EVALUATION OF THE CECABASE^{TM} RT WARM-MIX ADDITIVE

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1. INTRODUCTION

This report summarizes the test results for the laboratory evaluation that was conducted at the University of Nevada Reno (UNR) to assess the use of Cecabase™ RT warm-mix additive with a typical dense-graded asphalt mixture used in California and Nevada. The completed experimental plan followed largely the testing requirements for the warm-mix asphalt technology approval process in California. The WMA mixture was produced in the laboratory and compared to an HMA control using identical aggregates, binder and mix design.

2. MATERIALS AND MIX DESIGNS

2.1 Aggregate

The aggregate source for this study was a hard rock quarry in Nevada that supplies hot mix aggregates to California and Nevada. The aggregate blend selected for laboratory evaluation followed the Caltrans 19.0 mm Maximum, Type A specifications and the NDOT Type 2C specifications as prescribed by the Caltrans Standard Specifications *(1)* and NDOT Standard Specifications for Road and Bridge Construction *(2)*, respectively. Figure 1 shows the gradation of the aggregate blend developed for this study along with the Caltrans and NDOT specifications. The aggregate blend was achieved by blending five different aggregate stockpiles as shown in Table 1.

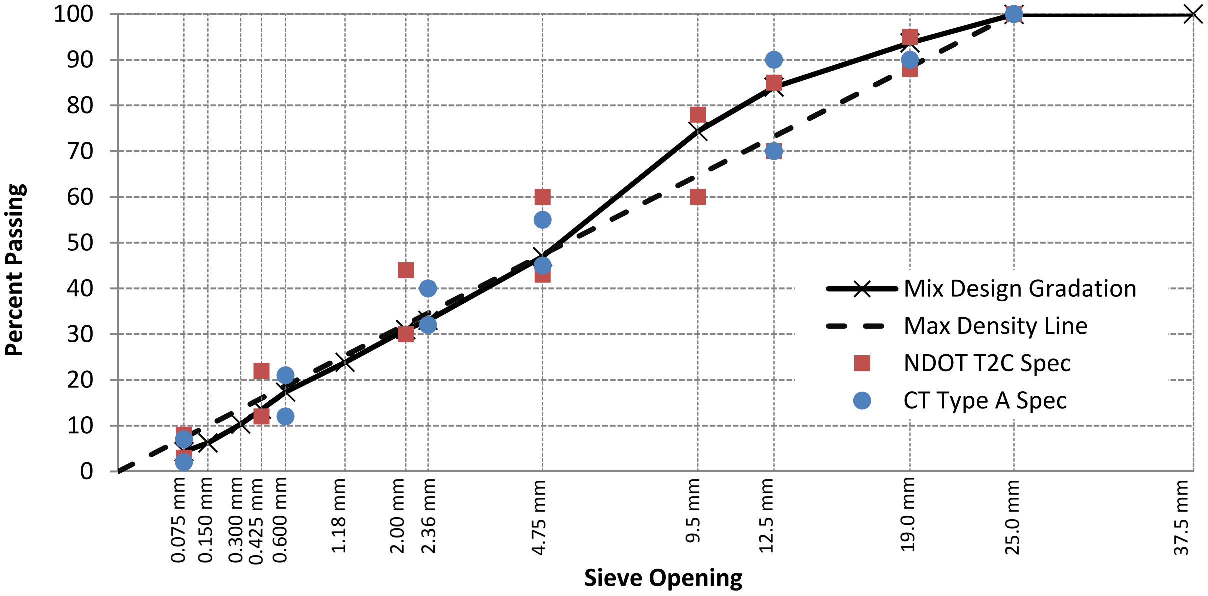


Figure 1 Aggregate blend gradation and control points

Table 1 Aggregate Bin Percentages

Aggregate Stockpile	**25 mm Crushed Rock**	**12.5 mm Crushed Rock**	**9.5 mm Crushed Rock**	**Crushed Fines**	**Wade Sand**
Bin Percentage (%)	16	16	30	28	10

2.2 Warm-Mix Additive

The Cecabase™ RT warm-mix additive was evaluated in this effort. The Cecabase™ RT is a patented chemical additive developed by CECA, a member company of Arkema Group. It has been developed in the early 2000's by the team of Gilles BARRETO in the Arkema's research center (CRRA) near Lyon (France). The additive contains surface active agents composed of at least 50% renewable raw materials. In this study, the Cecabase™ RT was added in the laboratory to the asphalt binder at a recommended rate of 0.4% by weight of binder.

2.3 Asphalt Binder

A PG64-28PM/NV polymer-modified asphalt binder typically utilized in California and Nevada was used in this study. The "PM" extension indicates that the binder meet the CalTrans performance grade (PG) "plus" specifications which includes the standard Superpave PG binder system plus the following properties: maximum phase angle on RTFO binder at the high critical performance temperature and elastic recovery on RTFO binder at 25°C. The "NV" extension indicates that the binder meet the NDOT PG "plus" specifications which includes the standard Superpave PG binder system plus the following properties: toughness and tenacity on original binder at 25°C and ductility on original and RTFO binder at 4°C. The asphalt binder was supplied by Paramount Petroleum Company.

The asphalt binder was fully graded at the University of Nevada Reno before and after the addition of the Cecabase™ RT following the AASHTO R29-08 procedure *(3)*. Tables 2 and 3 summarize the test results and the PG grading of the asphalt binders. The critical temperatures in Table 3 are the temperatures at which a binder meets the appropriate specified Superpave criteria. The data show that the asphalt binder, with and without Cecabase™ RT, met the Caltrans and NDOT specifications for polymer-modified asphalt binders. The use of 0.4% Cecabase™ RT resulted in 1.2 and 0.7°C decrease in the high and low critical temperatures of the asphalt binder, respectively. In other words, a slight softening in the asphalt binder was observed because of the use of the Cecabase™ RT. However, no change in the asphalt binder performance grade was observed.

Table 2 Asphalt Binders Grading Test Results and Specifications

Property		Specification	Test Results	
			PG64-28PM/NV	PG64-28PM/NV +0.4% Cecabase
Tests on Original Binder				
Flash Point, min,°C		230	283	279
RV at 135 °C, max, Pas		3.0	0.860	0.818
G*/sin(δ) at 64°C, min, kPa		1.00	1.96	1.81
Tests on Residue from RTFOT				
Mass Loss, max, %		1.00	0.463	0.510
G*/sin(δ) at 64°C, min, kPa		2.20	4.18	3.72
Tests on Residue from Pressure Aging Vessel @ 100°C				
G*sin(δ) at 22°C, max, kPa		5000	2929	3017
Creep Stiffness at -18°C, max, MPa		300	110	93
m-value at -18°C, min		0.300	0.331	0.353
PG Plus Requirement				
Tests on Original Binder				
NDOT	Ductility (5cm/min), cm, at 4°C, min	50.0	69	67
	Toughness (in-lbs) at 25 °C, min	110.0	162	156
	Tenacity (in-lbs) at 25 °C, min	75.0	146	140
Tests on Residue from RTFOT				
NDOT	Ductility (5cm/min), cm, at 4°C, min	25.0	34	37
Caltrans	δ when G*/sin(δ) = 2.2 kPa, max	80.0	64.5	63.8
	Elastic recovery at 25°C, min, %	75.0	83.8	85.0

Table 3 Asphalt Binders Critical Temperatures and PG Grades

Binder	Critical Temperatures, °C			PG Grade
	High	Intermediate	Low	
PG64-28PM/NV	71.1	11.2	-32.4	64-28
PG64-28PM/NV+0.4% Cecabase	69.9	11.6	-33.1	64-28

2.4 Mix Designs

The HMA mixture was designed to meet the Caltrans and NDOT specifications for the Hveem mix design methods with a minimum unconditioned tensile strength (TS) of 448 kPa and a minimum retained tensile strength ratio (TSR) of 70%. Even though NDOT mandates the use of hydrated lime in all its mixtures, it was not used in this study so that only the impact of the Cecabase™ RT on the mixture properties can be evaluated.

A mixing temperature of 160°C was used for preparing the HMA samples. The mixing temperature was determined utilizing the temperature-viscosity chart as described in AASHTO T 312 *(3)*. The loose mixture was short-term oven aged for 16±1 hours at 60°C before compaction at 110°C following Caltrans and NDOT Hveem mix design methods. The same process was followed for the WMA mixture with the exception that a mixing temperature of 132°C was used following the supplier recommendation for the Cecabase™ RT. The optimum binder content was determined for the HMA mixture and then verified for the WMA mixture. Table 4 summarizes the primary mix designs data for the HMA and WMA mixtures along with the corresponding Caltrans and NDOT specifications. The data in Table 4 show that the WMA mixture met both the Caltrans and NDOT specifications for mix design. A slight increase in the design air void (from 4.0 to 4.7%) was observed at the optimum binder content when the Cecabase™ RT was introduced to the mix. However, this slight increase in the design air voids is well considered within the testing variability and tolerance and would not necessitate adjustment to the optimum binder content for the WMA mix using the Cecabase™ RT.

The resistance of the HMA and WMA mixtures to moisture damage was evaluated by means of indirect tensile strength of the mixtures unconditioned and after one freeze-thaw (F-T) cycle. The samples preparation, F-T cycling and testing followed the procedure outlined in CTM 371 and Nev. T341. Cylindrical specimens 100 mm in diameter and 63 mm thick were prepared at UNR using Caltrans CTM 304 Kneading compaction. Both HMA and WMA loose samples were subjected to short-term oven aging of 16±1 hours at 60°C before compaction at 110°C. The CTM 371 requires samples with 6.5-7.5% air voids, while the Nev. T341 requires samples with 7.0-8.0% air voids; therefore, samples were made to contain 7.0% to 7.5% air voids. A total of 12 samples from each mix were evaluated following the procedure outlined below:

- Measure the unconditioned TS of 6 samples (i.e., 0 F-T cycles)
- Subject the other set of 6 samples to 70-80% saturation
- Subject the saturated samples to one F-T cycle: freezing at -18°C for 16 hours followed by 24 hours thawing at 60°C and 2 hours at 25°C.
- Conduct TS testing after 1 cycle.

Table 4 shows the average TS and TSR values for the evaluated mixtures. Both, the HMA and WMA mixtures met the minimum TS of 448 kPa and the minimum TSR of 70% at 25°C.

The mixture resistance to moisture damage was also evaluated at a different short-term oven aging condition using the indirect tensile strength test. Following AASHTO R30 *(3)*, loose HMA and WMA mixtures were short-term oven aged for 4 hours at 135°C before compaction at 110°C. Figure 2 shows the TS and TSR test results for the evaluated mixtures with the error bars representing the 95% confidence interval. Overlapping of the confidence intervals implies the similarity in the measured TS between the mixtures. The data in Figure 4 show an increase in the unconditioned TS value of the HMA and WMA mixtures when a 4 hour short-term oven aging at 135°C was used in comparison to the 16 hours at 60°C. Both mixtures exhibited similar unconditioned TS values for the 16 hours short-term oven aging. When a 4 hour short-term oven aging was used, the WMA mixture exhibited slightly higher unconditioned TS value than the HMA mixture. In all cases the HMA and WMA mixtures exhibited similar moisture-conditioned

TS values. Furthermore, similar TSR values were observed between the HMA and WMA mixtures. The use of a 4 hour short-term oven aging at 135°C instead of 16 hours at 60°C resulted in a similar reduction in the TSR value for the HMA and WMA mixtures.

Table 4 Mix Design Summary and Specifications

Property	**HMA**	**WMA**[1]	**Specifications**	
			Caltrans	NDOT
Mixing Temperature, °C	160	132	--	--
Compaction Temperature, °C	110	110	--	--
Optimum Binder (OBC), % DWA[2]	5.80	5.80	--	--
Design Air Voids, % TWM[3]	4.0	4.7	4.0	4.0 – 7.0
Maximum Theoretical Specific Gravity	2.425	2.445	--	--
Voids in Mineral Aggregates (VMA), %				
Caltrans Procedure	13.5	13.7	13 Min.	--
NDOT Procedure	15.9	16.1	--	12 – 22
Voids Filled with Asphalt (VFA), %				
Caltrans Procedure	70.6	65.5	65 – 75	--
NDOT Procedure	75.4	70.7	--	70 – 80
Hveem Stability	42	40	37 Min.	37 Min.
Unconditioned Tensile Strength, kPa	483	515	--	448 Min.
Tensile Strength Ratio, %	87	82	--	70 Min.

