Assessing Increased Use of Reclaimed Asphalt Pavement in Asphalt Mixtures

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16. Abstract:

In 2007, the Virginia Department of Transportation (VDOT) introduced specifications to allow asphalt surface mixtures to have up to 30% reclaimed asphalt pavement (RAP) without a change in the virgin binder grade. Since 2007, increasing material costs and a growing awareness of the quantity of RAP available for use have sparked interest in allowing asphalt mixtures to have a higher percentage of RAP.

By 2013, VDOT had begun to consider the feasibility of allowing the use of surface mixtures with up to 45% RAP, and several trial sections were constructed containing mixtures with 20%, 30%, 40%, and 45% RAP for evaluation. This report presents the initial construction and laboratory performance data and discusses the lessons learned from these trials.

In general, mixtures containing up to 45% RAP can be designed, produced, and constructed if proper procedures are followed and attention to detail is paid during design, production, and construction. As expected, all high RAP mixtures (i.e., mixtures containing >30% RAP) showed excellent rutting resistance based on laboratory testing. Laboratory performance testing indicated that the cracking resistance of high RAP mixtures depends on mixture and binder stiffness. The early field performance (2 to 3 years) of high RAP mixtures showed excellent rutting resistance and low values for the international roughness index, indicating smooth pavement. No premature cracks were observed in the high RAP sections. However, continued monitoring of these field sections is required to evaluate the long-term field performance.

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FINAL REPORT

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INTRODUCTION

The Virginia Department of Transportation (VDOT) adopted Superpave in 1997 and developed specifications allowing up to 20% reclaimed asphalt pavement (RAP) in surface and intermediate mixtures without adjustment of the virgin binder grade. For mixtures containing 20% to 30% RAP, binders one performance grade (PG) softer on the high and low ends of the temperature range were required (VDOT, 2007). In 2007, VDOT's specifications were changed to limit the amount of RAP added to surface mixtures to 30% and eliminate the requirement for changing the binder grade (VDOT, 2013a). Under this specification, adding 20% to 30% RAP to a mixture containing a PG 64-22 binder was expected to result in an in-service grade bump to PG 70-XX. An initial study of these higher RAP content mixtures (Maupin et al., 2008) indicated that in the laboratory, no significant differences existed between the mixtures with a higher RAP content (21% to 30%) and the control mixtures (having a RAP content of 20% or less) for fatigue, rutting, and susceptibility to moisture. A follow-up study (Diefenderfer et al., 2018) evaluated the in-service performance of these mixtures after approximately 7 years. Laboratory testing of field cores, extracted binder grading, and analysis from this study showed no trends in the results with regard to RAP content.

Research at the National Center for Asphalt Technology test track showed that mixtures with a high RAP content can have excellent rutting performance, with no sections exhibiting cracking (West et al., 2012). Two years of field performance at the test track indicated that using a standard grade of virgin binder in mixtures with a high RAP content provided performance equal to that using a softer binder; in addition, the work showed that higher asphalt contents improved durability, leading to longer expected pavement life. Although numerous field sections have been placed around the United States to evaluate Superpave mixtures with RAP contents greater than 20% to 25%, very little has been published on the topic of their long-term field performance.

The inclusion of RAP in asphalt mixtures has many benefits, including economic and environmental benefits. Recently, significant attention has been given to the use of RAP mainly because of increasing material costs and interest in environmental conservation, as well as large quantities of available RAP in certain areas. A 2014 survey by Hoppe et al. (2015) indicated that there was approximately 4.7 million tons of stockpiled RAP available in Virginia. Despite the current pavement recycling efforts and the use of RAP in asphalt mixtures, RAP stockpiles in Virginia continue to grow in size. Copeland et al. (2010) concluded that the most economical use of RAP is in asphalt mixtures that go into the intermediate and surface layers of flexible pavements, where RAP actually replaces a portion of the more expensive virgin binder. Despite the potential benefits of RAP, a major concern is that since RAP contains aged asphalt binder, mixtures with RAP may not perform as well as mixtures with virgin binder. The primary concern has been that RAP will overly stiffen mixtures, making them prone to premature cracking. Understanding and quantifying the effects of RAP content on the performance of mixtures are essential for the design of more economical and longer performing mixtures.

PURPOSE AND SCOPE

The purpose of this study was to examine the feasibility of designing, producing, and placing asphalt mixtures with RAP contents greater than 30% and less than 50% (called "high RAP" mixtures in this study) within the otherwise normal constraints of standard plant production and paving practices. This study also provided an opportunity to establish a baseline against which promising laboratory tests could predict ultimate field performance.

Test sections were constructed in VDOT's Fredericksburg, Hampton Roads, and Lynchburg districts to assess the challenges and feasibility of producing and constructing these high RAP mixtures. Production and construction details were documented. Materials were collected during production, and cores were taken at the time of construction. Initial field performance information was acquired from VDOT's Pavement Management System (PMS).

METHODS

Field Trials

General Description

Trial installations of mixtures using various binder types and RAP contents were placed for evaluation. A summary of constructed field trials is shown in Table 1.

For most sections, a base binder grade of PG 64-22 was used with RAP contents of 30% or greater. For lower RAP contents of 0% and/or 20%, PG 70-22 base binder was used. In one instance, for CR 639, a softer binder grade (PG 58-28) was used with a 40% RAP mixture to evaluate the effectiveness of binder "bumping" to address stiffening of the binder with higher RAP contents.

Table 1. Description of Field Trials

Location	Mix Type	RAP Content (Base Binder Grade)
SR 3, King George County	SM-12.5D	20% (PG 70-22); 30%, 40%, 45% (PG 64-22)
Sherdon Street, City of Hampton	SM-9.5A	30%, 40% (PG 64-22)
US 60, Cumberland County	SM-12.5D	0% (PG 70-22); 30%, 40%, 45% (PG 64-22)
CR 639, Caroline County	SM-12.5D	40% (PG 58-28)

RAP = reclaimed asphalt pavement.

