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Warm-Mix Asphalt Study: First-Level Analysis of Phase 2b Laboratory Testing on Laboratory-Prepared Specimens

June 2012

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Warm-Mix Asphalt Study: First-Level Analysis of Phase 2b Laboratory Testing on Laboratory-Prepared Specimens

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Partnered Pavement Research Program (PPRC) Contract Strategic Plan Element 4.18:
Warm Mix Asphalt

PREPARED FOR:

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

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Abstract:

This report describes laboratory testing of laboratory-prepared specimens as part of the second phase of a warm mix asphalt study, which compares the performance of a hot mix control produced at 310°F (155°C) against the performance of warm mixes produced at 250°F (120°C) with four different technologies (Advera, Evotherm, Sasobit, and Rediset). Key findings from the study include:

- The laboratory test results indicate that use of the warm mix technologies assessed in this study, which were produced and compacted at lower temperatures, did not significantly influence the performance of the asphalt concrete when compared to control specimens produced and compacted at conventional hot mix asphalt temperatures.
- Laboratory performance in all the tests appeared to be mostly dependent on air-void content and less dependent on mix production temperature.
- Test results were influenced by specimen air-void content, actual stress and strain levels, and actual test temperature. Variation in these parameters needs to be taken into consideration when comparing performance between the different mixes.
- All mixes were sensitive to moisture content. Rutting performance, fatigue-cracking performance, and tensile strength retained all deteriorated with increasing moisture content in the specimens.
- All mixes performed significantly better in the Hamburg Wheel-Track Test when subjected to additional curing, indicating that hot and warm mixes are likely to have similar performance on in-service pavements after a short period of aging (e.g., 6 to 12 months). This is consistent with performance on the test track.
- Test results were consistent with those from earlier testing phases.

The laboratory testing completed in this phase has provided no new results to suggest that warm mix technologies should not be used in dense- or open-graded mixes in California, provided that standard specified construction and performance limits for hot mix asphalt are met. It should be noted that lower production temperatures could lead to insufficient drying of aggregates, which in turn could result in moisture-related problems in the road. Moisture content in aggregates should be strictly controlled at asphalt plants and specified mix moisture contents (i.e., less than 1.0 percent by weight of the mix) should be adhered to.

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

Proposals for implementation:
Continue with statewide implementation.

Related documents:
UCPRC Workplan, WP-2007-01; Research Reports, RR-2008-11, RR-2009-02, RR-2011-02, RR-2011-03

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SUMMARY OF PROJECT OBJECTIVES

The objective of this warm mix asphalt study is to determine whether the use of additives that reduce the production and construction temperatures of hot mix asphalt influences performance of the mix. This will be achieved through the following tasks:

1. Preparation of a workplan to guide the research
2. Monitoring the construction of Heavy Vehicle Simulator (HVS) and in-service test sections
3. Sampling of mix and mix components during asphalt concrete production and construction
4. Trafficking of demarcated sections with the HVS in a series of tests to assess performance
5. Conducting laboratory tests to identify comparable laboratory performance measures
6. Monitoring the performance of in-service pilot sections
7. Preparation of first- and second-level analysis reports and a summary report detailing the experiment and the findings

This report covers Tasks 5 and 7.

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- The UCPRC Laboratory Staff

EXECUTIVE SUMMARY

Another phase of a comprehensive study into the use of warm mix asphalt has been completed for the California Department of Transportation (Caltrans) by the University of California Pavement Research Center (UCPRC). This phase of the study, which covered tests on laboratory-mixed, laboratory-compacted (LMLC) specimens and compared results from previous testing on plant-mixed, field-compacted (PMFC) and plant-mixed, laboratory-compacted specimens (PMLC), was based on a workplan approved by Caltrans. Laboratory tests assessed rutting and fatigue cracking performance, moisture sensitivity, and open-graded friction course durability. The objective of the study is to determine whether the use of technologies that reduce the production and construction temperatures of asphalt concrete influences performance of the mix. The study compared the performance of a control mix, produced and compacted at conventional hot mix asphalt temperatures (310°F [154°C]), with four warm mixes, produced and compacted at 36°F (20°C) lower than the control. These target production temperatures were the same as those used for the production of asphalt for the test track used in the Phase 1 and Phase 2 accelerated pavement testing studies. The warm-mix technologies assessed in the laboratory study included *Advera WMA®*, *Evotherm DAT™*, and *Sasobit®*. In this report, the results for a fourth technology (*Rediset™*) that was tested in a separate study, but using the same aggregates and testing procedures, are also included.

Specimens for this phase of the study were produced at the UCPRC laboratory in Richmond, California, using the same mix design developed by the Graniterock Company for the test track described above. No adjustments were made to the mix design to accommodate the warm mix technologies.

Key findings from this study include the following:

- The laboratory test results indicate that use of the warm mix technologies assessed in this study, which were produced and compacted at lower temperatures, did not significantly influence the performance of the asphalt concrete when compared to control specimens produced and compacted at conventional hot mix asphalt temperatures.
- Laboratory performance in all the tests appeared to be mostly dependent on air-void content and less dependent on mix production temperature.
- Test results were influenced by specimen air-void content, actual stress and strain levels, and actual test temperature. Variation in these parameters needs to be taken into consideration when comparing performance between the different mixes.
- All mixes were sensitive to moisture content. Rutting performance, fatigue-cracking performance, and tensile strength retained all deteriorated with increasing moisture content in the specimens.
- All mixes performed significantly better in the Hamburg Wheel-Track Test when subjected to additional curing, indicating that hot and warm mixes are likely to have similar performance on in-

service pavements after a short period of aging (e.g., 6 to 12 months). This is consistent with performance on the test track.
- Test results were consistent with those from earlier testing phases.

The laboratory testing completed in this phase of the study has provided no new results to suggest that warm mix technologies should not be used in dense- or open-graded mixes in California, provided that standard specified construction and performance limits for hot mix asphalt are met. It should be noted that lower production temperatures could lead to insufficient drying of aggregates, which in turn could result in moisture-related problems in the road. Moisture content in aggregates should be strictly controlled at asphalt plants and specified mix moisture contents (i.e., less than 1.0 percent by weight of the mix) should be adhered to.

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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
DCP	Dynamic Cone Penetrometer
DGAC	Dense-graded asphalt concrete
ESAL	Equivalent standard axle load
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
HMA	Hot mix asphalt
HVS	Heavy Vehicle Simulator
HWTT	Hamburg Wheel-Track Test
LMLC	Laboratory-mixed, laboratory-compacted
LVDT	Linear variable differential transformer
MDD	Multi-Depth Deflectometer
MPD	Mean profile depth
NCAT	National Center for Asphalt Technology
OGFC	Open-graded friction course
PMFC	Plant-mixed, field-compacted
PMLC	Plant-mixed, laboratory-compacted
PPRC	Partnered Pavement Research Center
PSS	Permanent shear strain
RHMA-G	Gap-graded rubberized hot mix asphalt
RWMA-G	Gap-graded rubberized warm mix asphalt
SPE	Strategic Plan Element
TSR	Tensile strength retained
UCPRC	University of California Pavement Research Center
WMA	Warm mix asphalt

CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

1. INTRODUCTION

1.1 Background

Warm mix asphalt (WMA) is a relatively new technology. It was developed in response to the needs for reduced energy consumption and stack emissions during the production of asphalt concrete, and to allow longer hauls, lower placement temperatures, improved workability, and better working conditions for plant and paving crews. Studies in the United States and Europe indicate that significant reductions in production and placement temperatures, and potentially related emissions, are possible.

Research initiatives on warm mix asphalt are currently being conducted in a number of states, as well as by the Federal Highway Administration (FHWA) and the National Center for Asphalt Technology (NCAT), with the latter currently carrying out accelerated pavement testing experiments.

The California Department of Transportation (Caltrans) has expressed interest in using warm mix asphalt with a view to reducing stack emissions at asphalt plants, to allowing longer haul distances between asphalt plants and construction projects, to improving construction quality (especially during nighttime closures), to improving working conditions during construction, and to extending the annual period for paving. However, use of warm mix asphalt technologies requires incorporating an additive into the mix, and/or changes in production and construction procedures specifically related to temperature, and these can influence the short- and long-term performance of the pavement as well as the emissions generated during production and placement. Consequently, Caltrans identified the need for research to address a range of concerns related to these changes before it would approve statewide implementation of the technology.

1.2 Project Objectives

The research presented in this report is part of Partnered Pavement Research Center Strategic Plan Element 4.18 (PPRC SPE 4.18), titled "Warm Mix Asphalt Study," which was undertaken for Caltrans by the University of California Pavement Research Center (UCPRC). The objective of this 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. This is to be achieved through the following tasks:

- Develop a detailed workplan *(1)* for Heavy Vehicle Simulator (HVS) and laboratory testing *(Completed in September 2007)*

- Construct test tracks (subgrade preparation, aggregate base-course, tack coat, and asphalt wearing course) at the Graniterock A.R. Wilson quarry near Aromas, California *(completed in September 2007 for the Phase 1 and Phase 2 studies),* and UCPRC facility in Davis, California *(completed in April 2010 for the Phase 3 study)*
- Undertake HVS testing in separate phases, with later phases dependent on the outcome of earlier phases and laboratory tests *(Phase 1 [rutting on HMA/WMA] completed in April 2008, Phase 2 [moisture sensitivity on HMA/WMA] completed in July 2009, and Phase 3 [rutting on RHMA-G/ R-WMA-G] completed in July 2011)*
- Carry out a series of laboratory tests to assess rutting and fatigue behavior *(Phase 1 [plant-mixed, field-compacted] completed in August 2008, Phase 2a [plant-mixed, laboratory-compacted] completed in August 2009, Phase 2b [laboratory-mixed, laboratory-compacted] completed in June 2010 and documented in this report, and Phase 3 [plant-mixed, field-compacted] completed in December 2011)*
- Prepare a series of reports describing the research
- Prepare recommendations for implementation

Selected pilot studies with warm mix technologies on in-service pavements will also be monitored as part of the study.

1.3 Overall Project Organization

This UCPRC project has been planned as a comprehensive study to be carried out in a series of phases, with later phases dependent on the results of the initial phase. The planned testing phases include *(1)* the following:

- Phase 1 compared early rutting potential at elevated temperatures (pavement temperature of 122°F at 2.0 in. [50°C at 50 mm]). HVS trafficking began approximately 45 days after construction. Cores and beams sawn from the sections immediately after construction were subjected to rutting, fatigue cracking, and moisture sensitivity testing in the laboratory. The workplan dictated that moisture sensitivity, additional rutting, and fatigue testing with the HVS would be considered if the warm mix asphalt concrete mixes performed differently than the conventional mixes. The results from this phase are discussed in a report entitled *Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 1 HVS and Laboratory Testing (2).*
- Depending on the outcome of laboratory testing for moisture sensitivity, a testing phase, if deemed necessary, would assess general performance under dry and wet conditions with special emphasis on moisture sensitivity. The Phase 1 laboratory testing indicated a potential for moisture damage, prompting initiation of a second phase. Phase 2 compared rutting potential at elevated temperatures (pavement temperature of 122°F at 2.0 in. [50°C at 50 mm] pavement depth) and under wet conditions. HVS trafficking started approximately 90 days after completion of the Phase 1 HVS testing was completed (12 months after construction). The results from Phase 2 are discussed in two reports entitled *Warm-Mix Asphalt Study: First-Level Analysis of Phase 2 HVS and Laboratory Testing, and Phase 1 and Phase 2 Forensic Assessments (3)* and *Warm-Mix Asphalt Study: First-Level Analysis of Phase 2b Laboratory Testing on Laboratory-Prepared Specimens* (this report).

- Depending on the outcome of laboratory testing for rutting, a testing phase, if deemed necessary, would assess rutting performance on artificially aged test sections at elevated temperatures (122°F at 2.0 in. [50°C at 50 mm]). The actual process used to artificially age the sections was not finalized, but it would probably follow a protocol developed by the Florida Department of Transportation Accelerated Pavement Testing program, which uses a combination of infrared and ultraviolet radiation. Phase 1 laboratory testing results and Phase 2 HVS testing results provided no indication of increased rutting on aged sections and consequently this phase was not undertaken.
- Depending on the outcome of the laboratory study for fatigue, a testing phase, if deemed necessary, would assess fatigue performance at low temperatures (59°F at 2.0 in. [15°C at 50 mm]). Phase 1 laboratory testing did not indicate that the warm mix asphalt technologies tested would influence fatigue performance and consequently this phase was not undertaken.
- Depending on the outcome of the above testing phases and if agreed upon by the stakeholders (Caltrans, contractors, and warm mix technology suppliers), the sequence listed above or a subset of the sequence would be repeated for gap-graded rubberized asphalt concrete (RHMA-G), and again for open-graded mixes. The testing of gap-graded rubberized mixes was undertaken in two sub-phases and is discussed in two reports entitled *Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3a HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #1) (4)* and *Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3b HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #2) (5)*.
- Periodic assessment of the performance of open- and gap-graded mixes in full-scale field experiments. This work is discussed in a separate report on that study entitled *Warm-Mix Asphalt Study: Field Test Performance Evaluation (6)*.

This test plan was designed to evaluate short-, medium-, and long-term performance of the mixes.

- Short-term performance is defined as failure by rutting of the asphalt-bound materials.
- Medium-term performance is defined as failure caused by moisture and/or construction-related issues.
- Long-term performance is defined as failure from fatigue cracking, reflective cracking, and/or rutting of the asphalt-bound and/or unbound pavement layers.

The following questions, raised by Caltrans staff in a pre-study meeting, will be answered during the various phases of the study *(1)*:

- What is the approximate comparative energy usage between HMA and WMA during mix preparation? This will be determined from asphalt plant records/observations in pilot studies where sufficient tonnages of HMA and WMA are produced to undertake an assessment.
- Can satisfactory compaction be achieved at lower temperatures? This will be established from construction monitoring and subsequent laboratory tests.
- What is the optimal temperature range for achieving compaction requirements? This will be established from construction monitoring and subsequent laboratory tests.
- What are the cost implications? These will be determined with basic cost analyses from pilot studies where sufficient tonnages of HMA and WMA are produced to undertake an assessment.
- Does the use of warm mix asphalt technologies influence the rutting performance of the mix? This will be determined from all HVS and laboratory tests.

- Is the treated mix more susceptible to moisture sensitivity given that the aggregate is heated to lower temperatures? This will be determined from Phase 1 laboratory tests and Phase 2 HVS testing.
- Does the use of warm mix asphalt technologies influence fatigue performance? This will be determined from Phase 1 and Phase 2 laboratory tests and potential additional laboratory and HVS testing.
- Does the use of warm mix asphalt technologies influence the performance of the mix in any other way? This will be determined from HVS and laboratory tests, and from field observations (all phases).
- If the experiment is extended to rubberized gap-graded mixes, and standard, rubberized and polymer-modified open-graded mixes, are the impacts of using the warm mix technologies in these mixes the same as for conventional dense-graded mixes? This will be determined from Phase 3 laboratory and HVS tests and from field studies.

1.3.1 Project Deliverables

Deliverables from the study will include the following:

- A detailed workplan for the entire study *(1)*
- A report detailing construction, first-level data analysis of the Phase 1 HVS testing, first-level data analysis of the Phase 1 laboratory testing, and preliminary recommendations *(2)*
- A report detailing first-level data analysis of the Phase 2 HVS testing, first-level data analysis of the Phase 2a laboratory testing, Phase 1 and Phase 2 forensic investigations, and preliminary recommendations *(3)*
- A report detailing first-level analysis of the Phase 2b laboratory testing on laboratory-mixed, laboratory-compacted specimens *(this report)*
- A report detailing first-level data analysis of the Phase 3a (mixes produced at Granite Construction's Bradshaw plant) HVS testing, first-level data analysis of the Phase 3a laboratory testing, a Phase 3a forensic investigation, and preliminary recommendations *(4)*
- A report detailing first-level data analysis of the Phase 3b (mixes produced at George Reed's Marysville plant) HVS testing, first-level data analysis of the Phase 3b laboratory testing, a Phase 3b forensic investigation, and preliminary recommendations *(5)*
- A report summarizing periodic observations from test sections on in-service pavements *(6)*
- A summary report for the entire study

A series of conference and journal papers documenting various components of the study will also be prepared.

1.4 Structure and Content of this Report

1.4.1 Warm Mix Technologies Tested

The three warm mix technologies used in the construction of the test track for the Phase 1 and Phase 2 HVS tests were also tested in this study to facilitate comparison of the results of tests on plant-mixed, field-compacted specimens sampled from the test track *(2)*, and plant-mixed, laboratory-compacted specimens prepared on site on the day of construction *(3)*. An additional technology (*Rediset*^{TM}) assessed as part of the Caltrans warm mix technology approval process was also included in selected tests. Details of the additives are as follows:

- *Advera WMA*®, chemical water-foaming technology, referred to as “Advera” in this report
- *Evotherm DAT*™, chemical surfactant technology, referred to as “Evotherm” in this report
- *Sasobit*®, organic wax technology, referred to as “Sasobit” in this report
- *Rediset*™, chemical surfactant technology, referred to as “Rediset” in this report

1.4.2 Report Layout

This report presents an overview of the work carried out in Phase 2b to continue meeting the objectives of the study, and is organized as follows:

- Chapter 2 summarizes the laboratory testing experimental design.
- Chapter 3 discusses the laboratory testing results.
- Chapter 4 compares the results of the different phases of laboratory testing.
- Chapter 5 provides conclusions and preliminary recommendations.

1.5 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, both English and metric units (provided in parentheses after the English units) are provided in general discussion. In keeping with convention, only metric units are used in HVS and laboratory data analyses and reporting. A conversion table is provided on page xi at the beginning of this report.

1.6 Terminology

The term “asphalt concrete” is used in this report as a general descriptor for the surfacing on the test tracks. The terms “hot mix asphalt (HMA)” and “warm mix asphalt (WMA)” are used as descriptors to differentiate between the control and warm mixes discussed in this study.

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2. EXPERIMENTAL DESIGN

2.1 Introduction

Phase 2b laboratory testing included rutting performance (Repeated Simple Shear Test), fatigue cracking (beam fatigue), moisture sensitivity (Hamburg Wheel-Track and Tensile Strength Retained), and open-graded friction course durability tests (Cantabro). Additional Hamburg Wheel-Track tests were carried out to assess the effects of moisture in the mix, and the effects of additional curing (i.e., short-term aging) of the loose mix prior to compaction. Tests on these mix properties were carried out on beams and cores prepared from materials sampled at the Graniterock Company's A.R. Wilson Quarry and asphalt plant on the day of construction of the test track used for the Phase 1 and Phase 2 accelerated pavement tests. The specimens used in the laboratory testing study of plant-mixed, field-compacted (PMFC) and plant-mixed, laboratory-compacted materials (PMLC) were sampled from this test track *(2,3)*. With the exception of the Cantabro tests, the same testing program used in the PMFC and PMLC studies was followed in this laboratory-mixed, laboratory-compacted study to facilitate comparison of results.

2.2 Experiment Design

Six mixes were tested. These included a Control mix produced at 310°F (153°C), Advera, Evotherm, Sasobit, and Rediset mixes produced at 250°F (121°C), and a Sasobit mix produced with a lower binder content (4.5 percent) that was similar to that unintentionally used in the Sasobit section of the test track used for the Phase 1 and Phase 2 accelerated pavement tests.

2.2.1 Rutting Performance Testing

<u>Test Method</u>

The AASHTO T 320 Permanent Shear Strain and Stiffness Test was used for shear testing in this study. In the standard test methodology, cylindrical test specimens 6.0 in. (152 mm) in diameter and 2.0 in. (50 mm) thick (cored from slabs compacted with a rolling wheel compactor) were 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 were applied while the permanent (unrecoverable) and recoverable shear strains were measured. The permanent shear strain versus applied repetitions was recorded up to a value of 5 percent although 5,000 repetitions are called for in the AASHTO procedure. During the test, constant temperatures representative of the high temperatures that can cause rutting on in-service pavements (113°F and 131°F [45°C and 55°C]) were maintained (these are termed the *critical temperatures)*.

Number of Tests

A total of 18 shear tests were carried out on each mix (total of 108 tests for six mixes) as follows:

- Two temperatures (45°C and 55°C [113°F and 131°F])
- Three stresses (70 kPa, 100 kPa, and 130 kPa [10.2, 14.5, and 18.9 psi])
- Three replicates

2.2.2 Beam Fatigue Testing

Test Method

The AASHTO T 321 Flexural Controlled-Deformation Fatigue Test Method was followed. In this test, three replicate beam test specimens, 2.0 in. (50 mm) thick by 2.5 in. (63 mm) wide by 15 in. (380 mm) long, cut from slabs compacted with a rolling wheel compactor, were subjected to four-point bending using a haversine waveform at a loading frequency of 10 Hz. Testing was performed in both dry and wet conditions at two different strain levels at one temperature. 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 was 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, 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 A. The beam was first vacuum-saturated to ensure a saturation level greater than 70 percent, and then placed in a water bath at 140°F (60°C) for 24 hours, followed by a second water bath at 68°F (20°C) for two hours. The beams were then wrapped with *Parafilm*™ and tested within 24 hours after soaking.

Number of Tests

A total of 12 beam fatigue tests and 12 flexural fatigue frequency sweep tests were carried out on each mix (total of 144 tests for the six mixes) as follows:

- Standard test:
  + Two conditions (wet and dry)
  + One temperature (20°C [68°F])
  + Two strains (200 microstrain and 400 microstrain)
  + Three replicates
- Frequency sweep test:
  + Two conditions (wet and dry)
  + Three temperatures (10°C, 20°C, and 30°C [50°F, 68°F, and 86°F])
  + One strain (100 microstrain)
  + Two replicates

2.2.3 Moisture Sensitivity Testing

Test Methods

In addition to the wet fatigue test described above, two other moisture sensitivity tests were conducted, namely the Hamburg Wheel-Track and the Tensile Strength Retained (TSR) tests:

- The AASHTO T 324 test method was followed for Hamburg Wheel-Track testing on 6.0 in. (152 mm) cores. All testing was carried out at 122°F (50°C).
- The Caltrans CT 371 test method was followed for the Tensile Strength Retained Test on 4.0 in. (100 mm) cores. This test method is similar to the AASHTO T 283 test, but it has some modifications specific to California conditions.

A literature review on laboratory testing of warm mixes *(1)* indicated that warm mixes had consistently poorer rutting performance compared to hot mix controls, and this was attributable to less aging of the binder at the lower mixing temperatures. A small experiment was therefore undertaken to assess the effects of additional curing on the Hamburg Wheel-Track specimens to assess the effects of this binder aging on early rutting performance, and whether additional aging would result in similar performance to the control specimens. Mixes were cured for an additional two hours and four hours prior to compaction. Rediset was not tested in this part of the experiment.

Additional Hamburg Wheel-Track tests were also carried out to assess the potential effects on moisture sensitivity of insufficient aggregate drying at the lower warm mix production temperatures. Additional specimens were prepared with 0.5, 1.5, and 3.0 percent water by weight of the mix, with the water added to the mix prior to compaction. The Caltrans Standard Specifications (Section 39) require that the water content in dense-graded asphalt mixes does not exceed one percent by weight of the total mix. Rediset was not tested in this part of the experiment.

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 each 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 only measure the point of maximum final rut depth, which usually results in a larger variance in the test results.

Number of Tests

Four replicates of the Hamburg Wheel-Track Test and four replicates of the Tensile Strength Retained Test were carried out for each mix (20 tests per method) in the standard test. Specimens were prepared as follows for the additional Hamburg Wheel-Track testing (144 cores [note that two specimens are required for each Hamburg Wheel-Track Test]):

- Three moisture contents (0.5, 1.5, and 3.0 percent)
- Two additional cure times (2 and 4 hours)
- Two replicates

2.2.4 Open-Graded Friction Course Durability Testing

Test Method

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 4.0 in. (100 mm) in diameter and 2.5 in. (63 mm) thick.