[1] 0.4% Cecabase by weight of binder
[2] DWA denotes "Dry Weight of Aggregate"
[3] TWM denotes "Total Weight of Mix"

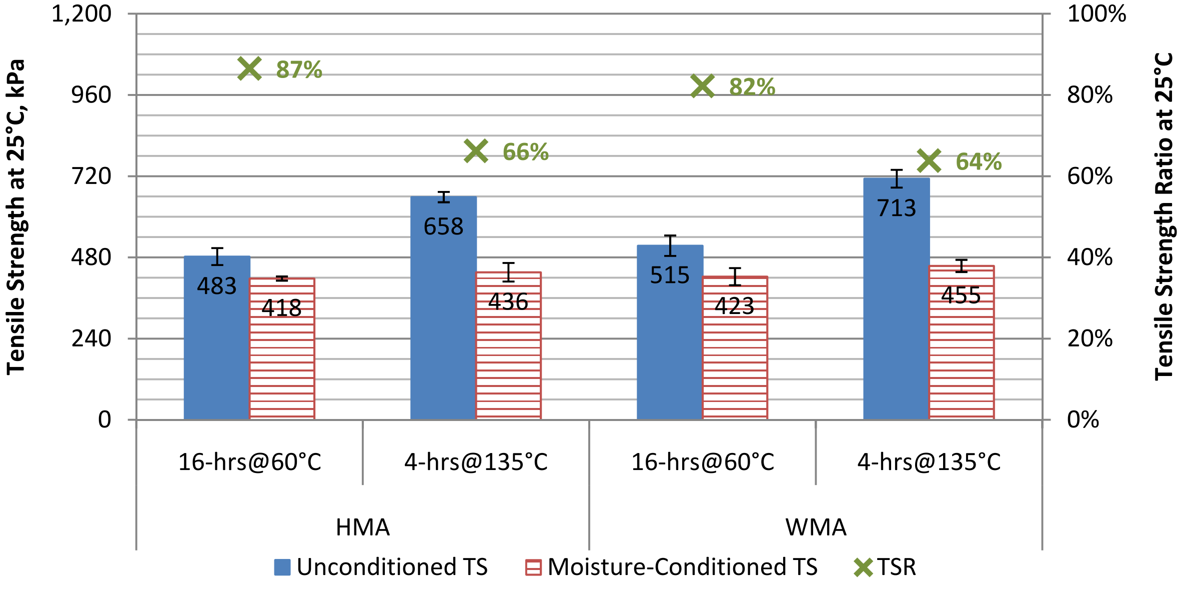


Figure 2 Tensile strength and TSR values at 25°C and for different short-term oven aging conditions of loose mixtures (Numbers inside bars represent mean values and whiskers represent mean ± 95% confidence interval)

3. MECHANICAL PROPERTIES OF MIXTURES

The HMA control and WMA mixtures were evaluated for rutting resistance, fatigue resistance and moisture damage resistance. Compaction temperatures of 135°C and 118°C were used to prepare the HMA and WMA samples for mechanical testing, respectively.

3.1 Superpave Shear Tester

The AASHTO T-320 test *(3)*: "Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST)," was used for rutting performance and stiffness evaluation. Cylindrical test specimens 150 mm in diameter and 50 mm thick were prepared in the laboratory using the Superpave Gyratory Compactor (SGC). After mixing, the loose HMA and WMA mixtures were short-term oven aged for 4 hours at 135°C before compaction. In the case of WMA, the loose mixture was allowed to cool down for 30 minutes in an oven at 118°C before compaction. All test specimens were compacted to an air void content of 7.0±0.5%. Table 5 summarizes the experimental program for the shear tests. A total of 24 specimens were tested for each mix.

Table 5 Experimental Program for Shear Tests

Test[1]	Test Temperature (°C)	Shear Stress (kPa)	Replicates	HMA	WMA
RSST-CH	45	35	3	X	X
		50	3	X	X
		65	3	X	X
	55	35	3	X	X
		50	3	X	X
		65	3	X	X
SFST-CH	45	--	3	X	X
	55	--	3	X	X

[1] RSST-CH denotes "Repeated Simple Shear Test at Constant Height"
SFST-CH denotes "Shear Frequency Sweep Test at Constant Height"

The rutting resistance of the mixtures was evaluated in accordance with the AASHTO T320 procedure for the repeated simple shear test at constant height (RSST-CH). The tests specimens 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 stress levels were applied while the permanent (unrecoverable) and recoverable shear strains were measured. The tests were conducted to 10,000 load repetitions so that the number of repetitions corresponding to 5 percent permanent shear strain could be determined directly or reasonably estimated by extrapolation. The mixtures were evaluated at 45 and 55°C with a constant temperature being maintained during the test.

Additionally, the stiffness of the HMA and WMA mixtures were determined according to the AASHTO T320 procedure for the shear frequency sweep test at constant height (SFST-CH). The test specimens were subjected to a sinusoidal shear strain of 0.0001 mm/mm (0.01 percent) at each of the following frequencies: 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02 and 0.01 Hz. To ensure that the specimens are tested in a nondestructive manner, the frequency sweep test was conducted from the highest frequency to the lowest in the sequence noted above. During testing, the shear and axial deformations and loads were recorded. The complex shear modulus (G*) and phase angle (δ) were determined at each frequency. The mixtures were evaluated at 45 and 55°C with a constant temperature being maintained during the test.

3.1.a RSST-CH test

Figures 3 to 8 show the permanent shear strain as a function of the number of loading repetitions for the HMA and WMA mixtures at the different test temperatures and shear stress levels. The initial resilient shear modulus at cycle number 100 and the measured permanent shear strain after 10,000 cycles for the various test conditions are summarized in Table 6. Additionally, Figure 9 shows the average permanent shear strain after 10,000 cycles with the error bars representing the 95% confidence interval. Overlapping of the confidence intervals implies the similarity in the measured permanent shear strain between the mixtures. Looking at Figure 9, the following observations can be made:

- As expected, an increase in the measured permanent shear strain was observed with the increase in the applied shear stress and temperature.
- No significant difference was observed between the HMA and WMA mixtures at all stress levels and for both evaluated temperatures.
- Both HMA and WMA mixtures exhibited a permanent shear strain that is significantly less than 5% after 10,000 cycles when tested at 55°C and 65 kPa.

The number of cycles to 5% permanent shear strain was extrapolated using a straight line approximation based on a log-log plot of repetitions versus permanent shear strain. All the cycles from the 300th cycle of data were used to estimate the slope (b) and y-intercept (a).

$$\gamma_p = aN^b \tag{1}$$

where N is the number of load applications (i.e. loading cycles), and a and b are regression coefficients that are dependent on loading and temperature conditions and are summarized in Table 7. Consequently, the extrapolated number of cycles to 5% permanent shear strain for every tested specimen was determined and the results are shown in Table 6. Furthermore, Figure 10 shows the average number of cycles to 5% permanent shear strain for all the evaluated testing conditions with the error bars representing the 95% confidence interval. Based on the presented data, the following observations can be made:

- In general, a decrease in the number of cycles was observed with the increase in the applied shear stress level.
- The WMA mixture resulted in similar or higher number of cycles to 5% permanent shear strain when compared to the HMA mixture.

In summary, the data reveals that the HMA and WMA mixtures are expected to have good and similar resistance to rutting.