Volumetrics

Quality control testing for volumetric properties was conducted onsite at the contractor's laboratory. VDOT personnel collected loose mixture monitor samples that were evaluated in the district laboratory. In addition, loose mixtures, RAP samples, and binder samples were collected for further testing at the Virginia Transportation Research Council (VTRC). For several trials, mixture samples were also collected and compacted onsite in the contractor's laboratory for determination of mixture volumetrics and performance testing.

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 the 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; percent binder absorbed (P_{ba}); and effective binder content (P_{be}).

Field Cores

Cores were taken from each site for evaluation during construction. Core locations were randomized along the length and width of the section. Air-void contents were determined in accordance with American Association of State Highway and Transportation Officials (AASHTO) standard AASHTO T 269. 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).

Laboratory Performance Testing

Dynamic Modulus

Dynamic modulus tests were performed with an Industrial Process Controls, Inc. universal testing machine (UTM 100) 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. For a few of the projects, tests were performed using an Asphalt Mixture Performance Tester with a 25 to 100 kN loading capacity in accordance with AASHTO TP 79, Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT). Tests on laboratory-produced specimens were performed on 100-mm-diameter by 150-mm-tall specimens. The specimen air-void contents were ±0.5%. For field cores, tests were performed on 38-mm-diameter by 110-mm-high specimens cored horizontally (Bowers et al., 2015; Diefenderfer et al., 2015). All tests were conducted in the uniaxial mode without confinement. Stress versus strain values were captured continuously and used to calculate dynamic modulus.

Flow Number Test

The same UTM 100 and Asphalt Mixture Performance Tester were used to conduct flow number tests. Tests were conducted at 54°C, which is 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 second every 1.0 second was applied to the specimens. The specimen air-void contents were 7.0 ± 0.5%. The tests were performed in the unconfined mode using a deviator stress of 600 kPa. For a few mixtures, tests were performed in the confined mode by using a confining stress of 10 psi and a deviator stress of 70 psi. 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 flow number. Flow number was determined numerically as the cycle number at which the strain rate is at a minimum based on the Francken model.

Asphalt Pavement Analyzer (APA) Test

The APA test was conducted in accordance with Virginia Test Method 110 (VDOT, 2013b). Three beam specimens 3 in thick by 5 in wide by 12 in long (75 mm x 125 mm x 300 mm) were tested in the APA at a test temperature of 49^{o}C (120^{o}F) for each type of mixture. The specimens were compacted in the laboratory to ensure an air-void content of 8.0 ± 0.5%. A vertical load of 120 lbf (533N) was applied through a rubber hose filled with compressed air at a pressure of 120 psi (830 kPa). The reported rut depth results after 8,000 cycles of load applications included measured rut depths of the left, middle, and right beams and the average rut depth of the three replicate beams for each mixture type.

Beam Fatigue Test

Beam fatigue tests were performed in accordance with AASHTO T 321 using three replicate specimens at three strain levels for a total of nine beams for each mixture type. For the fatigue tests, compacted beams approximately 75 mm thick by 125 mm wide by 381 mm long were fabricated. From these compacted beams, the 50.8 mm by 63.5 mm by 381 mm specimens required for the fatigue testing were saw-cut. The target air-void level for the fatigue beams was 7 ± 0.5%. The Industrial Process Controls, Inc. beam fatigue test equipment was used for testing. All tests were conducted at a single temperature of 20°C. The tests were conducted in the strain-controlled mode. The applied tensile strain levels ranged from 300 to 600 microstrain. Specimen failure was defined as the number of cycles at which beam stiffness degraded to 50% of the initial flexural stiffness.

Overlay Test

The Texas overlay test was performed in accordance with TX-248-F-09 (Texas Department of Transportation, 2019) to assess the susceptibility of mixtures to cracking. Testing was performed using a UTM with a loading capacity of 25 to 100 kN. Testing was performed at 25°C ± 0.5°C. Loading was applied for 1,200 cycles or until a reduction of 93% or more of the maximum load was reached. All tested specimens were within 7.0 ± 1.0% air voids.

Semi-Circular Bend (SCB) Test

The SCB Illinois Flexibility Index Test (I-FIT) was conducted in accordance with Illinois Test Procedure 405 (Illinois Department of Transportation, 2016) using an instrumented load frame. Tests were conducted at ambient laboratory temperature (~21ºC). All specimens were within 7.0 ± 0.5% air voids. Analysis of results was conducted using the I-FIT (IL-SCB) Analysis Tool developed by the Illinois Center for Transportation and the University of Illinois Urbana-Champaign.

Cantabro Mass Loss Test

The Cantabro test was conducted in accordance with AASHTO TP 108-14, Standard Method of Test for Abrasion Loss of Asphalt Mixture Specimens (Group 3, August 2016). The test is performed by placing one compacted specimen in a Los Angeles (LA) abrasion test drum and subjecting it to 300 drum revolutions in the absence of the abrasion charges. Mass loss is calculated at the end of the experiment. Relative loss is considered a durability indicator for dense-graded asphalt.

Binder Recovery and Grading

Extraction of binder from loose mixture was performed in accordance with AASHTO T 164, Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA), Method A (AASHTO, 2017) 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, 2017).

Virgin and extracted binder grading was performed in accordance with AASHTO M 320, Performance-Graded Asphalt Binder (AASHTO, 2017). The multiple stress and creep recovery (MSCR) test was also performed. Studies show that non-recoverable creep compliance (J_{nr}) based on the MSCR test is correlated to pavement rutting (Anderson, 2011).

Field Performance

Field condition data for the high RAP mixture installations on Virginia primary system roads (SR 3 and US 60) were extracted from VDOT's PMS. The PMS summarizes detailed distress data for each 0.1 mile of the right-lane pavement surface. Condition is reported on a scale from 0 to 100, completely failed to new or like new, respectively. The overall section rating, the critical condition index, is the lower of two ratings that summarize the load related and non-load related distresses for a pavement. PMS data also give the rutting performance and international roughness index for the sections.

