Florida Department of
TRANSPORTATION

Evaluation of the Performance of High-SBS Modified Asphalt Binder through Accelerated Pavement Testing

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EXECUTIVE SUMMARY

A full-scale experiment was conducted at the Florida Department of Transportation (FDOT)'s Accelerated Pavement Testing (APT) facility to evaluate the performance of a newly formulated asphalt binder, namely high styrene–butadiene–styrene (SBS) modified asphalt (HSMA) binder. Test sections were constructed using three dense-graded Superpave asphalt mixtures consisting of the same aggregate components and gradation. One mixture included a polymer-modified asphalt (PMA) binder meeting PG 76-22 requirements, another contained HSMA binder at the same effective binder content, and the third one also used HSMA binder but at an additional 0.5% binder content. The subsequent accelerated testing showed that, under similarly controlled conditions, test sections using HSMA binder exhibited better rutting and fatigue cracking performance than those with PG 76-22 PMA binder. The 0.5% additional HSMA binder content resulted in negligible added performance compared to the sections using HSMA binder at the design content. Furthermore, supplementary laboratory tests including dynamic shear rheometer (DSR), multiple stress creep recovery (MSCR), softening point, and indirect tensile (IDT) strength confirmed the improved properties of the HSMA binder and HSMA mixtures.

1 INTRODUCTION

Over the last two decades, the Florida Department of Transportation (FDOT) has evaluated the effect of various modified binders on pavement performance by utilizing accelerated pavement testing (APT). The benefit of using APT for these investigations was the relatively short assessment period compared to long-term field experiments. Moreover, results of the APT experiments provided supporting data for the implementation of modified binders in Florida *(1, 2).*

According to FDOT's annual pavement condition survey (PCS), deficient lane miles have steadily decreased since the adoption of PG 76-22 polymer modified asphalt (PMA) binder. However, excessive rutting and fatigue failure is still often observed at intersections and along localized roadway sections with highly concentrated truck traffic at low speeds *(2).* These observations led FDOT engineers to investigate the use of a newly formulated asphalt binder, namely high styrene–butadiene–styrene (SBS) modified asphalt (HSMA) binder, as an alternative to PG 76-22 PMA for the specific applications. The primary difference between these two binders is the amount of SBS modifier. The SBS content in PG 76-22 PMA is approximately 2 to 3% by weight of base binder, while according to binder producers, the SBS load of the HSMA binder is more than twice that of PG 76-22 PMA binder.

SBS is the most commonly used polymer as an asphalt binder modifier. Once the SBS is blended, its physical interaction with the bitumen components delivers better high temperature stiffness and low temperature elasticity to the base binder *(3, 4).* However, the relatively low polymer content in PG 76-22 PMA binder (approximately 2 to 3%) is not sufficient enough to formulate a continuous SBS-bitumen network. Multiple previous studies agreed that a minimum of 6% SBS content is required to formulate the continuous polymer network of an HSMA binder *(3, 5, 6).*

Laboratory studies on the properties of HSMA binder and corresponding mixtures indicated significantly enhanced stiffness and elasticity throughout the pavement service temperature range compared to other PMA binders modified with relatively low SBS contents *(7,* *8, 9)*. However, their field performance has not been as well investigated. Limited studies have addressed the enhanced field performance through computer simulation and short-term monitoring of field test sections with reduced lift thickness *(3, 5, 6)*. Consequently, a full-scale experiment was planned and conducted at FDOT's APT facility to assess the use of HSMA binder under closely simulated in-service conditions in terms of pavement design and traffic loading.

2 OBJECTIVE

The primary objective of this study is to investigate the performance of asphalt mixtures with HSMA binder using APT. Two binder contents representing the design asphalt content (5.1%) and the design plus 0.5% (5.6%) were used for the HSMA test sections. Another test section using PG 76-22 PMA at 5.1% binder content served as control. Laboratory tests including DSR, MSCR, softening point, and IDT strength were also performed.

3 EXPERIMENTAL DESIGN

To evaluate rutting resistance, three 12-foot wide by 150-foot long test sections were milled and resurfaced at the FDOT's APT facility. These test sections were resurfaced using each of the three dense-graded mixtures under evaluation by placing two identical 1.5-inch lifts on the milled surface. One mixture included a PG 76-22 PMA binder, the other contained the HSMA binder at the same effective binder content, and the third one also used the HSMA binder but at an additional 0.5% binder content. The additional asphalt content was thought to potentially provide additional resistance to fatigue cracking. All mixtures were Superpave mixtures with 12.5-mm nominal maximum aggregate size (SP-12.5) with the same aggregate components and gradation.