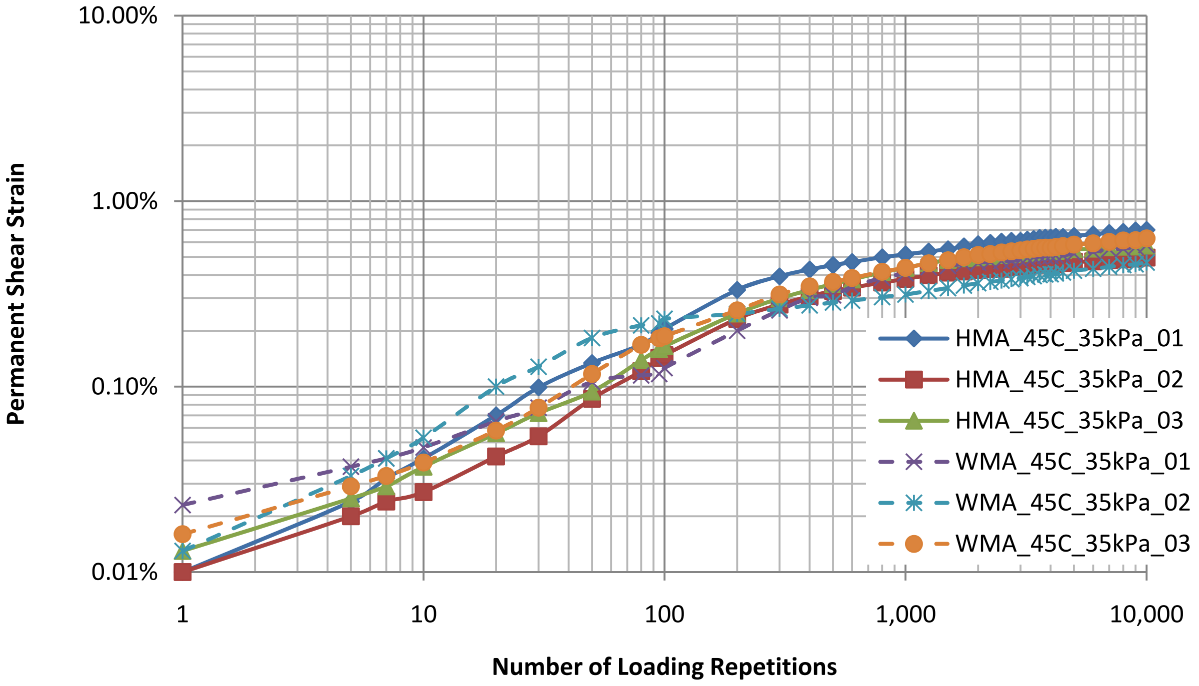


Figure 3 RSST-CH test results at 45°C and 35 kPa

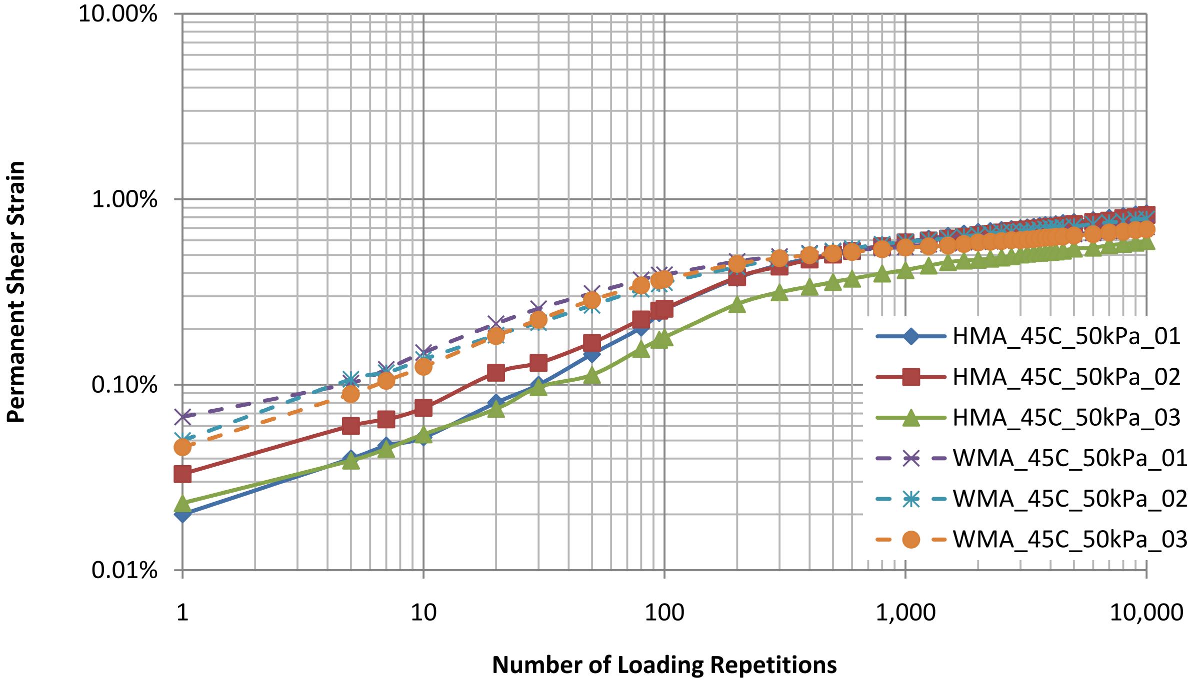


Figure 4 RSST-CH test results at 45°C and 50 kPa

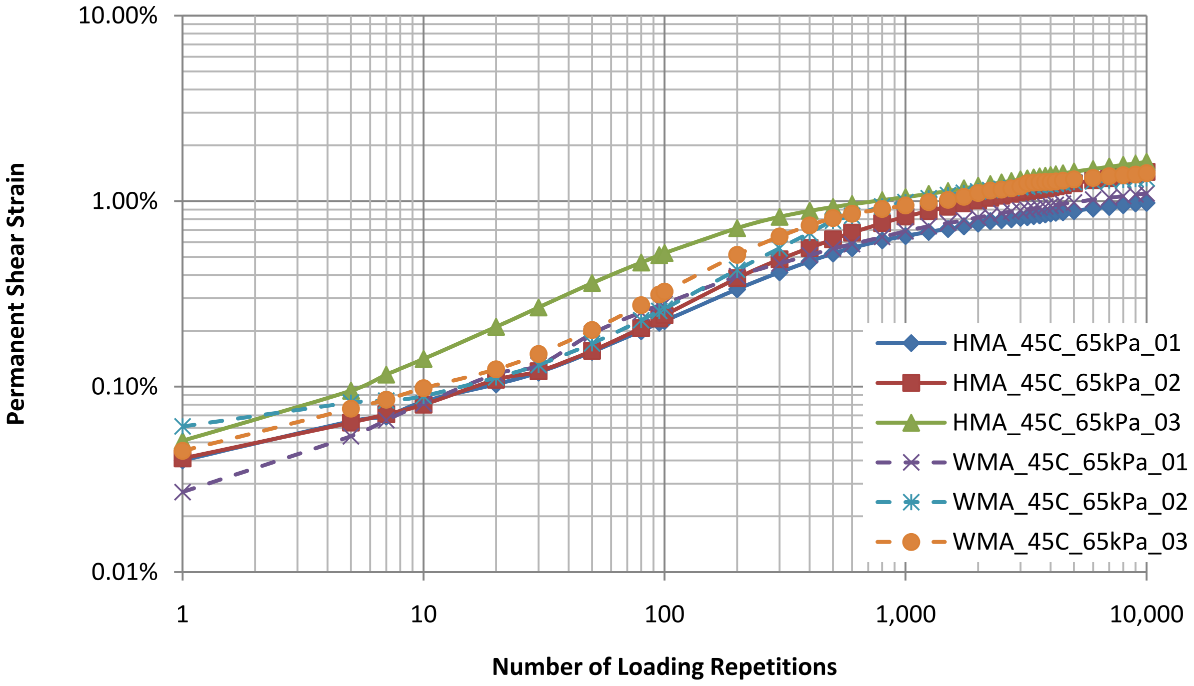


Figure 5 RSST-CH test results at 45°C and 65 kPa

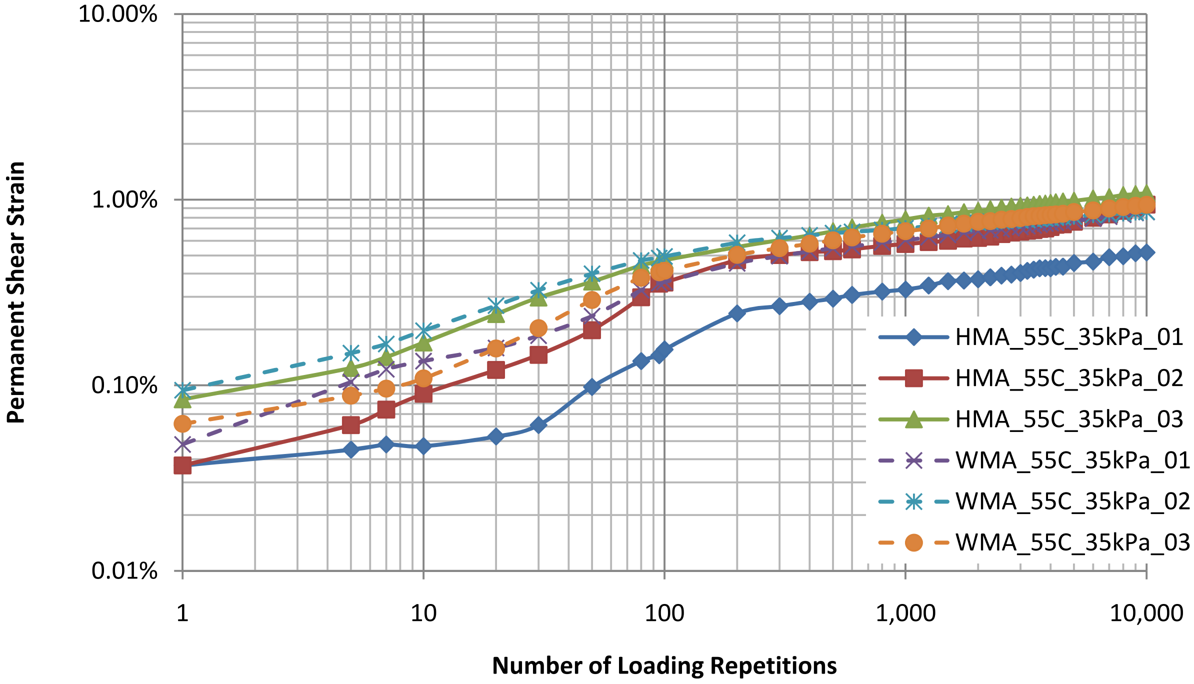


Figure 6 RSST-CH test results at 55°C and 35 kPa

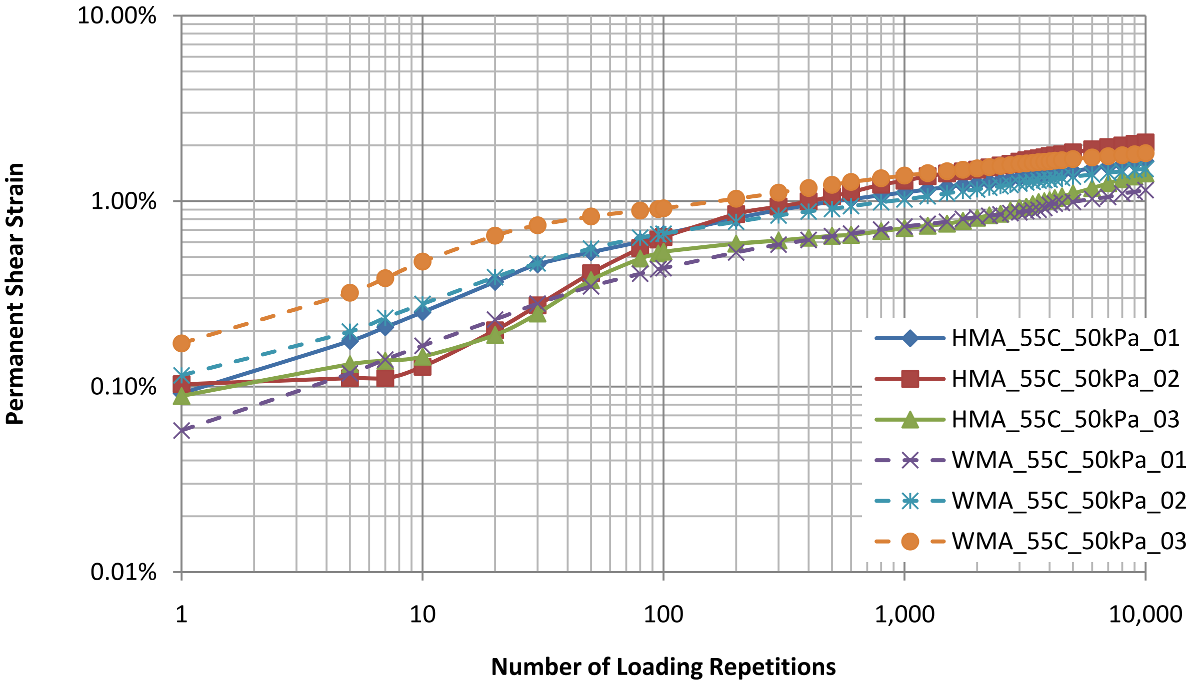


Figure 7 RSST-CH test results at 55°C and 50 kPa

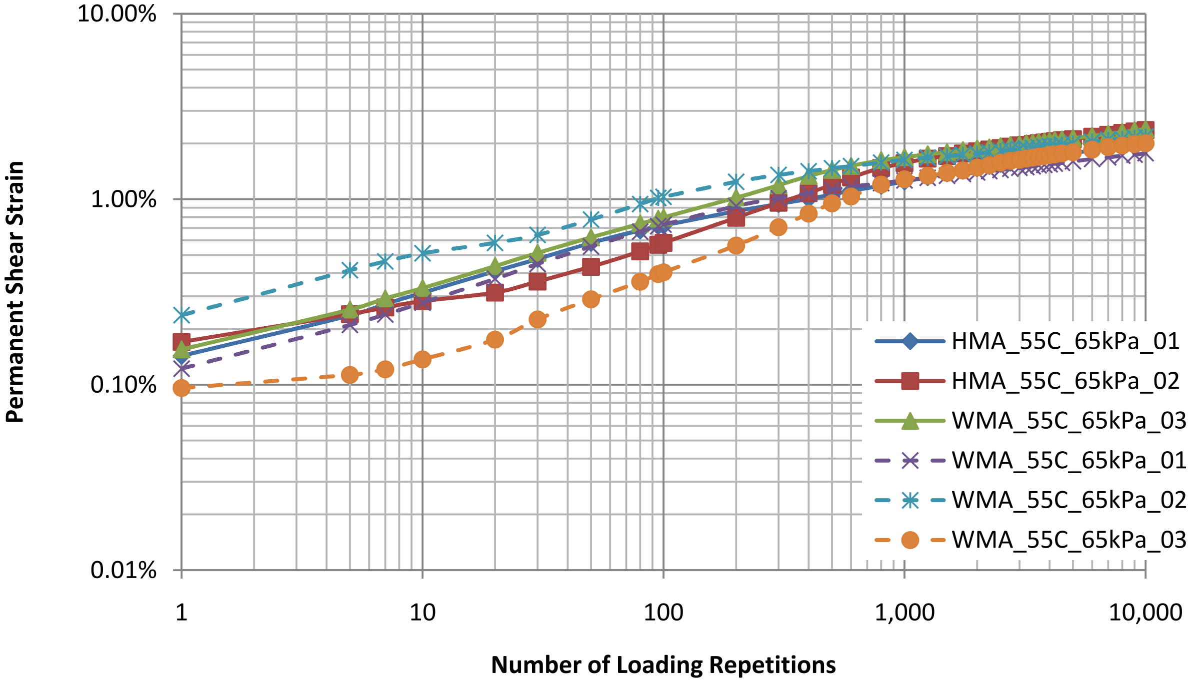


Figure 8 RSST-CH test results at 55°C and 65 kPa

Table 6 Summary of RSST-CH Test Results

Specimen ID	Air Void (%)	Test Temp. (°C)	Shear Stress Level (kPa)	Initial Resilient Shear Modulus (MPa)	Perm. Shear Str. after 10,000 cycles (%)	Average Perm. Shear Str. after 10,000 cycles (%)	Cycles to 5% Perm. Shear Strain	Average Cycles to 5% Perm. Shear Str.
HMA_45C_35kPa_01	3.6	45	36.0	61	0.70	0.59	2.112E+09	1.185E+10
HMA_45C_35kPa_02	3.2		36.3	68	0.50		3.184E+10	
HMA_45C_35kPa_03	3.1		36.5	77	0.58		1.600E+09	
WMA_45C_35kPa_01	3.6		36.9	80	0.58	0.56	3.255E+08	4.150E+09
WMA_45C_35kPa_02	3.0		33.9	98	0.47		1.174E+10	
WMA_45C_35kPa_03	3.2		34.7	97	0.63		3.882E+08	
HMA_45C_50kPa_01	3.1	45	50.2	84	0.84	0.75	2.885E+08	8.791E+08
HMA_45C_50kPa_02	2.9		49.8	58	0.82		5.037E+08	
HMA_45C_50kPa_03	3.1		49.8	78	0.60		1.845E+09	
WMA_45C_50kPa_01	3.2		49.8	57	0.71	0.73	5.523E+12	3.942E+12
WMA_45C_50kPa_02	2.9		49.9	90	0.78		8.520E+09	
WMA_45C_50kPa_03	3.6		49.9	59	0.69		6.296E+12	
HMA_45C_65kPa_01	2.5	45	66.7	83	0.98	1.35	9.797E+06	4.629E+06
HMA_45C_65kPa_02	3.5		65.3	58	1.44		9.145E+05	
HMA_45C_65kPa_03	3.0		65.9	64	1.63		3.177E+06	
WMA_45C_65kPa_01	3.6		63.9	45	1.33	1.28	3.993E+06	3.438E+06
WMA_45C_65kPa_02	3.0		67.4	72	1.42		3.483E+06	
WMA_45C_65kPa_03	3.1		64.6	63	1.10		2.839E+06	
HMA_55C_35kPa_01	3.5	55	33.8	25	0.52	0.85	1.631E+09	6.906E+08
HMA_55C_35kPa_02	3.0		34.8	32	0.94		3.267E+08	
HMA_55C_35kPa_03	2.7		33.9	59	1.09		1.142E+08	
WMA_55C_35kPa_01	3.5		34.9	41	0.86	0.89	1.038E+09	7.637E+11
WMA_55C_35kPa_02	2.9		33.8	43	0.86		2.289E+12	
WMA_55C_35kPa_03	2.9		34.9	31	0.94		6.257E+08	
HMA_55C_50kPa_01	3.4	55	50.9	36	1.64	1.71	7.641E+06	3.534E+06
HMA_55C_50kPa_02	3.5		51.8	36	2.07		4.193E+05	
HMA_55C_50kPa_03	3.5		50.2	34	1.41		2.543E+06	
WMA_55C_50kPa_01	3.0		49.8	48	1.15	1.48	2.719E+07	1.800E+07
WMA_55C_50kPa_02	3.1		49.9	40	1.49		1.152E+07	
WMA_55C_50kPa_03	3.2		49.8	28	1.81		1.530E+07	
HMA_55C_65kPa_01	3.1	55	65.2	25	2.01	2.25	5.836E+05	4.697E+05
HMA_55C_65kPa_02	3.6		67.6	27	2.36		2.385E+05	
HMA_55C_65kPa_03	3.1		65.3	23	2.39		5.871E+05	
WMA_55C_65kPa_01	2.9		63.7	40	1.77	1.99	3.703E+06	2.150E+06
WMA_55C_65kPa_02	3.2		63.0	36	2.18		2.538E+06	
WMA_55C_65kPa_03	3.5		63.0	20	2.01		2.100E+05	