RESULTS AND DISCUSSION

Field Trials

SR 3, King George County

Production and construction of the SR 3 field trial occurred from June 12 through June 25, 2013. These trials encompassed production and placement of five mixtures. All mixtures were 12.5-mm nominal maximum aggregate size mixtures designed in accordance with VDOT's 2007 specifications (VDOT volumetric and gradation specification for surface mixtures changed in 2016). These five mixtures were based on four mixture designs, summarized in Table 2, with the following designations:

1. 20% RAP content, PG 70-22 binder, containing only manufactured sand (MS): 20% RAP (MS)

2. 30% RAP content, PG 64-22 binder, containing only manufactured sand: 30% RAP (MS)

3. 30% RAP content, PG 64-22 binder, containing manufactured sand and natural sand (NS): 30% RAP (MS & NS)

4. 45% RAP content, PG 64-22 binder, containing manufactured sand and natural sand: 45% RAP (MS & NS)

5. 40% RAP content, PG 64-22 binder, containing manufactured sand and natural sand: 40% RAP (MS & NS).

The fifth mixture, a 40% RAP mixture containing manufactured sand and natural sand, designated 40% RAP (MS & NS), was the result of a plant adjustment made to the 45% RAP mixture to address the fact that the mixture was failing (exceeding) the requirements for VFA. This design was not submitted as a separate design but was produced using the following adjustments at the plant: RAP content was reduced to 40%; 6% of the natural sand content was replaced with manufactured sand; and virgin asphalt content was reduced by approximately 0.2%. Analysis indicated that the RAP asphalt content was higher than expected during production of the 45% RAP mixture, and thus the changes were required to meet volumetric specifications.

The mixtures in this study were designed with a RAP aggregate correction factor of 0.4 for the ignition furnace. The correction factor was calculated by comparing the RAP binder contents determined by extraction and by ignition. Table 3 shows the schedule of construction, temperatures, tonnage, and roller patterns for each mixture.

Table 2. Mixture Designs for SR 3 Trial

Material	20% RAP (MS)	30% RAP (MS)	30% RAP (MS & NS)	45% RAP (MS & NS)
No. 78 Diabase (Traprock)	24%	18%	22%	20%
No. 8 Diabase (Traprock)	14%	16%	13%	10%
Filler	1%	1%	1%	-
Manufactured Sand (Polishable Aggregate), Source 1	18%	13%	-	-
Manufactured Sand (Polishable Aggregate), Source 2	12%	22%	-	-
Manufactured Sand (Non-Polishable Aggregate)	-	-	23%	15%
Natural Sand	-	-	11%	10%
No. 10 Screenings	11%	-	-	-
RAP, ½ in	20%	30%	30%	45%
Asphalt Binder	5.3% (PG 70-22)	5.2% (PG 64-22)	5.2% (PG 64-22)	5.2% (PG 64-22)

RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand; - = not used.

Table 3. Trial Production/Construction Schedule for SR3 Trial

Date	Mix	Production/Delivery Temperatures, °F	Tonnage Placed	Roller Pattern
6/12-14, 21, 25, 2013	30% RAP (MS)	295-310 / 285-290	4885.07	4 vibratory / 3 vibratory, 1 static
6/17-18, 2013	30% RAP (MS & NS)	295-325 / 285-295	3130.79	4 vibratory / 2 vibratory, 2 static
6/19, 2013	45% RAP (MS & NS)	295-310 / 285-290	2401.49	4 vibratory / 2 vibratory, 3 static
6/20, 2013	40% RAP (MS & NS)	295-310 / 285-290	1598.51	4 vibratory / 2 vibratory, 3 static
6/24-25, 2013	20% RAP (MS)	295-310 / 285-290	3869.99	4 vibratory / 2 vibratory, 3 static

RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

The mixtures were produced by Superior Paving Corporation at their Stafford plant, located near Fredericksburg, Virginia. The plant was an Astec Double Barrel counter-flow drum plant with a Green System, a foaming warm-mix technology. The Green System was operating during all mixture production, although production temperatures were not reduced. The plant capacity was 350 tons/hour; during this project, the production rate was 280 tons/hour. The facility contained two asphalt binder storage tanks, two mixture storage silos, five aggregate bins, and two RAP bins. Unprocessed RAP materials were stored at the plant in three piles: one each for stone-matrix asphalt millings, dense-graded millings, and other unknown millings. Dense-graded source RAP was processed by crushing and then screening to produce two stockpiles: a minus 3/8-in material, and a 3/8-in to minus 1-in material. Each size material was stockpiled near the screening operation and kept blended during production to minimize any segregation of the stockpile. The minus 3/8-in material was used as the RAP source for this project. During production of the 40% and 45% RAP mixtures, approximately 0.7% baghouse fines were removed from the materials going into the plant. Table 3 provides a summary of the production and delivery temperatures.

The test sections were located along SR 3 in King George County, Virginia. Haul time from the plant to the project ranged from 45 minutes to 1 hour over a distance of approximately 28 miles. The route traverses gently rolling terrain and is a two-lane route with approximately 12-ft lanes. The existing surface was performance milled prior to paving. Performance milling uses more teeth on the milling drum at a closer spacing compared to typical milling. The paving train consisted of a Roadtec Material Transfer Vehicle (MTV) and Roadtec RP-190 paver. An Ingersoll Rand DD118 vibratory roller and Ingersoll Rand DD70 finishing roller were used; roller patterns are shown in Table 3. The compacted lift thickness was 2 in. Nuclear density readings and cores were collected for quality control and acceptance purposes. All test sections were reported as passing and within the VDOT acceptance range for density (98% to 102% of the target nuclear density). One observation of note during construction was that the 45% RAP mixture appeared to be finer than the other mixtures and showed indications of minor segregation in some areas, as illustrated in Figure 1.

Each mixture was evaluated in the field by selecting a 1,000-ft-long section of the paving mat. This evaluation section was selected based on when material was shipped from the plant. When the research team sampled material from the plant, the next load was tracked, and where it was placed was identified as the evaluation section at the paving site. Six cores were taken from random locations within the evaluation sections for further testing. The evaluation section locations were documented using GPS coordinates to locate the sections accurately in the future.

