NCAT Report 10-03

EVALUATION OF GENCOR GREEN MACHINE ULTRAFOAM GX:

FINAL REPORT

By
Andrea Kvasnak
Adam Taylor
James M. Signore
S. A. Bukhari

July 2010

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY
277 Technology Parkway ■ Auburn, AL 36830

EVALUATION OF GENCOR GREEN MACHINE ULTRAFOAM GX

FINAL REPORT

By

Andrea Kvasnak
Lead Research Engineer
National Center for Asphalt Technology
Auburn University, Auburn, Alabama
334-844-7303
ank0004@auburn.edu

Adam Taylor
Assistant Research Engineer
National Center for Asphalt Technology
Auburn University, Auburn, Alabama

James M. Signore
University of California Pavement Research Center
Berkeley, California

S. A. Bukhari
University of California Pavement Research Center
Berkeley, California

Sponsored by
Gencor Industries

NCAT Report 10-03

July 2010

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of Gencor Industries or the National Center for Asphalt Technology, or Auburn University. This report does not constitute a standard, specification, or regulation.

ABSTRACT

Gencor Industries developed a device that produces foamed asphalt to allow for the production of warm mix asphalt (WMA). The device is called the Green Machine Ultrafoam GX and can be attached to a variety of drum plants. Plant-produced WMA using the Green Machine Ultrafoam GX and HMA were evaluated in the laboratory and the results of the mix tests were compared. This report details the laboratory testing that was conducted and summarizes the comparison of the test results.

TABLE OF CONTENTS

INTRODUCTION

Gencor Industries developed a device that produces foamed asphalt to allow for the production of warm mix asphalt (WMA). The device is called the Green Machine Ultrafoam GX and can be attached to a variety of drum plants. The National Center for Asphalt Technology (NCAT) evaluated a WMA produced using the Green Machine Ultrafoam GX as well as a hot mix asphalt (HMA). Both mixes were produced at the same facility. The WMA and HMA consisted of the same aggregate gradation, liquid asphalt, and asphalt binder content. The differences between the two mixes were the mixing temperature and addition of water to the base asphalt for the WMA mix. The objective of the study was to determine if the WMA produced using the Gencor Green Machine Ultrafoam GX performed in the laboratory as well as or better than the HMA consisting of the same raw materials.

BACKGROUND

WMA is an emerging technology that allows for the production of asphalt mixes at lower temperatures than traditionally employed for HMA. The production of an asphalt mix at temperatures less than 275°F can result in lower emissions, decreased fuel usage, and reduced oxidation of the asphalt binder compared to mixes produced at 300°F and above (*1*). The reduced emissions and fuel usage can be environmentally beneficial and reduced fuel usage can be economically beneficial. The question that arises: Is the performance of the asphalt mix adversely affected by using a WMA technology? If it is, then the environmental and economic benefits are negated. If the performance of WMA pavements is as good as or better than HMA, then the change in production practices is worthwhile.

The asphalt mix properties that typically are of interest when evaluating a new WMA technology are moisture susceptibility, rutting susceptibility, strength, and stiffness. Moisture susceptibility is of concern since the reduced temperatures may result in incomplete drying of aggregate. Any moisture remaining in or on the aggregate could affect the bond between the asphalt and aggregate, thus resulting in premature pavement failure. The reduced mixing temperature of the WMA may also result in a softer asphalt than the same mix produced at HMA temperatures since there is less oxidation and volitization of the asphalt. The softer asphalt has raised some concern that WMA may be more prone to rutting and lower tensile strength. However, one of the benefits of a softer binder is the possibility of improved resistance to fatigue and thermal cracking. A less oxidized binder typically is less brittle and often more resistant to cracking.

Previous research (*1-4*) has shown that the moisture susceptibility results of WMA often are lower than HMA, which indicates the mix may be more prone to moisture damage. The tensile strengths of WMA also tend to be lower than HMA based on previous research. However, recent field evaluations conducted by NCAT indicate that the tensile strength of WMA increases with time to a similar tensile strength as that of HMA after two years (*5* and *8*). Rutting results in the laboratory often are greater or similar for WMA than HMA; however, often the difference is minimal. It should also be noted that recent field evaluations by NCAT have not revealed a substantial difference in the WMA rutting compared to rutting in control HMA sections.

Although laboratory results of WMA sometimes predict the WMA will not perform as well as HMA in terms of moisture susceptibility and rutting, field results indicate otherwise. As a result, some asphalt technologists have considered different conditioning methods for WMA specimens in the laboratory. The Texas Department of Transportation has employed a four-hour aging time for WMA specimens that will be tested using the Hamburg wheel tracking device.

In this project, similar testing protocols conducted in previous WMA evaluations were used to evaluate mix produced using the Gencor Green Machine Ultrafoam GX. The objective was to determine if properties of a state approved HMA design are negatively impacted by producing the mix as a WMA using the Gencor Green Machine Ultrafoam GX.

TESTING PLAN

Two plant-produced mixes, a WMA and a control HMA, were evaluated using multiple mix tests. The mix tests selected addressed the issues of moisture susceptibility, strength, permanent deformation, stiffness, fatigue, and compactability. TABLE 1 summarizes the tests used to evaluate the mixes. The results of these tests for WMA were compared to the HMA to determine if the performance was as good as or better than the HMA.

TABLE 1 Tests Conducted

Test	Mix Property Evaluated	Replicates
AASHTO T 329	Moisture Content	2 samples
AASHTO T 195	Coating	2 samples
Locking Point	Compactability	Minimum of 2 samples
AASHTO T 283	Moisture Susceptibility	1 set
AASHTO T 324	Moisture Susceptibility and Rutting	2 twin sets
AASHTO TP 63	Rutting	6 specimens
Aged Indirect Tensile Strength	Change in Tensile Strength with Aging	3 specimens per age
AASHTO TP 62	Stiffness	3 specimens
AASHTO T 321	Fatigue	3 specimens per microstrain level
AASHTO T 320 (Repeated Simple Shear Test)	Stiffness	3 specimens per stress and temperature combination
AASHTO T 320 (Shear Frequency Sweep)	Stiffness	2 Specimens per frequency and Temperature

Moisture Content of Bituminous Materials (AASHTO T 329)

AASHTO T 329, *Moisture Content of Hot Mix Asphalt (HMA) by Oven Method*, was used for evaluating the moisture content of a loose plant-produced mix. The temperature stipulated in AASHTO T 329 was not followed due to limited oven space in the NCAT mobile laboratory, which prevented one oven being used solely for moisture content testing. The oven temperature was set to the target compaction temperature plus 20°F since that was the temperature for compacting the performance specimens. Each sample was approximately 5000 g. The samples were heated to a constant weight (less than 0.05% change) as defined by AASHTO T 329.

Coating (AASHTO T 195)

AASHTO T 195, *Determining Degree of Particle Coating of Asphalt Mixtures*, was conducted to evaluate asphalt coating of the loose plant-produced mix. Material was sieved using a 3/8 in. (9.5 mm) sieve. Visual inspections of the material retained on the 3/8 in. (9.5 mm) sieve were conducted. The visual inspections consisted of classifying a particle as partially or completely coated. The percent of completely coated particles was then calculated.

Locking Point

Loose plant-produced mix was compacted to determine the locking point. Samples of 4700 g of loose plant-produced mix were compacted in a gyratory compactor. Samples were compacted until the height was the same for two consecutive gyrations. The height and gyrations were recorded and the air void content was determined.

Moisture Susceptibility (AASHTO T 283)

AASHTO T 283, *Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage*, is a moisture susceptibility test based on evaluating the change in tensile strength between dry and moisture-saturated specimens. The test is the most common moisture susceptibility test used by state agencies (*5*). The standard acceptance criterion is a tensile strength ratio that is equal to or exceeds 80 percent per AASHTO M 323. Specimens were compacted in the NCAT mobile laboratory from plant-produced mix without reheating the mix. The target compaction dimensions were 6 in. (150 mm) in diameter and 3.75 ± 0.2 in. (95 ± 5 mm) tall. The target air void content was 7 ± 0.5%. Specimens were grouped to result in two sets of three specimens with similar average air voids. One set of specimens was conditioned which encompassed saturating, freezing, and thawing specimens. The conditioned samples were vacuum saturated so that the internal voids were between 70 and 80 percent filled with water and subjected to one laboratory freeze-thaw cycle. Both conditioned and unconditioned specimens were at the test temperature of 77 ± 1°F (25 ± 0.5°C) prior to testing. After conditioning, specimens were loaded diametrically at a rate of 2 in./min. (50 mm/min.). The maximum compressive strength was recorded and then the indirect tensile strength and tensile strength ratios were calculated.

Hamburg Wheel Tracking Test (AASHTO T 324)

AASHTO T 324, *Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)*, is a loaded wheel test used to evaluate the stripping and rutting potential of a mix. Some state agencies and researchers use this test in lieu of, or in conjunction with, AASHTO T 283 to evaluate moisture susceptibility. The test employs the Hamburg wheel tracking device and specimens are typically tested in a heated water bath. For this study, two sets of specimens were prepared. The first set was plant-produced mix compacted without additional aging of the material. For the second set, reheated loose plant-produced mix was aged for four hours at 275°F (135°C) prior to compaction in accordance with the Texas Department of Transportation aging procedures for WMA Hamburg specimens. All specimens regardless of aging procedures were compacted to a 6 in. (150 mm) diameter by 3.75 in. (95 mm) tall specimen. The target air void content was 7 ± 0.5%. Specimens were cut horizontally to yield two 1.875 inch (47.6 mm) thick specimens. Four of the six sliced specimens were selected and approximately 0.5 inch (12.7 mm)was cut vertically from one side of each specimen (see FIGURE 1). Two specimens were placed in a mold at once with the cut vertical sides abutting one another. The mold with the specimens was conditioned in a 122°F (50°C) water bath. Specimens were then subjected to a loaded wheel traversing the length of the two specimens. Three values were determined from the testing for each mix: stripping inflection point, rutting rate, and total rutting at 10,000 cycles (20,000 passes). The acceptable stripping inflection point criterion was a value equal to or greater than 5,000 cycles (10,000 passes). The acceptable total rut depth at 10,000 cycles (20,000 passes) was less than 0.4 in. (10 mm). A criterion for rutting rate does not exist and the value was only used for comparing the two mixes.

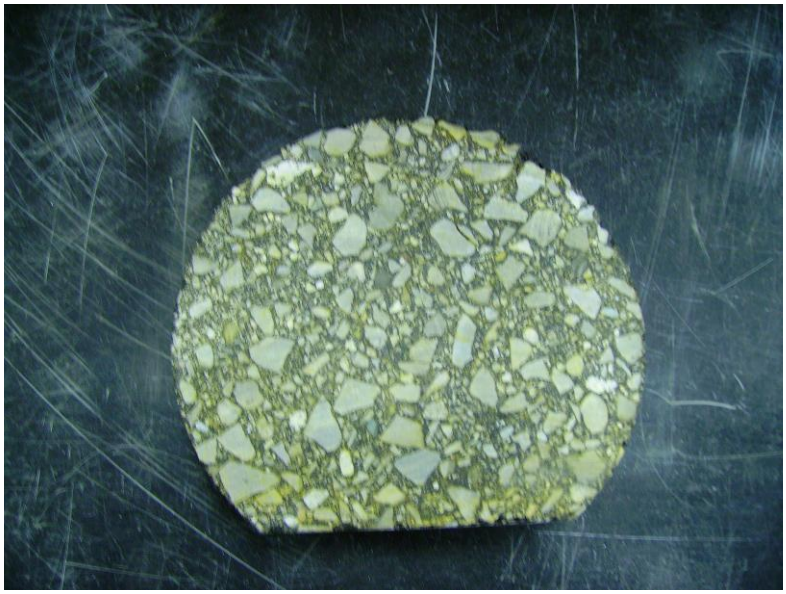

FIGURE 1 Cut Hamburg Specimen

Asphalt Pavement Analyzer Rut Test (AASHTO TP 63)

AASHTO TP 63, *Determining Rutting Susceptibility of Hot-Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)*, is a loaded wheel test for evaluating rutting potential. Typically, a state agency uses either AASHTO T 324 or AASHTO TP 63 for a rut performance test.