Table 7 Power Fitting Parameters of Permanent Shear Strain versus Load Repetitions (After 300 Cycles)

Mixture	**Test Temperature (°C)**	**Stress Level (kPa)**	**Specimen ID**	**Permanent Shear Strain = *a*×(Shear Load Cycles)^b**		
				a	***b***	**R^2**
HMA	45	35	HMA_45C_35kPa_01	-2.76436	0.15693	0.972
			HMA_45C_35kPa_02	-2.88486	0.15080	0.942
			HMA_45C_35kPa_03	-2.89796	0.17350	0.914
		50	HMA_45C_50kPa_01	-2.75557	0.17193	0.987
			HMA_45C_50kPa_02	-2.74655	0.16611	0.987
			HMA_45C_50kPa_03	-2.90788	0.17341	0.983
		65	HMA_45C_65kPa_01	-2.88893	0.22713	0.963
			HMA_45C_65kPa_02	-2.88724	0.26609	0.981
			HMA_45C_65kPa_03	-2.55606	0.19302	0.999
	55	35	HMA_55C_35kPa_01	-3.04754	0.18958	0.996
			HMA_55C_35kPa_02	-2.74790	0.16994	0.942
			HMA_55C_35kPa_03	-2.59765	0.16092	0.987
		50	HMA_55C_50kPa_01	-2.46022	0.16841	0.999
			HMA_55C_50kPa_02	-2.58232	0.22789	0.995
			HMA_55C_50kPa_03	-2.87140	0.24517	0.947
		65	HMA_55C_65kPa_01	-2.55816	0.21802	0.996
			HMA_55C_65kPa_02	-2.48594	0.22035	0.955
			HMA_55C_65kPa_03	-2.31907	0.17648	0.974
WMA	45	35	WMA_45C_35kPa_01	-3.02384	0.20239	0.929
			WMA_45C_35kPa_02	-3.00345	0.16907	0.998
			WMA_45C_35kPa_03	-2.93949	0.19076	0.966
		50	WMA_45C_50kPa_01	-2.55136	0.09813	0.991
			WMA_45C_50kPa_02	-2.64229	0.13507	0.994
			WMA_45C_50kPa_03	-2.55897	0.09828	0.998
		65	WMA_45C_65kPa_01	-2.90216	0.22426	0.981
			WMA_45C_65kPa_02	-2.66471	0.20845	0.874
			WMA_45C_65kPa_03	-2.66453	0.21129	0.967
	55	35	WMA_55C_35kPa_01	-2.67625	0.15253	0.999
			WMA_55C_35kPa_02	-2.42798	0.09118	0.998
			WMA_55C_35kPa_03	-2.62241	0.15022	0.995
		50	WMA_55C_50kPa_01	-2.70663	0.18907	0.991
			WMA_55C_50kPa_02	-2.49626	0.16927	0.999
			WMA_55C_50kPa_03	-2.27483	0.13554	0.991
		65	WMA_55C_65kPa_01	-2.42570	0.17122	0.978
			WMA_55C_65kPa_02	-2.24010	0.14662	0.983
			WMA_55C_65kPa_03	-2.74030	0.27042	0.938

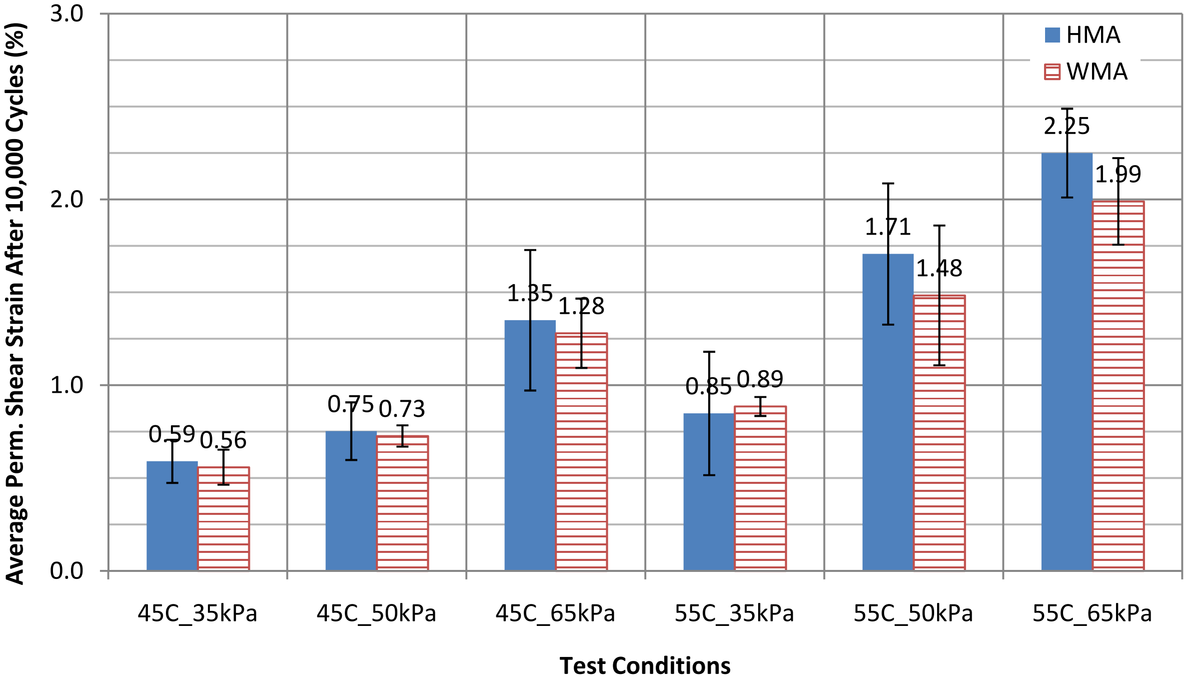


Figure 9 Average permanent shear strains after 10,000 cycles (Numbers above bars represent mean values and whiskers represent mean ± 95% confidence interval)

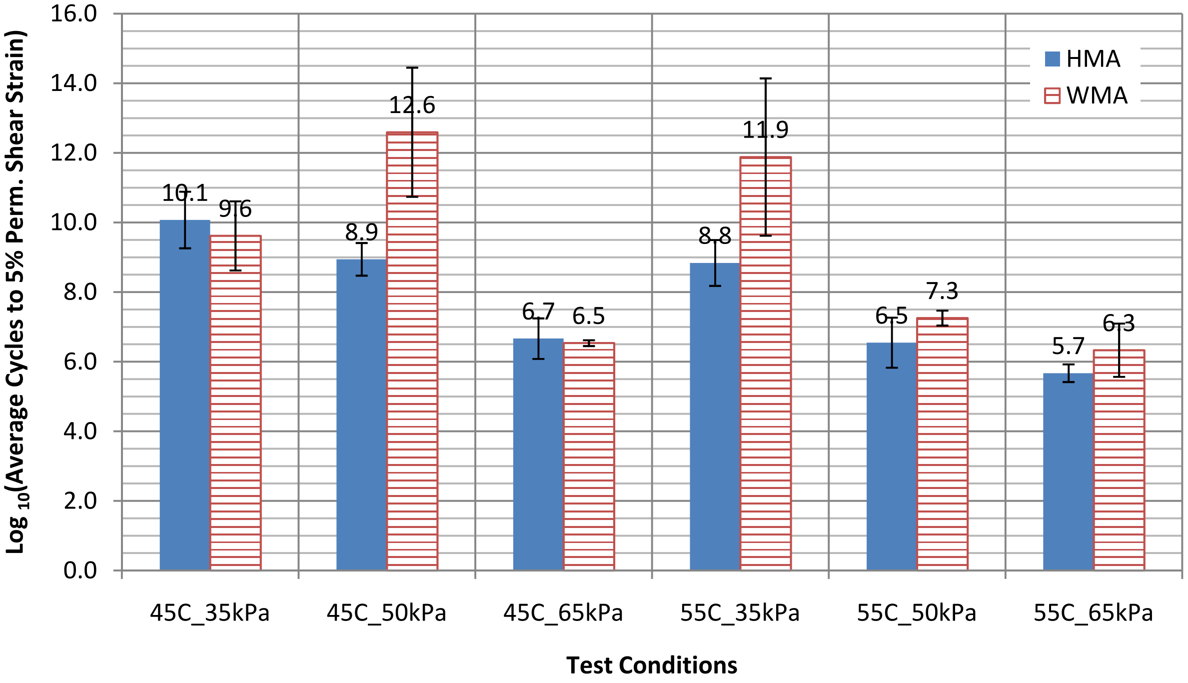


Figure 10 Average number of cycles to 5% permanent shear strain (Numbers above bars represent mean values and whiskers represent mean ± 95% confidence interval)

3.1.b SFST-CH test

Figures 11 and 12 show the test results for the SFST-CH test at 45 and 55°C with the error bars representing the 95% confidence interval. Overlapping of the confidence intervals implies the similarity in the measured shear modulus between the two mixtures. No statistical significant difference was observed between the HMA and WMA mixtures at all evaluated temperatures and loading frequencies. As expected, an increase in the shear modulus of the HMA and WMA mixtures was observed with the increase in shear loading frequency.

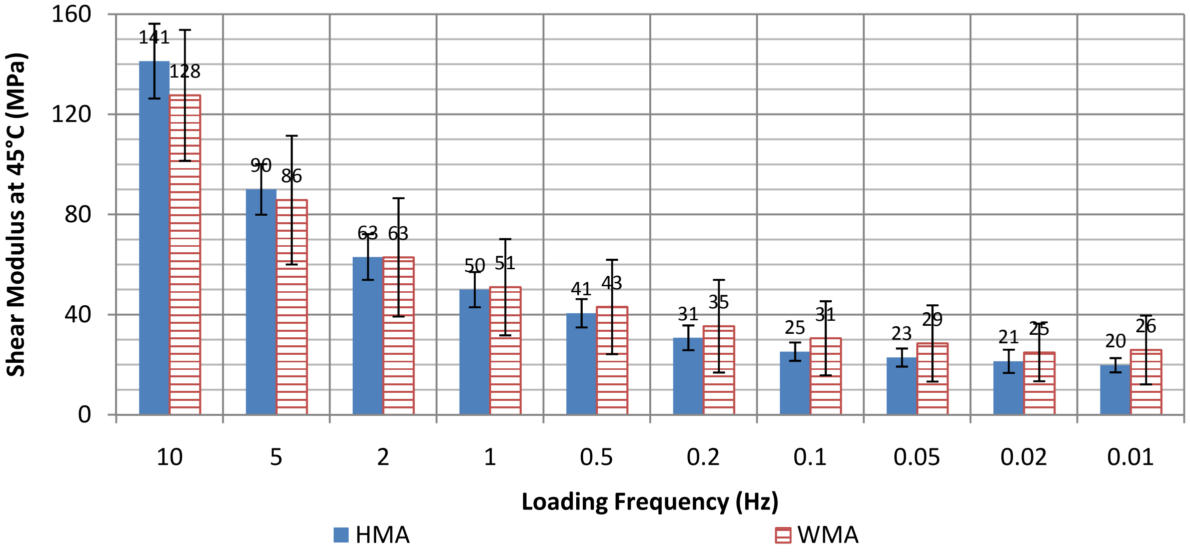


Figure 11 Shear modulus at 45°C (Numbers above bars represent mean values and whiskers represent mean ± 95% confidence interval)

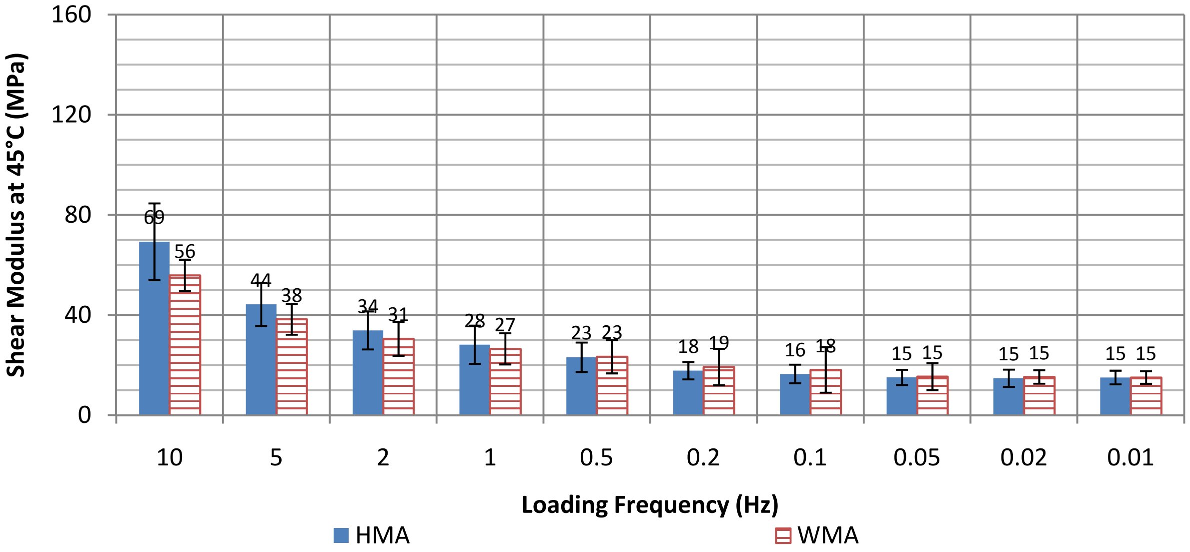


Figure 12 Shear modulus at 55°C (Numbers above bars represent mean values and whiskers represent mean ± 95% confidence interval)

3.2 Flexural Beam Fatigue

The AASHTO T321 test: "Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending," in strain controlled mode of testing was used for fatigue performance in this study. Beam fatigue specimens 400 mm long by 76 mm thick by 76 mm wide were compacted using the California kneading compactor to an air void level of 7±0.5%. Since fatigue cracking is more critical during the in-service life of the pavement, the compacted beams were subjected to long-term oven aging for five days at 85ºC, then cut using a diamond blade saw to 381 mm long by 51 mm thick by 51 mm wide. The tests specimens were subjected to four-point bending using a sinusoidal waveform at a loading frequency of 10 Hz. The initial flexural stiffness was measured at the 50th load cycle. Fatigue life or failure was defined as the number of cycles corresponding to a 50% reduction in the initial stiffness. Testing was performed in both dry and wet condition at two different strain levels and at one temperature.

