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ASPHALT MATERIALS CHARACTERIZATION IN SUPPORT OF IMPLEMENTATION OF THE PROPOSED MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE

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Abstract

The proposed Mechanistic-Empirical Pavement Design Guide (MEPDG) procedure is an improved methodology for pavement design and evaluation of paving materials. Since this new procedure depends heavily on the characterization of the fundamental engineering properties of paving materials, a thorough material characterization of mixes used in Virginia is needed to use the MEPDG to design new and rehabilitated flexible pavements.

The primary objective of this project was to perform a full hot-mix asphalt (HMA) characterization in accordance with the procedure established by the proposed MEPDG to support its implementation in Virginia. This objective was achieved by testing a sample of surface, intermediate, and base mixes. The project examined the dynamic modulus, the main HMA material property required by the MEPDG, as well as creep compliance and tensile strength, which are needed to predict thermal cracking. In addition, resilient modulus tests, which are not required by the MEPDG, were also performed on the different mixes to investigate possible correlations between this test and the dynamic modulus.

Loose samples for 11 mixes (4 base, 4 intermediate, and 3 surface mixes) were collected from different plants across Virginia. Representative samples underwent testing for maximum theoretical specific gravity, asphalt content using the ignition oven method, and gradation of the reclaimed aggregate. Specimens for the various tests were then prepared using the Superpave gyratory compactor with a target voids in total mix (VTM) of 7% ± 1% (after coring and/or cutting).

The investigation confirmed that the dynamic modulus test is an effective test for determining the mechanical behavior of HMA at different temperatures and loading frequencies. The test results showed that the dynamic modulus is sensitive to the mix constituents (aggregate type, asphalt content, percentage of recycled asphalt pavement, etc.) and that even mixes of the same type (SM-9.5A, IM-19.0A, and BM-25.0) had different measured dynamic modulus values because they had different constituents. The level 2 dynamic modulus prediction equation reasonably estimated the measured dynamic modulus; however, it did not capture some of the differences between the mixes captured by the measured data. Unfortunately, the indirect tension strength and creep tests needed for the low-temperature cracking model did not produce very repeatable results; this could be due to the type of extensometers used for the test.

Based on the results of the investigation, it is recommended that the Virginia Department of Transportation use level 1 input data to characterize the dynamic modulus of the HMA for projects of significant impact. The dynamic modulus test is easy to perform and gives a full characterization of the asphalt mixture. Level 2 data (based on the default prediction equation) could be used for smaller projects pending further investigation of the revised prediction equation incorporated in the new MEPDG software/guide. In addition, a sensitivity analysis is recommended to quantify the effect of changing the dynamic modulus on the asphalt pavement design. Since low-temperature cracking is not a widespread problem in Virginia, use of level 2 or 3 indirect tensile creep and strength data is recommended at this stage.

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NOTICE

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Each contract report is peer reviewed and accepted for publication by Research Council staff with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

ABSTRACT

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INTRODUCTION

The proposed Mechanistic-Empirical Pavement Design Guide (MEPDG) procedure, introduced in NCHRP Project 1-37A (NCHRP, 2004), is an improved methodology for pavement design and evaluation of paving materials. Unlike currently used empirical pavement design methods, this new procedure depends heavily on the characterization of the fundamental engineering properties of paving materials. For asphaltic materials, the term *material characterization* can be defined as the measurements and the analysis of the asphaltic material response to load and deformation at different loading rates or temperatures (i.e., environmental conditions). Implementation of the MEPDG in Virginia is expected to improve the efficiency of pavement designs, provide better capability for prediction of pavement lifetime maintenance needs, and strengthen Virginia's position as a leading state in emerging technology.

Use of the proposed MEPDG for the design of asphalt pavements requires a comprehensive characterization of the materials typically used in Virginia pavements. The MEPDG identifies and incorporates several fundamental properties and tests for asphalt mixtures and binders. The data required for asphalt mixtures include indirect tensile strength, creep compliance, and dynamic modulus. The required asphalt binder properties include the complex shear modulus and associated phase angle. General asphalt mixture properties include asphalt binder content, aggregate gradation, and volumetric properties. These material characteristics are also necessary to calibrate the proposed MEPDG for use with materials used in Virginia pavements. Accurate knowledge of these characteristics and calibration of the design guide will improve the efficiency and reliability of future asphalt pavement designs for new construction and rehabilitation in Virginia.

PURPOSE AND SCOPE

A thorough material characterization of hot-mix asphalt (HMA) mixes used in Virginia is needed to use the proposed MEPDG to design new and rehabilitated flexible pavements. These tests would provide level 1 input for the HMA material properties as required for the highest-priority flexible pavement designs. In addition, even for the level 2 input, the equations relating volumetric properties to the required mechanical properties need to be validated and possibly calibrated for the mixes used in Virginia. Level 3 designs require catalogued properties of the typical mixes used in Virginia, which are set as default values for the pavement designer.

Therefore, the primary objective of this project was to perform a full HMA material characterization in accordance with the procedure established by the proposed MEPDG in order to support the implementation of mechanistic-empirical pavement design procedures in Virginia. This objective was achieved by testing a sample of HMA used in Virginia as surface, intermediate, and base mixes. Dynamic modulus and creep compliance temperatures were measured at the recommended temperatures and frequencies for 11 typical mixes.

In addition, resilient modulus tests, which are not required by the MEPDG, were also performed on the different mixes in order to investigate possible correlations between this test and the dynamic modulus. The resilient modulus is used with the AASHTO 1993 pavement design method currently used in VDOT and for pavement analysis using multilayer linear elastic analysis software (e.g., ELSYM5) to calculate stresses and strains in the pavement.

METHODS AND MATERIALS

The main HMA material property required by the MEPDG is the dynamic modulus. Additional properties, namely the creep compliance and the tensile strength, are needed to predict thermal cracking. The dynamic modulus test was performed in accordance with AASHTO TP62-03. Five testing temperatures were used: 10°F, 30°F, 70°F, 100°F, and 130°F. Six testing frequencies, 0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, 10 Hz, and 25 Hz, were used at each temperature. Three specimens per mix were tested. Each specimen was first tested at the lowest temperature with all six frequencies from highest to lowest. The procedure was then repeated at consecutively higher temperatures until the sequence had been completed for all specimens. The creep test was performed in accordance with AASHTO T322-03. The three standard testing temperatures were used: −4°F, 14°F, and 32°F. At each temperature, a static load was applied for 100 seconds. Two specimens per mix were tested. The same specimens were then used to determine the mix tensile strength at 14°F. The resilient modulus test was performed in accordance with ASTM D4123 at the following three testing temperatures: 41°F, 77°F, and 104°F. Two specimens per mix were tested.

This study used 11 mixes. In total, 33 specimens were tested for dynamic modulus, 22 for creep compliance and tensile strength, and 22 for resilient modulus. The following section describes the 11 mixes and discusses the procedures used for preparing the specimens.

Specimen Preparation and Volumetric Analysis

Loose samples for 11 mixes were collected from different plants across the Commonwealth of Virginia. The mixes consisted of 4 base mixes (BM-25.0), 4 intermediate mixes (IM-19.0A), and 3 surface mixes (SM-9.5A). The mixes were labeled depending on their mix type (BM, IM, and SM) and were numbered randomly. The labels for the different mixes and the plants where they were collected are presented in Table 1. The job-mix formulas (JMF) for all the mixes are presented in Tables A1 to A3 in Appendix A.

Table 1. Labels and plant locations of mixes

Mix Type	Label	Contractor	Location
SM-9.5A	SM1	VA Paving Corp.	Stafford
	SM2	ADAMS	Rockydale
	SM3	Superior Paving	Warrenton
IM-19.0A	IM1	APAC	Occoquan
	IM2	Branscome	Norfolk
	IM3	Adams	Lowmoor
	IM4	B&S Contracting	Augusta
BM-25.0	BM1	VA Paving Corp.	Stafford
	BM2	Stuart M. Perry	Winchester
	BM3	Adams	Blacksburg
	BM4	Branscome	Norfolk

Once the mixes were collected, representative samples were used to perform the following tests: maximum theoretical specific gravity (G_{mm}) in accordance with AASHTO T209, asphalt content using the ignition method, and gradation of the reclaimed aggregate in accordance with AASHTO T27. Each of these tests was performed on four samples. Results of the individual tests are presented in Tables B1 to B11 in Appendix B. Table 2, Table 3, and Table 4 show the average properties for the SM-9.5A, IM-19.0A, and BM-25.0 mixes, respectively. The values that did not pass the acceptance range are shaded in gray. Although some properties were outside of the acceptance range, no mixture failed to the extent that they were removed and replaced.

Table 2. Asphalt content, G_{mm}, and aggregate gradation for the SM-9.5A mixes

	SM1		SM2		SM3	
	Avg.	**JMF**	**Avg.**	**JMF**	**Avg.**	**JMF**
Asp. Ct. (%)	4.93	5.3 ± 0.3	5.91	5.9 ± 0.3	6.32	5.6 ± 0.3
G_{mm}	2.630	2.626	2.648	2.618	2.596	2.599
Gradation						
Sieve opening, mm (No.)	**% Passing**	**Acceptance Range**	**% Passing**	**Acceptance Range**	**% Passing**	**Acceptance Range**
12.5 (1/2)	97.4	100	100.0	99-100	99.2	99-100
9.5 (3/8)	89.9	89-97	96.3	92-100	91.4	89-97
4.75 (#4)	57.2	56-64	57.1	56-64	55.8	55-63
2.36 (#8)	37.9	36-44	37.6	37-45	39.5	36-44
1.18 (#16)	27.9	-	28.1	-	30.0	-
0.6 (#30)	19.4	-	20.2	-	21.5	-
0.3 (#50)	10.9	-	12.8	-	13.4	-
0.15 (#100)	6.8	-	8.5	-	9.1	-
0.075 (#200)	5.0	4-6	6.3	4.9-6.9	6.3	4.7-6.7

Table 3. Asphalt content, G_{mm}, and aggregate gradation for the IM-19.0A mixes

	IM1		IM2		IM3		IM4	
	Avg.	**JMF**	**Avg.**	**JMF**	**Avg.**	**JMF**	**Avg.**	**JMF**
Asphalt content (%)	5.26	4.6 ± 0.3	4.52	4.6 ± 0.3	4.89	4.9 ± 0.3	5.43	5.5 ± 0.3
G_{mm}	2.477	2.504	2.513	2.500	2.523	2.524	2.486	2.502
Gradation								
Sieve opening, mm (No.)	**% Passing**	**Accept. Range**	**% Passing**	**Accept. Range**	**% Passing**	**Accept. Range**	**% Passing**	**Accept. Range**
25 (1)	100.0	100	100.0	100	100.0	100	100.0	100
19 (3/4)	100.0	92-100	97.6	92-100	96.4	92-100	98.8	92-100
12.5 (1/2)	95.8	84-92	84.6	80-88	79.8	76-84	85.3	82-90
9.5 (3/8)	87.5	-	73.3	-	69.5	-	75.4	-
4.75 (#4)	53.0	-	41.5	-	45.6	-	58.5	-
2.36 (#8)	37.7	29-37	29.8	29-37	30.4	28-36	40.0	26-34
1.18 (#16)	29.4	-	24.2	-	21.1	-	30.3	-
0.6 (#30)	21.8	-	18.1	-	15.4	-	23.4	-
0.3 (#50)	14.5	-	11.5	-	10.4	-	14.4	-
0.15 (#100)	9.9	-	6.6	-	7.2	-	8.0	-
0.075 (#200)	6.6	4-6	3.8	3.4-5.4	5.5	4-6	5.9	4-6

Table 4. Asphalt content, G_{mm}, and aggregate gradation for BM-25.0 mixes

	BM1		BM2		BM3		BM4	
	Avg.	**JMF**	**Avg.**	**JMF**	**Avg.**	**JMF**	**Avg.**	**JMF**
Asphalt content (%)	4.62	4.4 ± 0.3	4.86	4.9 ± 0.3	3.91	4.4 ± 0.3	4.51	4.4 ± 0.3
G_{mm}	2.691	2.668	2.509	2.515	2.640	2.605	2.516	2.525
Gradation								
Sieve opening, mm (No.)	**% Passing**	**Accept. Range**	**% Passing**	**Accept. Range**	**% Passing**	**Accept. Range**	**% Passing**	**Accept. Range**
37.5 (1.5)	100.0	100	100.0	100	100.0	100	100.0	100
25 (1)	99.2	92-100	84.1	90-98	97.3	90-98	100.0	92-100
19 (3/4)	94.4	82-90	73.8	73-81	87.6	82-90	95.5	81-89
12.5 (1/2)	75.9	-	69.6	-	73.3	-	82.5	-
9.5 (3/8)	66.0	-	66.6	-	64.8	-	70.6	-
4.75 (#4)	46.3	-	42.9	-	48.0	-	41.1	-
2.36 (#8)	31.3	26-34	26.5	25-33	24.2	25-33	30.3	33-41
1.18 (#16)	23.0	-	17.0	-	17.1	-	24.7	-
0.6 (#30)	16.6	-	11.4	-	13.1	-	18.2	-
0.3 (#50)	10.6	-	8.2	-	8.9	-	11.0	-
0.15 (#100)	7.4	-	6.5	-	7.1	-	6.2	-
0.075 (#200)	5.4	3-5	5.5	3.6-5.6	6.1	4-6	3.9	3.2-5.2

Once the G_{mm}, asphalt content, and aggregate gradation of the mixes were determined, the Superpave gyratory compactor was used to prepare the specimens for testing. A target voids in total mix (VTM) of 7% ± 1% was intended for all the specimens (after coring and/or cutting), which is approximately the air void content of newly constructed pavements in Virginia. Several trial specimens per mix were prepared before achieving the correct mix weight. The prepared gyratory specimen was 6 inches in diameter by 7 inches in height, thus, the number of gyrations was left variable to achieve the specified height of 7 inches. The prepared gyratory specimen was cut to 6 inches in thickness and cored to 4 inches in diameter to get the specimen for dynamic modulus testing.

For the resilient modulus and creep specimens, the ends (top and bottom 0.5 inch) of the gyratory specimen were removed, and then the top and bottom 1.5 inches were cut to obtain two specimens. The final dimensions of the specimens were 6 inches in diameter and 1.5 inches in thickness. Figure 1 shows a typical specimen for dynamic modulus and for the resilient modulus or creep tests. The bulk specific gravity (G_{mb}) of all produced specimens was measured using the AASHTO T166 procedure. Table 5 presents the measured G_{mb} and calculated VTM for all specimens prepared for the dynamic modulus, resilient modulus, and creep tests. The table shows that most prepared specimens met the VTM requirements of 7% ± 1% except for the dynamic modulus specimens for BM4. For this mix, decreasing the weight of mix placed in the gyratory to produce higher voids resulted in samples that broke after extraction from the gyratory machine. The first sample that held together provided a dynamic modulus specimen with a VTM of 5.1% as shown in Table 5. In addition, a few specimens had a VTM slightly above 8.0%.

Figure 1. Typical specimens for (a) dynamic modulus and (b) resilient modulus and creep test

Table 5. G_{mb} and VTM for all prepared specimens

SM				IM				BM			
Dynamic Modulus Specimens											
	Label	G_{mb}	VTM		Label	G_{mb}	VTM		Label	G_{mb}	VTM
SM1	SM1-1	2.458	6.5	IM1	IM1-2	2.305	6.9	BM1	BM1-2	2.493	7.4
	SM1-2	2.453	6.7		IM1-3	2.304	6.9		BM1-3	2.518	6.4
	SM1-3	2.464	6.3		IM1-4	2.309	6.8		BM1-4	2.505	6.9
	Avg.	2.458	6.5		Avg.	2.306	6.9		Avg.	2.505	6.9
SM2	SM2-1	2.475	6.5	IM2	IM2-3	2.353	6.4	BM2	BM2-1	2.354	6.2
	SM2-2	2.479	6.4		IM2-4	2.352	6.4		BM2-2	2.349	6.4
	SM2-3	2.477	6.5		IM2-5	2.347	6.6		BM2-3	2.353	6.2
	Avg.	2.477	6.5		Avg.	2.351	6.5		Avg.	2.352	6.3
SM3	SM3-3	2.400	7.5	IM3	IM3-2	2.350	6.9	BM3	BM3-2	2.462	6.8
	SM3-4	2.406	7.3		IM3-3	2.336	7.4		BM3-3	2.464	6.6
	SM3-5	2.399	7.6		IM3-4	2.365	6.3		BM3-4	2.457	6.9
	Avg.	2.402	7.5		Avg.	2.350	6.9		Avg.	2.461	6.8
				IM4	IM4-2	2.306	7.2	BM4	BM4-2	2.388	5.1
					IM4-3	2.305	7.3		BM4-3	2.373	5.7
					IM4-4	2.308	7.2		BM4-4	2.366	6.0
					Avg.	2.306	7.2		Avg.	2.376	5.6
Resilient Modulus Specimens											
	Label	G_{mb}	VTM		Label	G_{mb}	VTM		Label	G_{mb}	VTM
SM1	SM1-6B	2.459	6.5	IM1	IM1-5A	2.288	7.6	BM1	BM1-5B	2.473	8.1
	SM1-7A	2.453	6.7		IM1-5B	2.286	7.7		BM1-6B	2.487	7.6
	SM1-8B	2.458	6.5		IM1-6B	2.286	7.7		BM1-7B	2.474	8.0
	Avg.	2.457	6.6		Avg.	2.287	7.7		Avg.	2.478	7.9
SM2	SM2-4A	2.486	6.1	IM2	IM2-7A	2.326	7.5	BM2	BM2-4A	2.315	7.7
	SM2-5A	2.470	6.7		IM2-7B	2.329	7.3		BM2-6A	2.319	7.6
	SM2-6B	2.470	6.7		IM2-8A	2.326	7.4		BM2-6B	2.314	7.7
	Avg.	2.475	6.5		Avg.	2.327	7.4		Avg.	2.316	7.7
SM3	SM3-6B	2.404	7.4	IM3	IM3-5A	2.368	6.2	BM3	BM3-5B	2.463	7.0
	SM3-7B	2.395	7.8		IM3-6A	2.333	7.6		BM3-6A	2.453	7.1
	SM3-8A	2.395	7.8		IM3-7B	2.351	6.9		BM3-7B	2.453	7.1
	Avg.	2.398	7.7		Avg.	2.351	6.9		Avg.	2.456	7.1
				IM4	IM4-5B	2.298	7.6	BM4	BM4-5B	2.356	6.4
					IM4-6B	2.292	7.8		BM4-6B	2.335	6.2
					IM4-7B	2.297	7.6		BM4-7A	2.352	6.5
					Avg.	2.296	7.7		Avg.	2.348	6.4
Creep Specimens											
	Label	G_{mb}	VTM		Label	G_{mb}	VTM		Label	G_{mb}	VTM
SM1	SM1-6A	2.436	7.4	IM1	IM1-6A	2.284	7.8	BM1	BM1-5A	2.469	8.3
	SM1-7B	2.458	6.5		IM1-7A	2.271	8.3		BM1-6A	2.467	8.3
	SM1-8A	2.451	6.8		IM1-7B	2.277	8.1		BM1-7A	2.470	8.2
	Avg.	2.448	6.9		Avg.	2.277	8.1		Avg.	2.469	8.3
SM2	SM2-4B	2.459	7.1	IM2	IM2-6A	2.317	7.8	BM2	BM2-4B	2.288	8.8
	SM2-5B	2.489	6.0		IM2-6B	2.320	7.7		BM2-5A	2.307	8.0
	SM2-6A	2.466	6.9		IM2-8B	2.324	7.5		BM2-5B	2.309	8.0
	Avg.	2.471	6.7		Avg.	2.320	7.7		Avg.	2.301	8.3
SM3	SM3-6A	2.392	7.9	IM3	IM3-5B	2.376	5.9	BM3	BM3-5A	2.435	7.8
	SM3-7A	2.385	8.1		IM3-6B	2.363	6.4		BM3-6B	2.472	6.4
	SM3-8B	2.394	7.8		IM3-7A	2.343	7.2		BM3-7A	2.484	5.9
	Avg.	2.390	7.9		Avg.	2.361	6.5		Avg.	2.464	6.7
				IM4	IM4-5A	2.287	8.0	BM4	BM4-5A	2.347	6.7
					IM4-6A	2.282	8.2		BM4-6A	2.335	7.2
					IM4-7A	2.296	7.6		BM4-7B	2.346	6.7
					Avg.	2.288	7.9		Avg.	2.343	6.9

RESULTS AND DISCUSSION

Dynamic Modulus Test

Table 6 presents all the measured dynamic modulus and phase angle data for all SM1 specimens. Results for all the mixes are presented in Tables C1 to C11 in Appendix C. The tables also present the calculated coefficient of variation (COV) (defined as 100 times the standard deviation divided by the mean) for each testing temperature and frequency. For the dynamic modulus, the minimum and maximum calculated COV were 0.9% and 32.3%, respectively. For the phase angle, the minimum and maximum calculated COV were 0.2% and 30.5%, respectively. In general, the highest COV were obtained at the low temperatures and high frequencies, were the deformation measured are smallest.