Six cylindrical specimens per mix were compacted from plant-produced mix using a gyratory compactor. Specimens were compacted to 7 ± 0.5% air voids. The dimensions of the specimens were 6 in. (150 mm) in diameter and 3 in. (76 mm) tall. Specimens were placed into molds and conditioned in an environmental chamber heated to 147°F (64°C). The hose pressure and wheel load employed for the test were 100 ± 5 psi and 100 ± 5 lbs., respectively. The specimens were subjected to 8,000 cycles of loading at a test temperature of 147°F (64°C). The rut depths were manually measured at the completion of the testing. An acceptance criterion of 8 mm or less was employed.

Indirect Tensile Strength for Aged Unconditioned Mix

The tensile strength testing of unconditioned specimens was conducted using the AASHTO T 283 indirect tensile strength protocol at 77°F (25°C). Testing was conducted on plant-produced mix compacted in the NCAT laboratory. Specimens were aged to five different levels (no aging, 4 hours, 4 hours + 1 day, 4 hours + 3 days, and 4 hours + 5 days) using the temperatures for short and long term aging outlined in AASHTO R 30. Specimens were aged to determine if the tensile strength of the WMA differed from the HMA initially and if the tensile strength of the two mixes would be similar once the mixes were aged.

Dynamic Modulus (AASHTO TP 62)

AASHTO TP 62, *Determining Dynamic Modulus of Hot-Mix Asphalt (HMA)*, was used to evaluate the stiffness of the mixes. Dynamic modulus testing was conducted in accordance with AASHTO TP 62. Three specimens per mix were compacted in the NCAT mobile laboratory using a gyratory compactor to a height of 170 mm. These specimens were then cored with a 100 mm core drill and cut to yield 150 mm tall specimens. The target air void content of the final prepared samples was 7 ± 0.5%. The frequencies used were 0.1, 0.5, 1.0, 5.0, 10.0, and 25.0 Hz. The testing temperatures were 40, 70, 100, and 130°F (4.4, 21.1, 37.8, and 54.4°C). The confining pressure employed was 20 psi (138 kPa). The data from the dynamic modulus test was used to create a master curve, which relates a material's stiffness over a range of frequencies. There is no standard pass/fail criterion for AASHTO TP 62; therefore, the master curves of the dynamic modulus developed from the testing were used to compare the stiffness of the WMA to the HMA.

Beam Fatigue (AASHTO T 321)

Bending beam fatigue testing was performed in accordance with ASTM D 7460, *Standard Test Method for Determining Fatigue Failure of Compacted Asphalt Concrete Subjected to Repeated Flexural Bending*, and AASHTO T 321, *Determining the Fatigue Life of Compacted Hot Mix Asphalt Subjected to Repeated Flexural Bending*. Six beam specimens were prepared from plant-produced mix that was re-heated in the laboratory. The specimens were compacted in a kneading beam compactor then trimmed to the dimensions of 15 ± 0.2 in. (380 ± 6 mm) in length, 2.5 ± 0.08 in. (63 ± 2 mm) in width, and 2 ± 0.08 in. (50 ± 2 mm) in height. The orientation in which the beams were compacted (top and bottom) was marked and maintained for the fatigue testing. The specimens were prepared in this manner to satisfy both AASHTO and ASTM beam fatigue sample preparation requirements. The specimens were prepared to a target air void content of 7 ± 1% after trimming. The beams were then aged in accordance with AASHTO R 30 for 5 days at 185°F (85^{o}C) to simulate long-term aging effects. Within each set of six beams, three beams were tested at 200 microstrain and three beams were tested at 400 microstrain.

The beam fatigue apparatus applied haversine loading at a frequency of 10 Hz. During each cycle, a target level of strain was applied to the bottom of the specimen. The loading device consisted of four-point loading and reaction positions, which allowed for the application of the target strain to the bottom of the test specimen. Testing was performed at 68 ± 0.9°F (20 ± 0.5°C) and to a maximum number of 12,000,000 cycles. Data acquisition software was used to record load cycles, applied loads, and beam deflections. The software also computed and recorded the maximum tensile stress, maximum tensile strain, phase angle, beam stiffness, dissipated energy, and cumulative dissipated energy at user specified load cycle intervals. A photo of the IPC Global Beam Fatigue apparatus used for this testing is shown in FIGURE 2.

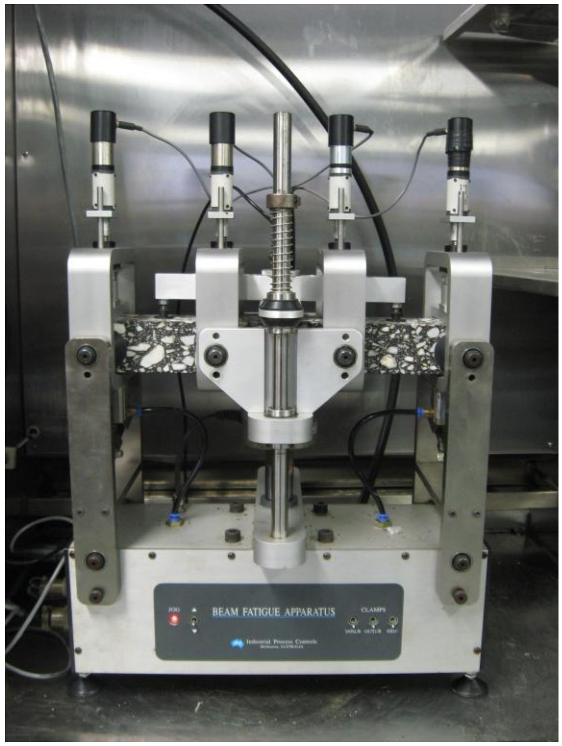

FIGURE 2 IPC Global Beam Fatigue Testing Apparatus.

At the beginning of each test, the initial beam stiffness was calculated by the data acquisition software after 50 conditioning cycles. ASTM D 7460 recommends that the test be terminated when the beam stiffness is reduced to 40% of the initial stiffness, while AASHTO T 321 defines termination at a 50% reduction in stiffness. To ensure a complete data set for the analysis, the beams for this project were allowed to run until the beam stiffness was reduced to 25% of the initial stiffness. The data acquired was used to calculate and compare fatigue life.

Simple Shear Test (AASHTO T 320)

The University of California Pavement Research Center (UCPRC) performed Repeated Simple Shear Test at a Constant Height (RSST-CH) and Shear Frequency Sweep (SFS) testing on cores according to AASHTO T 320 based on the test program summarized in TABLE 2. The RSST-CH test applies the loading shown in FIGURE 3.

TABLE 2 Shear Testing Parameters

AASHTOT 320 HMA and WMA	Stress Level, kPa	Temperature, °F (°C)	# Replicates
RSST-CH	70	113 (45)	3
RSST-CH	100	113 (45)	3
RSST-CH	130	113 (45)	3
RSST-CH	70	131 (55)	3
RSST-CH	100	131 (55)	3
RSST-CH	130	131 (55)	3
Frequency Sweep HMA and WMA	**Strain Level**	**Temperature, °F (°C)**	**# Replicates**
SFS	0.10%	113 and 131 (45 and 55)	2

The specimens for both the RSST-CH and SFS were produced in the same manner and at the same time. Reheated loose plant-produced mix was compacted using a slab compactor. The thickness of the slab was 2 inches. Six inch cores were cut from the slab. The cores with air voids of 7 ± 0.5% were retained for testing.

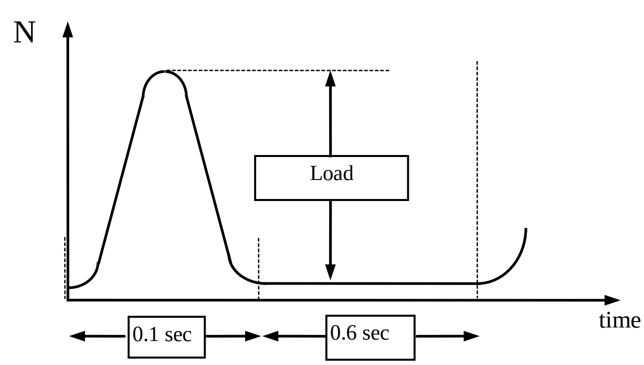

FIGURE 3 RSST-CH Loading

The RSST-CH samples were loaded with a haversine waveform to simulate the in-situ stress. The load is applied for 0.1 seconds followed by a 0.6 second rest period for a 0.7 second loading cycle, also described as Repeated Simple Shear Test repetition. In this study, the target stress levels were 70kPa, 100kPa, and 130kPa. Two key parameters of interest were number of cycles to 5% shear strain and resilient shear modulus in MPa. The test is scheduled to induce a 5% permanent shear strain over the 5000 repetition duration, which lasts approximately one hour. The test temperature was the critical high temperature as determined from the SHRP Superpave Specification (AASHTO M 320).

Maintaining constant height is achieved using an axial LVDT, which maintains a fixed position, allowing the axial load to vary accordingly.

The results of the RSST-CH are permanent shear strain versus repetitions. A plot of the two variables on a log-log scale approaches a linear relationship. The relevant test data to use in material comparison analysis are RSST-CH repetitions to 2 and 5% shear strain. Occasionally after 5000 repetitions, when 2 or 5% shear strain has not been achieved, linear extrapolation of the data is required. An estimate of the shear modulus can be determined if the elastic shear strain is calculated.

The raw data collected as time histories are listed below:

1. Shear Stress or Load
2. Axial Stress or Load
3. Shear Strain or Deformation (Either one or two shear LVDTs)
4. Axial Strain or Deformation (One axial LVDT)

The SFS testing was conducted at two temperatures, 113°F (45°C) and 131°F (55°C), at a constant strain of 100 microstrains in accordance with AASHTO T 320. The test frequencies used were 15, 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, and 0.01 Hz.

MATERIALS

The mixes produced were based on a 12.5 mm nominal maximum aggregate size Florida Department of Transportation dense graded mixture. The same mix design was used for each mix with the only differences being the addition of water and lower mixing temperatures for the WMA. The aggregate was predominantly granite with 30% reclaimed asphalt pavement (RAP). The base asphalt was a PG 64-22. The mix was designed at the 75 gyration level. The WMA had 0.13 tons (26 pounds) of moisture introduced to the asphalt binder per hour (1.25% water by weight of asphalt). The target mixing temperature for the HMA and WMA were 310 and 265°F, (154 and 129°C), respectively. Both mixes were produced at the same Gencor drum plant in Orlando, Florida.

LOOSE MIXTURE QUALITY EVALUATION

Evaluations were conducted on sampled loose mix to compare basic mix properties. The two evaluations conducted on the loose mix were moisture content and coating.

The moisture content (AASHTO T 329) was determined by sampling the mix after silo discharge and determining the quantity of moisture that evaporated through heating. The average moisture content for the WMA was 0.051% and the HMA moisture content was 0.010%. This difference in moisture was small, but was expected given the addition of moisture (about 0.075% moisture addition) to create the foaming in the WMA and the shorter silo time for the WMA. The WMA was produced solely for a test strip that was located at the plant, which resulted in a short silo time. The HMA was produced for a paving site that was 45 minutes from the plant, which resulted in mix being stored longer while trucks circulated back. The lower mixing temperatures may also have had an effect on the mixture moisture content.