Figure 1. Example of Segregation Observed for 45% RAP Mixture. RAP = reclaimed asphalt pavement.

Sherdon Street, City of Hampton

Production and construction of the Sherdon Street trials occurred on August 20, 2013. Two mixtures were produced and paved as part of this trial. All mixtures were 9.5 mm nominal maximum aggregate size mixtures (SM-9.5A) designed in accordance with VDOT specifications and summarized in Table 4. Mixtures in this study were designed without using a correction factor when determining the RAP binder content (RAP binder content varied from 5.3% to approximately 5.5%). Baghouse fines were also added to these mixtures.

Table 4. Mixture Designs for Sherdon Street Trial

Material	30% RAP (MS)	40% RAP (MS)
No. 8 (Granite)	30%	31%
Natural Sand	28%	23%
No. 10 Screenings	12%	6%
RAP, 1/2 in	30%	40%
Asphalt Binder	5.6% (PG 64-22)	5.6% (PG 64-22)

RAP = reclaimed asphalt pavement; MS = manufactured sand.

The mixtures were produced by Branscome, Inc. at their Hampton Roads plant. The asphalt mixture production temperature was 300°F. The plant was a Gencor Single Drum with a production capacity of 300 tons/hour. The facility contained two asphalt binder storage tanks, three mixture storage silos, and six aggregate bins. Unprocessed RAP materials were identified and stored separately as either stone-matrix asphalt or dense-graded asphalt millings. RAP was processed by crushing and then screening to produce a minus 1/2-in material.

The test sections were located along Sherdon Street. The route traverses flat terrain and is a three-lane route with approximately 10-ft-wide lanes. The existing surface was milled prior to paving. The paving train consisted of a PF 3200 paver, a CAT CB 434D vibratory roller, and a CAT CB50 finishing roller. The roller patterns included two vibratory and one static roller pass followed by two static passes using the finishing roller. The compacted lift thickness was 1.5 in. The final pavement is shown in Figure 2 (30% and 40% RAP mixtures were paved side by side). Both 30% and 40% RAP mixtures showed some indications of segregation in some areas (Figure 3).

Each mixture was evaluated in the field by selecting a 1,000-ft-long section of the paving mat. This evaluation section was selected based on when material was shipped from the plant. When the research team sampled material from the plant, the next load was tracked, and where it was placed was identified as the evaluation section at the paving site. Six cores were taken from random locations in these sections for further testing.

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Figure 2. Final Pavement Surface at Sherdon Street. RAP = reclaimed asphalt pavement.


(a) (b)

Figure 3. Example of Segregation Observed: (a) 30% RAP mixture; (b) 40% RAP mixture. RAP = reclaimed asphalt pavement.

US 60, Cumberland County

Production and construction of the US 60 trials occurred in August 2014 in VDOT's Lynchburg District. The trials were contiguous and ran from Route 630 to the Cumberland County Line for a total of 5.42 miles. The included asphalt mixtures contained 0%, 30%, 40%, and 45% RAP. With the exception of the 30% RAP mixture, which was paved for a distance of 2.42 miles, each mixture was placed for a distance of 1 mile. All mixtures were 12.5 mm nominal maximum aggregate size (SM-12.5D) designed in accordance with VDOT specifications and summarized in Table 5.

The mixtures were produced by Colony Construction Inc. at their Powhatan plant. The plant was an Astec Double-Barrel Green System with two asphalt binder storage tanks and three mixture storage silos. All RAP was processed by crushing and then screening to produce a minus 1/2-in material.

The route to the field project traverses flat and rolling terrain and is a two-lane route with approximately 12-ft-wide lanes. The existing surface was milled to a 2-in depth prior to paving. For virgin, 30%, and 40% RAP mixtures, the roller pattern included three vibratory and two static roller passes. The 45% RAP mixture used a higher compacting effort of three vibrations and six static roller passes to achieve the required density. The compacted lift thickness was 2 in. The higher RAP mixtures showed some indications of segregation in some areas. Ten cores were taken from random locations in these sections for further testing.

Table 5. Mix Designs for US 60 Trial

Material	0% RAP	30% RAP	40% RAP	45% RAP
No. 78 Diabase (Granite)	54%	42%	39%	35%
No. 10 Screenings (Granite)	34%	16%	-	-
Manufactured Sand	12%	12%	21%	20%
RAP, ½ in	0%	30%	40%	45%
Asphalt Binder	5.8% (PG 70-22)	5.8% (PG 64-22)	5.9% (PG 64-22)	5.9% (PG 64-22)

RAP = reclaimed asphalt pavement; - = not used.

Figure 4 shows a RAP feeder during production of the 30% and 45% RAP mixtures. Some plant adjustment was needed to accommodate the higher percentage of RAP.

(a) (b)

Figure 4. RAP Screen During Mixture Production: (a) 30% RAP; (b) 45% RAP. RAP = reclaimed asphalt pavement.

CR 639, Caroline County

Production and construction of the CR 639 trial occurred on July 25, 2014. The mixtures were produced by the Superior Paving Corporation at their Stafford plant located near Fredericksburg, Virginia. Table 6 shows the mixture design for the 40% RAP mixture, which used a softer binder grade (PG 58-28). This project also used a 30% RAP mixture having manufactured sand with the same design as shown in Table 2 (Mixture 2 from the SR 3 trial).

The test sections were located along the eastbound travel lane of CR 639 in Caroline County, Virginia. Haul time from the plant to the project was approximately 30 to 45 minutes over a distance of approximately 28 miles. The route traverses gently rolling terrain and is a two-lane route with approximately 12-ft lanes. The paving train consisted of a Roadtec Material Transfer Vehicle (MTV) and Roadtec paver. An Ingersoll Rand DD90 vibratory roller and Ingersoll Rand DD70 finishing roller were used.