Table 6. Measured dynamic modulus, E* (psi) and phase angle, δ (°) for the mix SM1

Temp. (°F)	Freq. (Hz)	SM1-1		SM1-2		SM1-3		Average		COV	
		E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	3,835,448	2.2	4,688,959	2.9	4,476,852	2.2	4,333,753	2.4	10.3	14.9
	10	3,751,927	3.3	4,106,812	3.5	4,312,782	3.1	4,057,174	3.3	7.0	5.7
	5	3,623,147	3.6	4,105,549	4.1	4,151,776	4.5	3,960,157	4.1	7.4	6.3
	1	3,292,053	3.8	3,692,480	5.4	3,795,503	6.7	3,593,345	5.3	7.4	14.7
	0.5	3,155,697	6.6	3,396,530	5.8	3,642,242	6.8	3,398,156	6.4	7.2	8.2
	0.1	2,751,969	7.8	3,349,788	6.1	3,220,936	7.5	3,107,564	7.1	10.1	10.5
40	25	2,386,559	9.4	2,280,613	8.2	3,018,213	8.6	2,561,795	8.8	15.6	3.0
	10	2,196,173	10.4	2,041,250	10.9	2,697,734	10.7	2,311,719	10.7	14.8	1.0
	5	2,038,852	11.2	1,866,631	11.4	2,509,424	9.5	2,138,302	10.7	15.6	9.3
	1	1,662,643	13.0	1,483,098	13.2	2,035,394	12.3	1,727,045	12.8	16.3	3.3
	0.5	1,489,189	15.5	1,313,927	16.0	1,815,690	15.6	1,539,602	15.7	16.5	1.4
	0.1	1,118,509	19.6	968,358	20.5	1,384,811	19.4	1,157,226	19.8	18.2	2.9
70	25	1,515,985	17.9	1,151,945	18.8	1,419,005	18.2	1,362,312	18.3	13.8	1.9
	10	1,242,674	20.1	959,039	20.1	1,167,187	20.2	1,122,966	20.1	13.1	0.2
	5	1,051,940	21.9	820,200	21.9	1,001,880	22.2	958,007	22.0	12.7	0.8
	1	683,430	26.4	540,774	26.2	669,826	26.8	631,343	26.5	12.5	1.2
	0.5	536,882	30.9	423,167	30.7	535,707	31.9	498,585	31.1	13.1	1.9
	0.1	322,957	34.2	260,197	34.6	334,983	36.5	306,046	35.1	13.1	2.8
100	25	497,636	31.2	376,334	32.2	490,104	31.9	454,691	31.8	14.9	0.7
	10	375,782	31.9	293,682	32.4	387,783	33.3	352,416	32.5	14.5	1.4
	5	292,950	33.2	230,763	33.3	307,610	34.3	277,108	33.6	14.7	1.4
	1	160,690	33.6	128,241	33.4	172,165	34.9	153,699	34.0	14.8	2.1
	0.5	119,358	34.9	96,715	34.6	128,156	36.7	114,743	35.4	14.1	3.0
	0.1	74,609	30.3	64,260	29.4	79,842	32.5	72,904	30.7	10.9	5.1
130	25	136,638	29.0	112,191	31.9	148,153	33.6	132,327	31.5	13.9	3.4
	10	98,011	27.0	83,799	28.8	103,967	30.8	95,259	28.8	10.9	4.0
	5	79,268	24.6	67,989	26.1	82,016	28.0	76,424	26.2	9.7	4.0
	1	54,640	18.7	47,650	19.9	53,286	21.6	51,859	20.0	7.1	4.7
	0.5	48,882	17.5	43,211	18.4	46,852	19.7	46,315	18.5	6.2	3.9
	0.1	42,635	14.3	38,933	14.7	39,923	15.4	40,497	14.8	4.7	2.7

Figure 2 shows the average measured dynamic modulus for mix SM1 as a function of frequency for each testing temperature. As expected, under a constant loading frequency, the magnitude of the dynamic modulus decreases with an increase in temperature; under a constant testing temperature, the magnitude of the dynamic modulus increases with an increase in the frequency. Figure 3 shows the measured phase angle results for the same mix.

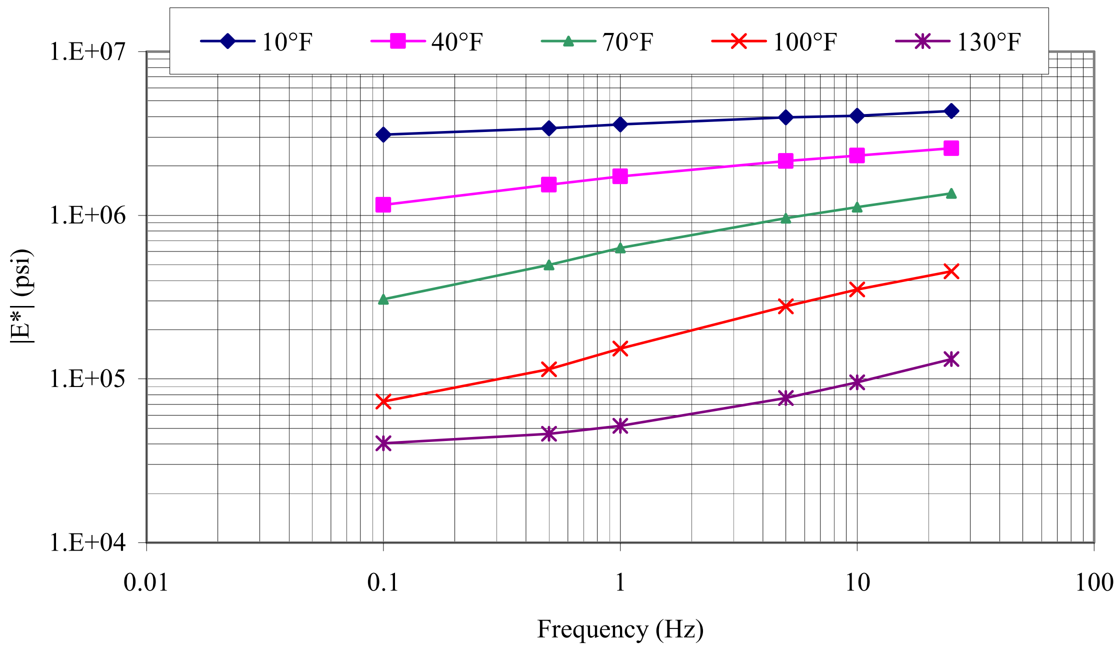

Figure 2. Dynamic modulus results for mix SM1

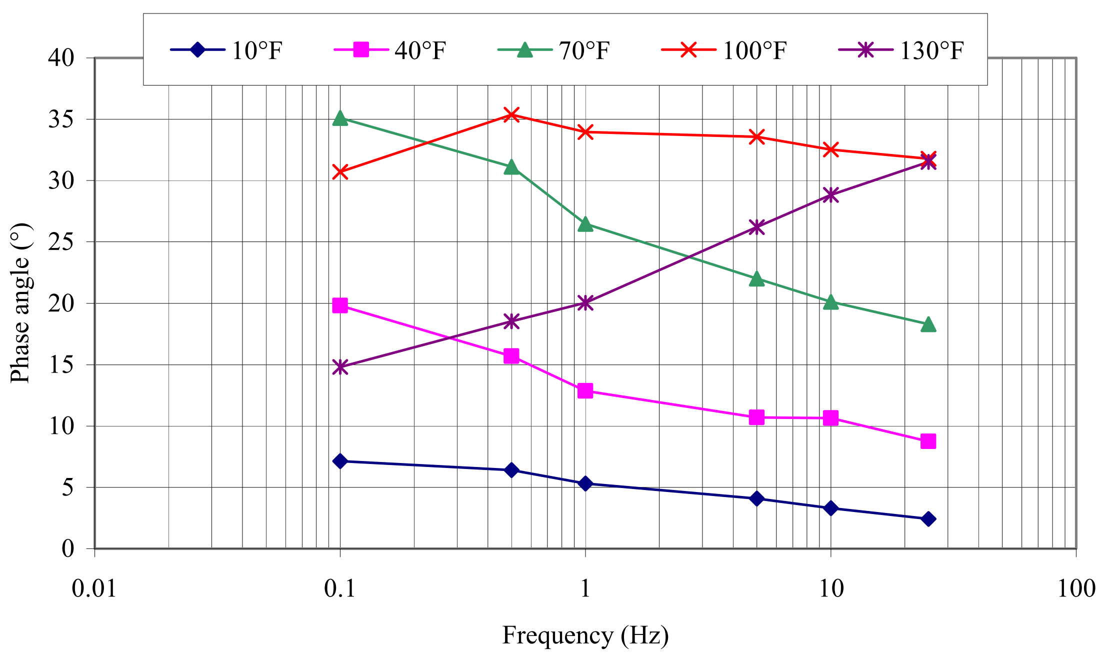

Figure 3. Phase angle results for mix SM1

Figure 3 shows that the phase angle decreases as the frequency increases at temperatures of 10°F, 40°F, and 70°F. However, at 100°F and 130°F, the behavior of the phase angle as a function of frequency is more complex. At 100°F, the phase angle seems to increase up to frequencies of 0.5 Hz, and then it starts to decrease as frequency increases. At 130°F, the phase angle increases with an increase in frequency. The complex behavior of the phase angle at higher temperatures or at lower frequencies could be attributed to the predominant effect of the aggregate interlock. This is in agreement with the findings of other researchers and previous testing in Virginia that reported that the elastic behavior of the aggregate dictates the response of the specimen at high temperatures and low frequencies (Flintsch et al., 2006; Clyne et al., 2003). Similar behavior was found for all other tested mixes.

A master curve of the dynamic modulus at the reference temperature of 70°F was constructed for all 11 mixes to complete their characterization. As an example, Figure 4 shows the developed master curve for mix SM1. The method developed by Pellinen and Witczak (Pellinen et al., 2002) was used in this study to construct the master curve. The method consists of fitting a sigmoidal curve to the measured dynamic modulus test data using nonlinear least-square regression techniques. The shift factors at each temperature are determined simultaneously with the other coefficients of the sigmoidal function. The function is given by Equation 1:

$$\log\left|E^*\right| = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log f_r}} \qquad (1)$$

where

δ, α, β, and γ = sigmoidal function coefficients (fit parameters), and

f_r = reduced frequency, which is given by the following equation:

$$\log f_r = \log f + \log a_T \qquad (2)$$

where

a_T = shift factor at temperature T.

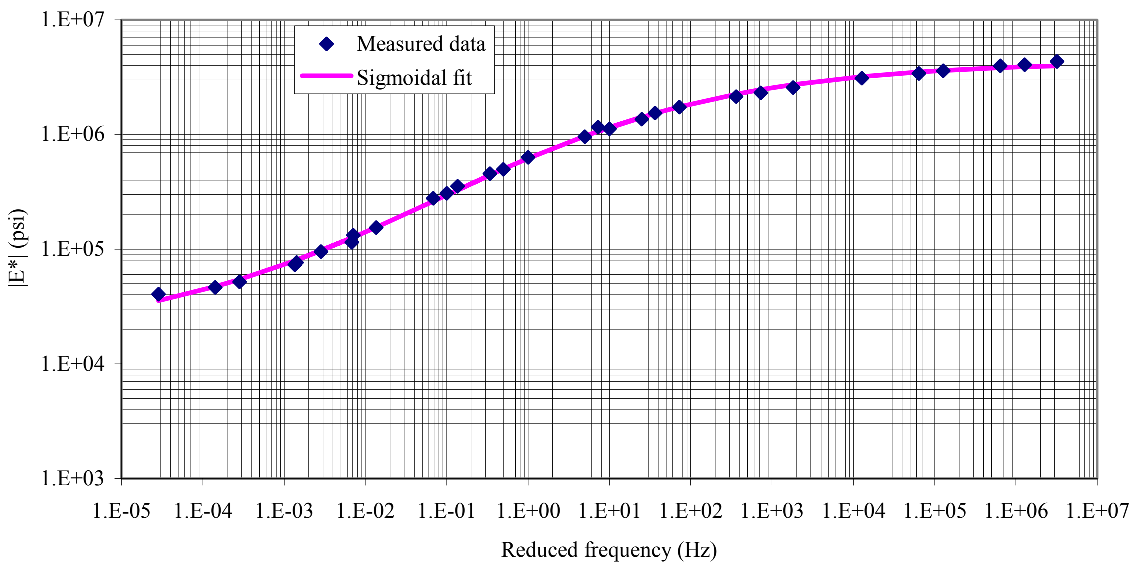

Figure 4. Measured data and sigmoidal fit for the dynamic modulus of mix SM1

The statistical software package SAS was used for the nonlinear regression analysis. Table 7 shows all the obtained sigmoidal function parameters and shift factors for all the mixes investigated. The parameters shown in Table 7 were used to construct and plot the master curves for all mixes in the frequency range of 10^{-5} Hz to 10^{5} Hz. Figure 5 shows the developed master curves for all SM-9.5A mixes. From this plot, it is clear that mix SM3 exhibits the lowest dynamic modulus values at all frequencies. This can probably be explained by this mix having the highest asphalt content (6.3% as compared to 4.9% for mix SM1 and 5.9% for mix SM2) and on average 1% more voids than the other two mixes (see Table 5).

Table 7. Parameters of the measured dynamic modulus master curve for all mixes

Mix	δ	α	β	γ	$\log(a_{10})$	$\log(a_{40})$	$\log(a_{70})$	$\log(a_{100})$	$\log(a_{130})$
SM1	4.23182	2.40375	-0.61155	0.5469	5.10729	1.86113	0	-1.86687	-3.5458
SM2	4.24358	2.34206	-0.52756	0.58509	4.60873	2.11614	0	-1.82198	-3.55407
SM3	3.96225	2.6038	-0.34476	0.5124	4.602	2.01282	0	-1.895	-3.47021
IM1	3.97617	2.59338	-0.89432	0.52568	4.55627	2.16329	0	-1.77346	-3.38386
IM2	4.1861	2.29254	-0.72547	0.57337	3.9556	2.03623	0	-1.77381	-3.36705
IM3	4.24285	2.41566	-0.7367	0.54358	4.99791	2.30204	0	-1.90961	-3.55711
IM4	4.25741	2.28306	-0.59524	0.63026	4.19403	2.34806	0	-1.899	-3.49271
BM1	4.10766	2.54327	-0.73887	0.49758	5.44215	2.03195	0	-1.93304	-3.51238
BM2	4.4979	2.2097	0.0689	0.55623	5.15319	2.20943	0	-1.85075	-3.44955
BM3	4.32085	2.33782	-1.14008	0.58795	4.9248	1.83275	0	-1.99614	-3.72051
BM4	4.07489	2.57073	-0.6343	0.51438	4.70522	2.18674	0	-1.85243	-3.43843

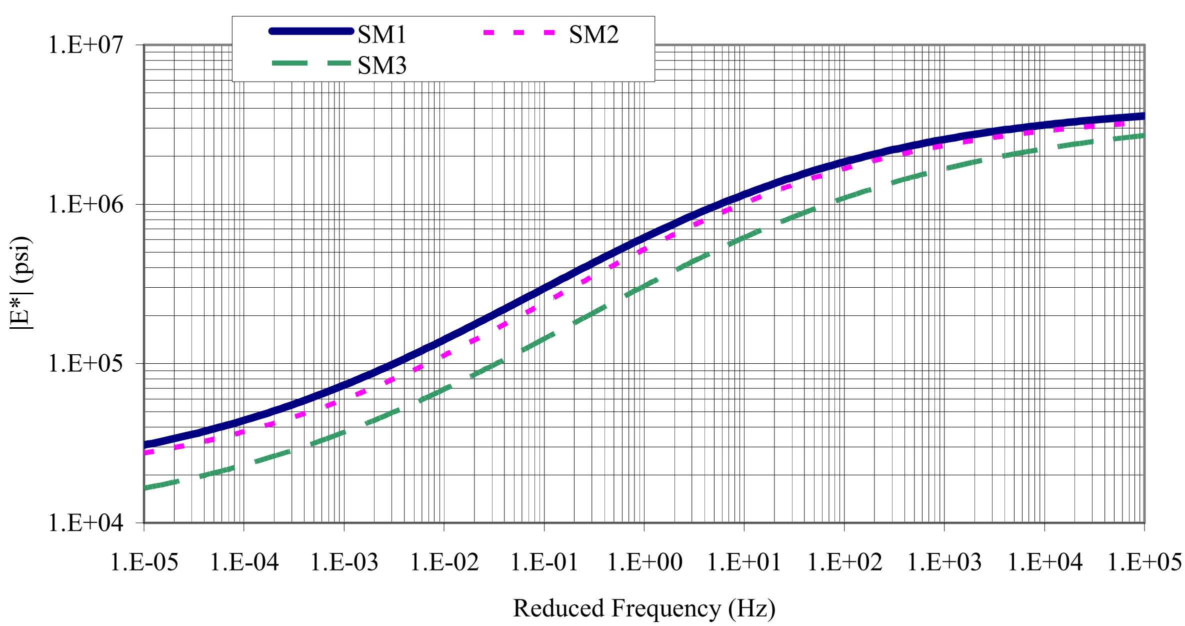

Figure 5. Dynamic modulus master curves for all SM-9.5A mixes

Figure 6 shows the developed master curves for all IM-19.0A mixes. This figure shows that all the investigated IM mixes have similar dynamic modulus values at all frequencies, with mix IM3 having slightly higher values than the others.