Additionally, fatigue frequency sweep test in strain-controlled mode of testing was used to establish the relationship between the flexural complex modulus and load frequency. The same sinusoidal waveform was used in a controlled deformation mode and at frequencies of 15, 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz (the upper limit of 15 Hz is a constraint imposed by the capabilities of the test machine). To ensure that the specimens are 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. The beam is first vacuum-saturated to ensure a saturation level greater than 70 percent, and then placed in a water bath at 60°C for 24 hours, followed by a second water bath at 20°C for two hours. The beams are then wrapped with Parafilm and tested within 24 hours after soaking. Table 8 summarizes the experimental program for the fatigue tests. A total of 24 specimens were tested for each mix.

Table 8 Experimental Program for Fatigue Tests

Test	Moisture Conditioning	Test Temperature (°C)	Strain Level (microstrain)	Replicates	HMA	WMA
Strain-controlled Fatigue	Dry	20	200	3	X	X
			400	3	X	X
	Wet	20	200	3	X	X
			400	3	X	X
Fatigue Frequency Sweep	Dry	10	100	2	X	X
		20		2	X	X
		30		2	X	X
	Wet	10	100	2	X	X
		20		2	X	X
		30		2	X	X

3.2.a Fatigue Life of Asphalt Mixtures

Figures 13 to16 show the fatigue test results at 20°C for the dry and wet conditions. Table 9 summarizes the fatigue lives for the various tested specimens. For the same mix, lower fatigue lives were observed at 400 microtrain level in comparison to the values at 200 microstrain level. At the dry condition, the HMA mixture exhibited higher and lower fatigue live values than the WMA mixture at 200 and 400 microstrain levels, respectively. In the case of wet condition, an increase in the average fatigue life was observed for the wet specimens when compared to the corresponding dry specimens. On average, the WMA mixture exhibited higher fatigue lives than the HMA mixture at both 200 and 400 microstrain levels. It should be noted that, lower flexural stiffness values were observed for the wet specimens when compared to the corresponding dry ones (see Figure 17). An average reduction of 30% in the dry initial flexural stiffness was observed for both HMA and WMA as a result of moisture conditioning. Hence, the increase in the wet specimens fatigue lives may well be associated with the mode of testing (i.e. strain-controlled) used in this study to evaluate the fatigue lives of the mixtures.

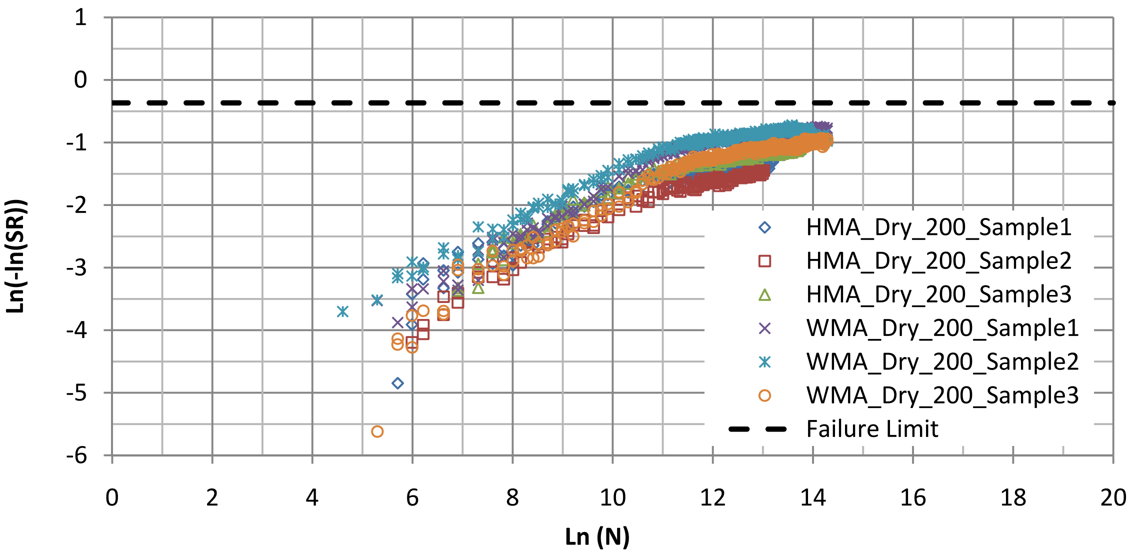


Figure 13 Fatigue test results under dry condition at 20°C and 200 microstrain

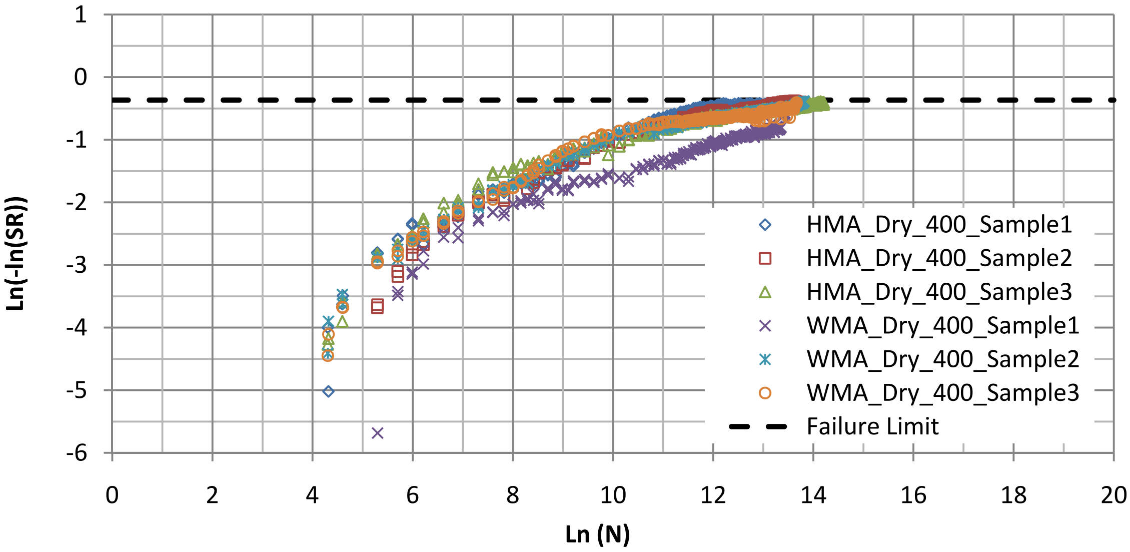


Figure 14 Fatigue test results under dry condition at 20°C and 400 microstrain

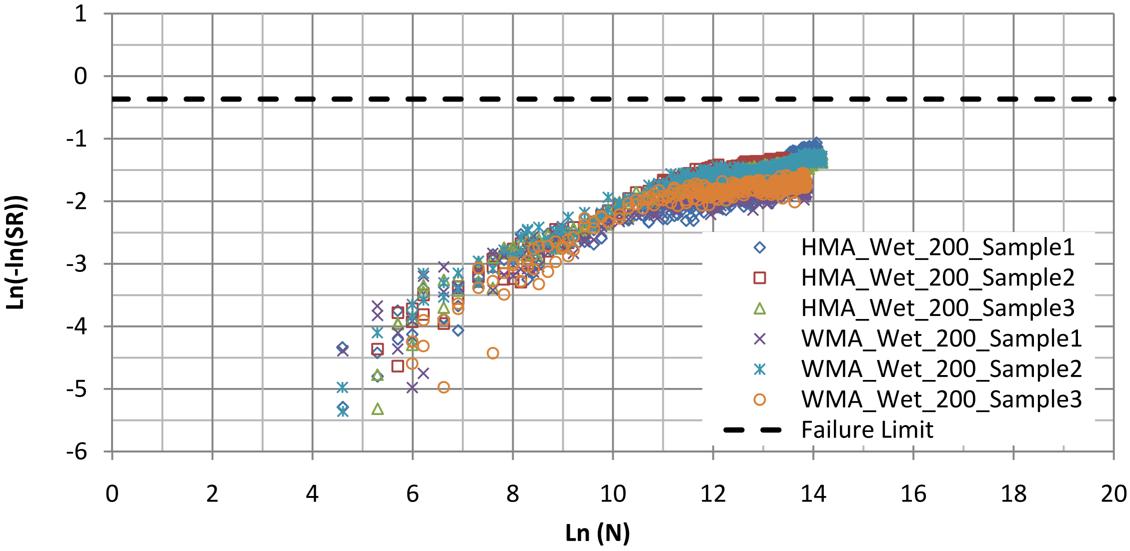


Figure 15 Fatigue test results under wet condition at 20°C and 200 microstrain

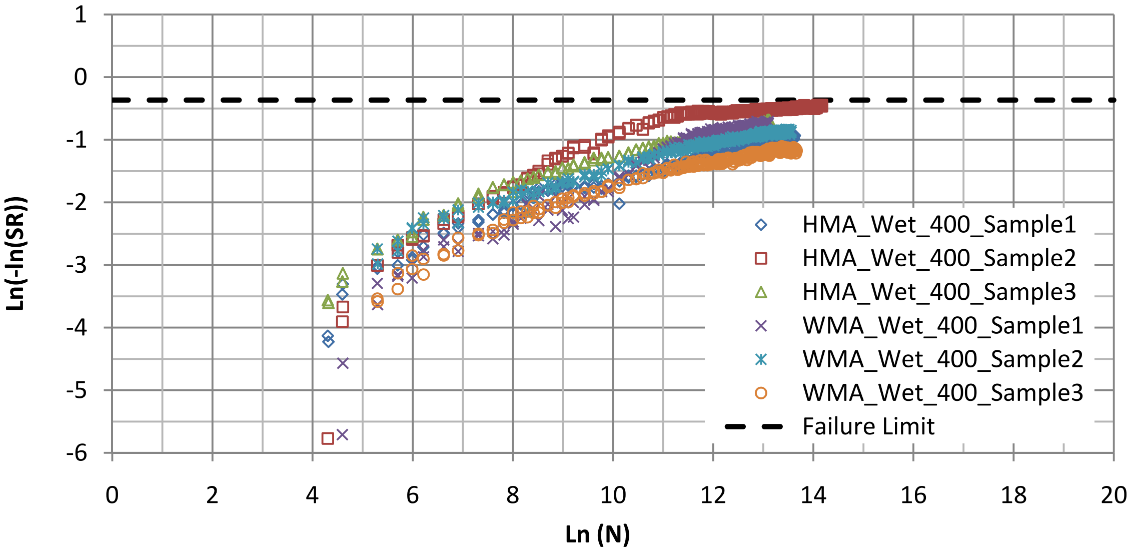


Figure 16 Fatigue test results under wet condition at 20°C and 400 microstrain

Table 9 Summary of the Flexural Beam Fatigue Test Results at 20°C

Condition	Mix	Specimen ID	Air Voids, %	Test Temp., °C	Test Strain Level, mm/mm	Initial Flexural Stiffness, MPa	Fatigue Life (N_f)
Dry	HMA	HMA_Dry_200_Sample1	6.45	19.6	0.000201	2,707	9,327,017
		HMA_Dry_200_Sample2	7.28	19.9	0.000200	3,005	8,790,648
		HMA_Dry_200_Sample3	6.03	20.1	0.000196	3,391	11,132,574
		HMA_Dry_400_Sample1	6.56	20.1	0.000409	2,768	513,153
		HMA_Dry_400_Sample2	6.80	20.0	0.000406	2,745	549,951
		HMA_Dry_400_Sample3	6.05	20.2	0.000384	2,430	968,705
	WMA	WMA_Dry_200_Sample1	7.58	19.6	0.000195	2,516	3,172,404
		WMA_Dry_200_Sample2	7.33	20.1	0.000195	2,681	4,367,746
		WMA_Dry_200_Sample3	6.63	20.0	0.000197	2,554	4,611,607
		WMA_Dry_400_Sample1	7.31	20.1	0.000391	1,918	2,001,791
		WMA_Dry_400_Sample2	6.41	20.0	0.000404	2,520	708,552
		WMA_Dry_400_Sample3	6.59	20.1	0.000409	2,439	683,956
Wet	HMA	HMA_Wet_200_Sample1	7.27	19.9	0.000200	1,834	23,775,311
		HMA_Wet_200_Sample2	6.85	19.5	0.000200	1,840	10,071,399
		HMA_Wet_200_Sample3	7.23	20.1	0.000200	2,140	31,986,956
		HMA_Wet_400_Sample1	7.08	20.5	0.000401	1,695	6,368,596
		HMA_Wet_400_Sample2	6.49	20.4	0.000404	2,394	810,081
		HMA_Wet_400_Sample3	6.50	20.4	0.000401	2,074	1,760,548
	WMA	WMA_Wet_200_Sample1	6.46	20.1	0.000200	1,615	210,990,528
		WMA_Wet_200_Sample2	7.46	19.9	0.000201	1,961	29,146,068
		WMA_Wet_200_Sample3	6.95	20.1	0.000200	1,654	81,282,103
		WMA_Wet_400_Sample1	7.30	20.2	0.000409	1,578	648,941
		WMA_Wet_400_Sample2	7.06	19.9	0.000407	1,593	5,316,990
		WMA_Wet_400_Sample3	7.15	20.1	0.000408	1,506	16,364,298