Three additional sections measuring 50 feet in length were constructed within test pits designed to allow control of the water table to evaluate fatigue cracking resistance. Similarly, each test section was resurfaced with two 1.5-inch lifts of dense-graded mixture placed directly on the base surface after application of a prime coat. Figure 1 shows the structural design of the rutting and fatigue cracking test sections and Table 1 summarizes the aggregate gradation of the three mixtures sampled from delivery trucks during construction of the test track.

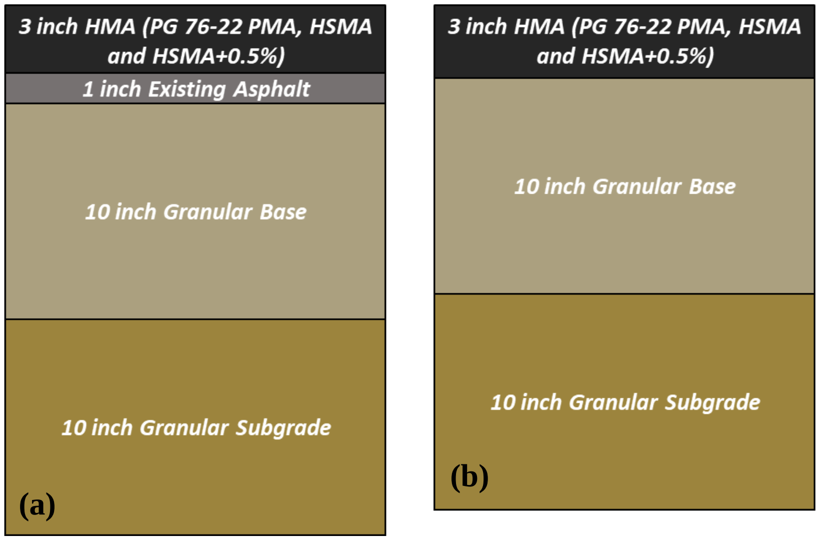

Figure 1. Structural designs for (a) rutting and (b) fatigue racking test sections

Table 1 Aggregate gradation of the three mixtures sampled from delivery trucks

Sieve Size	Aggregate Gradation (% Passing)			
	Design	PG 76-22 (PMA)	HSMA	HSMA + 0.5%
3/4”	100.0	100.0	100.0	100.0
1/2”	100.0	98.5	98.7	99.0
3/8”	88.0	89.9	89.5	91.4
#4	64.0	67.0	62.8	64.7
#8	43.0	44.5	42.6	44.2
#16	31.0	30.7	29.1	30.4
#30	21.0	22.6	21.5	22.8
#50	14.0	14.5	13.9	14.7
#100	6.0	7.5	7.8	8.4
#200	4.2	4.1	4.1	4.4

Three replicate loading areas of each mixture were tested for rutting performance whereas only one loading area for each fatigue cracking section was available due to limited space. Loading areas dedicated to fatigue cracking evaluation were instrumented with three horizontal strain gauges embedded at the bottom of the asphalt layer to measure tensile strain in the longitudinal direction. Figure 2 shows FDOT’s APT test track and layout of the test sections.

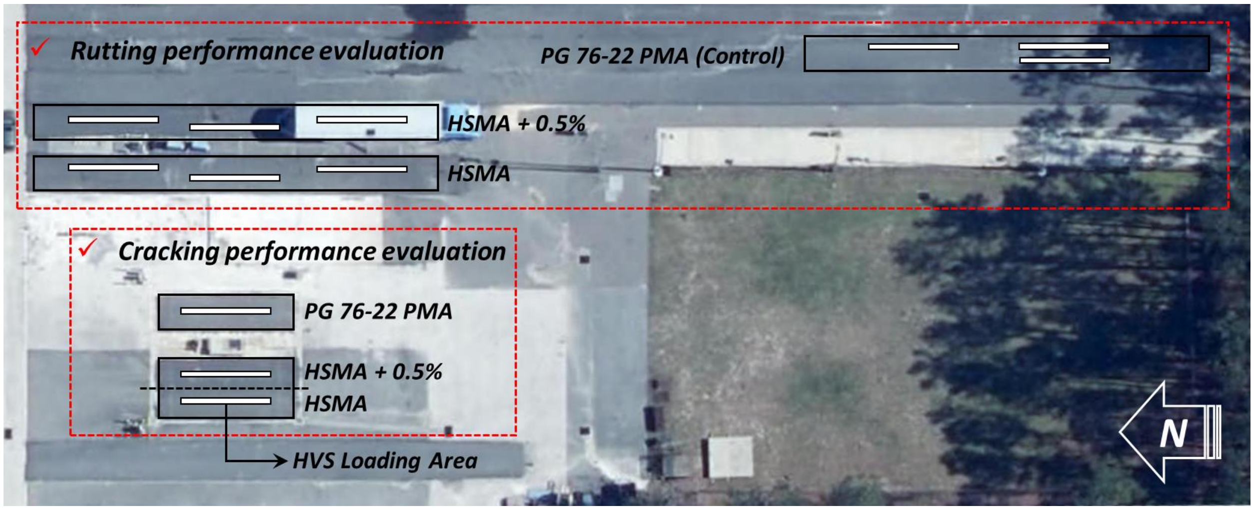

Figure 2. FDOT's APT test track and layout of the test sections

The respective Superpave mixtures were all placed while complying with all the standard FDOT construction and materials specifications and methods. Three cores were retrieved from each section to check layer thickness and density. According to the core specimens, all test sections met the target density of 93.0 ± 1.0% and target thickness of 3.00 ± 0.25inch.