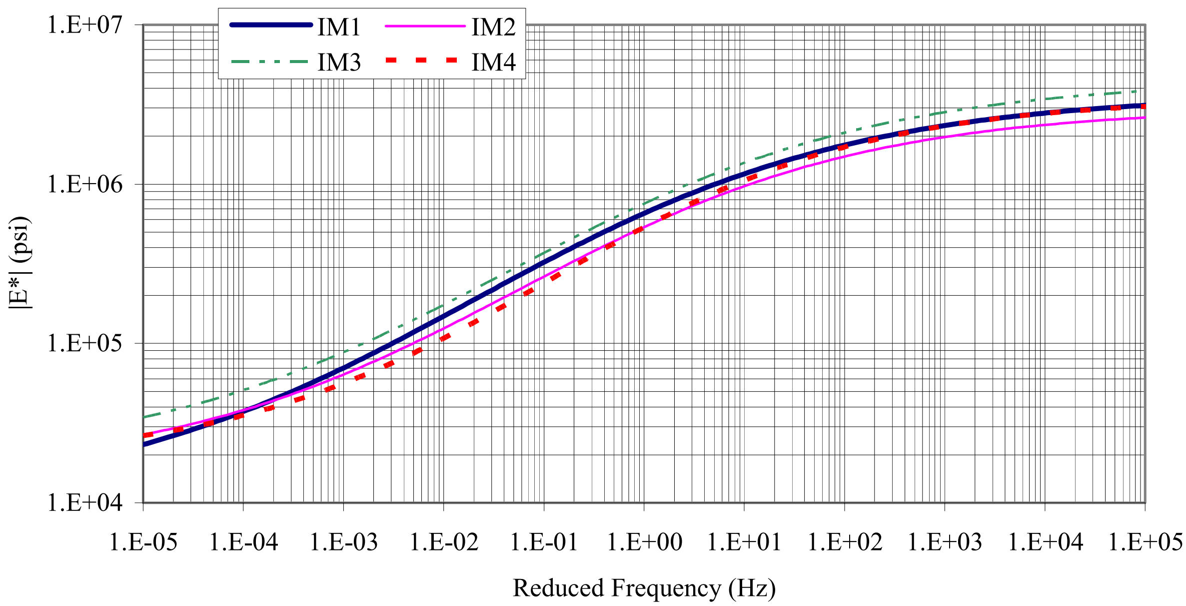

Figure 6. Dynamic modulus master curves for all IM-19.0A mixes

For the BM-25.0 mixes (Figure 7), mix BM3 exhibits the highest dynamic modulus values at all frequencies while mix BM2 has the lowest dynamic modulus values at all frequencies. Mix BM3 has the lowest asphalt content (3.9%) while mix BM2 has the highest asphalt content (4.9%).

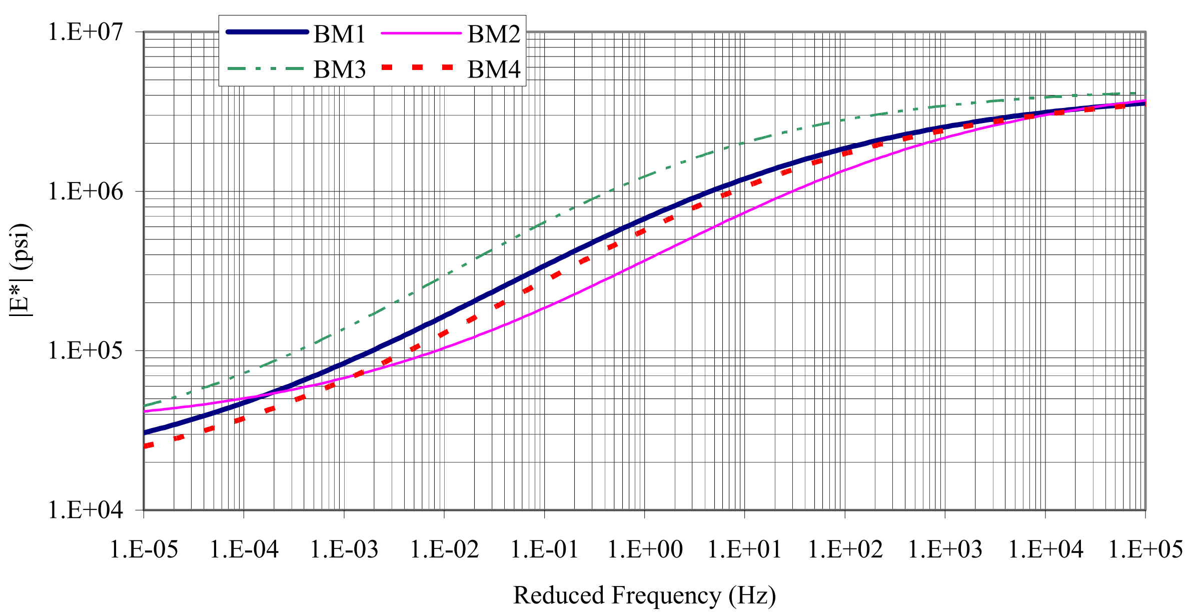

Figure 7. Dynamic modulus master curves for all BM-25.0 mixes

In addition, even though the JMF for mix BM2 reported the use the same binder than in the other BM mixes, the handling of the mix gave the impression that a different binder was used during production. The appearance of BM2 straight out of the box showed that the binder had concentrated in the bottom and had created what appeared to be splash marks on the box from where the material had been sampled. The mix was hard to compact, and after compaction the specimen remained spongy for a couple of hours with some small particles actually falling from the specimen. This abnormal behavior could also have been due to the absence of RAP in this mix.

Figure 8(a) compares the dynamic modulus master curves for all the mixes. Even though it is hard to distinguish between the lines, the graph shows that the BM3 mix has the highest dynamic modulus values at all frequencies while mix SM3 has the lowest dynamic modulus values at all frequencies. This indicates that the dynamic modulus test is sensitive to variation in the mix properties. However, if the mixes that did not meet the job-mix formula requirements are excluded from the plot, as shown in Figure 8(b), the master curves are much closer to each other. Furthermore, the average master curves for all the mixes that met the job-mix formula almost overlap as shown in Figure 8(c).

Once the dynamic modulus master curve was established for all mixes based on the measured values, the Witczak prediction equation (Equation 3) was used to generate the dynamic modulus master curves for the mixes. Witczak prediction equation is as follows:

$$\log E^* = 3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^2 - 0.058097V_a - 0.802208\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.005470\rho_{34}}{1+e^{-0.603313-0.313351\log(f)-0.393532\log(\eta)}} \quad (3)$$

where
E^* = dynamic modulus, psi,
ρ_{200} = percentage passing the #200 sieve,
ρ_4 = cumulative percentage retained on the #4 sieve,
ρ_{34} = cumulative percentage retained on the #3/4 sieve,
ρ_{38} = cumulative percentage retained on the #3/8 sieve,
f = frequency in Hz,
V_{beff} = effective bitumen content, percentage by volume,
V_a = air void content, and
η = bitumen viscosity, 10^6 Poise.

The bitumen viscosity varies with temperature according to Equation 4:

$$\log(\log(\eta)) = A + VTS\log(T_R) \quad (4)$$

where
η = binder viscosity expressed in cP,
T_R = temperature in degree Rankine, and
A and VTS = regression parameters.

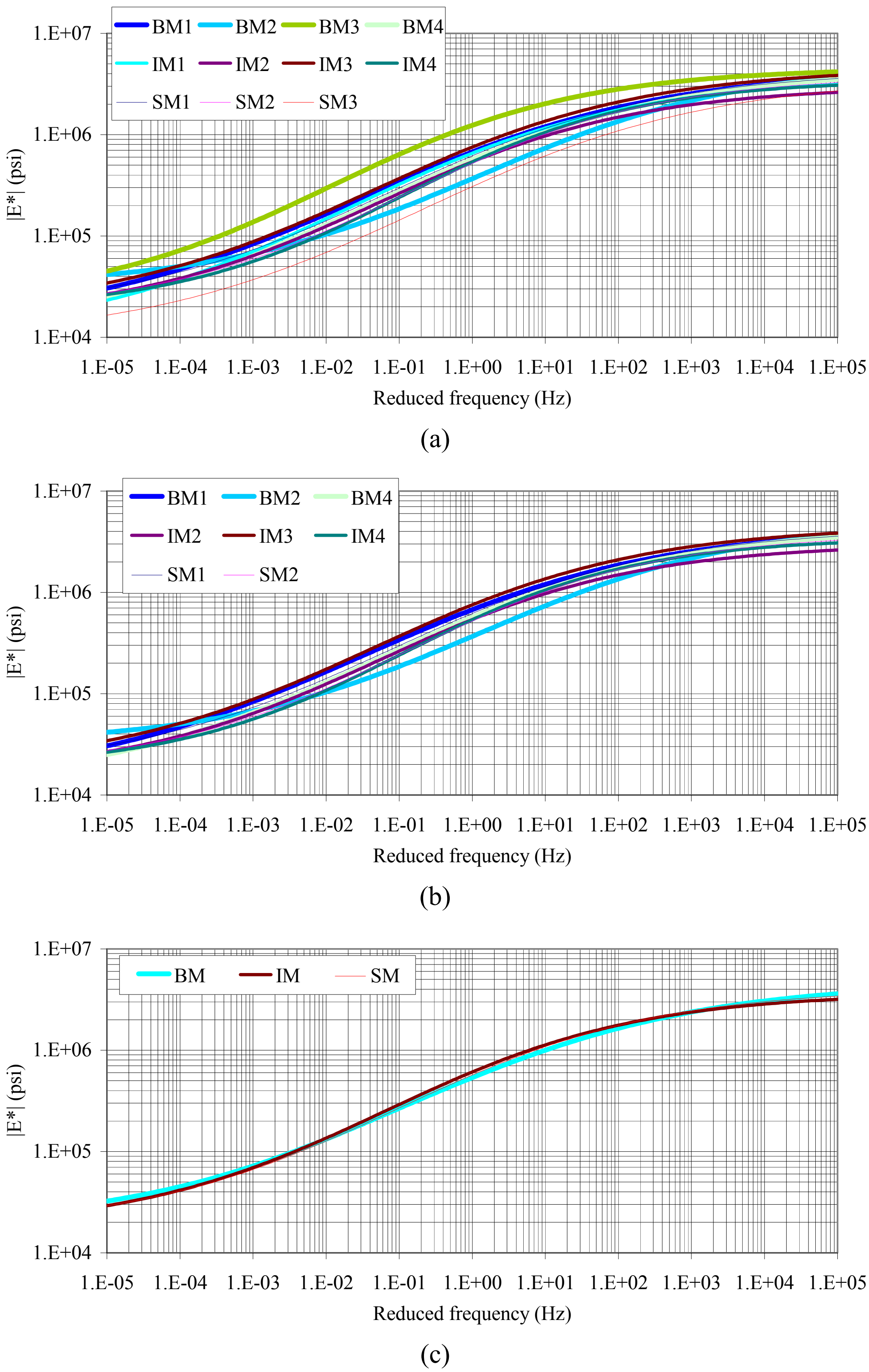

Figure 8. Dynamic modulus master curves for (a) All mixes; (b) Excluding those that did not meet binder content specifications; and (c) Averages for those mixes meeting specifications

For this investigation, the default values suggested by the proposed MEPDG for a PG64-22 binder were used for all mixes. These default values are 10.98 for A and −3.68 for VTS. The sigmoidal function parameters and the shift factors were then determined for all the mixes and are presented in Table 8. The shift factors and the β and γ parameters are the same for all the mixes because the same values for A and VTS were used for all the mixes. This is a limitation since the master curve equation is sensitive to these parameters. It is recommended that these values be determined for each mix in future work rather than using the default values.

Table 8. Parameters of the predicted dynamic modulus master curve for all mixes

Mix	δ	α	β	γ	$\log(a_{10})$	$\log(a_{40})$	$\log(a_{70})$	$\log(a_{100})$	$\log(a_{130})$
SM1	2.83869	3.81814	-0.99969	0.31361	4.29643	2.70454	0	-2.07415	-3.68771
SM2	2.83284	3.79412	-0.99969	0.31361	4.29643	2.70454	0	-2.07415	-3.68771
SM3	2.77352	3.80975	-0.99969	0.31361	4.29643	2.70454	0	-2.07415	-3.68771
IM1	2.8342	3.8179	-0.99969	0.31361	4.29643	2.70454	0	-2.07415	-3.68771
IM2	2.81245	3.8536	-0.99969	0.31361	4.29643	2.70454	0	-2.07415	-3.68771
IM3	2.81465	3.8801	-0.99969	0.31361	4.29643	2.70454	0	-2.07415	-3.68771
IM4	2.82705	3.87624	-0.99969	0.31361	4.29643	2.70454	0	-2.07415	-3.68771
BM1	2.80894	3.90252	-0.99969	0.31361	4.29643	2.70454	0	-2.07415	-3.68771
BM2	2.88335	4.00631	-0.99969	0.31361	4.29643	2.70454	0	-2.07415	-3.68771
BM3	2.87954	3.9466	-0.99969	0.31361	4.29643	2.70454	0	-2.07415	-3.68771
BM4	2.83202	3.87235	-0.99969	0.31361	4.29643	2.70454	0	-2.07415	-3.68771

Figure 9 compares the measured and predicted master curves for mix SM1. For this particular mix, the Witczak prediction equation underestimates the dynamic modulus at all frequencies; as shown by Figure 10, the ratio of the predicted to measured dynamic modulus varies between 0.5 and 0.9. This ratio varies from mix to mix. Table 9 presents the minimum and maximum values for this ratio for each mix. Since the predicted and measure values are close, level 2 input may be used with a reasonable degree of reliability.

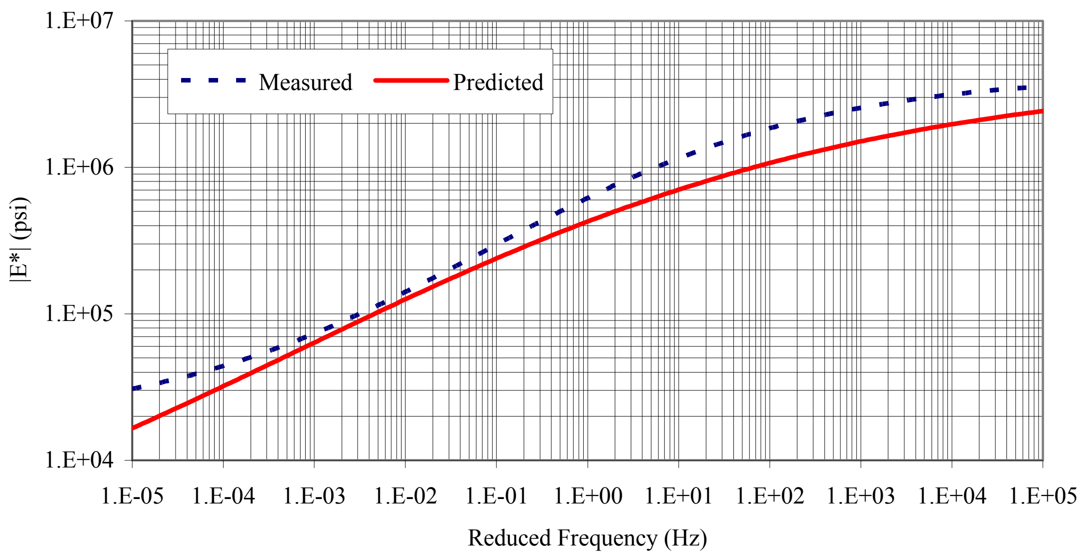

Figure 9. Measured and predicted dynamic modulus master curves for mix SM1

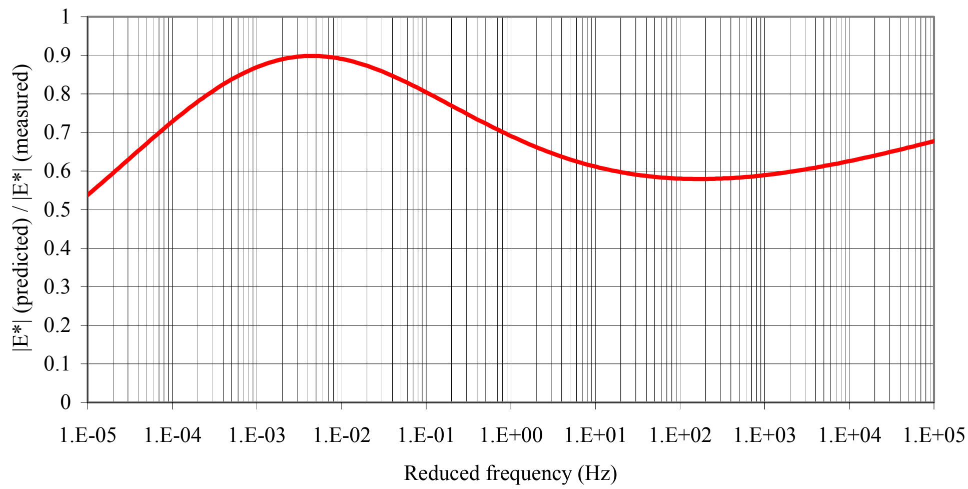

Figure 10. Ratio of predicted to measured dynamic modulus for mix SM1

Table 9. Minimum and maximum values for the ratio of the predicted to measured dynamic modulus

Ratio	SM1	SM2	SM3	IM1	IM2	IM3	IM4	BM1	BM2	BM3	BM4
Min.	0.54	0.58	0.75	0.60	0.60	0.48	0.64	0.54	0.52	0.45	0.68
Max.	0.90	1.07	1.56	0.90	1.01	0.75	1.24	0.80	1.90	0.84	1.05

Figure 11 shows the predicted dynamic modulus master curves for the three SM-9.5A mixes. The differences in the predicted dynamic modulus values between the three mixes (SM1, SM2, and SM3) are not as significant as the measured differences (see Figure 5). The same trend was found for the IM-19.0A and BM-25.0 mixes as shown in Figure 12 and Figure 13.