Table 6. Mix Design for CR 639 Trial

Material	40% RAP
No. 78 Diabase (Traprock)	18%
No. 8 Diabase (Traprock)	12%
Manufactured Sand	10%
No. 10 Screenings	20%
RAP, ½ in	40%
Asphalt Binder	5.1% (PG 58-28)

RAP = reclaimed asphalt pavement.

Volumetrics

SR 3, King George County

Volumetric results for the SR 3 trials are shown in Table 7. These results compared well with the quality control and acceptance data available from the producer and VDOT district, although those data are not shown. The results were fairly consistent among the mixtures. The plant adjustments made to the 45% RAP mixture to provide the 40% RAP mixture are evident in the volumetrics. The asphalt content was reduced, and adjustments to the RAP and sand percentages affected the gradation.

From Table 7 it may be seen that VMA decreased at the 40% and 45% RAP contents; this was likely due to the quantity of fine RAP in the mixtures. In addition, the presence of natural sand in the 30%, 40%, and 45% RAP mixtures had an impact on the binder absorption and thus effective asphalt content.

Table 7. Volumetric Results for SR 3 Mixtures

Property	20% RAP (MS)	30% RAP (MS)	30% RAP (MS & NS)	40% RAP (MS & NS)	45% RAP (MS & NS)
% AC	5.20	5.19	5.33	4.86	5.26
Rice Specific Gravity, G_{mm}	2.691	2.685	2.662	2.689	2.634
% Air Voids, V_a	3.2	3.9	4.5	4.0	3.0
% VMA	16.0	16.7	16.6	15.1	14.9
% VFA	79.9	76.5	72.7	73.4	80.2
Dust/Asphalt Ratio	1.22	1.11	1.07	1.19	1.16
Bulk Specific Gravity, G_{mb}	2.604	2.579	2.541	2.581	2.556
Effective Specific Gravity, G_{se}	2.951	2.944	2.922	2.931	2.883
Aggregate Specific Gravity, G_{sb}	2.938	2.937	2.885	2.894	2.846
% Binder Absorbed, P_{ba}	0.15	0.08	0.45	0.45	0.46
Effective % Binder, P_{be}	5.05	5.11	4.90	4.43	4.81
Effective Film Thickness, F_{be}	8.5	9.3	8.8	8.3	8.1
Sieve Size	**Average Percent Passing**				
3/4 in (19.0 mm)	100.0	100.0	100.0	100.0	100.0
1/2 in (12.5 mm)	98.6	98.2	97.0	97.3	99.2
3/8 in (9.5 mm)	90.7	90.7	89.6	88.6	90.3
No. 4 (4.75 mm)	61.6	58.7	63.6	55.0	62.2
No. 8 (2.36 mm)	39.6	37.2	45.4	37.1	45.7
No. 16 (1.18 mm)	28.0	26.1	33.9	27.3	34.7
No. 30 (600 µm)	20.8	19.0	23.2	19.7	24.6
No. 50 (300 µm)	14.9	13.3	12.8	12.9	14.5
No. 100 (150 µm)	9.6	8.6	7.8	8.2	8.5
No. 200 (75 µm)	6.16	5.65	5.25	5.26	5.61

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

Sherdon Street, City of Hampton

Volumetric results from the Sherdon Street trials are shown in Table 8. It can be seen that the VMA of the 40% RAP mixture was lower, which is consistent with the relatively lower asphalt content and air voids (VTM).

Table 8. Volumetric Results for Sherdon Street Mixtures

Property	30% RAP	40% RAP
% AC	5.5	5.38
Rice Specific Gravity, G_{mm}	2.487	2.497
% Air Voids, V_a	4.3	3.3
% VMA	16.4	15.3
% VFA	74	78.7
Dust/Asphalt Ratio	0.99	1.03
Bulk Specific Gravity, G_{mb}	2.381	2.415
Effective Specific Gravity, G_{se}	2.710	2.716
Aggregate Specific Gravity, G_{sb}	2.693	2.699
% Binder Absorbed, P_{ba}	0.24	0.24
Effective % Binder, P_{be}	5.27	5.15
Effective Film Thickness, F_{be}	9.1	9.0
Sieve Size	**Average Percent Passing**	
3/4 in (19.0 mm)	100	100
1/2 in (12.5 mm)	97.9	98.7
3/8 in (9.5 mm)	89.5	91.2
No. 4 (4.75 mm)	65.7	61.7
No. 8 (2.36 mm)	51.3	46.5
No. 16 (1.18 mm)	39.3	36
No. 30 (600 µm)	26.9	25.2
No. 50 (300 µm)	13.8	13.7
No. 100 (150 µm)	7.7	7.8
No. 200 (75 µm)	5.21	5.33

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

US 60, Cumberland County

Volumetric results from the US 60 trials are shown in Table 9. These results compared well with the quality control and acceptance data available from the producer and VDOT district, although those data are not shown. The virgin mixture had higher VMA and effective film thickness compared to other mixtures.

CR 639, Caroline County

Volumetric results from CR 639 are shown in Table 10. The major change noted among mixtures was that the effective binder content of the 40% RAP mixture with PG 58-28 binder was lower compared to the 30% RAP mixture.

