Virginia Center *for* Transportation
INNOVATION
& RESEARCH

Installation and Laboratory Evaluation of Alternatives to Conventional Polymer Modification for Asphalt

http://www.virginiadot.org/vtrc/main/online_reports/pdf/15-r15.pdf

STACEY D. DIEFENDERFER, Ph.D., P.E.
Senior Research Scientist

KEVIN K. MCGHEE, P.E.
Associate Principal Research Scientist

Final Report VCTIR 15-R15

VIRGINIA CENTER FOR TRANSPORTATION INNOVATION AND RESEARCH
530 Edgemont Road, Charlottesville, VA 22903-2454

www.VTRC.net

Standard Title Page—Report on State Project

Report No.: VCTIR 15-R15	Report Date: January 2015	No. Pages: 25	Type Report: Final	Project No.: RC00052
			Period Covered: July 2012–October 2014	Contract No.:

Title:
Installation and Laboratory Evaluation of Alternatives to Conventional Polymer Modification for Asphalt

Key Words:
polymer modification, binder elasticity, SBS-polyethylene, ground tire rubber, multiple stress creep

Author(s):
Stacey D. Diefenderfer, Ph.D., P.E., and Kevin K. McGhee, P.E.

Performing Organization Name and Address:
Virginia Center for Transportation Innovation and Research
530 Edgemont Road
Charlottesville, VA 22903

Sponsoring Agencies' Name and Address:
Virginia Department of Transportation
1401 E. Broad Street
Richmond, VA 23219

Supplementary Notes:

Abstract:

The Virginia Department of Transportation (VDOT) specifies polymer-modified asphalt binders for certain asphalt mixtures used on high-volume, high-priority routes. These binders must meet performance grade (PG) requirements for a PG 76-22 binder in addition to elastic recovery requirements. This typically results in the use of binders containing styrene-butadiene-styrene (SBS) modifiers. However, other polymer modifiers may also be used to achieve the PG 76-22 classification. One of these modifiers is a copolymer of SBS and polyethylene (PE) (SBS-PE); another modifier is ground tire rubber (GTR). This study was undertaken to investigate the suitability of SBS-PE–modified PG 76-22 binder and GTR-modified PG 76-22 binder for use in Virginia.

Each modified binder was used in a 12.5 mm nominal maximum aggregate size mixture to pave approximately 2.3 lane-miles. All mixtures were produced as warm mix asphalt using a foaming system. The binders evaluated included a typical SBS polymer-modified binder as a control and binders modified with SBS-PE and GTR. During construction, all processes were documented and material was sampled for evaluation. Binder and mixture tests were performed. Binder testing included performance grading and multiple stress creep and relaxation testing. Mixture testing included volumetric analysis, dynamic modulus, and flow number tests and cracking, rutting, and fatigue analysis.

Binder testing indicated that the control binder and SBS-PE–modified binders met VDOT specifications for classification as a PG 76-22 binder; the GTR-modified binder graded to a PG 70-22 binder, as it did not meet the PG 76-22 high-temperature specification and did not pass the elastic recovery requirement. Laboratory mixture testing indicated that the performance of the SBS-PE–modified mixture should be similar to that of the control mixture. Laboratory test results for the GTR-modified mixture were mixed, with some indicating that the performance was similar to that of the control mixture and some indicating that the performance may be less than that of the control.

Based on the study, SBS-PE–modified binders should continue to be allowed as an alternative to SBS-modified binder provided specifications for PG 76-22 binders are met. However, further investigation of GTR-modified binders is suggested before recommendations can be made. In addition, long-term evaluation of the field site is recommended for validation of the laboratory findings.

FINAL REPORT

INSTALLATION AND LABORATORY EVALUATION OF ALTERNATIVES TO CONVENTIONAL POLYMER MODIFICATION FOR ASPHALT

Stacey D. Diefenderfer, Ph.D., P.E.
Senior Research Scientist

Kevin K. McGhee, P.E.
Associate Principal Research Scientist

Virginia Center for Transportation Innovation and Research
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

January 2015
VCTIR 15-R15

DISCLAIMER

ABSTRACT

The Virginia Department of Transportation (VDOT) specifies polymer-modified asphalt binders for certain asphalt mixtures used on high-volume, high-priority routes. These binders must meet performance grade (PG) requirements for a PG 76-22 binder in addition to elastic recovery requirements. This typically results in the use of binders containing styrene-butadiene-styrene (SBS) modifiers. However, other polymer modifiers may also be used to achieve the PG 76-22 classification. One of these modifiers is a copolymer of SBS and polyethylene (PE) (SBS-PE); another modifier is ground tire rubber (GTR). This study was undertaken to investigate the suitability of SBS-PE–modified PG 76-22 binder and GTR-modified PG 76-22 binder for use in Virginia.

Each modified binder was used in a 12.5 mm nominal maximum aggregate size mixture to pave approximately 2.3 lane-miles. All mixtures were produced as warm mix asphalt using a foaming system. The binders evaluated included a typical SBS polymer-modified binder as a control and binders modified with SBS-PE and GTR. During construction, all processes were documented and material was sampled for evaluation. Binder and mixture tests were performed. Binder testing included performance grading and multiple stress creep and relaxation testing. Mixture testing included volumetric analysis, dynamic modulus, and flow number tests and cracking, rutting, and fatigue analysis.

Binder testing indicated that the control binder and SBS-PE–modified binders met VDOT specifications for classification as a PG 76-22 binder; the GTR-modified binder graded to a PG 70-22 binder, as it did not meet the PG 76-22 high-temperature specification and did not pass the elastic recovery requirement. Laboratory mixture testing indicated that the performance of the SBS-PE–modified mixture should be similar to that of the control mixture. Laboratory test results for the GTR-modified mixture were mixed, with some indicating that the performance was similar to that of the control mixture and some indicating that the performance may be less than that of the control.

Based on the study, SBS-PE–modified binders should continue to be allowed as an alternative to SBS-modified binder provided specifications for PG 76-22 binders are met. However, further investigation of GTR-modified binders is suggested before recommendations can be made. In addition, long-term evaluation of the field site is recommended for validation of the laboratory findings.

FINAL REPORT

INSTALLATION AND LABORATORY EVALUATION OF ALTERNATIVES TO CONVENTIONAL POLYMER MODIFICATION FOR ASPHALT

Stacey D. Diefenderfer, Ph.D., P.E.
Senior Research Scientist

Kevin K. McGhee, P.E.
Associate Principal Research Scientist

INTRODUCTION

When new asphalt mixtures are expected to be placed in a high-stress application, the Virginia Department of Transportation (VDOT) often requires that the asphalt binder used in the mixture be modified to improve elasticity and high-temperature stiffness characteristics. The typical modifier has been an approximate 1% to 5% loading (by weight) of styrene-butadiene-styrene (SBS) polymer to neat liquid asphalt. The main source of the SBS polymer is crude oil. SBS is also used in latex paint, latex gloves, and other products. In recent years as the price of crude oil has increased and more fractions are used for other more profitable products, the amount of SBS available from this source has decreased. The polymer industry is looking to natural gas as another source of SBS, but the yield of SBS from a natural gas source is far less than from crude oil.

As SBS becomes less plentiful, and thus more expensive, binder suppliers are looking for alternatives that achieve similar results when blended with asphalts. NuStar (now known as Axeon Specialty Products), a fuel and binder supplier, is experimenting with a new copolymer of SBS and polyethylene (PE) (SBS-PE) produced by Honeywell as one such alternative. In the spring of 2012, NuStar approached VDOT's Materials Division requesting an evaluation and field trial of the copolymer.

VDOT has also experimented recently with the use of ground tire rubber (GTR) as a modifier that may produce improved binder properties. Earlier trials with terminally blended rubber-modified asphalts had indicated that high-temperature and elasticity characteristics similar to those of the SBS-modified binders were also possible with the addition of approximately 10% to 12% GTR by weight of binder. So, as VDOT engineers and scientists began to consider the trial of SBS-PE, they also contacted Blacklidge Emulsions, a supplier of rubber-modified asphalts, to explore a second alternative to an SBS-only modifier.

In the early summer of 2012, VDOT identified a suitable trial location in its Fredericksburg District and worked with the district engineers, the contractor, and project management staff to revise an existing contract to accommodate a demonstration project. The original contract did not call for an asphalt mixture with a polymer-modified binder. For that reason, implementation funds from the Virginia Center for Transportation Innovation and

Research (VCTIR) were used to cover the delta costs for the higher liquid asphalt costs for the control section and the equivalent offset costs for the two alternative modifiers.

PURPOSE AND SCOPE

The purpose of this study was to explore alternatives to traditional SBS modification for achieving improved elasticity and high-temperature stiffness of liquid asphalt cement.

This report documents the material properties, project characteristics, mixture production, and construction processes involved in the installation of a conventional SBS polymer-modified mixture (SM-12.5E), an SBS/polyethylene copolymer (SM-12.5 [SBS-PE]), and a rubber-modified asphalt mixture (SM-12.5) [GTR]). It also reports the results from laboratory tests that were used to characterize and compare the behavior of the alternative materials/processes.

METHODS

Field Demonstration Project

The research approach was a traditional head-to-head field demonstration project in which a project of suitable size, structural makeup, and traffic-loading characteristics was selected and comparable quantities of the alternative materials were installed using typical production and construction processes. The project was selected from a 2012 VDOT resurfacing schedule: PM6B-089-F12, P401 in the Fredericksburg District. The specific project was a surface layer replacement for a 3.5-mile section of U.S. Route 1 in Spotsylvania County between County Route 603 and County Route 632. U.S. Route 1 is a four-lane undivided roadway at this location having an asphalt surface over a jointed concrete base. The originally prescribed treatment was a 2-in mill and fill with a 12.5 mm nominal maximum aggregate size dense-graded mixture with a PG 64-22 binder. The originally approved job mix was a VDOT-designated SM-12.5A mixture with a 30% recycled asphalt pavement (RAP) content.

