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Evaluation of Stone-Matrix Asphalt Mixtures Containing Recycled Asphalt Shingles (RAS)

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In recent years, there has been increased interest in the use of reclaimed material in asphalt mixtures. The use of recycled asphalt shingles (RAS) has been of interest because of the high asphalt content, although this asphalt is considerably stiffer than that typically used in paving mixtures. The Virginia Department of Transportation has specifications allowing the use of post-manufacturing waste and post-consumer RAS, although use has been limited. In addition, the specifications do not provide for the use of RAS in stone-matrix asphalt (SMA). In response to producer requests for RAS use in SMA, this study investigated the use of RAS in SMA mixtures in VDOT's Salem and Staunton districts.

Mixtures were sampled during production, characterized, and evaluated using a suite of laboratory tests including dynamic modulus, flow number, rut depth, and bending beam fatigue. Test results indicated that, as expected, the inclusion of RAS appears to improve high temperature / low frequency modulus values and rutting resistance. The inclusion of RAS had mixed effects on the mixture performance in laboratory fatigue testing. Binder testing on one set of mixtures indicated that the virgin binder grade may significantly affect the degree of blending of the RAS binder. In addition, extracted binder ΔT_c values indicated that the inclusion of either RAP or RAS may have adverse impacts on cracking susceptibility. These findings should be validated with field performance and additional mixtures.

The study recommends that the Virginia Department of Transportation not change specifications to allow RAS in SMA at this time. In specific situations, the use of RAS in SMA should be approached judiciously, as when effectively located and properly designed, produced, and placed. RAS mixtures have the potential for improved rutting performance, although impacts on cracking performance must be carefully assessed.

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FINAL REPORT

EVALUATION OF STONE-MATRIX ASPHALT MIXTURES CONTAINING RECYCLED ASPHALT SHINGLES (RAS)

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ABSTRACT

In recent years, there has been increased interest in the use of reclaimed material in asphalt mixtures. The use of recycled asphalt shingles (RAS) has been of interest because of the high asphalt content, although this asphalt is considerably stiffer than that typically used in paving mixtures. The Virginia Department of Transportation has specifications allowing the use of post-manufacturing waste and post-consumer RAS, although use has been limited. In addition, the specifications do not provide for the use of RAS in stone-matrix asphalt (SMA). In response to producer requests for RAS use in SMA, this study investigated the use of RAS in SMA mixtures in VDOT's Salem and Staunton districts.

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FINAL REPORT

EVALUATION OF STONE-MATRIX ASPHALT MIXTURES CONTAINING RECYCLED ASPHALT SHINGLES

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INTRODUCTION

Highway agencies have been using increasing amounts of reclaimed and recycled materials over the past number of years, as asphalt prices have continued to rise. The primary reclaimed and recycled materials used in asphalt materials are reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS).

RAP has commonly been used in asphalt mixtures since the late 1970s. The use of RAS is more recent, having been introduced in the late 1980s and early 1990s (Button et al., 1995; Newcomb et al., 1993; Paulson et al., 1987). With the introduction of Superpave in the 1990s, recycling became less prevalent as agencies learned to deal with a new design framework that was not particularly optimized for recycled materials. However, with increasing material prices and a greater emphasis on environmental stewardship, the interest in using increased amounts of these materials has grown rapidly. Recently, a large number of studies have investigated the increasing quantities of recycled and reclaimed material in asphalt mixtures, specifically RAP (Mogawer et al., 2012; West et al., 2013) and RAS (Im et al., 2016; Williams et al., 2013).

The Virginia Department of Transportation (VDOT) specifications for asphalt paving mixtures (VDOT, 2016) allow the use of up to 30% RAP in dense-graded surface mixtures. The percentage of RAP allowed in stone-matrix asphalt (SMA) mixtures is dependent upon the binder type specified for the mixture: up to 20% when Performance Grade (PG) 70-22 binder is used and up to 15% when PG 76-22 binder is used. In addition, the specifications allow up to 5% by weight of mixture of either post-consumer waste RAS or manufacturing waste RAS in dense-graded asphalt mixtures. The percentage of binder contributed by the RAP or RAS or combination thereof must not exceed 30% of the total binder content of the mixture. Currently, VDOT specifications do not allow the use of RAS in SMA mixtures; the effect of such use was investigated through the mixtures evaluated in this study and other projects.

PURPOSE AND SCOPE

Although VDOT allows the use of both post-manufacturing waste and post-consumer RAS in dense-graded asphalt mixtures (VDOT, 2013a), VDOT has had limited experience with their use. Two asphalt producers requested permission from VDOT to use RAS in SMA, which had not been previously permitted by VDOT. This study was developed to provide support to the VDOT districts for projects involving the use of RAS through the compilation of design, construction, testing, and performance data.

The scope of the study was limited to investigating the use of RAS in SMA mixtures in VDOT's Salem and Staunton districts. The study examined the impact of RAS on SMA mixture properties and performance. Testing performed included volumetric analysis, dynamic modulus, flow number, rut, and fatigue testing of the mixtures and binder extraction and testing for one set of mixtures.

METHODS

Materials

Salem District Mixtures

Salem District mixtures (hereinafter Salem mixtures) comprised two SMA-12.5 (PG 76-22) mixtures, both containing 5% RAS and 10% RAP, and a control SMA-12.5 (PG 76-22) mixture containing 15% RAP. The two RAS mixtures were produced at two different plants using the same mix design and were placed in two different locations. The control mixture was placed at the same location as the second RAS mixture.

The first RAS mixture (RAS A) was placed as a test section at the Ironto Safety Rest Area located at Milepost 129 on I-81 North in Montgomery County, Virginia. The test section was composed of a section of roadway leading to and through the truck parking area. The test section was paved on April 12, 2012.

The second RAS mixture (RAS B) and the control mixture were placed on a section of I-77 Northbound in Carroll County between Milepost 16.1 and Milepost 18.05. The control mixture was also placed on a section of I-81 Northbound in Pulaski County, located from the Wythe County line to Milepost 88.0. The mixtures were paved in late July and early August 2012.

All loose mixture samples were collected at the plant during the collection of VDOT monitor samples. Samples were boxed and sent to the Virginia Transportation Research Council (VTRC) for analysis.

Staunton District Mixtures

Staunton District mixtures (hereinafter Staunton mixtures) comprised two versions of an SMA-12.5 (PG 70-22) mixture containing 4% RAS and a control SMA-12.5 (PG 70-22) mixture containing 10% RAP. The two RAS SMA mixtures were produced with different virgin binders; the first mixture contained PG 70-22 binder and is denoted RAS (PG 70-22), and the second contained PG 64-22 binder and is denoted RAS (PG 64-22).

The Staunton mixtures were placed on I-81 Northbound between Milepost 301.7 and Milepost 306.18 in both lanes. Five hundred tons of the RAS (PG 70-22) mixture was paved in the left lane beginning at Milepost 301.7. The remaining paving was completed with the control mixture. These mixtures were paved and sampled for this study on August 14 and 15, 2013. The RAS (PG 70-22) mixture did not meet density specifications and was removed and replaced with the RAS (PG 64-22) mixture on September 3, 2013.

Loose mixture and RAP stockpile samples were collected at the plant during the collection of VDOT monitor samples. Samples were boxed and returned to VTRC for analysis. Binder tank samples of the PG 64-22 and PG 70-22 binders were collected along with the loose mixtures. Six-inch-diameter cores were taken from the control mixture and the RAS (PG 64-22) mixture at the time of construction and randomly located in the test section.

Laboratory Evaluation

Core Air Voids

Air void contents were determined in accordance with AASHTO T 269, Percent Air Voids in Compacted Dense and Open Asphalt Mixtures (American Association of State Highway and Transportation Officials [AASHTO], 2013).

Permeability

Permeability testing was performed on cores in accordance with Virginia Test Method 120, Method of Test for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter (VDOT, 2013b).

Dynamic Modulus Test

Dynamic modulus tests were performed with a universal testing machine with a loading capacity of 25 to 100 kN 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. Five testing temperatures ranging from -10.0°C to 54.4°C and six testing frequencies ranging from 0.1 to 25 Hz were used. All tests were conducted in the uniaxial mode without confinement. Dynamic modulus was computed automatically using Industrial Process Controls, Inc. (IPC) |E*| software. The results at each temperature-frequency combination for each mixture type are reported for three replicate specimens.

Flow Number Test

The flow number test is used to evaluate the rutting resistance of asphalt mixtures. A universal testing machine with a loading capacity of 25 to 100 kN was used to conduct tests. All flow number testing was conducted on 100-mm-diameter by 150-mm-height specimens previously tested for dynamic modulus. 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. Deviator stresses of either 600 kPa or 206 kPa were used; specific values are noted with test results. 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 Franken model.

Asphalt Pavement Analyzer Rutting Analysis

Rut testing was conducted using the Asphalt Pavement Analyzer (APA) and APA-Jr. (Pavement Technologies, Inc.) in accordance with Virginia Test Method 110, Method of Test for Determining Rutting Susceptibility Using the Asphalt Pavement Analyzer – (Asphalt Lab) (VDOT, 2013b). The APA was used to test a set of three replicate beams, and the APA-Jr. was used to test a pair of replicate beams. Other than the number of replicates, there were no differences in the manner in which the testing was performed in the two devices. Laboratory-prepared beams 75 mm thick by 125 mm wide by 300 mm long were tested at a test temperature of 49°C. Sets of beams were tested simultaneously. A 120 lbf load was applied at a pressure of 120 psi for 8,000 load cycles. 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, Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending (AASHTO, 2013) using at least three replicate specimens at three strain levels (minimum total of nine beams) for each mixture type. IPC beam fatigue test equipment was used. All tests were conducted at a single temperature of 20°C. The tests were conducted in the strain-controlled mode. Applied tensile strain levels ranging from 300 to 600 microstrains were used. 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.

The endurance limit of each mixture, defined as the maximum strain that can be experienced for nearly an infinite fatigue life, was calculated in accordance with the procedure proposed by Prowell et al. (2010).

Binder Extraction and Recovery

Extraction of binder from cores was performed in accordance with AASHTO T 164, Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA), Method A (AASHTO, 2013) using n-propyl bromide as the solvent. Binder was recovered from the solvent using the Rotavap recovery procedure specified in AASHTO T 319, Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures (AASHTO, 2013).

Binder Testing

Binder grading was performed in accordance with AASHTO M 320, Performance-Graded Asphalt Binder (AASHTO, 2013). Multiple stress creep recovery testing was performed in accordance with AASHTO T 350, Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR) (AASHTO, 2013).

RESULTS AND DISCUSSION

Salem Mixtures

The Salem mixtures evaluated were SMA-12.5 (PG 76-22) mixtures. The control mixture included 15% reclaimed asphalt pavement (RAP). The RAS mix design incorporated 10% RAP and 5% RAS, resulting in a binder replacement of approximately 29%. The mix designs are summarized in Table 1. Differences in the percentages of No. 7 stone and limestone filler are due to the differences in gradation between the RAP and RAS, as RAP contains coarse aggregate whereas the RAS material is finer.

Table 1. Salem Mix Designs

Material	RAS A	RAS B	Control
No. 7 Quartzite	67%	67%	64%
No. 8 Quartzite	10%	10%	10%
Limestone filler	8%	8%	11%
Reclaimed asphalt pavement (-½ inch)	10%	10%	15%
Recycled asphalt shingles	5%	5%	-
Asphalt binder	6.80%	6.80%	6.80%

RAS = recycled asphalt shingles.

Mixture Properties

Volumetric results for the Salem mixtures are shown in Table 2. Properties were determined from loose mixture samples collected during production. Most properties were fairly consistent among the mixtures. The RAS B and control mixtures had slightly low voids in mineral aggregate (VMA) and voids in total mix (VTM) for the compacted volumetric specimens. Volumetric values compared well with VDOT quality assurance data except for the VMA results, in which case all quality assurance specimens met the specification requirements.