Coating was evaluated to determine if the WMA technology achieved similar coating with asphalt as the HMA exhibited. The coating evaluation was conducted in accordance with AASHTO T 195. The HMA particles were 90% coated while the WMA particles were 86% coated. The difference in coating was small and may be a result of different storage times in the silo. The HMA was stored longer in the silo than the WMA. The WMA was in the silo for less than 45 minutes while the HMA was in the silo for several hours. Multiple samples of the HMA were collected throughout the evening; therefore, the silo storage time varied.

COMPACTION RESISTANCE MIX TESTING

The locking point of each mix was determined by compacting the mix in a gyratory compactor. The point at which the height was the same for two successive gyrations was identified as the locking point. A minimum of two design samples of each mixture were compacted. The locking point range for the WMA was 27 to 37 gyrations and the locking point range for the HMA was 33 to 34 gyrations. FIGURE 4 illustrates the changes in height with gyrations. Only two readings were obtained for the WMA due to the third file becoming corrupt. The WMA height of the design specimens was slightly higher than the HMA. The average final difference in height was 1.6 mm. The data shows similar gyratory compaction behavior for the WMA and the HMA, with the HMA being slightly more compactable than the WMA. This result suggests that the difference in compaction temperatures between the WMA and HMA did not substantially affect the compactability of the mix.

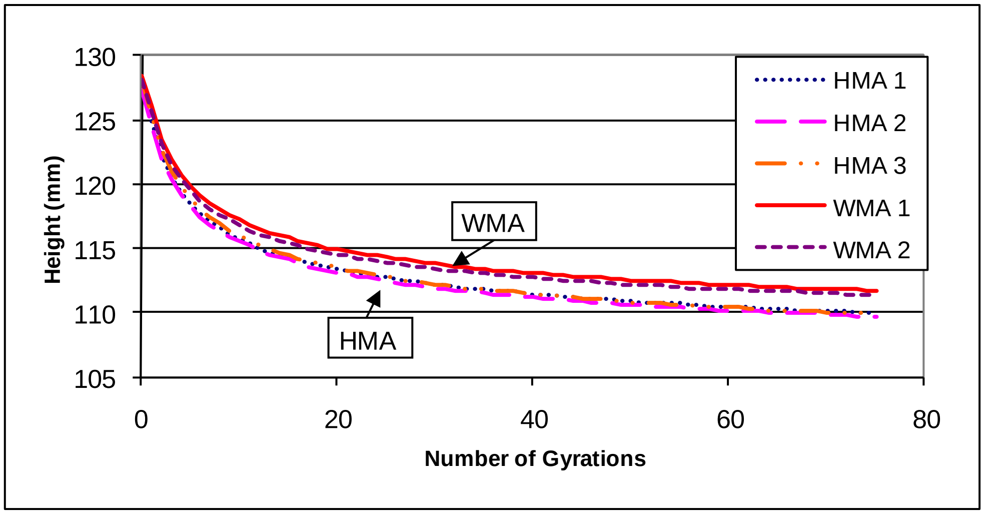

FIGURE 4 Changes in Compaction Height with Gyrations

MIXTURE PERFORMANCE TESTING

Tests on compacted mix were conducted to evaluate the affect of the WMA technology on the mechanical properties of the mix. The mix tests were moisture susceptibility (AASHTO T 283), Hamburg Wheel Tracking Test (AASHTO T 324), Asphalt Pavement Analyzer (AASHTO TP63), indirect tensile strength (AASHTO T 283), dynamic modulus (AASHTO TP 62), beam fatigue (AASHTO T 321 and ASTM D 7460), and simple shear test (AASHTO T 320). The following sections present the results of the mix testing that was completed.

Moisture Susceptibility Testing and Results (AASHTO T 283)

TABLE 3 and FIGURE 5 summarize the results of the moisture susceptibility testing conducted in accordance with AASHTO T 283. The whiskers in FIGURE 5 represent minimum and maximum values. All of the individual tensile strengths exceeded 100 psi, which is a favorable result. The tensile strengths of the WMA tended to be less than the

HMA, which is typical for WMA results. The ratio of the average tensile strengths of the conditioned specimens to the average tensile strengths of the unconditioned specimens is defined as the tensile strength ratio (TSR). The TSR value for the WMA was 0.76 and the TSR for the HMA was 0.94. A typical pass/fail criterion for tensile strength moisture susceptibility testing stipulated in AASHTO R 35 is a TSR value of 0.8. The HMA showed an acceptable TSR value while the WMA TSR value was slightly below this acceptable threshold value. FIGURE 6 shows photographs of broken samples for both the conditioned and unconditioned AASHTO T 283 WMA samples. FIGURE 7 shows the same comparison for the HMA. From these figures, a small amount of stripping is evident in the conditioned WMA specimens while virtually no stripping was visible in the HMA conditioned specimens. This was to be expected given the lower TSR value for the WMA as opposed to the HMA.

TABLE 3 AASHTO T 283 Results

Mix	Treatment	Additive	Air Voids (%)	Saturation (%)	Tensile Strength (psi)	TSR
WMA	Conditioned	Water	7.0	70.5	137.2	0.76
			7.0	72.3	123.9	
			6.9	74.3	151.5	
	Unconditioned		7.2	N/A	184.6	
			7.2	N/A	169.0	
			7.1	N/A	191.2	
HMA	Conditioned	None	6.7	70.8	175.5	0.94
			7.0	70.1	176.5	
			7.0	70.3	197.0	
	Unconditioned		6.8	N/A	189.6	
			6.5	N/A	210.3	
			7.1	N/A	185.0	

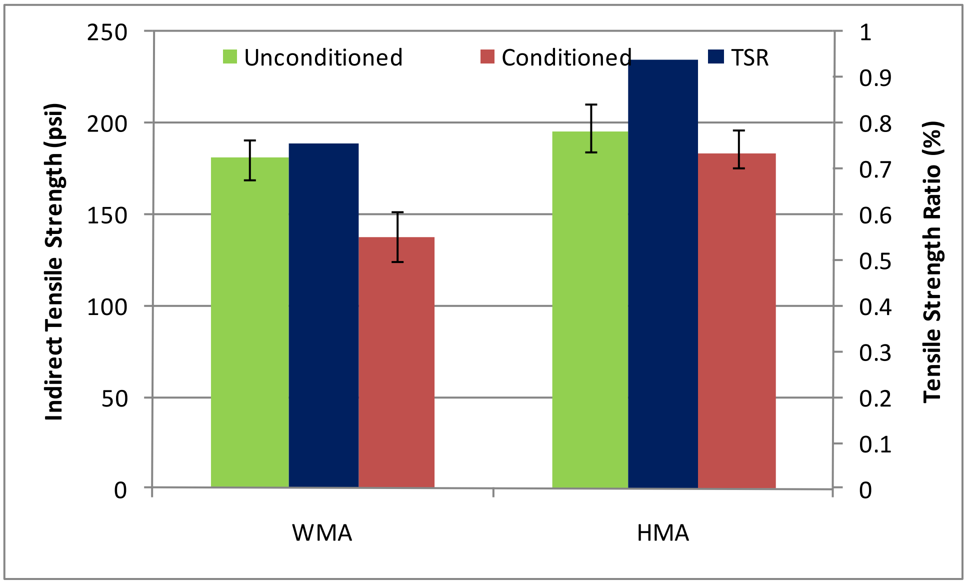

FIGURE 5 Moisture Susceptibility Results

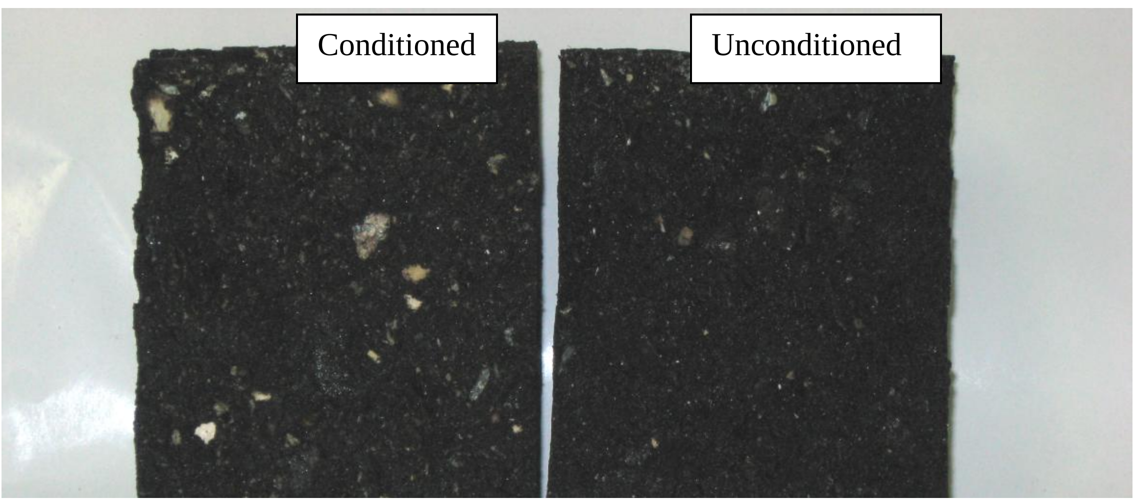

FIGURE 6 WMA AASHTO T 283 Specimens

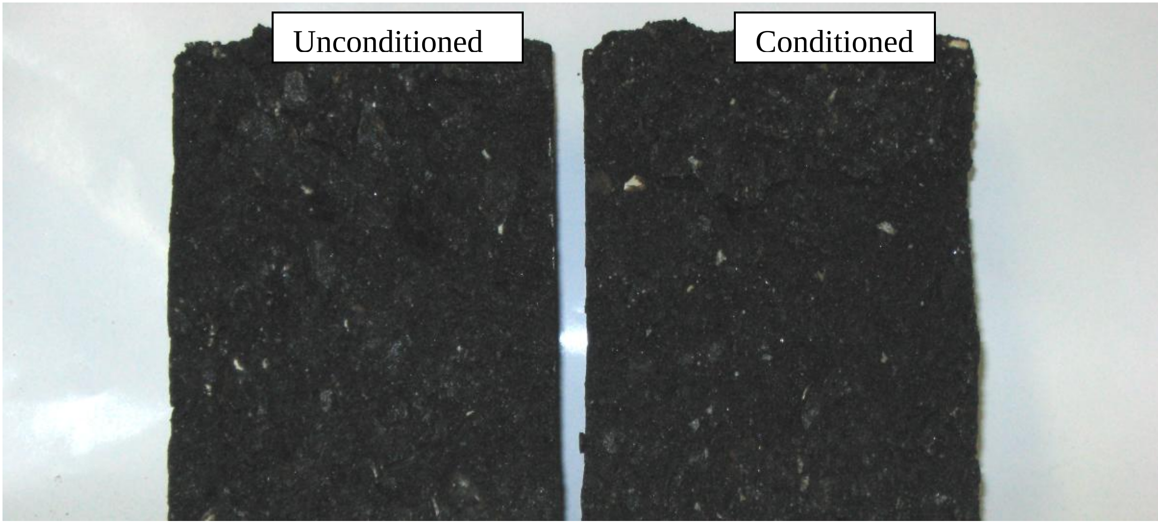

FIGURE 7 HMA AASHTO T 283 Specimens

Hamburg Wheel Tracking Testing Results (AASHTO T 324)

The Hamburg testing was conducted in accordance with AASHTO T 324 and the stripping inflection point, rutting rate, and total rut depth were determined for each mix. Each data point was generated from two replicate samples. Four specimens per mix were tested (two at a time) in the Hamburg. TABLE 4 summarizes the results of the Hamburg testing for the specimens compacted without additional aging. TABLE 5 summarizes the Hamburg testing results for the laboratory-aged specimens (aging in accordance with Texas Department of Transportation procedure).