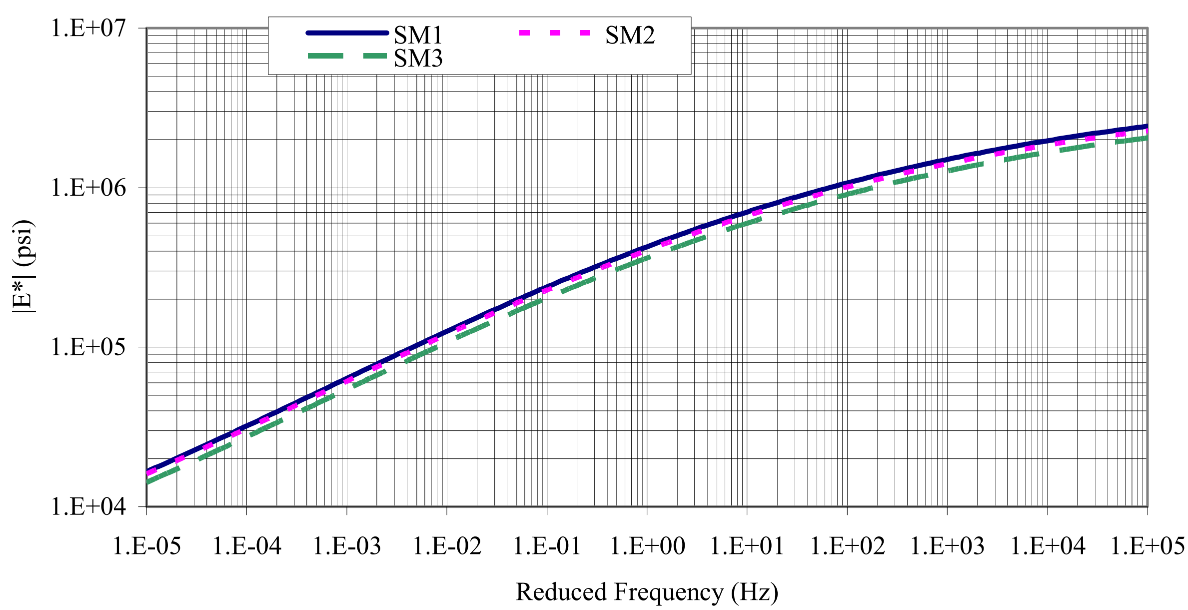

Figure 11. Predicted dynamic modulus master curves for SM-9.5A mixes

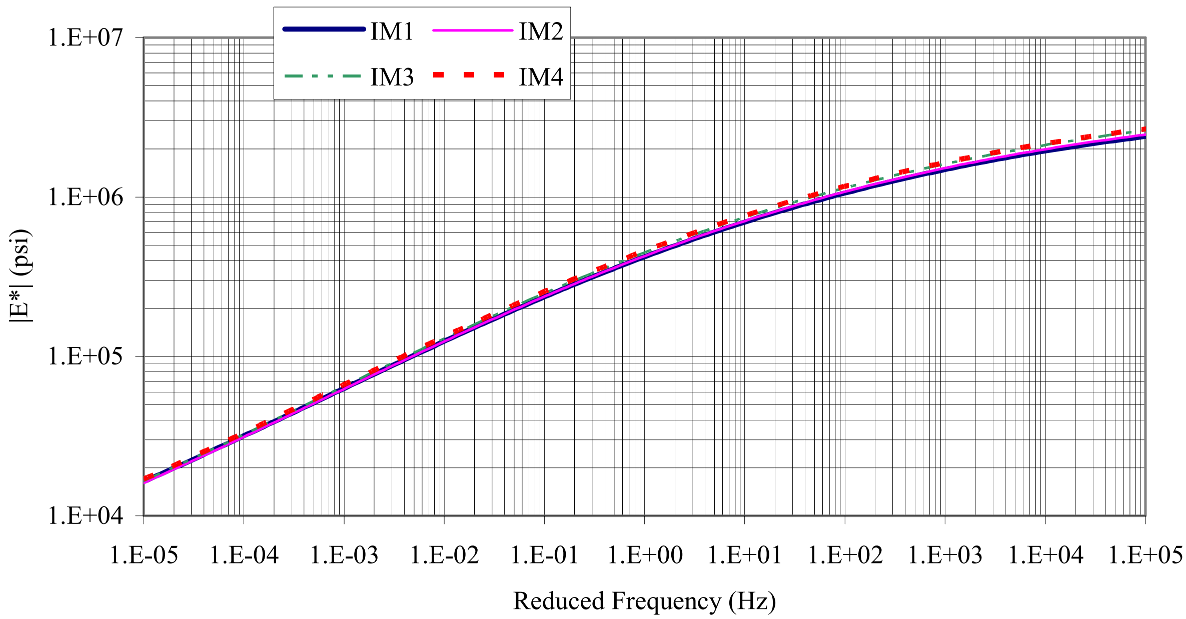

Figure 12. Predicted dynamic modulus master curves for IM-19.0D mixes

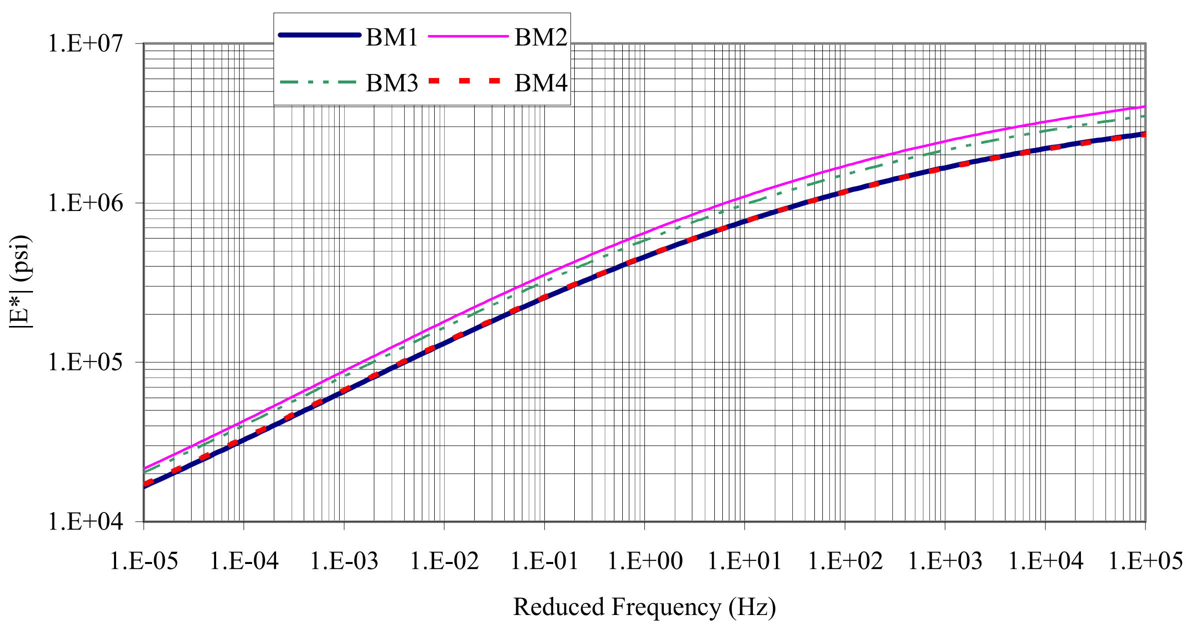

Figure 13. Predicted dynamic modulus master curves for BM-25.0 mixes

The predicted master curves show some differences between the various mixes. However, these are not as marked as in the case of the measured master curves test. This may be due to the use of default binder properties (A and VTS) as previously discussed.

Creep Test

The creep test results were used only in the low-temperature cracking model. In this project a master curve at a reference temperature of 32°F was determined for each tested specimen, and a power model was fit to the data to determine the slope parameter, m, which is required to compute several fracture (crack propagation) parameters in the fracture model of the MEPDG. The power model is defined by the following equation:

$$D(t_r) = D_0 + D_1 t_r^m \tag{4}$$

where
$D(t_r)$ = the creep compliance at the reduced time t_r and
D_0, D_1, and m = the power model parameters.

Figure 14 shows the developed master curve and its power model fit for specimen BM1-5A. It is important to note that several difficulties were encountered during the creep test. The data were not repeatable between specimens of the same mix, as can be seen in the obtained m values shown in Table 10. These problems are suspected to be due to the effect of the very low test temperature on the type of extensometers used. It is notable that five extensometers were damaged during the low-temperature creep tests. More problems were also encountered with mix BM2 as only one specimen could be tested. The other two prepared specimens broke during the testing.

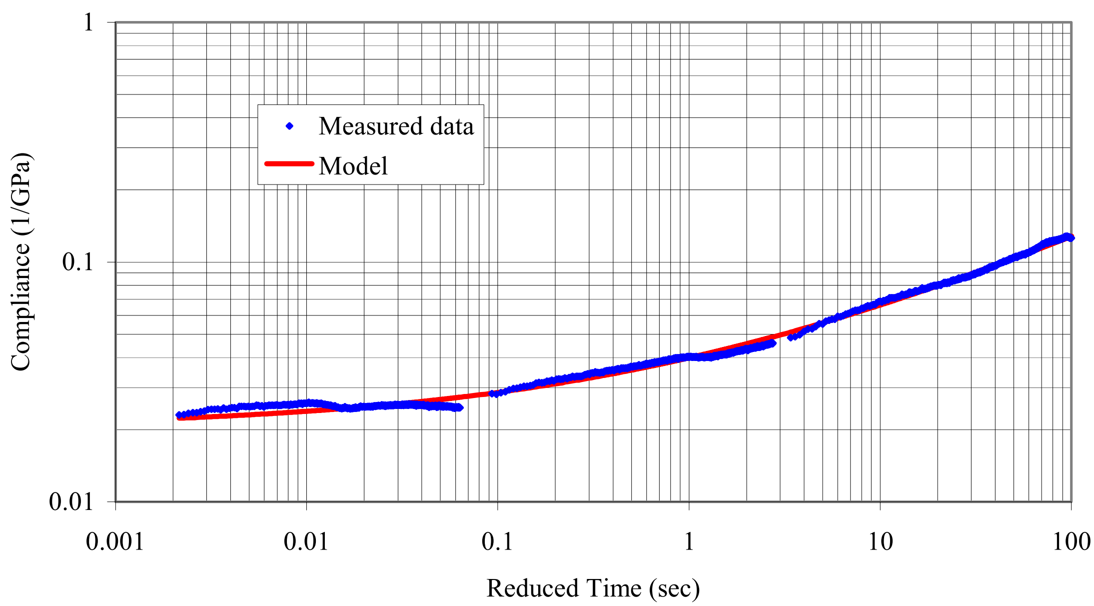

Figure 14. Creep compliance master curve and power model fit for specimen BM1-5A

Table 10. m-parameter for all tested specimens

Mix	Label	m-value	Mix	Label	m-value	Mix	Label	m-value
SM1	SM1-6A	0.45566	IM1	IM1-6A	0.37085	BM1	BM1-5A	0.37065
	SM1-7B	0.19337		IM1-7A	0.43889		BM1-7A	0.33526
	Avg.	0.324515		Avg.	0.40487		Avg.	0.352955
SM2	SM2-6A	0.36777	IM2	IM2-6A	0.34614	BM2	BM2-5B	0.46935
	SM2-4B	0.52053		IM2-6B	0.29375			
	Avg.	0.44415		Avg.	0.319945		Avg.	0.46935
SM3	SM3-7A	0.7344	IM3	IM3-6B	0.19798	BM3	BM3-5A	0.37385
	SM3-8B	0.40476		IM3-7A	0.34905		BM3-6B	0.18151
	Avg.	0.56958		Avg.	0.273515		Avg.	0.27768
			IM4	IM4-5A	0.35881	BM4	BM4-5A	0.21
				IM4-6A	0.30452		BM4-6A	0.20983
				Avg.	0.331665		Avg.	0.209915

Indirect Tensile Strength Test

The IDT strength at 14°F is also used in the low-temperature cracking model. The IDT tests for this investigation were conducted in the same specimens used for the creep test. Table 11 presents the results for all tested specimens.

Table 11. IDT strength results for all the mixes (ksi)

Mix	Label	Strength	Mix	Label	Strength	Mix	Label	Strength
SM1	SM1-6A	475	IM1	IM1-6A	420	BM1	BM1-5A	470
	SM1-7B	499		IM1-7B	404		BM1-7A	392
	Average	487		Average	412		Average	431
SM2	SM2-4B	477	IM2	IM2-6A	384	BM2	BM2-5B	354
	SM2-5B	579		IM2-8B	424			
	Average	528		Average	404		Average	354
SM3	SM3-6A	409	IM3	IM3-6B	472	BM3	BM3-5A	479
	SM3-7A	387		IM3-7A	463		BM2-6B	479
	Average	398		Average	467		Average	479
			IM4	IM4-6A	397	BM4	BM4-5A	415
				IM4-7A	491		BM4-7B	367
				Average	444		Average	393

Resilient Modulus Test

The resilient modulus tests were performed to investigate possible correlations with the dynamic modulus test. Table 12 presents all the measured resilient modulus values for all the mixes at the testing temperatures of 41°F, 77°F, and 104°F. Some of the specimens for the two weak mixes, SM3 and BM2, could not be tested because the specimens could not hold the applied load and broke before the final cycle of the test was achieved (as indicated by "N/A" in the table). It is recommended that the load applied be adjusted based on the results of the IDT strength test for future testing.

Table 12. Resilient modulus values for all mixes (ksi)

Mix	Label	Temperature (°F)			Mix	Label	Temperature (°F)			Mix	Label	Temperature (°F)		
		41	77	104			41	77	104			41	77	104
SM1	SM1-6B	1,125	401	142	IM1	IM1-5B	1,235	448	229	BM1	BM1-7B	1,523	592	318
	SM1-7A	1,107	424	154		IM1-5A	1,231	420	173		BM1-5B	1,502	451	232
	Average	1,116	412	148		Average	1,233	434	201		Average	1,513	522	275
SM2	SM2-5A	1,186	461	170	IM2	IM2-7B	995	345	163	BM2	BM2-6A	1,401	354	N/A
	SM2-4A	1,203	449	206		IM2-7A	944	327	126		BM2-4A	870	N/A	N/A
	Average	1,195	455	188		Average	969	336	145		Average	1,135	354	N/A
SM3	SM3-8A	914	329	N/A	IM3	IM3-5A	1,765	762	293	BM3	BM3-7B	1,843	654	272
	SM3-6B	851	255	87		IM3-6A	1,474	593	363		BM3-6A	1,693	656	290
	Average	883	292	87		Average	1,619	677	328		Average	1,768	655	281
					IM4	IM4-7B	1,270	531	143	BM4	BM4-7A	866	370	149
						IM4-6B	1,031	397	144		BM4-5B	960	365	154
						Average	1,151	464	144		Average	913	368	152

Figure 15, Figure 16, and Figure 17 show the variation of the resilient modulus values with temperature for the SM-9.5A mixes, IM-19.0A mixes, and BM-25.0 mixes, respectively. As expected, the resilient modulus decreases with an increase in temperature. Furthermore, the relative values for the various mixes follow a similar trend to that observed for the dynamic modulus tests. Mix SM3 has the lowest resilient modulus values at all temperatures for the SM-9.5A mixes. Mix IM3 has the highest resilient modulus values among the IM-19.0A mixes. Mix BM3 has the highest resilient modulus values at all temperatures among the BM-25.0 mixes. All these results are consistent with the behavior observed for the dynamic modulus tests.

To investigate whether there is any correlation between the dynamic modulus and the resilient modulus , the dynamic modulus values at temperatures of 41°F, 77°F, and 104°F at a frequency of 1.6 Hz (frequency that simulates the 0.1-second loading time used in the resilient modulus test) were needed. For that purpose, the shift factors at these temperatures were first determined, then the reduced frequencies were calculated using Equation 2, and finally the regressed sigmoidal equation for the master curve was used to calculate the corresponding dynamic modulus value.