Table 2. Mixture Properties for Salem Mixtures

Property	RAS A	RAS B	Control	VDOT Specification (VDOT, 2013a)
Asphalt content, %	6.52	6.47	6.60	6.3% min.
Rice specific gravity, G_{mm}	2.458	2.422	2.433	
VTM, %	5.4	1.7	1.6	2.0%-4.0%
VMA, %	20.0	16.5	16.8	17.0% min.
VFA, %	73.2	89.5	90.3	
VCA_{DRC}, %	42.3	42.3	42.4	
VCA_{mix}, %	42.0	36.5	40.8	$<VCA_{DRC}$[a]
FA ratio	1.59	1.72	1.70	1.2-2.0
Mixture bulk specific gravity, G_{mb}	2.327	2.380	2.394	
Aggregate effective specific gravity, G_{se}	2.722	2.672	2.692	
Aggregate bulk specific gravity, G_{sb}	2.718	2.668	2.688	
Absorbed binder content, P_{ba}, %	0.06	0.06	0.06	
Effective binder content, P_{be}, %	6.47	6.41	6.54	
Effective film thickness, F_T, microns	9.6	8.8	9.0	
Gradation				
Sieve Size	**% Passing**			
¾ in (19.0 mm)	100.0	100.0	100.0	
½ in (12.5 mm)	83.3	81.9	83.6	
3/8 in (9.5 mm)	63.2	59.0	60.9	
No. 4 (4.75 mm)	28.2	24.5	28.7	
No. 8 (2.36 mm)	19.8	20.8	22.0	
No. 16 (1.18 mm)	16.9	18.4	18.6	
No. 30 (600 µm)	14.9	16.2	16.5	
No. 50 (300 µm)	13.4	14.7	14.3	
No. 100 (150 µm)	12.2	13.4	12.9	
No. 200 (75 µm)	10.28	11.03	11.11	

VTM = voids in total mix; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; VCA_{mix} = voids in coarse aggregate of mix; FA ratio = fines to asphalt ratio; RAP = reclaimed asphalt pavement; RAS = recycled asphalt shingles; VCA_{DRC} = voids in coarse aggregate, dry-rodded condition.

[a] See Virginia Test Method 99, The Design of Stone Matrix Asphalt (SMA) Mixtures – (Asphalt Lab) (VDOT, 2013b).

Dynamic Modulus

Dynamic modulus results for the Salem mixtures are shown in Figure 1. It can be seen that at reduced frequencies above approximately 0.1 Hz, the mixtures showed good agreement in moduli values. At reduced frequencies below approximately 0.1 Hz, the control mixture was less stiff than the RAS mixtures. Despite being produced at different plants, the two RAS mixtures had good agreement in moduli values.

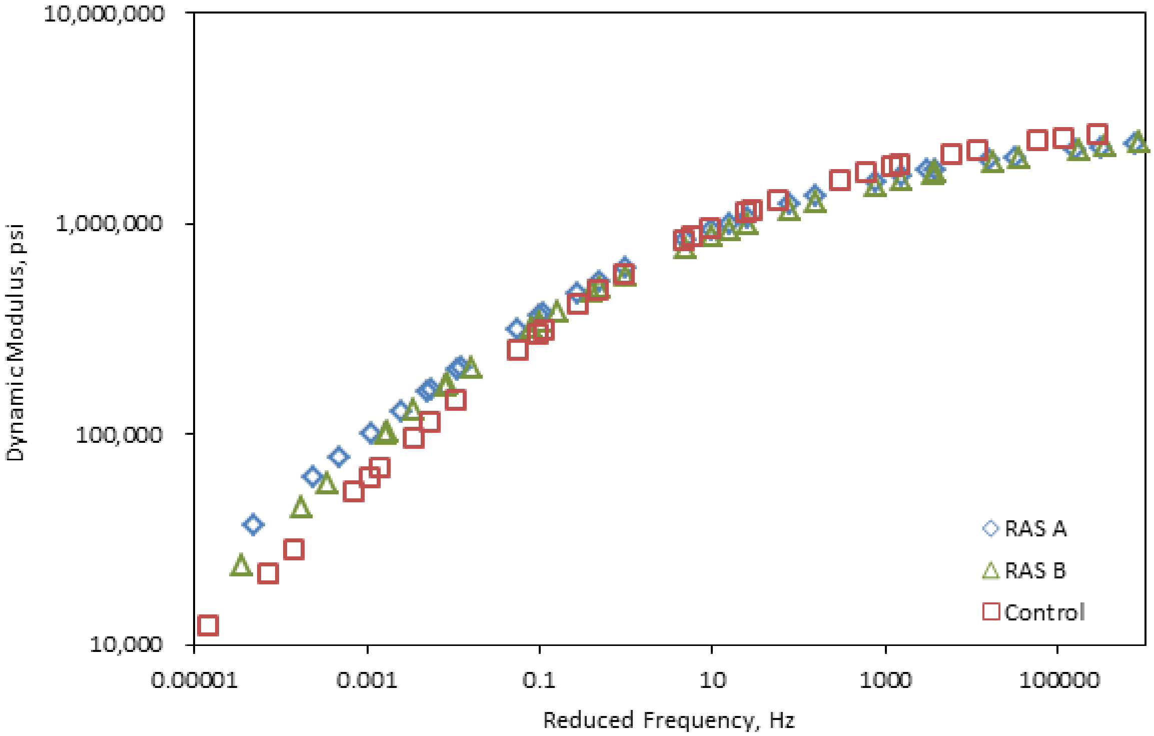
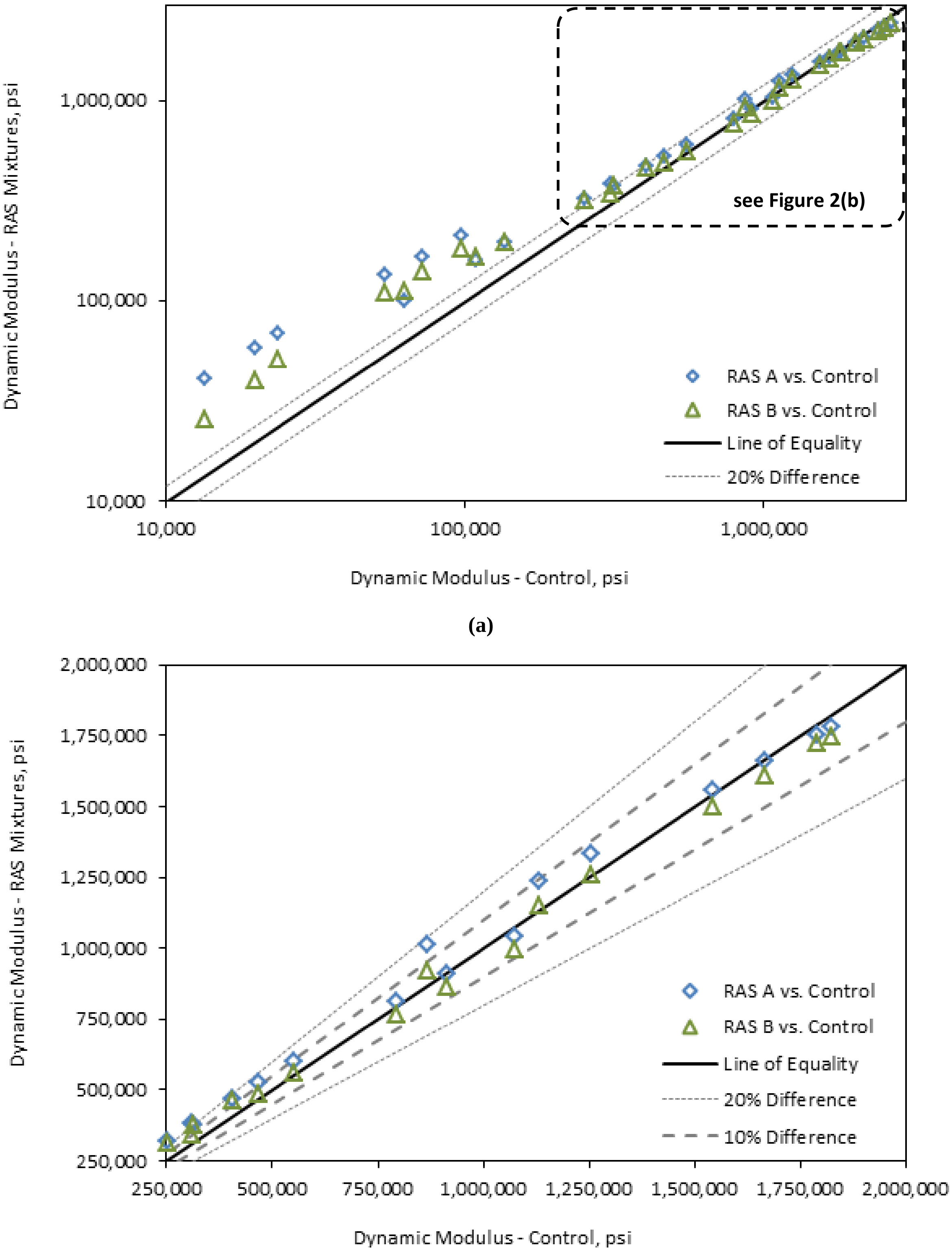


Figure 1. Dynamic Modulus Curves for Salem Mixtures. RAS = recycled asphalt shingles.

Direct comparisons of the dynamic moduli for the RAS and control mixtures are shown in Figure 2, where the dashed lines indicate 20% and 10% (Figure 2[b] only) difference from the line of equality. Figure 2(a) shows that at moduli values below about 200,000 psi, the RAS mixtures are considerably stiffer than the control mixture. These values correspond to tests performed at 54.4°C at all frequencies and the 0.1, 0.5, and 1.0 Hz tests performed at 37.8°C. This region of response indicates the material response at higher temperatures or heavy, slow load applications. Figure 2(b) provides a linear presentation of the data above 250,000 psi to distinguish the data better. This figure shows that at higher modulus values, the differences between the RAS mixtures and the control mixture become considerably less, to within 10%. These higher modulus values are seen at lower test temperatures when the mixture is responding in a more elastic manner such as experienced under fast loading.



(a)

(b)

Figure 2. Comparison of Modulus Values for Recycled Asphalt Shingle (RAS) Mixtures Versus Control Mixture

Flow Number

Figure 3 presents the flow number values and air void contents for each specimen tested. The percentages at the base of each bar indicate the specimen air void content, and I-bars indicate one standard deviation about the average flow number. All mixtures were tested with a deviator stress of 600 kPa; however, material quantity limitations prevented the testing of RAS A at 206 kPa deviator stress. For the 600 kPa testing, the air voids for all specimens were consistent and were well within the acceptable test tolerance of 7.0% ± 0.5% air voids. Both RAS mixtures performed significantly better than the control mixture in the 600 kPa flow number test. In the 206 kPa deviator stress test, the RAS B mixture still performed better than the control mixture; however, the difference between the two (as well as the difference between the 600 kPa and 206 kPa tests) was also likely influenced by the difference in air voids, as it can be seen that the air voids for the RAS B mixture were at the low end of the acceptable range for testing (7.0% ± 0.5%) whereas those for the control mixture were at the high end (with one specimen having 7.7% air voids and exceeding the acceptable tolerance).