* Not tested because samples air voids were outside the allowable range of 6 to 8%.

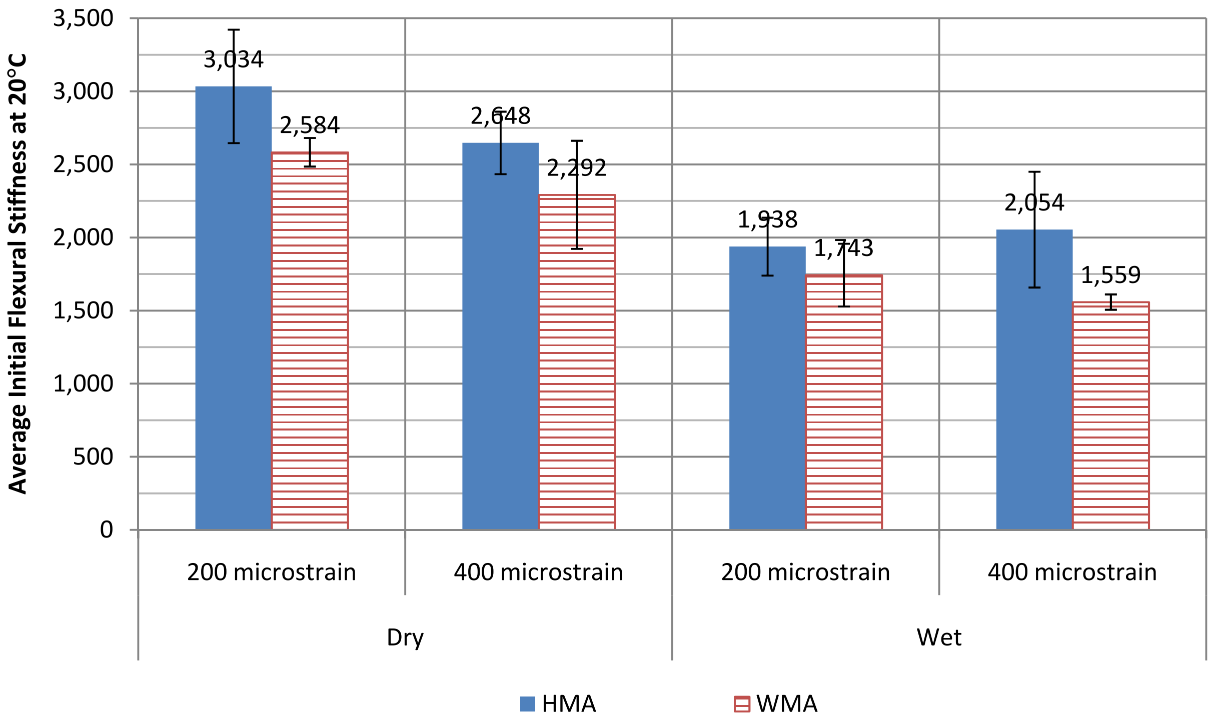


Figure 17 Initial flexural stiffness at 20°C for dry and wet conditions (Numbers above bars represent mean values and whiskers represent mean ± 95% confidence interval)

3.2.b Fatigue Frequency Sweep test results

Figures 18 and 19 show, for both dry and wet conditions, the fatigue frequency sweep test results at 10, 20 and 30°C for the HMA and WMA mixtures, respectively. As expected, an increase in the flexural stiffness was observed with the increase in loading frequency. In all cases, a lower flexural stiffness was observed for the wet specimens when compared to the corresponding dry ones.

Figures 20 to 22 show the average flexural stiffness for the HMA and WMA mixtures at 10, 20 and 30°C, respectively. For the evaluated temperatures and loading frequencies, a lower stiffness was observed for the WMA mixture when compared to the HMA mixture. Figures 23 to 25 show the flexural stiffness ratio (SR) for the HMA and WMA mixtures at 10, 20 and 30°C, respectively. In general, for the 20°C and 30°C testing temperatures, higher SR values were observed for the WMA mixture at each of the evaluated frequencies. In contrary, the SR values at 10°C for the WMA mixture were lower than those of the WMA mixture at each of the evaluated frequencies.