Number of Tests

Six replicates were tested for OGFC durability for each mix (total of 30 tests). The Sasobit mix with 4.5 percent binder content was not tested.

2.3 Material Sampling

Mix constituents were collected on the day of test track construction *(2)*. A 20-ton truckload of aggregate sample was collected off a feed from the aggregate conveyor into the asphalt plant drum. Asphalt binder samples were collected from the delivery tanker. Warm mix additive samples were provided by the manufacturers. All samples were transported to and stored at the UCPRC Richmond Field Station prior to processing, specimen preparation, and testing.

2.4 Specimen Preparation

2.4.1 Aggregate

The bulk aggregate sample collected on the day of construction was dried and then screened into 11 different size fractions. These fractions were then reconstituted to prepare specimens for testing. For the shear, fatigue, Hamburg Wheel-Track, and Tensile Strength Retained tests (hereafter referred to as standard tests), samples weighing 258 oz. (7,300 g) were prepared according to the original mix design as shown in Table 2.1. For the Cantabro tests, a separate open-graded friction course mix design was used, with selected fractions reconstituted into 42 oz. (1,200 g) samples as shown in Table 2.2.

Aggregates used in the Control mixes were heated to 310°F (153°C) prior to mixing, while aggregates used in the warm mixes were heated to 250°F (121°C). Both temperatures were consistent with those used during mix production for the Phase 1 and Phase 2 test track.

Table 2.1: Mix Design for Standard Test Specimen Preparation

Grading		Mix Design Target (% Passing)	Weight (g)
U.S.	Metric (mm)		
1"	25.0	100	0
3/4"	19.0	96	315
1/2"	12.5	84	1,005
3/8"	9.5	72	875
#4	4.75	49	1,670
#8	2.36	36	940
#16	1.19	26	810
#30	0.595	18	650
#50	0.297	11	585
#100	0.150	7	285
#200	0.075	4	165
		Total	7,300

Table 2.2: Mix Design for Cantabro Test Specimen Preparation

Grading		Mix Design Target (% Retained on sieve)	Weight (g)
U.S.	Metric (mm)		
1/2"	12.5	0	0
3/8"	9.5	5	60
#4	4.75	62	750
#8	2.36	20	240
#30	0.595	8	90
#200	0.075	4	42
Pan	Pan	1	18
		Total	1,200

2.4.2 Warm Mix Additives

The warm mix additives were added to the binder at the following rates as recommended by the manufacturers and consistent with those used during mix production for the test track:

- Advera: 4.8 percent by mass of binder
- Evotherm: 0.5 percent by mass of binder
- Sasobit: 1.5 percent by mass of binder
- Rediset: 2.0 percent by mass of binder (Rediset was not used in the test track.)

The additives were mixed into the binder following the procedures provided by the warm mix technology providers.

2.4.3 Asphalt Binder

A PG 64-16 asphalt binder, sourced from the Valero refinery at Martinez, California, was used in the study. Asphalt samples collected on the day of test track construction were stored in sealed 5 gallon (20 L) containers at a constant temperature of 59°F (15°C). Prior to specimen preparation, a 5 gallon (20 L) container of binder was gently heated to a temperature sufficiently high to reduce the viscosity to a point that the binder could be poured into smaller containers.

The design asphalt binder content used in the test track was 5.2 percent (range of 5.1 to 5.4 percent) by mass of the dry aggregate. Actual binder contents recorded during test track mix production were 5.3, 5.2, 5.2, and 4.5 percent for the Control, Advera, Evotherm, and Sasobit mixes, respectively. The asphalt binder content for the standard tests in this laboratory study was therefore set at 5.2 percent. An additional set of Sasobit specimens prepared with an asphalt binder content of 4.5 percent was included to facilitate comparison of results from tests on specimens sampled from the test track *(2,3)*. Binder contents of 5.2 and 4.5 percent equate to binder weights of 379.6 g and 328.5 g, respectively for the 7,300 g aggregate sample. For the Cantabro test, a binder content of 5.9 percent was used, equating to a binder weight of 70.8 g for the 1,200 g aggregate sample.

The measured asphalt binder samples were heated to 310°F (154°C). The warm mix additives were then added to the binder, which was constantly stirred with an electric laboratory mixer. Stirring continued for at least three minutes after addition of the additive. The binder was then mixed into the aggregate in a laboratory mixer.

2.4.4 Curing

After mixing, the control mix was cured for four hours at 275°F (135°C) prior to compaction, while the warm mixes were cured for four hours at 250°F (121°C, i.e., the mix production temperatures) prior to compaction. Selected samples were subjected to a further two or four hours of curing prior to compaction to assess the effects of different aging conditions on the Hamburg Wheel-Track Test results.

2.4.5 Compaction

<u>Standard Tests</u>

After curing, mixes were compacted in ingot molds with a rolling wheel compactor according to the AASHTO PP3-94 *Standard Practice for Preparing Hot Mix Asphalt (HMA) Specimens by Means of the Rolling Wheel Compactor* test method. This method of compaction was chosen over gyratory compaction to better facilitate comparison with the results obtained from specimens sampled from the test track. Specimens prepared for additional Hamburg Wheel-Track testing (i.e., different moisture contents and additional curing periods) were compacted in a gyratory compactor since there was no direct comparison with field-compacted mixes. Specimens for Tensile Strength Retained tests were also compacted in a gyratory compactor to meet the higher air-void contents required for this test.

<u>Cantabro Tests</u>

Test specimens prepared to measure the durability of open-graded friction courses were compacted in a gyratory compactor since there was no direct comparison with field-compacted mixes.

3. TEST RESULTS

3.1 Rutting Performance Tests

Shear test results are listed in Table B.1 through Table B.6 in Appendix B. Key individual components of the testing are discussed in the following sections.

3.1.1 Air-Void Content

Air-void contents were measured using the *CoreLok* method and results are listed in Table B.1 through Table B.6 in Appendix B. Table 3.1 summarizes the air-void distribution categorized by mix type, test temperature, and test shear stress level. Figure 3.1 summarizes the mean air-void contents and standard deviations for each warm mix technology. Air-void contents for the specimens prepared with the 5.2 percent binder content were consistent. The air-void contents of the Sasobit specimens prepared with 4.5 percent binder content were higher than those on the 5.2 percent binder content specimens, as expected.

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

Temperature		Stress Level	Air-Void Content (%)					
			Control		Advera		Evotherm	
°C	°F	(kPa)	Mean[1]	SD[2]	Mean	SD	Mean	SD
45	113	70	4.3	0.4	4.6	0.5	4.4	0.4
		100	4.8	0.2	4.4	0.2	4.6	0.3
		130	4.6	0.3	4.8	0.2	4.1	0.2
55	131	70	4.7	0.4	4.4	0.4	4.6	0.4
		100	4.5	0.5	4.9	0.0	4.6	0.3
		130	4.7	0.3	4.8	0.3	4.1	0.2
		Overall	4.6	0.3	4.7	0.3	4.4	0.3
Temperature		**Stress Level**	**Air-Void Content (%)**					
			Sasobit (5.2%)		**Sasobit (4.5%)**		**Rediset**	
°C	**°F**	**(kPa)**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
45	113	70	4.8	0.4	7.3	0.5	4.3	0.1
		100	4.9	0.8	7.8	0.3	4.4	0.5
		130	5.1	0.1	7.3	0.7	4.6	0.3
55	131	70	6.4	0.6	7.2	0.8	4.4	0.1
		100	4.7	0.1	7.3	0.3	4.4	0.1
		130	4.7	0.2	7.4	0.2	4.5	0.4
		Overall	5.1	0.7	7.4	0.5	4.4	0.3

[1] Mean of three replicates [2] SD: Standard deviation

3.1.2 Resilient Shear Modulus *(G)*

The resilient shear modulus results for the six mixes are summarized in Table 3.2 and Figure 3.2. The following observations were made:

- The resilient shear modulus was influenced by temperature, with the modulus increasing with decreasing temperature. Resilient shear modulus was not influenced by stress.

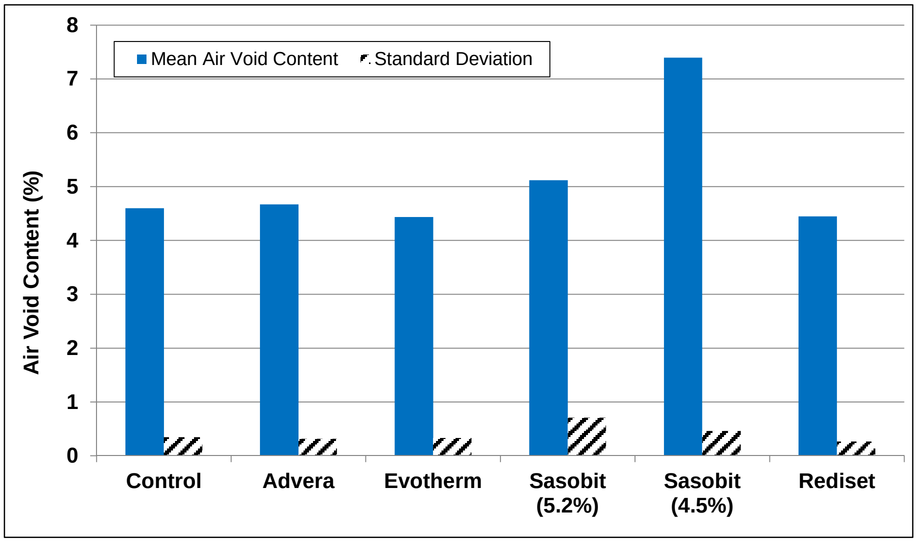


Figure 3.1: Mean air-void contents of shear specimens.

- The variation of resilient shear moduli at 45°C was higher than at 55°C for all mixes and was generally attributed to higher sensitivity to air-void content variation at this testing temperature.
- The Control mix had higher resilient shear moduli at both temperatures, which was attributed to the higher production temperatures and consequent additional binder aging.
- The Sasobit had the highest resilient shear modulus of the warm mix technologies, a result consistent with findings from the literature and observations on the test track.
- The Sasobit (5.2%) mix had a higher resilient shear modulus than the Sasobit (4.5%) mix, which was attributed primarily to the difference in air-void contents.

Table 3.2: Summary of Resilient Shear Modulus Results

Temperature		Stress Level	Resilient Shear Modulus (kPa)					
			Control		Advera		Evotherm	
°C	°F	(kPa)	Mean[1]	SD[2]	Mean	SD	Mean	SD
45	113	70	345	49	208	26	220	75
		100	359	44	200	65	230	21
		130	332	28	210	30	231	11
		Overall	345	40	206	40	227	36
55	131	70	142	28	130	43	111	21
		100	189	35	113	14	102	15
		130	142	8	116	19	105	33
		Overall	158	24	120	25	106	23
Temperature		**Stress Level**	**Resilient Shear Modulus (kPa)**					
			Sasobit (5.2%)		**Sasobit (4.5%)**		**Rediset**	
°C	**°F**	**(kPa)**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
45	113	70	305	17	187	32	287	78
		100	333	215	188	22	259	52
		130	234	37	173	26	241	24
		Overall	291	89	183	27	262	51
55	131	70	115	36	107	26	105	12
		100	118	8	100	11	142	23
		130	102	4	87	13	117	2
		Overall	112	16	98	16	121	13

[1] Mean of three replicates [2] SD: Standard deviation

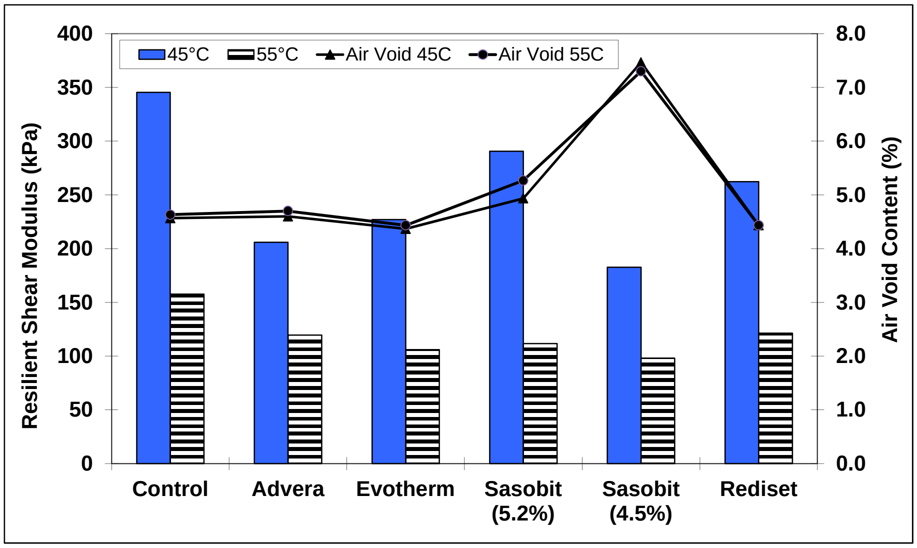


Figure 3.2: Average Resilient Shear Modulus at 45°C and 55°C.
(Average air-void content shown)

3.1.3 Permanent Shear Strain at 5,000 Cycles

The measurement of permanent shear strain (PSS) accumulated after 5,000 cycles provides an indication of the rut-resistance capacity of an asphalt mix. The smaller the permanent shear strain, the better the mixture's rut-resistance capacity. Table 3.3 and Figure 3.3 summarize the rutting performance of the six mixes.

Table 3.3: Summary of Permanent Shear Strain at 5,000 Cycles

Temperature		Stress Level	Permanent Shear Strain					
			Control		Advera		Evotherm	
°C	°F	(kPa)	Mean[1]	SD[2]	Mean	SD	Mean	SD
45	113	70	0.0082	0.0016	0.0199	0.0013	0.0247	0.0083
		100	0.0139	0.0043	0.0212	0.0020	0.0255	0.0028
		130	0.0158	0.0024	0.0283	0.0021	0.0252	0.0065
		Overall	0.0126	0.0028	0.0231	0.0018	0.0251	0.0058
55	131	70	0.0172	0.0052	0.0289	0.0145	0.0347	0.0112
		100	0.0153	0.0041	0.0324	0.0045	0.0526	0.0160
		130	0.0283	0.0038	0.0397	0.0057	0.0626	0.0098
		Overall	0.0203	0.0043	0.0337	0.0013	0.0484	0.0123
Temperature		Stress Level	Permanent Shear Strain					
			Sasobit (5.2%)		Sasobit (4.5%)		Rediset	
°C	°F	(kPa)	Mean	SD	Mean	SD	Mean	SD
45	113	70	0.0125	0.0027	0.0267	0.0069	0.0134	0.0035
		100	0.0236	0.0154	0.0302	0.0048	0.0155	0.0034
		130	0.0244	0.0073	0.0421	0.0096	0.0180	0.0042
		Overall	0.0202	0.0084	0.0330	0.0071	0.0157	0.0037
55	131	70	0.0281	0.0077	0.0303	0.0062	0.0211	0.0004
		100	0.0341	0.0163	0.0468	0.0167	0.0266	0.0037
		130	0.0373	0.0133	0.0690	0.0105	0.0320	0.0076
		Overall	0.0332	0.0124	0.0487	0.0111	0.0266	0.0039

[1] Mean of three replicates [2] SD: Standard deviation

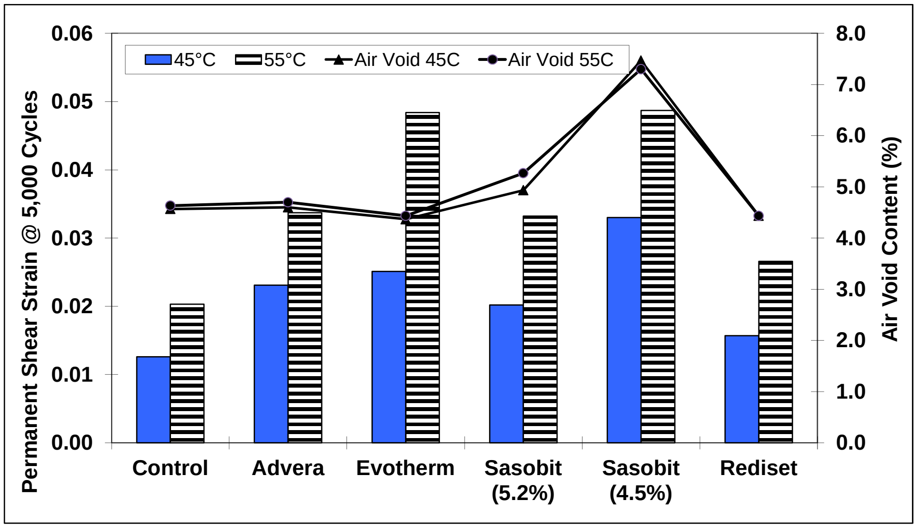


Figure 3.3: Permanent shear strain at 5,000 cycles at 45°C and 55°C.
(Average air-void content shown)

The following observations were made:

- Variation between results was in line with typical result ranges for this test.
- As expected, the effect of shear stress level was more significant at higher temperatures, and the higher the temperature and stress level the larger the cumulative permanent shear strain.
- The results were generally consistent with the resilient shear modulus results.

3.2 Beam Fatigue Tests

Beam fatigue test results are listed in Table B.7 through Table B.12 in Appendix B. Key individual components of the testing are discussed in the following sections.

3.2.1 Air-Void Content

Air-void contents were measured using the *CoreLok* method and the results are summarized in Table 3.4 and Figure 3.4. The air-void contents in the Control, Sasobit (4.5 percent), and Rediset specimens were consistent with those recorded on the shear specimens. Air-void contents on the Advera, Evotherm, and Sasobit (5.2 percent) were higher. This was attributed to different technicians preparing the specimens with the rolling wheel compactor. Additional specimens could not be prepared at the time due to other project commitments. The differences in air-void content were factored into the test results analysis, discussed below.

Table 3.4: Summary of Air-Void Contents of Beam Fatigue Specimens

Condition	Strain (µstrain)	Air-Void Content (%)					
		Control		Advera		Evotherm	
		Mean[1]	SD[2]	Mean	SD	Mean	SD
Dry	200	4.9	0.4	6.2	0.2	6.2	0.4
	400	4.7	0.3	5.8	0.3	5.7	0.2
Wet	200	4.5	0.1	6.0	0.4	6.4	0.1
	400	4.9	0.2	5.8	0.1	6.1	0.5
	Overall	4.8	0.2	6.0	0.2	6.1	0.3
Condition	Strain (µstrain)	Air-Void Content (%)					
		Sasobit (5.2%)		Sasobit (4.5%)		Rediset	
		Mean	SD	Mean	SD	Mean	SD
Dry	200	6.7	0.6	7.7	0.3	4.5	0.5
	400	7.0	0.4	7.4	0.3	4.7	0.2
Wet	200	6.5	0.2	7.4	0.4	4.6	0.2
	400	7.0	0.4	7.3	0.4	4.5	0.2
	Overall	6.8	0.4	7.4	0.3	4.6	0.3

[1] Mean of three replicates [2] SD: Standard deviation

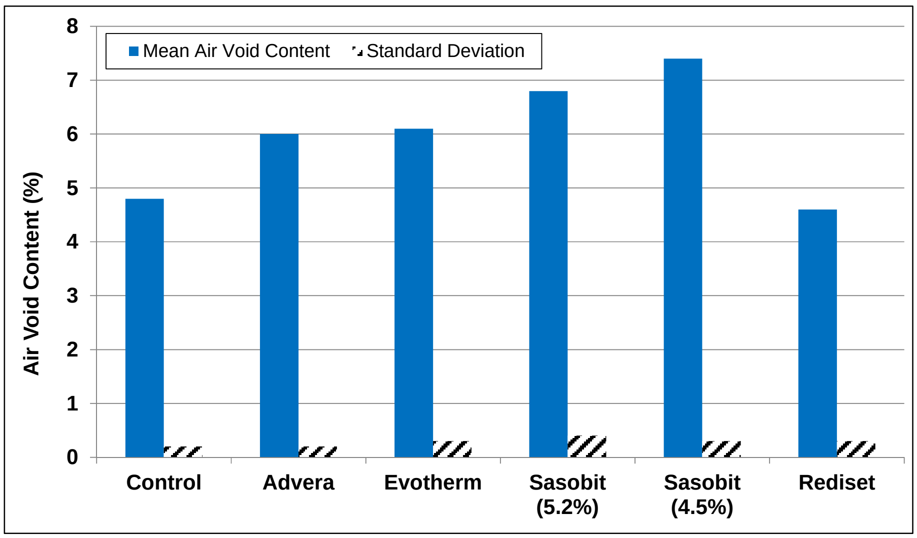


Figure 3.4: Mean air-void contents of beam fatigue specimens.

3.2.2 Initial Stiffness

Initial stiffness test results are summarized in Table 3.5 and Figure 3.5 in terms of test condition (dry or wet) and test strain level (200 or 400 microstrain). The following observations were made:

- Variation between results was in line with typical result ranges for this test.
- Initial stiffness was generally strain-independent for both the dry and wet tests.
- The Control mix had the highest initial stiffnesses, and this was attributed to the higher production temperatures and consequent additional binder aging.
- The Control and Rediset mixes had higher initial stiffnesses compared to the other four mixes, and this was attributed to the higher air-void contents in the specimens from these four mixes. After air-void content and both the variation in actual test strain level and actual test temperature (see tables in Appendix B) were taken into consideration, in this test there was no statistically significant

difference (confidence level of 0.1) in performance between the different warm mixes in the dry condition.

- With the exception of the Rediset mix, initial stiffnesses on all mixes dropped significantly after soaking, indicating a potential loss of structural capacity due to moisture damage. The better performance on the Rediset mix was attributed to the liquid anti-strip that is incorporated into the Rediset technology. The Advera and Sasobit (4.5%) mixes had lower initial stiffnesses after soaking compared to the other warm mixes.
- The different binder contents in the two Sasobit mixes did not appear to have a significant effect in these test results. A reduction of initial stiffness due to soaking was apparent for each mix type.

Table 3.5: Summary of Initial Stiffness Results at 20°C

Condition	Strain Level	Initial Stiffness (MPa)					
		Control		Advera		Evotherm	
	(μStrain)	Mean[1]	SD[2]	Mean	SD	Mean	SD
Dry	200	6,105	205	4,716	106	4,085	153
	400	5,886	473	4,471	464	3,984	200
Wet	200	4,201	534	2,109	140	2,988	201
	400	3,853	314	1,701	119	2,413	406
Condition	**Strain Level**	**Initial Stiffness (MPa)**					
		Sasobit (5.2%)		**Sasobit (4.5%)**		**Rediset**	
	(μStrain)	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Dry	200	4,503	581	4,723	932	5,219	332
	400	3,911	626	4,397	674	4,891	674
Wet	200	2,900	9	2,350	717	5,079	290
	400	2,507	119	1,921	582	3,743	288

[1] Mean of three replicates [2] SD: Standard deviation

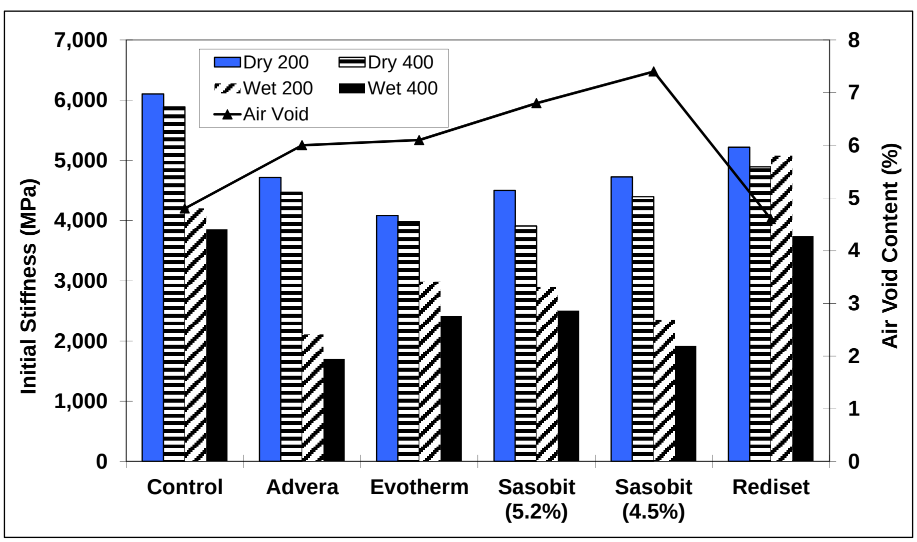


Figure 3.5: Plot of average initial stiffness for dry test.
(Average air-void content shown)

3.2.3 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. Phase angle test results are summarized in Table 3.6 and Figure 3.6 in terms of test condition (dry or wet) and test strain level (200 or 400 microstrain).