4 ACCELERATED PAVEMENT TESTING

4.1 Accelerated Loading

Accelerated loading was performed using FDOT's heavy vehicle simulator (HVS) shown in Figure 3. Each loading area was trafficked with unidirectional passes of a Super Single tire (Goodyear G286 A SS, 425/65R22.5) and 4-inches of wheel wander. For rutting performance evaluation, 100,000 passes of a 9,000-pound wheel load were applied. This loading was performed under a controlled temperature of 50°C.

Additionally, 400,000 passes of the same Super Single tire loaded to 11,500 pounds were applied for the fatigue study (loading was equivalent to one million ESALs according to the fourth power damage law). HVS loading for the fatigue study was performed during the winter season at ambient temperature. The water level for both test pits was raised to the bottom of the base and maintained during testing to reduce the subgrade stiffness. Falling weight deflectometer (FWD) tests indicated that the subgrade modulus for the test pits was reduced from approximately 40 ksi to 17 ksi after the water level was raised and had stabilized.

Figure 3. FDOT's heavy vehicle simulator (HVS) Mark IV

4.2 APT Rutting Performance Evaluation

Average rut depth progression for each test section is depicted in Figure 4. As can be seen in the figure, significantly less rutting was observed in both HSMA and HSMA + 0.5% sections compared to the control section along the HVS loading while negligible differences were observed between HSMA and HSMA + 0.5% sections. The rut depths after 100,000 HVS passes were 0.20, 0.11 and 0.12 inches for the control, HSMA and HSMA + 0.5% sections, respectively.

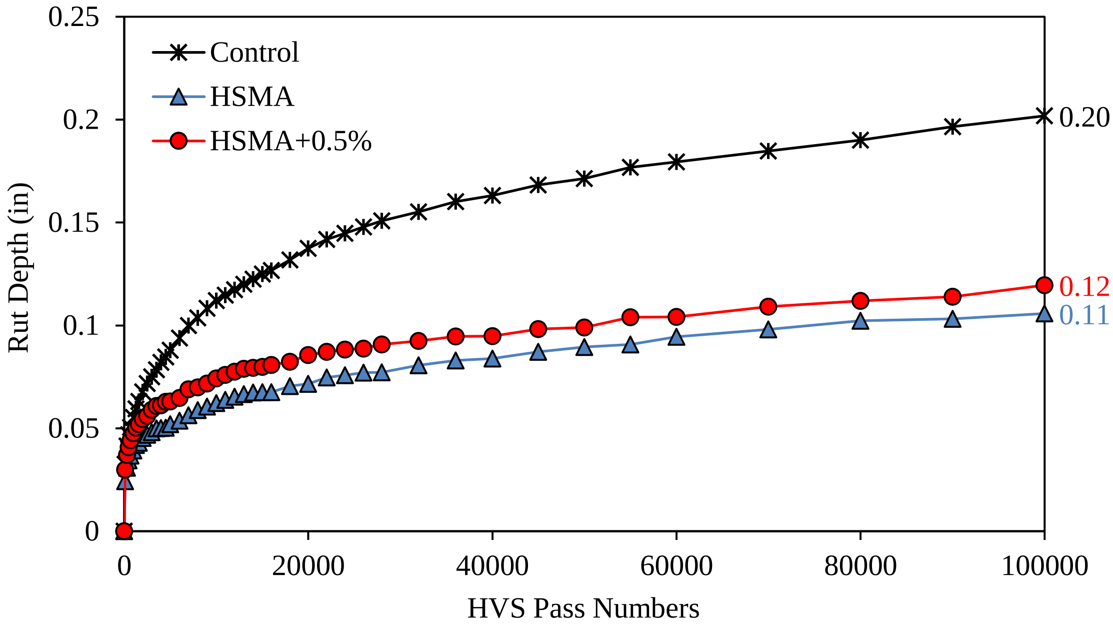

Figure 4. Comparison of average rut depth

Previous studies agreed that rutting in HMA layers is caused by a combination of densification and shear flow of the asphalt concrete *(10, 11, 12)*. Densification is a reduction in the volume of the asphalt concrete due to HVS loading whereas shear flow is caused by the lateral movement of material without any reduction in volume *(10, 11, 12)*. Figure 5 presents (a) schematic of humps and densification areas and (b) comparison of average transverse profiles.