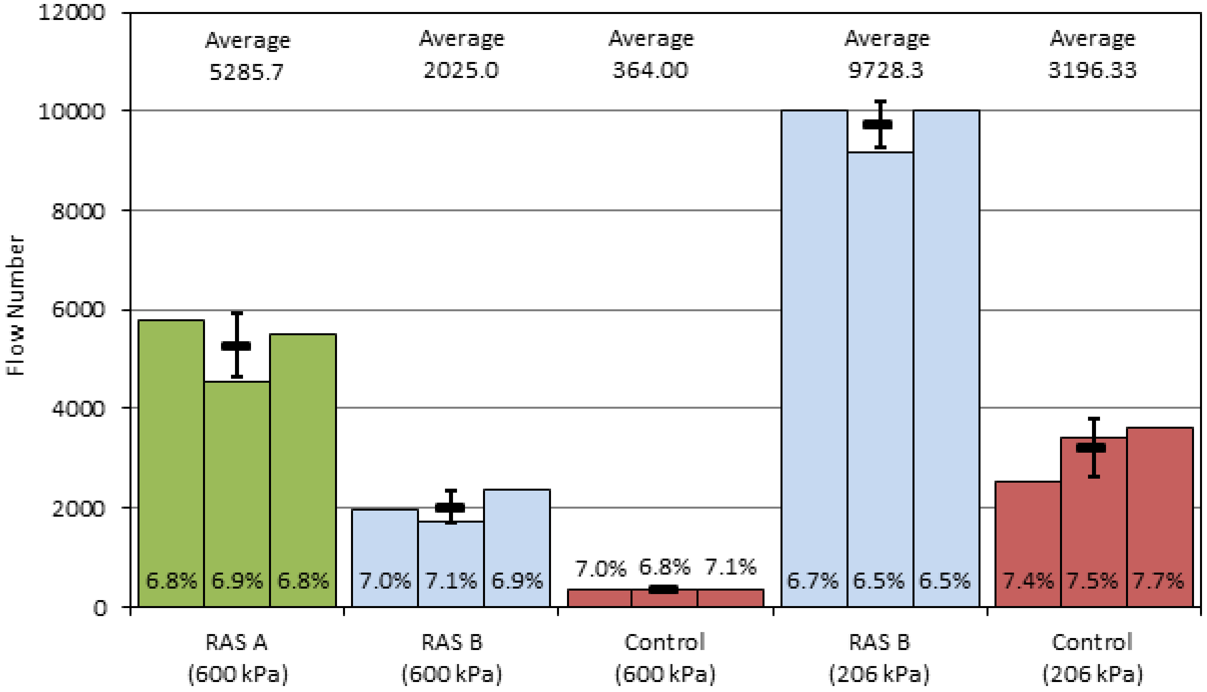


Figure 3. Flow Number Test Results for Salem Mixtures. Black bars show average values, and I-bars indicate standard deviations. Specimen air void contents are shown in percentages near the base of each column. RAS = recycled asphalt shingles.

APA Rutting Analysis

Rut testing was performed only on mixtures RAS A and RAS B because of a lack of material for the control mixture. The rut testing results are summarized in Table 3. Both mixtures rutted significantly less than the maximum VDOT criterion of 4.0 mm for SMA mixtures, despite the fact that the air void contents of all but one specimen were outside the specification requirement of 8.0% ± 0.5%. The rutting performance trend, with RAS B having a greater rut depth than RAS A, follows that shown by the flow number and indicates that RAS A should be more rut resistant than RAS B.

Table 3. APA Rutting Results for Salem Mixtures

Replicate	RAS A		RAS B	
	Air Voids, %	**Measured Rutting, mm**	**Air Voids, %**	**Measured Rutting, mm**
1	9.4	0.86	8.5	1.69
2	9.8	1.18	5.2	1.41
3	9.8	0.89	-	-
Average	9.7	0.98	6.9	1.55

APA = Asphalt Pavement Analyzer; RAS = recycled asphalt shingles.

Fatigue Analysis

Fatigue testing was performed only on the RAS B and control mixtures because of a lack of material for the RAS A mixture. Figure 4 presents the fatigue curves and their regressed ε-N equations. The slope of the curve for the control mixture is greater than that for the RAS B mixture, indicating that at applied strains above approximately 350 microstrains, the control mixture is expected to fail in fatigue sooner than the RAS mixture. However, at the lowest strain, the control mixture would be expected to perform longer.

In addition to the regression analysis of the fatigue data, the test results were investigated to determine if the initial stiffness of each mixture was particularly sensitive to applied strain level or specimen air void content. These results are shown in Figures 5 and 6.

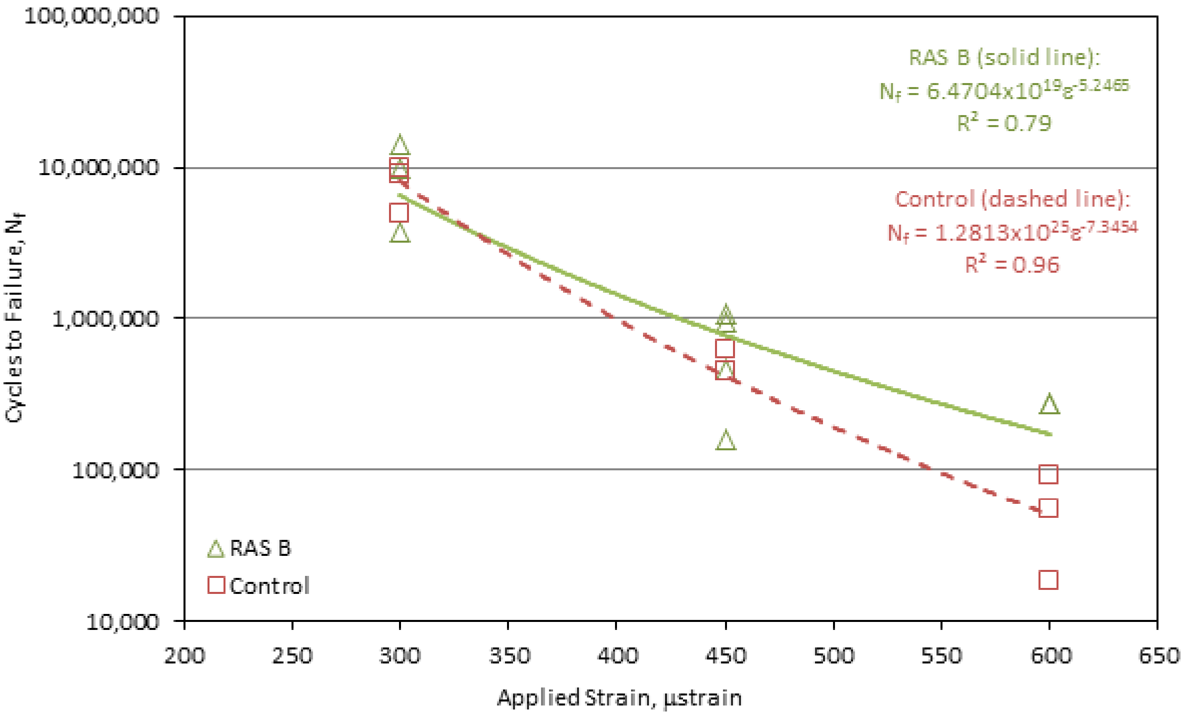


Figure 4. Fatigue Curves for Salem Mixtures. RAS = recycled asphalt shingles.

Figure 5 indicates a slight relationship between the applied strain and initial stiffness, although with R^2 values of only 0.30 and 0.52 for the RAS B and control mixtures, respectively, these relationships are not substantial. Figure 6 shows very little correlation in this study between the specimen air void contents and initial stiffness, with both data sets having R^2 values less than 0.38.

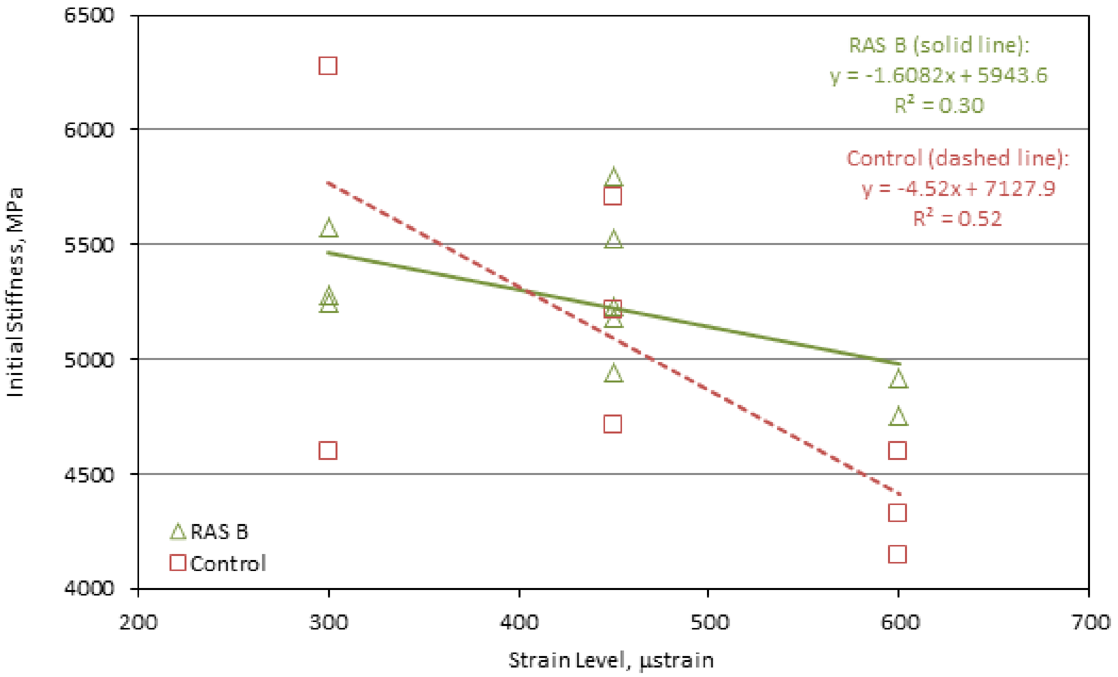


Figure 5. Applied Strain Versus Initial Stiffness for Salem Mixtures. RAS = recycled asphalt shingles.

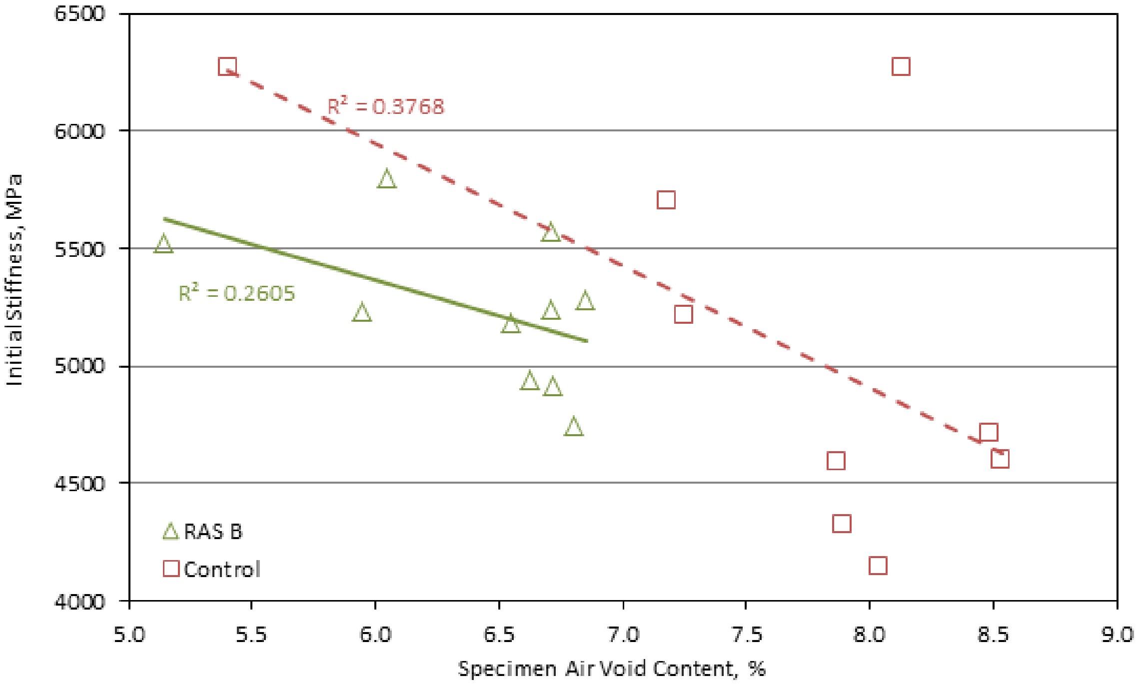


Figure 6. Specimen Air Void Content Versus Initial Stiffness for Salem Mixtures. RAS = recycled asphalt shingles.

Finally, an analysis of fatigue endurance limit was performed. Tables 4 and 5 summarize the analysis of estimated strain endurance limits for the mixtures. Results showed that the RAS B and control mixtures had endurance limits of 173 and 201 microstrains, respectively.