Table 9. Volumetric Results for US 60 Mixtures

Property	0% RAP	30% RAP	40% RAP	45% RAP
% AC	6.24	5.79	5.77	5.83
Rice Specific Gravity, G_{mm}	2.474	2.501	2.486	2.508
% Air Voids, V_a	4.7	3.0	2.1	3.3
% VMA	18	15.9	15.4	17
% VFA	73.6	81.4	86.4	80.7
Dust/Asphalt Ratio	0.91	1.27	1.03	1.07
Bulk Specific Gravity, G_{mb}	2.357	2.427	2.434	2.426
Effective Specific Gravity, G_{se}	2.729	2.742	2.721	2.753
Aggregate Specific Gravity, G_{sb}	2.695	2.718	2.711	2.753
% Binder Absorbed, P_{ba}	0.48	0.33	0.14	0.00
Effective % Binder, P_{be}	5.79	5.48	5.64	5.83
Effective Film Thickness, F_{be}	11.9	9.0	10.1	10.0
Sieve Size	**Average Percent Passing**			
3/4 in (19.0 mm)	100	100	100	100
1/2 in (12.5 mm)	93.8	95.1	93.1	94.0
3/8 in (9.5 mm)	82.7	83.4	80.7	82.0
No. 4 (4.75 mm)	56.3	54.5	54.3	56.8
No. 8 (2.36 mm)	34.3	36.6	38.7	40.1
No. 16 (1.18 mm)	22.7	26.8	28.2	29.1
No. 30 (600 µm)	15.7	19.8	20.2	20.7
No. 50 (300 µm)	11.0	14.1	13.5	14.0
No. 100 (150 µm)	7.6	9.8	8.6	9.2
No. 200 (75 µm)	5.29	6.98	5.79	6.22

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

Table 10. Volumetric Results for CR 639 Mixtures

Property	30% RAP	40% RAP
% AC	5.21	5.03
Rice Specific Gravity, G_{mm}	2.680	2.667
% Air Voids, V_a	3.5	2.5
% VMA	16.5	14.3
% VFA	79.1	82.4
Dust/Asphalt Ratio	1.10	1.26
Bulk Specific Gravity, G_{mb}	2.587	2.600
Effective Specific Gravity, G_{se}	2.939	2.912
Aggregate Specific Gravity, G_{sb}	2.939	2.882
% Binder Absorbed, P_{ba}	0.00	0.37
Effective % Binder, P_{be}	5.21	4.68
Effective Film Thickness, F_{be}	8.9	8.0
Sieve Size	**Average Percent Passing**	
3/4 in (19.0 mm)	100	100
1/2 in (12.5 mm)	97.7	97.4
3/8 in (9.5 mm)	90.3	88.9
No. 4 (4.75 mm)	59.6	55.9
No. 8 (2.36 mm)	39.4	36.8
No. 16 (1.18 mm)	28.7	27.3
No. 30 (600 µm)	21.3	20.5
No. 50 (300 µm)	15.2	14.9
No. 100 (150 µm)	9.6	9.7
No. 200 (75 µm)	5.75	5.88

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

Core Air Voids and Permeability

SR 3, King George County

Air voids and permeability results from cores taken at construction for the SR 3 trials are shown in Table 11. For all mixtures, the average air voids met the VDOT requirements. For surface mixtures, VDOT's specification requires an average permeability not to exceed 150 x 10^{-5} cm/s. The 20% and 30% RAP mixtures with manufactured sand did not meet this requirement. The permeability of all other mixtures containing natural sand did, however, meet VDOT's requirement.

Table 11. Air Voids and Permeability Results for SR 3 Cores

Mix	Mix ID	Air Voids and Permeability	Specimen No.						Avg.	Std. Dev.
			1	2	3	4	5	6		
20% RAP (PG 70-22, MS)	13-1065	Air voids, %	7.4	9.2	7.9	11	8.1	8.7	8.7	1.3
		Permeability, x 10^{-5} cm/s	26	233	75	536	69	118	176	189
30% RAP (PG 64-22, MS)	13-1040	Air voids, %	7.5	7.3	8.1	7.8	8.8	7.7	7.9	0.5
		Permeability, x 10^{-5} cm/s	237	113	449	208	589	204	300	180
30% RAP (PG 64-22, MS & NS)	13-1048	Air voids, %	7.5	7.7	8.2	9.2	8.7	7.1	8.1	0.8
		Permeability, x 10^{-5} cm/s	3	7	3	21	10	0	7.3	7.6
40% RAP (PG 64-22, MS & NS)	13-1058	Air voids, %	9.9	7.7	8.3	9.1	8.8	6.8	8.4	1.1
		Permeability, x 10^{-5} cm/s	338	6	211	199	188	10	158	128
45% RAP (PG 64-22, MS & NS)	13-1054	Air voids, %	7.7	7.4	7.9	8.0	6.9	7.1	7.5	0.4
		Permeability, x 10^{-5} cm/s	2	4	11	11	5	8	6.8	3.8

RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

Sherdon Street, City of Hampton

Air voids and permeability results from cores taken at construction for Sherdon Street are shown in Table 12. Core air voids and permeability were higher for the 40% RAP mixture as compared to the 30% RAP mixture.

Table 12. Air Voids and Permeability Results for Sherdon Street Cores

Mix	Mix ID	Air Voids and Permeability	Specimen No.						Avg.	Std. Dev.
			1	2	3	4	5	6		
30% RAP	13-1090	Air voids, %	8.3	5.8	6.4	7.2	9.2	8.7	7.6	1.3
		Permeability, x 10^{-5} cm/s	144	2	5	20	211	89	78	85
40% RAP	13-1091	Air voids, %	8.9	10.5	11.9	10	-	7.7	9.8	1.6
		Permeability, x 10^{-5} cm/s	81	285	906	282	-	54	321	344

RAP = reclaimed asphalt pavement.

US 60, Cumberland County

Air voids and permeability results for cores taken at construction from US 60 are shown in Table 13. Air voids and permeability results of the 40% and 45% RAP mixtures were comparable to the virgin mixture. Only the 30% RAP mixture had relatively higher air voids and permeability.