Figure 1 is a plan view of the demonstration project. After completing construction on the two interior lanes, the contractor started at the southern end of the northbound direction with the first control section, the SM-12.5E mixture, for approximately 1.2 miles. The next day, the contractor produced and installed about the same amount of the first experimental material, the SM-12.5 (SBS-PE) mixture. Three days later the contractor placed the final northbound section using the second alternative material, the SM-12.5 (GTR) mixture. Production continued for the next 3 days, with southbound paving completed in reverse order starting with the GTR material, then the SBS-PE material, and finally the last control section.

During the installation period, researchers and technical support staff from the contractor and the VDOT district monitored the plant operation, production, placement, and compaction activities for the alternative materials. The contractor and VDOT conducted typical production sampling and testing while research staff secured additional material, some for onsite specimen preparation and more for additional testing in the laboratory at a later time.

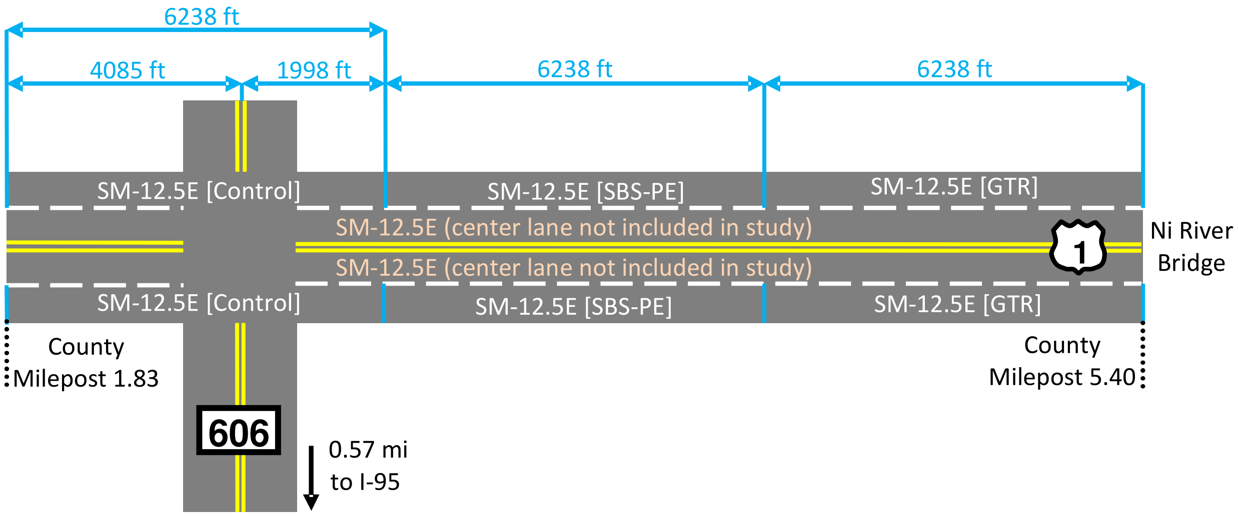

Figure 1. Plan View of Demonstration Project: Route 1 Near Thornburg

Laboratory Evaluation

Table 1 summarizes the research sample and specimen preparation matrix for the production phase of each material. The table also indicates the tests that were to be conducted with the samples and/or specimens. The dynamic modulus test determines the stiffness characteristics of the materials. The flexural beam fatigue test and Texas overlay test (Texas Department of Transportation, 2009) were included to gauge resistance to cracking. The repeated load permanent deformation test was used to measure stability or resistance to rutting for the three materials. The tensile strength ratio (TSR) test is a common method for determining susceptibility to moisture damage. In addition, binder samples were collected for performance grading.

Table 1. Study Test Plan

Test	Control SM-12.5E			SM-12.5E (SBS-PE)			SM-12.5E (GTR)		
	Onsite[a]	**Reheat[b]**	**Cores[c]**	**Onsite**	**Reheat**	**Cores**	**Onsite**	**Reheat**	**Cores**
Volumetric analysis	X	X	X	X	X	X	X	X	X
Tensile strength ratio	X			X			X		
Permeability			X			X			X
Dynamic modulus	X	X		X	X		X	X	
Repeated load permanent deformation	X	X		X	X		X	X	
Asphalt Pavement Analyzer		X			X			X	
Third-point bending fatigue		X			X			X	
Texas overlay test	X	X	X	X	X	X	X	X	X

[a] Onsite specimens were compacted immediately after production in the contractor's laboratory without reheating.
[b] Reheat specimens were made from loose mixture sampled during production and returned to the laboratory of the Virginia Center for Transportation Innovation and Research prior to being reheated for compaction.
[c] Cores were collected at the time of construction.

Binder Evaluation

Binder testing for quality assurance was conducted at the asphalt laboratory of VDOT's Materials Division (hereinafter VDOT Materials Division lab) in accordance with AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder (American Association of State Highway and Transportation Officials [AASHTO], 2013). Performance grading was also conducted at the VCTIR laboratory (hereinafter VCTIR lab) in accordance with AASHTO M 320 (AASHTO, 2013); in addition, multiple stress creep recovery tests were performed in accordance with AASHTO TP 70, Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR) (AASHTO, 2013), on material aged in the rolling thin film oven (RTFO) at a test temperature of 64ºC.

Volumetrics

Volumetric analyses were performed to determine fundamental mixture properties. Data collected included asphalt content and gradation; bulk and Rice specific gravities (G_{mb} and G_{mm}); voids in total mix (VTM); voids in mineral aggregate (VMA); voids filled with asphalt (VFA); aggregate bulk and effective specific gravities (G_{sb} and G_{se}); dust to asphalt ratio (D/A ratio); percent binder absorbed (P_{ba}); and effective binder content (P_{be}).

Permeability

Permeability testing was performed on cores collected for each mixture in accordance with Virginia Test Method (VTM) 120, Method of Test for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter (VDOT, 2009).

Dynamic Modulus

Dynamic modulus tests were performed with a universal testing machine (UTM 100) (Industrial Process Controls, Inc. [IPC]) with a 25 to 100 kN loading capacity in accordance with AASHTO T 342, Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures (AASHTO, 2013). Tests were performed on specimens 100 mm in diameter by 150 mm in height. Specimen air void levels of 7 ± 0.5% were obtained for each test specimen with the exception of one mixture, which averaged 8.0% air voids. Five testing temperatures ranging from -10.0 to 54.4ºC and six testing frequencies ranging from 0.1 to 25 Hz were used. Tests were conducted starting from the coldest temperatures to the warmest temperatures. In addition, at each test temperature, the tests were performed starting from the highest to the lowest frequency. Load levels were selected in such a way that at each temperature-frequency combination, the applied strain was in the range of 75 to 125 microstrain. All tests were conducted in the uniaxial mode without confinement. Stress versus strain values were captured continuously and used to calculate dynamic modulus. Dynamic modulus was computed automatically using IPC |E*| software. The results at each temperature-frequency combination for each mixture type are reported for three replicate specimens.

Repeated Load Permanent Deformation

The repeated load permanent deformation (RLPD) test (also known as the flow number test) is used to evaluate the rutting resistance of asphalt mixtures. It is generally accepted that the higher the flow number, the lower the rutting susceptibility.

The IPC UTM 100 with a 25 to 100 kN loading capacity was used to conduct the flow number tests. Testing was performed on specimens 100 mm in diameter by 150 mm in height having air void levels of 7 ± 0.5% with the exception of one mixture, which averaged 8.0% air voids. Tests were conducted at 54°C based on LTPPBind software that represents the 50% reliability maximum high pavement temperature at locations in central Virginia. A repeated haversine axial compressive load pulse of 0.1 s every 1.0 s was applied to the specimens. The tests were performed in the unconfined mode using a deviator stress of 600 kPa. The tests were continued for 10,000 cycles or a permanent strain of 5%, whichever came first. During the test, permanent strain (εp) versus the number of loading cycles was recorded automatically, and the results were used to estimate the flow number. The flow number was determined numerically as the cycle number at which the strain rate is at a minimum based on the Francken model. All flow number testing was conducted on specimens previously tested for dynamic modulus.

Rutting Analysis

Rut testing was conducted using the Asphalt Pavement Analyzer (APA) (Pavement Technologies, Inc.) in accordance with VTM 110, Method of Test for Determining Rutting Susceptibility Using the Asphalt Pavement Analyzer (VDOT, 2009). Sets of three replicate beams 75 mm thick by 125 mm wide by 300 mm long were tested simultaneously at a test temperature of 49°C. A vertical load of 120 lbf was applied through a rubber hose filled with compressed air at a pressure of 120 psi. The loading wheel speed was 2 ft/sec, and a total of about 135 min was required to complete 8,000 cycles of load applications. Total deformation after 8,000 cycles of load applications is considered the total rut depth. The reported test result is the average rut depth for the replicate beams of each mixture type tested simultaneously.