TABLE 4 Hamburg Wheel Tracking Results: No Additional Aging

Mix	Rutting Rate (mm/hr)	Total Rut Depth (mm) @ 10,000 Cycles	Stripping Inflection Point (cycles)	Average Stripping Inflection Point
WMA	1.260	5.00	4250	5125
	1.424	5.65	6000	
HMA	1.346	5.34	None	None
	1.177	4.67	None	

TABLE 5 Hamburg Wheel Tracking Results: Additional Aging

Mix	Rutting Rate (mm/hr)	Total Rut Depth (mm) @ 10,000 Cycles	Stripping Inflection Point (cycles)	Average Stripping Inflection Point
WMA	2.293	9.10	4050	5325
	1.764	7.00	6600	
HMA	1.688	6.70	7450	6860
	1.499	5.95	6270	

The rutting rate was determined for both the WMA and HMA Hamburg specimens made from non-aged and aged plant-produced mix (see TABLE 4 and TABLE 5). FIGURE 8 illustrates the Hamburg rutting rate results. The rutting rate of the WMA was higher than that of the HMA for both non-aged and aged mix. The difference in rutting rate was magnified by the aging of the mixes. Both the WMA and HMA rutting rates increased with the aging. The difference between the WMA and HMA that were non-aged and compacted from the plant mix without reheating was minimal. FIGURE 9 illustrates the total rut depth at 10,000 cycles (20,000 passes). The aging had the same effect on the rut depth as it did on the rutting rate. The WMA did rut more than the HMA; however, both exhibited a rut depth that was less than 10 mm (0.4 in) regardless of aging.

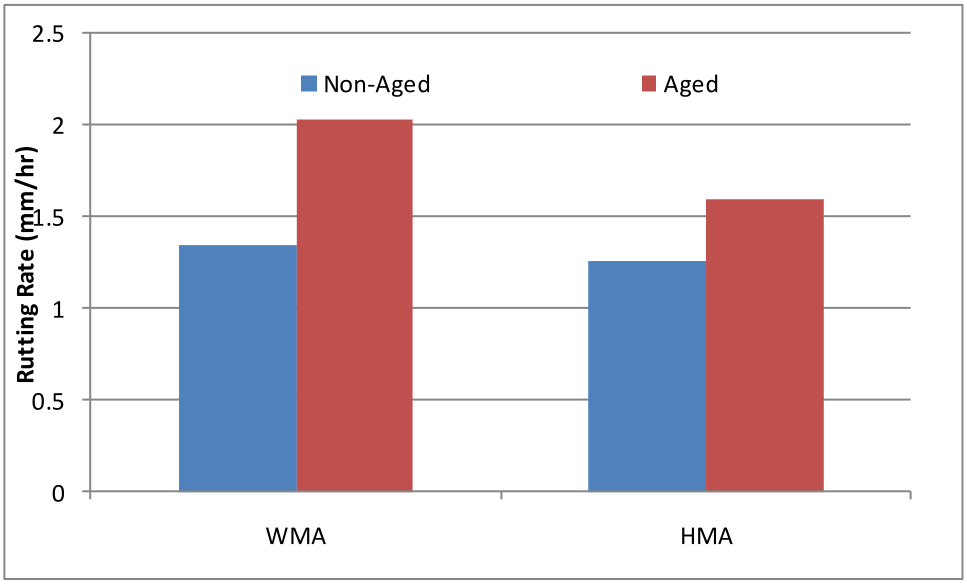

FIGURE 8 Hamburg Rutting Rate

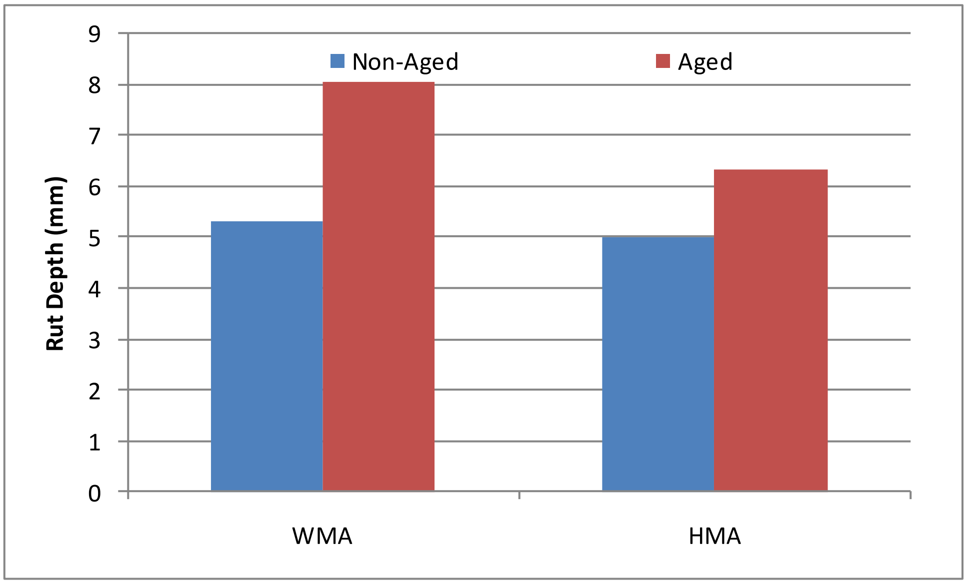

FIGURE 9 Hamburg Rut Depth

The stripping inflection points were determined from the test results based on the procedure outlined in AASHTO T 324. The average stripping inflection points of the non-aged (non-reheated) and aged (reheated) mixes are displayed in FIGURE 10.

A stripping inflection point of 5,000 cycles (10,000 passes) or more was considered acceptable. The average stripping inflection point of both the WMA and

HMA yielded acceptable average stripping inflection points for the non-aged and aged specimens. The WMA showed higher moisture susceptibility than the HMA for both sets of specimens, though the WMA still exceeded the minimum acceptable stripping inflection point for moisture resistance for the Hamburg Wheel Tracking testing. The average stripping inflection point of the WMA was largely unaffected by the laboratory aging time, while the stripping inflection point of the HMA was reduced by the aging process.

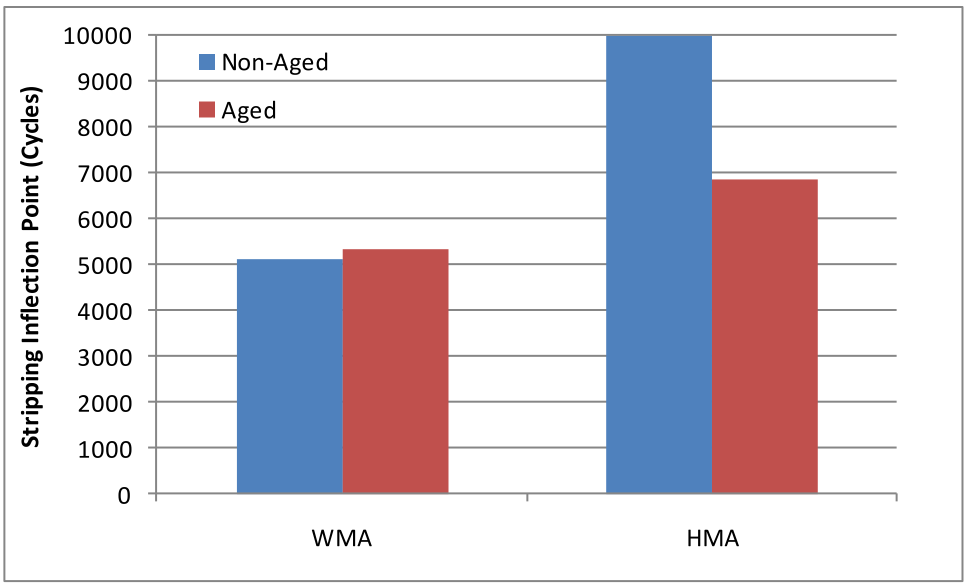

FIGURE 10 Hamburg Stripping Inflection Point Results

The Hamburg testing indicated that the aging of the mix tended to negatively affect both the HMA and WMA in terms of rutting rate and rut depth. The WMA regardless of aging did tend to exhibit a greater propensity for rutting and stripping than the HMA.

Asphalt Pavement Analyzer Rut Test Results (AASHTO TP 63)

The Asphalt Pavement Analyzer testing was conducted in accordance with AASHTO TP 63. TABLE 6 and FIGURE 11 summarize the results of the Asphalt Pavement Analyzer rut test. The average rut depth of the WMA was slightly deeper than the HMA; however, the results were not statistically different (p-value = 0.60). The average air voids of the HMA specimens were also lower than the WMA, which could have affected the rut depth measurements (as shown in FIGURE 12). Both the WMA and HMA had average rut depths of less than 8 mm, which is a common acceptable maximum rut depth for low volume APA rut testing.

TABLE 6 Asphalt Pavement Analyzer Rut Test Results

Mix	Rut Depth (mm)	Average Rut Depth (mm)	Standard Deviation of Rut Depth
WMA	5.82	6.08	0.89
	6.42		
	7.49		
	5.05		
	6.38		
	5.30		
HMA	4.55	5.75	1.23
	7.60		
	4.60		
	5.23		
	5.71		
	6.78		

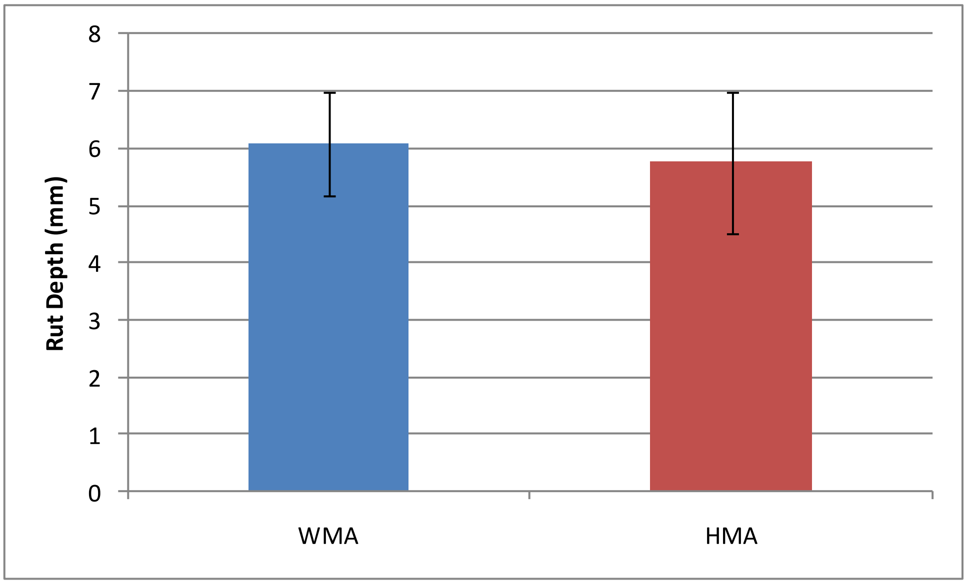

FIGURE 11 Asphalt Pavement Analyzer Average Rut Depths

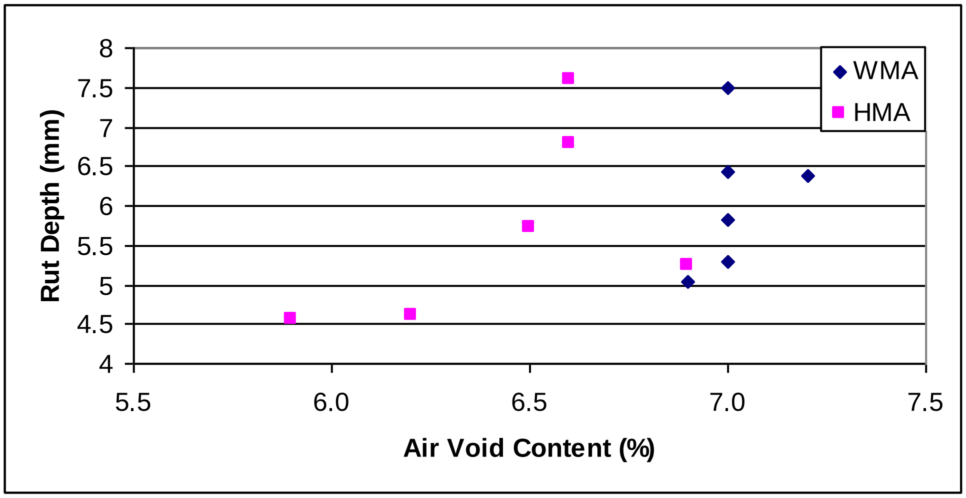

FIGURE 12 Asphalt Pavement Analyzer Rut Depths

Dynamic Modulus Test Results (AASHTO TP 62)