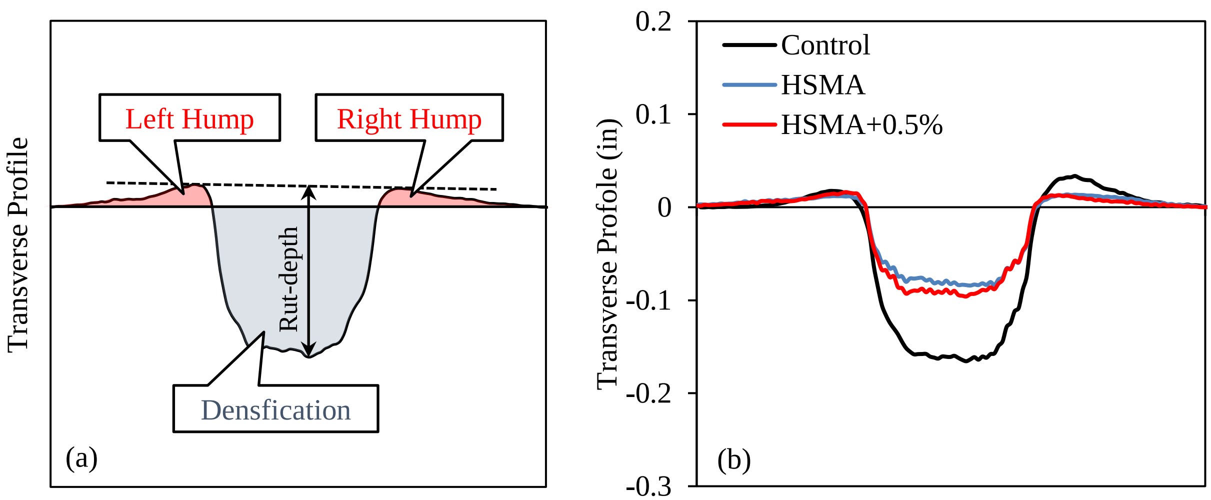

Figure 5. (a) Schematic and (b) comparison of transverse profiles

As can be seen in Figure 6, the hump and densification areas of HSMA and HSMA + 0.5% sections after 100,000 HVS passes were approximately half of the areas of the control section. The ratio of hump to densification areas indicates the proportion of rut depth attributable to shear flow as opposed to densification. This ratio is affected by air void content, aggregate characteristics and binder type *(10, 11).* John et al. in 2000 identified that the ratio varied between 19 to 100%, with well-compacted dense-graded asphalt concrete resulting in the lowest ratio *(12).* In addition, Gokhale et al. in 2005 concluded that SBS modified binder showed a low hump-to-densification ratio of 20 to 30% whereas unmodified binders showed 50% or higher *(10).* Calculated hump-to-densification ratios were comparable for the three test sections (17% to 23%) and in agreement with the ratios found in previous studies.