Table 3.6: Summary of Phase Angle Results at 20°C

Condition	Strain Level (µStrain)	Phase Angle (degrees)					
		Control		Advera		Evotherm	
		Mean[1]	SD[2]	Mean	SD	Mean	SD
Dry	200	23.8	0.6	29.0	0.2	30.2	0.9
	400	26.1	0.9	22.6	0.4	26.9	4.9
Wet	200	25.0	3.1	34.8	0.9	28.6	2.8
	400	24.4	4.3	37.4	0.4	34.7	1.6
Condition	**Strain Level (µStrain)**	**Phase Angle (degrees)**					
		Sasobit (5.2%)		**Sasobit (4.5%)**		**Rediset**	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Dry	200	29.1	3.4	28.6	2.8	25.4	2.4
	400	26.4	1.7	23.5	6.7	25.0	5.4
Wet	200	31.4	1.0	34.0	4.2	25.9	1.4
	400	28.8	3.6	33.4	7.6	31.9	0.7

[1] Mean of three replicates [2] SD: Standard deviation

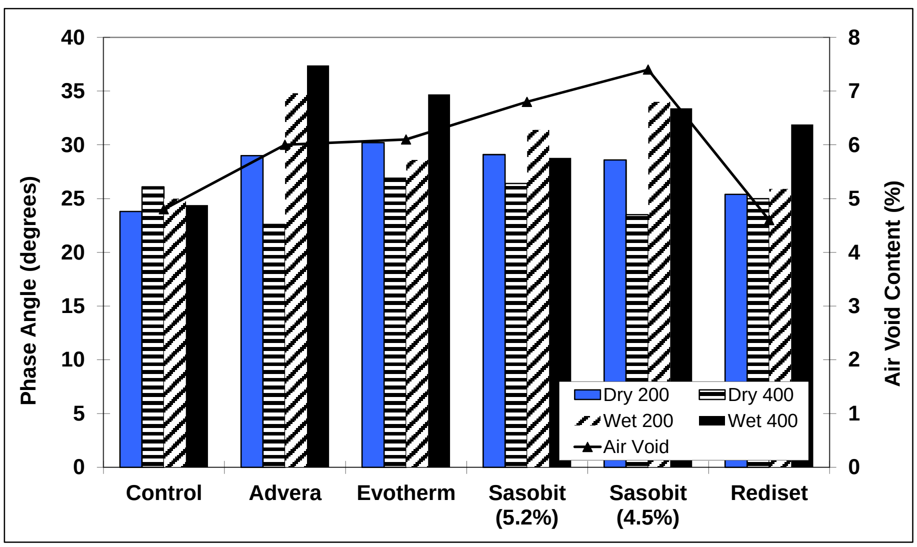


Figure 3.6: Plot of average initial phase angle.
(Average air-void content shown)

The following observations were made:

- The initial phase angle appeared to be strain-independent.
- Soaking appeared to increase the phase angle slightly on most mixes.
- The initial phase angle was highly negative-correlated with the initial stiffness.
- Air-void content had some influence on the results, as expected. After air-void content and both the variation in actual test strain level and the actual test temperature were taken into consideration (see

tables in Appendix B), in this test there was no statistically significant difference (confidence level of 0.1) in performance between the three warm mixes with higher air-void contents. The lower binder content in the Sasobit (4.5 percent) mix appeared to have some influence on test results, especially in the wet condition.

3.2.4 Fatigue Life at 50 Percent Stiffness Reduction

Mix stiffness decreases with increasing test-load repetitions. Conventional fatigue life is defined as the number of load repetitions that have been applied when a 50 percent stiffness reduction has been reached. A high fatigue life implies a slow fatigue damage rate and consequently higher fatigue-resistance. The results of fatigue life testing are summarized in Table 3.7 and a side-by-side fatigue life comparison of dry and wet tests is plotted in Figure 3.7. The following observations were made:

- Fatigue life was strain-dependent as expected, with higher strains resulting in shorter fatigue life. The difference between the two strain levels was significant.

Table 3.7: Summary of Fatigue Life Results at 20°C

Condition	Strain Level	Fatigue Life (load repetitions)					
		Control		Advera		Evotherm	
	(µStrain)	Mean[1]	SD[2]	Mean	SD	Mean	SD
Dry	200	>5,000,000	-	4,441,721	966,967	>5,000,000	-
	400	335,744	252,394	129,622	94,633	274,093	149,915
Wet	200	>5,000,000	-	4,036,537	1,264,902	3,910,968	2,213,106
	400	95,623	40,454	26,868	6,101	90,290	30,086
Condition	**Strain Level**	**Fatigue Life (load repetitions)**					
		Sasobit (5.2%)		**Sasobit (4.5%)**		**Rediset**	
	(µStrain)	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Dry	200	4,047,760	1,649,327	2,490,166	697,343	>5,000,000	-
	400	216,246	72,495	286,043	238,723	195,213	46,107
Wet	200	825,984	627,429	1,539,086	909,366	5,000,000	-
	400	13,300	6,126	11,010	5,569	393,145	158,308

[1] Mean of three replicates [2] SD: Standard deviation

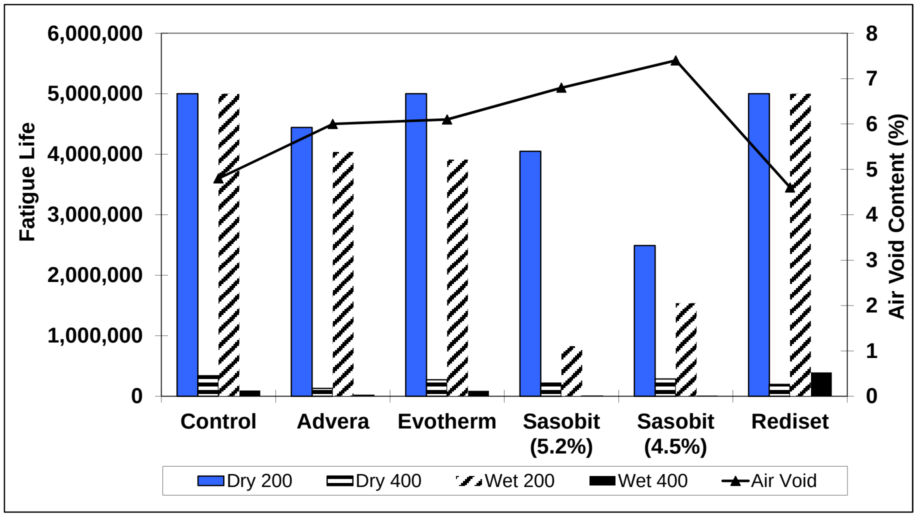


Figure 3.7: Plot of average fatigue life.
(Average air-void content shown)

- Results varied between the mixes, with air-void content and binder content appearing to have the biggest influence on performance. Soaking generally resulted in a lower fatigue life compared to the unsoaked specimens.
- The two Sasobit mixes had the shortest fatigue lives, with the mix with the 4.5 percent binder content having the lowest performance, as expected.

3.3 Flexural Frequency Sweep Test

Flexural frequency sweep test results are listed in Table B.13 through Table B.24 in Appendix B. Key individual components of the testing are discussed in the following sections.

3.3.1 Air-Void Content

Air-void contents were measured using the *CoreLok* method and results are summarized in Table 3.8 and Figure 3.8. The air-void contents were consistent with those recorded on the beam fatigue specimens. The differences in air-void content were factored into the test result analysis, discussed below.

Table 3.8: Summary of Air-Void Contents of Flexural Frequency Sweep Specimens

Condition	Air-Void Content (%)					
	Control		Advera		Evotherm	
	Mean[1]	SD[2]	Mean	SD		
Dry	4.6	0.4	5.8	0.4	6.2	0.3
Wet	4.5	0.4	5.7	0.2	6.1	0.4
Condition	**Air-Void Content (%)**					
	Sasobit (5.2%)		**Sasobit (4.5%)**		**Rediset**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Dry	6.8	0.2	7.6	0.3	4.5	0.4
Wet	7.1	0.2	7.6	0.3	4.6	0.3

[1] Mean of three replicates [2] SD: Standard deviation

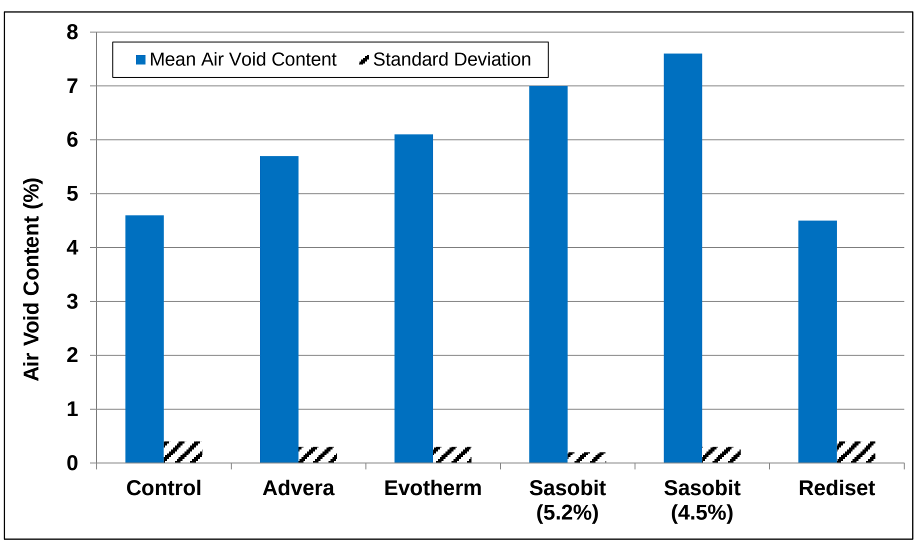


Figure 3.8: Mean air-void contents of flexural frequency sweep specimens.

3.3.2 Complex Modulus

The average stiffness values of the two replicates tested at the three temperatures were used to develop the flexural complex modulus (E^*) master curves. 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 generic algorithm approach can be appropriately fitted with the following modified Gamma function (Equation 3.1):

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

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 3.2);
A, *B*, *C*, *D*, and *n* are the experimentally-determined parameters.

$$\ln aT = A \cdot \left(1 - \exp\left(-\frac{T - Tref}{B}\right)\right) \quad \textbf{(3.2)}$$

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 3.9, together with the parameters in the temperature-shifting relationship.

Figure 3.9 and Figure 3.10 show the shifted master curves with Gamma-fitted lines and the temperature-shifting relationships, respectively, for the dry 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-shift (ln*aT*) value needs to be applied when the temperature is lower than the reference temperature, while a negative temperature-shift value needs to be used when the temperature is higher than the reference temperature.

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

- The complex modulus master curves appeared to be influenced primarily by specimen air-void content and binder content.
- The temperature-shifting relationships indicate that there was very little difference in temperature sensitivity between the six mixes. Higher temperature-sensitivity implies that a per unit change of temperature will cause a larger change of stiffness (i.e., larger change of ln*aT*).

Table 3.9: Summary of Master Curves and Time-Temperature Relationships

Mix	Condition	Master Curve					Time-Temperature Relationship	
		Number	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
Advera		3	13871.85	4.68803	-6.399148	225.4214	5.55125	-21.7964
Evotherm		3	11101.56	3.018703	-6.702452	181.9296	67.2594	-196.972
Sasobit (5.2%)		3	24590.84	7.495027	-8.130092	128.7522	3.91754	-13.5595
Sasobit (4.5%)		3	10614.49	3.318411	-8.269827	205.1302	17.4034	-47.9363
Rediset		3	38,681.50	7.815,284	-7.757,588	232.400,6	-16.056,4	-56.745,8
Control	Wet	3	3,575,422.00	58.034,36	-10.745,750	190.097,6	1.456,68	-7.685,26
Advera		3	186135.9	13.07768	-8.795148	107.0896	-26.3866	113.501
Evotherm		3	351446.0	24.26692	-6.66192	126.6793	-8.52654	26.6757
Sasobit (5.2%)		3	2006338.0	48.18033	-6.892147	109.0283	-8.48256	24.8558
Sasobit (4.5%)		3	146586.8	12.74489	-9.4747	85.28821	3.5444	-12.399
Rediset		3	36,070.81	8.046,71	-7.211,638	252.660,9	-10.015,00	30.754,10

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

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

4. Time-temperature relationship:

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

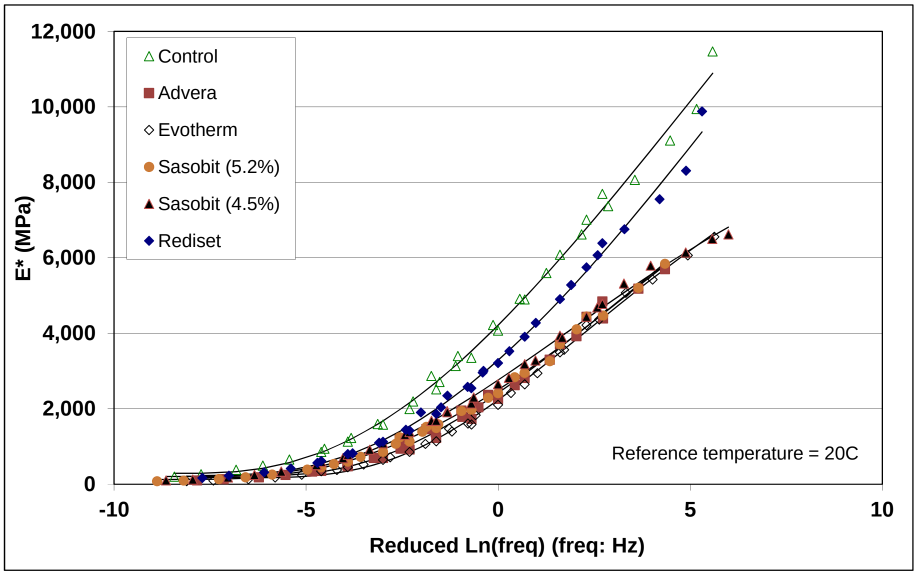


Figure 3.9: Complex modulus (*E) master curves (dry) at 20°C reference temperature.**

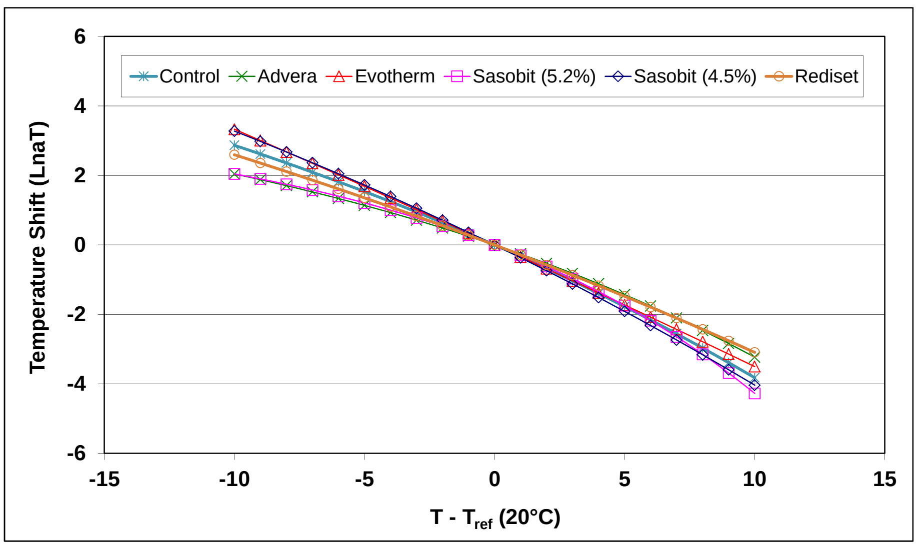


Figure 3.10: Temperature-shifting relationship (dry) at 20°C reference temperature.

Figure 3.11 and Figure 3.12 respectively show the shifted master curves with Gamma-fitted lines and the temperature-shifting relationships for the wet frequency sweep tests. The comparison of dry and wet complex modulus master curves is shown in Figure 3.13 for each mix type. The following observations were made with regard to the wet frequency sweep test results:

- The complex modulus master curves appeared to be influenced primarily by specimen air-void content and binder content and showed similar trends to the dry tests.
- Compared to the dry tests, there was a larger difference in temperature-sensitivity between the six mixes at lower temperatures (i.e., lower than 20°C). At higher temperatures (i.e., higher than 20°C),

the Control and Sasobit (5.2%) mixes appeared to be more temperature-sensitive than the other mixes.

- Some loss of stiffness attributed to moisture damage was apparent in all six mixes, with air-void content having the biggest influence on results.

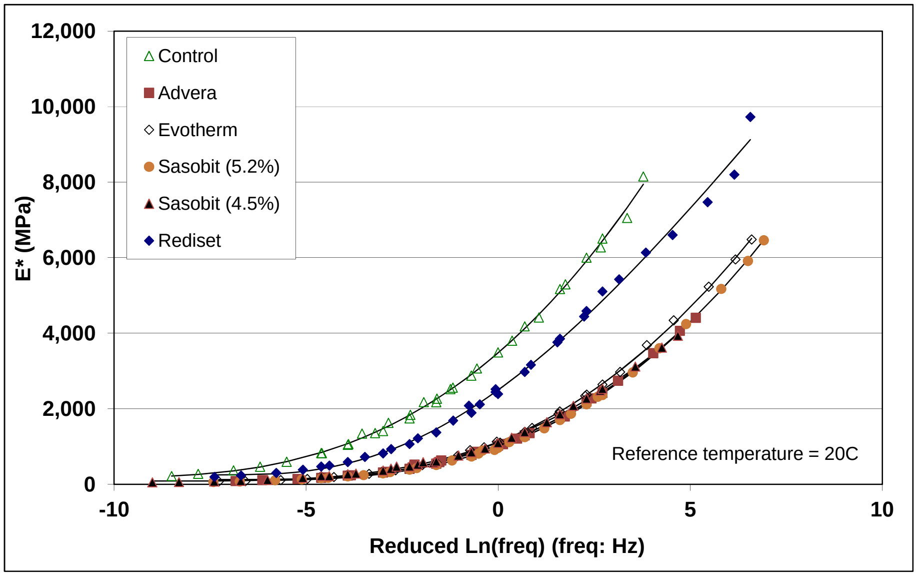


Figure 3.11: Complex modulus (*E) master curves (wet) at 20°C reference temperature.**

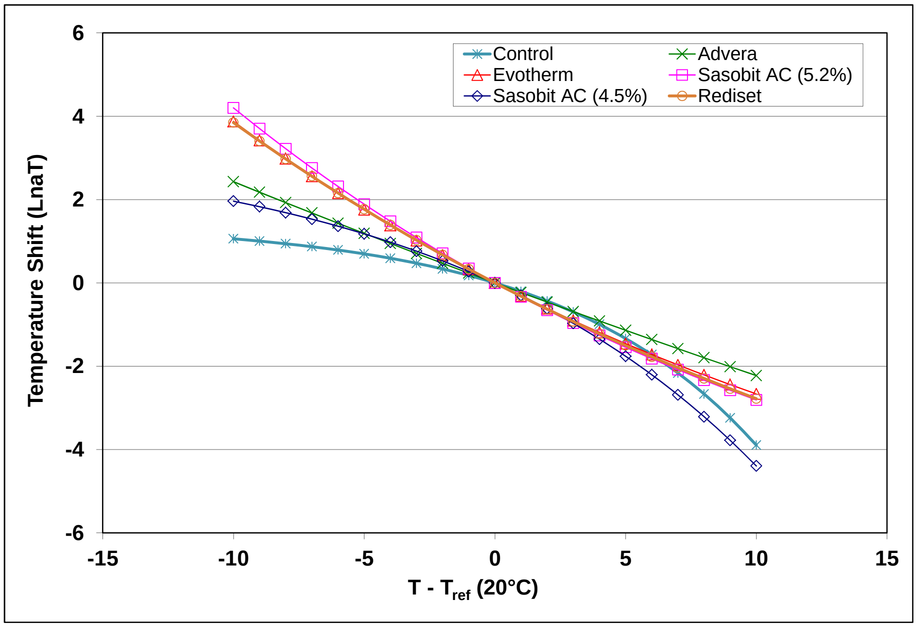


Figure 3.12: Temperature-shifting relationship (wet) at 20°C reference temperature.