Overall, test results indicated that the RAS mixture should provide improved rutting resistance. Fatigue performance was mixed, as the RAS B mixture had a greater fatigue life at strains of approximately 330 microstrains and above whereas the fatigue endurance analysis indicated a higher endurance strain limit for the control mixture. This implies that the RAS B mixture may be better able to withstand higher strain events than the control mixture but may fatigue sooner under repeated low strain loading. From a practical standpoint, if one follows the assumption of bottom-up fatigue cracking, the mixtures are essentially equally likely to perform relative to fatigue if the supporting pavement structure is adequate. The topic of top-down fatigue cracking is more complex and is not adequately addressed by the testing performed during this study.

Table 4. Fatigue Analysis Summary for Salem Mixtures

RAS B					**Control**				
Cycles to Failure, N_f	**Log (N_f), x_i**	**$(x_i-\bar{x})^2$**	**Applied Strain, ε**	**Log (ε)**	**Cycles to Failure, N_f**	**Log (N_f), x_i**	**$(x_i-\bar{x})^2$**	**Applied Strain, ε**	**Log (ε)**
3,742,180	6.5731	0.3625	300	2.4771	4,866,000	6.6872	0.8894	300	2.4771
10,000,000	7.0000	1.0587	300	2.4771	8,908,620	6.9498	1.4537	300	2.4771
14,248,000	7.1538	1.3988	300	2.4771	10,000,000	7.0000	1.5773	300	2.4771
156,560	5.1947	0.6027	450	2.6532	442,720	5.6461	0.0096	450	2.6532
170,820	5.2325	0.5454	450	2.6532	452,050	5.6552	0.0079	450	2.6532
465,060	5.6675	0.0921	450	2.6532	625,390	5.7962	0.0027	450	2.6532
965,540	5.9848	0.0002	450	2.6532	*4,100,000*	-	-	*450*	-
1,083,490	6.0348	0.0041	450	2.6532	18,620	4.2700	2.1731	600	2.7782
95,900	-	-	*600*	-	54,140	4.7335	1.0213	600	2.7782
271,830	5.4343	0.2881	600	2.7782	91,000	4.9590	0.6163	600	2.7782
272,260	5.4350	0.2874	600	2.7782					
	$\bar{x}$ = 5.9710	Σ = 4.6400				$\bar{x}$ = 5.7441	Σ = 7.7512		

Values in italics were found to be outlier data. RAS = recycled asphalt shingles.

Table 5. Calculation of Predicted Endurance Limit for Salem Mixtures

Variable	**RAS B**	**Control**
Intercept	3.4355	3.3259
Slope	-0.1357	-0.1180
R^2	0.7331	0.8215
Standard Error	0.0623	0.0527
Log (Estimated Strain at 50,000,000 cycles), y_0	2.3909	2.4286
Number of Specimens, n	10	9
Value of *t* distribution, $t_{n-2,\,\alpha=0.05}$	1.8595	1.8946
Standard Error of Regression, s	0.062337881	0.052676257
Sample Corrected Sum of Squares, S_{xx}	4.6400	7.7512
Log (50,000,000 Cycles), x_0	7.6990	7.6990
Mean Fatigue Life Results, $\bar{x}$	5.9710	5.7441
One-sided Lower 95% Prediction Limit	2.2379	2.3022
Predicted Endurance Strain, µstrain	**173**	**201**

RAS = recycled asphalt shingles.

Staunton Mixtures

The Staunton mixtures were specified as SMA-12.5 (PG 70-22) mixtures. Initially, only two mixtures were planned: one control SMA mixture containing 10% RAP, and one SMA mixture containing 4% RAS. Both mixtures were produced using PG 70-22 binder. Unfortunately, the RAS SMA mixture produced using PG 70-22 binder (denoted RAS [PG 70-22]) had issues in the field and the density was below acceptable limits. The mixture was removed and replaced with a mixture with the same mix design using PG 64-22 binder, denoted RAS (PG 64-22). The mix designs are summarized in Table 6.

Table 6. Staunton Mix Designs

Material	RAS (PG 64-22)	RAS (PG 70-22)	Control (PG 70-22)
No. 78 Diabase (Traprock)	73%	73%	69%
No. 8 Diabase (Traprock)	7%	7%	8%
Limestone manufactured sand	6%	6%	5%
Limestone filler	10%	10%	8%
Recycled asphalt pavement (-½ in)	-	-	10%
Recycled asphalt shingles	4%	4%	-
Asphalt binder	6.4%	6.4%	6.3%

RAS = recycled asphalt shingles.

Mixture Properties

Mixture properties for the Staunton mixtures (Table 7) were determined from loose mixture samples collected during production. Asphalt contents varied somewhat among the mixtures, and void contents were low although acceptable. Volumetric values compared reasonably well with VDOT quality assurance data except for the RAS mixture binder contents and RAS (PG 64-22) and control VCA_{MIX} values, both of which were higher than the quality assurance results.

Core Air Voids and Permeability

Cores were collected during construction, and air voids and permeability were determined. No cores were collected from the RAS (PG 70-22) mixture because of lane closure time constraints. Only three cores were collected for the RAS (PG 64-22) mixture because of lane closure time constraints. Void contents ranged from approximately 4.0% to 8.0%, as shown in Figure 7.

Table 7. Mixture Properties for Staunton Mixtures

Property	RAS (PG 64-22)	RAS (PG 70-22)	Control (PG 70-22)	VDOT Specification (VDOT, 2013a)
Asphalt content, %	6.49	6.92	6.28	6.3% minimum
Rice specific gravity, G_{mm}	2.607	2.604	2.614	
VTM, %	2.7	3.3	3.2	2.0%-4.0%
VMA, %	17.1	18.7	18.1	17.0% minimum
VFA, %	84.4	82.3	82.2	
VCA_{DRC}, %	41.0	41.0	41.1	
VCA_{MIX}, %	41.9	40.2	41.9	$< VCA_{DRC}$[a]
FA ratio	2.20	1.67	2.03	1.2-2.0
Mixture bulk specific gravity, G_{mb}	2.538	2.517	2.529	
Aggregate effective specific gravity, G_{se}	2.917	2.938	2.914	
Aggregate bulk specific gravity, G_{sb}	2.863	2.884	2.894	
Absorbed binder content, P_{ba}, %	0.67	0.66	0.24	
Effective binder content, P_{be}, %	5.86	6.31	6.05	
Effective film thickness, F_T, microns	7.0	9.2	7.6	
Gradation				
Sieve Size	**Percent Passing**			
¾ in (19.0 mm)	100	100	100	
½ in (12.5 mm)	91.6	89.2	90.4	
3/8 in (9.5 mm)	57.5	55.6	57.4	
No. 4 (4.75 mm)	29.3	26.3	28.2	
No. 8 (2.36 mm)	23.8	19.8	22.9	
No. 16 (1.18 mm)	20.1	16.4	19.3	
No. 30 (600 µm)	17.7	14.6	16.9	
No. 50 (300 µm)	16.5	13.5	15.7	
No. 100 (150 µm)	15.4	12.5	14.5	
No. 200 (75 µm)	12.9	10.5	12.3	

VTM = voids in total mix; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; VCA_{DRC} = voids in coarse aggregate, dry-rodded condition; VCA_{MIX} = voids in coarse aggregate of mix; FA ratio = fines to asphalt ratio; RAP = reclaimed asphalt pavement; RAS = recycled asphalt shingles.

[a] See Virginia Test Method 99 (VDOT, 2013b).

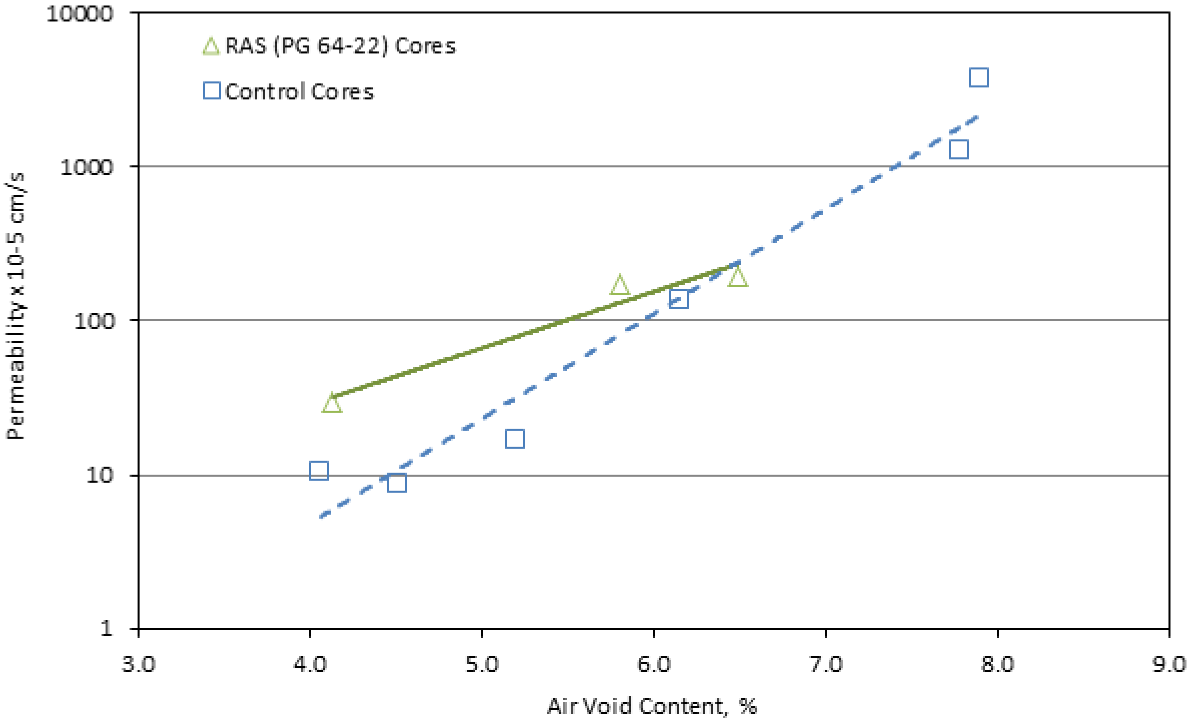


Figure 7. Permeability Results for Staunton Mixtures. RAS = recycled asphalt shingles.

Dynamic Modulus Test

Dynamic modulus results for the Staunton mixtures are shown in Figure 8. The RAS mixtures show good agreement in moduli values across all frequencies. This is surprising considering the difference in the virgin binder grades used in the RAS mixtures. At reduced frequencies below approximately 0.5Hz, the control mixture is stiffer than the RAS mixtures, whereas at frequencies of 10Hz and above, the control mixture is softer than the RAS mixtures. Interestingly, this is the opposite trend from that seen with the Salem mixtures, although the cause is not clear.

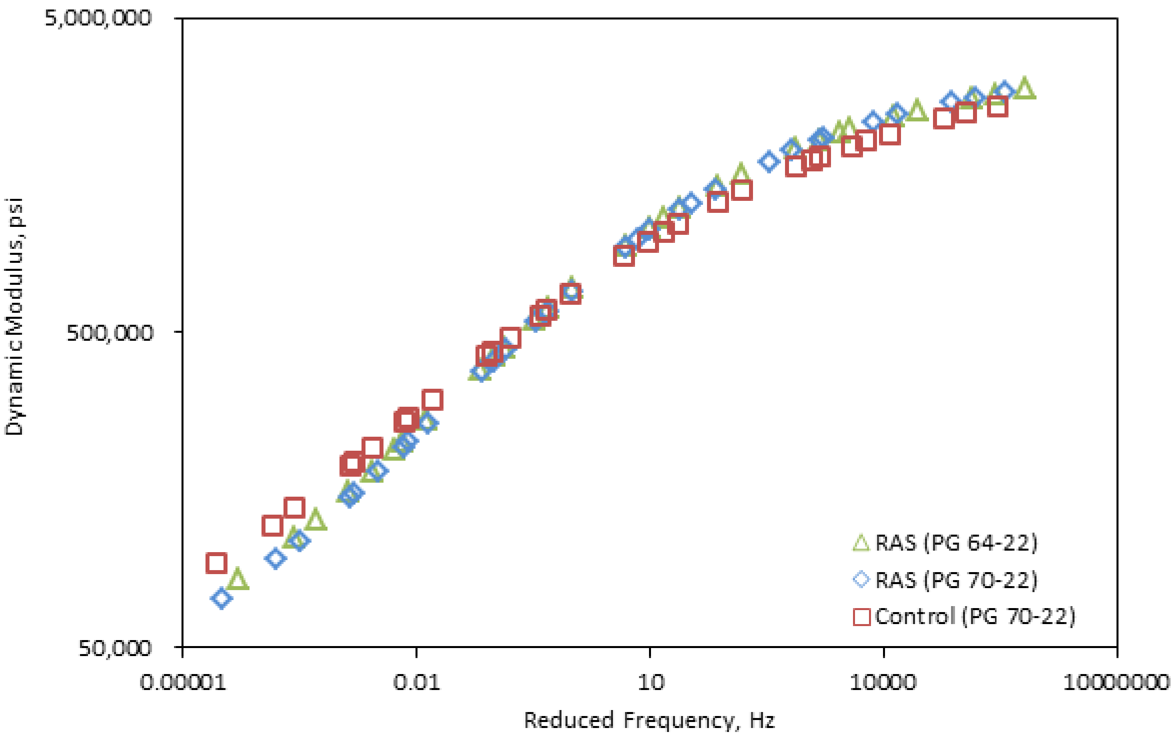


Figure 8. Dynamic Modulus Curves for Staunton Mixtures. RAS = recycled asphalt shingles.