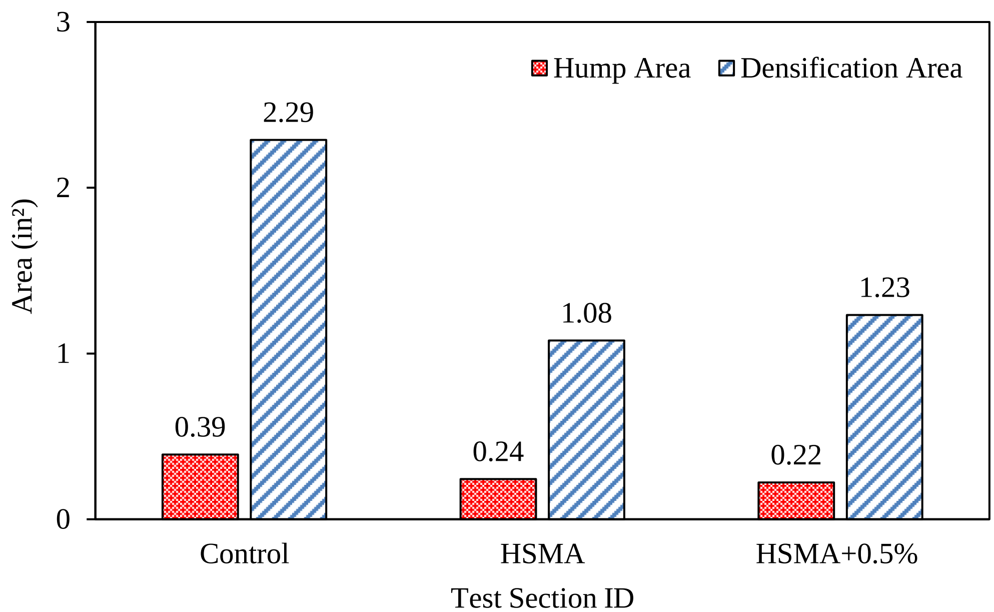

Figure 6. Comparison of hump and densification areas

4.3 APT Fatigue Cracking Performance Evaluation

Despite the significant reduction in subgrade stiffness caused by the raised water table, none of the sections showed signs of fatigue distress. Therefore, horizontal tensile strain readings at the bottom of the AC layer were employed to compare the relative fatigue cracking performance of the three test sections. Tensile strain was recorded in the longitudinal direction at 8-hour intervals, for 30 seconds at a rate of 100 readings per second. Pavement temperature was also recorded at 2 inches below the pavement surface at every 15 minutes. Based on temperature history, a five-day time window with comparable pavement temperatures for all three sections was selected to compare the strain readings. Figure 7 shows the temperature history for all three sections. Figure 8 plots the elastic (resilient) tensile strain in the longitudinal direction versus pavement temperature for the selected five-day time window. HSMA and HSMA + 0.5% sections showed approximately 35 to 40% and 20 to 25% lower strains than the control section over the recorded temperature range.