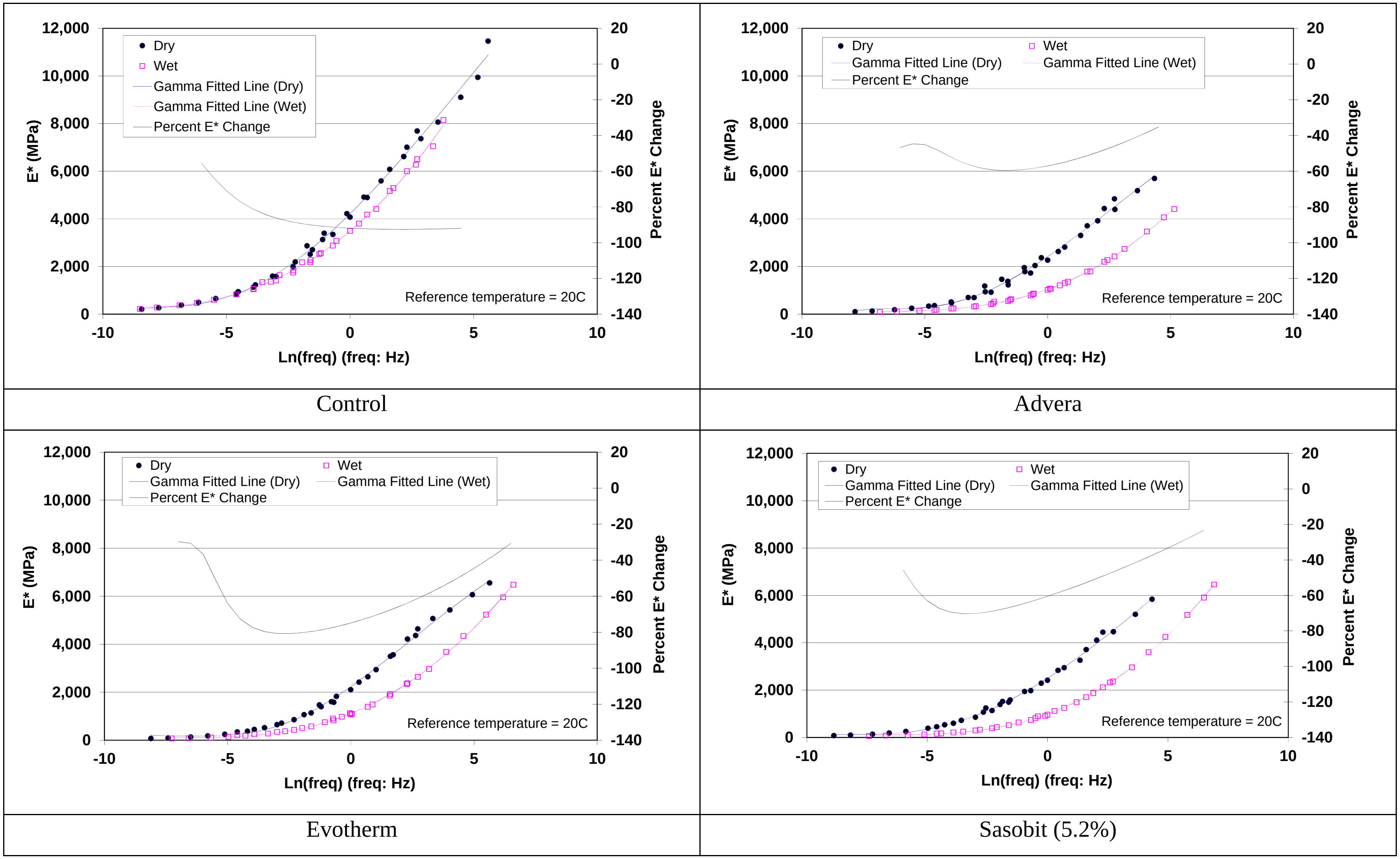
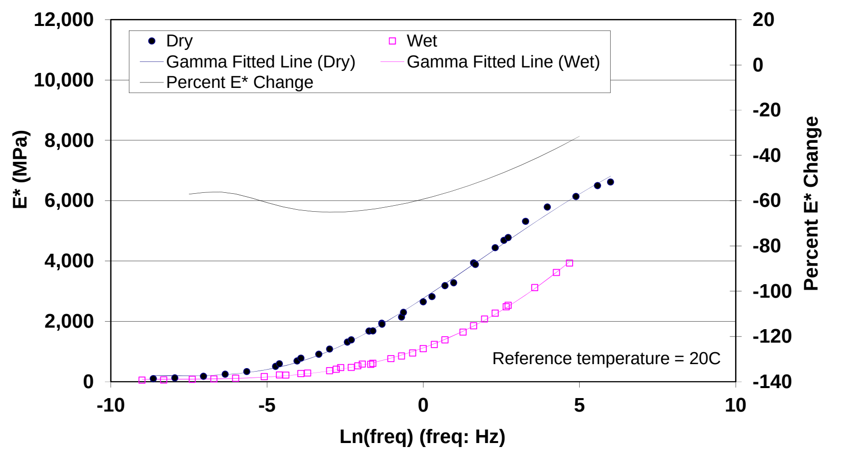
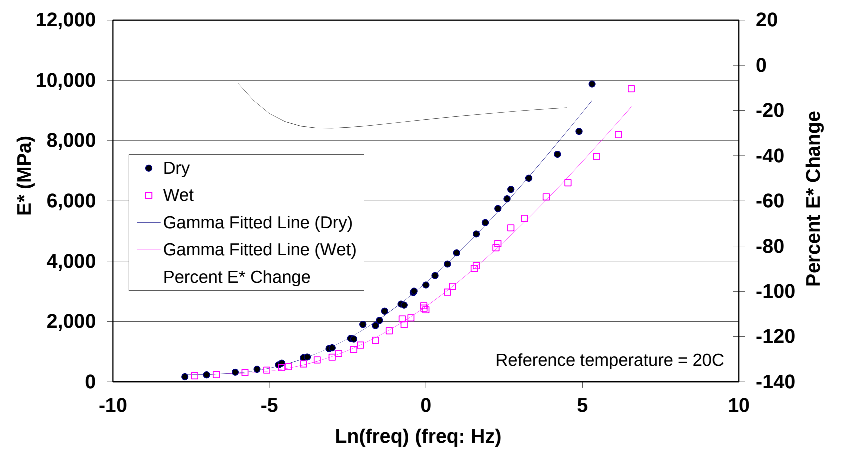


Figure 3.13: Percent change in stiffness between wet and dry tests.



Sasobit (4.5%)



Rediset

Figure 3.13: Percent change in stiffness between wet and dry tests *(continued)*.

3.4 Moisture Sensitivity: Hamburg Wheel-Track Test

3.4.1 Air-Void Content

The air-void content of each core was determined using the *CoreLok* method. Results are listed in Table B.25 in Appendix B and summarized in Table 3.10 and Figure 3.14. The air-void contents ranged between 4.5 and 7.1 percent and showed similar trends to those observed for the specimens used in the other tests.

Table 3.10: Summary of Air-Void Contents of Hamburg Test Specimens

Mix	Air-Void Content (%)	
	Mean[1]	SD[2]
Control	4.9	0.1
Advera	4.6	0.3
Evotherm	4.0	0.4
Sasobit (5.2%)	4.9	0.5
Sasobit (4.5%)	7.3	0.6
Rediset	4.6	0.3

[1] Mean of four replicates [2] SD: Standard deviation

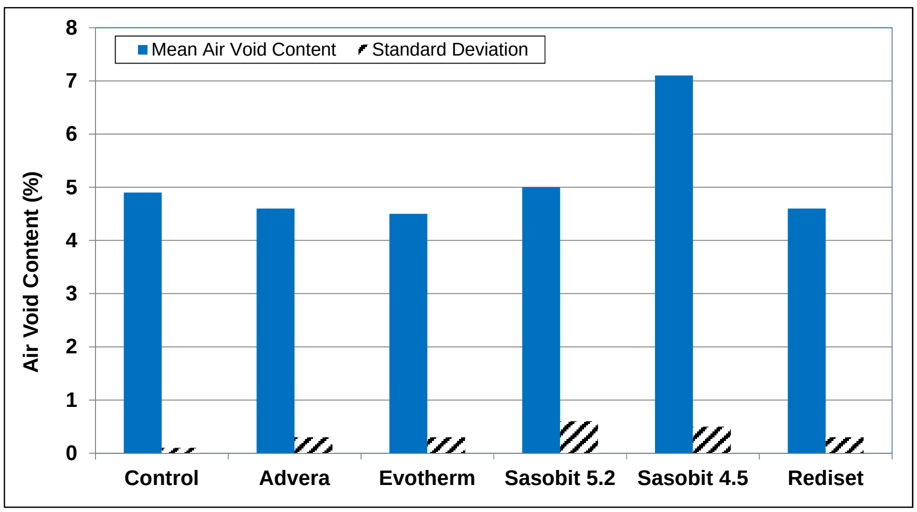


Figure 3.14: Mean air-void contents of Hamburg Wheel-Track specimens.

3.4.2 Hamburg Wheel-Track Rutting

Hamburg Wheel-Track test results are summarized in Table B.25 in Appendix B. Average maximum rut depths after 10,000 passes and the stripping inflection point for the standard test are summarized in Table 3.11. The Sasobit mix with 4.5 percent binder content was not tested due to time and equipment limitations. Figure 3.15 shows the average rut progression curves for each mix. Although clear inflection points are visible on the Control and Sasobit mix curves, none of the mixes were considered to be moisture sensitive.

Table 3.11: Summary of Hamburg Wheel-Track Test Results

Mix	Rut Depth @ 10,000 passes (mm)	Stripping Inflection Point (No. of passes)
Control	3.8	8,900
Advera	3.5	9,800
Evotherm	3.4	>12,000
Sasobit	3.3	9,100
Rediset	3.5	>12,000

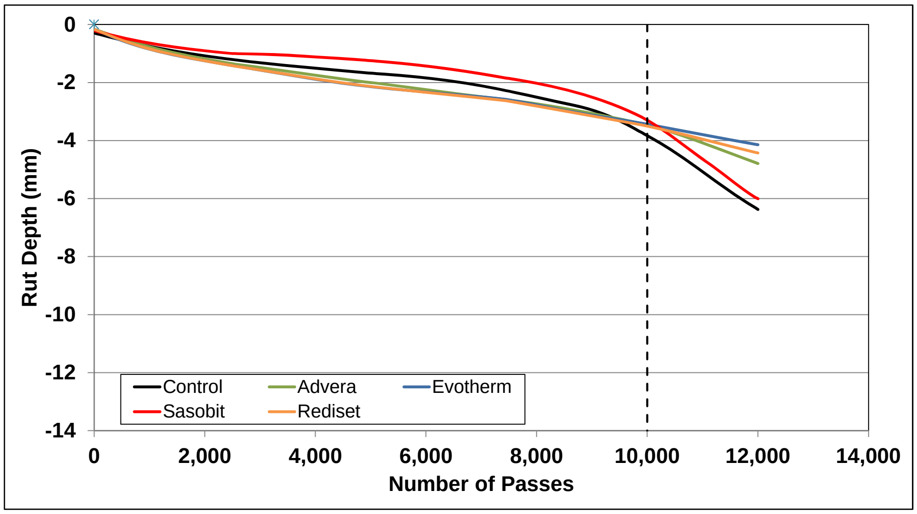


Figure 3.15: Average Hamburg Wheel-Track rut progression curves.

3.4.3 Hamburg Wheel-Track Rutting: Effect of Cure Time and Aggregate Moisture Content

Hamburg Wheel-Track test results quantifying the effect of both additional cure time (i.e., two and four hours) and aggregate moisture content are summarized in Table B.25 in Appendix B. The Rediset mix was not tested in this phase of the experiment. Average maximum rut depths after 10,000 passes and the stripping inflection point for the modified tests for each mix are summarized in Table 3.12 and Figure 3.16.

The results clearly indicate the effect of moisture on performance, indicating that using wet aggregates in the production of warm mix asphalt without increasing the aggregate drying time to compensate for the lower production temperature could lead to early moisture-related failures on the road. Additional curing of the mix had a significant influence on the performance. This was attributed to a combination of additional drying of the aggregate and aging of the binder.

Table 3.12: Summary of Hamburg Wheel-Track Test Results (Cure Time and Moisture Content)

Moisture Content (%)[1]	Rut Depth @ 10,000 passes (mm)			Stripping Inflection Point (No. of passes)		
	0-Hr Cure[2]	2-Hr Cure[3]	4-Hr Cure[4]	0-Hr Cure[2]	2-Hr Cure[3]	4-Hr Cure[4]
Control						
0.0	3.8	1.4	1.2	8,900	>12,000	>12,000
0.5	7.2	1.9	1.9	7,200	>12,000	>12,000
1.5	7.5	2.3	1.7	4,700	9,800	>12,000
3.0	11.3	2.5	2.3	4,950	8,800	>12,000
Advera						
0.0	3.5	1.2	1.4	9,800	>12,000	>12,000
0.5	5.5	1.9	2.1	7,900	>12,000	>12,000
1.5	8.5	2.2	2.2	5,900	>12,000	>12,000
3.0	14.6	2.8	2.2	2,200	10,900	>12,000
Evotherm						
0.0	3.4	1.8	1.3	>12,000	>12,000	>12,000
0.5	3.9	2.2	1.5	8,900	>12,000	>12,000
1.5	5.7	2.3	1.7	7,600	>12,000	>12,000
3.0	5.2	3.1	4.1	7,100	10,500	>12,000
Sasobit						
0.0	3.3	1.5	1.8	9,100	>12,000	>12,000
0.5	5.6	2.5	1.5	7,800	>12,000	>12,000
1.5	6.7	3.4	1.9	7,800	8,400	>12,000
3.0	6.8	4.2	1.5	7,200	7,200	>12,000

[1] Moisture content by mass of dry aggregate
[2] No additional curing [3] Two-hour additional cure [4] Four-hour additional cure

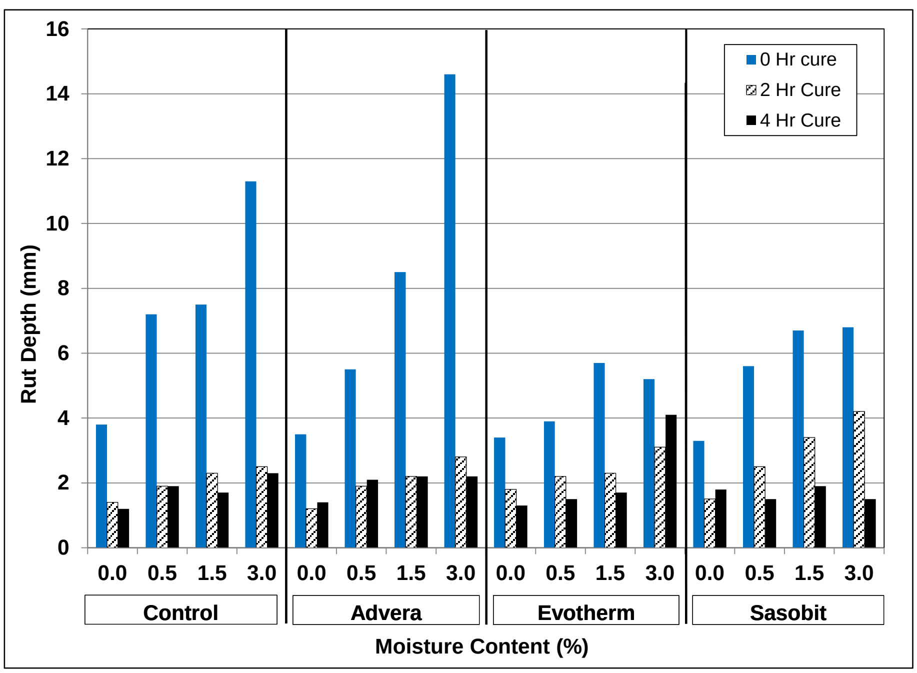


Figure 3.16: Effect of cure time and moisture content on Hamburg Wheel-Track test results.

3.5 Moisture Sensitivity: Tensile Strength Retained (TSR) Test

3.5.1 Air-Void Content

The air-void content of each core was determined using the *CoreLok* method. The results are listed in Table B.26 in Appendix B and summarized in Table 3.13 and Figure 3.17. The air-void contents ranged between 6.8 and 7.7 percent, consistent with the requirements of the CT 371 test, but higher than those recorded for the other tests.

Table 3.13: Summary of Air-Void Contents of Tensile Strength Retained Test Specimens

Mix	Air-Void Content (%)			
	Dry Test		Wet Test	
	Mean[1]	SD[2]		
Control	7.0	0.3	7.5	0.1
Advera	7.2	0.2	6.9	0.3
Evotherm	6.8	0.2	7.1	0.3
Sasobit (5.2%)	6.9	0.3	7.5	0.2
Sasobit (4.5%)	7.5	0.4	7.3	0.2
Rediset	7.7	0.3	7.3	0.3

[1] Mean of four replicates [2] SD: Standard deviation

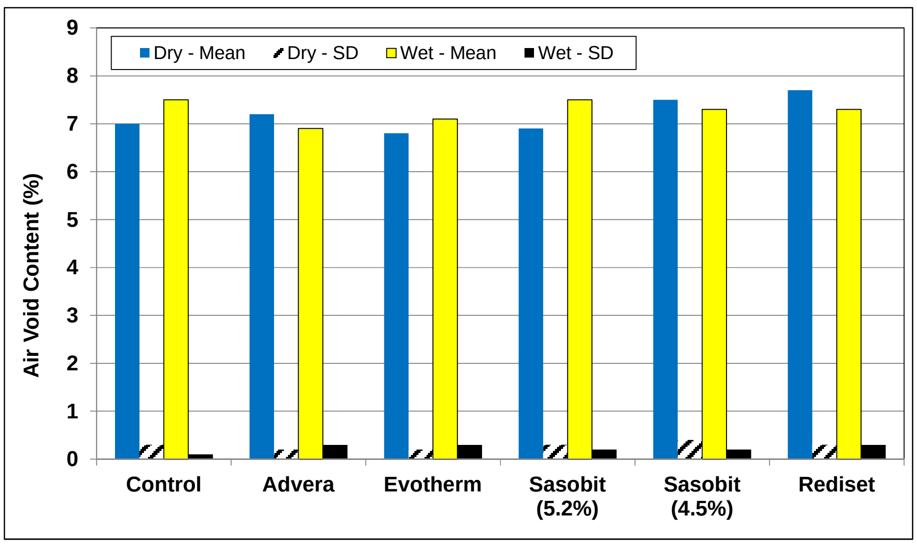


Figure 3.17: Mean air-void contents of TSR specimens.

3.5.2 Tensile Strengths

Results of Tensile Strength Retained (TSR) tests are listed in Table B.26 in Appendix B and summarized for each mix in Table 3.14. A plot of the average results is shown in Figure 3.18. The results indicate that although the dry strengths were consistent across the different mixes, the wet strengths and associated retained tensile strength varied considerably, with the warm mixes outperforming the Control mix. None of the mixes met the target TSR of 75 percent for medium and high environmental-risk regions, and only the Rediset met the target TSR of 70 percent for low environmental-risk regions, indicating that all mixes were potentially moisture sensitive and would typically require treatment to reduce the risk of moisture damage in the pavement. The results generally did not show trends similar to the Hamburg Wheel-Track test results; however, the mixes had the same ranking in terms of TSR performance when compared to the Hamburg Wheel-Track stripping inflection point values (i.e., Rediset followed by Evotherm, Advera, Sasobit, and then the Control).

Table 3.14: Summary of Tensile Strength Retained Test Results

Mix	Indirect Tensile Strength (kPa)				TSR (%)	Damage[3]
	Dry Test		Wet Test			
	Mean[1]	SD[2]	Mean[1]	SD[2]		
Control	2,487	191	613	36	25	Yes
Advera	2,248	104	1,012	40	45	Yes
Evotherm	2,163	76	1,350	51	62	Yes
Sasobit (5.2%)	2,306	357	963	80	42	Yes
Sasobit (4.5%)	2,567	269	1,328	47	52	Yes
Rediset	2,552	92	1,790	120	70	Yes

[1] Mean of four replicates [2] SD: Standard deviation [3] Damage based on visual evaluation of stripping

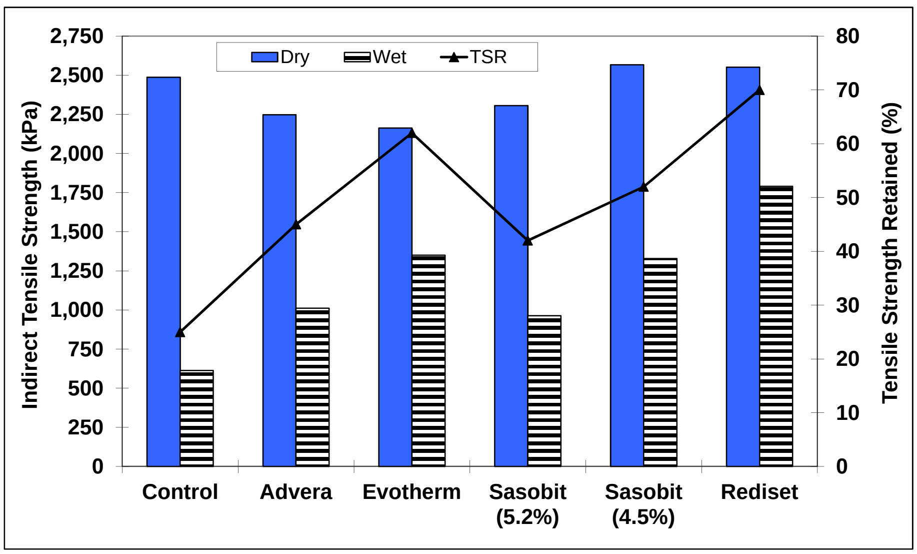


Figure 3.18: Average tensile strength retained for each mix.

Observation of the split faces of the cores revealed that all 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 D2041). Results are listed in

Table B.27 in Appendix B and summarized in Table 3.15 and Figure 3.19. The air-void contents were typical of laboratory-compacted open-graded mix specimens and there was little difference between the Control and warm mix specimens. Note that Cantabro testing was not undertaken on the dense-graded test track specimens and that only one Sasobit mix was tested.

Table 3.15: Summary of Air-Void Contents of Cantabro Test Specimens

Mix	Air-Void Content (%)	
	Mean[1]	SD[2]
Control	18.0	0.2
Advera	17.7	0.5
Evotherm	16.7	0.5
Sasobit	16.5	0.5
Rediset	17.3	1.0

[1] Mean of six replicates [2] SD: Standard deviation

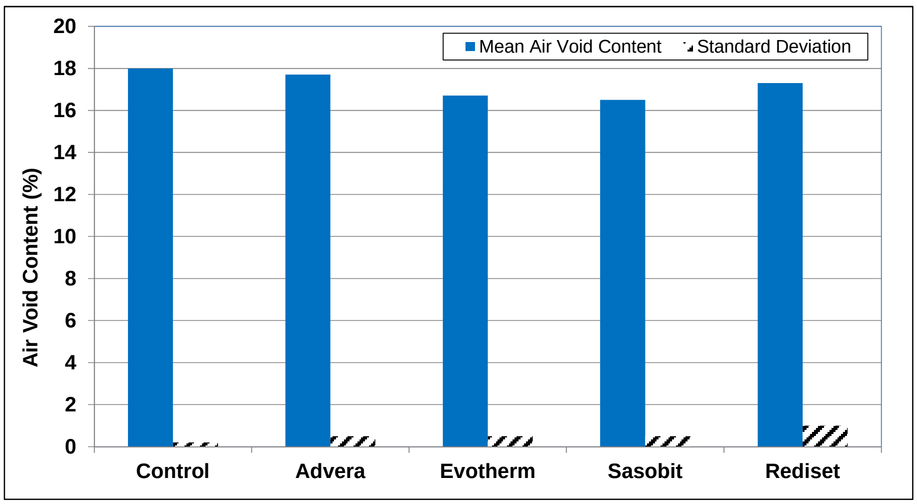


Figure 3.19: Mean air-void contents of Cantabro specimens.

3.6.2 Abrasion Loss

The durability in terms of mass loss for each specimen in each mix is listed in Table B.25 in Appendix B and summarized in Table 3.16 and Figure 3.20.

Table 3.16: Summary of Cantabro Test Results

Mix	Mass Before (g)		Mass After (g)		Mass Loss (%)	
	Mean	SD	Mean	SD	Mean	SD
Control	1,198	3.9	1,096	14.2	9	1.3
Advera	1,179	0.5	1,021	61.7	13	5.2
Evotherm	1,176	1.5	1,016	44.4	14	3.8
Sasobit	1,184	3.7	934	87.7	21	7.7
Rediset	1,198	2.1	1,064	30.8	11	2.6

[1] Mean of six replicates [2] SD: Standard deviation

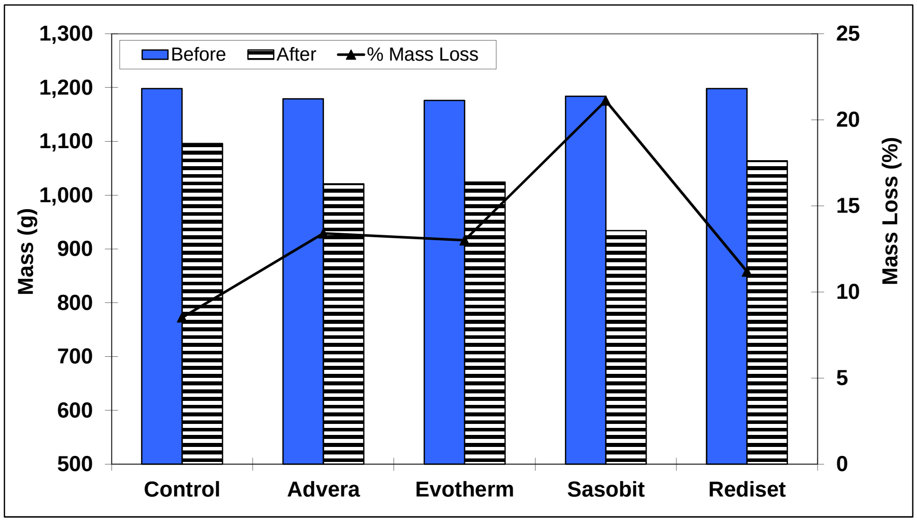


Figure 3.20: Cantabro test results.

