0.000098	30.12	38.12	1,154	1,098
0.50	0.0786	0.000101	30.03	43.36	775	0.50	0.0861	0.000100	30.21	41.08	858	817
0.20	0.0520	0.000098	30.10	43.87	529	0.20	0.0581	0.000098	30.14	43.01	593	561
0.10	0.0376	0.000099	30.08	45.04	381	0.10	0.0433	0.000097	30.06	40.45	445	413
0.05	0.0273	0.000098	30.10	45.37	278	0.05	0.0338	0.000097	30.10	42.58	348	313
0.02	0.0196	0.000098	30.07	45.30	200	0.02	0.0242	0.000097	30.04	46.85	250	225
0.01	0.0143	0.000098	30.07	41.67	146	0.01	0.0178	0.000097	30.14	45.81	184	165

Table D.12: Flexural Frequency Sweep Test Results: Rediset (Wet)

AN-34B1 @ 10°C (AV = 4.2%)						AN-16B1 @ 10°C (AV = 4.9%)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa))	
15.17	0.2876	0.000029	9.87	14.21	9,964	15.10	0.2355	0.000025	9.84	13.02	9,477	9,720
9.99	0.8549	0.000102	9.80	17.76	8,378	9.99	0.7805	0.000097	9.85	18.72	8,018	8,198
5.00	0.7660	0.000100	9.93	17.01	7,672	5.00	0.7326	0.000101	9.99	17.82	7,262	7,467
2.00	0.6594	0.000099	9.95	16.65	6,681	2.00	0.6300	0.000097	9.98	17.53	6,513	6,597
1.00	0.5972	0.000096	9.85	18.27	6,212	1.00	0.5898	0.000097	9.88	18.30	6,056	6,134
0.50	0.5535	0.000100	9.86	19.08	5,556	0.50	0.5239	0.000099	9.93	18.86	5,290	5,423
0.20	0.4553	0.000099	10.00	20.41	4,578	0.20	0.4226	0.000098	10.03	21.83	4,303	4,441
0.10	0.3835	0.000098	9.95	20.99	3,896	0.10	0.3521	0.000097	9.91	22.75	3,619	3,757
0.05	0.3226	0.000097	9.89	24.85	3,310	0.05	0.2919	0.000097	9.93	26.32	3,014	3,162
0.02	0.2594	0.000098	9.89	25.93	2,652	0.02	0.2300	0.000096	9.90	27.92	2384	2,518
0.01	0.2159	0.000097	9.88	27.30	2,216	0.01	0.1887	0.000097	9.92	28.08	1,948	2,082

AN-23A1 @ 20°C (AV = 5.0%)						AN-33A1 @ 20°C (AV = 4.3%),						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa))	
15.15	0.1518	0.000030	19.70	21.51	5,096	15.14	0.2083	0.000041	19.85	22.60	5,111	5,103
10.00	0.4719	0.000103	19.77	23.01	4,602	10.01	0.4691	0.000103	19.76	24.72	4,572	4,587
5.00	0.3927	0.000101	19.76	25.24	3,873	5.01	0.3891	0.000102	19.64	26.49	3,825	3,849
2.00	0.3009	0.000100	19.68	27.54	3,018	2.00	0.2932	0.000100	19.66	29.36	2,928	2,973
1.00	0.2430	0.000100	19.73	30.30	2,435	1.00	0.2331	0.000100	19.81	31.41	2,341	2,388
0.50	0.1918	0.000100	19.78	31.45	1,922	0.50	0.1845	0.000099	19.83	32.57	1,865	1,893
0.20	0.1363	0.000097	19.83	34.19	1,412	0.20	0.1288	0.000097	19.71	35.82	1,333	1,372
0.10	0.1079	0.000098	19.66	34.95	1,097	0.10	0.1006	0.000098	19.70	35.50	1,029	1,063
0.05	0.0820	0.000096	19.78	34.63	850	0.05	0.0760	0.000097	19.69	38.12	781	816
0.02	0.0592	0.000097	19.70	36.87	613	0.02	0.0543	0.000096	19.71	37.63	565	589
0.01	0.0467	0.000095	19.72	33.99	490	0.01	0.0429	0.000096	19.73	36.94	445	468

AN-7A1 @ 30°C (AV = 4.7%)						AN-29A1 @ 30°C (AV = 4.6%)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (C)	Phase Angle (Degrees)	Stiffness (E*) (MPa))	
15.15	0.2060	0.000084	29.74	33.33	2,450	15.13	0.1884	0.000078	29.73	31.95	2,427	2,439
9.99	0.2234	0.000105	29.53	33.67	2,137	10.01	0.2247	0.000107	29.75	34.05	2,098	2,118
4.99	0.1774	0.000106	29.65	35.36	1,677	5.01	0.1760	0.000104	29.67	34.78	1,690	1,684
2.00	0.1229	0.000102	29.59	37.13	1,205	2.00	0.1241	0.000101	29.70	36.47	1,224	1,215
1.00	0.0924	0.000100	29.73	36.58	927	1.00	0.0926	0.000099	29.60	36.38	935	931
0.50	0.0702	0.000099	29.58	39.43	710	0.50	0.0723	0.000099	29.71	36.77	732	721
0.20	0.0470	0.000098	29.65	39.52	481	0.20	0.0497	0.000098	29.69	39.56	506	494
0.10	0.0359	0.000096	29.63	38.60	374	0.10	0.0386	0.000098	29.64	37.91	395	384
0.05	0.0281	0.000096	29.62	39.03	293	0.05	0.0301	0.000097	29.58	40.49	311	302
0.02	0.0212	0.000097	29.60	38.02	220	0.02	0.0234	0.000097	29.60	33.98	242	231
0.01	0.0177	0.000097	29.60	35.10	183	0.01	0.0202	0.000097	29.63	33.31	209	196