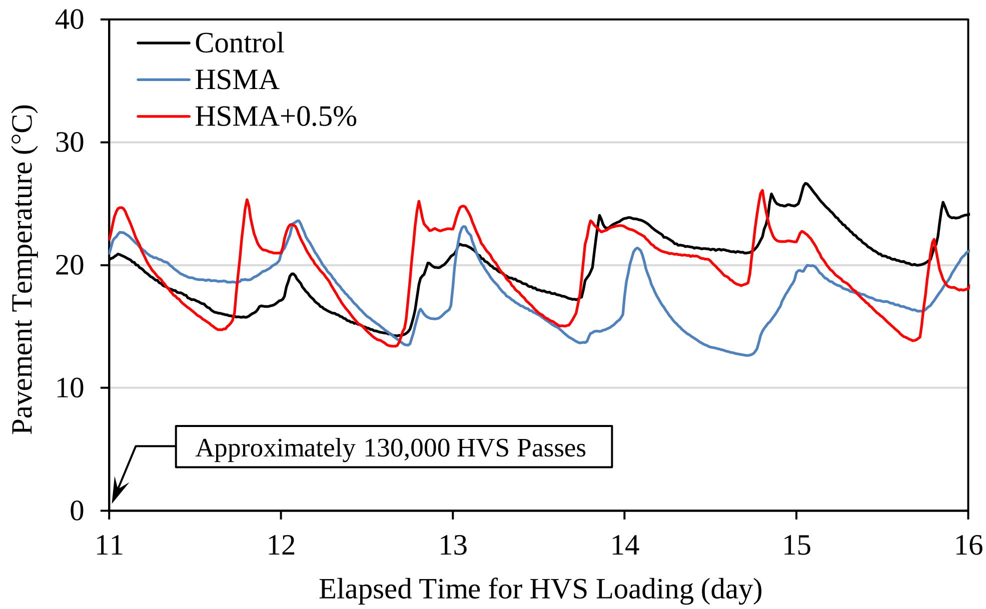

Figure 7. Pavement temperature history at 2 inches below surface

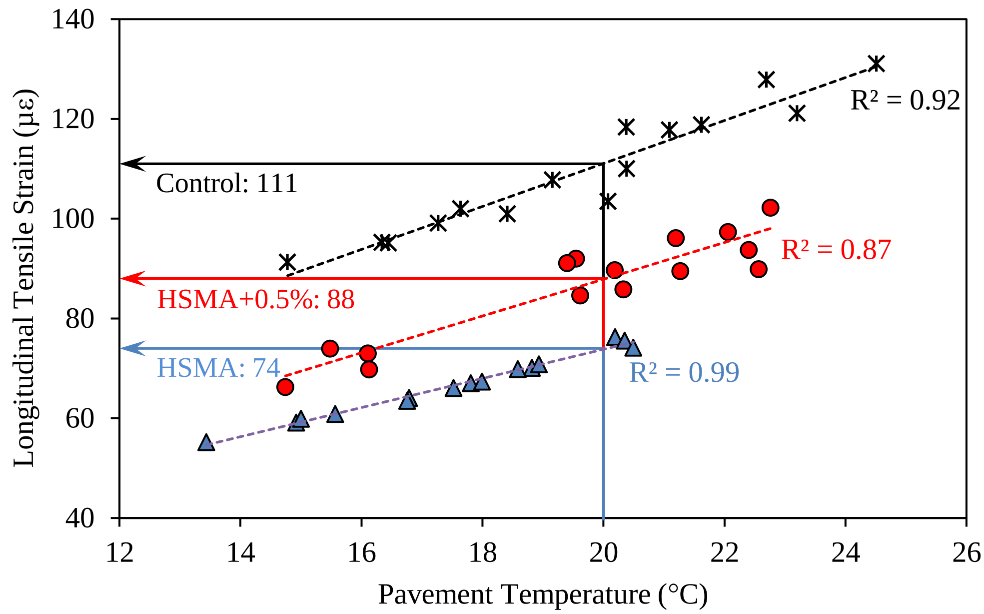

Figure 8. Comparison of longitudinal tensile strain readings

Fatigue life can be estimated using multiple transfer functions proposed by different studies. One such function is presented in AASHTO's Mechanistic Empirical Pavement Design Guide (MEPDG) as follows:

$$N_f = 0.00432 \times K \times C \times (\frac{1}{\varepsilon_t})^{3.9492} \times (\frac{1}{E})^{1.281}$$

where, N_f = repetitions until fatigue failure (50% cracking of lane area), K = thickness calibration factor, C = regional or national calibration factor, ε_t = tensile strain, and E = asphalt modulus (psi).

Tensile strains at a reference temperature of 20°C were interpolated from the temperature-strain relationships shown in Figure 8. Furthermore, asphalt modulus under 10 Hz cyclic loading at the same reference temperature of 20°C was obtained with the asphalt mixture performance tester (AMPT). Table 2 summarizes the asphalt modulus, longitudinal strain, and results of the transfer function for all three test sections. At the reference temperature, the predicted fatigue lives of the HSMA and HSMA + 0.5% sections were 3.5 and 2.3 times greater than that of PG 76-22 PMA section, respectively.

Table 2 Summary of Input and Relative Output for Prediction of Fatigue Lives

Section ID	Control Mix (PG-76-22PMA)	HSMA	HSMA + 0.5%
Longitudinal Tensile Stain @ 20°C (με)	111	74	88
Dynamic Modulus E* @ 20°C (ksi)	1,066	1,425	1,135
Relative Fatigue Life	100%	346%	233%

5 SUPPLIMENTARY LABORATORY TESTS

Supplementary laboratory tests were also conducted to assess performance related properties of HSMA binder and mixture in comparison to those of PG 76-22 PMA binder and mixture as described below:

5.1 Dynamic Shear Rheometer (DSR)

The DSR test measures the complex modulus (G*) and phase angle (δ) of asphalt binder to characterize the viscous and elastic behavior. G*/sinδ at the high testing temperature is commonly used as an indicator of rutting performance whereas G*•sinδ at the intermediate temperature is considered as an indicator of fatigue cracking potential. G*/sinδ was measured on original binders whereas G*•sinδ was measured on binder specimens after rolling-thin film oven (RTFO) plus pressure aging vessel (PAV) conditioning.

Figure 9 summarizes DSR test results for the comparison of rutting and fatigue cracking performances. The higher G*/sinδ values observed on HSMA samples indicated that the HSMA binder behaved more elastic-solid at a high temperature whereas the lower G*·sinδ value represented more elastic-soft response at an intermediate temperature *(13)*. Hence, it can be speculated that a mixture using HSMA binder may exhibit better rutting and fatigue resistance than that with PG 76-22 PMA binder.