The average mass loss and variability between specimens was slightly higher on the Advera, Evotherm and Sasobit specimens compared to the Control and Rediset specimens, with Sasobit showing the highest mass loss. However, the difference between the five sets of specimens is considered to be acceptable in terms of the typical variation in Cantabro test results.

3.7 Summary of Laboratory Testing Results

The laboratory test results indicate that use of the warm-mix technologies assessed in this study to produce and compact specimens at lower temperatures than those used to produce the conventional hot mix control specimens, did not significantly influence the performance of the asphalt concrete. Specific observations include:

- Laboratory performance in all the tests appeared to be mostly dependent on air-void content and binder content, as expected, and less dependent on mix production temperature.
- Test results were influenced by mix production temperatures, actual binder content, specimen air-void content, actual stress and strain levels, and actual test temperature. Variation in these parameters needs to be taken into consideration when comparing performance between the different mixes.
- All mixes were sensitive to moisture content.
- All mixes performed significantly better in the Hamburg Wheel-Track Test when subjected to additional curing, indicating that hot and warm mixes are likely to have similar performance on in-service pavements after a short period of aging (e.g., 6 to 12 months). This is consistent with performance on the test track.

4. COMPARISON OF TEST RESULTS

Results from this phase of testing were compared to those from Phase 1 (tests on specimens cored or cut from the test track) and Phase 2a (plant-mixed, laboratory-compacted specimens compacted at the test track on the day of construction). Only a limited number of specimens could be prepared for the Phase 2a experiment, and consequently only shear and beam fatigue tests were conducted. The results for the Sasobit mix prepared with 5.2 percent binder content and the Rediset mix are not discussed as they were not part of the Phase 1 and Phase 2a experiments. Observations from the comparisons are summarized as follows:

- The air-void contents measured in this phase were generally similar to those measured on the Phase 2a specimens and lower than those measured on the Phase 1 specimens, with the exception of the Sasobit with 4.5 percent binder, which had air-void contents similar to those recorded in the specimens removed from the test track. Tensile strength retained results could not be compared between Phase 1 and this phase due to the higher air-void contents of the Phase 2b specimens, which were prepared according to Caltrans CT 371 test method.
- Resilient shear moduli and permanent shear strain at 5,000 cycles were consistent across all phases with differences in the results attributed to air-void content.
- Initial stiffnesses, phase angles, and fatigue life recorded on fatigue beams were consistent across all phases with differences in the results attributed to air-void content.
- Complex modulus values were similar for the specimens tested in Phase 1 and Phase 2b; however, the temperature-shifting relationships were different, indicating that the Phase 1 specimens were potentially more temperature-sensitive than the laboratory-prepared specimens. Differences were also attributed to the difference in air-void content.
- Average maximum rut depths after 10,000 Hamburg Wheel-Track passes were significantly lower on the Phase 2b specimens compared to the Phase 1 specimens. This was attributed to the lower air-void contents of the Phase 2b specimens.
- The TSR results for the warm mix specimens were similar for both phases; however, the results for the Control were significantly different, with the TSR for the Phase 2b tests significantly lower than that recorded in the Phase 1 tests. The reason for this is unclear.

This comparison indicates that comparable results can be obtained from specimens sampled from test tracks and roads or prepared in the laboratory, provided that air-void content, binder content, and degree of aging are taken into consideration.

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5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This report describes laboratory testing of laboratory-prepared specimens as part of the second phase of a warm mix asphalt (WMA) study, which compares the performance of a hot mix control produced at 310°F (155°C) against the performance of warm mixes produced at 250°F (120°C) using four different technologies (*Advera, Evotherm, Sasobit, and Rediset*).

Key findings from the study include the following:

- The laboratory test results indicate that use of the warm mix technologies assessed in this study, which were produced and compacted at lower temperatures, did not significantly influence the performance of the asphalt concrete when compared to control specimens produced and compacted at conventional hot mix asphalt temperatures.
- Laboratory performance in all tests appeared to be mostly dependent on air-void content and less dependent on mix production temperature.
- Test results were influenced by specimen air-void content, actual stress and strain levels, and actual test temperature. Variation in these parameters needs to be taken into consideration when comparing performance between the different mixes.
- All the mixes were sensitive to moisture content. Rutting performance, fatigue cracking performance, and tensile strength retained all deteriorated with increasing moisture content in the specimens.
- All the mixes performed significantly better in the Hamburg Wheel-Track Test when subjected to additional curing, indicating that hot and warm mixes are likely to have similar performance on in-service pavements after a short period of aging (e.g., 6 to 12 months). This is consistent with performance on the test track.
- Test results were consistent with those from earlier testing phases.

5.2 Recommendations

The laboratory testing completed in this phase has provided no new results to suggest that warm mix technologies should not be used in dense- or open-graded mixes in California, provided that standard specified construction and performance limits for hot mix asphalt are met. It should be noted that lower production temperatures could lead to insufficient drying of aggregates, which in turn could result in moisture-related problems in the road. Moisture content in aggregates should be strictly controlled at asphalt plants and specified mix moisture contents (i.e., less than 1.0 percent by weight of the mix) should be adhered to.

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APPENDIX A: BEAM FATIGUE SOAKING PROCEDURE

A.1 Preparation of Specimens

Specimens are prepared as follows:

1. Measure and record the bulk specific gravity, width, and height of each beam.
2. Dry each beam 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). Record the final dry mass. Note that beams should be placed on a rigid, flat surface during drying.
3. Using epoxy resin, bond a nut to the beam for supporting the LVDT.
4. Record the mass of the beam with the nut.

A.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. 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 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 two 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.

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APPENDIX B: LABORATORY TEST RESULTS

B.1 Shear Test Results

Shear test results are summarized in Table B.1 through Table B.6.

B.2 Beam Fatigue Test Results

Beam fatigue test results are summarized in Table B.7 through Table B.12.

B.3 Flexural Frequency Sweep Test Results

Flexural frequency sweep test results are summarized in Table B.13 through Table B.24.

B.4 Hamburg Wheel-Track Test Results

Hamburg Wheel-Track test results are summarized in Table B.25.

B.5 Tensile Strength Retained Test Results

Tensile Strength Retained test results are summarized in Table B.26.

B.6 Open-Graded Friction Course Durability Test Results

Open-graded friction course durability (Cantabro) test results are summarized in Table B.27.

Table B.1: Summary of Shear Test Results for Control Mix

Specimen Designation	Air-Void Content (%)	Test Temperature (°C)	Shear Stress (kPa)	Initial Resilient Shear Modulus (kPa)	Permanent Shear Strain at 5,000 Cycles (%)
CL-3-1A-7045	4.0	45.0	75.4	290.0	0.006663
CL-6-1B-7045	4.1	45.2	79.4	383.1	0.008191
CL-7-3A-7045	4.7	45.0	84.0	361.6	0.009852
CL-1-1A-10045	4.7	45.6	106.0	387.6	0.009806
CL-2-1B-10045	4.8	45.1	102.5	381.9	0.018421
CL-5-2A-10045	5.0	44.9	108.5	308.7	0.013424
CL-4-3B-13045	4.5	45.0	136.9	328.4	0.017948
CL-5-3A-13045	4.9	45.0	132.5	361.2	0.016156
CL-9-2A-13045	4.3	44.9	137.2	306.2	0.01327
CL-5-1A-7055	5.0	54.8	71.8	110.3	0.017655
CL-6-3B-7055	4.2	54.9	74.8	164.5	0.011791
CL-10-2B-7055	4.9	54.9	74.0	151.6	0.022169
CL-1-2A-10055	4.5	54.9	103.8	179.7	0.013414
CL-2-3B-10055	5.0	54.9	102.8	159.4	0.020001
CL-3-3A-10055	4.1	54.9	104.1	226.6	0.012614
CL-7-2A-13055	5.0	54.9	132.1	147.0	0.024971
CL-10-1B-13055	4.4	55.0	131.4	133.0	0.027456
CL-10-3B-13055	4.7	54.7	132.7	146.9	0.032392

Table B.2: Summary of Shear Test Results for Advera Mix

Specimen Designation	Air-Void Content (%)	Test Temperature (°C)	Shear Stress (kPa)	Initial Resilient Shear Modulus (kPa)	Permanent Shear Strain at 5,000 Cycles (%)
A-52-1-3B-7045	4.8	44.7	79.3	235.8	0.018450
A-52-1-9B-7045	5.0	44.8	80.7	202.6	0.020410
A-52-2-5B-7045	4.0	45.1	75.7	184.1	0.020860
A-52-2-1B-10045	4.6	45.2	104.8	241.0	0.020671
A-52-2-4B-10045	4.5	44.8	108.5	234.8	0.019510
A-52-3-5B-10045	4.2	45.0	102.8	125.3	0.023475
A-52-1-7B-13045	4.6	45.1	138.2	218.1	0.030562
A-52-2-3B-13045	4.7	45.1	139.2	234.6	0.027926
A-52-3-9B-13045	5.0	45.3	138.0	176.3	0.026355
A-52-1-4B-7055	4.1	54.9	77.5	130.6	0.028458
A-52-2-8B-7055	4.7	54.8	71.8	172.4	0.014657
A-52-3-1B-7055	4.9	55.3	75.5	85.8	0.043722
A-52-1-6B-10055	4.9	55.0	103.1	125.7	0.037079
A-52-2-6B-10055	4.9	55.0	101.4	98.6	0.028159
A-52-3-8B-10055	4.9	54.8	100.0	116.0	0.031880
A-52-2-7B-13055	4.9	54.7	139.1	131.8	0.036822
A-52-3-2B-13055	4.4	54.9	141.8	95.0	0.046281
A-52-3-4B-13055	5.0	54.5	139.3	119.7	0.035943

Table B.3: Summary of Shear Test Results for Evotherm Mix

Specimen Designation	Air-Void Content (%)	Test Temperature (°C)	Shear Stress (kPa)	Initial Resilient Shear Modulus (kPa)	Permanent Shear Strain at 5,000 Cycles (%)
E-52-1-7B-7045	4.9	45.0	77.1	154.4	0.032064
E-52-3-6B-7045	4.2	44.9	78.7	301.2	0.015789
E-52-3-8B-7045	4.2	45.0	78.3	203.2	0.026326
E-52-3-4B-10045	4.3	45.0	108.1	233.2	0.022827
E-52-4-3B-10045	4.7	45.0	107.3	207.0	0.025243
E-52-4-6B-10045	4.9	45.2	105.8	248.3	0.028436
E-52-3-3B-13045	4.3	44.9	140.5	230.5	0.022528
E-52-3-5B-13045	4.1	44.9	142.5	219.6	0.032515
E-52-3-9B-13045	4.0	45.0	143.2	242.3	0.020429
E-52-2-7B-7055	5.0	55.0	77.4	86.7	0.046064
E-52-3-1B-7055	4.3	54.9	81.2	119.0	0.023647
E-52-4-4B-7055	4.6	55.0	75.3	126.0	0.034286
E-52-2-8B-10055	4.9	55.0	102.2	84.4	0.070614
E-52-4-1B-10055	4.6	55.2	109.6	113.1	0.040291
E-52-4-5B-10055	4.4	55.1	109.5	107.5	0.046746
E-52-1-8B-13055	4.3	54.9	135.3	72.4	0.100883
E-52-3-7B-13055	4.1	55.5	137.0	102.6	0.055658
E-52-4-2B-13055	4.0	55.1	140.4	138.6	0.069506

Table B.4: Summary of Shear Test Results for Sasobit (5.2%) Mix

Specimen Designation	Air-Void Content (%)	Test Temperature (°C)	Shear Stress (kPa)	Initial Resilient Shear Modulus (kPa)	Permanent Shear Strain at 5,000 Cycles (%)
S-52-3-1B-7045	4.8	45.2	83.5	292.4	0.011119
S-52-3-9B-7045	4.5	45.1	80.7	297.7	0.010818
S-52-1-7B-7045	5.2	45.1	80.0	324.1	0.015553
S-52-1-5B-10045	5.8	45.2	108.5	186.7	0.041218
S-52-3-2B-10045	4.5	44.9	107.6	232.8	0.016729
S-52-3-8B-10045	4.5	44.9	113.8	579.7	0.012801
S-52-1-2B-13045	5.1	44.9	138.4	191.5	0.031031
S-52-1-3B-13045	5.1	45.0	145.5	252.6	0.025598
S-52-1-10B-13045	5.2	45.1	143.0	256.7	0.016645
S-52-1-11B-7055	6.4	55.0	77.7	124.1	0.029553
S-52-2-9B 7055	7.0	54.6	75.0	74.6	0.035027
S-52-1-1B-7055	5.8	55.2	81.2	145.7	0.019798
S-52-3-5B-10055	4.6	55.4	106.7	120.9	0.018019
S-52-1-5B-10055	4.6	54.8	103.3	109.5	0.050597
S-52-1-8B-10055	4.8	54.8	106.7	123.9	0.033630
S-52-3-4B-13055	4.5	55.4	133.3	100.8	0.033072
S-52-3-6B-13055	4.8	54.8	136.1	106.3	0.026656
S-52-1-6B-13055	4.9	55.0	139.4	97.6	0.052160

Table B.5: Summary of Shear Test Results for Sasobit (4.5%) Mix

Specimen Designation	Air-Void Content (%)	Test Temperature (°C)	Shear Stress (kPa)	Initial Resilient Shear Modulus (kPa)	Permanent Shear Strain at 5,000 Cycles (%)
S-45-1-2B-7045	7.6	44.8	79.2	154.6	0.034491
S-45-2-1B-7045	6.8	44.9	80.0	187.9	0.024308
S-45-3-6B-7045	7.6	45.1	80.6	219.0	0.021290
S-45-1-11B-10045	8.1	45.4	104.1	174.2	0.034159
S-45-3-2B-10045	7.6	45.2	105.4	177.4	0.031426
S-45-3-7B-10045	7.8	45.0	110.0	213.4	0.024882
S-45-1-4B-13045	7.5	44.9	142.5	143.2	0.053163
S-45-1-8B-13045	6.6	44.9	139.8	183.0	0.037536
S-45-1-9B-13045	7.9	45.0	139.3	192.9	0.035655
S-45-1-6B-7055	6.9	54.9	78.6	94.8	0.033830
S-45-1-10B-7055	8.1	54.8	76.1	89.2	0.034038
S-45-2-5B-7055	6.6	54.8	76.9	136.1	0.023142
S-45-2-2B-10055	7.3	55.0	104.1	88.8	0.040169
S-45-2-8B-10055	7.0	55.2	105.8	109.5	0.034393
S-45-3-5B-10055	7.5	54.7	102.9	102.6	0.065721
S-45-2-10B-13055	7.5	55.4	138.4	93.3	0.067961
S-45-2-11B-13055	7.2	54.7	134.9	73.1	0.079984
S-45-3-8B-13055	7.5	54.9	139.0	96.0	0.058970

Table B.6: Summary of Shear Test Results for Rediset Mix

Specimen Designation	Air-Void Content (%)	Test Temperature (°C)	Shear Stress (kPa)	Initial Resilient Shear Modulus (kPa)	Permanent Shear Strain at 5,000 Cycles (%)
AN-2-1B-7045	4.4	44.9	77.4	341.3	0.009685
AN-8-2B-7045	4.3	45.0	77.3	197.7	0.016707
AN-9-1A-7045	4.2	44.9	79.6	320.7	0.013912
AN-1-2A-10045	3.8	44.9	103.0	210.7	0.015462
AN-1-3A-10045	4.6	45.1	103.7	314.4	0.012149
AN-4-2B-10045	4.8	45.2	103.9	251.9	0.018938
AN-2-3B-13045	4.3	45.0	138.7	258.9	0.013932
AN-6-1B-13045	4.5	45.0	134.9	250.8	0.017908
AN-8-3B-13045	4.9	45.0	134.5	213.8	0.022280
AN-4-3B-7055	4.4	54.9	76.0	99.0	0.020923
AN-5-1A-7055	4.4	55.0	77.0	118.5	0.021598
AN-8-1B-7055	4.5	55.0	84.6	97.6	0.020814
AN-4-1B-10055	4.5	55.2	102.6	127.9	0.025808
AN-7-1A-10055	4.5	54.8	97.0	129.5	0.030551
AN-10-2B-10055	4.3	55.0	104.6	169.2	0.023302
AN-1-1A-13055	4.7	54.9	130.5	116.7	0.027924
AN-5-2A-13055	4.1	54.9	130.1	119.4	0.027365
AN-9-2A-13055	4.8	54.9	131.4	114.7	0.040790

Table B.7: Summary of Beam Fatigue Test Results for Control Mix

Condition	Specimen Designation	Air-Void Content[1] (%)	Test Temp. (°C)	Test Strain Level (µstrain)	Initial Phase Angle (Deg.)	Initial Stiffness (MPa)	Fatigue Life (Nf)
Dry	CL-12B2	4.8	19.6	0.000204	24.28	5,974	>5,000,000
	CL-6B2	5.0	20.3	0.000210	24.04	6,341	>5,000,000
	CL-7A1	5.0	20.1	0.000200	23.09	6,000	>5,000,000
	CL-6B1	4.6	20.0	0.000399	25.11	6,066	44,604
	CL-10B2	4.4	20.1	0.000395	26.16	6,243	469,873
	CL-14B2	5.0	20.4	0.000414	26.92	5,350	492,755
Wet	CL-4B2	4.9	20.1	0.000202	23.67	4,613	>5,000,000
	CL-8B1	4.4	20.3	0.000210	28.53	4,393	>5,000,000
	CL-14B1	4.3	19.7	0.000206	22.66	3,598	>5,000,000
	CL-7A2	4.9	19.7	0.000405	22.97	3,840	87,366
	CL-9A1	5.0	20.3	0.000423	29.18	3,546	139,568
	CL-9A2	4.8	19.7	0.000403	20.96	4,173	59,935

[1] Air-void content was measured with the *CoreLok* method [2] Temperature * Extrapolated results

Table B.8: Summary of Beam Fatigue Test Results for Advera Mix

Condition	Specimen Designation	Air-Void Content[1] (%)	Test Temp. (°C)	Test Strain Level (µstrain)	Initial Phase Angle (Deg.)	Initial Stiffness (MPa)	Fatigue Life (Nf)
Dry	A-5.2-1B1	6.2	19.9	0.000203	29.26	4,601	>5,000,000
	A-5.2-1B2	6.4	19.9	0.000203	28.80	4,739	3,325,164
	A-5.2-3B8	6.1	20.1	0.000206	28.97	4,809	>5,000,000
	A-5.2-2B8	5.5	19.9	0.000410	22.17	4,972	43,974
	A-5.2-4B2	5.9	19.9	0.000406	22.69	4,384	113,677
	A-5.2-4B6	6.1	19.9	0.000407	23.00	4,056	231,214
Wet	A-5.2-2B6	5.7	20.2	0.000209	35.63	2,032	>5,000,000
	A-5.2-4B4	5.8	19.8	0.000207	34.89	2,271	2,604,132
	A-5.2-4B8	6.4	20.1	0.000206	33.87	2,024	4,505,480
	A-5.2-2B1	5.9	20.0	0.000412	36.86	1,765	31,356
	A-5.2-2B3	5.8	20.3	0.000420	37.61	1,774	29,328
	A-5.2-3B2	5.7	20.3	0.000410	37.60	1,564	19,921

[1] Air-void content was measured with the *CoreLok* method [2] Temperature * Extrapolated results

Table B.9: Summary of Beam Fatigue Test Results for Evotherm Mix

Condition	Specimen Designation	Air-Void Content[1] (%)	Test Temp. (°C)	Test Strain Level (µstrain)	Initial Phase Angle (Deg.)	Initial Stiffness (MPa)	Fatigue Life (Nf)
Dry	E-5.2-2B4	6.5	20.4	0.000208	30.80	3,815	>5,000,000
	E-5.2-4B5	5.8	20.1	0.000208	29.12	4,024	>5,000,000
	E-5.2-4B8	6.2	19.9	0.000203	30.69	4,112	>5,000,000
	E-5.2-3B4	6.0	19.9	0.000407	24.92	3,855	414,855
	E-5.2-3B8	5.6	19.6	0.000407	23.32	4,186	290,970
	E-5.2-4B1	5.6	20.1	0.000402	32.52	4,215	116,453
Wet	E-5.2-1B8	6.4	19.6	0.000207	26.46	2,943	1,364,367
	E-5.2-2B7	6.4	19.8	0.000206	27.53	2,813	5,368,537
	E-5.2-2B8	6.5	20.1	0.000209	31.75	3,207	>5,000,000
	E-5.2-1B2	6.5	20.1	0.000416	34.01	2,602	113,525
	E-5.2-2B1	6.3	20.3	0.000410	36.56	1,947	56,306
	E-5.2-3B5	5.5	20.2	0.000409	33.60	2,690	101,038

[1] Air-void content was measured with the *CoreLok* method [2] Temperature * Extrapolated results

Table B.10: Summary of Beam Fatigue Test Results for Sasobit (5.2%) Mix

Condition	Specimen Designation	Air-Void Content[1] (%)	Test Temp. (°C)	Test Strain Level (µstrain)	Initial Phase Angle (Deg.)	Initial Stiffness (MPa)	Fatigue Life (Nf)
Dry	S-5.2-1B5	6.4	20.3	0.000207	27.15	4,958	>5,000,000
	S-5.2-2B5	6.3	20.1	0.000203	27.20	4,703	>5,000,000
	S-5.2-15B8	7.3	20.0	0.000203	33.06	3,848	2,143,281
	S-5.2-1B2	7.2	19.8	0.000401	27.99	4,462	295,044
	S-5.2-14B2	6.5	19.6	0.000407	24.68	4,041	201,314
	S-5.2-15B7	7.3	19.6	0.000410	26.50	3,230	152,380
Wet	S-5.2-2B1	6.3	20.0	0.000207	30.91	2,894	729,135
	S-5.2-2B4	6.4	19.8	0.000206	32.51	2,897	252,610
	S-5.2-2B7	6.7	20.1	0.000206	30.80	2,910	1,496,206
	S-5.2-1B4	6.5	19.9	0.000415	27.90	2,507	6,330
	S-5.2-1B6	7.3	19.7	0.000415	25.64	2,626	15,742
	S-5.2-1B8	7.2	19.8	0.000413	32.73	2,389	17,828

[1] Air-void content was measured with the *CoreLok* method [2] Temperature * Extrapolated results

Table B.11: Summary of Beam Fatigue Test Results for Sasobit (4.5%) Mix

Condition	Specimen Designation	Air-Void Content[1] (%)	Test Temp. (°C)	Test Strain Level (µstrain)	Initial Phase Angle (Deg.)	Initial Stiffness (MPa)	Fatigue Life (Nf)
Dry	S-4.5-4A2	7.4	19.9	0.000199	25.60	5,473	3,274,475
	S-4.5-10B7	7.7	20.5	0.000205	31.23	3,878	1,940,112
	S-4.5-11B4	7.9	20.3	0.000203	28.87	3,839	2,255,911
	S-4.5-1A1	7.2	19.8	0.000407	19.40	5,373	284,795
	S-4.5-5B2	7.2	19.8	0.000409	19.91	4,767	525,387
	S-4.5-12B8	7.8	20.3	0.000412	31.23	4,028	47,946
Wet	S-4.5-2B2	7.0	19.9	0.000205	29.26	3,173	2,201,756
	S-4.5-10B6	7.7	20.1	0.000204	37.17	1,862	1,913,157
	S-4.5-11B1	7.5	20.2	0.000209	35.68	2,014	502,345
	S-4.5-8B1	7.0	19.6	0.000412	24.58	2,586	17,063
	S-4.5-10B5	7.1	20.2	0.000414	38.07	1,671	6,102
	S-4.5-12B2	7.8	20.1	0.000408	37.45	1,505	9,865

[1] Air-void content was measured with the *CoreLok* method [2] Temperature * Extrapolated results