Master curves were developed to compare the response of the HMA to that of the WMA technology. Master curves are developed by shifting dynamic modulus test results from different testing temperatures and frequencies to form one smooth curve. A reference temperature over several frequencies was used to develop the master curves. FIGURE 13 illustrates the master curves generated from the HMA and WMA dynamic modulus testing. There was a difference in stiffness between the two mixes. The HMA was stiffer than the WMA most likely because the mixing temperature for the HMA was higher than that of the WMA and the increased time in the silo. The higher HMA mixing temperature most likely oxidized the binder more resulting in a stiffer binder than the WMA. Tukey's mean comparisons of the data indicated that for all temperatures and frequencies, with the exception of the highest temperature at the four highest frequencies, the HMA was significantly stiffer than the WMA.

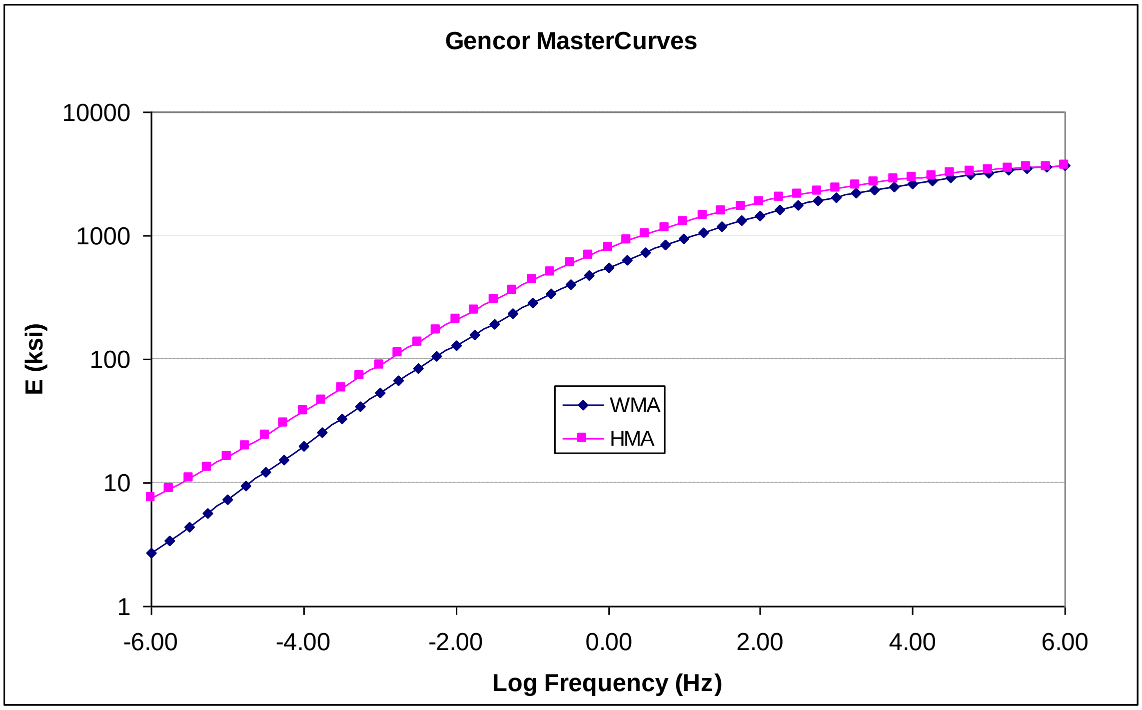

FIGURE 13 Dynamic Modulus Master Curves

Indirect Tensile Strength of Aged Specimens Test Results

Indirect tensile strength testing was conducted on WMA and HMA specimens with various degrees of laboratory aging in accordance with unconditioned specimen preparation and testing described in AASHTO T 283 for this project. As stated earlier, this testing was performed to determine if the tensile strength of the WMA was comparable to the HMA initially and with time.

For both the WMA and HMA, tensile strength values were determined at five different aging conditions. The control was the tensile strength of mix that had not been aged and was compacted in the NCAT mobile laboratory. The other four sets of tensile strength specimens were compacted from mix aged in the laboratory to different extents. The aging was conducted for 4 hours, 1 day plus 4 hours, 3 days plus 4 hours, and 5 days plus 4 hours at 135°F.

FIGURE 14 shows the results of the indirect tensile strength testing for both the WMA and HMA. The plot illustrates the average, minimum, and maximum for the indirect tensile strength of the WMA and HMA at various degrees of laboratory aging. It can be seen that the HMA tensile strength is typically 10 to 22 psi higher than the WMA.

This difference is less than 10% of the original tensile strength of the HMA, on average. Additionally, this plot shows the difference in tensile strength between the WMA and HMA as a function of time. Both mixes gained tensile strength with aging. It can be observed that the softer asphalt of the WMA does not converge with the HMA after five days of aging. This may be a function of the length of aging. Extending the test beyond five days may show comparable values because the rate of indirect tensile strength gain was higher for the WMA. It should be noted that the WMA aged for four hours indirect tensile strength equaled the control HMA without aging.

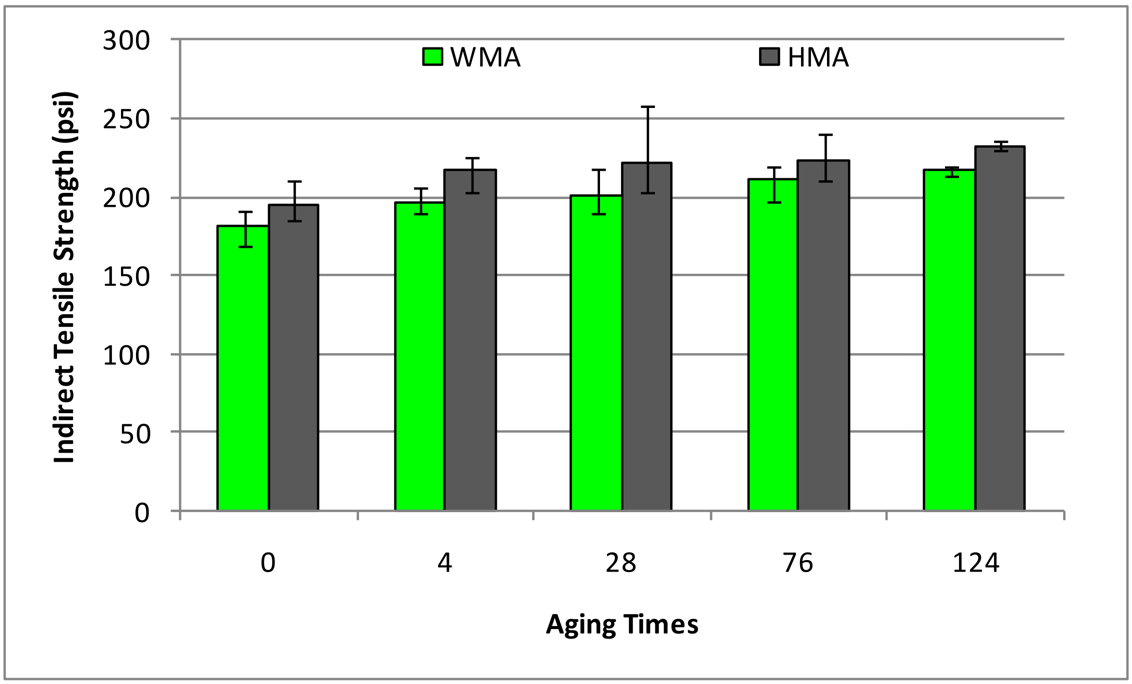

FIGURE 14 Average Indirect Tensile Strength of Over Time

Beam Fatigue Results (AASHTO T 321)

The fatigue resistance of the two mixes was evaluated via AASHTO T 321 testing. Based on the collected data, the value of Normalized Modulus × Cycles was calculated using Equation 1 to interpret the point of failure. According to ASTM D 7460, the failure point occurs at the maximum point on a plot of Normalized Modulus × Cycles versus number of testing cycles. An example of this type of plot is shown in FIGURE 15. This maximum point also corresponds to a sudden reduction in stiffness of the specimen.

$$NM = \frac{S_i x N_i}{S_o x N_o}$$ (Equation 1)

where:

NM = Normalized Modulus × Cycles

S_i = flexural beam stiffness at cycle i

N_i = cycle i

S_o = initial flexural beam stiffness (estimated at 50 cycles)

N_o = actual cycle number where initial flexural beam stiffness is estimated

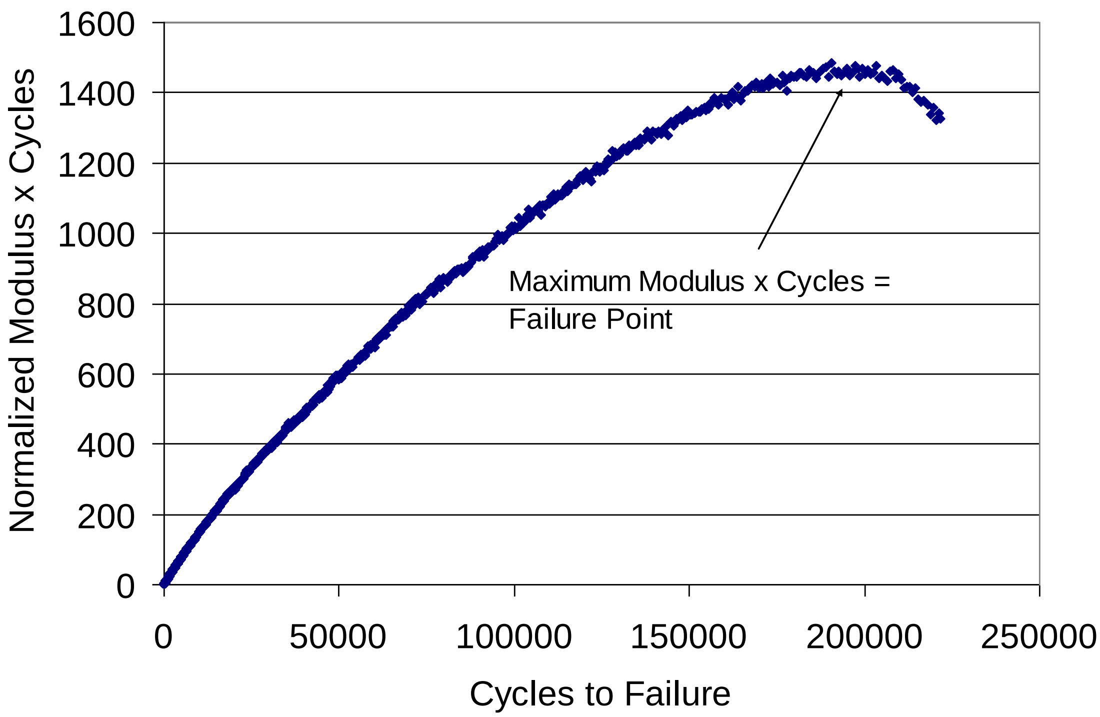

FIGURE 15 Sample Plot of Normalized Modulus × Cycles versus Number of Cycles

Another failure point was also calculated for each beam specimen in accordance with AASHTO T 321. AASHTO T 321 defines failure as the number of cycles after which the initial modulus of the beam has been reduced by 50%. By running the test to a reduction in initial stiffness of 25%, both an ASTM and an AASHTO number of cycles to failure was determined for each beam specimen.