Fatigue Analysis

Four-point flexural beam fatigue tests were performed in accordance with AASHTO T 321, Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending (AASHTO, 2013), in an Industrial Process Controls, Inc. (IPC) pneumatic beam fatigue test apparatus. At least three replicate specimens were tested at three strain levels (minimum total of nine beams) for each mixture type. All tests were conducted at the single temperature of 20ºC. The tests were conducted in the strain-controlled mode. Applied tensile strain levels ranging from 300 to 600 microstrain were used so that fatigue curves of strain versus number of cycles to failure could be developed. During the test, repeated application of the specified strain was continued until failure occurred in the test specimen. Specimen failure was defined as the number of cycles at which beam stiffness degraded to 50% of the initial flexural stiffness.

Cracking Analysis

The Texas overlay test was performed to assess the susceptibility of each mixture to cracking. Testing was performed using the IPC UTM 100 with a 25 to 100 kN loading capacity generally in accordance with TX-248-F, Test Procedure for Overlay Test (Texas Department of Transportation, 2009), on test specimens having a 150 mm diameter and 38 mm minimum height. Laboratory-produced test specimens were cut in pairs from the center of gyratory specimens 150 mm in diameter by 170 mm in height, taking care to minimize any influence of air void differential at the top and bottom of the specimen. Testing was performed at a temperature of 25 ± 0.5°C. Loading was applied for a total of 1,200 cycles or until a 93% or greater reduction of the maximum load was reached.

RESULTS AND DISCUSSION

Installation

A short (19 tons) section of control mixture was placed on U.S. Route 1 Northbound on August 22, 2012. The demonstration project went "production" on the next day with placement of the first full control section. The SBS-PE materials were placed on August 24 and 29, and the GTR materials were placed on August 27 and 28. The final control section was placed on August 30.

All mixtures were produced with a TENEX Counter Flow Drum plant using the Green Machine Warm Mix Foaming System by Gencor. The plant's operating capacity is 500 tons per hour. Table 2 includes some notes relating to the production of each mixture as recorded at a post-construction meeting with the project team on September 7.

Table 2. Mixture Production Notes

Production Characteristic	Control PG 76-22	SBS-PE	GTR 8/24	GTR 8/27
Plant target temperature settings	290° F	290° F	290° F	325° F
Warm-mix Technology	Foam	Foam	Foam	Foam
Target production rate	300 tons/hour	300 tons/hour	300 tons/hour	300 tons/hour
Target RAP content, %	15	15	15	15
Volumetric contrast with mix design (QC testing)		High voids	High voids	High voids – Rubber acting like a fine material. (fines)
Adjustments to mixture (production)	None	None	None	Increased plant setting by 0.1% AC
Binder tonnage	4 loads ~ 100 tons	4 loads ~ 100 tons	4 loads ~ 100 tons total for both days	
Antistrip additive	0.2% AD Here HP +	0.2% AD Here HP +	0.2% AD Here HP +	0.2% AD Here HP +
Silo storage time			No more than 1 hour	No more than 1 hour
Binder delivery (to mixture)	Storage tank at plant	Straight from truck tanker	Straight from truck tanker	Straight from truck tanker
Adjustments to plant for binder	None	Removed screens in binder lines	Removed screens in binder lines	Removed screens in binder lines

RAP = recycled asphalt pavement; QC = quality control; AC = asphalt content.

The same meeting provided an opportunity to discuss the placement of the control and two demonstration materials. Table 3 reports various notes that pertain to mixture workability. All materials were placed with an AP1055E Caterpillar track paver with a Blaw Knox insert. A Blaw Knox MC-30 materials transfer vehicle was used to transfer materials from haul trucks to the insert/paver. The compaction train included a CB 54 Caterpillar breakdown roller (with VERSA-VIBE) and a smaller HAMM HD 14 (Wirtgen Group) 67733R finish roller.

Table 3. Mixture Placement Notes

Placement Characteristics	**Control PG 76-22**	**SBS-PE**	**GTR 8/24**	**GTR 8/27**
Handwork		More workable	Same as control	Same as control
Transverse joint	No comments	No comments	No comments	No comments
Longitudinal joint	No comments	No comments	No comments	No comments
Screed	Nothing different	Nothing different	Nothing different	Nothing different
MTV	Yes	Yes	Yes	Yes
Compaction Effort				
Breakdown roller	3V 1S	3V 1S	3V 1S	4V
Second roller	5S	6S	6S	2V 2S
Tenderness	225 to 200° F tender zone			

MTV = materials transfer vehicle; V = vibratory pass of the roller, S = static (non-vibratory) pass of the roller.

Volumetric Properties and Gradations

Routine quality assurance testing was performed by the VDOT district. The results of the testing are available from the authors**.** The VDOT Materials Division lab and VCTIR researchers also collected samples of the three mixtures and the various binders used to produce them.

Table 4 presents the volumetric properties as determined from the materials evaluated at the VCTIR lab. Table 5 shows the gradation data that accompany the volumetric data.

Table 4. Volumetric Properties of Mixtures

Property	**12-1037 SM-12.5E Control Day 1**	**12-1038 SM-12.5E (SBS-PE) Day 1**	**12-1051 SM-12.5E (SBS-PE) Day 2**	**12-1041 SM-12.5E (GTR) Day 1**	**12-1050 SM-12.5E (GTR) Day 2**
% AC	5.15	5.08	4.99	5.16	5.00
Rice specific gravity, G_{mm}	2.658	2.647	2.653	2.644	2.634
% Air voids, V_a	5.0	4.5	5.9	4.3	4.7
% VMA	17.1	16.4	17.4	16.4	16.3
% VFA	70.6	72.5	66.2	73.8	71.3
Dust/AC ratio	1.14	1.08	1.07	1.07	1.22
Bulk specific gravity, G_{mb}	2.524	2.528	2.496	2.530	2.511
Effective specific gravity, G_{se}	2.908	2.890	2.892	2.890	2.869
Aggregate specific gravity, G_{sb}	2.889	2.871	2.873	2.871	2.850
% Binder absorbed, P_{ba}	0.23	0.24	0.24	0.24	0.24
Effective % binder, P_{be}	4.93	4.85	4.76	4.93	4.77
Effective film thickness, F_{be}	8.8	9.4	9.2	9.7	8.7

AC = asphalt content; VMA = voids in mineral aggregate; VFA = voids filled with asphalt.

Table 5. Mixture Gradations

Sieve	12-1037 SM-12.5E Control Day 1	12-1038 SM-12.5E (SBS-PE) Day1	12-1051 SM-12.5E (SBS-PE) Day 2	12-1041 SM-12.5E (GTR) Day1	12-1050 SM-12.5E (GTR) Day 2
3/4 in (19.0 mm)	100.0	100.0	100.0	100.0	100.0
1/2 in (12.5 mm)	95.9	95.0	97.3	95.1	95.4
3/8 in (9.5 mm)	85.5	83.7	86.3	83.4	84.9
No. 4 (4.75 mm)	66.8	59.1	64.1	60.1	61.0
No. 8 (2.36 mm)	45.2	39.0	42.4	39.1	41.7
No. 16 (1.18 mm)	31.4	27.7	29.3	27.4	29.8
No. 30 (600 µm)	21.4	19.2	19.6	18.2	19.9
No. 50 (300 µm)	12.5	11.3	11.5	10.9	11.8
No. 100 (150 µm)	8.2	7.4	7.4	7.5	7.9
No. 200 (75 µm)	5.62	5.25	5.09	5.3	5.8

Binder Properties

Table 6 summarizes the results from acceptance testing on the three binders by the VDOT Materials Division lab. The testing determined the SBS-PE blend to be acceptable and consistent. Although also consistent, the lab results for the GTR blend indicated that both samples of the material did not grade to a PG 76 binder and failed the elastic recovery requirement. The actual high-temperature performance grading for the two GTR samples was 74.3 and 74.5, respectively. The GTR product missed the elastic recovery requirement by a more substantial margin: -58% recovery when 70% was required. It is thought that the GTR "loading" for the materials delivered to the contractor was not sufficient to meet the criteria for a PG 76 binder. Although it was thought that 10% to 12% ground rubber by weight of binder is required to meet the PG 76 elastic recovery requirement, notes on the bills of lading for the loads shipped for the project indicated that the binder contained only 8% to10% ground rubber.

Table 6. Binder Acceptance Test Results From VDOT Materials Division Lab

Material	PG76-22 (Control)	SBS-PE 1	SBS-PE 2	GTR 1	GTR 2	Specification
Rotational Viscosity (AASHTO T 316)						
Viscosity at 135°C	1.212	1.075	1.050	1.538	1.638	<3 Pa sec
Viscosity at 165°C	0.338	0.300	0.288	0.363	0.388	
Dynamic Shear Rheometer, 10 rad/sec (AASHTO T 315)						
Orig. G*/Sin delta at 76°C	1.333	1.527	1.411	1.069	1.107	>1.00 kPa
Orig. G*/Sin delta at 82°C	0.6905	0.8413	0.7766	0.6142	0.6337	
Rolling Thin Film Oven Residue (AASHTO T 240)						
RTFO Mass Change, %	-0.375	-0.329	-0.493	-0.218	-0.230	<1.00%
DSR, 10 rad/sec (AASHTO T 315)						
RTFO G*/Sin delta at 76°C	3.035	3.397	3.272	1.819	1.867	>2.20 kPa
RTFO G*/Sin delta at 82°C	1.589	1.807	1.749	[a]	[a]	
Elastic Recovery	77%	75%	75%	**58%**	**58%**	>70%
Pressure Aging Vessel Residue at 100ºC (AASHTO R 28)						
DSR, 10 rad/sec (AASHTO T 315)						
PAV G*Sin delta at 25°C				2837	2285	<5000 kPa
PAV G*Sin delta at 31 C	1506	1758	1922			
Bending Beam Rheometer (AASHTO T 313)						
S at -12°C	208	239	239	153	143	<300 MPa
M at -12°C	0.328	0.322	0.329	0.324	0.327	>0.300

Values in bold typeface represent failing elastic recovery test results.