Table B.12: Summary of Beam Fatigue Test Results for Rediset Mix

Condition	Specimen Designation	Air-Void Content[1] (%)	Test Temp. (°C)	Test Strain Level (µstrain)	Initial Phase Angle (Deg.)	Initial Stiffness (MPa)	Fatigue Life (Nf)
Dry	AN-5A2	4.7	19.8	0.000205	25.35	5,584	>5,000,000
	AN-28B2	4.0	20.3	0.000208	27.90	4,933	>5,000,000
	AN-36B2	4.9	20.0	0.000200	23.01	5,141	>5,000,000
	AN-13A1	4.8	20.0	0.000394	21.17	5,584	157,172
	AN-32B2	4.9	19.9	0.000397	22.57	4,852	246,490
	AN-35A1	4.5	19.6	0.000402	31.18	4,238	181,977
Wet	AN-5A1	4.5	19.8	0.000207	25.76	4,970	>5,000,000
	AN-7A2	4.8	20.3	0.000209	27.36	4,860	>5,000,000
	AN-19A1	4.5	20.1	0.000199	24.58	5,408	>5,000,000
	AN-15A2	4.3	20.4	0.000420	31.06	3,594	360,542
	AN-31A1	4.6	20.0	0.000399	32.17	4,075	565,216
	AN-35A2	4.7	20.4	0.000415	32.35	3,559	253,677

[1] Air-void content was measured with the *CoreLok* method [2] Temperature * Extrapolated results

Table B.13: Flexural Frequency Sweep Test Results for Control Mix (Dry)

Sample	CL-15A1	**Air-voids**	4.6%	**Test**	10°C	**Sample**	CL-4B1	**Air-voids**	4.9%	**Test**	10°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (°C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.17	0.3219	0.000028	12.4	11,360	10.5	15.14	0.2589	0.000022	11.1	11,572	9.9	11,466
9.99	0.9649	0.000100	18.3	9,659	10.5	9.99	1.0022	0.000098	15.3	10,226	10.0	9,943
5.00	0.8809	0.000102	17.0	8,677	10.4	5.01	0.9428	0.000099	15.7	9,532	9.9	9,105
2.00	0.7458	0.000098	17.0	7,588	10.4	2.00	0.8153	0.000096	15.1	8,535	9.9	8,062
1.00	0.6645	0.000097	17.3	6,825	10.3	1.00	0.7685	0.000097	15.7	7,910	9.8	7,367
0.50	0.6091	0.000099	19.4	6,133	10.3	0.50	0.6987	0.000098	16.6	7,101	9.8	6,617
0.20	0.4997	0.000096	20.8	5,191	10.2	0.20	0.5962	0.000099	18.7	6,000	10.1	5,595
0.10	0.4495	0.000098	22.5	4,608	10.1	0.10	0.5244	0.000101	20.1	5,215	10.1	4,911
0.05	0.3863	0.000097	24.2	3,693	10.0	0.05	0.4452	0.000100	22.0	4,474	9.9	4,219
0.02	0.3086	0.000097	27.1	3,187	9.8	0.02	0.3579	0.000099	24.5	3,606	10.1	3,397
0.01	0.2630	0.000097	27.6	2,714	9.9	0.01	0.2981	0.000099	25.8	3,018	9.9	2,866
Sample	CL-12B1	**Air-voids**	4.5%	**Test**	20°C	**Sample**	CL-3A1	**Air-voids**	4.0%	**Test**	20°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (°C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.12	0.2784	0.000040	19.5	6,972	19.7	15.16	0.2721	0.000032	16.3	8,410	20.0	7,691
10.00	0.6395	0.000102	20.8	6,272	19.8	10.00	0.7940	0.000102	17.7	7,746	20.0	7,009
5.00	0.5326	0.000099	22.4	5,397	19.8	5.00	0.6844	0.000101	19.9	6,791	20.2	6,079
2.00	0.4276	0.000100	24.9	4,292	19.9	2.00	0.5380	0.000098	22.1	5,493	20.3	4,893
1.00	0.3438	0.000097	27.4	3,538	20.1	1.00	0.4451	0.000097	24.0	4,599	20.4	4,068
0.50	0.2924	0.000102	30.1	2,881	20.2	0.50	0.3829	0.000100	25.9	3,813	20.4	3,347
0.20	0.2079	0.000099	32.7	2,101	20.3	0.20	0.2899	0.000099	28.3	2,921	20.3	2,511
0.10	0.1613	0.000099	33.2	1,634	20.4	0.10	0.2316	0.000099	29.8	2,345	20.3	1,990
0.05	0.1247	0.000097	35.4	1,280	20.3	0.05	0.1811	0.000097	31.8	1,872	20.3	1,576
0.02	0.0871	0.000098	38.3	892	20.3	0.02	0.1329	0.000098	34.3	1,361	20.4	1,127
0.01	0.0655	0.000098	38.5	670	20.4	0.01	0.1014	0.000097	35.4	1,040	20.4	855
Sample	CL-5A1	**Air-voids**	5.0%	**Test**	30°C	**Sample**	CL-12B2	**Air-voids**	4.8%	**Test**	30°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (°C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.22	0.2296	0.000072	30.3	3,195	30.3	15.14	0.2279	0.000074	30.5	3,068	30.2	3,132
9.99	0.2894	0.000104	30.9	2,785	30.2	9.99	0.2796	0.000107	32.9	2,624	30.2	2,705
5.00	0.2350	0.000103	31.4	2,275	30.2	5.00	0.2150	0.000102	34.8	2,107	30.0	2,191
2.00	0.1671	0.000100	34.2	1,676	30.1	2.00	0.1505	0.000100	36.9	1,509	30.0	1,593
1.00	0.1278	0.000099	36.8	1,286	30.2	1.00	0.1145	0.000099	39.3	1,162	30.1	1,224
0.50	0.1036	0.000103	39.0	1,009	30.1	0.50	0.0886	0.000102	41.2	869	30.0	939
0.20	0.0697	0.000099	41.6	701	30.0	0.20	0.0604	0.000100	43.0	604	30.0	653
0.10	0.0529	0.000099	41.4	534	30.1	0.10	0.0446	0.000100	42.3	447	30.1	490
0.05	0.0401	0.000098	43.7	408	30.1	0.05	0.0345	0.000099	38.5	349	30.1	379
0.02	0.0284	0.000098	43.9	290	30.1	0.02	0.0231	0.000099	39.8	235	30.0	262
0.01	0.0214	0.000098	49.2	218	30.1	0.01	0.0180	0.000099	43.7	183	30.1	200

Table B.14: Flexural Frequency Sweep Test Results for Control Mix (Wet)

Sample	CL-8B2	Air-voids	4.5%	Test	10°C	Sample	CL-11A2	Air-voids	5.0%	Test	10°C	Avg. E*
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.16	0.2519	0.000027	13.7	9,304	9.9	15.18	0.2650	0.000038	15.8	6,992	9.9	8,148
9.99	0.7782	0.000101	18.9	7,728	9.8	9.99	0.6608	0.000104	16.5	6,369	9.8	7,049
5.00	0.6904	0.000100	18.4	6,906	9.8	5.00	0.5727	0.000102	17.8	5,639	9.9	6,273
2.00	0.5685	0.000097	19.8	5,844	9.8	2.00	0.4696	0.000099	19.4	4,747	10.0	5,296
1.00	0.4668	0.000099	19.2	4,725	9.9	1.00	0.3965	0.000097	21.0	4,105	9.9	4,415
0.50	0.4143	0.000101	20.4	4,113	10.0	0.50	0.3494	0.000100	22.3	3,486	9.9	3,800
0.20	0.3327	0.000099	21.5	3,353	9.9	0.20	0.2739	0.000099	24.2	2,777	9.8	3,065
0.10	0.2700	0.000098	21.3	2,741	9.8	0.10	0.2247	0.000098	25.5	2,303	9.9	2,522
0.05	0.2398	0.000098	25.5	2,442	9.9	0.05	0.1845	0.000097	28.0	1,905	9.9	2,173
0.02	0.1758	0.000098	26.2	1,794	9.9	0.02	0.1403	0.000096	29.0	1,456	9.9	1,625
0.01	0.1460	0.000098	27.7	1,496	9.9	0.01	0.1149	0.000096	29.7	1,192	9.9	1,344
Sample	CL-1A2	**Air-voids**	4.2%	**Test**	20°C	**Sample**	CL-10B1	**Air-voids**	4.0%	**Test**	20°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.14	0.2663	0.000040	18.2	6,602	19.8	15.15	0.2853	0.000045	18.9	6,406	19.6	6,504
10.00	0.6279	0.000102	18.6	6,168	19.9	10.01	0.5924	0.000102	20.0	5,828	19.7	5,998
5.00	0.5334	0.000100	20.0	5,327	20.0	5.00	0.5019	0.000100	21.9	5,006	19.8	5,166
2.00	0.4254	0.000097	22.2	4,368	20.1	2.00	0.3924	0.000098	23.8	3,992	19.9	4,180
1.00	0.3550	0.000097	23.7	3,662	20.2	1.00	0.3268	0.000098	25.1	3,320	20.1	3,491
0.50	0.3072	0.000101	25.9	3,043	20.3	0.50	0.2789	0.000103	27.4	2,711	20.1	2,877
0.20	0.2302	0.000099	28.1	2,324	20.4	0.20	0.2027	0.000100	29.5	2,020	20.2	2,172
0.10	0.1859	0.000098	27.4	1,891	20.5	0.10	0.1588	0.000099	30.0	1,600	20.3	1,746
0.05	0.1502	0.000098	31.4	1,529	20.3	0.05	0.1272	0.000098	32.4	1,294	20.5	1,412
0.02	0.1119	0.000098	33.0	1,139	20.3	0.02	0.0928	0.000098	33.4	946	20.4	1,043
0.01	0.0884	0.000098	33.5	903	20.4	0.01	0.0731	0.000098	34.5	743	20.4	823
Sample	CL-3A2	**Air-voids**	4.5%	**Test**	30°C	**Sample**	CL-15A2	**Air-voids**	4.8%	**Test**	30°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.13	0.1994	0.000068	28.4	2,935	30.0	15.13	0.2214	0.000102	32.3	2,179	30.2	2,557
9.99	0.2630	0.000102	29.3	2,586	30.0	10.00	0.2005	0.000103	32.4	1,947	30.1	2,266
5.00	0.2195	0.000105	30.8	2,091	30.0	5.00	0.1643	0.000104	33.4	1,580	30.1	1,835
2.00	0.1576	0.000101	32.1	1,563	30.0	2.00	0.1138	0.000099	33.8	1,149	30.2	1,356
1.00	0.1209	0.000099	33.8	1,225	30.1	1.00	0.0893	0.000099	34.0	903	30.1	1,064
0.50	0.0955	0.000101	35.4	945	30.1	0.50	0.0704	0.000100	34.3	702	30.1	824
0.20	0.0678	0.000099	35.6	688	30.2	0.20	0.0501	0.000098	37.5	508	30.1	598
0.10	0.0520	0.000097	37.3	535	30.1	0.10	0.0384	0.000097	36.3	395	30.1	465
0.05	0.0412	0.000096	37.0	427	30.1	0.05	0.0303	0.000097	31.7	313	30.1	370
0.02	0.0294	0.000096	37.0	305	30.1	0.02	0.0239	0.000097	34.4	247	30.	276
0.01	0.0246	0.000096	35.0	255	30.1	0.01	0.0173	0.000097	38.2	178	30.1	217

Table B.15: Flexural Frequency Sweep Test Results for Advera Mix (Dry)

Sample	AD-2B4	Air-voids	5.7%	Test	10°C	Sample	AD-3B3	Air-voids	5.5%	Test	10°C	Avg. E* (MPa)
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (°C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	
15.14	0.282991	0.000049	15.1	5,815	9.7	15.14	0.338626	0.000040	16.1	8,506	10.1	7,161
10.00	0.597805	0.000130	17.8	4,604	9.8	10.00	0.724906	0.000107	18.0	6,783	10.0	5,694
5.00	0.543970	0.000129	18.7	4,218	9.8	5.00	0.651093	0.000106	17.1	6,145	9.9	5,182
2.00	0.462927	0.000129	19.4	3,593	9.8	2.00	0.530231	0.000102	16.2	5,190	9.9	4,392
1.00	0.386457	0.000124	20.6	3,114	9.7	1.00	0.465245	0.000098	18.5	4,724	9.8	3,919
0.50	0.330665	0.000125	19.3	2,653	9.7	0.50	0.404664	0.000103	19.7	3,947	9.7	3,300
0.20	0.254590	0.000129	21.4	1,980	9.8	0.20	0.316325	0.000097	22.3	3,269	9.7	2,625
0.10	0.223961	0.000127	25.5	1,764	9.8	0.10	0.295634	0.000100	26.4	2,968	9.8	2,366
0.05	0.181009	0.000124	33.9	1,458	9.7	0.05	0.240912	0.000099	32.0	2,442	9.9	1,950
0.02	0.135915	0.000122	35.6	1,110	9.7	0.02	0.177929	0.000098	34.2	1,807	9.8	1,459
0.01	0.108558	0.000120	39.7	904	9.8	0.01	0.141804	0.000098	36.8	1,449	9.8	1,177
Sample	AD-1B3	**Air-voids**	6.5%	**Test**	20°C	**Sample**	AD-1B6	**Air-voids**	6.0%	**Test**	20°C	**Avg. E* (MPa)**
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (°C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	
15.16	0.459097	0.000093	23.5	4,940	19.9	15.16	0.450806	0.000095	22.9	4,741	19.9	5,278
10.01	0.472986	0.000104	24.0	4,553	19.8	10.00	0.440994	0.000102	23.9	4,313	19.9	4,459
5.00	0.395159	0.000104	25.8	3,788	19.9	5.00	0.368064	0.000101	25.7	3,630	19.8	3,924
1.99	0.285699	0.000100	29.4	2,853	19.7	2.00	0.286354	0.000103	28.9	2,775	19.9	3,184
1.00	0.241158	0.000104	33.2	2,310	19.8	1.00	0.226955	0.000103	32.1	2,213	19.8	2,664
0.50	0.180776	0.000105	35.5	1,716	20.0	0.50	0.170896	0.000099	32.4	1,734	19.8	2,194
0.20	0.122025	0.000099	37.5	1,237	19.9	0.20	0.119638	0.000098	37.4	1,217	19.8	1,599
0.10	0.090737	0.000098	40.1	922	19.8	0.10	0.089471	0.000098	38.8	912	19.9	1,338
0.05	0.067386	0.000097	41.2	694	19.9	0.05	0.067032	0.000097	43.8	693	19.8	1,076
0.02	0.045422	0.000097	45.3	470	19.9	0.02	0.045574	0.000096	43.9	477	19.9	794
0.01	0.033656	0.000096	47.0	350	19.8	0.01	0.033964	0.000096	43.3	353	19.8	629
Sample	AD-1B4	**Air-voids**	5.7%	**Test**	30°C	**Sample**	AD-4B3	**Air-voids**	5.5%	**Test**	30°C	**Avg. E* (MPa)**
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	
15.15	0.477609	0.000213	36.7	2,245	29.9	15.14	0.391837	0.000214	41.3	1,827	30.23	2,036
10.01	0.409220	0.000208	37.5	1,972	29.9	9.99	0.327903	0.000206	41.8	1,591	29.97	1,782
5.00	0.313664	0.000206	40.2	1,524	29.8	5.00	0.252437	0.000207	42.5	1,220	29.98	1,372
2.00	0.211893	0.000202	42.3	1,049	29.9	2.00	0.165380	0.000201	44.8	824	29.88	937
1.00	0.157357	0.000203	41.4	775	29.9	1.00	0.124923	0.000203	45.9	615	29.90	695
0.50	0.117789	0.000203	45.7	579	29.8	0.50	0.090489	0.000203	47.7	446	29.79	513
0.20	0.074573	0.000200	46.5	374	29.8	0.20	0.058189	0.000199	47.0	292	29.77	333
0.10	0.055116	0.000198	46.9	278	29.8	0.10	0.042291	0.000199	51.0	213	29.81	246
0.05	0.040392	0.000198	42.6	205	29.9	0.05	0.031265	0.000198	47.7	158	29.78	182
0.02	0.027788	0.000197	45.7	141	29.8	0.02	0.023588	0.000198	43.4	119	29.81	130
0.01	0.019282	0.000196	52.8	98	29.8	0.01	0.019296	0.000196	59.6	99	29.80	99

Table B.16: Flexural Frequency Sweep Test Results for Advera Mix (Wet)

Sample	AD-2B5	Air-voids	5.7%	Test	10°C	Sample	AD-2B7	Air-voids	5.5%	Test	10°C	Avg. E*
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (°C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.14	0.396131	0.000105	22.8	3,769	10.4	15.17	0.510857	0.000101	20.2	5,049	9.8	4,409
10.00	0.350509	0.000102	23.3	3,447	10.3	10.01	0.481832	0.000103	21.4	4,675	9.8	4,061
5.00	0.307481	0.000105	24.0	2,926	10.2	5.00	0.411258	0.000102	21.9	4,015	9.9	3,471
2.00	0.242507	0.000105	26.6	2,301	10.2	2.00	0.320756	0.000101	24.7	3,179	9.8	2,740
1.00	0.190754	0.000101	28.0	1,884	10.1	1.00	0.263949	0.000099	26.3	2,664	9.7	2,274
0.50	0.151878	0.000101	29.4	1,509	10.0	0.50	0.212608	0.000102	28.3	2,081	9.8	1,795
0.20	0.109273	0.000097	32.1	1,122	10.0	0.20	0.154367	0.000097	29.5	1,590	9.8	1,356
0.10	0.086468	0.000098	31.9	879	9.9	0.10	0.122529	0.000098	31.1	1,246	9.7	1,063
0.05	0.069159	0.000098	35.1	709	9.7	0.05	0.097150	0.000096	33.3	1,007	9.8	858
0.02	0.049178	0.000097	37.3	509	9.7	0.02	0.072164	0.000096	36.9	749	9.7	629
0.01	0.042349	0.000097	42.3	437	9.7	0.01	0.058115	0.000097	35.7	602	9.7	520
Sample	AD-3B1	**Air-voids**	5.5%	**Test**	20°C	**Sample**	AD-3B6	**Air-voids**	5.6%	**Test**	20°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (°C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.17	0.251868	0.000107	30.7	2,361	19.8	15.15	0.265288	0.000107	31.2	2,481	19.8	2,421
9.99	0.224852	0.000105	31.0	2,146	20.0	9.99	0.236880	0.000106	31.4	2,240	20.0	2,193
5.00	0.182494	0.000104	31.4	1,750	19.9	5.00	0.192481	0.000106	32.5	1,818	19.9	1,784
2.00	0.129950	0.000102	34.2	1,277	19.8	2.00	0.137096	0.000104	34.8	1,318	19.8	1,298
1.00	0.101790	0.000100	35.0	1,017	19.9	1.00	0.103225	0.000101	36.6	1,026	19.8	1,022
0.50	0.076490	0.000098	37.0	779	19.9	0.50	0.075932	0.000097	36.6	780	20.0	780
0.20	0.052472	0.000096	36.0	547	19.9	0.20	0.050988	0.000094	39.1	542	19.8	545
0.10	0.040010	0.000096	36.3	415	19.9	0.10	0.038456	0.000095	39.4	406	19.8	411
0.05	0.031369	0.000095	41.4	329	19.9	0.05	0.028136	0.000094	43.4	299	19.8	314
0.02	0.022236	0.000095	38.6	234	19.9	0.02	0.021112	0.000094	40.5	225	19.9	230
0.01	0.015937	0.000095	38.3	168	19.9	0.01	0.015994	0.000093	46.3	173	19.9	171
Sample	AD-2B2	**Air-voids**	5.7%	**Test**	30°C	**Sample**	AD-4B1	**Air-voids**	5.9%	**Test**	30°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.15	0.308944	0.000210	38.2	1,474	30.0	15.16	0.198525	0.000211	42.1	939	28.9	1,207
10.00	0.269176	0.000208	37.7	1,296	29.9	10.00	0.177256	0.000210	40.2	842	30.0	1,069
5.00	0.208568	0.000207	38.2	1,007	29.9	5.00	0.139331	0.000210	39.8	663	30.0	835
2.00	0.142337	0.000202	39.5	703	30.0	2.00	0.095580	0.000202	39.9	473	29.9	588
1.00	0.106327	0.000202	40.5	526	29.9	1.00	0.071964	0.000198	39.8	363	29.8	445
0.50	0.077238	0.000201	39.2	385	29.8	0.50	0.055864	0.000200	36.5	279	30.0	332
0.20	0.052580	0.000199	39.4	264	29.8	0.20	0.040678	0.000196	37.2	207	30.0	236
0.10	0.039777	0.000197	40.5	201	29.8	0.10	0.031178	0.000196	37.5	159	29.9	180
0.05	0.029060	0.000196	36.1	148	29.8	0.05	0.026121	0.000196	32.8	133	29.9	141
0.02	0.021172	0.000196	39.0	108	29.8	0.02	0.021505	0.000196	25.2	110	29.9	109
0.01	0.015281	0.000196	42.2	78	29.8	0.01	0.018247	0.000196	35.0	93	29.9	86

Table B.17: Flexural Frequency Sweep Test Results for Evotherm Mix (Dry)

Sample	AV-2B6	Air-voids	6.4%	Test	10°C	Sample	EV-3B3	Air-voids	6.0%	Test	10°C	Avg. E*
Freq. (Hz)	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.19	0.584556	0.000069	16.4	8,519	10.0	15.13	0.498871	0.000049	26.2	10,270	10.4	9,395
10.01	0.622089	0.000101	20.5	6,189	10.0	9.99	0.711183	0.000103	25.0	6,918	10.3	6,554
5.00	0.580654	0.000101	19.8	5,737	9.9	5.00	0.656042	0.000103	24.9	6,388	10.3	6,063
2.00	0.503785	0.000096	19.1	5,225	9.8	2.00	0.550951	0.000098	24.9	5,621	10.2	5,423
1.00	0.480684	0.000099	20.4	4,870	9.7	1.00	0.523778	0.000099	26.1	5,274	10.2	5,072
0.50	0.425606	0.000100	24.1	4,267	9.7	0.50	0.468468	0.000105	28.7	4,456	10.1	4,362
0.20	0.338403	0.000097	25.3	3,485	9.6	0.20	0.360914	0.000099	30.7	3,636	10.0	3,561
0.10	0.278524	0.000098	27.0	2,829	9.7	0.10	0.305958	0.000100	32.8	3,049	10.0	2,939
0.05	0.220969	0.000097	31.5	2,280	9.7	0.05	0.252428	0.000099	38.2	2,555	9.8	2,418
0.02	0.166521	0.000097	34.1	1,725	9.8	0.02	0.188894	0.000098	40.7	1,934	9.8	1,830
0.01	0.130649	0.000096	36.8	1,356	9.8	0.01	0.155462	0.000098	43.7	1,584	9.7	1,470
Sample	EV-1B4	**Air-voids**	6.4%	**Test**	20°C	**Sample**	EV-3B3	**Air-voids**	6.0%	**Test**	20°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.18	0.497206	0.000105	24.2	4,734	19.8	15.17	0.468502	0.000103	27.9	4,543	19.7	4,639
9.99	0.441162	0.000102	24.8	4,312	19.7	9.99	0.428743	0.000104	28.5	4,118	19.9	4,215
5.00	0.372147	0.000104	26.9	3,579	19.8	5.00	0.346404	0.000102	30.5	3,408	19.8	3,494
2.00	0.276125	0.000101	29.7	2,727	19.7	2.00	0.261510	0.000102	33.9	2,562	19.8	2,645
1.00	0.217482	0.000100	32.4	2,174	19.8	1.00	0.202391	0.000100	37.0	2,031	19.8	2,103
0.50	0.172892	0.000101	34.0	1,704	19.7	0.50	0.149922	0.000103	42.7	1,455	19.9	1,580
0.20	0.118598	0.000098	36.8	1,210	19.8	0.20	0.105933	0.000100	42.3	1,062	19.9	1,136
0.10	0.087972	0.000096	39.5	915	19.9	0.10	0.078345	0.000099	43.8	793	19.9	854
0.05	0.066951	0.000096	42.4	695	19.9	0.05	0.058268	0.000098	45.1	593	19.9	644
0.02	0.046559	0.000096	45.7	486	19.8	0.02	0.040051	0.000097	44.3	413	19.8	450
0.01	0.034846	0.000095	46.5	367	19.8	0.01	0.031271	0.000097	43.4	321	19.8	344
Sample	EV-1B4	**Air-voids**	6.4%	**Test**	30°C	**Sample**	EV-4B6	**Air-voids**	5.8%	**Test**	30°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.16	0.315354	0.000207	41.5	1,522	30.0	15.13	0.363792	0.000216	42.4	1,685	29.9	1,604
10.00	0.271662	0.000205	41.6	1,322	29.8	10.00	0.307632	0.000210	42.4	1,465	298	1,394
5.00	0.204098	0.000202	42.6	1,012	29.8	5.00	0.227339	0.000203	42.5	1,118	29.8	1,065
2.00	0.134629	0.000198	44.2	678	29.9	2.00	0.150374	0.000202	44.5	745	29.9	712
1.00	0.098682	0.000201	45.7	492	29.9	1.00	0.111645	0.000202	46.1	552	29.8	522
0.50	0.071924	0.000204	46.7	353	29.8	0.50	0.080619	0.000202	46.0	398	29.9	376
0.20	0.046436	0.000200	50.1	232	29.8	0.20	0.053405	0.000200	48.2	267	29.8	250
0.10	0.033127	0.000198	50.4	167	29.9	0.10	0.038154	0.000199	47.9	191	29.8	179
0.05	0.022937	0.000198	49.5	116	29.9	0.05	0.028891	0.000197	40.8	146	29.8	131
0.02	0.016065	0.000197	56.8	82	29.9	0.02	0.020681	0.000198	45.0	104	29.8	93
0.01	0.012699	0.000199	54.1	64	29.9	0.01	0.016966	0.000198	37.4	86	29.8	75