Given the cycles to failure for two different strain levels, the fatigue endurance limit was then calculated for each mix. Using a proposed procedure developed under NCHRP 9-38 (*10*), the endurance limit for each of the five mixes was estimated using Equation 2 based on a 95% lower prediction limit of a linear relationship between the log-log transformation of the strain levels (200 and 400 microstrain) and cycles to failure. All the calculations were conducted using a spreadsheet developed under NCHRP 9-38.

$$\text{Endurance Limit} = \hat{y}_0 - t_\alpha s\sqrt{1+\frac{1}{n}+\frac{(x_0-\bar{x})^2}{S_{xx}}} \quad \text{(Equation 2)}$$

where:

$\hat{y}_o$ = log of the predicted strain level (microstrain)

t_α = value of *t* distribution for n-2 degrees of freedom = 2.131847 for n = 6 with α = 0.05

s = standard error from the regression analysis

n = number of samples = 6

S_{xx} = $\sum_{i=1}^{n}(x_i-\bar{x})^2$ (Note: log of fatigue lives)

x_o = log (50,000,000) = 7.69897

$\bar{x}$ = log of average of the fatigue life results

TABLE 7 lists the results of each of the individual beam fatigue tests. For each test, the following is reported: testing strain level, sample air voids, and both the ASTM and AASHTO defined cycles to failure. All of the beams failed in less than 12 million cycles with one exception. Sample number 5 of the HMA ran to the full 12 million cycles without exhibiting an ASTM failure point. It did fail by the AASHTO definition prior to that. Since there is no extrapolation method to determine an ASTM failure point from the measured data, it was reported as having a failure point of 12 million cycles for the purposes of reporting.

TABLE 7 Summary of Individual Beam Fatigue Test Results

Mix	Strain Level (ms)	Sample Air Voids (%)	Cycles to Failure (ASTM)	Cycles to Failure (AASHTO)
WMA	200	7.3	2,537,720	2,811,180
WMA	200	7.7	8,024,980	8,844,360
WMA	200	7.3	4,190,070	4,042,650
WMA	400	6.9	55,940	55,510
WMA	400	7.6	129,320	95,010
WMA	400	6.1	117,940	106,740
HMA	200	7.2	12,000,000**	9,308,690
HMA	200	7.2	7,822,270	8,360,300
HMA	200	6.8	4,810,850	5,089,400
HMA	400	7.9	42,220	41,580
HMA	400	7.4	126,370	102,320
HMA	400	6.6	171,790	137,500

** = Test Terminated at 12 Million Cycles – Did not reach ASTM failure limit

FIGURE 16 shows the average and minimum and maximum (represented by the error bars) of the cycles to failure for each mix type at the two different strain levels for both the ASTM and AASHTO failure criteria. From this figure, it appears that the failure points defined by ASTM and AASHTO were similar when comparing the same mix at an equivalent strain level. This plot also shows that the HMA had a slightly higher fatigue life at the low strain level of 200 microstrain than the WMA. The results of testing at 400 microstrain indicated that the fatigue lives are similar to one another. A complete analysis was performed on the data set as determined by both the ASTM and AASHTO failure points. However, given the similarities in the ASTM and AASHTO data (as shown in FIGURE 16) coupled with the fact that one of the beams did not demonstrate a true ASTM failure point, only the complete AASHTO results are documented for the purposes of this report. The complete analysis of the ASTM data yielded similar results to that of the AASTHO analysis, however.

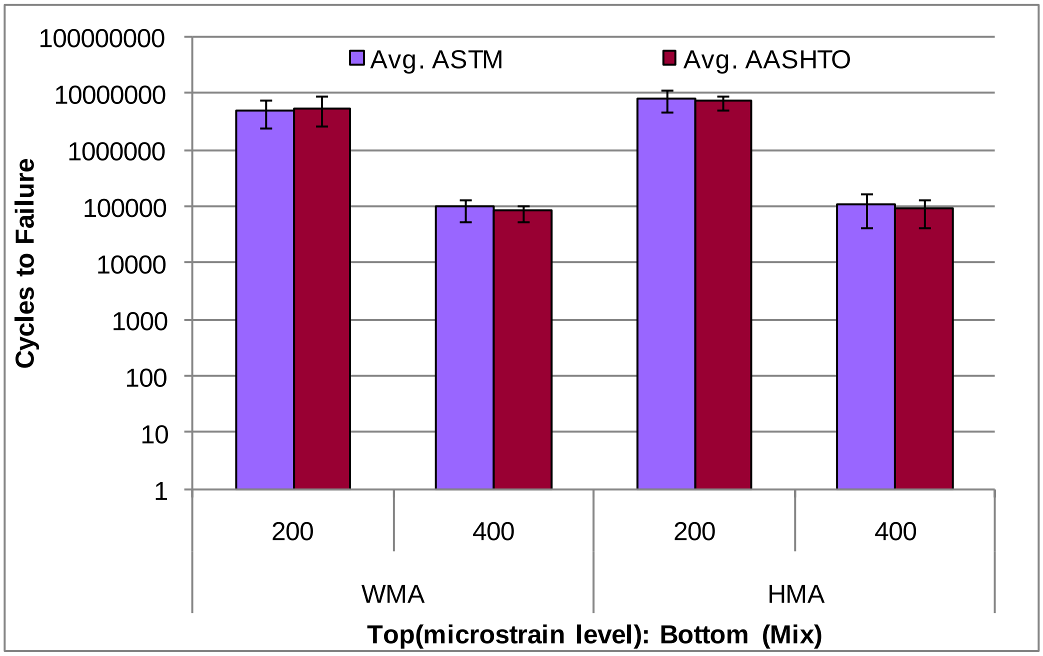

FIGURE 16 Average Cycles to Failure by Strain Level and Mix Type

FIGURE 17 shows the fatigue curves as defined by the AASHTO failure criterion. The curves in this figure represent the strain level as a function of cycles to failure for both the WMA and HMA. The curves are fitted to the data through a basic power model. This data shows that the WMA and HMA had similar fatigue resistance at the higher 400 microstrain testing level and that the HMA showed a slightly longer fatigue life at the lower strain level of 200 microstrain. For each mix, an endurance fatigue limit was calculated using the procedure outlined above (see Equation 2). The endurance limits, along with the regression coefficients for the fatigue life curves, are shown in TABLE 8. The endurance limits for the WMA using the AASHTO and ASTM failure criteria were within 5 microstrain of each other. From the data in TABLE 8, it can be seen that the WMA has an endurance limit of 107 microstrain (AASHTO failure criterion) while the HMA has an endurance limit of 123 microstrain (AASHTO failure criterion). Practically, this means that the WMA pavement will incur damage at a lower loading level than the HMA pavement.

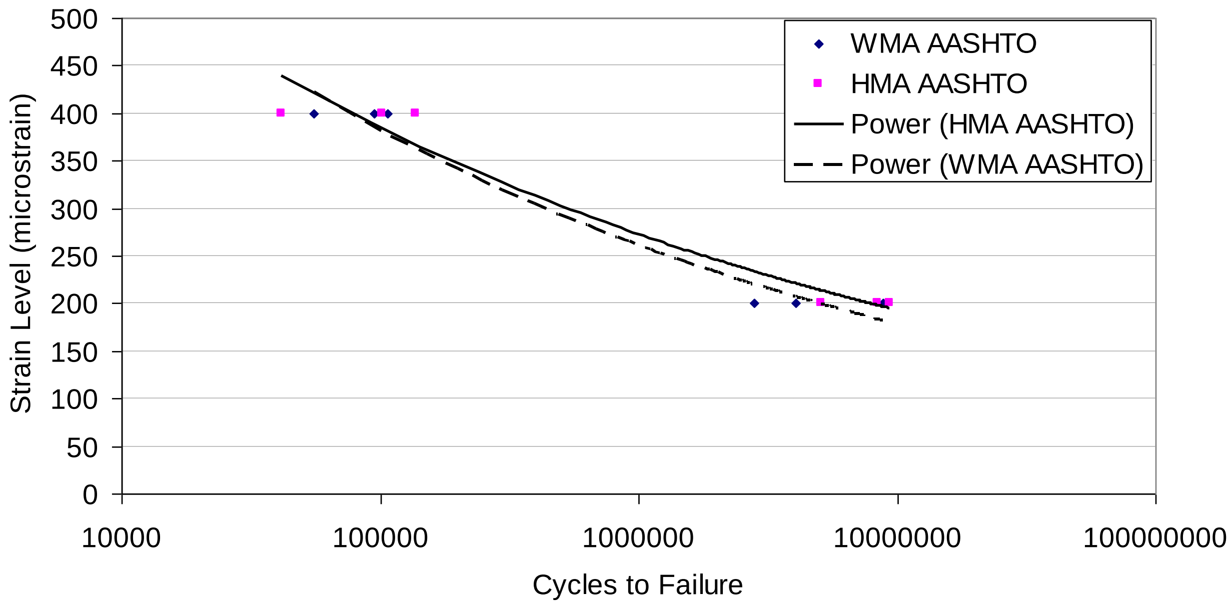

FIGURE 17 AASHTO Fatigue Life Curve

TABLE 8 Summary of Fatigue Curve Regression and Endurance Limits

Mix ID	Endurance Limit	α_1	α_2	R^2
WMA AASHTO	107	2576.1	-0.1656	0.963
HMA AASHTO	123	2165.4	-0.1500	0.968

Simple Shear Test Results (AASHTO T 320)

The RSST-CH was conducted to evaluate the rutting resistance of each of the field mixes. The test consists of determining the number of cycles the mix can endure before a 5% shear strain is realized. The higher the number of cycles that are endured before 5% shear strain is reached, the more resistant a mix is to rutting. The number of cycles to 5% strain shown for each test was either interpolated from test data or extrapolated, depending upon whether a test reached 5% strain during the allotted 30,000 testing cycles. Fifteen of eighteen Gencor WMA tests reached 5% strain in fewer than 30,000 testing cycles. Six of eighteen HMA tests reached 5% strain in fewer than 30,000 testing cycles. Tests were separated by comparable stress levels within each temperature grouping to facilitate performance comparison.

FIGURE 21 illustrates the mean cycles at 5% shear strain. In general, both mixes decreased in permanent deformation resistance with increasing stress level. The HMA however, did endure more cycles prior to reaching 5% shear strain.