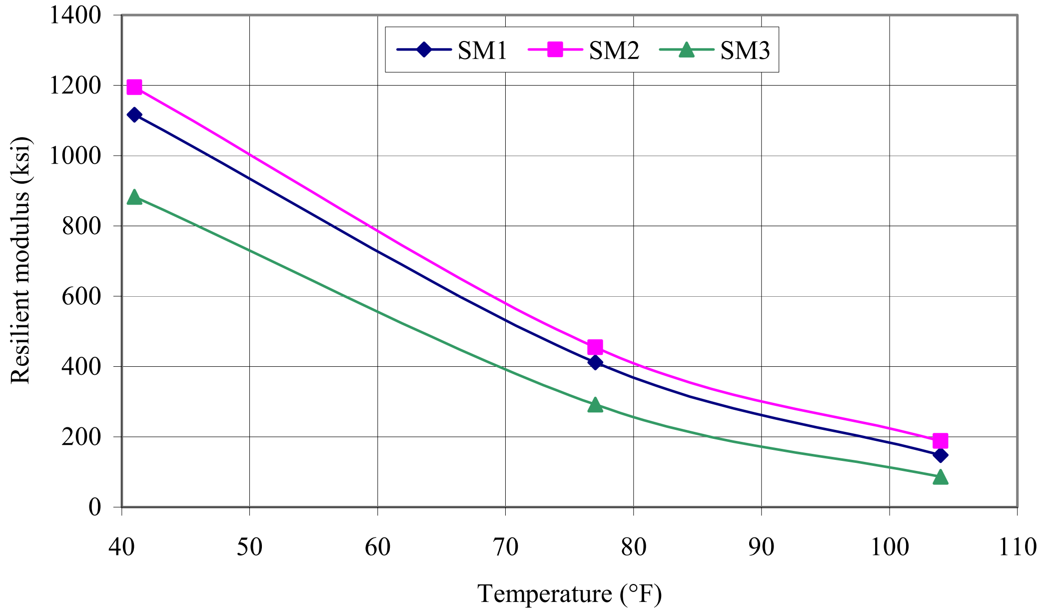

Figure 15. Resilient modulus versus temperature for the SM-9.5A mixes

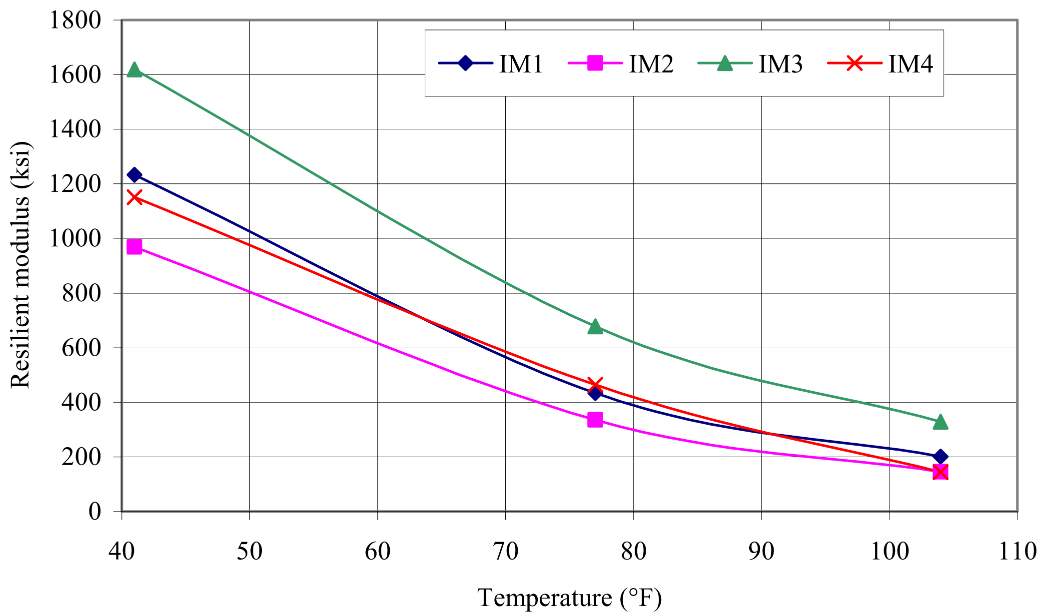

Figure 16. Resilient modulus versus temperature for the IM-19.0A mixes

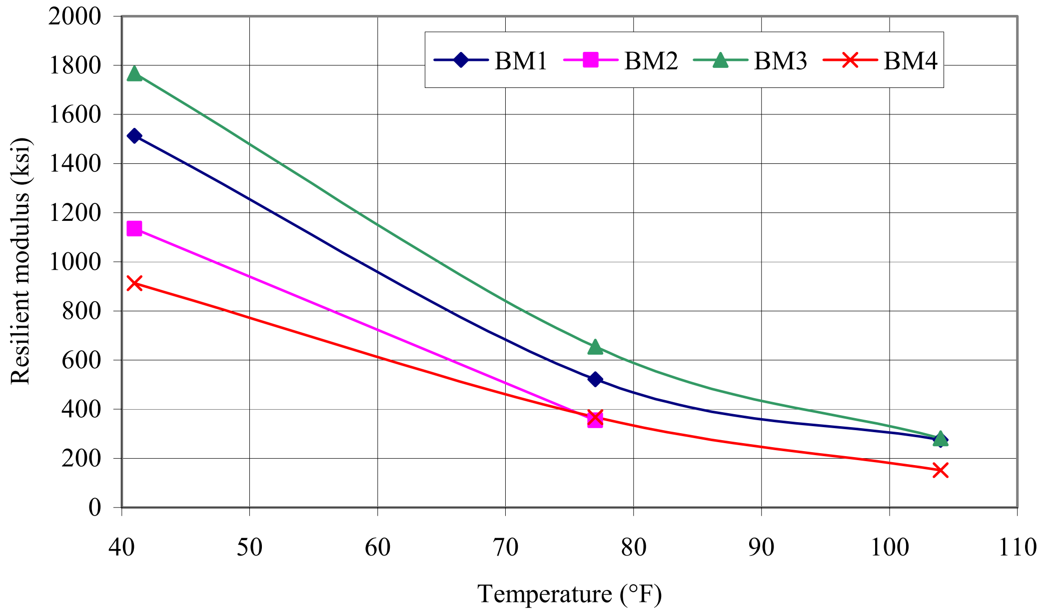

Figure 17. Resilient modulus versus temperature for the BM-25.0 mixes

Figure 18 shows the resilient modulus versus the dynamic modulus for all mixes. This figure shows that at low temperatures (high modulus values), the dynamic modulus is larger than the resilient modulus values, while at high temperatures (low modulus values), the values are closer to each other. The plots suggest that the relationship may not be linear and could possibly be mix dependent.

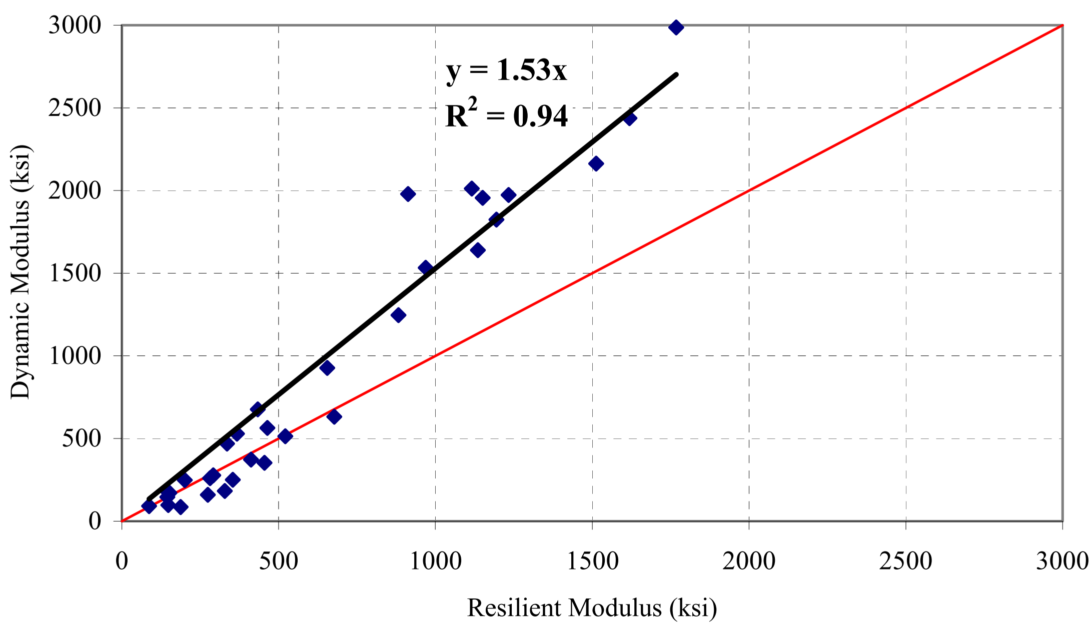

Figure 18. Resilient modulus versus dynamic modulus for all mixes

To determine if there was a clear trend with temperature, the ratio of the dynamic modulus to the resilient modulus for all mixes was determined at all temperatures. Table 13 summarizes the values of this ratio. On average, the dynamic modulus value is 1.62 times the resilient modulus value at 41°F, 1.12 times the resilient modulus value at 77°F, and 0.88 times the resilient modulus value at 104°F. Furthermore, the ratio appears to be mix dependent.

These results suggest that if the resilient modulus values are used at low temperatures, the prediction of the low-temperature cracking may be underestimated; if the resilient modulus values are used at high temperatures, the rutting prediction may also be underestimated.

Table 13. Ratio of dynamic modulus to resilient modulus for all mixes

Mix	Temperature (°F)		
	41	77	104
SM1	1.80	0.90	0.65
SM2	1.53	0.78	0.46
SM3	1.41	0.95	1.04
IM1	1.60	1.56	1.23
IM2	1.58	1.40	1.00
IM3	1.51	0.93	0.55
IM4	1.70	1.22	1.27
BM1	1.43	0.98	0.58
BM2	1.44	0.70	N/A
BM3	1.69	1.42	0.92
BM4	2.17	1.44	1.13
Average	1.62	1.12	0.88

FINDINGS

- As expected, under a constant loading frequency, the magnitude of the dynamic modulus decreases with an increase in temperature; under a constant testing temperature, the magnitude of the dynamic modulus increases with an increase in the frequency.
- The phase angle decreases as the frequency increases at testing temperatures of 10°F, 40°F, and 70°F. At 100°F, the phase angle seems to increase up to frequencies of 0.5 Hz, and then it starts to decrease with an increase in frequency. At 130°F, the phase angle increases with an increase in frequency.
- A sigmoidal function can be used for modeling the dynamic modulus data with very good statistical fit.
- Mixes of the same type (SM-9.5A, IM-19.0A, and BM-25.0) had different measured dynamic modulus values because they had different constituents (aggregate type, asphalt content, percentage RAP, etc.).
- The level 2 dynamic modulus prediction (Witczak) equation reasonably estimated the measured dynamic modulus. For all mixes, the ratio of the predicted to the measured

dynamic modulus fell in the range of 0.45 to 1.9. However, this equation did not fully capture differences between the mixes that were clearly shown by the measured data.

- The indirect tensile creep tests needed for the low-temperature cracking model did not produce repeatable results. This is thought to be due to the type of extensometers used in this investigation, which showed low reliability at very low temperatures.
- The measured dynamic moduli were higher than the resilient moduli determined at low temperatures and comparable (but in general lower) at high temperatures.

CONCLUSIONS

- The dynamic modulus test is a good test to characterize HMA mechanical behavior at different temperatures and loading frequencies. The test results showed that the dynamic modulus is sensitive to the mix constituents. For example, this test method was able to differentiate between similar mixtures at the same nominal maximum aggregate size as in the case of SM-1 and SM-3.
- The default (Witczak) level 2 dynamic modulus prediction equation could be used with the design of low and medium traffic volumes pending future investigation of the revised prediction equation incorporated in the new MEPDG software/guide.
- The creep test and the IDT strength test that are needed to obtain the parameters required for predicting low-temperature cracking may not be repeatable; this could be due to the type of extensometers used for the test.

RECOMMENDATIONS

1. *VDOT's Materials Division should use level 1 analysis for characterizing HMA for pavement design projects of significant impact.* The dynamic modulus test is easy to perform and gives a full characterization of the mix. This could be implemented by developing a catalog of mechanical properties for typical VDOT mixes. The catalog would provide a better characterization of the HMA than just using the default prediction equation.
2. *VDOT's Materials Division can use level 2 data (based on the default Witczak prediction equation) for projects not requiring high levels of reliabilityAs an alternative to level 1 analysis for projects not requiring high levels of reliability, VDOT's Materials Division can use level 2 analysis based on the default Witczak prediction equation for characterization of HMA.*
3. *VTRC should perform a sensitivity analysis to see the effect of changing the modulus on the predicted pavement performance.* For example, if the dynamic modulus as predicted by the default equation is used instead of the measured dynamic modulus, how would the predicted pavement performance (fatigue and rutting) change? Of particular interest is the quantification of the effect of various surface mixes on pavement performance and designed layer thicknesses.
4. *If the MEPDG proves sensitive to the thin layer modulus, VTRC should perform a characterization of special mixes (SMAs, OGFC, and OGDL mixes, etc.) used in Virginia.*

COSTS AND BENEFITS ASSESSMENT

The results of this study directly support implementation efforts currently underway to initiate statewide usage of the proposed MEPDG. The characterization findings provide necessary inputs for the design guide. Use of the design guide is expected to improve the efficiency of asphalt pavement designs and result in more accurate predictions of maintenance and rehabilitation needs over the life of the asphalt pavement. This will allow for more economical scheduling practices to optimize maintenance strategies. Cost savings of these efficiencies cannot be directly calculated at this time, as they must be determined at either the project or network level; such determination is beyond the scope of this study. However, these savings are expected to be significant when applied to the almost 58,000 miles of roadways that are maintained by VDOT considerable mileage of HMA-surfaced pavements that are maintained by VDOT. .

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APPENDIX A
JOB-MIX FORMULA FOR ALL MIXES

Table A1. JMF for the SM-9.5A mixes

Type	Percentage (%)	Source	Location
SM1			
#8 Aggregate	40	Vulcan Garrisonville	Garrisonville
#10 Screening	28	Vulcan Garrisonville	Garrisonville
Natural Sand	12	Luck Stone New Market Plant	New Market
RAP	20	Virginia Paving Co.	
PG 64-22	5.3	Citgo	
Kling Beta 2700	0.5	Akzo-Nobel	Waco , Texas
SM2			
# 8 Amphible Gneiss	45	Rockydale @ Jacks Mtn.	Glade Hill, VA
#10 Limestone	20	Rockydale Quarry	Roanoke, VA
Sand	20	McCarty Sand Works	Danville, VA
Processed RAP	15	Adams Construction Co.	Roanoke, VA
PG 64-22	5.9	Associated Asphalt	Roanoke, VA
Adhere HP+	0.5	Arr-Maz Products	Winter Haven, FL
SM3			
#8 Aggregate	41	Vulcan Materials, Sanders Quarry	
#78 Aggregate	8	Vulcan Materials, Sanders Quarry	
Natural Sand	15	Ennstone Quarry/Morie Quarry	
Crushed RAP	12	Superior Paving, Warrenton Plant	
#10 Screening	15	Vulcan Materials, Sanders Quarry	
Man. Sand	9	Vulcan Materials, Sanders Quarry	
PG 64-22	5.6	Citgo	Dumfries, VA
Anti-strip	0.5	Morelife 3300	Roam/Haas, OH

Table A2. JMF for the IM-19.0 mixes

Type	Percentage (%)	Source	Location
IM1			
#8 Aggregate	21	Vulcan Materials	Lorton, VA
#68 Aggregate	30	Vulcan Materials	Lorton, VA
Man. Sand	19	Vulcan Materials	Lorton, VA
Natural Sand	10	Mid Atlantic	King George, VA
½-inch Recl. RAP	20	APAC, Inc.	Occoquan, VA
PG 64-22	4.6	Citgo	Dumfries, VA
Adhere HP+	0.5	Arr-Maz Products	Winter Haven, FL
IM2			
#67 Aggregate	35	Vulcan Materials	
#8 Aggregate	25	Vulcan Materials	
Sand	20	Vulcan Materials	
RAP	20	Branscome	
PG 64-22	4.6	Kock Fuels Inc.	
Adhere HP+	0.3	Arr-Maz Products	Winter Haven, FL
IM3			
#68 Limestone	50	Boxley	Rich Patch, VA
#10 Limestone	25	Boxley	Rich Patch, VA
Sand	5	Brett Aggregates Inc.	Stuart Draft, VA
Processed RAP	20	Adams Construction Co.	Lowmoore, VA
PG 64-22	4.9	Associated Asphalt, Inc.	Roanoke, VA
Adhere HP+	0.5	Arr-Maz Products	Winter Haven, FL
IM4			
#68 Limestone	47	Luck Stone	Staunton, VA
#8 Limestone	10	Luck Stone	Staunton, VA
#10 Limestone	32	Luck Stone	Staunton, VA
Sand	10	DM Conner	Stuarts Drafts, VA
Lime	1	Greer Lime	Riverton, WV
PG 64-22	5.5	Associated Asphalt	Roanoke, VA

Table A3. JMF for the BM-25.0 mixes

Type	Percentage (%)	Source	Location
BM1			
#5 Aggregate	22	Vulcan Garrisonville	
#68 Aggregate	27	Vulcan Garrisonville	
Natural sand	10	Luck Stone	New Market
#10 screening	16	Vulcan Garrisonville	
RAP millings	25	Virginia Paving Co.	
PG 64-22	4.4	Citgo	
Kling Beta 2700	0.5	Akzo-Nobel	Waco , Texas
BM2			
#8 Limestone	32	Stuart M. Perry Inc.	Winchester
#56 Limestone	30	Stuart M. Perry Inc.	Winchester
#10 Limestone	30	Stuart M. Perry Inc.	Winchester
Sand	8	Stuart M. Perry Inc.	Winchester
PG 64-22	4.9	Citgo Asphalt Refining	Dumfries, VA
Kling Beta 2700	0.5	Citgo Asphalt Refining	Dumfries, VA
BM3			
#357 Limestone	18	Acco Stone	Blacksburg, VA
#68 Limestone	30	Acco Stone	Blacksburg, VA
#10 Limestone	27	Acco Stone	Blacksburg, VA
Concrete Sand	10	Wythe Sand Co.	Wytheville, VA
Processed RAP	15	Adams Construction Co.	Blacksburg, VA
PG 64-22	4.4	Associated Asphalt, Inc.	Roanoke, VA
Adhere HP+	0.5	Arr-Maz Products	Winter Haven, FL
BM4			
#67 Aggregate	15	Vulcan Materials	
#8 Aggregate	15	Vulcan Materials	
#5 Aggregate	28	Vulcan Materials	
Sand	27	Vulcan Materials	
RAP	15	Branscome Inc.	
PG 64-22	4.4	Koch Fuels Inc.	
Adhere HP+	0.5	Arr-Maz Products	Winter Haven, FL

APPENDIX B
ASPHALT CONTENT, G_{mm}, AND GRADATION FOR ALL MIXES

Table B1. Asphalt content, G_{mm}, and aggregate gradation for SM1

	Sample 1	Sample 2	Sample 3	Sample 4	Average	JMF*	Acceptance
Asphalt content (%)	4.99	4.84	5.06	4.82	4.93	5.3	5.0-5.6
G_{mm}	2.635	2.633	2.630	2.622	2.630	2.626	
Gradation							
Sieve opening, mm (No.)	**% Passing Sample 1**	**% Passing Sample 2**	**% Passing Sample 3**	**% Passing Sample 4**	**% Passing Avg.**	**Acceptance range***	
						Lower limit	**Upper limit**
12.5 (1/2)	96.6	97.3	97.8	97.9	97.4	-	100
9.5 (3/8)	886	88.7	91.5	90.6	89.9	89	97
4.75 (#4)	55.6	55.7	59.5	57.1	57.2	56	64
2.36 (#8)	37.3	37.1	39.2	37.8	37.9	36	44
1.18 (#16)	27.6	27.4	28.6	27.8	27.9	-	-
0.6 (#30)	19.2	19.1	19.9	19.4	19.4	-	-
0.3 (#50)	10.8	10.7	11.2	10.9	10.9	-	-
0.15 (#100)	6.7	6.7	7.1	6.8	6.8	-	-
0.075 (#200)	4.9	4.9	5.2	5.0	5.0	4	6