Table B.18: Flexural Frequency Sweep Test Results for Evotherm Mix (Wet)

Sample	EV-3B2	Air-voids	6.0%	Test	10°C	Sample	EV-3B6	Air-voids	5.5%	Test	10°C	Avg. E*
Freq. (Hz)	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.18	0.480591	0.000072	17.4	6,718	10.0	15.18	0.397877	0.000064	18.2	6,240	9.8	6,479
10.01	0.634066	0.000102	17.7	6,237	9.9	9.99	0.584755	0.000103	18.3	5,668	9.8	5,953
5.00	0.570546	0.000103	18.1	5,531	9.8	5.00	0.509426	0.000103	20.1	4,928	9.7	5,230
2.00	0.480264	0.000103	20.4	4,645	9.7	2.00	0.419577	0.000104	22.2	4,036	9.7	4,341
0.99	0.404341	0.000103	23.1	3,945	9.7	1.00	0.345864	0.000101	23.4	3,419	9.8	3,682
0.49	0.315523	0.000102	22.8	3,085	9.8	0.50	0.267276	0.000094	25.3	2,858	9.8	2,972
0.20	0.253923	0.000102	28.3	2,486	9.8	0.20	0.220203	0.000100	28.4	2,195	9.7	2,341
0.10	0.195081	0.000100	27.4	1,960	9.8	0.10	0.173856	0.000099	29.0	1,753	9.7	1,857
0.05	0.153946	0.000099	32.7	1,560	9.9	0.05	0.139552	0.000098	32.5	1,424	9.8	1,492
0.02	0.115384	0.000098	36.0	1,176	9.8	0.02	0.103731	0.000096	35.3	1,081	9.7	1,129
0.01	0.089278	0.000096	36.5	930	9.8	0.01	0.083042	0.000096	35.8	869	9.8	900
Sample	EV-2B5	**Air-voids**	6.1%	**Test**	20°C	**Sample**	EV-4B7	**Air-voids**	6.1%	**Test**	20°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.14	0.278574	0.000107	31.3	2,608	19.9	15.13	0.289307	0.000108	30.8	2,667	19.9	2,638
10.00	0.243642	0.000104	31.9	2,346	19.8	10.02	0.247232	0.000103	30.7	2,402	19.7	2,374
5.00	0.197945	0.000104	33.1	1,906	20.0	4.99	0.202917	0.000104	32.8	1,942	19.9	1,924
2.00	0.139700	0.000102	35.9	1,372	19.8	1.99	0.144099	0.000103	35.2	1,405	19.8	1,389
1.00	0.107442	0.000102	37.6	1,055	19.9	1.00	0.113584	0.000104	37.3	1,095	19.9	1,075
0.50	0.072884	0.000090	39.5	813	19.8	0.50	0.079799	0.000095	37.8	838	19.8	826
0.20	0.052921	0.000095	39.2	556	19.9	0.20	0.055825	0.000095	38.7	589	19.9	573
0.10	0.040678	0.000096	44.3	423	19.8	0.10	0.042074	0.000096	38.0	440	19.9	432
0.05	0.032063	0.000095	42.7	337	20.0	0.05	0.033297	0.000095	39.0	352	19.9	345
0.02	0.022710	0.000097	39.5	235	19.9	0.02	0.024958	0.000095	38.9	264	19.9	250
0.01	0.018361	0.000094	39.3	195	19.8	0.01	0.021098	0.000094	33.1	223	19.8	209
Sample	EV-1B7	**Air-voids**	6.5%	**Test**	30°C	**Sample**	EV-3B1	**Air-voids**	6.5%	**Test**	30°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.15	0.213202	0.000214	45.5	998	29.7	15.15	0.251200	0.000209	43.4	1,204	29.9	1,101
9.99	0.183035	0.000207	43.5	885	29.8	10.01	0.220839	0.000207	42.2	1,068	30.0	977
5.01	0.142354	0.000208	43.1	684	29.9	5.00	0.168241	0.000207	42.1	811	29.9	748
2.00	0.096187	0.000207	43.3	465	29.8	2.00	0.113195	0.000206	42.4	549	29.9	507
1.00	0.068500	0.000202	44.4	339	29.8	1.00	0.084500	0.000207	43.8	408	29.9	374
0.50	0.049897	0.000200	42.5	249	29.9	0.50	0.060623	0.000203	42.0	299	29.9	274
0.20	0.034243	0.000196	45.2	175	29.8	0.20	0.040775	0.000199	39.2	205	29.8	190
0.10	0.025092	0.000197	43.4	127	29.9	0.10	0.030429	0.000200	45.7	152	29.8	140
0.05	0.020371	0.000195	36.1	104	29.8	0.05	0.023398	0.000197	44.2	119	29.8	112
0.02	0.015511	0.000195	36.7	79	29.9	0.02	0.016570	0.000198	38.3	84	29.9	82
0.01	0.013293	0.000194	40.1	69	29.9	0.01	0.014513	0.000197	35.1	74	29.9	72

Table B.19: Flexural Frequency Sweep Test Results for Sasobit (5.2%) Mix (Dry)

Sample	S5-1B3	**Air-voids**	6.5%	**Test**	10°C	**Sample**	S5-2B3	**Air-voids**	7.1%	**Test**	10°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.15	0.673093	0.000066	12.8	10,131	9.8	15.16	0.542654	0.000106	19.9	5,130	10.7	7,631
10.00	0.734791	0.000105	19.0	6,979	9.7	10.00	0.492149	0.000105	20.1	4,696	10.7	5,838
5.00	0.661280	0.000104	17.7	6,349	9.7	5.00	0.416669	0.000103	22.0	4,051	10.6	5,200
2.00	0.557856	0.000099	17.8	5,661	9.7	2.00	0.332120	0.000102	24.4	3,269	10.6	4,465
1.00	0.524591	0.000096	18.1	5,459	9.8	1.00	0.272989	0.000099	25.4	2,479	10.5	3,969
0.50	0.433982	0.000100	19.5	4,319	9.8	0.50	0.222278	0.000101	29.2	2,200	10.4	3,260
0.20	0.392864	0.000099	21.9	3,986	9.7	0.20	0.165801	0.000099	32.3	1,682	10.4	2,834
0.10	0.322203	0.000099	21.6	3,270	9.7	0.10	0.127497	0.000097	32.0	1,308	10.3	2,289
0.05	0.277983	0.000098	29.5	2,841	9.8	0.05	0.099874	0.000096	37.0	1,038	10.2	1,940
0.02	0.218608	0.000098	32.5	2,237	9.8	0.02	0.077031	0.000097	39.4	798	9.9	1,518
0.01	0.174794	0.000096	33.1	1,815	9.8	0.01	0.064404	0.000096	39.7	671	9.8	1,243
Sample	S5-2B2	**Air-voids**	6.8%	**Test**	20°C	**Sample**	S5-2B6	**Air-voids**	6.7%	**Test**	20°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.16	1.028947	0.000141	34.9	7,292	19.6	15.16	0.850498	0.000210	24.1	4,059	19.6	5,676
10.00	1.052526	0.000204	33.8	5,153	19.7	10.00	0.775645	0.000208	25.3	3,733	19.7	4,443
4.99	0.841514	0.000199	30.6	4,233	19.7	5.00	0.649618	0.000204	23.8	3,181	19.7	3,707
2.00	0.648248	0.000193	33.9	3,364	19.6	2.00	0.498478	0.000197	26.5	2,528	19.6	2,946
1.00	0.540528	0.000200	37.0	2,706	19.7	1.00	0.426729	0.000201	30.8	2,119	19.6	2,413
0.50	0.432255	0.000200	37.2	2,160	19.7	0.50	0.360242	0.000202	32.7	1,787	19.6	1,974
0.20	0.337929	0.000204	41.7	1,657	19.7	0.20	0.264158	0.000201	36.9	1,317	19.7	1,487
0.10	0.253025	0.000201	42.4	1,261	19.6	0.10	0.199290	0.000199	39.1	1,002	19.7	1,132
0.05	0.188955	0.000199	45.7	948	19.6	0.05	0.150318	0.000198	40.7	759	19.7	854
0.02	0.131845	0.000197	45.5	670	19.6	0.02	0.103815	0.000198	43.3	524	19.7	597
0.01	0.098179	0.000197	46.2	499	19.6	0.01	0.079038	0.000198	44.0	400	19.6	450
Sample	S5-2B8	**Air-voids**	7.0%	**Test**	30°C	**Sample**	S5-15B3	**Air-voids**	6.9%	**Test**	30°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.14	0.351615	0.000209	39.9	1,681	29.9	15.15	0.309560	0.000209	42.8	1,484	29.8	1,583
10.00	0.304748	0.000205	39.7	1,484	30.0	10.00	0.268384	0.000207	42.7	1,295	29.9	1,390
5.00	0.238591	0.000208	41.3	1,149	29.9	5.00	0.204202	0.000207	44.0	984	29.8	1,067
2.00	0.157800	0.000201	43.7	787	29.8	2.00	0.132103	0.000201	45.8	657	29.8	722
1.00	0.117320	0.000199	44.6	588	29.9	1.00	0.095561	0.000200	47.2	479	29.9	534
0.50	0.086187	0.000200	46.4	430	29.9	0.50	0.068825	0.000201	49.0	342	29.8	386
0.20	0.056581	0.000198	47.8	285	29.9	0.20	0.044433	0.000198	53.5	224	29.8	255
0.10	0.040980	0.000197	46.1	208	29.8	0.10	0.031538	0.000198	49.2	159	29.9	184
0.05	0.030923	0.000196	48.6	157	29.8	0.05	0.023158	0.000198	44.9	117	29.9	137
0.02	0.021713	0.000197	45.5	110	29.8	0.02	0.015070	0.000197	46.1	76	29.9	93
0.01	0.017683	0.000196	52.9	90	29.8	0.01	0.011843	0.000197	40.0	60	29.9	75

Table B.20: Flexural Frequency Sweep Test Results for Sasobit (5.2%) Mix (Wet)

Sample	S5-1B7	Air-voids	7.1%	Test	10°C	Sample	S5-14B1	Air-voids	7.1%	Test	10°C	Avg. E*
Freq. (Hz)	Stress (MPa)	Strain (µstrain)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Temp. (C)	Freq. (Hz)	Stress (MPa)	Strain (µstrain)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Temp. (C)	(MPa)
15.16	0.498320	0.000072	16.5	6,914	9.9	15.15	0.610620	0.000102	18.8	6,006	9.9	6,460
10.00	0.649037	0.000103	16.9	6,306	9.8	10.00	0.561840	0.000102	19.1	5,513	9.8	5,910
5.00	0.562475	0.000102	17.9	5,519	9.7	5.00	0.496228	0.000103	20.0	4,826	9.7	5,173
2.00	0.475070	0.000104	20.3	4,548	9.7	2.00	0.409286	0.000104	22.3	3,941	9.7	4,245
1.00	0.392025	0.000101	22.3	3,865	9.8	1.00	0.340428	0.000102	23.7	3,335	9.7	3,600
0.50	0.319914	0.000102	23.3	3,150	9.8	0.50	0.275060	0.000099	26.6	2,773	9.6	2,962
0.20	0.245300	0.000099	25.3	2,488	9.7	0.20	0.209924	0.000098	28.1	2,149	9.6	2,319
0.10	0.199776	0.000099	27.5	2,025	9.6	0.10	0.168762	0.000099	29.0	1,710	9.7	1,868
0.05	0.158263	0.000097	30.5	1,623	9.7	0.05	0.129905	0.000097	33.0	1,342	9.6	1,483
0.02	0.118591	0.000096	33.0	1,229	9.7	0.02	0.096527	0.000096	34.8	1,001	9.7	1,115
0.01	0.095570	0.000097	33.9	990	9.7	0.01	0.076735	0.000097	37.4	794	9.7	892
Sample	S5-15B2	**Air-voids**	7.1%	**Test**	20°C	**Sample**	S5-15B4	**Air-voids**	6.8%	**Test**	20°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.16	0.515563	0.000207	30.8	2,494	19.8	15.15	0.473560	0.000212	31.3	2,234	19.7	2,364
10.00	0.459918	0.000207	31.5	2,222	19.8	9.99	0.416153	0.000207	31.7	2,009	19.9	2,116
5.01	0.367445	0.000205	32.9	1,791	19.6	5.01	0.331891	0.000206	32.9	1,613	19.7	1,702
2.00	0.263133	0.000200	35.5	1,314	19.8	2.00	0.237672	0.000201	35.4	1,181	19.9	1,248
1.00	0.204976	0.000203	36.7	1,011	19.9	1.00	0.184919	0.000203	36.8	912	19.9	962
0.50	0.156305	0.000202	38.8	772	19.8	0.50	0.141591	0.000202	38.2	701	19.8	737
0.20	0.106480	0.000199	40.6	536	19.8	0.20	0.097508	0.000198	39.0	491	19.9	514
0.10	0.081112	0.000199	40.1	407	19.8	0.10	0.073143	0.000198	39.3	370	19.8	389
0.05	0.057773	0.000194	43.8	297	19.9	0.05	0.056426	0.000197	40.3	287	19.8	292
0.02	0.041099	0.000197	45.5	208	19.8	0.02	0.039682	0.000193	40.4	205	19.8	207
0.01	0.031043	0.000198	42.2	157	19.8	0.01	0.032400	0.000198	44.5	164	19.8	161
Sample	S5-1B1	**Air-voids**	7.3%	**Test**	30°C	**Sample**	S5-15B6	**Air-voids**	7.1%	**Test**	30°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.16	0.222460	0.000214	42.0	1,041	30.1	15.15	0.167723	0.000217	47.6	774	29.8	908
10.00	0.192317	0.000207	41.2	927	30.0	10.00	0.144958	0.000210	44.8	692	29.9	810
5.00	0.149855	0.000207	40.6	723	29.9	5.00	0.111667	0.000208	43.1	537	29.9	630
2.00	0.102877	0.000208	41.5	496	29.9	2.00	0.074988	0.000203	43.8	396	29.8	446
1.00	0.076202	0.000204	41.5	374	29.9	1.00	0.056057	0.000202	40.6	277	29.9	326
0.50	0.057086	0.000202	41.6	283	29.9	0.50	0.040967	0.000202	40.9	203	29.8	243
0.20	0.039285	0.000199	42.6	198	29.9	0.20	0.029106	0.000200	40.5	145	29.8	172
0.10	0.029082	0.000198	44.8	147	29.9	0.10	0.021411	0.000199	34.4	108	29.9	128
0.05	0.023139	0.000196	39.6	118	29.9	0.05	0.019003	0.000197	37.8	96	29.9	107
0.02	0.016006	0.000197	32.8	81	29.9	0.02	0.013337	0.000197	31.1	68	29.8	75
0.01	-	-	-	-	-	0.01	0.011466	0.000196	34.7	59	29.8	59

Table B.21: Flexural Frequency Sweep Test Results for Sasobit (4.5%) Mix (Dry)

Sample	S4-5B1	Air-voids	7.2%	Test	10°C	Sample	S4-12B7	Air-voids	7.5%	Test	10°C	Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain (µstrain)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Temp. (C)	Freq. (Hz)	Stress (MPa)	Strain (µstrain)	Phase Angle (Degrees)	Stiffness (E*) (MPa)	Temp. (C)	
15.15	0.690938	0.000100	17.9	6,919	10.4	15.15	0.724956	0.000115	19.4	6,315	10.0	6,617
10.00	0.723894	0.000104	16.0	6,929	10.4	9.99	0.598261	0.000099	21.9	6,065	9.9	6,497
5.00	0.691721	0.000104	13.1	6,660	10.3	5.00	0.555666	0.000099	19.5	5,615	9.8	6,138
2.00	0.645163	0.000100	14.9	6,423	10.2	2.00	0.493241	0.000096	17.5	5,153	9.8	5,788
1.00	0.569475	0.000099	15.6	5,768	10.1	1.00	0.471902	0.000097	20.5	4,861	9.7	5,315
0.50	0.503939	0.000098	17.0	5,133	10.0	0.50	0.427610	0.000101	22.7	4,228	9.6	4,681
0.20	0.408925	0.000097	18.0	4,222	9.9	0.20	0.350863	0.000099	25.8	3,541	9.7	3,882
0.10	0.351081	0.000096	19.0	3,646	9.8	0.10	0.285498	0.000098	26.2	2,909	9.8	3,278
0.05	0.311185	0.000096	23.2	3,254	9.7	0.05	0.231446	0.000097	30.0	2,381	9.7	2,818
0.02	0.264508	0.000095	25.8	2,782	9.7	0.02	0.176096	0.000097	34.6	1,811	9.8	2,297
0.01	0.229572	0.000096	27.6	2,394	9.8	0.01	0.143116	0.000097	35.5	1,480	9.8	1,937
Sample	S4-8B2	**Air-voids**	7.3%	**Test**	20°C	**Sample**	S4-11B5	**Air-voids**	7.8%	**Test**	20°C	**Avg. E* (MPa)**
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	
15.16	1.061128	0.000197	19.8	5,380	19.8	15.15	0.904800	0.000217	23.6	4,174	19.7	4,777
9.99	1.035982	0.000205	20.2	5,055	19.8	9.99	0.783086	0.000205	24.6	3,823	19.8	4,439
5.00	0.923646	0.000206	20.1	4,479	19.8	5.00	0.690144	0.000203	24.5	3,393	19.7	3,936
2.00	0.728919	0.000198	22.2	3,679	19.7	2.00	0.518847	0.000194	26.8	2,679	19.7	3,179
1.00	0.621704	0.000201	24.0	3,087	19.6	1.00	0.455767	0.000207	29.8	2,207	19.8	2,647
0.50	0.504258	0.000204	25.5	2,471	19.6	0.50	0.382192	0.000211	32.1	1,812	19.8	2,142
0.20	0.393807	0.000200	28.0	1,972	19.7	0.20	0.283547	0.000204	35.5	1,389	19.6	1,681
0.10	0.338587	0.000201	31.3	1,687	19.7	0.10	0.218299	0.000203	37.1	1,076	19.6	1,382
0.05	0.266276	0.000200	34.7	1,331	19.7	0.05	0.168077	0.000202	39.3	833	19.8	1,082
0.02	0.191740	0.000199	37.1	963	19.7	0.02	0.119186	0.000201	41.0	593	19.7	778
0.01	0.142874	0.000198	38.7	723	19.6	0.01	0.091617	0.000200	41.7	459	19.7	591
Sample	S4-11B3	**Air-voids**	7.9%	**Test**	30°C	**Sample**	S4-11B7	**Air-voids**	7.8%	**Test**	30°C	**Avg. E* (MPa)**
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	
15.16	0.357825	0.000209	40.6	1,713	29.9	15.16	0.428344	0.000204	36.0	2,097	29.7	1,905
10.01	0.306624	0.000204	40.7	1,503	29.7	9.99	0.382069	0.000206	36.7	1,852	29.8	1,678
5.00	0.241627	0.000208	42.0	1,164	29.8	5.00	0.299614	0.000206	37.6	1,456	29.8	1,310
2.00	0.160078	0.000201	44.2	797	29.7	2.00	0.205078	0.000200	40.6	1,028	29.7	913
1.00	0.118344	0.000200	45.8	592	29.6	1.00	0.156145	0.000200	42.1	782	29.7	687
0.50	0.087204	0.000200	46.6	436	29.8	0.50	0.116141	0.000201	42.9	578	29.7	507
0.20	0.055172	0.000199	48.0	277	29.8	0.20	0.077803	0.000200	44.7	390	29.7	334
0.10	0.040607	0.000197	49.5	206	29.8	0.10	0.056478	0.000198	44.2	286	29.8	246
0.05	0.028752	0.000196	49.0	147	29.8	0.05	0.041381	0.000197	47.4	210	29.7	179
0.02	0.019861	0.000195	55.3	102	29.8	0.02	0.028259	0.000197	49.4	143	29.8	123
0.01	0.016160	0.000196	53.6	82	29.8	0.01	0.022664	0.000197	51.6	115	29.8	99

Table B.22: Flexural Frequency Sweep Test Results for Sasobit (4.5%) Mix (Wet)