[a] Binder did not meet performance grading for PG 76-XX.

Table 7 summarizes the VCTIR lab binder test results. The control binder met the specification for performance grading as a PG 76-22 binder. In addition, it met the specification requirements of AASHTO MP 19, Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test (AASHTO, 2013), to be graded as a PG 64E-22 binder. However, the control binder did not exceed the minimum value recommended in AASHTO TP 70 (AASHTO, 2013) for $R_{3.2kPa}$, the average percent recovery at 3.2 kPa, which is an indication of sufficient modification with an acceptable elastomeric polymer.

The SBS-PE binder met the specification for performance grading as a PG 76-22 binder in accordance with AASHTO M 320 (AASHTO, 2013); in addition, the binder was graded as a PG 64E-22 binder under the specification in AASHTO MP 19 (AASHTO, 2013) and exceeded the AASHTO TP 70 recommended minimum value for $R_{3.2kPa}$ (AASHTO, 2013), indicating sufficient modification with an acceptable elastomeric polymer.

The GTR binder was specified to be a PG 76-22 binder in accordance with AASHTO M 320; however, it failed to meet the requirements and graded as a PG 70-22 binder. In accordance with AASHTO MP 19, the GTR binder was graded as a PG 64H-22 binder and did not exceed the minimum value for $R_{3.2kPa}$ recommended in AASHTO TP 70, indicating insufficient modification with an acceptable elastomeric polymer.

It should be noted that none of the binders in this study was required to meet the AASHTO MP 19 or AASHTO TP 70 specifications; these data were collected for informational purposes only.

Laboratory Performance

In addition to binder testing, the VCTIR lab subjected the asphalt mixtures to a series of laboratory performance tests.

Dynamic Modulus

Figure 2 plots the reduced frequency characteristic curves for dynamic modulus for several variations on the control material and the SBS-PE mixture alternative. There are curves for specimens that were prepared onsite for both the control and the first day of SBS-PE mixture production. There are also curves for specimens that were prepared from reheated material. The reheated data are available for the control and both days of SBS-PE mixture production. ”Reheat” specimens were collected as loose mixture during production and reheated to compact specimens. “Onsite” specimens were produced onsite during production without reheating of the mixture.

Figure 2 indicates that the SBS-PE mixtures were slightly stiffer than the control SBS mixture. In general, reheating and compacting mixtures was shown to increase the modulus for both mixture types. Figure 3 indicates an approximate 10% increase in stiffness for the SBS-PE mixture when compared to the control mixture, although for reheated mixtures, that difference was less at lower moduli values.

Table 7. Summary of VCTIR Lab Binder Test Data

Lab Test No.	**13-009**	**13-010**	**13-014**	**13-011**	**13-013**
Material	**PG76-22 Control Day 1**	**PG76-22 SBS-PE Day 1**	**PG76-22 SBS-PE Day 2**	**PG76-22 GTR Day 1**	**PG76-22 GTR Day 2**
Viscosity at 135ºC	1.263	1.096	1.112	1.679	1.362
Viscosity at 165ºC	0.313	0.267	0.275	0.367	0.3
Orig. G*/sin delta at 76ºC, kPa	1.309	1.551	1.569	1.190	1.039
Orig. G* at 76ºC, kPa	1.289	1.515	1.534	1.163	1.021
Phase angle, º	79.9	77.6	77.8	77.7	79.5
Orig. G*/sin delta at 82ºC, kPa	0.6911	849.2	0.8711	0.6946	0.6201
Orig. G* at 82ºC, kPa	685.8	1.832	855.9	0.6794	609.3
Phase angle, º	82.86	78.69	79.27	77.97	79.32
Failure temperature	78.53	80.52	80.59	77.94	76.44
RTFO Mass Loss	-0.42	-0.37	-0.4	-0.28	-0.25
RTFO G*/sin delta, 70ºC, kPa	-	-	-	3.384	3.107
RTFO G*, 70ºC, kPa	-	-	-	3.314	3.054
Phase angle, º	-	-	-	78.29	79.39
RTFO G*/sin delta, 76ºC, kPa	3.139	3.57	3.418	1.954	1.566
RTFO G*, 76ºC, kPa	2.998	3.398	3.255	1.905	1.548
Phase angle, º	72.8	72.1	72.22	78.87	81.22
RTFO G*/sin delta, 82ºC, kPa	1.659	1.901	1.811	1.065	-
RTFO G*, 82ºC, kPa	1.609	1.832	1.747	1.045	-
Phase angle, º	75.94	74.53	74.71	80.16	-
Failure temperature	79.34	80.61	80.16	74.83	73.02
PAV G*sin delta, 19.0ºC, kPa	-	-	-	6132	6072
PAV G*, 19.0ºC, kPa	-	-	-	9.49E+06	9.27E+06
Phase angle, º	-	-	-	40.27	46.73
PAV G*sin delta, 22.0ºC, kPa	5397	6841	6507	4280	4283
PAV G*, 22.0ºC, kPa	7.790E+06	9.949E+06	9.359E+06	6.25E+06	6.19E+06
Phase angle, º	43.86	43.45	44.05	43.21	43.82
PAV G*sin delta, 25.0ºC, kPa	3689	4726	4443	2985	2931
PAV G*, 25.0ºC, kPa	5.093E+06	6.563E+06	6.107E+06	4.15E+06	4.03E+06
Phase angle, º	76.41	46.06	46.68	45.95	46.73
PAV G*sin delta, 28.0ºC, kPa	-	-	-	2017	-
PAV G*, 28.0ºC, kPa	-	-	-	2.68E+06	-
Phase angle, º	-	-	-	48.78	-
Failure temperature	22.61	24.5	24.07	20.7	20.64
S, -12ºC	221	252	263	156	164
m-value, -12ºC	0.326	0.306	0.321	0.315	0.315
S, -18ºC	416	503	525	313	329
m-value, -18ºC	0.268	0.26	0.26	0.264	0.275
Performance Grade	76-22	76-22	76-22	70-22	70-22
Multiple Stress Creep and Recovery RTFO DSR Report, AASHTO TP 70-07					
Test Temperature	64	64	64	64	64
Avg. % Recovery, $R_{1.0kPa}$	42.46	48.06	46.94	29.95	22.52
Non Recoverable $J_{nr1.0kPa}$	0.3377	0.2553	0.2788	0.7634	0.9772
Avg. % Recovery, $R_{3.2kPa}$	**34.33**	41.17	39.73	**14.51**	**10.02**
Non Recoverable $J_{nr3.2kPa}$	0.3962	0.2934	0.3231	1.021	1.239
% Difference in Recovery	19.14	14.33	15.35	51.56	55.49
% Difference in J_{nr}	17.33	14.93	15.91	33.72	26.84
AASHTO MP 19 Grade	64-22E	64-22E	64-22E	64-22H	64-22H
AASHTO TP 70 $R_{3.2kPa}$, min.	37.48	40.56	39.55	29.21	27.76

- = no testing was performed at the specific temperature. Values in bold typeface indicate failing values based on the AASHTO TP 70 specification.