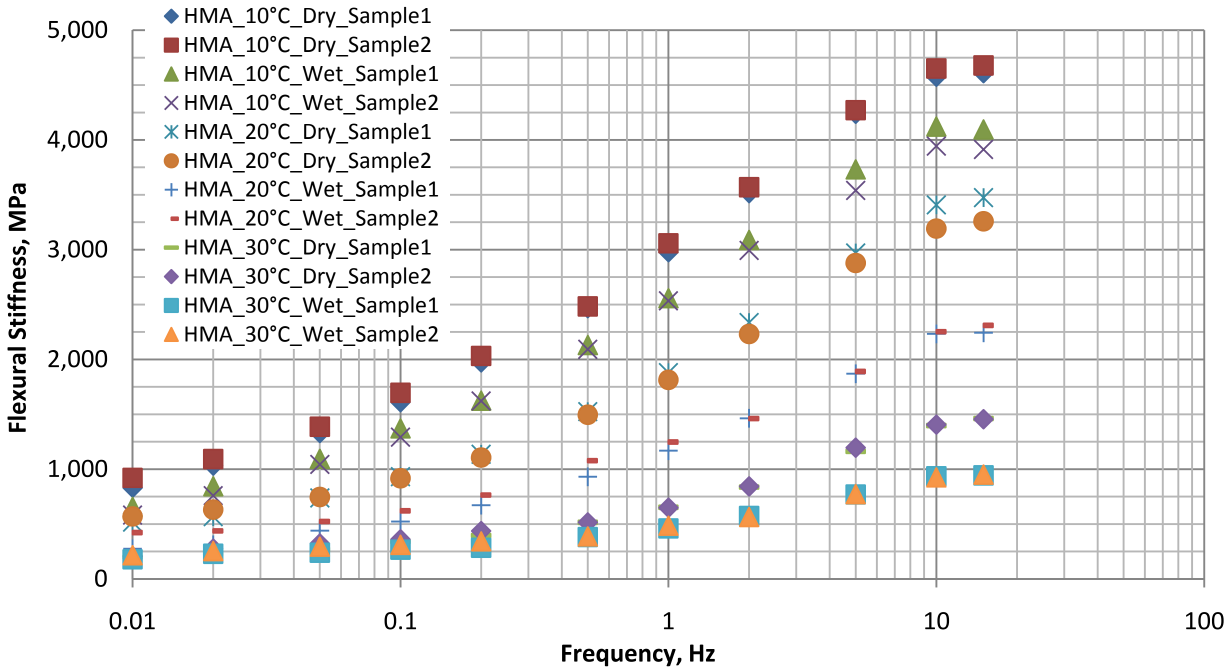


Figure 18 Frequency sweep test results for HMA

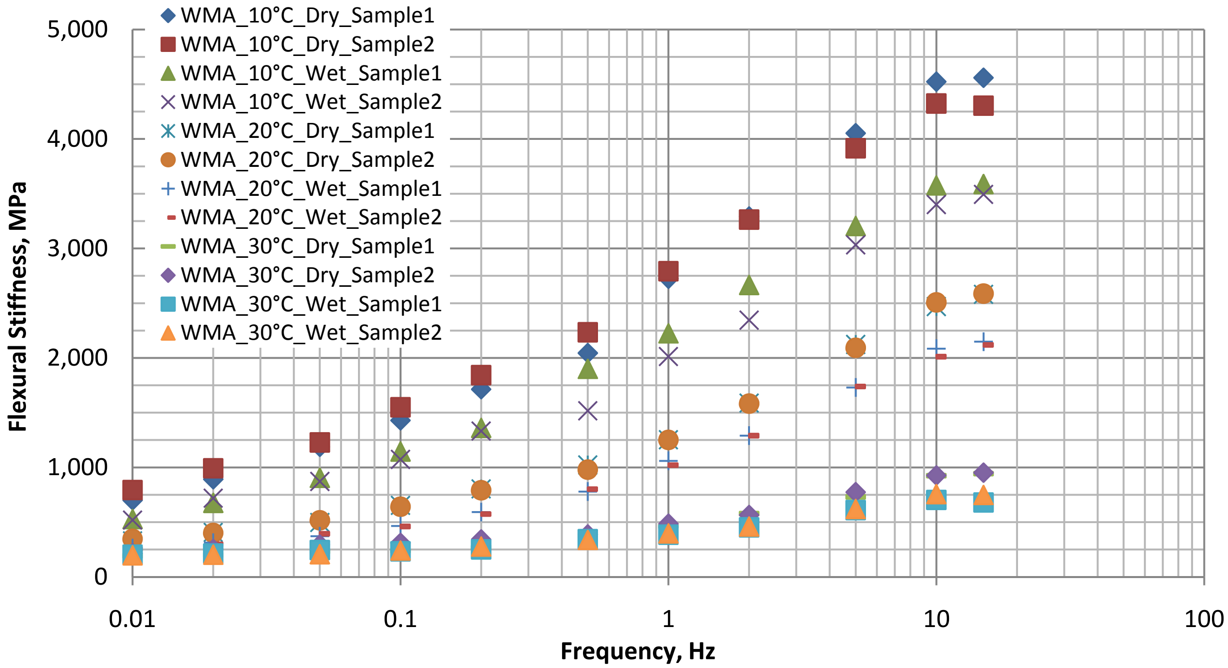


Figure 19 Frequency sweep test results for WMA

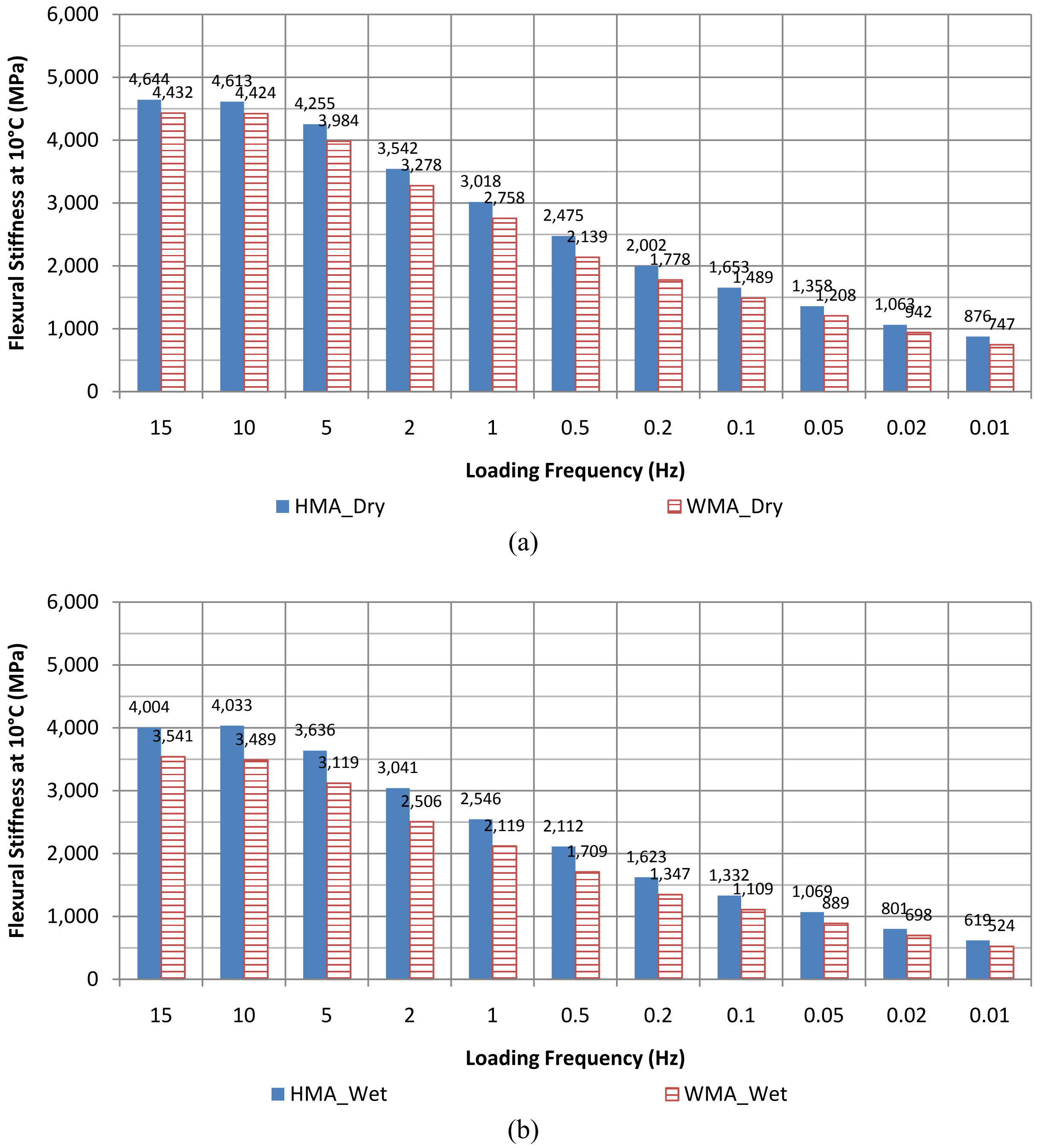
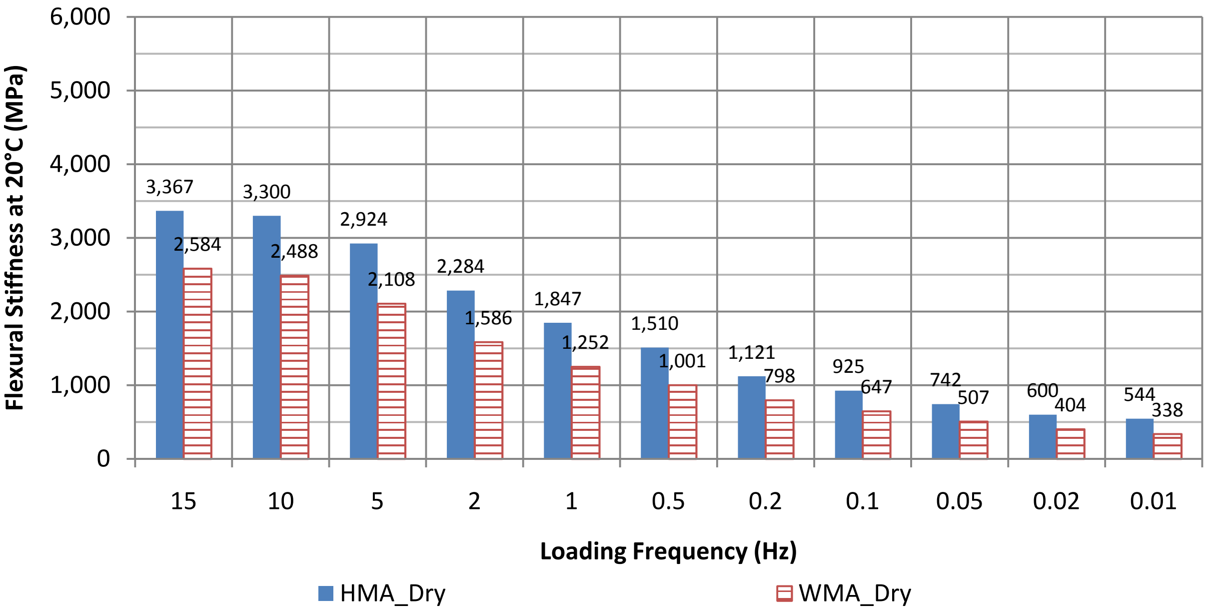
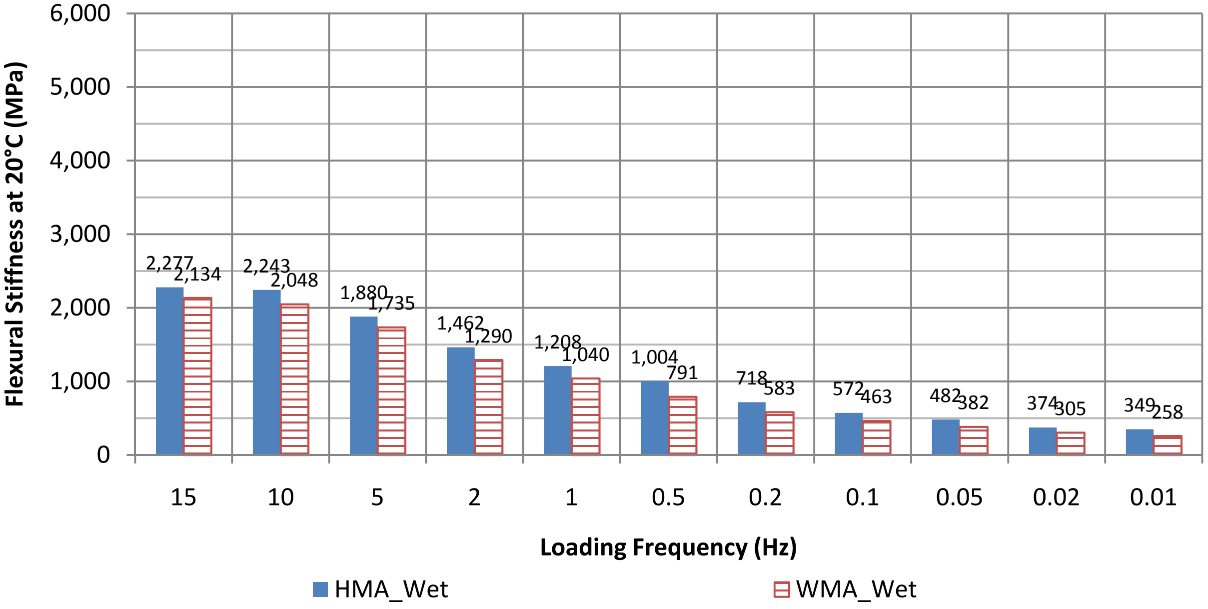


Figure 20 Average flexural stiffness at 10°C for (a) dry and (b) wet conditions

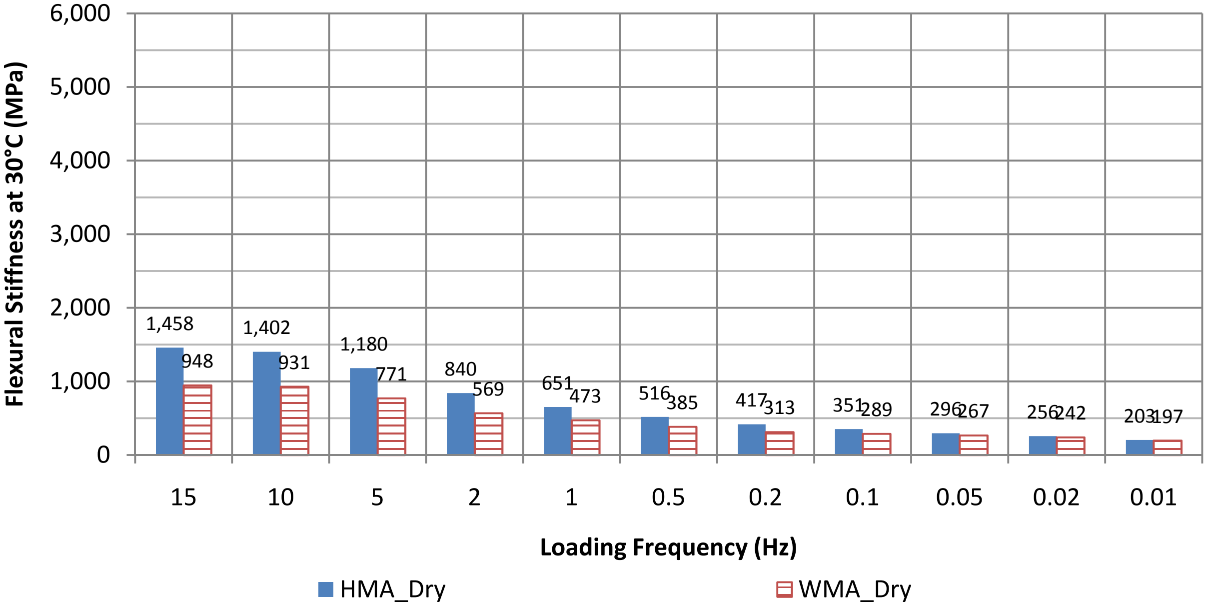


(a)

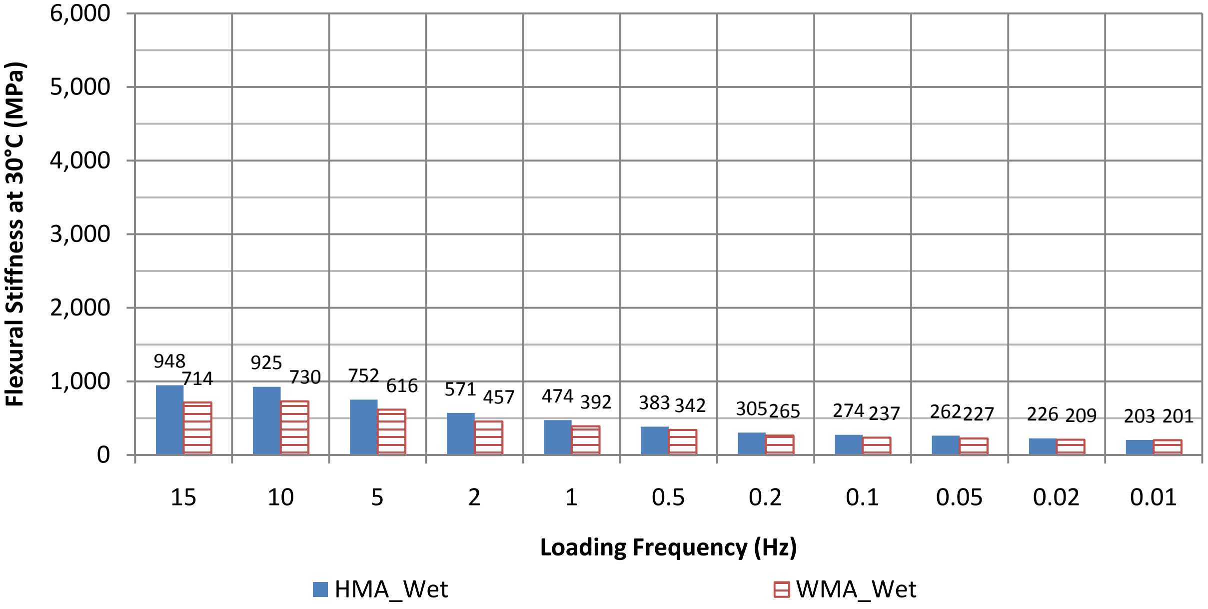


(b)

Figure 21 Average flexural stiffness at 20°C for (a) dry and (b) wet conditions



(a)



(b)