Figure 9 shows the comparison of dynamic moduli between the control and RAS mixtures at each test temperature and frequency. The dashed lines indicate 20% and 10% (Figure 9[b] only) differences from the line of equality. Figure 9(a) shows that at moduli values of less than 600,000 psi, the control mixture was stiffer than the RAS mixtures. The RAS (PG 64-22) mixture is most similar to the control mixture in this range of values, although even the difference between the control and RAS (PG 70-22) mixtures is generally less than 20%. Figure 9(b) is a linear presentation of the data above 750,000 psi to show better the differences in the data. This chart shows that at the lower test temperatures associated with these higher moduli value, both RAS mixtures are stiffer than the control mixture. In a trend reversal from the lower stiffness range in Figure 9(a), the RAS (PG 70-22) mixture is shown to have results closer to those of the control mixture; again, most of the RAS mixture moduli were within 20% of that of the control mixture.

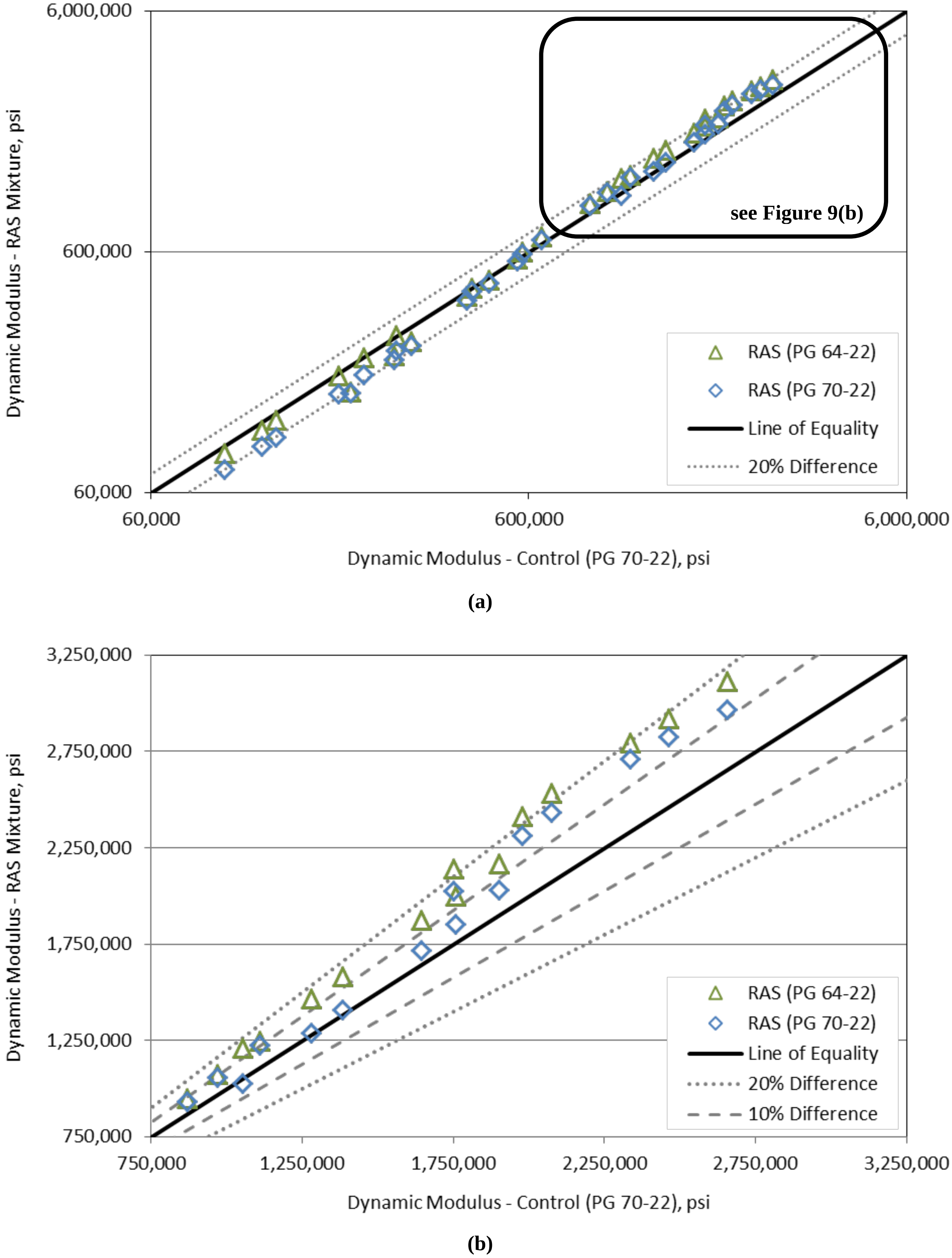


Figure 9. Comparison of Modulus Values for Recycled Asphalt Shingles (RAS) Mixtures Versus Control Mixture

Flow Test

Figure 10 presents the flow number values and air void contents for each specimen tested. The percentages at the base of each bar indicate the specimen air void content, and I-bars indicate one standard deviation about the average flow number. All mixtures were tested with a deviator stress of 600 kPa. The RAS (PG 64-22) and control (PG 70-22) mixtures are shown to have statistically similar flow numbers, at approximately 2,000 cycles. The RAS (PG 70-22) mixture had a significantly lower flow number, averaging 352 cycles. This is surprising, as it would be expected that the combination of a PG 70-22 binder and RAS would result in a very rut-resistant mixture. The RAS (PG 70-22) mixture contained a higher asphalt content than the other two mixtures (6.9% versus 6.5% and 6.3% for the RAS (PG 64-22) and control mixtures, respectively); however, this would not be expected to be a significant enough difference to affect flow number results to the degree seen, especially considering the similarities in the dynamic modulus results. However, the gradations of the RAS (PG 70-22) mixture contained fewer fines than the other two mixtures, resulting in a calculated film thickness of 1.6 to 2.2 microns thicker than the control (PG 70-22) and RAS (PG 64-22) mixtures, respectively, which likely influenced the flow number results.

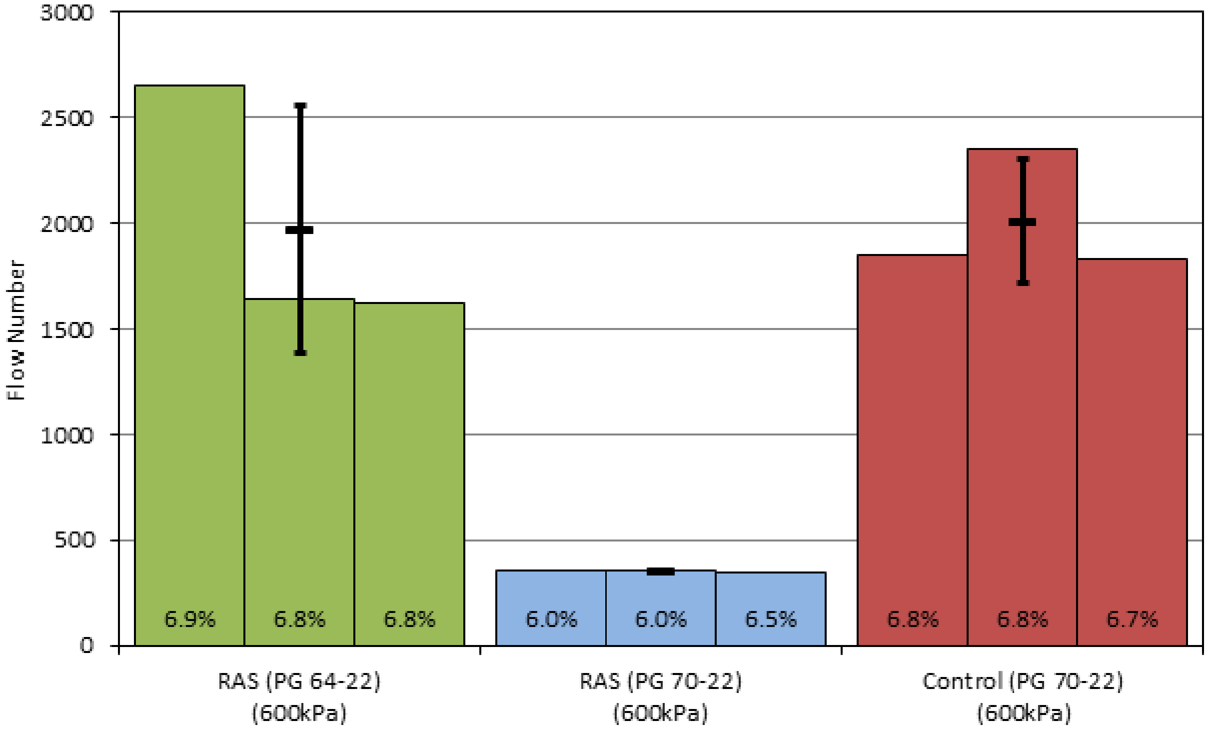


Figure 10. Flow Number Results for Staunton Mixtures. Black bars show average values, and I-bars indicate standard deviation. Specimen air void contents are shown at the base of each column. RAS = recycled asphalt shingles.

APA Rutting Analysis

Rutting analysis was performed using the APA; the results are shown in Table 8. All mixtures rutted significantly less than the maximum VDOT criterion of 4.0 mm for SMA mixtures. It should be noted that the specimen void contents for all RAS (PG 70-22) specimens and two control (PG 70-22) specimens were less than the specification requirements of 8.0% ± 0.5%. The APA rutting results indicate that all mixtures should perform well in rutting, as all are statistically equivalent; this is in contrast to the flow number test results for the RAS (PG 70-22) mixture.

Table 8. APA Rutting Results for Staunton Mixtures

	RAS (PG 64-22)		RAS (PG 70-22)		Control (PG 70-22)	
Replicate	**Air Voids, %**	**Measured Rutting, mm**	**Air Voids, %**	**Measured Rutting, mm**	**Air Voids, %**	**Measured Rutting, mm**
1	7.7	1.67	7.1	1.19	7.8	1.29
2	8.0	1.23	7.0	1.16	7.3	1.01
3	7.9	1.84	7.2	1.41	7.0	1.21
Average	7.9	1.58	7.1	1.25	7.4	1.17
Std. Dev.		0.31		0.14		0.14

APA = asphalt pavement analyzer; RAS = recycled asphalt shingles.

Fatigue Analysis

Fatigue testing was performed on all Staunton mixtures. Figure 11 shows the fatigue curves and their regressed ε-N_f equations. The curves for the control and RAS (PG 70-22) mixtures are visually similar. However, at the strains tested, the RAS (PG 64-22) mixture is offset below the other two mixtures as applied, indicating a reduced life with increasing strain in laboratory fatigue testing. Overall, the three mixtures show a converging trend as the applied strain decreases, leading to similar endurance fatigue limits.