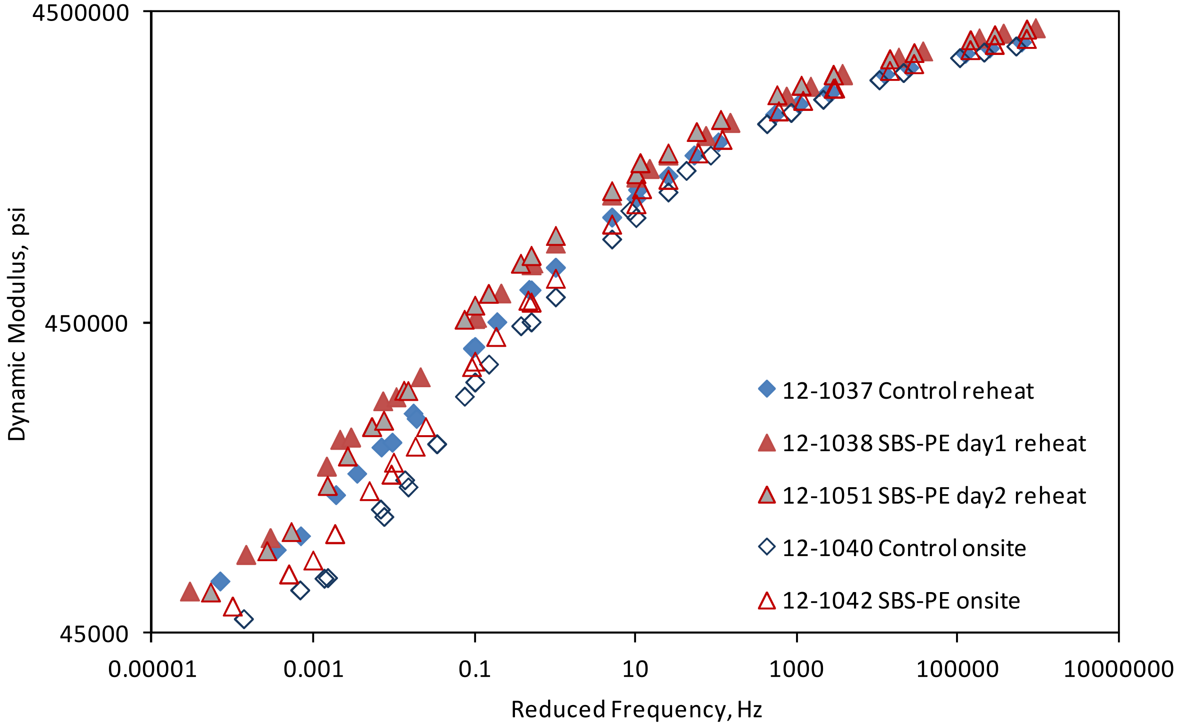

Figure 2. Dynamic Modulus Mastercurves for Control and SBS-PE Mixtures

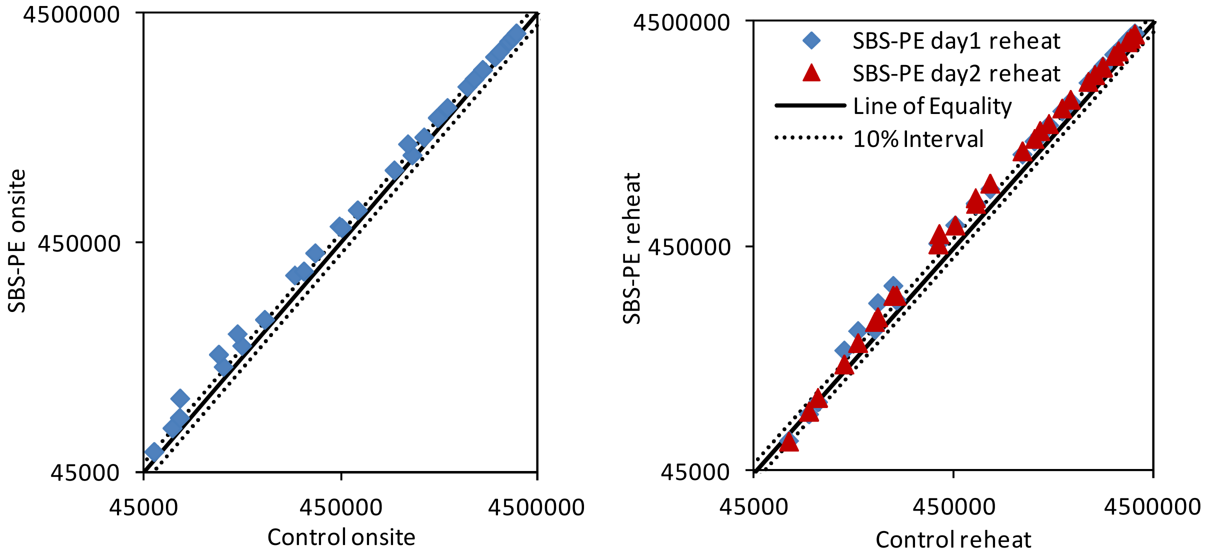

Figure 3. Comparison of SBS-PE Specimens Made Onsite and After Reheating

Figures 4 and 5 present dynamic modulus results for the control and GTR mixtures. Figures 4 and 5 indicate the effect of the binder grade on the GTR mixtures, especially for the Day1 mixtures, as the GTR mixture moduli are shown to be similar to or less than those of the control mixture. The Day 2 mixture indicated an increase in modulus values, showing an approximate 10% increase over those of the control mixture at all but the four lowest modulus values.

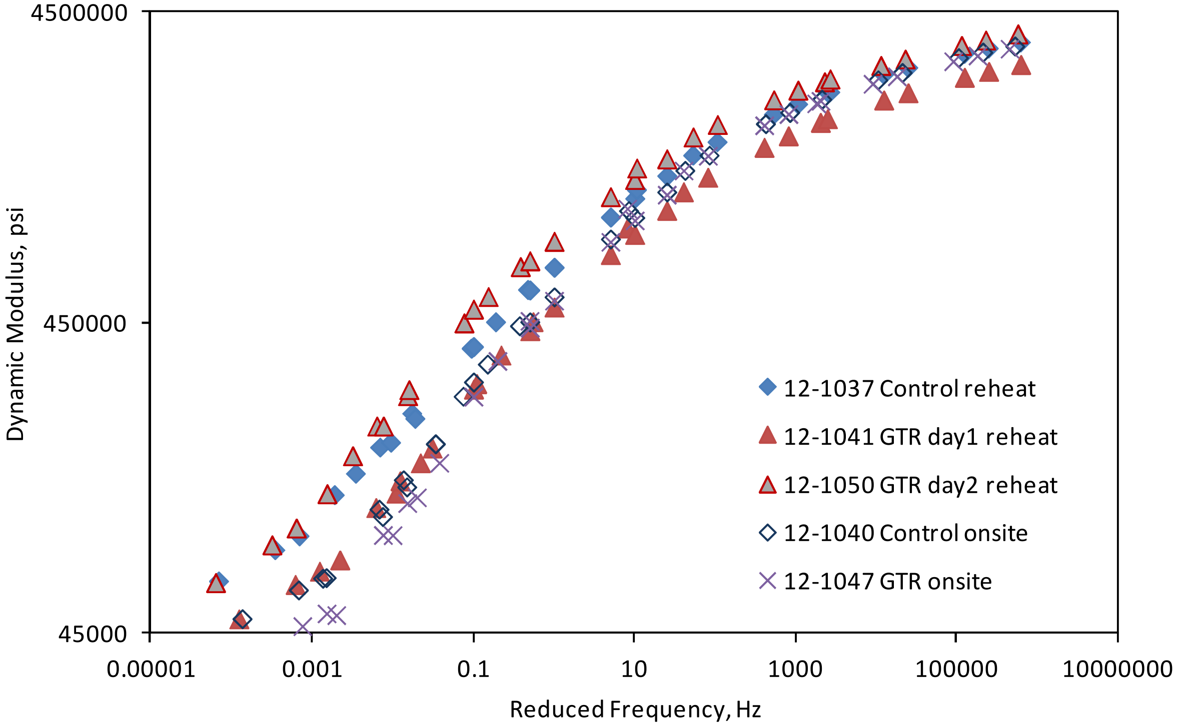

Figure 4. Dynamic Modulus Mastercurves for Control and Rubber-Modified Mixtures. GTR = ground tire rubber.

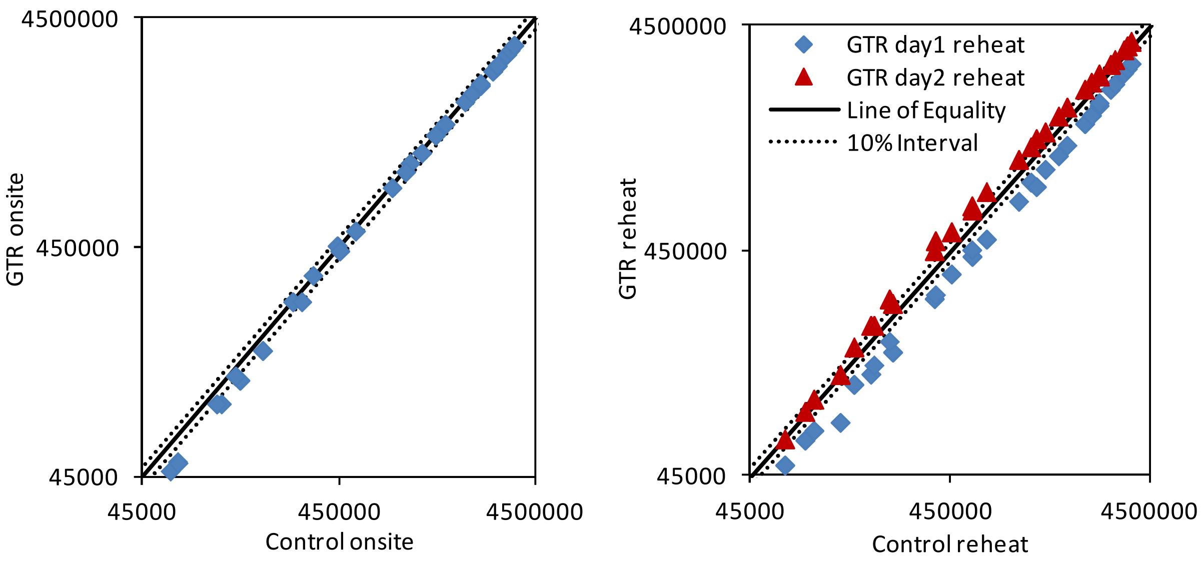

Figure 5. Comparison of Rubber-Modified Specimens Made Onsite and After Reheating. GTR = ground tire rubber.

Repeated Load Permanent Deformation

Figures 6 and 7 present the flow number test results for the SBS-PE and GTR mixtures, respectively. Figure 6 indicates that the SBS-PE mixture had a significantly higher flow number than the control mixture for both onsite-compacted and reheated specimens, indicating greater rutting resistance. Figure 7 indicates that the GTR mixture may be more rut-susceptible than the control mixture, as the GTR flow numbers were lower than the control flow numbers. The difference between the flow numbers for the onsite specimens was statistically significant. The results of the reheated specimens were mixed; the difference between the control and GTR Day 1 reheated mixtures was statistically significant, and that between the control and GTR Day 2 mixtures was not.