Table 13. Air Voids and Permeability Results for US 60 Cores

Mix	Mix ID	Air Voids and Permeability	Specimen No. 1	2	3	4	5	6	7	8	9	10	Avg.	Std. Dev.
0% RAP	14-1032	Air voids, %	7.3	6.4	8.7	6.6	9.3	7.6	7.6	9.0	6.8	9.7	7.9	1.2
		Permeability, x 10^{-5} cm/s	3	0	15	0	39	4	4	37	1	46	14.9	8.4
30% RAP	14-1044	Air voids, %	10.6	8.5	10.6	9.6	8.0	8.8	11.6	9.4	8.2	11.9	9.7	1.4
		Permeability, x 10^{-5} cm/s	92	69	317	301	39	154	2	130	513	61	167.8	160.5
40% RAP	14-1035	Air voids, %	5.0	5.8	4.9	7.9	6.0	8.1	8.0	5.9	10.3	6.2	6.8	1.7
		Permeability, x 10^{-5} cm/s	0	0	0	1	0	3	2	0	203	0	20.9	64.0
45% RAP	14-1039	Air voids, %	7.0	8.8	7.7	5.8	5.9	7.1	8.4	10.6	7.8	8.2	7.7	1.4
		Permeability, x 10^{-5} cm/s	3	82	10	0	0	9	13	264	23	29	43.3	81.2

RAP = reclaimed asphalt pavement.

CR 639, Caroline County

Air voids and permeability results for CR 639 cores are shown in Table 14. With the exception of a couple of core samples, in general, air voids and permeability results met VDOT specifications.

Table 14. Air Voids and Permeability Results for CR 639 Cores

Mix	Mix ID	Air Voids and Permeability	Specimen No. 1	2	3	4	5	6	7	8	9	10	Avg.	Std. Dev.
40% RAP	14-1017	Air voids, %	9.1	7.2	7.2	9.4	9.9	10.2	12	11.9	10.3	9.8	9.7	1.6
		Permeability, x 10^{-5} cm/s	108	17	32	7	245	542	1912	7	325	389	358.4	76.9

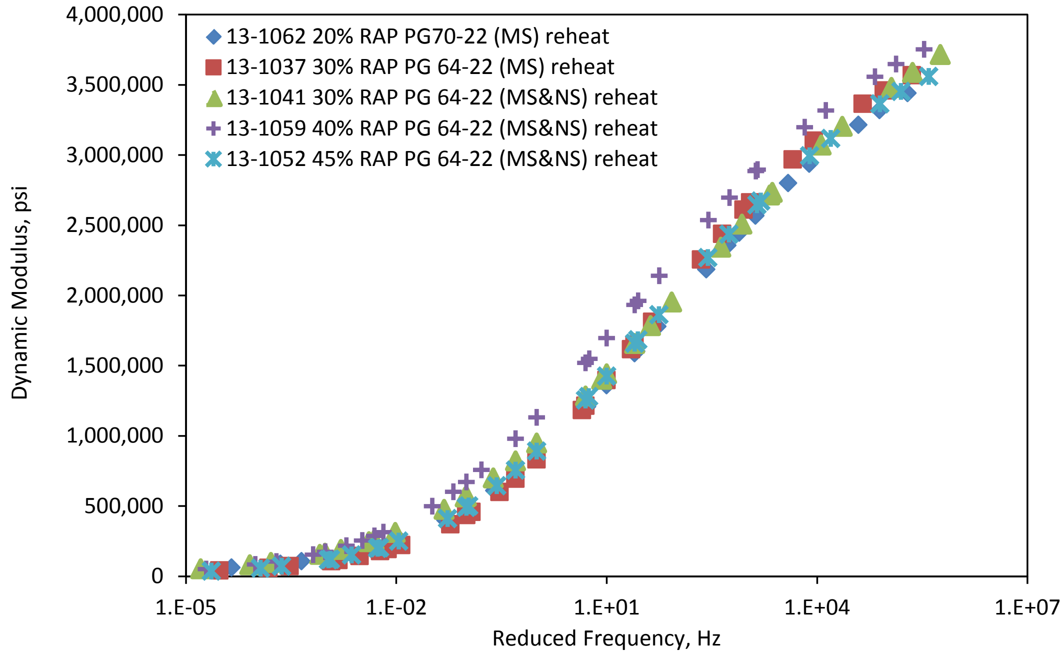
RAP = reclaimed asphalt pavement.

Laboratory Performance

Dynamic Modulus

SR 3, King George County

Dynamic modulus results for the SR 3 mixtures are shown in Figure 5. These results are the average of three tested specimens. The impact of the additional stiffness provided to the mixture by the increasing RAP contents can be seen, as 30% and 40% RAP mixtures have slightly greater stiffness across most reduced frequencies. However, any increase in stiffness was generally within 20%, as shown in Figure 6. It is interesting to note that the 20% RAP mixture was softer despite the use of a PG 70-22 base binder. This indicates that the PG 64-22 binder used in all other mixtures is being sufficiently stiffened by the RAP binders to provide mixture moduli greater than those provided by the PG 70-22 mixture.



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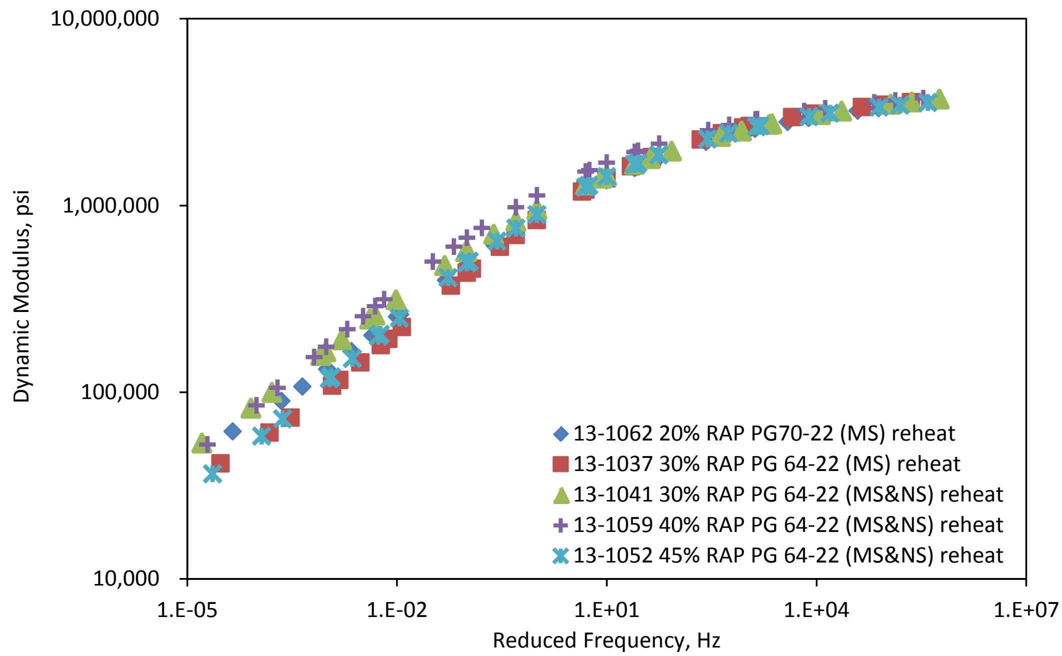