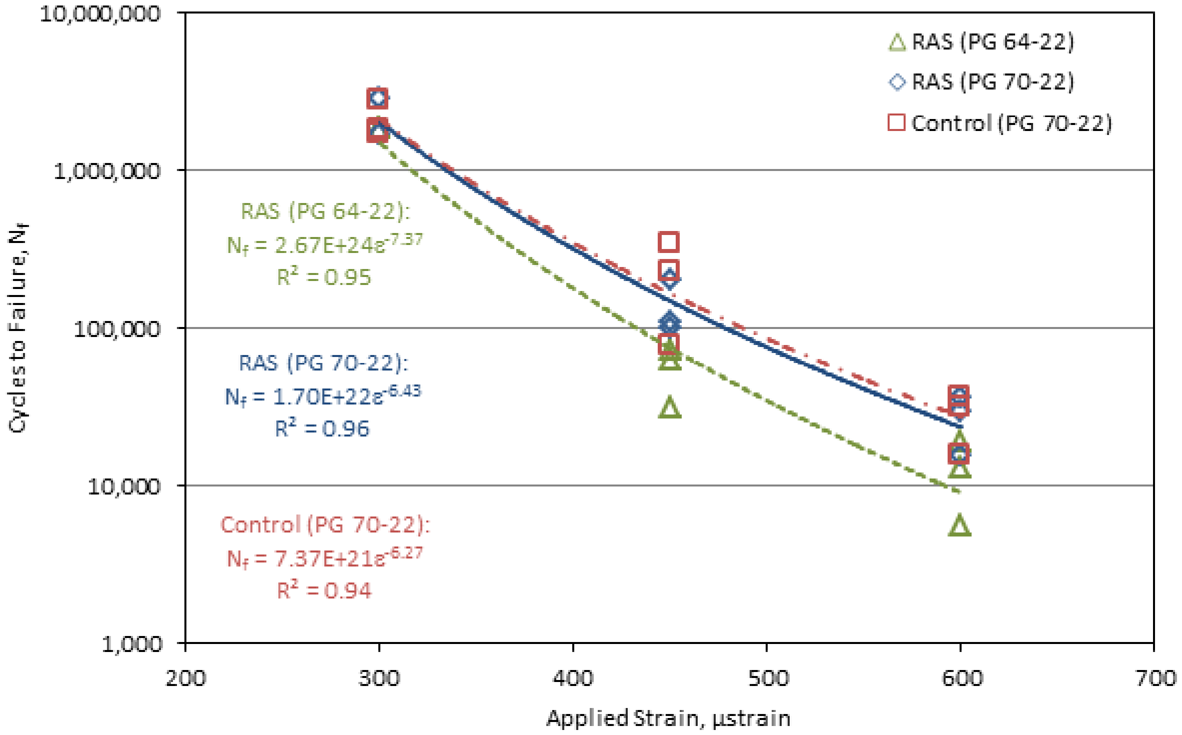


Figure 11. Strain Versus Cycles to Failure for Staunton Mixtures. RAS = recycled asphalt shingles.

Figures 12 and 13 present the influence of applied strain and specimen air void content on initial stiffness. Figure 12 indicates that initial stiffness was primarily mixture dependent, although some relationship is observed with applied strain, particularly for the RAS (PG 70-22) mixture. Initial stiffness showed no statistically significant correlations with air voids in Figure 13, likely because of the limited air void ranges seen in the test specimens.

An analysis of the fatigue endurance limit of each mixture was also performed; the results are summarized in Tables 9 and 10. Table 10 indicates that the control mixture had an endurance limit of 154 microstrains, whereas both RAS mixtures had endurance limits of 157 microstrains. This indicates that all three mixtures would be expected to perform similarly in low strain fatigue; however, the laboratory fatigue results indicated that at higher fatigue strains, the RAS (PG 64-22) mixture is likely to show poorer performance than the control and RAS (PG 70-22) mixtures. As with the Salem mixtures, if bottom-up fatigue cracking is of concern, the adequacy of the supporting pavement structure will be the primary factor in the development of fatigue distress.

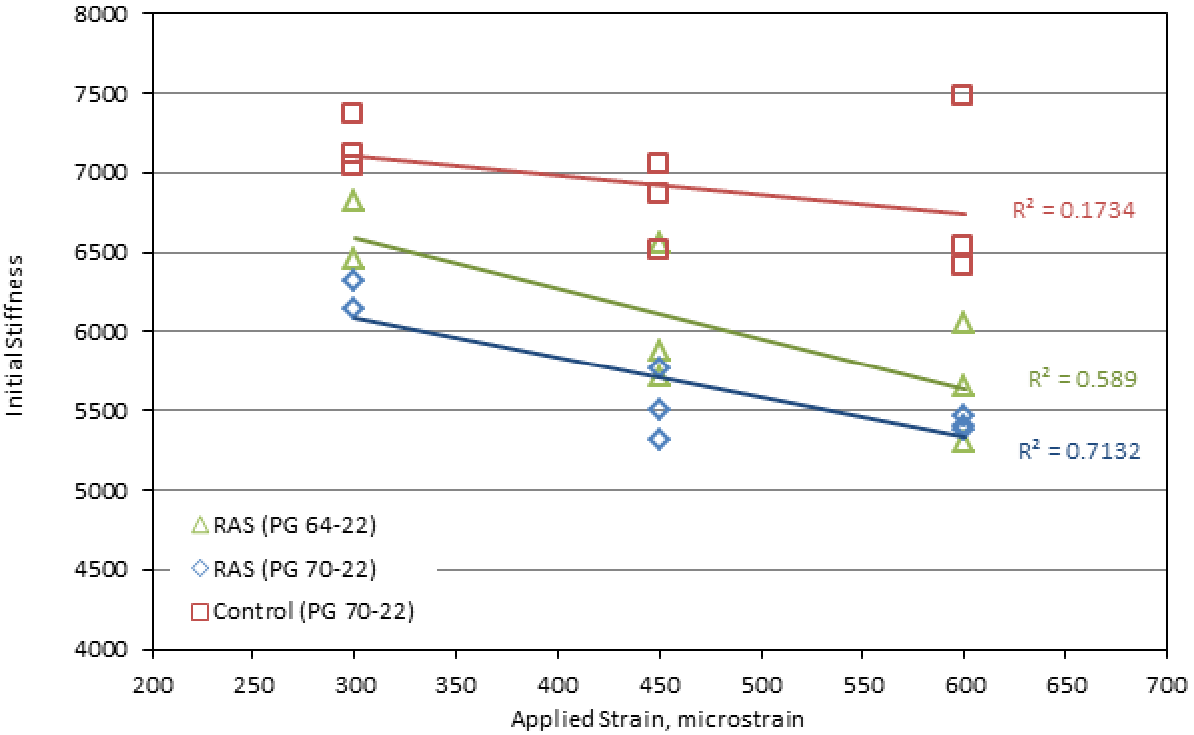


Figure 12. Initial Stiffness Versus Strain for Staunton Mixtures. RAS = recycled asphalt shingles.

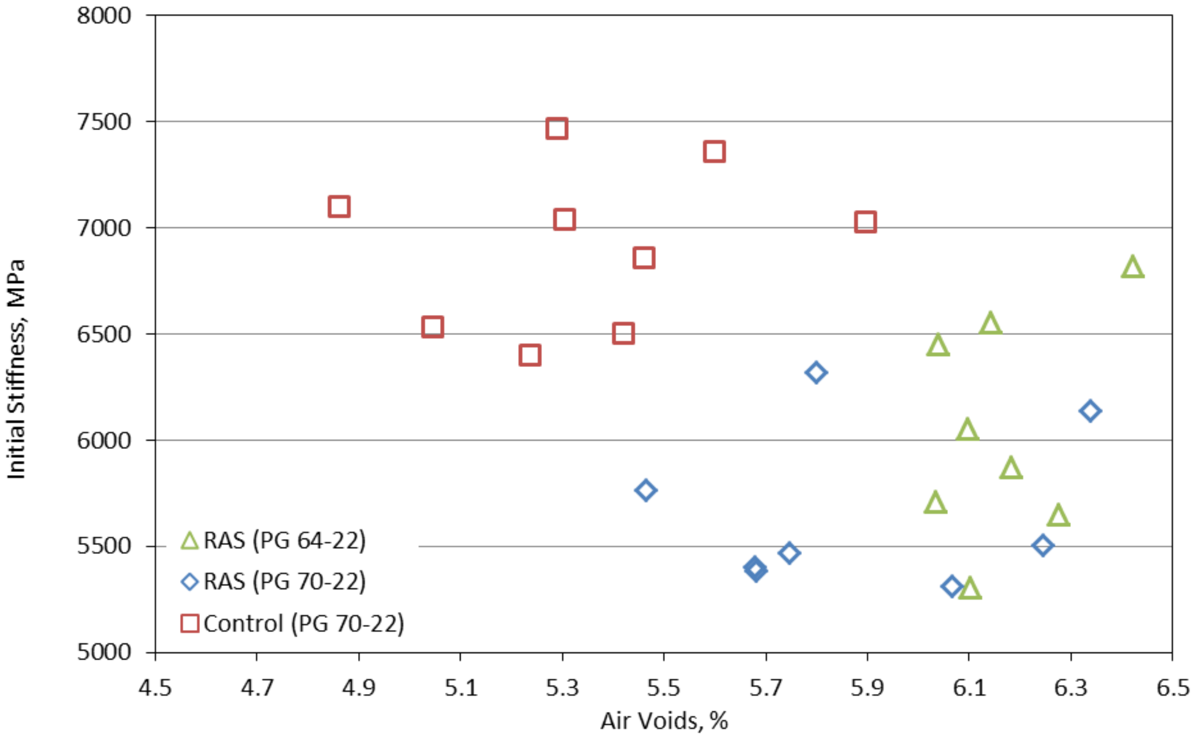


Figure 13. Initial Stiffness Versus Air Voids for Staunton Mixtures. RAS = recycled asphalt shingles.

Table 9. Fatigue Analysis Summary for Staunton Mixtures

RAS (PG 64-22)					RAS (PG 70-22)					RAP Control				
Cycles to Failure, N_f	**Log (N_f), x_i**	**$(x_i-\bar{x})^2$**	**Applied Strain, ε**	**Log (ε)**	**Cycles to Failure, N_f**	**Log (N_f), x_i**	**$(x_i-\bar{x})^2$**	**Applied Strain, ε**	**Log (ε)**	**Cycles to Failure, N_f**	**Log (N_f), x_i**	**$(x_i-\bar{x})^2$**	**Applied Strain, ε**	**Log (ε)**
1,853,660	6.2680	1.9991	300	2.4771	2,855,370	6.4557	1.6927	300	2.4771	1,709,460	6.2329	0.8213	300	2.4771
1,866,200	6.2710	2.0073	300	2.4771	1,687,530	6.2273	1.1505	300	2.4771	1,776,240	6.2495	0.8517	300	2.4771
1,140,350	-	-	*300*	-	100,400	5.0017	0.0234	450	2.6532	2,756,550	6.4404	1.2405	300	2.4771
31,490	4.4982	0.1267	450	2.6532	109,890	5.0410	0.0129	450	2.6532	77,970	4.8919	0.1889	450	2.6532
63,500	4.8028	0.0026	450	2.6532	199,450	5.2998	28.089	450	2.6532	226,520	5.3551	0.0008	450	2.6532
71,980	4.8572	0.0000	450	2.6532	15,310	4.1850	0.9402	600	2.7782	342,300	5.5344	0.0432	450	2.6532
5,590	3.7474	1.2249	600	2.7782	29,550	4.4706	0.4680	600	2.7782	15,290	4.1844	1.3046	600	2.7782
13,030	4.1149	0.5464	600	2.7782	35,980	4.5561	0.3583	600	2.7782	31,600	4.4997	0.6838	600	2.7782
18,780	4.2737	0.3369	600	2.7782						35,580	4.5512	0.6012	600	2.7782
	$\bar{x} = 4.8541$	$\Sigma = 6.2440$				$\bar{x} = 5.1546$	$\Sigma = 4.6671$				$\bar{x} = 5.3266$	$\Sigma = 5.7361$		

Values in italics were found to be outlier data. RAS = recycled asphalt shingles.