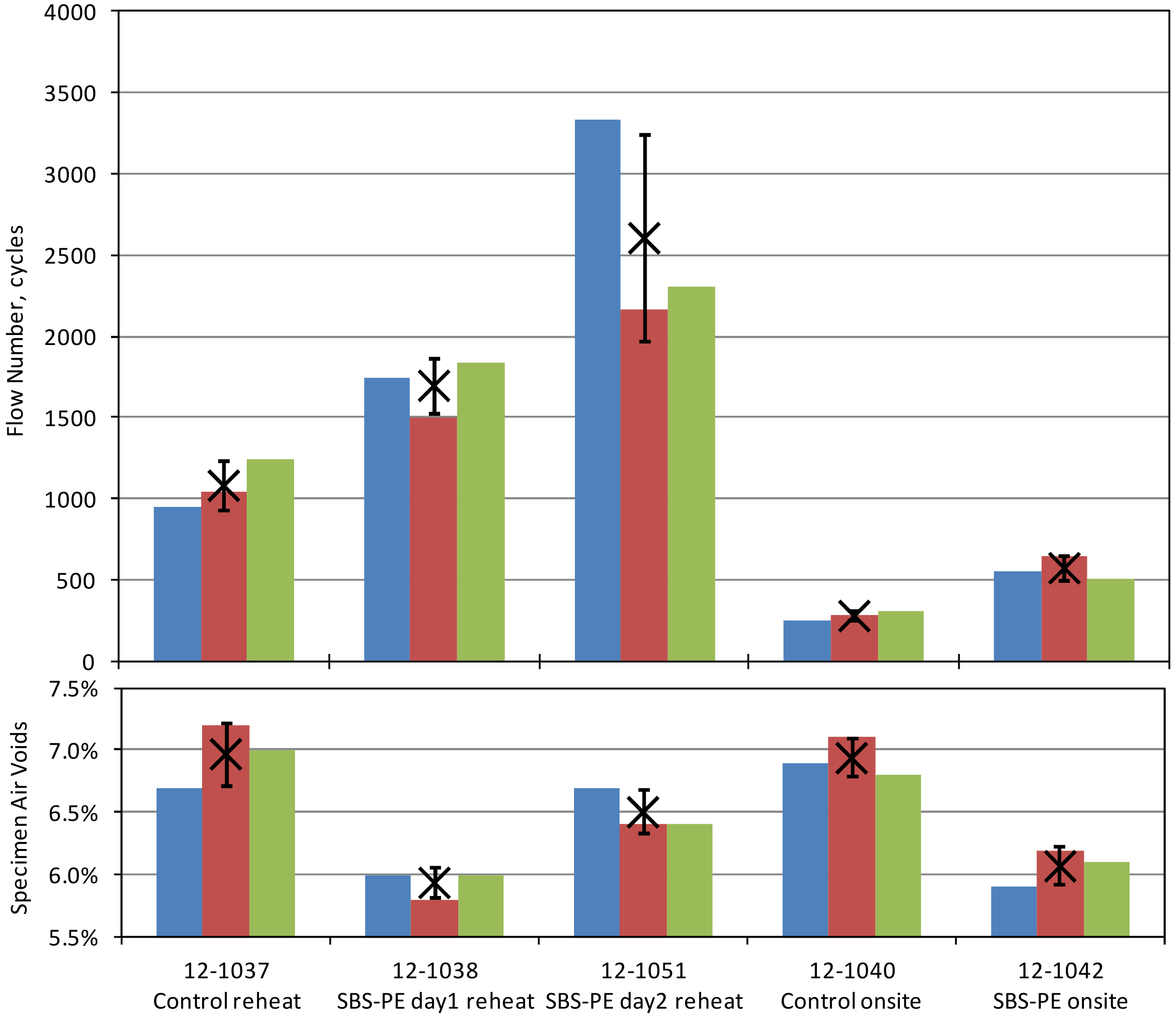

Figure 6. Flow Number and Specimen Air Voids for Control and SBS-PE Mixtures

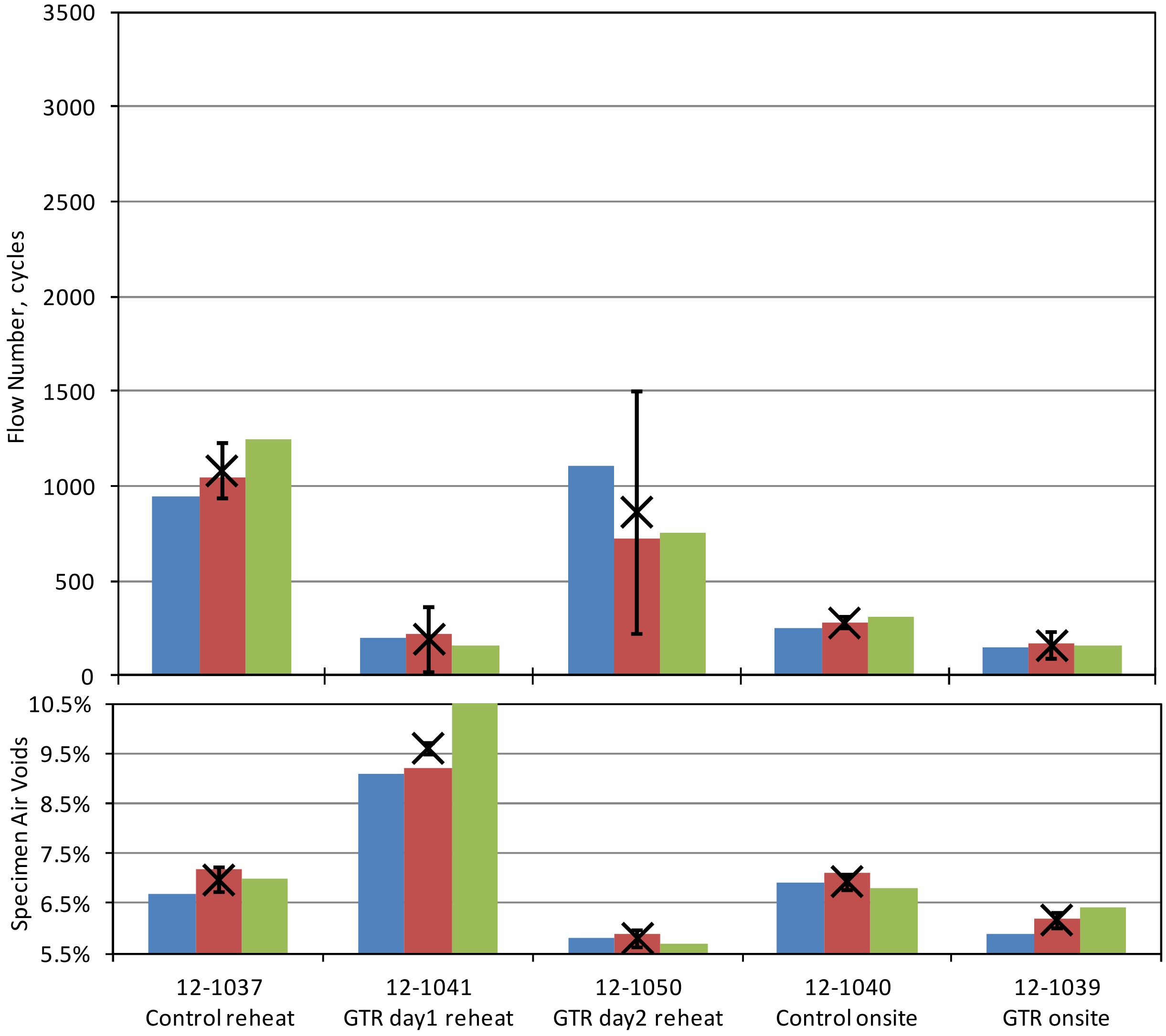

Figure 7. Flow Number and Specimen Air Voids for Control and GTR Mixtures. GTR = ground tire rubber.

APA Rut Test

APA rut testing was also performed to assess rutting susceptibility. All specimens were fabricated from reheated mixture. Table 8 summarizes the test results for all mixtures. The maximum rutting allowed by VTM 110 (VDOT, 2009) for SM-12.5E mixtures is 3.5 mm; this requirement was easily met by all three mixtures. The difference between the control and SBS-PE mixtures was not statistically significant. The difference in the reduction in measured rutting between the GTR mixture and the control mixture was statistically significant; however, the difference was not considered practically significant.

Table 8. APA Rut Test Results

12-1037 SM-12.5E Control Mixture					
Specimen	**Air Voids, %**	**Average**	**Rut Depth, mm**	**Average**	**Standard Deviation**
Left	8.2	8.2	0.55	0.9	0.3
Center	8.0		0.99		
Right	8.3		1.05		
12-1038 SM-12.5E (SBS-PE) Mixture					
Specimen	**Air Voids, %**	**Average**	**Rut Depth, mm**	**Average**	**Standard Deviation**
Left	7.8	8.2	0.44	0.8	0.3
Center	8.4		1.01		
Right	8.3		1.05		
12-1041 SM-12.5E (GTR) Mixture					
Specimen	**Air Voids, %**	**Average**	**Rut Depth, mm**	**Average**	**Standard Deviation**
Left	7.6	7.7	0.15	0.1	0.1
Center	7.9		0.07		
Right	7.7		0.18		

Beam Fatigue Test

Figure 8 shows the results of third-point beam fatigue testing for the control and SBS-PE mixtures. The average void content for the control mixture was 10.4%; the average void content for the SBS-PE mixture was 9.1%. The SBS-PE mixture had a reduced laboratory fatigue life when compared to the control mixture.