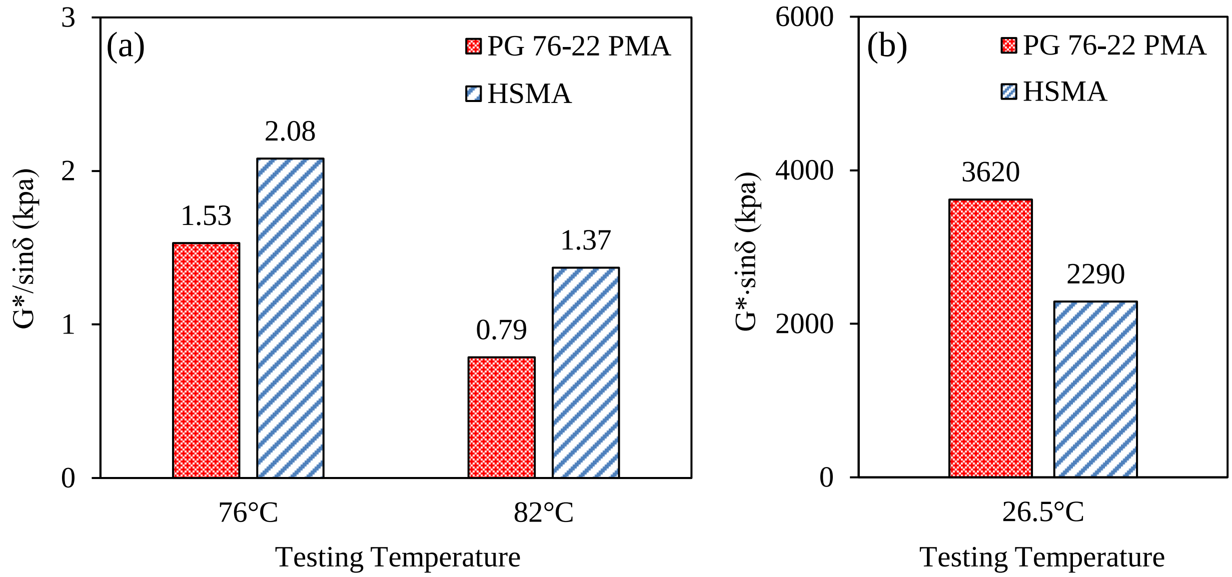

Figure 9. Comparisons of (a) G*/sinδ and (b) G*·sinδ

5.2 Multiple Stress Creep Recovery (MSCR)

The MSCR test evaluates the rutting resistance of an asphalt binder sample using the DSR apparatus. Ten creep/recovery cycles are performed with a stress of 0.1 kPa applied for a second with a consecutive 9-second rest period. The stress level is then increased to 3.2 kPa for ten additional cycles. The average non-recoverable strain for the ten creep/recovery cycles is divided by the applied stress to calculate the non-recoverable creep compliance, J_{nr}. A Federal Highway Administration (FHWA) study concluded that the reduction in J_{nr} of 50% may decrease roadway rutting by 50%, and additional APT results at the FHWA Accelerated Loading Facility (ALF) showed a reduction of 30 to 40% *(14).* The percent recovery measured in the MSCR test shows elastic response of the binder sample. The grater percent recovery at the high testing temperature is believed to represent the better rutting resistance *(14).*

Asphalt binder samples were conditioned in a rolling thin film oven (RTFO) in accordance with AASHTO M332. Then, MSCR tests were performed on both binders at a testing temperature of 67°C. An additional MSCR test was conducted on the HSMA binder at a testing temperature of 76°C to determine if the HSMA binder meets the required binder properties of high polymer (HP) binder. Of note, the HP binder requirement was added in FDOT specification approximately one year after construction of the test sections. Table 3 summarizes MSCR test result and required binder properties of PG 76-22 PMA and HP binder in Florida.

The HSMA binder exhibited greater elastic response and better rutting resistance potential than PG 76-22 PMA binder as indicated by the percent recovery and J_{nr} values. However, the HSMA binder did not meet the required properties for the HP binder.

Table 3 Summary MSCR Test Result and Current FDOT Specification Requirement

Test Temp. (°C)	MSCR Properties	Test Result		FDOT Specification	
		PG 76-22 PMA	HSMA	PG 76-22 PMA	HP
67	% Recovery, 3.2 kPa^{-1}	66.41	91.53	N/A	N/A
	J_{nr}, 3.2 kPa^{-1}	0.30	0.07	Max. 1.0 kPa^{-1}	
	J_{nr}, % Difference	37.56	98.34	Max. 75%	
76	% Recovery, 3.2 kPa^{-1}	N/A	85.76	N/A	Min. 90%
	J_{nr}, 3.2 kPa^{-1}		0.246		Max 0.1 kPa^{-1}
	J_{nr}, % Difference		77.77		N/A

5.3 Softening Point

The softening point is the highest temperature at which an asphalt binder keeps an arbitrary stiffness and elasticity. Multiple studies have concluded that the binder softening point may be used as an indicator of high temperature rutting resistance of HMA roadways. When the binder softening point is lower than the service temperature, the roadway may exhibit excessive rutting *(15, 16, 17).* The ring and ball testing apparatus was used to measure the softening point in accordance with ASTM D6493. As can be seen in Figure 10, HSMA binder showed significantly higher softening point than the PG 76-22 PMA binder. With consideration of the highest asphalt temperature of 70°C during the summertime, the use of HSMA binder may reduce rutting failure *(18).*