*Reported from the JMF sheet

Table B2. Asphalt content, G_{mm}, and aggregate gradation for SM2

	Sample 1	Sample 2	Sample 3	Sample 4	Average	JMF*	Acceptance
Asphalt content (%)	5.98	6.01	5.85	5.79	5.91	5.9	5.6-6.2
G_{mm}	2.669	2.632	2.642	2.651	2.648	2.618	
Gradation							
Sieve opening, mm (No.)	**% Passing Sample 1**	**% Passing Sample 2**	**% Passing Sample 3**	**% Passing Sample 4**	**% Passing Avg.**	**Acceptance range***	
						Lower limit	**Upper limit**
12.5 (1/2)	100.0	100.0	100.0	100.0	100.0	99	100
9.5 (3/8)	94.5	96.9	96.7	97.1	96.3	92	100
4.75 (#4)	53.9	58.1	59.2	57.5	57.1	56	64
2.36 (#8)	36.0	38.0	38.7	37.7	37.6	37	45
1.18 (#16)	27.4	28.2	28.8	28.3	28.1	-	-
0.6 (#30)	19.8	20.1	20.7	20.3	20.2	-	-
0.3 (#50)	12.7	12.5	13.1	12.8	12.8	-	-
0.15 (#100)	8.6	8.2	8.7	8.5	8.5	-	-
0.075 (#200)	6.5	5.8	6.4	6.3	6.3	4.9	6.9

*Reported from the JMF sheet

Table B3. Asphalt content, G_{mm}, and aggregate gradation for SM3

	Sample 1	Sample 2	Sample 3	Sample 4	Average	JMF*	Acceptance
Asphalt content (%)	6.30	6.40	6.43	6.12	6.32	5.6	5.3-5.9
G_{mm}	2.597	2.593	2.591	2.605	2.596	2.599	
Gradation							
Sieve opening, mm (No.)	**% Passing Sample 1**	**% Passing Sample 2**	**% Passing Sample 3**	**% Passing Sample 4**	**% Passing Avg.**	**Acceptance range* Lower limit**	**Upper limit**
12.5 (1/2)	99.5	99.7	99.2	98.5	99.2	99	100
9.5 (3/8)	91.1	90.3	92.8	91.6	91.4	89	97
4.75 (#4)	55.2	55.8	57.3	54.8	55.8	55	63
2.36 (#8)	39.4	39.9	40.4	38.5	39.5	36	44
1.18 (#16)	29.8	30.1	30.7	29.4	30.0	-	-
0.6 (#30)	21.3	21.5	21.9	21.0	21.5	-	-
0.3 (#50)	13.3	13.5	13.7	13.2	13.4	-	-
0.15 (#100)	9.0	9.2	9.2	9.0	9.1	-	-
0.075 (#200)	6.1	6.3	6.4	6.3	6.3	4.7	6.7

*Reported from the JMF sheet

Table B4. Asphalt content, G_{mm}, and aggregate gradation for IM1

	Sample 1	Sample 2	Sample 3	Sample 4	Average	JMF*	Acceptance
Asphalt content (%)	5.35	5.29	5.21	5.20	5.26	4.60	4.3-4.9
G_{mm}	2.480	2.482	2.468	2.477	2.477	2.504	
Gradation							
Sieve opening, mm (No.)	**% Passing Sample 1**	**% Passing Sample 2**	**% Passing Sample 3**	**% Passing Sample 4**	**% Passing Avg.**	**Acceptance range* Lower limit**	**Upper limit**
25 (1)	100.0	100.0	100.0	100.0	100.0	-	100
19 (3/4)	100.0	100.0	100.0	100.0	100.0	92	100
12.5 (1/2)	97.1	94.9	96.0	95.0	95.8	84	92
9.5 (3/8)	88.0	86.9	88.3	86.9	87.5	-	-
4.75 (#4)	53.5	53.9	54.4	50.4	53.0	-	-
2.36 (#8)	37.7	38.3	38.5	36.5	37.7	29	37
1.18 (#16)	29.4	29.7	29.8	28.6	29.4	-	-
0.6 (#30)	21.9	22.0	22.0	21.4	21.8	-	-
0.3 (#50)	14.5	14.7	14.6	14.3	14.5	-	-
0.15 (#100)	9.8	10.0	9.8	9.8	9.9	-	-
0.075 (#200)	6.5	6.8	6.6	6.7	6.6	4.0	6.0

*Reported from the JMF sheet

Table B5. Asphalt content, G_{mm}, and aggregate gradation for IM2

	Sample 1	Sample 2	Sample 3	Sample 4	Average	JMF*	Acceptance
Asphalt content (%)	4.56	4.54	4.41	4.57	4.52	4.6	4.3-4.9
G_{mm}	2.512	2.510	2.511	2.521	2.513	2.500	
Gradation							
Sieve opening, mm (No.)	**% Passing Sample 1**	**% Passing Sample 2**	**% Passing Sample 3**	**% Passing Sample 4**	**% Passing Avg.**	**Acceptance range***	
						Lower limit	**Upper limit**
25 (1)	100.0	100.0	100.0	100.0	100.0	-	100
19 (3/4)	100.0	97.8	95.0	97.7	97.6	92	100
12.5 (1/2)	85.4	86.0	82.6	84.3	84.6	80	88
9.5 (3/8)	74.2	73.9	70.9	74.1	73.3	-	-
4.75 (#4)	41.8	40.7	41.1	42.2	41.5	-	-
2.36 (#8)	29.8	29.3	29.9	30.0	29.8	29	37
1.18 (#16)	24.4	24.0	24.2	24.4	24.2	-	-
0.6 (#30)	18.3	18.0	18.0	18.3	18.1	-	-
0.3 (#50)	11.6	11.4	11.4	11.6	11.5	-	-
0.15 (#100)	6.7	6.5	6.5	6.7	6.6	-	-
0.075 (#200)	3.9	3.7	3.8	3.9	3.8	3.4	5.4

*Reported from the JMF sheet

Table B6. Asphalt content, G_{mm}, and aggregate gradation for IM3

	Sample 1	Sample 2	Sample 3	Sample 4	Average	JMF*	Acceptance
Asphalt content (%)	4.76	5.16	4.80	4.83	4.89	4.9	4.6-5.2
G_{mm}	2.533	2.516	2.523	2.523	2.524		
Gradation							
Sieve opening, mm (No.)	**% Passing Sample 1**	**% Passing Sample 2**	**% Passing Sample 3**	**% Passing Sample 4**	**% Passing Avg.**	**Acceptance range***	
						Lower limit	**Upper limit**
25 (1)	100.0	100.0	100.0	100.0	100.0	-	100
19 (3/4)	96.3	97.4	93.7	98.3	96.4	92	100
12.5 (1/2)	75.6	83.3	79.8	80.6	79.8	76	84
9.5 (3/8)	66.3	73.9	69.0	68.6	69.5	-	-
4.75 (#4)	42.7	48.7	45.5	45.6	45.6	-	-
2.36 (#8)	28.7	32.3	30.4	30.1	30.4	28	36
1.18 (#16)	20.1	22.2	21.2	21.0	21.1	-	-
0.6 (#30)	14.7	16.2	15.5	15.4	15.4	-	-
0.3 (#50)	10.0	10.9	10.5	10.4	10.4	-	-
0.15 (#100)	7.0	7.5	7.3	7.2	7.2	-	-
0.075 (#200)	5.3	5.6	5.5	5.4	5.5	4.0	6.0

*Reported from the JMF sheet

Table B7. Asphalt content, G_{mm}, and aggregate gradation for IM4

	Sample 1	Sample 2	Sample 3	Sample 4	Average	JMF*	Acceptance
Asphalt content (%)	5.29	5.49	5.22	5.72	5.43	5.5	5.2-5.8
G_{mm}	2.489	2.489	2.486	2.481	2.486	2.502	
Gradation							
Sieve opening, mm (No.)	**% Passing Sample 1**	**% Passing Sample 2**	**% Passing Sample 3**	**% Passing Sample 4**	**% Passing Avg.**	**Acceptance range***	
						Lower limit	**Upper limit**
25 (1)	100.0	100.0	100.0	100.0	100.0	-	100
19 (3/4)	98.6	98.3	98.1	100.0	98.8	92	100
12.5 (1/2)	85.0	85.6	83.4	87.1	85.3	82	90
9.5 (3/8)	75.8	74.7	72.8	78.3	75.4	-	-
4.75 (#4)	57.8	58.2	56.6	61.5	58.5	-	-
2.36 (#8)	39.4	39.6	39.1	41.9	40.0	26	34
1.18 (#16)	30.0	30.1	29.7	31.4	30.3	-	-
0.6 (#30)	23.2	23.3	23.0	24.2	23.4	-	-
0.3 (#50)	14.3	14.3	14.1	14.7	14.4	-	-
0.15 (#100)	8.1	8.0	7.9	8.2	8.0	-	-
0.075 (#200)	6.0	5.9	5.8	6.0	5.9	4.0	6.0

*Reported from the JMF sheet

Table B8. Asphalt content, G_{mm}, and aggregate gradation for BM1

	Sample 1	Sample 2	Sample 3	Sample 4	Average	JMF*	Acceptance
Asphalt content (%)	4.51	5.22	4.27	4.50	4.62	4.4	4.1-4.7
G_{mm}	2.690	2.692	2.698	2.685	2.691	2.668	
Gradation							
Sieve opening, mm (No.)	**% Passing Sample 1**	**% Passing Sample 2**	**% Passing Sample 3**	**% Passing Sample 4**	**% Passing Avg.**	**Acceptance range***	
						Lower limit	**Upper limit**
37.5 (1.5)	100.0	100.0	100.0	100.0	100.0		100
25 (1)	100.0	100.0	98.5	98.2	99.2	92	100
19 (3/4)	95.3	97.4	92.3	92.6	94.4	82	90
12.5 (1/2)	77.9	76.8	72.2	76.7	75.9	-	-
9.5 (3/8)	67.8	65.6	62.8	67.7	66.0	-	-
4.75 (#4)	47.9	46.4	43.6	47.2	46.3	-	-
2.36 (#8)	32.3	31.5	29.7	31.9	31.3	26	34
1.18 (#16)	23.5	23.2	22.0	23.4	23.0	-	-
0.6 (#30)	16.9	16.6	15.9	16.8	16.6	-	-
0.3 (#50)	10.8	10.6	10.2	10.8	10.6	-	-
0.15 (#100)	7.5	7.3	7.1	7.5	7.4	-	-
0.075 (#200)	5.6	5.4	5.2	5.6	5.4	3.0	5.0

*Reported from the JMF sheet

Table B9. Asphalt content, G_{mm}, and aggregate gradation for BM2

	Sample 1	Sample 2	Sample 3	Sample 4	Average	JMF*	Acceptance
Asphalt content (%)	5.01	4.55	5.03	4.86	4.86	4.9	4.6-5.2
G_{mm}	2.493	2.522	2.504	2.519	2.509	2.515	
Gradation							
Sieve opening, mm (No.)	**% Passing Sample 1**	**% Passing Sample 2**	**% Passing Sample 3**	**% Passing Sample 4**	**% Passing Avg.**	**Acceptance range***	
						Lower limit	**Upper limit**
37.5 (1.5)	100.0	100.0	100.0	100.0	100.0		100
25 (1)	82.5	83.7	82.4	87.8	84.1	90	98
19 (3/4)	73.6	71.4	75.4	74.9	73.8	73	81
12.5 (1/2)	71.2	66.1	70.8	70.4	69.6	-	-
9.5 (3/8)	67.8	63.8	67.5	67.5	66.6	-	-
4.75 (#4)	43.5	41.5	44.2	42.5	42.9	-	-
2.36 (#8)	26.8	25.7	27.2	26.3	26.5	25	33
1.18 (#16)	17.3	16.3	17.6	16.8	17.0	-	-
0.6 (#30)	11.6	10.9	11.9	11.2	11.4	-	-
0.3 (#50)	8.4	7.8	8.6	8.0	8.2	-	-
0.15 (#100)	6.7	6.2	7.0	6.3	6.5	-	-
0.075 (#200)	5.5	5.2	5.9	5.2	5.5	3.6	5.6

*Reported from the JMF sheet

Table B10. Asphalt content, G_{mm}, and aggregate gradation for BM3

	Sample 1	Sample 2	Sample 3	Sample 4	Average	JMF*	Acceptance
Asphalt content (%)	3.87	3.96	3.74	4.05	3.91	4.4	4.1-4.7
G_{mm}	2.646	2.638	2.645	2.631	2.640	2.605	
Gradation							
Sieve opening, mm (No.)	**% Passing Sample 1**	**% Passing Sample 2**	**% Passing Sample 3**	**% Passing Sample 4**	**% Passing Avg.**	**Acceptance range***	
						Lower limit	**Upper limit**
37.5 (1.5)	100.0	100.0	100.0	100.0	100.0		100
25 (1)	95.8	100.0	96.2	97.2	97.3	90	98
19 (3/4)	87.4	87.6	86.7	88.8	87.6	82	90
12.5 (1/2)	72.6	72.9	72.1	75.7	73.3	-	-
9.5 (3/8)	64.6	63.7	62.4	68.3	64.8	-	-
4.75 (#4)	46.1	47.3	47.6	50.9	48.0	-	-
2.36 (#8)	23.6	24.2	23.5	25.4	24.2	25	33
1.18 (#16)	16.8	17.2	16.8	17.8	17.1	-	-
0.6 (#30)	12.9	13.1	13.0	13.6	13.1	-	-
0.3 (#50)	8.7	8.8	8.8	9.2	8.9	-	-
0.15 (#100)	7.0	7.0	7.0	7.3	7.1	-	-
0.075 (#200)	6.0	6.0	6.0	6.3	6.1	4.0	6.0

*Reported from the JMF sheet

Table B11. Asphalt content, G_{mm}, and aggregate gradation for BM4

	Sample 1	Sample 2	Sample 3	Sample 4	Average	JMF*	Acceptance
Asphalt content (%)	4.70	4.50	4.53	4.32	4.51	4.4	4.1-4.7
G_{mm}	2.506	2.514	2.520	2.525	2.516	2.525	
Gradation							
Sieve opening, mm (No.)	**% Passing Sample 1**	**% Passing Sample 2**	**% Passing Sample 3**	**% Passing Sample 4**	**% Passing Avg.**	**Acceptance range***	
						Lower limit	**Upper limit**
37.5 (1.5)	100.0	100.0	100.0	100.0	100.0		100
25 (1)	100.0	100.0	100.0	100.0	100.0	92	100
19 (3/4)	95.5	96.1	95.6	94.6	95.5	81	89
12.5 (1/2)	85.0	80.8	82.7	81.4	82.5	-	-
9.5 (3/8)	73.2	68.7	70.5	69.8	70.6	-	-
4.75 (#4)	42.4	40.9	41.5	39.6	41.1	-	-
2.36 (#8)	31.2	30.2	30.7	29.3	30.3	33	41
1.18 (#16)	25.2	24.6	24.8	24.0	24.7	-	-
0.6 (#30)	18.5	18.1	18.2	17.9	18.2	-	-
0.3 (#50)	11.1	10.9	10.9	10.9	11.0	-	-
0.15 (#100)	6.3	6.2	6.2	6.3	6.2	-	-
0.075 (#200)	3.9	3.8	3.8	4.0	3.9	3.2	5.2

*Reported from the JMF sheet

APPENDIX C
MEASURED DYNAMIC MODULUS RESULTS

Table C1. Measured dynamic modulus (psi) and phase angle (°) for mix SM1

Temp.	Freq.	SM1-1		SM1-2		SM1-3		Average		COV	
(°F)	(Hz)	E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	3,835,448	2.2	4,688,959	2.9	4,476,852	2.2	4,333,753	2.4	10.3	14.9
	10	3,751,927	3.3	4,106,812	3.5	4,312,782	3.1	4,057,174	3.3	7.0	5.7
	5	3,623,147	3.6	4,105,549	4.1	4,151,776	4.5	3,960,157	4.1	7.4	6.3
	1	3,292,053	3.8	3,692,480	5.4	3,795,503	6.7	3,593,345	5.3	7.4	14.7
	0.5	3,155,697	6.6	3,396,530	5.8	3,642,242	6.8	3,398,156	6.4	7.2	8.2
	0.1	2,751,969	7.8	3,349,788	6.1	3,220,936	7.5	3,107,564	7.1	10.1	10.5
40	25	2,386,559	9.4	2,280,613	8.2	3,018,213	8.6	2,561,795	8.8	15.6	3.0
	10	2,196,173	10.4	2,041,250	10.9	2,697,734	10.7	2,311,719	10.7	14.8	1.0
	5	2,038,852	11.2	1,866,631	11.4	2,509,424	9.5	2,138,302	10.7	15.6	9.3
	1	1,662,643	13.0	1,483,098	13.2	2,035,394	12.3	1,727,045	12.8	16.3	3.3
	0.5	1,489,189	15.5	1,313,927	16.0	1,815,690	15.6	1,539,602	15.7	16.5	1.4
	0.1	1,118,509	19.6	968,358	20.5	1,384,811	19.4	1,157,226	19.8	18.2	2.9
70	25	1,515,985	17.9	1,151,945	18.8	1,419,005	18.2	1,362,312	18.3	13.8	1.9
	10	1,242,674	20.1	959,039	20.1	1,167,187	20.2	1,122,966	20.1	13.1	0.2
	5	1,051,940	21.9	820,200	21.9	1,001,880	22.2	958,007	22.0	12.7	0.8
	1	683,430	26.4	540,774	26.2	669,826	26.8	631,343	26.5	12.5	1.2
	0.5	536,882	30.9	423,167	30.7	535,707	31.9	498,585	31.1	13.1	1.9
	0.1	322,957	34.2	260,197	34.6	334,983	36.5	306,046	35.1	13.1	2.8
100	25	497,636	31.2	376,334	32.2	490,104	31.9	454,691	31.8	14.9	0.7
	10	375,782	31.9	293,682	32.4	387,783	33.3	352,416	32.5	14.5	1.4
	5	292,950	33.2	230,763	33.3	307,610	34.3	277,108	33.6	14.7	1.4
	1	160,690	33.6	128,241	33.4	172,165	34.9	153,699	34.0	14.8	2.1
	0.5	119,358	34.9	96,715	34.6	128,156	36.7	114,743	35.4	14.1	3.0
	0.1	74,609	30.3	64,260	29.4	79,842	32.5	72,904	30.7	10.9	5.1
130	25	136,638	29.0	112,191	31.9	148,153	33.6	132,327	31.5	13.9	3.4
	10	98,011	27.0	83,799	28.8	103,967	30.8	95,259	28.8	10.9	4.0
	5	79,268	24.6	67,989	26.1	82,016	28.0	76,424	26.2	9.7	4.0
	1	54,640	18.7	47,650	19.9	53,286	21.6	51,859	20.0	7.1	4.7
	0.5	48,882	17.5	43,211	18.4	46,852	19.7	46,315	18.5	6.2	3.9
	0.1	42,635	14.3	38,933	14.7	39,923	15.4	40,497	14.8	4.7	2.7