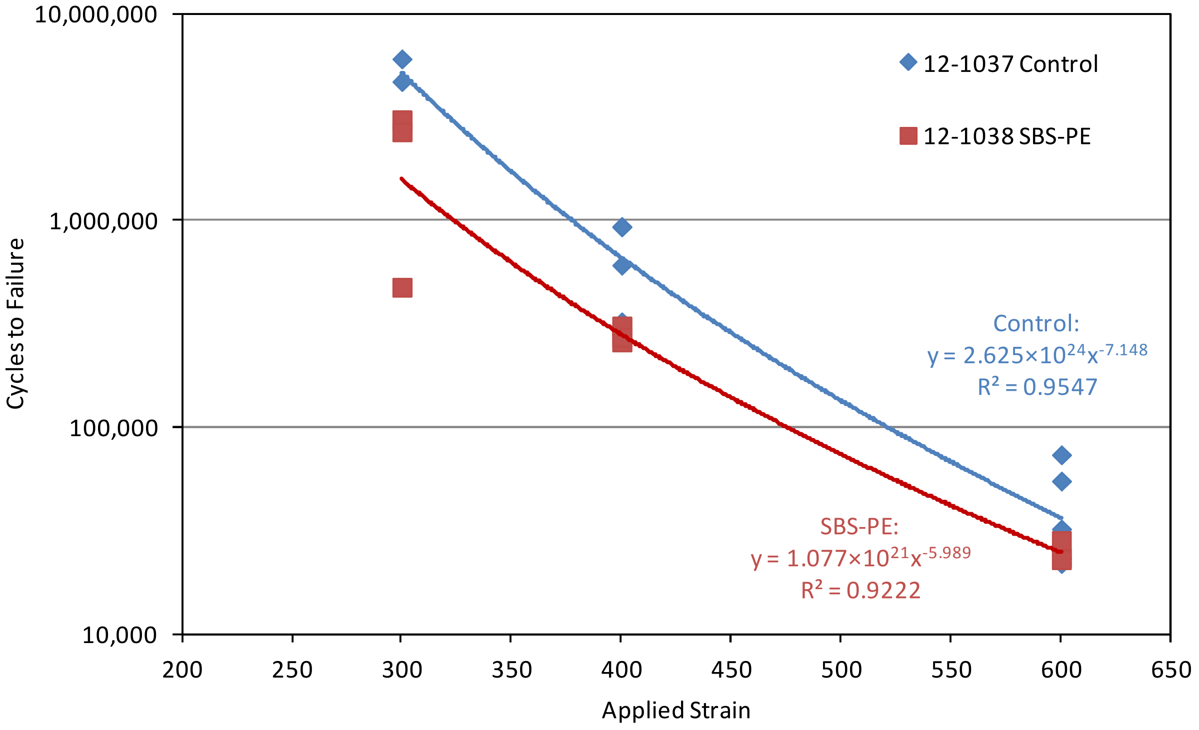

Figure 8. Fatigue Life Curves for Control and SBS-PE Mixtures

Figure 9 presents the results of third-point beam fatigue testing for the control and GTR mixtures. The average void content for the control mixture was 10.4%; the average void content for the GTR mixture was 8.4%. The results indicated that the GTR mixture had fewer cycles to failure than the control mixture at applied strains below approximately 475µε and improved performance at strains exceeding approximately 475µε.

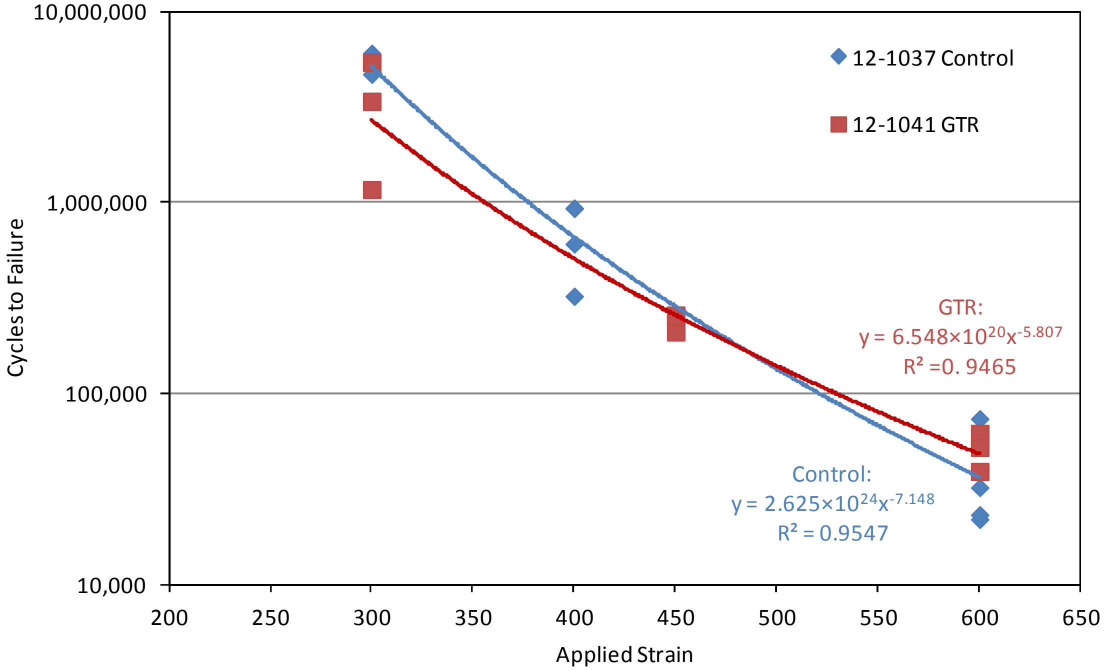

Figure 9. Fatigue Life Curves for Control and GTR Mixtures. GTR = ground tire rubber.

Overlay Test

Table 9 shows the results of overlay testing for the control, SBS-PE, and GTR mixtures. Failure was defined as a 93% reduction of the initial applied load or 1,200 cycles, whichever occurred first. Results for each set of specimens were averaged for comparative purposes, as sufficient numbers of the reheated and cored specimens were not available to analyze the trimmed average. For the onsite-produced specimens, overall and trimmed results are shown; trimming involved removing the highest and lowest test result prior to averaging results and determining the standard deviation and coefficient of variation (COV). Table 9 indicates that trimming the results for the onsite-produced specimens had little impact on the average, although the standard deviations and COVs for the control and GTR mixtures were considerably reduced.

Results of the overlay test indicated that the SBS-PE mixture should resist cracking similar to the control. No specimen sets resulted in a significant difference between the control and SBS-PE. Comparison of the control and GTR overlay test results was mixed. Significant differences were found for the onsite-compacted specimen sets and for the road cores, with the GTR specimen having fewer cycles to failure than the control mixture; however, test results for the reheated specimens indicated no significant difference between the control and GTR performance. It is not clear why these differences were found for these specimen sets.

Table 9. Texas Overlay Test Results

Mixture	Specimen	Voids, %	Cycles to Failure	Average	Standard Deviation	Coefficient of Variation	Trimmed Average	Trimmed Standard Deviation	Trimmed Coefficient of Variation
12-1040 Control (onsite)	4A	7.3	706	*718.0*	*284.4*	39.6%	639.7	76.5	12.0%
	4B	7.7	*471*						
	6A	6.9	*1200*						
	7A	6.6	657						
	7B	6.9	556						
12-1042 SBS-PE (onsite)	6A	6.7	*460*	800.0	368.6	46.1%	780.0	365.1	46.8%
	6B	6.8	*1200*						
	7A	6.3	1200						
	7B	7.4	602						
	8B	6	538						
12-1047 GTR (onsite)	4A	6	512	475.2	106.3	22.4%	471.7	58.2	12.3%
	4B	7	498						
	5A	6.4	*619*						
	5B	6.7	405						
	6B	6.9	*342*						
12-1037 Control (reheat)	4A	7	346	589.8	407.9	69.2%			
	4B	7.7	398						
	5A	6.1	415						
	5B	7.1	1200						
12-1038 SBS-PE (reheat)	4A	6.5	1200	815.5	480.5	58.9%			
	4B	6.9	1200						
	5A	5.8	656						
	5B	6.2	206						
12-1041 GTR (reheat)	2A	6.3	355	851.5	420.2	49.3%			
	2B	5.8	1200						
	3A	6	1200						
	3B	6.1	651						
12-1044 Control (cores)	C1	10.9	1200	1200.0	0.0	0.0%			
	C3	6.9	1200						
	C6	7.2	1200						
12-1045 SBS-PE (cores)	PE1	9	1200	1200.0	0.0	0.0%			
	PE3	10.3	1200						
	PE5	9.2	1200						
12-1046 GTR (cores)	R2	8.9	1200	1046.7	147.0	14.0%			
	R5	8.6	907						
	R6	10.2	1033						

Values in italics indicate the high and low test value eliminated from consideration during the trimming process.

Tensile Strength Ratio

Tensile strength testing was performed on onsite-compacted specimens of all mixtures, and the results are presented in Table 10. Both the control and GTR mixtures passed the VDOT minimum specification of a TSR greater than or equal to 0.80. It should be noted that the dry and wet strengths of the GTR specimens were slightly over half the magnitude of those measured for the control specimens. The SBS-PE mixture did not meet the TSR requirement, although the dry and wet strengths were comparable to those of the control specimens and should mitigate the risk of susceptibility.