Sample	S4-10B1	Air-voids	7.7%	Test	10°C	Sample	S4-11B2	Air-voids	7.5%	Test	10°C	Avg. E*
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.17	0.330910	0.000105	25.0	3,164	10.8	15.13	0.500536	0.000107	20.4	4,696	10.1	3,930
9.99	0.296572	0.000103	25.3	2,893	10.8	9.99	0.449390	0.000103	21.2	4,348	10.1	3,621
4.99	0.255271	0.000104	25.6	2,464	10.7	5.01	0.390659	0.000104	22.0	3,765	10.1	3,115
2.00	0.197879	0.000103	27.4	1,927	10.7	2.00	0.309409	0.000102	24.4	3,038	10.1	2,483
1.00	0.162805	0.000101	29.2	1,608	10.6	1.00	0.254170	0.000100	26.0	2,545	10.1	2,077
0.50	0.126191	0.000100	30.8	1,265	10.6	0.50	0.202018	0.000100	26.6	2,022	10.1	1,644
0.20	0.093545	0.000100	34.4	940	10.5	0.20	0.149589	0.000098	30.0	1,528	10.0	1,234
0.10	0.069335	0.000098	34.4	711	10.4	0.10	0.115197	0.000097	28.5	1,185	10.0	948
0.05	0.056195	0.000097	34.4	579	10.3	0.05	0.090909	0.000096	34.5	946	10.0	763
0.02	0.042846	0.000096	32.9	444	10.1	0.02	0.069219	0.000096	35.9	723	9.8	584
0.01	0.035424	0.000098	41.4	362	9.8	0.01	0.055542	0.000097	37.9	574	9.7	468
Sample	S4-2B1	**Air-voids**	7.1%	**Test**	20°C	**Sample**	S4-12B5	**Air-voids**	7.9%	**Test**	20°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.16	0.562711	0.000207	27.7	2,723	20.3	15.15	0.487016	0.000209	31.8	2,335	19.8	2,529
10.00	0.504136	0.000205	28.4	2,465	20.2	10.00	0.429413	0.000206	32.3	2,082	19.7	2,274
5.00	0.415461	0.000204	29.5	2,034	20.1	5.01	0.341819	0.000205	33.6	1,670	19.5	1,852
2.00	0.307068	0.000199	31.5	1,546	20.1	2.00	0.243195	0.000199	35.7	1,223	19.5	1,385
1.00	0.251061	0.000202	33.3	1,245	20.0	1.00	0.189152	0.000200	37.0	948	19.7	1,097
0.50	0.199786	0.000204	34.8	979	19.9	0.50	0.146954	0.000204	39.2	721	19.7	850
0.20	0.143882	0.000203	35.8	710	19.9	0.20	0.099975	0.000200	39.5	501	19.6	606
0.10	0.112382	0.000202	37.5	558	19.8	0.10	0.077226	0.000200	42.7	387	19.7	473
0.05	0.088057	0.000200	38.6	440	19.8	0.05	0.057458	0.000198	41.3	290	19.6	365
0.02	0.065340	0.000201	39.5	326	19.8	0.02	0.041111	0.000198	44.2	207	19.6	267
0.01	0.056065	0.000201	40.1	279	19.8	0.01	0.032458	0.000199	40.4	163	19.6	221
Sample	S4-12B1	**Air-voids**	7.6%	**Test**	30°C	**Sample**	S4-12B6	**Air-voids**	7.9%	**Test**	30°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.15	0.113847	0.000209	53.0	545	30.2	15.15	0.128934	0.000216	51.9	598	29.9	572
10.01	0.102439	0.000205	47.2	499	29.9	10.00	0.114160	0.000209	47.8	546	29.8	523
5.00	0.083024	0.000208	45.3	400	29.8	5.00	0.087908	0.000206	45.6	427	29.7	414
2.00	0.053702	0.000197	43.3	273	30.0	2.00	0.059188	0.000202	44.0	293	29.8	283
1.00	0.040622	0.000198	42.0	205	29.8	1.00	0.045827	0.000200	42.0	229	29.7	217
0.50	0.030199	0.000201	44.4	151	29.9	0.50	0.037707	0.000199	36.7	189	29.9	170
0.20	0.021702	0.000200	44.0	109	29.8	0.20	0.023533	0.000199	37.2	118	29.9	114
0.10	0.016895	0.000199	42.5	85	29.9	0.10	0.018083	0.000197	40.6	92	29.8	89
0.05	0.014627	0.000198	37.9	74	29.9	0.05	0.014689	0.000197	36.6	74	29.8	74
0.02	0.011592	0.000197	39.9	59	29.8	0.02	0.011308	0.000197	42.6	57	29.8	58
0.01	0.011003	0.000196	39.0	56	29.8	0.01	0.009870	0.000196	46.6	50	29.8	53

Table B.23: Flexural Frequency Sweep Test Results for Rediset Mix (Dry)

Sample	AN-14B1	Air-voids	4.9%	Test	10°C	Sample	AN-29A2	Air-voids	4.2%	Test	10°C	Avg. E*
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.11	0.2636	0.000030	15.0	8,832	9.6	15.12	0.2502	0.000023	13.0	10,928	9.9	9,880
9.99	0.7503	0.000099	20.2	7,580	9.7	9.99	0.9182	0.000102	17.6	9,029	9.8	8,304
5.00	0.6895	0.000101	19.5	6,850	9.7	5.01	0.8251	0.000100	17.8	8,244	9.9	7,547
2.00	0.6119	0.000098	19.4	6,243	9.8	2.00	0.7070	0.000097	18.5	7,266	10.0	6,755
1.00	0.5359	0.000097	20.3	5,503	9.9	1.00	0.6366	0.000096	18.9	6,635	9.9	6,069
0.50	0.4725	0.000102	23.2	4,623	9.9	0.50	0.5765	0.000097	20.6	5,933	9.9	5,278
0.20	0.3681	0.000100	26.9	3,673	9.8	0.20	0.4777	0.000098	22.9	4,874	9.8	4,274
0.10	0.2929	0.000099	24.5	2,952	9.7	0.10	0.4026	0.000098	23.4	4,088	9.8	3,520
0.05	0.2424	0.000099	32.3	2,452	9.5	0.05	0.3375	0.000097	27.3	3,462	9.9	2,957
0.02	0.1932	0.000100	33.1	1,942	9.3	0.02	0.2677	0.000098	30.3	2,742	9.9	2,342
0.01	0.1577	0.000100	34.6	1,576	9.9	0.01	0.2178	0.000098	30.8	2,228	9.9	1,902
Sample	AN-25A1	**Air-voids**	4.8%	**Test**	20°C	**Sample**	AN-27A1	**Air-voids**	4.0%	**Test**	20°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.12	0.2487	0.000040	19.5	6,205	19.4	15.11	0.2857	0.000044	19.1	6,560	19.3	6,383
10.00	0.5771	0.000101	21.6	5,709	19.4	10.00	0.5866	0.000101	22.5	5,780	19.4	5,745
5.00	0.4837	0.000100	22.8	4,841	19.5	5.00	0.4998	0.000101	23.7	4,960	16.5	4,901
2.00	0.3742	0.000097	25.3	3,872	19.6	2.00	0.3855	0.000098	26.4	3,940	19.5	3,906
1.00	0.3089	0.000096	27.5	3,215	19.7	1.00	0.3141	0.000098	28.7	3,205	19.6	3,210
0.50	0.2617	0.000103	31.4	2,533	19.7	0.50	0.2576	0.000101	31.8	2,549	19.7	2,541
0.20	0.1887	0.000101	34.8	1,867	19.8	0.20	0.1845	0.000099	34.8	1,860	19.7	1,863
0.10	0.1422	0.000100	32.8	1,418	19.7	0.10	0.1398	0.000099	34.8	1,417	19.8	1,418
0.05	0.1125	0.000099	38.6	1,135	19.6	0.05	0.1105	0.000099	40.2	1,114	19.7	1,124
0.02	0.0792	0.000098	40.5	806	19.7	0.02	0.0771	0.000098	40.1	782	19.7	794
0.01	0.0614	0.000100	42.3	616	19.7	0.01	0.0598	0.000098	39.9	609	19.7	612
Sample	AN-12B1	**Air-voids**	4.0%	**Test**	30°C	**Sample**	AN-21A1	**Air-voids**	4.8%	**Test**	30°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (µstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.14	0.2272	0.000078	31.8	2,912	30.1	15.09	0.2310	0.000075	30.3	3,093	30.2	3,002
10.01	0.2524	0.000102	33.8	2,478	30.1	10.00	0.2692	0.000101	32.6	2,675	30.2	2,576
5.01	0.2009	0.000103	35.5	1,953	30.1	5.00	0.2160	0.000102	33.4	2,114	30.2	2,034
2.00	0.1371	0.000100	38.5	1,375	30.1	2.00	0.1488	0.000099	36.1	1,502	30.1	1,438
1.00	0.1030	0.000099	40.9	1,041	30.1	1.00	0.1128	0.000098	38.1	1,154	30.1	1,098
0.50	0.0786	0.000101	43.4	775	30.0	0.50	0.0861	0.000100	41.1	858	30.2	817
0.20	0.0520	0.000098	43.9	529	30.1	0.20	0.0581	0.000098	43.0	593	30.1	561
0.10	0.0376	0.000099	45.0	381	30.1	0.10	0.0433	0.000097	40.5	445	30.1	413
0.05	0.0273	0.000098	45.4	278	30.1	0.05	0.0338	0.000097	42.6	348	30.1	313
0.02	0.0196	0.000098	45.3	200	30.1	0.02	0.0242	0.000097	46.9	250	30.0	225
0.01	0.0143	0.000098	41.7	146	30.1	0.01	0.0178	0.000097	45.8	184	30.1	165

Table B.24: Flexural Frequency Sweep Test Results for Rediset Mix (Wet)

Sample	AN-34B1	Air-voids	4.2%	Test	10°C	Sample	AN-16B1	Air-voids	4.9%	Test	10°C	Avg. E*
Freq. (Hz)	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.17	0.2876	0.000029	14.2	9,964	9.9	15.10	0.2355	0.000025	13.0	9,477	9.8	9,720
9.99	0.8549	0.000102	17.8	8,378	9.8	9.99	0.7805	0.000097	18.7	8,018	9.9	8,198
5.00	0.7660	0.000100	17.0	7,672	9.9	5.00	0.7326	0.000101	17.8	7,262	10.0	7,467
2.00	0.6594	0.000099	16.7	6,681	10.0	2.00	0.6300	0.000097	17.5	6,513	10.0	6,597
1.00	0.5972	0.000096	18.3	6,212	9.9	1.00	0.5898	0.000097	18.3	6,056	9.8	6,134
0.50	0.5535	0.000100	19.1	5,556	9.9	0.50	0.5239	0.000099	18.9	5,290	9.9	5,423
0.20	0.4553	0.000099	20.4	4,578	10.0	0.20	0.4226	0.000098	21.8	4,303	10.0	4,441
0.10	0.3835	0.000098	21.0	3,896	10.0	0.10	0.3521	0.000097	22.8	3,619	9.9	3,757
0.05	0.3226	0.000097	24.9	3,310	9.9	0.05	0.2919	0.000097	26.3	3,014	9.9	3,162
0.02	0.2594	0.000098	25.9	2,652	9.9	0.02	0.2300	0.000096	28.0	2,384	9.9	2,518
0.01	0.2159	0.000097	27.3	2,216	9.9	0.01	0.1887	0.000097	28.1	1,948	9.9	2,082
Sample	AN-23A1	**Air-voids**	5.0%	**Test**	20°C	**Sample**	AN-33A1	**Air-voids**	4.3%	**Test**	20°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.15	0.1518	0.000030	21.5	5,096	19.7	15.14	0.2083	0.000041	22.6	5,111	19.9	5,103
10.00	0.4719	0.000103	23.0	4,602	19.8	10.01	0.4691	0.000103	24.7	4,572	19.8	4,587
5.00	0.3927	0.000101	25.2	3,873	19.8	5.01	0.3891	0.000102	26.5	3,825	19.6	3,849
2.00	0.3009	0.000100	27.5	3,018	19.7	2.00	0.2932	0.000100	29.4	2,928	19.7	2,973
1.00	0.2430	0.000100	30.3	2,435	19.7	1.00	0.2331	0.000100	31.4	2,341	19.8	2,388
0.50	0.1918	0.000100	31.5	1,922	19.8	0.50	0.1845	0.000099	32.6	1,865	19.8	1,893
0.20	0.1363	0.000097	34.2	1,412	19.8	0.20	0.1288	0.000097	35.8	1,333	19.7	1,372
0.10	0.1079	0.000098	35.0	1,097	19.7	0.10	0.1006	0.000098	35.5	1,029	19.7	1,063
0.05	0.0820	0.000096	34.6	850	19.8	0.05	0.0760	0.000097	38.1	781	19.7	816
0.02	0.0592	0.000097	36.9	613	19.7	0.02	0.0543	0.000096	37.6	565	19.7	589
0.01	0.0467	0.000095	34.0	490	19.7	0.01	0.0429	0.000096	36.9	445	19.7	468
Sample	AN-7A1	**Air-voids**	4.7%	**Test**	30°C	**Sample**	AN-29A1	**Air-voids**	4.6%	**Test**	30°C	**Avg. E***
Freq. (Hz)	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain (μstrain)**	**Phase Angle (Degrees)**	**Stiffness (E*) (MPa)**	**Temp. (C)**	**(MPa)**
15.15	0.2060	0.000084	33.3	2,450	29.7	15.13	0.1884	0.000078	32.0	2,427	29.7	2,439
9.99	0.2234	0.000105	33.7	2,137	29.5	10.01	0.2247	0.000107	34.1	2,098	29.8	2,118
4.99	0.1774	0.000106	35.4	1,677	29.7	5.01	0.1760	0.000104	34.8	1,690	29.7	1,684
2.00	0.1229	0.000102	37.1	1,205	29.6	2.00	0.1241	0.000101	36.5	1,224	29.7	1,215
1.00	0.0924	0.000100	36.6	927	29.7	1.00	0.0926	0.000099	36.4	935	29.6	931
0.50	0.0702	0.000099	39.4	710	29.6	0.50	0.0723	0.000099	36.8	732	29.7	721
0.20	0.0470	0.000098	39.5	481	29.7	0.20	0.0497	0.000098	39.6	506	29.7	494
0.10	0.0359	0.000096	38.6	374	29.6	0.10	0.0386	0.000098	37.9	395	29.6	384
0.05	0.0281	0.000096	39.0	293	29.6	0.05	0.0301	0.000097	40.5	311	29.6	302
0.02	0.0212	0.000097	38.0	220	29.6	0.02	0.0234	0.000097	34.0	242	29.6	231
0.01	0.0177	0.000097	35.1	183	29.6	0.01	0.0202	0.000097	33.3	209	29.6	196

Table B.25: Hamburg Wheel-Track Results (Effect of Aggregate Moisture Content and Cure Time)

Moisture Content (%)	Left			Right			Average		
	Creep Slope (mm/pass)	Strip Slope (mm/pass)	Infl. Pt. (pass no.)	Creep Slope (mm/pass)	Strip Slope (mm/pass)	Infl. Pt. (pass no.)	Creep Slope (mm/pass)	Strip Slope (mm/pass)	Infl. Pt. (pass no.)
	Control								
	0 Hour Cure Time								
0.0	-0.0002	-0.0016	7,895	-0.0002	-0.0015	14,024	-0.0002	-0.0016	10,959
0.5	-0.0003	-0.0008	5,425	-0.0004	-0.0014	3,719	-0.0004	-0.0011	4,572
1.5	-0.0002	-0.0014	6,580	-0.0003	-0.0014	7,210	-0.0003	-0.0014	6,895
3.0	-0.0004	-0.0022	5,610	-0.0003	-0.0013	6,764	-0.0004	-0.0018	6,187
	2 Hour Cure Time								
0.0	-0.0001	-0.0011	16,153	-0.0001	-0.0010	14,936	-0.0001	-0.0011	15,545
0.5	-0.0001	-0.0010	13,084	-0.0001	-0.0005	11,050	-0.0001	-0.0008	12,067
1.5	-0.0001	-0.0004	15,935	-0.0001	-0.0004	15,112	-0.0001	-0.0004	15,524
3.0	-0.0002	-0.0011	14,596	-0.0001	-0.0008	9,802	-0.0002	-0.0010	12,199
	4 Hour Cure Time								
0.0	-0.0001	NA	NA	-0.0001	NA	NA	-0.0001	NA	NA
0.5	-0.0001	NA	NA	-0.0001	NA	NA	-0.0001	NA	NA
1.5	-0.0001	-0.0004	16,237	-0.0001	-0.0008	17,590	-0.0001	-0.0006	16,914
3.0	-0.0001	-0.0006	14,758	-0.0002	-0.0004	14,759	-0.0002	-0.0005	14,759
Advera									
	0 Hour Cure Time								
0.0	-0.0002	-0.0013	9,413	-0.0003	-0.0017	9,174	-0.0003	-0.0015	9,293
0.5	-0.0001	-0.0012	15,082	-0.0005	-0.0011	9,863	-0.0003	-0.0012	12,472
1.5	-0.0003	-0.0008	7,971	-0.0004	-0.0022	6,015	-0.0004	-0.0015	6,993
3.0	-0.0007	-0.0022	5,145	-0.0005	-0.0021	6,651	-0.0006	-0.0022	5,898
	2 Hour Cure Time								
0.0	0.0000	-0.0003	10,423	-0.0001	-0.0002	15,186	-0.0001	-0.0003	12,805
0.5	-0.0001	NA	NA	-0.0001	NA	NA	-0.0001	NA	NA
1.5	-0.0002	-0.0009	11,900	0.0000	-0.0005	13,743	-0.0001	-0.0007	12,822
3.0	-0.0001	-0.0001	13,283	-0.0003	-0.0013	10,276	-0.0002	-0.0007	11,779
	4 Hour Cure Time								
0.0	-0.0001	NA	NA	-0.0001	NA	NA	-0.0001	NA	NA
0.5	-0.0002	NA	NA	-0.0001	NA	NA	-0.0002	NA	NA
1.5	-0.0002	-0.0006	14,022	-0.0001	-0.0004	11,899	-0.0002	-0.0005	12,961
3.0	-0.0001	NA	NA	-0.0001	NA	NA	-0.0001	NA	NA

Table B.25: Hamburg Wheel-Track Results (Effect of Aggregate Moisture Content and Cure Time) *(continued)*

Moisture Content (%)	Left			Right			Average		
	Creep Slope (mm/pass)	Strip Slope (mm/pass)	Infl. Pt. (pass no.)	Creep Slope (mm/pass)	Strip Slope (mm/pass)	Infl. Pt. (pass no.)	Creep Slope (mm/pass)	Strip Slope (mm/pass)	Infl. Pt. (pass no.)
	Evotherm								
	0 Hour Cure Time								
0.0	-0.0001	-0.0013	5,797	-0.0002	-0.0018	11,349	-0.0002	-0.0016	8,573
0.5	-0.0004	-0.0014	10,303	-0.0003	-0.0014	8,189	-0.0004	-0.0014	9,246
1.5	-0.0002	-0.0007	17,826	-0.0004	-0.0015	12,853	-0.0003	-0.0011	15,339
3.0	-0.0003	-0.0016	10,186	-0.0002	-0.0012	15,648	-0.0003	-0.0014	12,917
	2 Hour Cure Time								
0.0	-0.0001	-0.0005	10,869	-0.0001	-0.0005	14,530	-0.0001	-0.0005	12,699
0.5	-0.0001	-0.0006	15,862	-0.0001	-0.0003	10,911	-0.0001	-0.0005	13,387
1.5	-0.0003	-0.0012	10,345	-0.0002	-0.0014	13,602	-0.0003	-0.0013	11,974
3.0	-0.0001	-0.0001	11,805	-0.0002	-0.0004	18,446	-0.0001	-0.0002	15,126
	4 Hour Cure Time								
0.0	-0.0001	NA	NA	-0.0001	NA	NA	-0.0001	NA	NA
0.5	-0.0001	-0.0003	22,327	-0.0003	-0.0005	43,871	-0.0002	-0.0004	33,099
1.5	-0.0001	NA	NA	-0.0001	NA	NA	-0.0001	NA	NA
3.0	-0.0001	NA	NA	-0.0001	NA	NA	-0.0001	NA	NA
Sasobit									
	0 Hour Cure Time								
0.0	-0.0002	-0.0019	8,444	-0.0001	-0.0012	14,167	-0.0002	-0.0016	11,306
0.5	-0.0003	-0.0016	7,433	-0.0003	-0.0015	17,049	-0.0003	-0.0016	12,241
1.5	-0.0004	-0.0021	9,427	-0.0003	-0.0013	6,660	-0.0004	-0.0017	8,044
3.0	-0.0004	-0.0017	8,981	-0.0004	-0.0011	10,099	-0.0004	-0.0014	9,540
	2 Hour Cure Time								
0.0	0.0000	-0.0001	9,480	-0.0001	-0.0006	16,076	-0.0001	-0.0003	12,778
0.5	-0.0001	-0.0002	13,062	-0.0001	-0.0002	13,805	-0.0001	-0.0002	13,433
1.5	-0.0001	-0.0008	11,338	-0.0002	-0.0014	10,218	-0.0002	-0.0011	10,778
3.0	-0.0002	-0.0012	15,825	-0.0002	-0.0012	6,978	-0.0002	-0.0012	11,402
	4 Hour Cure Time								
0.0	-0.0001	-0.0002	12,081	-0.0001	-0.0002	12,204	-0.0001	-0.0002	12,142
0.5	-0.0001	-0.0001	13,463	0.0000	-0.0001	13,835	0.0000	-0.0001	13,649
1.5	-0.0001	-0.0006	9,157	-0.0002	-0.0007	10,864	-0.0002	-0.0007	10,011
3.0	-0.0001	-0.0002	9,536	-0.0001	-0.0004	12,712	-0.0001	-0.0003	11,124

Table B.26: Summary of Tensile Strength Retained Test Results

Mix	Condition	AV (%)	Strength (kPa)	Average (kPa)	Std. Dev	TSR (%)
Control	Dry	7.5	2,761	2,487	191	25
		7.1	2,474			
		6.6	2,355			
		6.8	2,357			
	Wet	7.5	572	613	36	
		7.5	629			
		7.5	597			
		7.5	654			
Advera	Dry	7.53	2,093	2,248	104	45
		7.07	2,307			
		7.42	2,307			
		7.14	2,288			
	Wet	7.21	975	1,012	40	
		6.49	1,032			
		6.72	1,058			
		6.95	982			
Evotherm	Dry	6.71	2,208	2,163	76	62
		6.50	2,155			
		6.92	2,216			
		6.95	2,099			
	Wet	6.65	1,317	1,350	51	
		7.34	1,350			
		7.30	1,422			
		6.85	1,309			
Sasobit (5.2%)	Dry	6.98	2,372	2,306	357	42
		6.50	2,785			
		7.50	2,018			
		7.47	2,049			
	Wet	6.79	1,068	963	80	
		7.31	920			
		7.57	977			
		7.56	885			
Sasobit (4.5%)	Dry	7.29	2,184	2,567	269	52
		7.18	2,741			
		7.12	2,575			
		7.08	2,768			
	Wet	7.51	1,288	1,328	47	
		7.07	1,395			
		7.45	1,306			
		7.25	1,322			
Rediset	Dry	7.5	2,515	2,552	92	70
		7.7	2,449			
		7.5	2,663			
		7.9	2,582			
	Wet	7.0	1,636	1,790	120	
		7.0	1,814			
		7.5	1,782			
		7.5	1,927			

Table B.27: Summary of Cantabro Abrasion Loss Test Results

Mix	Air-voids (%)	Mass Before (g)	Mass After (g)	Mass Loss (%)
Control	17.8	1,193	1,115	7
	18.2	1,199	1,109	8
	18.1	1,196	1,099	8
	17.9	1,200	1,089	9
	17.8	1,204	1,088	10
	18.2	1,196	1,077	10
Average	18.0	1,198	1,096	9
Std. Deviation	0.2	3.9	14.2	1.3
Advera	17.5	1,180	1,027	13
	17.1	1,179	1,076	9
	18.3	1,179	1,075	9
	17.3	1,179	1,070	9
	18.3	1,179	950	19
	17.6	1,179	946	20
Average	17.7	1,179	1,024	13
Std. Deviation	0.5	0.5	61.7	5.2
Evotherm	17.1	1,174	1,093	7
	16.1	1,177	1,042	11
	17.4	1,176	1,005	15
	16.8	1,176	997	15
	16.5	1,178	981	17
	16.5	1,175	976	17
Average	16.7	1,176	1,016	14
Std. Deviation	0.5	1.5	44.4	3.8
Sasobit	16.2	1,177	1,103	6
	16.2	1,183	946	20
	16.5	1,186	913	23
	16.5	1,186	895	25
	16.0	1,182	891	25
	17.4	1,186	857	27
Average	16.5	1,184	934	21
Std. Deviation	0.5	3.7	87.7	7.7
Rediset	16.0	1,194	1,115	7
	16.8	1,199	1,081	10
	16.9	1,198	1,065	11
	18.9	1,200	1,058	12
	17.3	1,198	1,041	13
	17.7	1,197	1,028	14
Average	17.3	1,198	1,064	11
Std. Deviation	1.0	2.1	30.8	2.6

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