Table C2. Measured dynamic modulus (psi) and phase angle (^{o}) for mix SM2

Temp.	Freq.	SM2-1		SM2-2		SM2-3		Average		COV	
(°F)	(Hz)	E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	3,361,675	2.7	3,853,492	2.2	3,900,886	2.5	3,705,351	2.5	8.1	7.4
	10	3,119,653	3.5	3,605,338	4.1	3,776,419	3.6	3,500,470	3.7	9.7	7.6
	5	2,975,516	4.2	3,440,721	4.8	3,673,327	3.9	3,363,188	4.3	10.6	10.9
	1	2,891,353	5.8	3,201,201	5.9	3,303,212	4.8	3,131,922	5.5	6.8	9.8
	0.5	2,835,376	6.5	3,053,679	6.4	3,274,504	5.5	3,054,520	6.2	7.2	7.6
	0.1	2,377,251	8.6	2,717,761	6.8	2,717,750	7.8	2,604,254	7.7	7.5	7.4
40	25	2,692,772	7.9	2,733,359	7.0	2,391,087	7.3	2,605,739	7.4	7.2	2.8
	10	2,435,325	8.8	2,473,170	10.7	2,139,470	9.9	2,349,322	9.8	7.8	5.1
	5	2,206,687	11.7	2,273,719	10.9	1,986,331	11.2	2,155,579	11.2	7.0	1.9
	1	1,788,554	14.5	1,830,099	14.8	1,586,363	14.0	1,735,005	14.5	7.5	2.8
	0.5	1,584,017	16.8	1,604,446	17.9	1,423,560	18.0	1,537,341	17.6	6.4	1.3
	0.1	1,145,724	23.2	1,203,918	21.9	1,042,206	21.8	1,130,616	22.3	7.2	1.2
70	25	1,245,189	19.4	1,202,700	19.3	1,143,550	19.8	1,197,146	19.5	4.3	1.4
	10	1,008,604	21.9	997,219	22.0	939,208	22.1	981,677	22.0	3.8	0.4
	5	851,962	24.4	851,258	24.1	794,911	24.3	832,710	24.3	3.9	0.5
	1	546,002	29.6	552,658	29.4	512,563	29.6	537,074	29.6	4.0	0.4
	0.5	421,218	34.6	430,229	34.7	398,904	34.9	416,784	34.8	3.9	0.2
	0.1	250,352	38.1	259,003	37.8	239,780	38.1	249,712	38.0	3.9	0.5
100	25	369,309	33.4	375,195	34.3	447,021	33.7	397,175	33.8	10.9	0.9
	10	268,965	33.5	280,337	34.5	325,518	33.9	291,607	34.0	10.3	1.0
	5	204,861	34.0	215,984	34.5	249,150	34.1	223,332	34.2	10.3	0.6
	1	112,268	31.6	118,099	32.2	137,892	31.8	122,753	31.9	10.9	0.7
	0.5	87,110	31.8	91,483	32.1	108,427	31.5	95,673	31.8	11.8	0.9
	0.1	57,925	26.3	59,823	26.4	74,060	25.7	63,936	26.1	13.8	1.3
130	25	98,187	29.4	118,232	27.8	93,799	29.7	103,406	28.9	12.6	3.3
	10	73,442	25.8	86,912	25.5	68,876	26.9	76,410	26.1	12.3	2.6
	5	60,440	23.6	70,988	23.4	56,187	24.4	62,538	23.8	12.2	2.2
	1	43,126	18.4	49,601	18.9	38,936	19.4	43,888	18.9	12.2	1.5
	0.5	38,922	17.4	44,204	18.1	34,144	18.3	39,090	17.9	12.9	0.9
	0.1	34,194	15.3	37,633	16.4	28,866	15.4	33,564	15.7	13.2	3.2

Table C3. Measured dynamic modulus (psi) and phase angle (°) for mix SM3

Temp.	Freq.	SM3-3		SM3-4		SM3-5		Average		COV	
(°F)	(Hz)	E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	2,983,947	3.3	3,159,968	3.5	3,212,086	3.7	3,118,667	3.5	3.8	4.2
	10	2,774,559	4.9	3,044,689	4.9	3,077,795	5.4	2,965,681	5.1	5.6	4.9
	5	2,645,241	6.0	2,914,124	5.6	2,954,835	6.1	2,838,067	5.9	5.9	3.9
	1	2,336,639	7.7	2,580,539	7.1	2,608,025	7.7	2,508,401	7.5	6.0	4.4
	0.5	2,189,525	8.7	2,443,996	8.6	2,459,759	8.8	2,364,427	8.7	6.4	1.1
	0.1	1,839,427	11.4	2,069,365	10.3	2,087,677	11.3	1,998,823	11.0	6.9	4.5
40	25	1,745,398	10.4	1,938,607	10.8	1,886,781	10.9	1,856,929	10.7	5.4	0.8
	10	1,537,887	13.4	1,694,713	11.8	1,656,442	12.7	1,629,681	12.6	5.0	4.0
	5	1,379,286	16.0	1,521,620	13.5	1,499,349	14.6	1,466,752	14.7	5.2	4.5
	1	1,015,539	19.8	1,167,131	17.7	1,132,291	18.3	1,104,987	18.6	7.2	2.5
	0.5	864,401	22.7	1,006,109	21.1	970,848	22.1	947,119	22.0	7.8	2.6
	0.1	580,466	29.2	682,960	26.4	659,131	27.8	640,852	27.8	8.4	2.9
70	25	754,173	25.0	815,983	22.6	792,607	24.9	787,588	24.2	4.0	4.9
	10	596,386	27.4	650,060	25.1	630,115	26.0	625,520	26.2	4.3	2.2
	5	488,170	29.4	535,729	27.1	515,923	28.0	513,274	28.1	4.7	2.1
	1	293,147	32.9	325,934	31.4	311,024	31.7	310,035	32.0	5.3	1.0
	0.5	221,368	36.9	247,073	35.2	237,512	35.7	235,317	36.0	5.5	1.0
	0.1	134,660	36.5	150,171	35.3	144,582	34.9	143,138	35.6	5.5	1.0
100	25	190,047	32.6	223,707	31.5	238,863	33.2	217,539	32.4	11.5	2.6
	10	136,541	31.3	156,512	31.1	170,240	31.7	154,431	31.4	11.0	1.0
	5	107,558	30.3	122,935	30.5	131,664	30.7	120,719	30.5	10.1	0.3
	1	64,815	26.2	73,274	27.3	77,425	26.7	71,838	26.7	8.9	1.2
	0.5	52,956	25.5	58,729	27.3	62,641	26.1	58,109	26.3	8.4	2.5
	0.1	38,697	21.7	41,710	23.4	45,375	22.1	41,927	22.4	8.0	3.0
130	25	64,192	24.3	70,470	27.9	70,362	27.1	68,341	26.4	5.3	2.9
	10	48,012	22.3	51,133	24.3	51,209	23.0	50,118	23.2	3.6	2.9
	5	38,509	21.2	42,767	22.6	42,418	21.5	41,232	21.8	5.7	2.5
	1	27,409	17.8	28,355	19.2	30,054	17.1	28,606	18.0	4.7	5.7
	0.5	23,437	19.0	24,216	19.2	26,723	17.3	24,792	18.5	6.9	5.2
	0.1	18,070	16.8	18,920	16.9	22,475	15.2	19,822	16.3	11.8	5.1

Table C4. Measured dynamic modulus (psi) and phase angle (^{o}) for mix IM1

Temp.	Freq.	IM1-2		IM1-3		IM1-4		Average		COV	
(°F)	(Hz)	E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	3,799,959	2.6	2,601,843	2.0	3,982,446	2.1	3,461,416	2.3	21.7	5.3
	10	3,753,837	3.8	2,496,021	3.2	3,688,202	3.2	3,312,687	3.4	21.4	3.5
	5	3,652,951	4.2	2,415,023	3.7	3,613,686	3.6	3,227,220	3.8	21.8	2.7
	1	3,335,630	5.7	2,248,723	4.8	3,350,664	4.7	2,978,339	5.1	21.2	4.1
	0.5	3,215,055	6.1	2,159,253	5.6	3,237,335	5.1	2,870,548	5.6	21.5	5.3
	0.1	2,848,330	8.7	1,930,030	6.9	2,936,947	6.5	2,571,769	7.4	21.7	5.9
40	25	2,936,588	7.6	2,306,023	7.4	2,628,656	6.2	2,623,756	7.1	12.0	8.7
	10	2,669,243	9.4	2,123,850	8.4	2,387,624	7.5	2,393,572	8.4	11.4	6.4
	5	2,479,104	10.4	1,978,205	9.4	2,219,253	8.9	2,225,520	9.6	11.3	3.7
	1	2,023,680	12.5	1,647,065	11.8	1,831,862	11.7	1,834,202	12.0	10.3	1.2
	0.5	1,832,462	14.5	1,496,472	13.8	1,661,792	13.3	1,663,575	13.9	10.1	2.2
	0.1	1,395,838	18.6	1,171,372	17.4	1,286,889	16.7	1,284,699	17.6	8.7	2.6
70	25	1,381,109	17.5	1,209,487	16.1	1,374,778	16.0	1,321,791	16.6	7.4	1.7
	10	1,148,381	19.6	1,051,873	18.2	1,168,932	18.4	1,123,062	18.7	5.6	1.4
	5	990,657	21.6	924,039	20.0	1,013,266	20.5	975,987	20.7	4.8	1.7
	1	667,963	26.2	645,987	24.8	696,341	25.6	670,097	25.5	3.8	1.7
	0.5	532,884	31.1	527,143	29.3	558,669	30.4	539,565	30.3	3.1	2.0
	0.1	326,688	36.4	336,008	34.5	347,226	35.7	336,641	35.6	3.1	1.8
100	25	531,206	29.8	497,958	31.0	533,845	29.7	521,003	30.2	3.8	2.2
	10	399,284	30.7	388,278	32.1	411,298	30.9	399,620	31.2	2.9	2.0
	5	311,190	31.4	309,009	32.7	324,458	32.3	314,886	32.1	2.7	0.9
	1	174,020	33.9	174,376	34.1	182,008	33.5	176,801	33.9	2.6	0.9
	0.5	129,253	36.5	127,438	36.3	135,339	36.1	130,677	36.3	3.2	0.4
	0.1	78,904	33.2	80,889	34.1	82,429	32.9	80,740	33.4	2.2	1.7
130	25	146,053	31.5	155,146	34.1	162,314	32.7	154,504	32.8	5.3	2.5
	10	103,815	30.2	111,168	32.0	114,847	30.9	109,943	31.0	5.1	1.9
	5	81,819	29.3	86,641	31.0	89,527	28.8	85,996	29.7	4.5	3.8
	1	50,453	25.7	52,232	27.0	55,751	24.4	52,812	25.7	5.1	5.1
	0.5	41,790	25.1	42,382	26.3	46,695	23.8	43,622	25.0	6.1	4.8
	0.1	31,118	20.4	31,020	22.4	35,485	19.3	32,541	20.7	7.8	7.4

Table C5. Measured dynamic modulus (psi) and phase angle (^{o}) for mix IM2

Temp.	Freq.	IM2-3		IM2-4		IM2-5		Average		COV	
(°F)	(Hz)	E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	2,605,963	1.9	3,033,936	1.6	2,806,081	1.8	2,815,327	1.8	7.6	6.1
	10	2,447,338	3.3	2,843,993	3.9	2,636,216	3.6	2,642,516	3.6	7.5	5.1
	5	2,358,315	3.9	2,728,723	4.4	2,538,667	4.5	2,541,902	4.3	7.3	2.4
	1	2,152,103	4.9	2,481,817	5.4	2,300,639	5.8	2,311,520	5.4	7.1	4.1
	0.5	2,046,140	6.3	2,357,737	6.4	2,192,267	6.4	2,198,715	6.4	7.1	0.4
	0.1	1,814,534	8.0	2,102,922	8.1	1,949,646	8.1	1,955,701	8.1	7.4	0.3
40	25	2,128,822	6.9	2,079,287	8.0	2,283,495	8.4	2,163,868	7.7	4.9	4.2
	10	1,953,805	9.3	1,883,446	9.4	2,068,485	9.4	1,968,579	9.4	4.7	0.3
	5	1,805,862	10.7	1,745,094	10.9	1,923,983	10.5	1,824,980	10.7	5.0	1.5
	1	1,477,836	13.6	1,426,612	13.6	1,557,069	13.3	1,487,172	13.5	4.4	1.2
	0.5	1,326,630	16.0	1,282,367	16.0	1,402,179	15.8	1,337,059	15.9	4.5	0.6
	0.1	1,005,749	20.5	989,641	21.0	1,060,961	20.6	1,018,784	20.7	3.7	1.0
70	25	1,164,844	17.7	1,039,816	17.9	1,159,003	17.7	1,121,221	17.8	6.3	0.6
	10	981,247	20.6	892,251	19.5	990,120	20.2	954,540	20.1	5.7	1.8
	5	838,401	22.7	772,477	21.4	851,263	22.4	820,714	22.2	5.1	2.3
	1	556,741	27.5	526,349	25.9	564,424	27.6	549,171	27.0	3.7	3.1
	0.5	438,200	32.0	419,561	30.7	442,962	32.5	433,575	31.7	2.9	2.9
	0.1	273,853	34.6	266,525	34.0	275,763	35.8	272,047	34.8	1.8	2.5
100	25	431,713	29.4	408,029	29.7	427,375	30.5	422,372	29.9	3.0	1.5
	10	325,805	30.1	310,328	29.9	329,354	31.1	321,829	30.3	3.1	2.0
	5	257,763	31.1	245,458	30.6	257,528	32.3	253,583	31.3	2.8	2.8
	1	149,487	30.3	140,355	30.1	145,038	31.9	144,960	30.8	3.2	3.0
	0.5	116,629	31.2	106,821	31.2	110,680	33.3	111,376	31.9	4.4	3.4
	0.1	77,841	27.3	70,007	27.3	70,706	28.5	72,851	27.7	6.0	2.2
130	25	131,571	29.7	131,743	28.7	138,224	31.0	133,846	29.8	2.8	3.9
	10	95,559	27.4	94,123	27.2	95,565	29.1	95,082	27.9	0.9	3.4
	5	75,952	25.1	74,372	25.6	75,673	27.6	75,332	26.1	1.1	3.9
	1	52,245	19.6	49,839	20.7	48,044	22.4	50,043	20.9	4.2	4.3
	0.5	46,451	18.6	43,082	19.4	40,782	21.4	43,438	19.8	6.6	5.4
	0.1	37,988	15.8	36,192	15.2	31,357	18.3	35,179	16.4	9.7	9.5

Table C6. Measured dynamic modulus (psi) and phase angle (^{o}) for mix IM3

Temp.	Freq.	IM3-2		IM3-3		IM3-4		Average		COV	
(°F)	(Hz)	E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	4,452,108	1.4	4,855,793	1.3	3,972,295	1.7	4,426,732	1.5	10.0	12.7
	10	4,147,984	2.7	4,774,115	2.0	3,749,068	3.4	4,223,722	2.7	12.2	26.4
	5	4,061,687	3.1	4,609,931	2.6	3,648,963	3.9	4,106,860	3.2	11.7	19.7
	1	3,732,299	3.6	4,406,009	4.0	3,381,910	4.6	3,840,073	4.1	13.6	7.1
	0.5	3,601,152	4.5	4,256,903	4.3	3,281,101	4.7	3,713,052	4.5	13.4	4.4
	0.1	3,193,363	5.9	3,832,866	5.8	2,953,355	6.5	3,326,528	6.1	13.7	5.5
40	25	3,293,186	7.0	3,264,995	6.9	3,083,954	6.6	3,214,045	6.8	3.5	2.6
	10	3,034,184	7.9	2,990,993	8.8	2,803,589	8.5	2,942,922	8.4	4.2	2.7
	5	2,856,427	8.9	2,803,244	9.4	2,619,815	9.3	2,759,829	9.2	4.5	1.0
	1	2,423,009	11.7	2,293,669	12.2	2,199,691	11.5	2,305,456	11.8	4.9	2.9
	0.5	2,212,741	13.3	2,083,455	13.7	2,011,295	13.6	2,102,497	13.5	4.9	0.8
	0.1	1,732,610	17.3	1,589,018	18.0	1,586,123	16.9	1,635,917	17.4	5.1	3.2
70	25	1,671,721	14.9	1,536,779	15.9	1,510,027	16.3	1,572,842	15.7	5.5	1.9
	10	1,423,630	17.4	1,235,485	18.8	1,283,071	18.4	1,314,062	18.2	7.4	1.7
	5	1,236,177	19.4	1,026,527	20.8	1,119,150	20.0	1,127,285	20.1	9.3	2.4
	1	849,901	24.0	680,152	25.9	773,213	25.0	767,755	25.0	11.1	2.1
	0.5	685,036	29.4	540,821	30.6	624,662	29.9	616,840	30.0	11.7	1.2
	0.1	429,012	35.2	337,372	35.7	392,263	34.3	386,216	35.0	11.9	1.9
100	25	629,206	28.4	458,595	29.9	542,246	30.2	543,349	29.5	15.7	1.2
	10	475,783	29.1	354,810	30.2	413,327	30.8	414,640	30.0	14.6	1.3
	5	373,945	30.6	282,296	31.4	324,580	32.1	326,940	31.3	14.0	1.4
	1	212,183	31.8	162,819	32.7	178,584	33.1	184,529	32.6	13.7	0.9
	0.5	162,625	33.6	124,567	34.7	134,239	34.6	140,477	34.3	14.1	0.6
	0.1	103,135	29.9	79,681	30.8	82,001	29.8	88,272	30.2	14.6	1.7
130	25	187,590	31.0	145,030	33.8	148,449	33.2	160,356	32.6	14.7	1.7
	10	134,521	27.6	109,175	29.2	105,573	30.0	116,423	28.9	13.6	1.9
	5	107,288	26.2	88,131	26.4	83,579	27.6	92,999	26.7	13.5	2.3
	1	68,735	20.9	60,075	20.1	54,684	21.8	61,165	21.0	11.6	3.9
	0.5	60,064	19.8	53,125	18.9	46,832	20.4	53,340	19.7	12.4	3.7
	0.1	48,331	16.1	45,660	14.7	37,749	16.4	43,913	15.7	12.5	5.3