Table 10. Calculation of Fatigue Endurance Limit for Staunton Mixtures

Variable	**RAS (PG 64-22)**	**RAS (PG 70-22)**	**Control (PG 70-22)**
Intercept	3.2792	3.4285	3.4358
Slope	-0.1284	-0.1499	-0.1501
R Square	0.9460	0.9634	0.9420
Standard Error	0.0313	0.0257	0.0337
Log (Estimated Strain at 50,000,000 cycles), y_0	2.2908	2.2748	2.2800
Number of Specimens, n	8	8	9
Value of *t* distribution, $t_{n-2,\ \alpha=0.05}$	1.9432	1.9432	1.8946
Standard Error of Regression, s	0.0313	0.0257	0.0337
Sample Corrected Sum of Squares, S_{xx}	6.2440	4.6671	5.7361
Log (50,000,000 Cycles), x_0	7.6990	7.6990	7.6990
Mean Fatigue Life Results, $\bar{x}$	4.8541	5.1546	5.3266
One-sided Lower 95% Prediction Limit	2.1962	2.1955	2.1876
Predicted Endurance Strain, µstrain	**157**	**157**	**154**

RAS = recycled asphalt shingles.

Binder Testing

Performance grading was carried out on tank samples from each day of production, as well as on recovered binder from each mixture. In addition, the RAP stockpile used to produce the control mixture was sampled and binder was extracted and recovered for grading. Table 11 summarizes the grading results for all binders. The RAP stockpile binder was fairly stiff on both the high and low temperature grades as a PG 82-10 (Continuous Grade [CG] 85.9-15.3) binder and affected the control mixture accordingly, which graded as a PG 82-16 (CG 86.5-18.7) binder although the virgin binder was a PG 70-22 (CG 73.1-24.5). The RAS mixtures were stiffened by the presence of the RAS binder, although the RAS (PG 64-22) mixture was more affected than the RAS (PG 70-22) mixture. This may have been due to increased blending of the RAS binder with the softer PG 64-22 virgin binder in the RAS (PG 64-22) mixture.

A detailed investigation of Table 11 reveals some interesting findings. Rolling thin-film oven (RTFO) aging did not have a strong impact on the virgin binders, the failure temperatures for which increased 1.5°C or less. It appeared that the virgin binder grade substantially affected the blending of the RAS binder; the binder extracted from the RAS (PG 70-22) mixture showed considerably less impact because of the presence of RAS than did the binder extracted from the RAS (PG 64-22) mixture. This is not expected, as it is typically assumed that the extraction and recovery process provides additional blending over that experienced during production and construction. The change in RTFO and pressure aging vessel (PAV) failure temperatures was substantial for the RAS (PG 64-22) mixture; the RAS (PG 70-22) mixture was affected much less. In addition, although the stiffness failure temperature for both mixtures increased approximately 1.5°C, the RAS (PG 64-22) mixture saw a substantial increase in the m-value failure temperature of 5.2°C, indicating that the RAS interaction caused an important change in the relaxation capacity of the binder.

With regard to the control mixture data, the RAP content had a considerable impact at all test points: comparing the RTFO and PAV failure temperatures between the virgin PG 70-22 binder and the extracted control mix binder indicated increases of 11.9°C and 2.2°C, respectively, and although the stiffness failure temperature decreased slightly, the m-value failure temperature rose from -24.5°C for the virgin binder to -18.7°C for the extracted and recovered binder. The changes in the low temperature failure temperatures are concerning, as recent work has indicated that increasing differences between the stiffness and m-value failure temperatures, called ΔT_c, are indicative of a loss of ductility in mixtures that may lead to increased cracking susceptibility (Anderson et al., 2011). An initial suggestion of the value at which ΔT_c may become of concern is $\Delta T_c = 2.5$°C; Table 11 indicates that this value has been exceeded for recovered binders from every mixture as well as the recovered binder from the RAP stockpile. As the work investigating ΔT_c and cracking potential has not conclusively established acceptable ranges for the criteria, this should be taken as a signal that further efforts are still needed to determine the performance impacts of RAP and RAS. Interestingly, the binder and fatigue testing results were analogous, as both show similar performance indications for the RAS and control mixtures.

Table 11. Binder Grading Results for Tank Samples and Recovered Binders for Staunton Mixtures

Property	PG 64-22 Tank	PG 70-22 Tank	RAS (PG 64-22)	RAS (PG 70-22)	Control (PG 70-22)	RAP Stockpile
Rotational Viscosity, AASHTO T 316						
Viscosity, Pa sec, 135°C	0.485	0.723	-	-	-	-
Viscosity, Pa sec, 165°C	0.130	0.183	-	-	-	-
Dynamic Shear, AASHTO T 315, 10 rad/sec, specification: G*/sin delta >1.00 kPa						
Original G*/sin delta, kPa, 64°C	1.777	-	-	-	-	-
Original G*/sin delta, kPa, 70°C	0.8767	1.434	-	-	-	-
Original G*/sin delta, kPa, 76°C	-	0.7119	-	-	-	-
Original G*, kPa, 64°C	1.773	-	-	-	-	-
Original G*, kPa, 70°C	0.826	1.429	-	-	-	-
Original G*, kPa, 76°C	-	0.7107	-	-	-	-
Original phase angle, °, 64°C	86.28	-	-	-	-	-
Original phase angle, °, 70°C	87.62	85.17	-	-	-	-
Original phase angle, °, 76°C	-	86.73	-	-	-	-
Original failure temperature	*68.51*	*73.09*	-	-	-	-
Dynamic Shear, AASHTO T 315, 10 rad/sec, specification: G*/sin delta > 2.20 kPa						
RTFO G*/sin delta, kPa, 64°C	4.322	-	-	-	-	-
RTFO G*/sin delta, kPa, 70°C	1.956	3.853	4.456	-	-	-
RTFO G*/sin delta, kPa, 76°C	-	1.861	3.590	2.718	6.766	6.942
RTFO G*/sin delta, kPa, 82°C	-	-	1.770	1.363	3.538	3.397
RTFO G*/sin delta, kPa, 88°C	-	-	-	-	1.879	1.718
RTFO G*, kPa, 64°C	4.284	-	-	-	-	-
RTFO G*, kPa, 70°C	1.947	3.797	7.211	-	-	-
RTFO G*, kPa, 76°C	-	1.846	3.515	2.684	6.468	6.798
RTFO G*, kPa, 82°C	-	-	1.748	1.354	3.432	3.354
RTFO G*, kPa, 88°C	-	-	-	-	1.843	1.706
RTFO phase angle, °, 64°C	82.38	-	-	-	-	-
RTFO phase angle, °, 70°C	54.53	80.2	75.29	-	-	-
RTFO phase angle, °, 76°C	-	82.64	78.21	80.93	72.95	78.32
RTFO phase angle, °, 82°C	-	-	80.86	83.19	75.99	80.85
RTFO phase angle, °, 88°C	-	-	-	-	78.74	83.06
RTFO failure temperature	*69.1*	*74.6*	*80.2*	*77.8*	*86.5*	*85.9*
Dynamic Shear, AASHTO T 315, 10 rad/sec, specification: G* sin delta <5000kPa						
PAV G* sin delta, kPa, 22.0°C	5132	5403	-	5289	6619	-
PAV G* sin delta, kPa, 25.0°C	3501	3806	6042	3855	4988	-
PAV G* sin delta, kPa, 28.0°C	-	-	4460	2743	3700	-
PAV G* sin delta, kPa, 31.0°C	-	-	-	-	-	5765

Property	**PG 64-22 Tank**	**PG 70-22 Tank**	**RAS (PG 64-22)**	**RAS (PG 70-22)**	**Control (PG 70-22)**	**RAP Stockpile**
PAV G* sin delta, kPa, 34.0°C	-	-	-	-	-	4294
PAV G*, kPa, 22.0°C	7360	8135	-	8177	11760	-
PAV G*, kPa, 25.0°C	4765	5457	10190	5681	8443	-
PAV G*, kPa, 28.0°C	-	-	7134	3864	5969	-
PAV G*, kPa, 31.0°C	-	-	-	-	-	8808
PAV G*, kPa, 34.0°C	-	-	-	-	-	6281
PAV phase angle, °, 22.0°C	44.21	41.62	-	40.3	34.25	-
PAV phase angle, °, 25.0°C	47.29	44.22	36.36	42.73	36.22	-
PAV phase angle, °, 28.0°C	-	-	38.69	45.22	38.3	-
PAV phase angle, °, 31.0°C	-	-	-	-	-	40.88
PAV phase angle, °, 34.0°C	-	-	-	-	-	43.13
PAV failure temperature	*22.2*	*22.7*	*26.9*	*22.6*	*24.9*	*32.5*
Creep Stiffness, AASHTO T 313, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300						
Stiffness, MPa, 0°C	-	-	-	-	-	102
M-value, 0°C	-	-	-	-	-	0.341
Stiffness, MPa, -6°C	-	-	110	-	85	217
M-value, -6°C	-	-	0.315	-	0.312	0.288
Stiffness, MPa, -12ºC	206	170	195	161	165	381
M-value, -12°C	0.316	0.32	0.282	0.316	0.285	0.248
Stiffness, MPa, -18°C	443	347	-	304	-	-
M-value, -18°C	0.265	0.272	-	0.256	-	-
Stiffness failure temperature, °C	*-24.9*	*-26.8*	*-26.5*	*-27.9*	*-27.4*	*-19.8*
M-value failure temperature, °C	*-23.9*	*-24.5*	*-18.7*	*-23.6*	*-18.7*	*-15.3*
ΔT_c, *°C*	*1.0*	*2.3*	*7.8*	*4.3*	*8.7*	*4.5*
Performance Grade	**64-22**	**70-22**	**76-16**	**76-22**	**82-16**	**82-10**
Continuous Grade	**68.5-23.9**	**73.1-24.5**	**80.2-18.7**	**77.8-23.6**	**86.5-18.7**	**85.9-15.3**

RAS = recycled asphalt shingles.

Table 12 presents the results of multiple stress and creep recovery tests performed in accordance with AASHTO T 350. It should be noted that these mixtures were produced before VDOT specified binders using the AASHTO M 332 specification. The PG 64-22 tank sample graded as a PG 64S-22 as expected, although the PG 70-22 tank sample graded as a PG 64V-22 rather than the expected PG 64H-22 because of a slightly lower value of $J_{nr\,3.2}$. Because of the RAP content, the control mixture binder grade increased from the PG 64V-22 of the virgin binder to PG 64E-16. Interestingly, the RAS had a greater stiffening effect (in terms of $J_{nr\,3.2}$) on the RAS (PG 64-22) mixture than on the RAS (PG 70-22) mixture. This was also seen in Table 11, where the RAS (PG 64-22) mixture had an increase on the low temperature grade whereas the RAS (PG 70-22) mixture was not as adversely affected by the RAS binder. This may be due to increased blending of the RAS binder with the softer PG 64-22 base binder, although chemical analysis would be necessary to investigate this theory further. None of the binders met the requirement for percentage recovery that is indicative of polymer modification, as expected.

Table 12. MSCR Test Results for Tank Samples and Recovered Binders for Staunton Mixtures

Property	**PG 64-22 Tank**	**PG 70-22 Tank**	**RAS (PG 64-22)**	**RAS (PG 70-22)**	**Control (PG 70-22)**	**RAP Stockpile**
Multiple Stress Creep & Recovery, AASHTO T 350, RTFO Material						
Test Temperature, °C	64	64	64	64	64	64
Avg. % Recovery, R_{100}, Pa	5.661	13.29	30.11	17.62	39.76	29.72
Avg. % Recovery, $R_{3200,}$ Pa	2.077	7.46	23.52	11.82	35.24	27.62
% Difference	53.30	43.88	21.90	32.87	11.35	7.087
$J_{nr\,100}$, Pa^{-1}	1.995	0.8716	0.2518	0.5952	0.1606	0.1341
$J_{nr\,3.2}$, kPa^{-1}	2.177	0.9621	0.2809	0.6496	0.1717	0.1376
% J_{nr}	9.163	10.38	11.55	9.142	6.929	2.579
AASHTO M 332 Grade (no polymer modification)	**64S-22**	**64V-22**	**64E-16**	**64V-22**	**64E-16**	**64E-10**

MSCR = multiple stress creep and recovery; RAS = recycled asphalt shingles; RAP = recycled asphalt pavement; RTFO = rolling thin film oven.