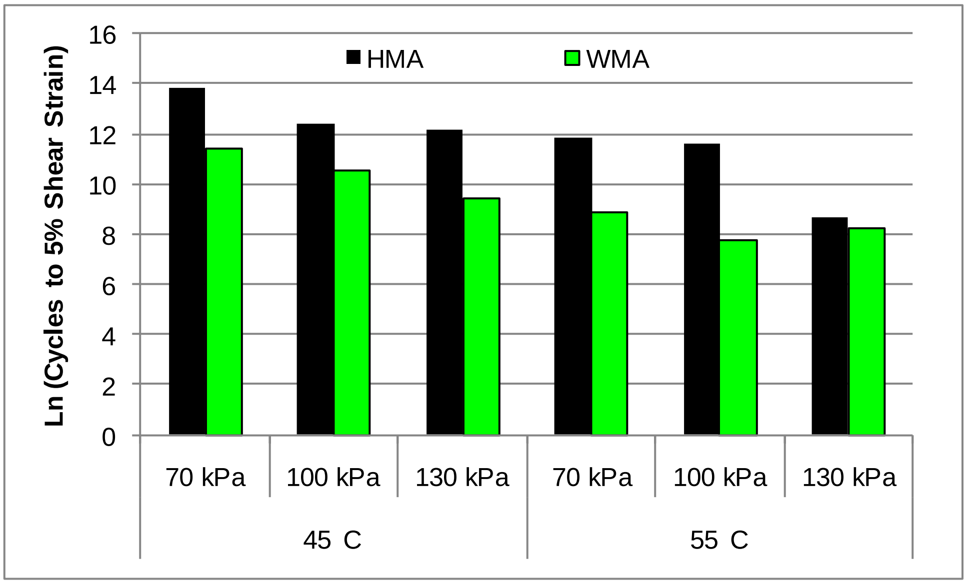

FIGURE 18 Mean Cycles to 5% Shear Strain

Analysis of variance (ANOVA) was conducted to determine which factors significantly affected the variability of number of cycles attained at 5% shear strain. The factors considered were mix type (HMA or WMA), test temperature (113°F (45°F) and 131°F (55°F)), and shear stress (70, 100, and 130 kPa). The ANOVA of all of the RSST-CH data for number of cycles to 5% strain indicated that the only significant factor was mix type. This implies that the production of the mix at the WMA temperature and WMA process significantly affected the variability of the RSST-CH testing. TABLE 9 summarizes the results of the mean comparisons conducted for the different test temperatures and stresses along with the difference and coefficient of variation for each set. The results indicated that half of the time, the WMA cycles to 5% shear strain was statistically lower than the HMA cycles. The results of the RSST-CH to 5% shear strain indicate that the WMA may be more prone to permanent deformation than the HMA. .

TABLE 9 Mean Comparison Results for RSST-CH 5% Shear Strain

Test Temperature °F (°C)	Stress kPa	Significant Difference?	HMA Coefficient of Variation	WMA Coefficient of Variation
45	70	No	106	115
45	100	Yes	10	93
45	130	No	87	22
55	70	Yes	14	26
55	100	No	153	13
55	130	No	82	69

The resilient shear modulus was also recorded as part of the RSST-CH test. FIGURE 19 illustrates the mean shear modulus at the various test temperatures and stresses. The resilient shear modulus of the HMA was higher than that of the WMA. The shear modulus for both mixes was affected by the test temperature. Mean comparisons were conducted to identify differences within a temperature and frequency combination (see TABLE 10). In three of the cases (lower stress levels) the WMA was significantly lower than the HMA. ANOVA was conducted and it was determined that mix type and test temperature significantly affected the resilient shear modulus variability.

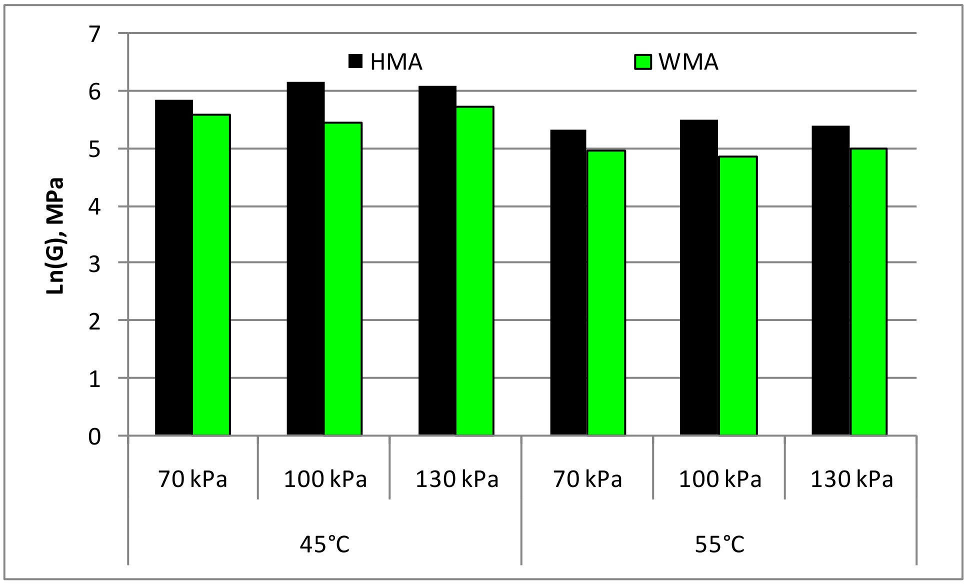

FIGURE 19 Mean Resilient Shear Modulus Results

TABLE 10 Mean Comparison Results and Coefficient of Variation for Resilient Shear Modulus

Test Temperature °F (°C)	Stress kPa	Significant Difference?	HMA Coefficient of Variation	WMA Coefficient of Variation
113 (45)	70	Yes	7	14
113 (45)	100	Yes	9	7
113 (45)	130	No	29	6
131 (55)	70	No	39	14
131 (55)	100	Yes	19	9
131 (55)	130	No	34	9

FIGURE 20 presents shear stiffness versus frequency for HMA and Gencor WMA for four specimens each. In most cases, WMA specimens exhibited increased rates (higher slopes) of permanent deformation versus cycle at the end of tests.

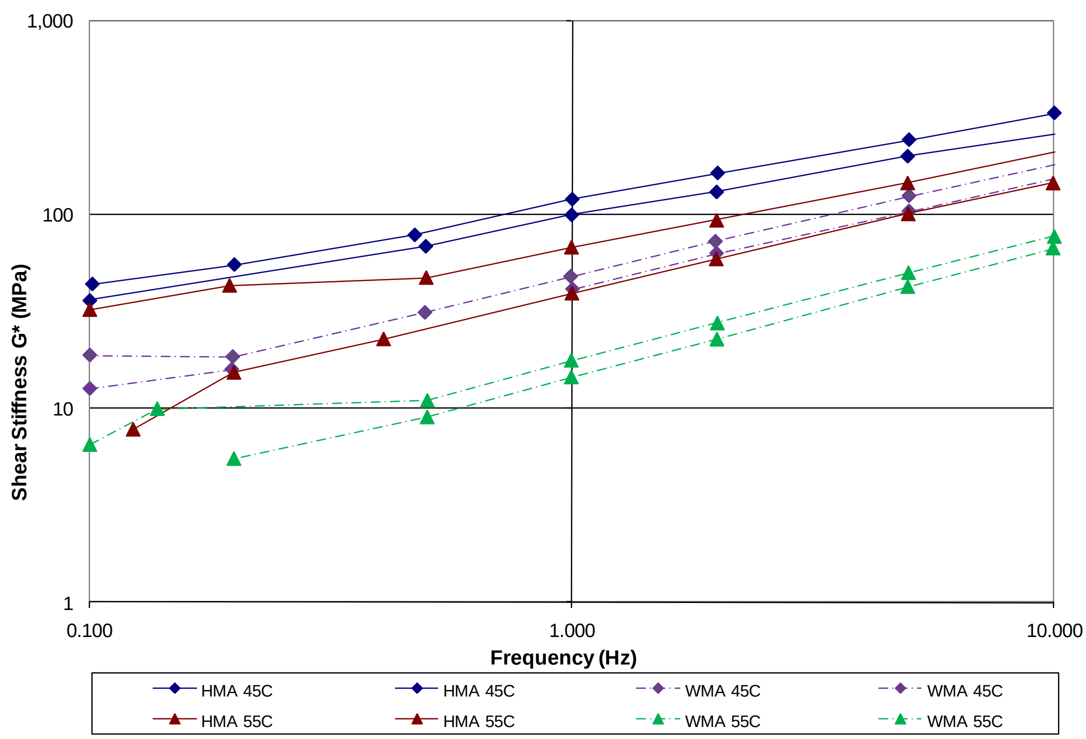

FIGURE 20 Shear Stiffness versus Frequency for HMA and Gencor WMA from Shear Frequency Sweep Test

ANOVA was conducted for both the shear modulus and phase angle to determine which factors significantly contributed to the variability of the results. The factors that were considered were mix type, frequency and test temperature. The results of the ANOVA for the shear modulus indicated that all three factors were significant while the mix type was the only significant factor for the phase angle.

CONCLUSIONS

Several mix tests were conducted to determine if a WMA, produced using the Gencor Green Machine Ultrafoam GX, had similar properties as an HMA. The moisture susceptibility testing conducted in accordance with AASHTO T 283 indicated that the WMA might be more susceptible to moisture damage. The reduced moisture resistance based on AASHTO T 283 for WMA is common and in some cases has been corrected by using an anti-stripping agent. The Hamburg results indicated that, without aging the WMA, the average stripping inflection point was slightly lower than the HMA, but acceptable. Once the mix was aged, the average stripping inflection point of the WMA increased slightly. The Hamburg stripping inflection point data indicates that while the WMA may initially have a lower resistance to moisture damage than the HMA, the resistance will increase with time.

The rutting rate of the WMA was slightly higher than the HMA for the Hamburg testing, but the difference was not substantial. The total rutting after 10,000 cycles for the WMA Hamburg specimens was higher than the HMA Hamburg specimens. The aging of the mix appeared to magnify the difference in rut resistance of the two mixes. Both mixes, however, did meet the Hamburg rut depth criterion of less than 10 mm. The other rutting test that was employed was the Asphalt Pavement Analyzer. The results from the Asphalt Pavement Analyzer were in agreement with the rut testing conducted with the Hamburg in that the WMA was slightly more prone to rutting than the HMA. The difference in the WMA and HMA Asphalt Pavement Analyzer rut data was minimal and may be due to the difference in air voids. Both mixes were below the rut depth threshold of 8 mm for Asphalt Pavement Analyzer testing. Therefore, based on both the Hamburg and Asphalt Pavement Analyzer data, the WMA produced using the Gencor Green Machine Ultrafoam GX is only slightly more prone to rutting and meets the criterion established for laboratory rut testing. The results of the simple shear testing supported the conclusions that the WMA may be slightly more prone to permanent deformation.

The dynamic modulus testing indicated that the HMA is slightly stiffer than the WMA. The indirect tensile strength testing showed that the WMA does have a lower tensile strength, but like the HMA, it gained strength with time. The tensile strength of the WMA exceeded 150 psi initially and 200 psi after five days plus four hours of aging. Tensile strength of unconditioned specimens increases rapidly for WMA and was still increasing after the final aging period while the HMA leveled off. This may indicate that with time the WMA may reach similar indirect tensile strength as the HMA.

The beam fatigue testing indicated that the WMA at lower microstrains exhibits a lower fatigue life; however, at the higher microstrains the difference between the HMA and WMA is negligible. The endurance limit of each mix was determined and indicated that the WMA may incur damage at a lower loading level than the HMA.

Overall, while the laboratory performance of the WMA was lower than the HMA for many of the tests, the WMA performance exceeded minimum laboratory performance thresholds in most cases. The rutting results of both mixes were acceptable for the two rut tests. The tensile strength for the WMA was high and improved with age. The tensile strength ratio of the WMA did not meet the 0.8 criterion, however the indirect tensile strengths were high and the TSR could be improved with the addition of an anti-stripping agent. Based on the testing results of a field mix, the Gencor Green Machine Ultrafoam GX is a promising WMA technology.

REFERENCES

1. G. C. Hurley, “Evaluation of New Technologies for Use in Warm Mix Asphalt”, MS Thesis Auburn University (2006).
2. G. C. Hurley and B. D. Prowell, "Evaluation of Evotherm for use in Warm Mix Asphalt", NCAT Report 06-02 (2006).
3. G. C. Hurley and B. D. Prowell, "Evaluation of Sasobit for use in Warm Mix Asphalt", NCAT Report 05-06 (2005).