Table 10. Tensile Strength Test Results

12-1040 Control Onsite Mixture							
Dry				**Conditioned**			
Sample	**Voids, %**	**Load, lb**	**Strength, psi**	**Sample**	**Voids, %**	**Load, lb**	**Strength, psi**
2	7.4	6080	260	1	7.2	6020	258
4	8.1	6200	265	3	7.1	5080	217
6	7.6	6800	290	5	7.3	5280	226
Average	7.7		272	Average	7.2		234
Std. Dev.	0.360555		16.3	Std. Dev.	0.1		21.3
Tensile strength ration = 0.86							
12-1042 SBS-PE Onsite Mixture							
Dry				**Conditioned**			
Sample	**Voids, %**	**Load, lb**	**Strength, psi**	**Sample**	**Voids, %**	**Load, lb**	**Strength, psi**
2	7.0	6140	262	1	7.0	4440	190
4	7.2	6100	260	3	7.0	5000	214
6	7.5	5840	249	5	6.7	4700	201
Average	7.2		257	Average	6.9		201
Std. Dev.	0.25		7.0	Std. Dev.	0.17		12.1
Tensile strength ratio = 0.78							
12-1047 Rubber Onsite Mixture							
Dry				**Conditioned**			
Sample	**Voids, %**	**Load, lb**	**Strength, psi**	**Sample**	**Voids, %**	**Load, lb**	**Strength, psi**
1	7.0	3440	147	2	7.1	3360	144
3	6.6	3840	164	4	7.0	3120	133
5	7.2	3900	167	5	6.9	3400	145
Average	6.9		159	Average	7.0		141
Std. Dev.	0.32		10.7	Std. Dev.	0.08		6.6
Tensile strength ratio = 0.88							

SUMMARY OF FINDINGS

Binder Properties

- The control binder met the requirements to be a PG 76-22 binder, including the elastic recovery requirement. In addition, the control binder graded as a PG 64E-22 binder in accordance with AASHTO MP 19. However, the control binder did not exceed the AASHTO TP 70 recommended minimum value for $R_{3.2kPa}$, the average percent recovery at 3.2 kPa. This is an indication of insufficient modification with an acceptable elastomeric polymer for PG-plus purposes.

- The SBS-PE binder met the specification for performance grading as a PG 76-22 binder in accordance with AASHTO M 320; in addition, the binder was graded as a PG 64E-22 binder in accordance with AASHTO MP 19 and exceeded the AASHTO TP 70 recommended minimum value for $R_{3.2kPa}$, indicating sufficient modification with an acceptable elastomeric polymer.

- The GTR blend material did not meet the specifications for a PG 76-22 binder. The material failed the elastic recovery requirement for both samples tested. In VCTIR lab testing, the GTR material graded as a PG 70-22 binder in accordance with AASHTO M 320, and graded as a PG 64H-22 binder in accordance with AASHTO MP 19. The material did not exceed the AASHTO TP 70 recommended minimum value for $R_{3.2kPa,}$ indicating insufficient modification with an acceptable elastomeric polymer. The GTR bill of lading indicated a rubber content of 8% to 10%.

Mixture Performance

SBS-PE Versus Control Mixtures

- The SBS-PE mixtures were slightly stiffer than the control SBS mixture as determined by the dynamic modulus mastercurve. In general, reheating and compacting mixtures increased the modulus for both mixture types.

- The SBS-PE mixture had a significantly higher flow number than the control mixture for both onsite-compacted and reheated specimens, indicating greater rutting resistance.

- APA rut test results indicated no statistically significant difference between the control and SBS-PE mixtures.

- Bending beam fatigue testing showed the SBS-PE mixture to have a reduced laboratory fatigue life when compared to the control mixture.

- Results of the overlay test indicated that the SBS-PE mixture should resist cracking similar to the control as no significant differences were found.

- The SBS-PE mixture did not pass the VDOT minimum specification of a TSR greater than or equal to 0.80, although both the dry and wet strengths exceeded 200 psi.

- The SBS-PE mixture was slightly stiffer than the control SBS mixture and thus should be slightly more rut-resistant, although the APA rut test indicated no statistically significant difference in rutting potential. The bending beam fatigue results indicated that the increase in stiffness may lead to a reduced fatigue life; however, the overlay test indicated that the SBS-PE mixture should resist crack initiation similar to the control SBS mixture. The failure of the SBS-PE mixture to meet TSR requirements typically indicates a potential for moisture sensitivity, although the high dry and wet strengths tend to mitigate the potential risk. Based on these results, performance could be expected to be similar between the two mixtures, with the possible exception of the fatigue performance. However, as fatigue performance in service is highly dependent on the underlying pavement structure and traffic loading, the differential in laboratory fatigue life requires verification in field performance.

GTR Versus Control Mixtures

- The GTR mixture moduli were similar to or less than those of the control mixture.

- The GTR mixture had lower flow numbers than the control mixture. Onsite-compacted specimens had significantly different flow numbers between the control and GTR mixtures. The results of the reheated specimens were mixed; a statistically significant difference was found between the control and GTR Day 1 reheated mixtures and no statistically significant difference was found between the control and GTR Day 2 mixtures.

- The reduced APA-measured rutting in the GTR mixture was statistically significant as compared to the control mixture. However, the difference was only 0.8 mm, which would not be considered a practical difference.

- The GTR mixture had fewer cycles to failure in the bending beam fatigue test than the control mixture at applied strains below approximately 475με and improved performance at strains exceeding approximately 475με.

- Comparison of the control and GTR overlay test results was mixed. Significant differences were found in the onsite-compacted specimen sets and in the road cores, with the GTR specimen having fewer cycles to failure than the control mixture; however, test results of reheated specimens indicated no significant differences between the control and GTR performance.

- Both the control and GTR mixtures met the VDOT minimum specification of a TSR greater than or equal to 0.80. However, the dry and wet strengths of the GTR specimens were only slightly over half the magnitude of those measured for the control specimens.

- The GTR mixture dynamic modulus and flow number results appeared generally reflective of the binder grade. When compared to the control SBS mixture, the GTR mixture dynamic moduli were similar to or less in magnitude than for the SBS mixture and the flow numbers were lower, indicating less resistance to rutting. The APA rut test indicated a statistically significant improvement in rutting resistance for the GTR mixture, but the 0.8 mm difference was not considered a practical difference. Bending beam fatigue results indicated the GTR mixture to be strain sensitive when compared to the SBS mixture, with the performance of the GTR mixture suffering at lower applied strain levels. Overlay test results were mixed, with the reheated specimens indicating different responses relative to the control than those produced onsite or cored; the differences may have been influenced by the reheating process.

CONCLUSIONS

- *The evaluated SBS-PE modified asphalt binder meets the specifications for a PG 76-22 binder and is expected to perform similar to a traditional SBS-modified PG 76-22 binder. Laboratory performance testing indicated that similar performance should be expected of the mixtures containing the SBS-PE modified and traditional SBS-modified binders.*

- *The evaluated GTR-modified binder does not meet the specifications for a PG 76-22 binder and instead meets the specifications for a PG 70-22 binder. Because of this discrepancy, laboratory performance test results for the GTR-modified mixture did not compare well with those for the control SBS-modified mixture, with some tests showing similar predicted performance and others indicating that the GTR-modified mixture would not perform as well as the control mixture.*

RECOMMENDATIONS

1. *VDOT's Materials Division should continue to allow the use of SBS-PE–modified binders as an alternative to SBS-modified binders provided the binders meet current purchase specifications for a PG 76-22 binder.*

2. *VCTIR and VDOT's Materials Division should initiate a project to continue to monitor the field section constructed as part of this study to evaluate the long-term performance of the evaluated mixtures and binders.* Recommendations in this study are based on initial construction experience and laboratory testing and should be validated with long-term performance results.

3. *VCTIR should further investigate the use of GTR-modified binders.* The binder used in this study did not meet the specifications for a PG 76-22 binder and thus was not representative of the binder type intended for evaluation; the relative performance was indicative of this discrepancy. Further evaluation of GTR-modified binders that meet the specifications for a PG 76-22 binder is suggested before recommendations as to the use of this modifier can be made.

BENEFITS AND IMPLEMENTATION PROSPECTS

This study evaluated the potential for alternatives to SBS copolymer to be used in PG 76-22 binders. The alternatives evaluated were an SBS-PE copolymer and GTR. The SBS-PE–modified binder met VDOT specifications for a PG 76-22 binder. In addition, the laboratory performance of the mixture produced with the SBS-PE–modified binder was similar to that of the control SBS mixture. Based on these results, VDOT's Materials Division (1) determined that SBS-PE–modified PG 76-22 binders would continue to be allowed for use provided the binders met all applicable specifications, and (2) informed the product manufacturer of this decision.

ACKNOWLEDGMENTS

The authors thank Bill Bailey, Rob Crandol, David Kaulfers, and Todd Rorrer of VDOT's Materials Division; Tommy Schinkel of VDOT's Richmond District; and Trenton Clark of the Virginia Asphalt Association for their efforts and contributions to this project. Appreciation is extended to Ron Jackson and Alex Teklu of VDOT's Fredericksburg District for their assistance in providing a trial location, sampling assistance, and data sharing. The assistance of Virginia Paving Company is also appreciated. The authors thank Troy Deeds, Donnie Dodds, Ben Earl, Ken Elliton, and Kim Snead of VCTIR and Shane Moomaw, formerly of VCTIR, for their outstanding efforts in sample collection, preparation, and testing. Appreciation is also extended to Linda Evans of VCTIR for her editorial assistance. The authors are also appreciative of the project review panel, Bill Bailey, Trenton Clark, Tommy Schinkel, and Cody Sullivan, for their assistance.

REFERENCES

American Association of Highway and Transportation Officials. *Standard Specifications for Transportation and Methods of Sampling and Testing*, 33rd Ed. Washington, DC, 2013.

Texas Department of Transportation. Test Procedure for Overlay Test. Tex-248-F. Effective Dates: January 2009–October 2013. http://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/200-F_series/archives/248-0109.pdf. Accessed August 7, 2014.

Virginia Department of Transportation. Virginia Test Methods. 2009. http://www.virginiadot.org/business/resources/bu-mat-VTMs070704.pdf. Accessed August 7, 2014.