SUMMARY OF FINDINGS

Test results indicated that for the SMA mixtures evaluated in this study, the inclusion of RAS affects the mixture in various ways. These impacts are highly dependent on the binders used in the mixtures, as well as the RAS source.

As expected, the inclusion of RAS stiffens the mixture, although the effect is influenced by the virgin binder properties as well as the degree of blending between the RAS and virgin binders. The inclusion of RAS had mixed effects on the mixture performance in laboratory fatigue testing. Additional evaluation is required to determine if in-service cracking or fatigue performance is significantly or practically affected. In general, there is considerable work still required to understand better the impact of RAS use, especially in SMA mixtures.

Salem Mixtures

- Dynamic modulus results indicated that at moduli values above approximately 200,000 psi, the mixtures showed agreement in values within approximately 20%. At modulus values below 200,000 psi, corresponding to testing at 37.8°C and 54.4°C and specific frequencies, the RAS mixtures were significantly stiffer than the control mixture.

- Flow number results from testing at a deviator stress of 600 kPa indicated that the RAS mixtures should be less susceptible to rutting than the control mixture. Testing was also performed on the RAS B and control mixtures using a deviator stress of 206 kPa; these results were consistent with those of tests performed at 600 kPa and indicated greater resistance to rutting from the RAS B mixture.

- With regard to the APA rut testing, which was performed only on the RAS mixtures, both RAS mixtures rutted significantly less than the VDOT maximum criterion of 4.0 mm maximum rut depth.

- Four-point beam fatigue testing was performed on the RAS B and control mixtures. Results indicated that the RAS B mixture may have better fatigue performance than the control mixture at applied strains above 350 microstrains; however, this trend was reversed at lower strains.

- Determination of the fatigue endurance limit indicated that the control mixture has greater resistance to fatigue than the RAS B mixture, as the endurance limits were 201 and 173 microstrains, respectively.

Staunton Mixtures

- Dynamic modulus results indicated similar moduli values for the RAS mixtures, with less than a 20% difference for nearly all results. Unexpectedly, RAS mixture moduli were less than control mixture moduli at reduced frequencies of 0.2 Hz and below (corresponding to testing at 37.8°C and 54.4°C), which is contrary to the trends generally expected. The RAS mixture moduli were greater than control mixture moduli at reduced frequencies of 5 Hz and above (corresponding to testing at -10.0°C, 4.4°C, and specific frequencies at 21.1°C).

- Flow number testing indicated no significant difference in rutting susceptibility for the control and RAS (PG 64-22) mixtures; however, the RAS (PG 70-22) mixture had a significantly lower flow number. No definitive reason for this result was seen.

- APA rut testing indicated no significant difference in rutting susceptibility for the mixtures.

- Four-point beam fatigue testing indicated that the RAS (PG 64-22) mixture was more susceptible to fatigue cracking than the control and RAS (PG 70-22) mixtures, which performed similarly in testing.

- Fatigue endurance limit analysis found that all three mixtures had similar fatigue endurance limits, indicating that the mixtures should perform similarly under low strain fatigue loading.

- Performance grading of the extracted binder from each mixture showed that the control mixture had a stiffer high temperature grade, PG 82, than the RAS mixtures, both of which had PG 76 high temperature grades. However, both the control and RAS (PG 64-22) mixtures had low temperature grades of -16°C, whereas the RAS (PG 70-22) mixture had a low temperature grade of -22°C. Overall, the RAS (PG 64-22) mixture was affected by the inclusion of RAS more than the RAS (PG 70-22) mixture.

- Investigation of continuous grading failure temperatures revealed that the PG 64-22 binder used in the RAS (64-22) mixture was more affected by the inclusion of RAS than the PG 70-22 binder used in the RAS (70-22) mixture, even after the binders were recovered.

- All mixtures had ΔT_c values exceeding 2.5°C, indicating a potential for increased cracking susceptibility.

- MSCR binder testing showed that the PG 64-22 and PG 70-22 tank samples corresponded to PG 64S-22 and PG64H-22 designations. Extracted binder from the RAS (PG64-22) and control mixtures corresponded to the PG 64E-16 designation, whereas extracted binder from the RAS (PG 70-22) mixture corresponded to the PG 64V-22 designation. All binders failed the percent recovery requirements indicative of polymer modification, as expected.

CONCLUSIONS

- *SMA mixtures containing RAS can be produced with expectations of a laboratory performance similar to that of typical SMA mixtures.* However, the interactions of the RAS, RAP, and virgin binder in each mixture are unique and must be considered when the use of these mixtures is chosen.

- *SMA mixtures containing RAS may be susceptible to variations in expected performance because of the effects of blending the RAS binder with the virgin binder.* Stiffer virgin binders may not blend as well as softer virgin binders with the stiff RAS binder. This should be taken into consideration.

- *The inclusion of RAP and RAS in SMA mixtures may have subtle impacts on laboratory properties that are indicative of cracking performance, although the relationship to the in-service performance of these mixtures has not been validated.*

RECOMMENDATIONS

1. *VDOT's Materials Division should not change specifications regarding the inclusion of RAS in SMA at this time.* Current specifications do not allow RAS inclusion in SMA.

2. *VDOT's Materials Division and the VDOT districts should carefully consider any proposals to incorporate RAS in SMA to determine if the specific benefits outweigh any potential disadvantages.* If the use is determined to be beneficial and approved, VTRC should be notified, as additional testing to assess the impact of RAS on binder grade and mixture durability should be performed and monitoring of the locations should be undertaken to assess performance.

3. *VTRC should continue to monitor the performance of the SMA mixtures assessed in this study to determine if the indications of cracking susceptibility seen in laboratory testing are confirmed in service*. These indications were seen in both the RAS SMA mixtures and the control mixtures and may be important factors to consider in the future. In addition, any additional SMA mixtures placed that contain RAS should also be considered for further assessment and monitoring.

BENEFITS AND IMPLEMENTATION

Benefits

The benefit of implementing Recommendation 1 is that the inclusion of RAS in SMA will continue to be restricted and considered only where appropriate. This minimizes the risk of premature pavement failure attributable to inappropriate material use.

The benefit of implementing Recommendation 2 is that the consideration of proposals to incorporate RAS in SMA on a project-by-project basis may identify instances where such use is beneficial to VDOT. Notification of VTRC and the subsequent collection of additional data on these projects will further support VDOT in identifying projects where the use of RAS in SMA is beneficial.

The benefit of implementing Recommendation 3 is that when the use of RAS once again becomes economically viable, VDOT will have additional performance data to support the decision-making process for inclusion of RAS in SMA.

Implementation

With regard to Recommendation 1, VDOT's Materials Division concurs that VDOT specifications should not be changed to allow the inclusion of RAS in SMA mixtures at this time.

With regard to Recommendation 2, if the situation arises wherein the use of RAS is considered for SMA, VDOT's Materials Division and the VDOT districts will assess whether the specific benefits outweigh any potential disadvantages. The following factors should be considered:

- potential reduction in rutting susceptibility because of increased mixture stiffness, which may be useful in areas of heavy truck traffic or slow-moving traffic

- potential increase in cracking susceptibility, which may be a concern under repeated traffic loading or in locations with insufficient pavement structure

- potential for interactions between the virgin binder and RAS binder that change the resulting mixture binder grade; softer virgin binder grades may allow greater blending of the RAP binder whereas stiffer virgin binders may not undergo such blending

- potential difficulty in compaction because of increased stiffness of the mixture; RAS mixtures are not recommended for areas requiring handwork or when temperatures are such that mixture/pavement cooling may affect the ability to reach density.

If SMA mixtures containing RAS are used, VDOT districts will notify VTRC so that the production, construction, and performance of the mixture can be assessed. The assessment will include collection of loose mixture, source binder, and road cores for laboratory evaluation; documentation of the production and construction processes; and the addition of the site to the list of RAS SMA locations for long-term monitoring of performance. VDOT's Materials Division has agreed to remind the districts to notify VTRC about any such use so that the mixtures can be evaluated to increase VDOT's knowledge base regarding RAS use.

With regard to Recommendation 3, VTRC will continue to monitor the performance of the mixtures evaluated in this study. This will be accomplished according to the following plan:

- Revisit the sites when the mixtures are approximately 6 to 8 years of age (or immediately prior to replacement).

- Conduct a visual survey of the sites to assess surface condition and collect cores for laboratory testing.

- Compare mixture properties after the in-service period with those assessed at the time of construction to evaluate the evolution of properties and associated performance over time.

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REFERENCES

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part 2B: Tests.* Washington, DC, 2013.

Anderson, R.M., King, G.N., Hanson, D.I., and Blankenship P.B. Evaluation of the Relationship Between Asphalt Binder Properties and Non-Load Related Cracking. *Journal of the Association of Asphalt Paving Technologists,* Vol. 80, 2011, pp. 615-664.

Button, J.W., Williams, D., and Scherocman, J.A. *Roofing Shingles and Toner in Asphalt Pavements.* 1344-2F. Texas Transportation Institute, College Station, 1995.

Im, S., Hu, S., and Zhou F. *Performance Studies and Future Directions for Mixes Containing RAP/RAS: Technical Report.* FHWA/TX-15/0-6738-2. Texas Transportation Institute, Austin, 2016.

Maupin, G.W., Jr. *Use of Manufactured Waste Shingles in a Hot-Mix Asphalt Field Project.* VTRC 08-R11. Virginia Transportation Research Council, Charlottesville, 2008.

Mogawer, W.S., Bennert, T., Daniel, J.S., Bonaquist, R., Austerman, A., and Booshehrian A. Performance Characteristics of Plant Produced High RAP Mixtures. In *Road Materials and Pavement Design, Vol. 13, Supplement 1.* Taylor and Francis, Abingdon, Oxfordshire, UK, 2012, pp. 183-208.

Newcomb, D.E., Stroup-Gardiner, M., Weikle, B.M., and Drescher, A. Properties of Dense-Graded and Stone Mastic Asphalt Mixtures Containing Roofing Shingles. In *Use of Waste Materials in Hot-Mix Asphalt,* H.F. Waller, Ed. ASTM STP 1193. American Society for Testing and Materials, West Conshohocken, PA, 1993.

Paulson, G.A, Stroup-Gardiner, M.A., and Epps, J.A. Recycling Waste Roofing Material in Asphalt Paving Mixtures. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1115, 1987, pp. 171-182.

Prowell, B.D., Brown, E.R., Anderson, R.M., Daniel, J.S., Swamy, A.K., Von Quintus, H., Shen, S., Carpenter, S.H., Bhattacharjee, S., and Maghsoodloo, S. *Validating the Fatigue Endurance Limit of Hot Mix Asphalt.* NCHRP Report 646. Transportation Research Board, Washington, DC, 2010.

Virginia Department of Transportation. *Construction Resource Guidebook: Standard Provisions for 2013 Paving Schedules: Special Provision Copied Notes, Special Provisions, and Supplemental Specifications for Plant Mix Schedules—Statewide.* Richmond, 2013a.

http://www.virginiadot.org/business/resources/const/constructionresourceguidbookpavingschedulesonly.pdf. Accessed April 21, 2017.

Virginia Department of Transportation, Materials Division. *Virginia Test Methods.* Richmond, 2013b. http://www.virginiadot.org/business/resources/materials/bu-mat-vtms.pdf. Accessed April 20, 2017.

Virginia Department of Transportation. *2016 Road and Bridge Specifications.* Richmond, 2016. http://www.virginiadot.org/business/resources/const/VDOT_2016_RB_Specs.pdf. Accessed May 16, 2017.

West, R., Willis, J.R., and Marasteanu, M. *Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content.* NCHRP Report 752. Transportation Research Board, Washington, DC, 2013.

Williams, R.C., Cascione, A., Yu, J., Haugen D., Marasteanu, M., and McGraw, J. *Performance of Recycled Asphalt Shingles in Hot Mix Asphalt.* TPF-5(213). Iowa State University, Ames, 2013.