Table D.13: Hamburg Wheel Track Test: Specimen Air-void Contents

Specimen		Bulk Specific Gravity (g/cm^3)	Max Specific Gravity (g/cm^3)	Air-Void Content (%)
Control	H1-1	2.452	2.576	4.8
	H1-2	2.448	2.576	4.9
	H1-3	2.450	2.576	4.9
	H1-4	2.453	2.576	4.8
Rediset	H2-1	2.446	2.575	5.0
	H2-2	2.456	2.575	4.6
	H2-3	2.455	2.575	4.7
	H2-4	2.466	2.575	4.2

Table D.14: Hamburg Wheel Track Test: Summary of Average Rut Progression Curves

Specimen		Stripping Slope (mm/pass)	Stripping Inflection Point	Rut Depth @ 10,000 passes (mm)	Rut Depth @ 20,000 passes (mm)
Control	H1-1	-0.0006	17,875	6.5	13.8
	H1-2	-0.0010	2,821	6.0	14.2
	H1-3	-0.0009	8,002	6.9	19.7
	H1-4	-0.0010	6,216	9.3	19.3[1]
	Average	-0.0009	8,728	7.2	16.8
Rediset	H2-1	-0.0012	6,955	8.6	15.2
	H2-2	-0.0009	9,502	7.6	16.1[1]
	H2-3	-0.0008	717	6.6	14.1
	H2-4	-0.0011	6,903	10.1	20.6[1]
	Average	-0.0001	6,019	8.2	16.5
Test Track Control	D35A[2]	-0.0014	7,858	8.2	22.5
	D35B	-0.0013	8,804	12.4	25.5
	D03A	-0.0018	6,889	15.1	33.1
	D03B	-0.0023	8,837	11.0	34.0
	Average	-0.0017	8,177	12.9	30.9

[1] Extrapolated value [2] Outlier not used in analysis

Table D.15: Tensile Strength Retained Test: Specimen Air-Void Contents

Control	C01	C03	2.388	2.387	2.576	2.575	7.3	7.3
	C02	C16	2.406	2.382	2.576	2.575	6.6	7.5
	C13	C04	2.383	2.382	2.576	2.575	7.5	7.5
	C15	C18	2.401	2.382	2.576	2.575	6.8	7.5
	C17	C07	2.393	2.382	2.576	2.575	7.1	7.5
	C19	C14	2.401	2.382	2.576	2.575	6.8	7.5
							7.0	7.5
Rediset	R03	R04	2.384	2.395	2.575	2.575	7.4	7.0
	R05	R11	2.377	2.395	2.575	2.575	7.7	7.0
	R06	R14	2.366	2.400	2.575	2.575	8.1	6.8
	R08	R16	2.374	2.382	2.575	2.575	7.8	7.5
	R10	R21	2.384	2.382	2.575	2.575	7.4	7.5
	R12	R23	2.372	2.382	2.575	2.575	7.9	7.5
	-	R26	-	2.382	-	2.575	-	7.5
							7.7	7.3
Test Track Control	33-20C	33-15C	2.434	2.429	2.576	2.576	5.5	5.7
	33-08C	33-13C	2.424	2.424	2.576	2.576	5.9	5.9
	33-17C	33-02C	2.421	2.424	2.576	2.576	6.0	5.9
	33-07C	33-06C	2.419	2.411	2.576	2.576	6.1	6.4
	33-09C	33-10C	2.411	2.409	2.576	2.576	6.4	6.5
	33-11C	33-01C	2.409	2.406	2.576	2.576	6.5	6.6
						Average	6.1	6.2

Table D.16: Tensile Strength Retained Test: Results

Specimen	Control		Rediset		FMFC Control	
	Dry ITS	Wet ITS	Dry ITS	Wet ITS	Dry ITS	Wet ITS
1	2,761	572	2,515	1,636	1,111.4	660.2
2	2,474	629	2,449	1,814	841.7	516.8
3	2,355	597	2,663	1,782	825.9	482.4
4	2,357	654	2,582	1,927	841.3	598.4
Average	2,487	613	2,552	1,790	905.8	564.4
TSR	25%		70%		62%	
Damage	-	Yes	-	Yes	-	Yes

Table D.17: Cantabro Durability Test: Specimen Air-Void Contents

Specimen ID		Bulk Specific Gravity (g/cm^3)	Max Specific Gravity (g/cm^3)	Air-Void Content (%)
Control	C01	2.116	2.576	17.8
	C02	2.115	2.576	17.9
	C03	2.108	2.576	18.1
	C04	2.116	2.576	17.8
	C05	2.106	2.576	18.2
	C06	2.108	2.576	18.2
			Average	18.0
Rediset	R01	2.125	2.571	17.3
	R02	2.116	2.571	17.7
	R03	2.139	2.571	16.8
	R04	2.084	2.571	18.9
	R05	2.160	2.571	16.0
	R06	2.135	2.571	16.9
			Average	17.3

Table D.18: Cantabro Durability Test: Results

Specimen	Control		Rediset	
	Mass Before (g)	Mass After (g)	Mass Before (g)	Mass After (g)
1	1,204	1,088	1,198	1,041
2	1,200	1,089	1,197	1,028
3	1,196	1,099	1,199	1,081
4	1,193	1,115	1,200	1,058
5	1,196	1,077	1,194	1,115
6	1,199	1,109	1,198	1,065
Average	1,198	1,096	1,198	1,065
Mass Loss (%)	8.5		11.1	