Figure 22 Average flexural stiffness at 30°C for (a) dry and (b) wet conditions

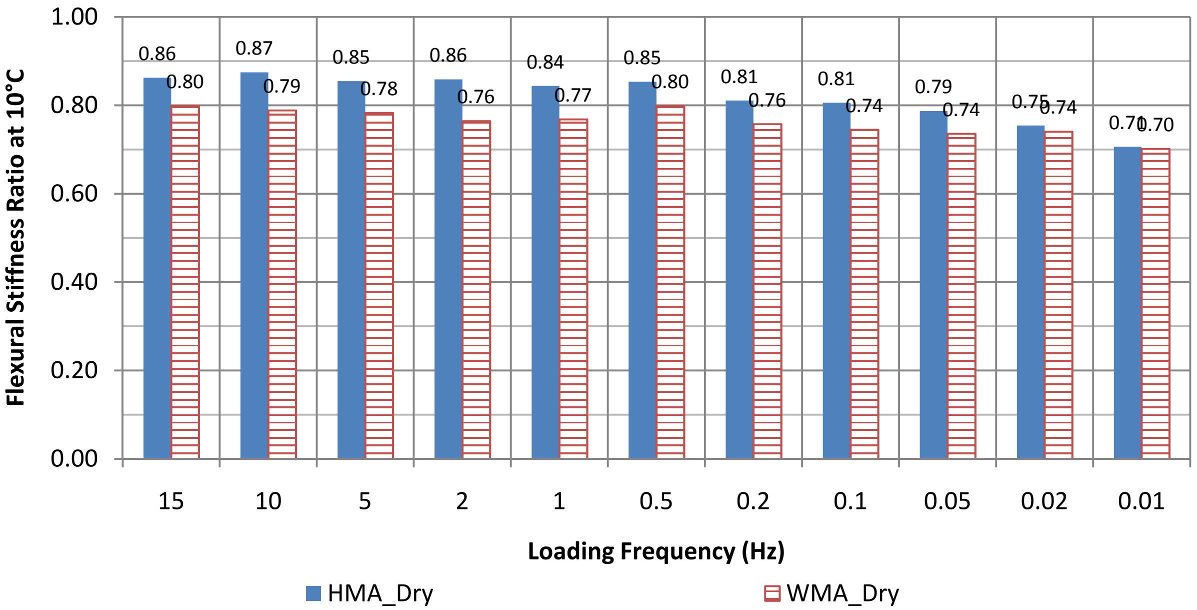


Figure 23 Flexural stiffness ratio at 10°C

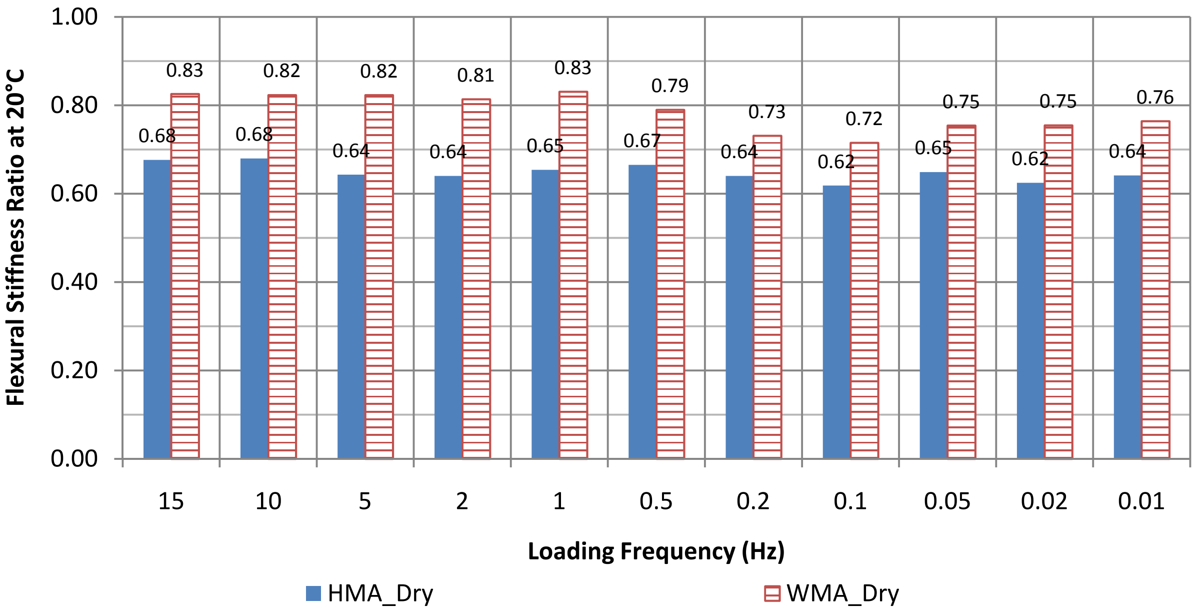


Figure 24 Flexural stiffness ratio at 20°C

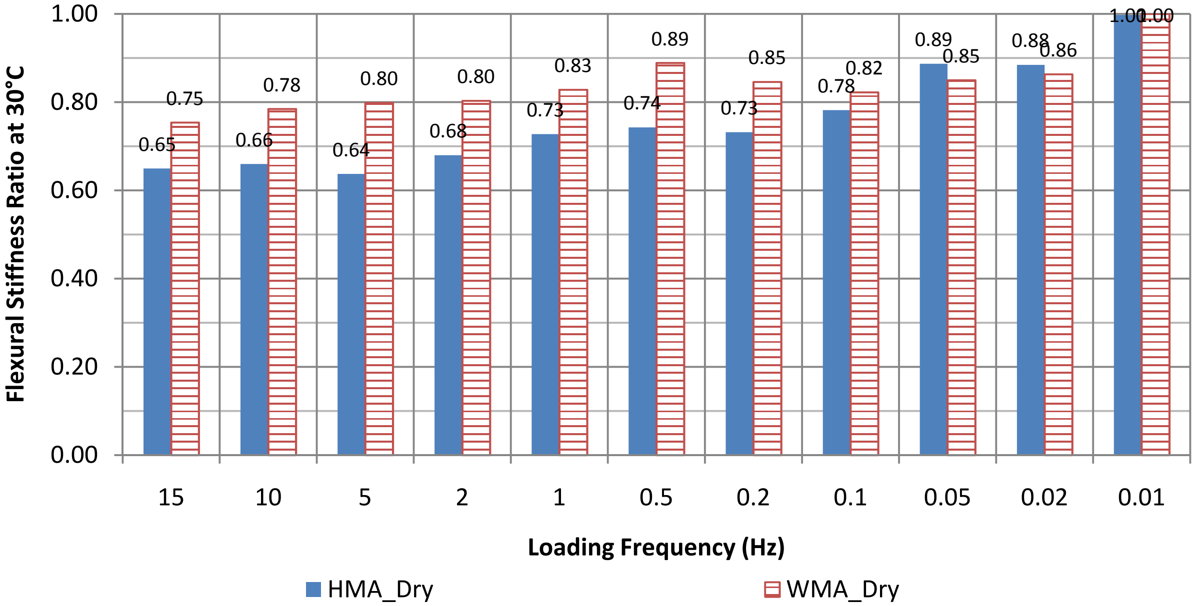


Figure 25 Flexural stiffness ratio at 30°C

The flexural stiffness ratio values at the evaluated loading frequencies were averaged for each of the testing temperatures and the results are illustrated in Figure 26. The error bars presented in Figure 26 represent the 95% confidence interval of the corresponding data. Overlapping of the confidence intervals implies the similarity in the calculated SR values between the HMA and WMA mixtures. The data show that the WMA mixture exhibits statistically similar or significantly higher SR values than the HMA mixture.

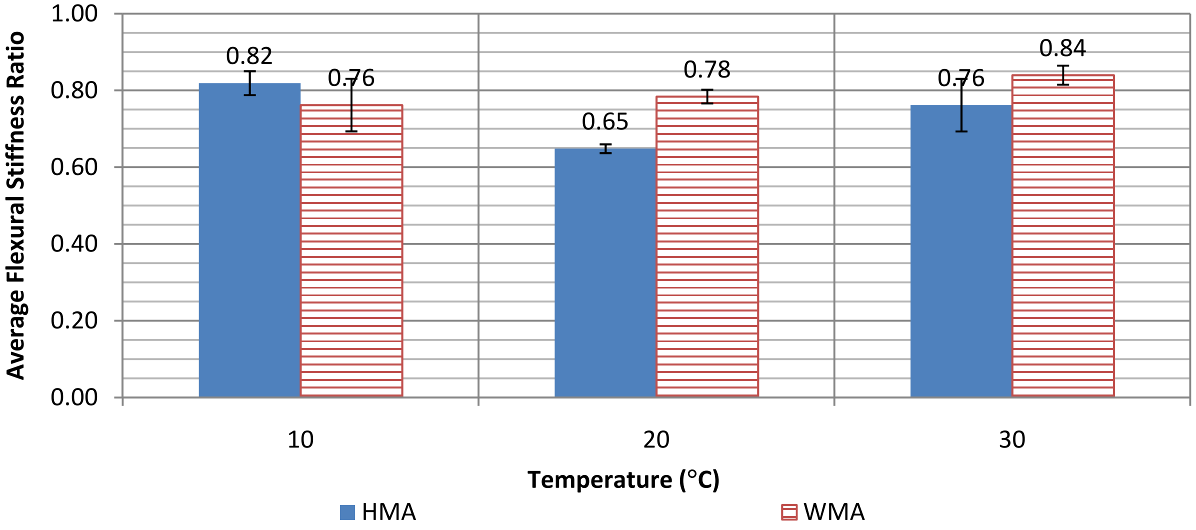


Figure 25 Average flexural stiffness ratios at 10, 20 and 30°C

3.3 Hamburg Wheel-Tracking

The moisture-susceptibility of the HMA and WMA mixtures was also evaluated in the Hamburg Wheel-Tracking Device (HWTD) in accordance with AASHTO T324 *(3)*. Cylindrical specimens of 150 mm diameter by 50 mm high were compacted in the Superpave Gyratory Compactor (SGC) to 7±0.5%. A total of 16 samples (8 samples per mix) were prepared at the University of Nevada Reno and transported to the University of California Pavement Research Center (UCPRC) for testing. Two sets of samples, 4 replicates each, were prepared for each mix. The first set of specimens was compacted right after mixing (i.e. no short-term oven aging). The second set of specimens was subjected to short-term oven aging for 4 hours at 135°C before compaction. Table 10 shows the bulk specific gravities, air voids and dimensions of the prepared specimens. Four runs of the HWTD were performed totaling eight specimen group (two cores per group) tests. The test groupings of each set of two specimens are listed in Table 11. Twenty thousand (20,000) wheel passes were applied over the core specimens with a constant force of 705N, while submerged in a 50°C bath. More information related to the HWTD testing and results can be found in the report: "Arkema Chemical Cecabase HWTD Testing Results" *(4)* prepared by Signore and Townsend.

Table 11 summarizes the maximum rut depths at 50°C for each of the tests performed. Overall, a good repeatability of results was observed except for the WMA specimens with 4 hours short-term aging (i.e. test D). In general, comparable rut depths were observed between the HMA and WMA mixtures. Specimens that were short-term aged for 4 hours at 135°C before compaction exhibited lower rut depth values than those that were not subjected to any short-term aging.

Table 10 Hamburg Wheel-Tracking Test Specimens

Mixture	**Specimen ID**	**Loose Mixture Short-term Oven Aging**	**Max Theoretical Specific Gravity (G_{mm})**	**Mixture Bulk Specific Gravity (G_{mb})**	**Air Voids, %**	**Average Specimen Height, mm**
HMA	HMA 0_A	None	2.425	2.256	7.0	50.79
	HMA 0_B			2.249	7.2	50.59
	HMA 0_C			2.261	6.8	50.71
	HMA 0_D			2.257	6.9	50.67
	HMA 4_A	4 hours at 135°C	2.425	2.249	7.3	50.83
	HMA 4_B			2.242	7.6	50.66
	HMA 4_C			2.260	6.8	50.66
	HMA 4_D			2.262	6.7	50.73
WMA	WMA 0_A	None	2.445	2.280	6.7	51.10
	WMA 0_B			2.268	7.2	50.69
	WMA 0_C			2.257	7.7	50.69
	WMA 0_D			2.270	7.2	50.82
	WMA 4_A	4 hours at 135°C	2.445	2.273	7.0	50.76
	WMA 4_B			2.284	6.6	50.71
	WMA 4_C			2.268	7.2	50.77
	WMA 4_D			2.280	6.8	50.78

Table 11 HWTD Test Groupings

Test	Test Grouping	Specimen ID-1	Specimen ID-2	Maximum Rut Depth (mm)	Average Maximum Rut Depth (mm)
A	1	HMA 0_A	HMA 0_B	-17.6	-13.3
	2	HMA 0_C	HMA 0_D	-9.1	
B	1	HMA 4_A	HMA 4_B	-4.9	-5.3
	2	HMA 4_C	HMA 4_D	-5.7	
C	1	WMA 0_A	WMA 0_B	-7.7	-9.1
	2	WMA 0_C	WMA 0_D	-10.5	
D	1	WMA 4_A	WMA 4_B	-3.9	-7.7
	2	WMA 4_C	WMA 4_D	-11.4	

4. CONCLUSION

An extensive evaluation of the Cecabase™ RT warm-mix additive was conducted in this study. Mix designs and laboratory performance testing were conducted on HMA mixtures and WMA mixtures prepared with Cecabase™ RT additive. The mixtures were evaluated for their resistance to rutting, fatigue cracking and moisture damage following largely the testing requirements for the warm-mix asphalt technology approval process in California. Overall, comparable properties were obtained between the HMA and WMA mixtures.

5. REFERENCES

1. California Department of Transportation. Standard Specifications. State of California, Department of Transportation, Sacramento, CA. May 2006, amended June 5, 2009.
2. Nevada Department of Transportation. Standard Specifications for Road and Bridge Construction. Carson City, NV. 2001.
3. American Association of State Highway and Transportation Officials (AASHTO). Standard Specifications for Transportation Materials and Methods of Sampling and Testing. 29th Edition, Washington, D.C., 2010.
4. Signore, J. M. and B. C, Townsend. “Arkema Chemical Cecabase HWTD Testing Results,” Final Report, University of California Pavement Research Center, UC Davis, UC Berkeley, July 2011.