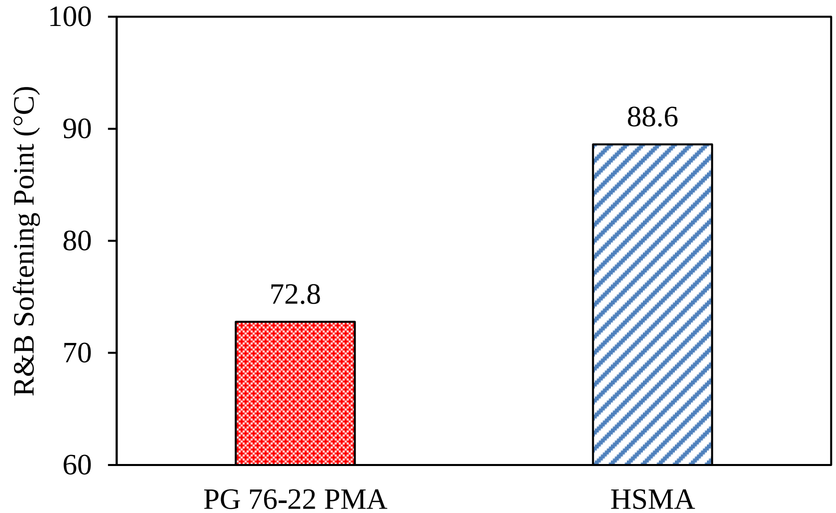

Figure 10. Comparison of softening point

5.4 Indirect Tensile Strength

Indirect tensile strength was measured to determine the relative cracking resistance of the HSMA, HSMA + 0.5% and control mixtures *(19).* Three 4-inch cores were retrieved at randomly selected locations on each test section. The surface layer (top 1.5 inches) was trimmed and used to measure the indirect tensile strength in accordance with ASTM D6931. As presented in Figure 11, field cores from HSMA and HSMA + 0.5% sections showed approximately 13% and 11% higher tensile strengths than cores from the control section. The test results indicate that the use of HSMA binder, regardless of binder contents, may improve the cracking resistance.

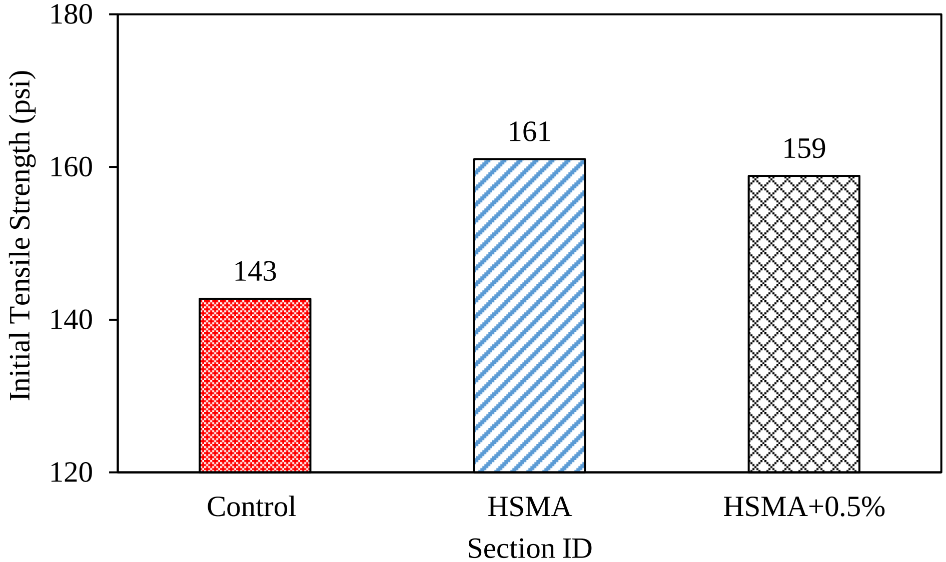

Figure 11. Comparison of initial tensile strength

6 SUMMARY AND CONCLUSION

The findings of this research are summarized as follows:

- After application of 100,000 HVS passes under identical loading conditions, significantly less rutting was observed in both HSMA and HSMA + 0.5% sections compared to the control section. Minimal differences were observed between the rut-depth of HSMA and HSMA + 0.5% sections.

- HSMA and HSMA + 0.5% sections showed approximately 35 to 40% and 20 to 25%, respectively, lower tensile strains at the bottom of AC layer than the strain of control section throughout the recorded temperature range. Based on the MEPDG fatigue model, the estimated fatigue lives of the HSMA and HSMA + 0.5% sections were approximately 3.5 and 2.3 times greater than the fatigue life of PG 76-22 PMA section at the reference temperature of 20°C.

- The higher $G^*/\sin\delta$ and the lower $G^*\cdot\sin\delta$ of the HSMA binder compared to those of PG 76-22 PMA imply that the HSMA binder has potentially better rutting and fatigue cracking resistance.

- The higher strain recovery and lower J_{nr} of the HSMA binder obtained through the MSCR test at a testing temperature of 67 °C represent greater elastic response along with better rutting resistance than PG 76-22 PMA binder.

- HSMA and PG 76-22 PMA binders showed softening points of 88.6°C and 72.8°C, respectively. With consideration of the extreme asphalt temperature of 70°C during summer season, the use of HSMA binder may help to mitigate rutting failure.

- On average, indirect tensile strengths of core specimens obtained from the HSMA and HSMA + 0.5% sections were approximately 13% and 11% higher than the specimens obtained from the control section.

ACKNOWLEDGEMENTS

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