4. G. C. Hurley and B. D. Prowell, "Evaluation of Aspha-Min Zeolite for use in Warm Mix Asphalt", NCAT Report 05-04 (2005).
5. Hurley, G., Prowell, B., and A. Kvasnak. *Ohio Field Trial of Warm Mix Asphalt Technologies: Construction Summary*. NCAT Report 09-04. Auburn, Al, 2009.
6. Hurley, G., Prowell, B., and A. Kvasnak. *Michigan Field Trial of Warm Mix Asphalt Technologies: Construction Summary*. (in review), Auburn, Al, 2009.
7. Hurley, G., Prowell, B., and A. Kvasnak. *Wisconsin Field Trial of Warm Mix Asphalt Technologies: Construction Summary*. (in review), Auburn, Al, 2009.
8. Hurley, G., Prowell, B., and A. Kvasnak. *Missouri Field Trial of Warm Mix Asphalt Technologies: Construction Summary*. (in review), Auburn, Al, 2009.
9. --, Moisture Sensitivity of Asphalt Pavements A National Seminar, Transportation Research Board, 2003.

APPENDIX A: REPEATED SIMPLE SHEAR TEST RESULTS

TABLE 11 Repeated Simple Shear at Constant Height Test Results for 45°C

Sample Name	Air Void	Temp °C	τ (kPa)	Mr (MPa)	Mr @ Cycle	Cycles to 2% γ Perm Nonadj	Int/Ext	Deacon	Int/Ext	Cycles to 5% γ Perm Nonadj	Int/Ext	Deacon	Int/Ext
HMA-GNCAT-4-2-7045		45	70	337.3	100	27,927	Int	27,929	Int	464,961	Ext	464,810	Ext
HMA-GNCAT-7-6-7045	7.0	45	70	338.5	100	22,411	Int	22,513	Int	335,565	Ext	330,325	Ext
HMA-GNCAT-7-8-7045	7.3	45	70	377.8	100	62,355	Ext	62,322	Ext	2,274,648	Ext	2,281,376	Ext
WMA-GNCAT-1-9-7045	7.3	45	70	263.2	100	1,851	Int	1,892	Int	34,840	Ext	34,956	Ext
WMA-GNCAT-2-3-7045	7.2	45	70	236.7	100	3,164	Int	3,272	Int	26,513	Int	26,653	Int
WMA-GNCAT-3-8-7045	6.6	45	70	309.2	100	5,045	Int	4,979	Int	211,300	Ext	211,556	Ext
HMA-GNCAT-3-1-10045	7.3	45	100	478.2	100	25,454	Int	25,450	Int	227,918	Ext	225,754	Ext
HMA-GNCAT-3-3-10045	6.7	45	100	423.7	100	22,151	Int	22,488	Int	225,429	Ext	221,222	Ext
HMA-GNCAT-6-4-10045	6.9	45	100	504.5	100	22,987	Int	23,033	Int	269,075	Ext	265,525	Ext
WMA-GNCAT-2-1-10045	7.3	45	100	215.1	100	1,523	Int	1,404	Int	16,999	Int	16,739	Int
WMA-GNCAT-2-6-10045	6.6	45	100	247.6	100	2,706	Int	2,799	Int	77,407	Ext	77,544	Ext
WMA-GNCAT-2-8-10045	6.8	45	100	230.4	100	2,052	Int	2,062	Int	17,873	Int	17,886	Int
HMA-GNCAT-3-4-13045	7.3	45	130	531.9	100	24,583	Int	24,623	Int	335,940	Ext	333,835	Ext
HMA-GNCAT-5-3-13045	6.7	45	130	295.4	100	820	Int	825	Int	8,964	Int	8,979	Int
HMA-GNCAT-6-6-13045	6.8	45	130	480.6	100	20,884	Int	20,965	Int	237,431	Ext	233,180	Ext
WMA-GNCAT-1-1-13045	6.9	45	130	319.7	100	1,187	Int	1,202	Int	9,778	Int	9,803	Int
WMA-GNCAT-2-4-13045	6.5	45	130	285.9	100	1,277	Int	1,323	Int	15,284	Int	15,389	Int
WMA-GNCAT-3-4-13045	7.0	45	130	316.3	100	1,434	Int	1,483	Int	12,368	Int	12,458	Int

TABLE 12 Repeated Simple Shear at Constant Height Test Results for 55°C

Sample Name	Air	Temp	τ	Mr		Cycles to 2% γ Perm				Cycles to 5% γ Perm			
	Void	°C	(kPa)	(MPa)	@ Cycle	Nonadj	Int/Ext	Deacon	Int/Ext	Nonadj	Int/Ext	Deacon	Int/Ext
HMA-GNCAT-3-9-7055	7.0	55	70	137.6	100	4,788	Int	5,022	Int	165,493	Ext	164,725	Ext
HMA-GNCAT-6-3-7055	6.7	55	70	182.2	100	10,357	Int	10,662	Int	137,799	Ext	135,014	Ext
HMA-GNCAT-7-2-7055	6.9	55	70	291.0	100	7,017	Int	6,889	Int	124,931	Ext	125,563	Ext
WMA-GNCAT-4-2-7055	7.0	55	70	135.6	100	780	Int	704	Int	8,669	Int	8,519	Int
WMA-GNCAT-7-2-7055	7.0	55	70	122.7	100	1,020	Int	1,026	Int	8,408	Int	8,415	Int
WMA-GNCAT-7-3-7055	7.5	55	70	161.6	100	574	Int	584	Int	5,144	Int	5,165	Int
HMA-GNCAT-1-9-10055		55	100	296.3	100	9,734	Int	9,967	Int	315,274	Ext	312,229	Ext
HMA-GNCAT-4-4-10055	6.6	55	100	222.6	100	1,253	Int	1,288	Int	14,172	Int	14,253	Int
HMA-GNCAT-4-5-10055	7.1	55	100	210.2	100	998	Int	1,022	Int	12,134	Int	12,211	Int
WMA-GNCAT-4-3-10055	6.6	55	100	133.8	100	314	Int	311	Int	2,380	Int	2,375	Int
WMA-GNCAT-6-5-10055	7.2	55	100	138.9	100	387	Int	411	Int	2,549	Int	2,582	Int
WMA-GNCAT-6-7-10055	6.8	55	100	116.3	100	264	Int	292	Int	1,944	Int	1,996	Int
HMA-GNCAT-5-2-13055	7.0	55	130	141.0	100	169	Int	179	Int	1,404	Int	1,432	Int
HMA-GNCAT-6-5-13055		55	130	286.8	100	1,523	Int	1,568	Int	10,948	Int	11,018	Int
HMA-GNCAT-6-9-13055	7.5	55	130	221.5	100	483	Int	545	Int	4,976	Int	5,133	Int
WMA-GNCAT-3-5-13055	6.7	55	130	151.0	100	1,672	Int	1,718	Int	6,480	Int	6,513	Int
WMA-GNCAT-5-2-13055	6.5	55	130	154.8	100	385	Int	375	Int	2,493	Int	2,477	Int
WMA-GNCAT-5-3-13055	6.5	55	130	130.0	100	202	Int	210	Int	1,871	Int	1,890	Int

TABLE 13 Shear Frequency Sweep Test Results HMA

Specimen Name	Frequency (hz)	Shear Stress (MPa)	Shear Strain	Shear_G*	Phase Angle	Average Temp (ºC)
HMA-GNCAT-3-6-45	10.006	0.304	1.18E-03	259.1	42.2	45.1
	4.981	0.178	8.90E-04	200.4	42.2	45.0
	1.999	0.143	1.09E-03	131.2	45.9	45.0
	1.000	0.095	9.47E-04	99.9	47.9	44.9
	0.498	0.108	1.57E-03	68.9	53.1	44.9
	0.298	0.005	6.07E-04	8.3	0.6	44.9
	0.100	0.021	5.85E-04	36.2	50.7	44.8
HMA-GNCAT-3-2-45	9.988	0.339	1.02E-03	334.1	45.2	45.4
	4.990	0.260	1.07E-03	242.9	47.2	45.3
	2.001	0.160	9.76E-04	163.6	49.9	45.5
	0.999	0.129	1.08E-03	119.7	308.5	45.5
	0.471	0.149	1.90E-03	78.3	45.0	45.5
	0.199	0.046	8.32E-04	55.0	303.5	45.4
	0.101	0.030	6.79E-04	43.7	56.7	45.4
HMA-GNCAT-6-2-55	10.052	0.212	1.00E-03	212.4	48.4	55.2
	4.980	0.164	1.12E-03	146.8	48.4	55.2
	1.999	0.114	1.22E-03	93.9	50.0	55.3
	0.999	0.082	1.20E-03	68.0	53.2	55.4
	0.499	0.046	9.79E-04	47.3	54.5	55.3
	0.195	0.019	4.47E-04	43.0	61.8	55.2
	0.100	0.026	8.18E-04	32.2	56.0	55.2
HMA-GNCAT-7-2-55	9.977	0.136	9.30E-04	146.3	52.7	55.3
	4.994	0.088	8.70E-04	101.3	56.2	55.3
	1.995	0.052	8.82E-04	59.2	58.2	55.3
	1.001	0.042	1.06E-03	39.4	59.6	55.3
	0.407	0.037	1.62E-03	22.9	46.0	55.3
	0.199	0.016	1.05E-03	15.3	293.9	55.3
	0.123	0.008	1.08E-03	7.8	38.7	55.3

TABLE 14 Shear Frequency Sweep Test Results for Gencor WMA

Specimen Name	Frequency (hz)	Shear Stress (MPa)	Shear Strain	Shear_G*	Phase Angle	Average Temp (ºC)
WMA-GNCAT-4-4-45	10.002	0.214	1.18E-03	181.2	54.7	45.4
	5.013	0.128	1.03E-03	124.7	57.8	45.4
	1.988	0.073	1.00E-03	72.7	57.7	45.4
	0.995	0.051	1.06E-03	47.9	59.8	45.4
	0.496	0.048	1.53E-03	31.2	295.6	45.3
	0.198	0.021	1.12E-03	18.5	296.1	45.3
	0.100	0.020	1.07E-03	18.8	61.6	45.2
WMA-GNCAT-6-3-45	10.043	0.172	1.13E-03	152.5	51.4	45.2
	5.003	0.112	1.08E-03	104.0	54.7	45.3
	1.996	0.063	1.00E-03	63.1	57.0	45.3
	1.003	0.041	9.93E-04	41.2	58.6	45.4
	0.500					
	0.197	0.022	1.39E-03	15.9	62.9	45.6
	0.100	0.016	1.29E-03	12.7	66.9	45.6
WMA-GNCAT-2-2-55	9.955	0.064	9.55E-04	66.9	62.2	55.2
	4.973	0.044	1.04E-03	42.4	293.8	55.1
	1.999	0.026	1.14E-03	22.7	66.6	55.2
	0.997	0.017	1.18E-03	14.5	292.3	55.2
	0.501	0.012	1.36E-03	9.0	64.5	55.2
	0.199	0.006	1.07E-03	5.5	294.7	55.2
	-0.023	0.004	1.18E-03	3.5	441.3	55.3
WMA-GNCAT-6-2-55	9.996	0.084	1.08E-03	77.3	297.7	55.3
	4.982	0.050	9.88E-04	50.2	297.9	55.3
	2.001	0.031	1.12E-03	27.6	64.4	55.4
	0.996	0.021	1.18E-03	17.7	294.3	55.3
	0.501	0.014	1.26E-03	11.0	62.7	55.3
	0.138	0.006	5.62E-04	10.0	274.5	55.3
	0.100	0.008	1.22E-03	6.5	64.0	55.2