Table C7. Measured dynamic modulus (psi) and phase angle (°) for mix IM4

Temp.	Freq.	IM4-2		IM4-3		IM4-4		Average		COV	
(°F)	(Hz)	E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	2,657,970	2.3	2,812,233	2.7	4,580,072	1.7	3,350,092	2.2	31.9	22.9
	10	2,475,741	3.6	2,644,419	4.1	4,164,395	3.1	3,094,851	3.6	30.1	13.7
	5	2,419,100	4.0	2,567,555	4.2	4,045,120	4.1	3,010,592	4.1	29.9	1.8
	1	2,233,736	4.8	2,407,288	5.2	3,709,436	4.7	2,783,487	4.9	29.0	5.9
	0.5	2,143,259	5.7	2,322,889	5.8	3,573,326	5.7	2,679,825	5.7	29.1	1.2
	0.1	1,925,529	7.5	2,105,238	7.3	3,390,296	7.5	2,473,688	7.4	32.3	1.3
40	25	2,643,782	5.4	2,429,997	8.2	3,321,266	4.5	2,798,348	6.0	16.6	30.5
	10	2,407,619	8.9	2,214,430	9.9	2,965,105	8.0	2,529,051	8.9	15.4	10.7
	5	2,232,901	10.4	2,044,376	10.9	2,731,903	9.2	2,336,393	10.2	15.2	8.1
	1	1,833,855	13.3	1,667,274	13.6	2,211,338	12.6	1,904,156	13.1	14.6	3.7
	0.5	1,651,763	15.3	1,507,748	16.4	1,975,491	15.0	1,711,667	15.6	14.0	4.4
	0.1	1,237,071	20.6	1,125,176	21.5	1,466,763	19.4	1,276,337	20.5	13.6	5.1
70	25	1,285,329	18.1	1,141,262	19.3	1,240,421	18.5	1,222,337	18.6	6.0	2.1
	10	1,073,681	20.4	940,392	21.4	1,009,489	21.4	1,007,854	21.0	6.6	1.0
	5	912,361	22.4	799,226	23.9	857,114	23.5	856,234	23.3	6.6	1.4
	1	586,279	28.4	512,119	29.6	554,227	28.7	550,875	28.9	6.8	1.5
	0.5	457,702	34.0	395,819	34.7	432,541	33.5	428,687	34.1	7.3	1.6
	0.1	264,301	37.6	232,494	38.1	259,250	37.3	252,015	37.6	6.8	1.0
100	25	392,634	33.2	320,708	33.3	416,349	32.6	376,564	33.0	13.2	1.1
	10	284,060	33.4	229,886	33.5	303,165	33.6	272,370	33.5	14.0	0.1
	5	216,991	33.7	174,849	33.6	228,749	34.3	206,863	33.9	13.7	1.1
	1	120,020	31.5	95,694	30.8	122,776	33.2	112,830	31.8	13.2	3.9
	0.5	93,060	31.3	74,265	30.2	92,747	33.2	86,691	31.6	12.4	4.8
	0.1	62,819	25.4	50,296	24.1	60,531	27.4	57,882	25.6	11.5	6.4
130	25	106,757	27.8	88,874	29.6	118,890	30.3	104,840	29.2	14.4	1.8
	10	77,808	24.6	62,763	26.3	83,239	27.7	74,603	26.2	14.2	3.3
	5	63,655	22.4	50,928	23.7	66,665	25.3	60,416	23.8	13.8	3.8
	1	46,059	17.2	36,741	17.9	45,635	19.7	42,812	18.3	12.3	5.0
	0.5	40,996	16.4	32,916	17.3	39,905	18.9	37,939	17.5	11.6	4.8
	0.1	34,751	14.3	28,956	14.9	33,278	16.5	32,328	15.2	9.3	5.6

Table C8. Measured dynamic modulus (psi) and phase angle (°) for mix BM1

Temp.	Freq.	BM1-2		BM1-3		BM1-4		Average		COV	
(°F)	(Hz)	E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	5,447,739	2.1	3,485,635	2.6	3,882,122	2.1	4,271,832	2.3	24.3	10.9
	10	5,413,769	3.1	3,327,852	4.0	3,785,768	4.1	4,175,796	3.7	26.3	5.3
	5	5,324,707	4.1	3,184,952	4.0	3,682,742	4.1	4,064,134	4.0	27.6	2.3
	1	4,913,648	4.5	2,949,123	5.3	3,403,574	5.2	3,755,448	5.0	27.4	3.1
	0.5	4,645,392	5.3	2,843,608	5.9	3,256,281	6.8	3,581,760	6.0	26.4	8.3
	0.1	4,165,139	6.2	2,561,345	7.5	2,926,127	7.2	3,217,537	6.9	26.1	4.1
40	25	3,553,105	8.0	2,650,021	7.4	2,108,273	8.3	2,770,466	7.9	26.3	5.6
	10	2,887,174	9.0	2,360,778	8.3	1,884,691	9.7	2,377,548	9.0	21.1	8.0
	5	2,665,246	10.0	2,176,510	9.8	1,760,262	10.5	2,200,672	10.1	20.6	3.3
	1	2,387,308	12.7	1,767,299	12.4	1,454,401	12.7	1,869,669	12.6	25.4	1.1
	0.5	2,153,432	14.7	1,587,311	14.5	1,314,041	14.8	1,684,928	14.7	25.4	1.1
	0.1	1,594,256	18.7	1,185,581	18.5	1,179,444	18.9	1,319,760	18.7	18.0	0.9
70	25	1,765,965	16.9	1,182,073	18.1	1,310,017	17.5	1,419,351	17.5	21.6	2.0
	10	1,449,398	19.3	1,007,644	20.1	1,104,885	19.7	1,187,309	19.7	19.6	1.1
	5	1,228,859	21.4	880,915	21.9	951,448	21.6	1,020,407	21.6	18.0	0.7
	1	803,462	26.5	612,984	26.3	644,093	26.8	686,846	26.5	14.9	1.1
	0.5	632,776	31.5	498,213	31.1	518,879	32.0	549,956	31.5	13.2	1.4
	0.1	380,176	35.7	317,447	35.1	335,334	36.1	344,319	35.6	9.4	1.4
100	25	525,283	30.1	418,352	31.7	489,516	31.7	477,717	31.2	11.4	1.0
	10	401,153	30.2	339,781	31.4	399,793	31.9	380,242	31.1	9.2	1.3
	5	315,981	31.2	270,744	31.9	310,619	32.8	299,115	31.9	8.3	1.6
	1	179,849	31.4	158,322	32.1	174,455	33.2	170,875	32.2	6.6	1.9
	0.5	136,912	32.7	123,285	33.7	131,194	35.2	130,464	33.9	5.2	2.5
	0.1	88,572	29.0	80,196	30.8	82,686	31.6	83,818	30.4	5.1	1.9
130	25	176,818	30.6	139,727	31.0	152,199	31.5	156,248	31.0	12.1	0.8
	10	124,760	28.2	104,543	29.0	113,799	29.1	114,367	28.8	8.8	0.6
	5	100,603	26.7	83,649	27.5	90,773	27.9	91,675	27.4	9.3	1.0
	1	65,282	22.6	53,867	22.8	57,180	23.6	58,776	23.0	10.0	1.9
	0.5	56,188	21.3	46,972	21.7	48,735	22.6	50,632	21.9	9.7	2.3
	0.1	45,979	17.3	38,053	18.3	37,690	18.7	40,574	18.1	11.5	1.6

Table C9. Measured dynamic modulus (psi) and phase angle (^{o}) for mix BM2

Temp.	Freq.	BM2-1		BM2-2		BM2-3		Average		COV	
(°F)	(Hz)	E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	4,651,571	2.1	4,714,695	2.3	4,267,176	3.0	4,544,481	2.5	5.3	15.2
	10	4,518,000	5.1	4,526,405	4.5	4,190,307	5.4	4,411,571	5.0	4.3	9.7
	5	4,367,265	5.8	4,342,129	5.2	4,021,055	5.5	4,243,483	5.5	4.5	3.1
	1	3,858,460	6.5	4,074,193	5.8	3,633,689	8.0	3,855,447	6.8	5.7	16.5
	0.5	3,685,568	7.6	3,873,692	7.7	3,401,185	8.6	3,653,482	8.0	6.5	5.4
	0.1	3,170,742	9.9	3,319,661	9.8	2,534,385	10.6	3,008,263	10.1	13.9	3.8
40	25	2,549,444	8.7	2,656,520	10.1	2,428,547	9.7	2,544,837	9.5	4.5	3.1
	10	2,213,821	12.0	2,342,522	10.9	2,130,873	12.4	2,229,072	11.7	4.8	6.4
	5	2,003,846	13.9	2,150,109	13.9	1,959,750	13.6	2,037,902	13.8	4.9	1.0
	1	1,524,369	17.1	1,623,750	17.3	1,495,662	17.2	1,547,927	17.2	4.3	0.3
	0.5	1,294,042	20.4	1,379,798	20.7	1,259,423	22.2	1,311,087	21.1	4.7	3.8
	0.1	870,244	27.2	919,171	28.5	846,866	28.5	878,760	28.1	4.2	0.9
70	25	911,738	24.2	921,885	23.0	971,132	23.2	934,918	23.5	3.4	1.0
	10	727,513	25.9	725,356	25.6	782,963	24.7	745,277	25.4	4.4	1.8
	5	599,049	27.9	590,919	27.6	654,171	26.4	614,713	27.3	5.6	2.4
	1	365,923	31.5	356,618	31.6	404,076	30.2	375,539	31.1	6.7	2.3
	0.5	284,493	35.5	273,293	35.5	313,885	34.0	290,557	35.0	7.2	2.1
	0.1	177,334	35.4	167,309	35.6	198,888	35.2	181,177	35.4	8.9	0.6
100	25	263,263	32.2	268,881	32.2	312,267	29.8	281,470	31.4	9.5	4.0
	10	191,351	30.2	200,622	29.4	228,510	28.7	206,827	29.4	9.4	1.5
	5	152,247	28.5	160,347	27.7	183,511	26.8	165,368	27.7	9.8	1.8
	1	97,052	23.4	104,271	22.7	120,186	21.7	107,170	22.6	11.0	2.4
	0.5	82,578	22.4	89,528	21.6	104,784	20.1	92,297	21.4	12.3	3.7
	0.1	64,200	18.8	70,283	18.0	87,139	16.1	73,874	17.6	16.1	5.6
130	25	85,700	24.1	101,687	28.9	130,659	21.7	106,016	24.9	21.5	14.5
	10	69,581	21.1	76,132	24.5	99,583	17.9	81,765	21.2	19.3	15.6
	5	59,519	19.4	65,951	20.6	86,538	15.4	70,669	18.4	20.0	14.3
	1	44,679	15.6	56,015	15.2	71,538	10.5	57,411	13.8	23.5	17.7
	0.5	39,750	16.2	52,816	16.2	68,337	10.5	53,635	14.3	26.7	20.3
	0.1	31,541	16.7	45,642	18.3	66,560	14.8	47,915	16.6	36.8	10.5

Table C10. Measured dynamic modulus (psi) and phase angle (^{o}) for mix BM3

Temp.	Freq.	BM3-2		BM3-3		BM3-4		Average		COV	
(°F)	(Hz)	E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	3,905,150	1.0	4,500,290	1.2	5,846,646	0.7	4,750,695	1.0	20.9	25.8
	10	3,700,068	2.8	4,299,523	2.9	5,799,677	2.8	4,599,756	2.8	23.5	2.3
	5	3,611,326	3.0	4,166,157	3.2	5,656,177	3.0	4,477,887	3.1	23.6	4.4
	1	3,378,276	4.0	3,879,639	4.3	5,246,119	4.4	4,168,011	4.2	23.2	2.1
	0.5	3,278,735	4.5	3,721,678	4.6	5,089,470	4.6	4,029,961	4.6	23.4	0.9
	0.1	3,034,728	5.4	3,383,135	5.6	4,565,363	6.0	3,661,075	5.6	21.9	3.4
40	25	3,326,260	6.1	2,918,242	7.0	3,740,895	5.9	3,328,466	6.3	12.4	8.2
	10	3,132,914	7.6	2,694,654	8.3	3,467,443	7.1	3,098,337	7.6	12.5	8.0
	5	2,962,230	8.3	2,552,201	9.0	3,266,949	7.6	2,927,127	8.3	12.3	8.4
	1	2,512,802	10.7	2,169,892	11.4	2,792,918	9.5	2,491,871	10.5	12.5	8.8
	0.5	2,786,871	12.3	1,979,919	12.9	3,065,746	11.4	2,610,845	12.2	21.6	6.1
	0.1	2,219,083	15.6	1,581,851	16.9	2,401,845	14.4	2,067,593	15.6	20.8	7.9
70	25	2,478,302	14.6	2,451,896	16.4	2,118,546	14.6	2,349,581	15.2	8.5	6.1
	10	2,154,928	16.1	2,131,138	18.0	1,812,104	16.7	2,032,723	16.9	9.4	4.0
	5	1,890,333	17.8	1,873,017	19.9	1,590,944	18.7	1,784,765	18.8	9.4	3.6
	1	1,324,571	23.4	1,303,774	25.0	1,114,390	23.9	1,247,578	24.1	9.3	2.4
	0.5	1,074,409	28.5	1,061,624	30.1	909,894	29.0	1,015,309	29.2	9.0	2.0
	0.1	675,622	35.0	655,186	34.6	580,895	34.7	637,234	34.7	7.8	0.2
100	25	949,573	27.0	756,416	27.9	889,094	27.7	865,027	27.5	11.4	0.7
	10	719,699	29.0	577,747	29.2	666,049	29.1	654,499	29.1	11.0	0.2
	5	575,496	30.9	455,777	31.2	530,107	31.1	520,460	31.1	11.6	0.2
	1	326,092	34.0	256,419	32.8	301,151	32.7	294,554	33.2	12.0	0.8
	0.5	244,189	37.4	193,379	35.2	228,570	34.9	222,046	35.8	11.7	1.3
	0.1	147,025	36.0	115,953	32.0	144,868	32.3	135,949	33.4	12.8	2.3
130	25	255,963	33.0	196,535	34.4	257,083	31.4	236,527	32.9	14.6	4.5
	10	180,644	31.0	141,720	31.3	179,485	30.0	167,283	30.7	13.2	2.2
	5	141,426	29.3	111,404	29.4	141,275	28.1	131,368	28.9	13.2	2.2
	1	86,980	25.2	70,200	23.3	90,302	23.1	82,494	23.9	13.1	1.6
	0.5	72,547	24.5	59,844	22.0	75,484	21.7	69,292	22.7	12.0	2.4
	0.1	55,925	20.7	47,528	16.5	57,005	17.7	53,486	18.3	9.7	4.9

Table C11. Measured dynamic modulus (psi) and phase angle (^{o}) for mix BM4

Temp.	Freq.	BM4-2		BM4-3		BM4-4		Average		COV	
(°F)	(Hz)	E*	δ	E*	δ	E*	δ	E*	δ	E*	δ
10	25	3,540,046	2.1	3,842,694	1.4	4,707,724	1.9	4,030,155	1.8	15.0	15.4
	10	3,368,617	3.8	3,577,179	3.6	4,544,577	3.9	3,830,124	3.8	16.4	4.9
	5	3,263,571	4.4	3,451,583	4.1	4,392,572	4.6	3,702,575	4.3	16.3	6.4
	1	2,981,059	5.6	3,147,331	5.4	3,949,895	5.9	3,359,428	5.6	15.4	4.7
	0.5	2,840,533	6.6	2,999,772	6.5	3,772,071	6.9	3,204,125	6.7	15.6	2.9
	0.1	2,543,403	8.1	2,642,462	7.9	3,333,092	8.9	2,839,652	8.3	15.1	5.6
40	25	2,721,273	7.1	2,507,241	7.8	3,041,786	8.3	2,756,767	7.8	9.8	4.0
	10	2,479,387	8.5	2,264,334	9.9	2,745,971	9.5	2,496,564	9.3	9.7	3.4
	5	2,287,170	10.2	2,087,871	11.5	2,530,745	10.9	2,301,929	10.9	9.6	3.2
	1	1,846,520	13.3	1,663,513	14.7	2,018,162	13.7	1,842,732	13.9	9.6	4.1
	0.5	1,653,696	16.0	1,476,546	17.5	1,796,165	16.2	1,642,136	16.5	9.8	4.1
	0.1	1,227,941	21.3	1,088,847	22.7	1,318,185	20.7	1,211,658	21.6	9.5	4.5
70	25	1,228,439	20.4	1,197,603	20.5	1,333,620	18.6	1,253,220	19.8	5.7	4.9
	10	1,027,762	22.1	1,002,541	21.9	1,115,483	20.7	1,048,595	21.6	5.7	2.8
	5	874,549	24.3	857,984	24.0	950,821	22.8	894,451	23.7	5.5	2.8
	1	565,797	29.0	557,965	28.6	630,825	27.5	584,862	28.4	6.8	2.0
	0.5	438,742	33.8	432,133	33.3	497,287	32.3	456,054	33.1	7.9	1.6
	0.1	266,331	35.6	264,959	36.2	307,673	35.4	279,654	35.7	8.7	1.1
100	25	392,481	30.5	333,837	31.9	521,892	29.8	416,070	30.7	23.1	3.3
	10	293,821	31.3	263,456	32.2	399,434	29.7	318,904	31.1	22.4	3.9
	5	229,641	31.7	206,954	32.5	314,677	31.0	250,424	31.7	22.7	2.4
	1	130,671	29.8	116,785	31.2	178,562	31.4	142,006	30.8	22.8	1.0
	0.5	100,790	30.0	89,973	32.1	134,823	32.9	108,528	31.7	21.6	2.0
	0.1	67,640	25.1	58,320	27.3	85,374	29.0	70,445	27.1	19.5	3.8
130	25	119,647	29.8	112,410	31.0	158,656	30.5	130,238	30.4	19.1	0.9
	10	86,973	26.6	79,318	28.8	112,840	28.4	93,043	27.9	18.9	1.5
	5	70,839	24.5	62,337	27.2	89,867	26.9	74,348	26.2	19.0	2.0
	1	47,882	19.5	40,235	22.7	58,469	22.3	48,862	21.5	18.7	2.8
	0.5	41,575	18.8	34,007	22.6	49,814	21.8	41,799	21.1	18.9	3.6
	0.1	33,536	15.9	26,082	18.5	39,175	19.3	32,931	17.9	19.9	4.0