(b)

Figure 5. Dynamic Modulus Curves for SR 3: (a) reheated mixtures (semi-log scale); (b) reheated mixtures (log-log scale). RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

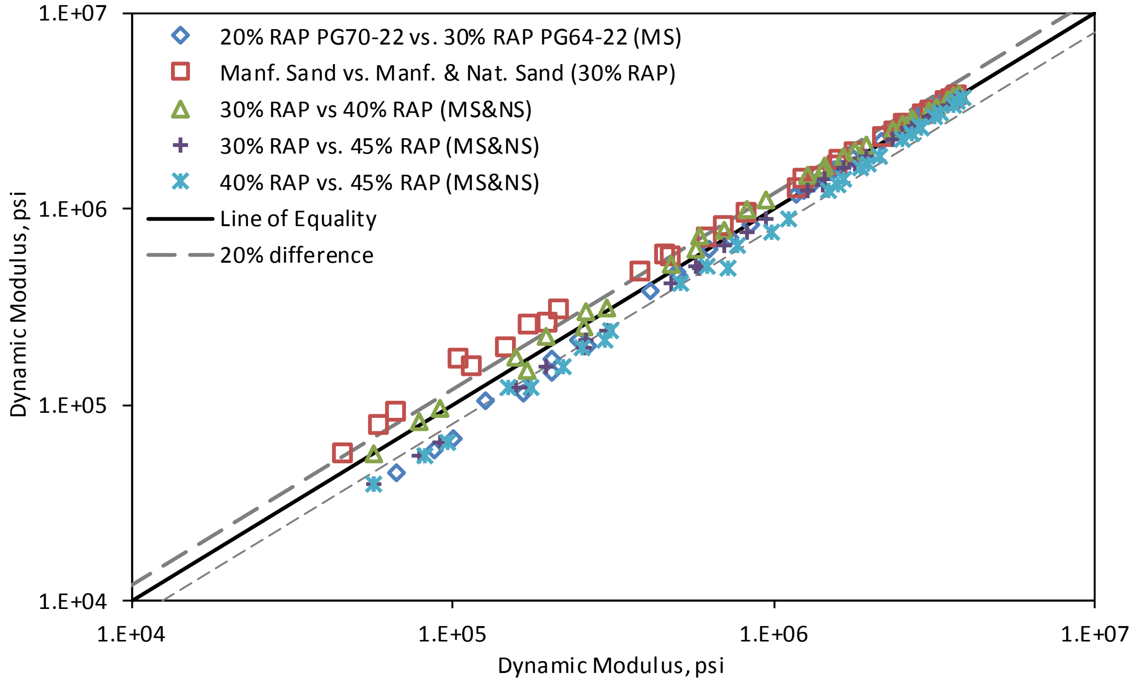
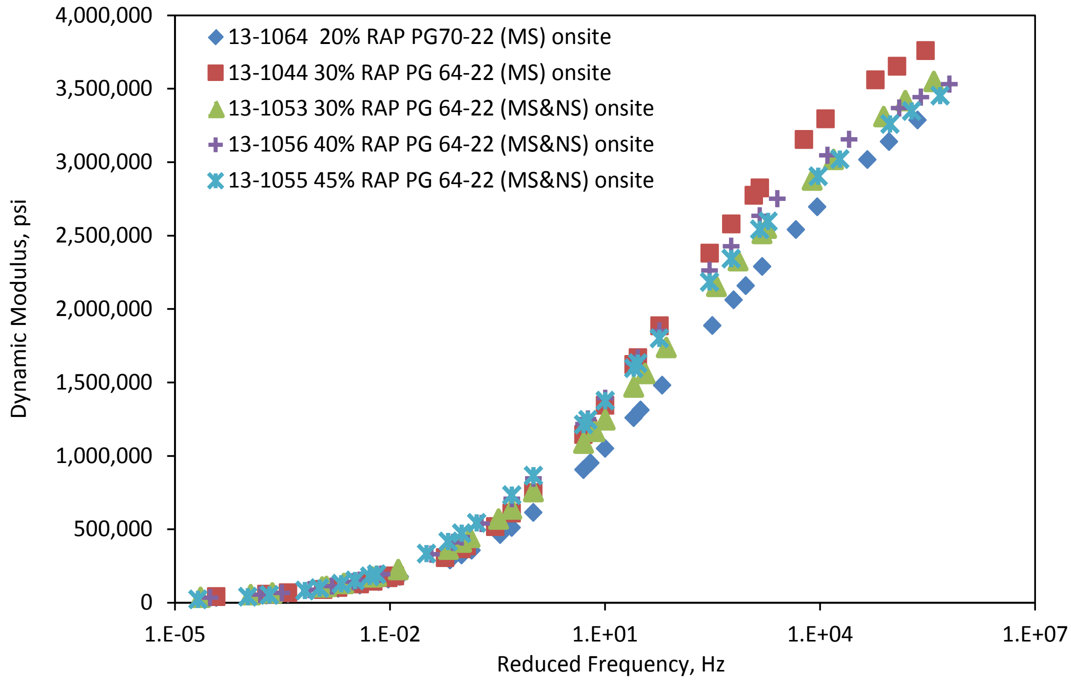


Figure 6. Comparison of Dynamic Modulus for SR 3 Reheated Mixtures With Different RAP Contents. RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

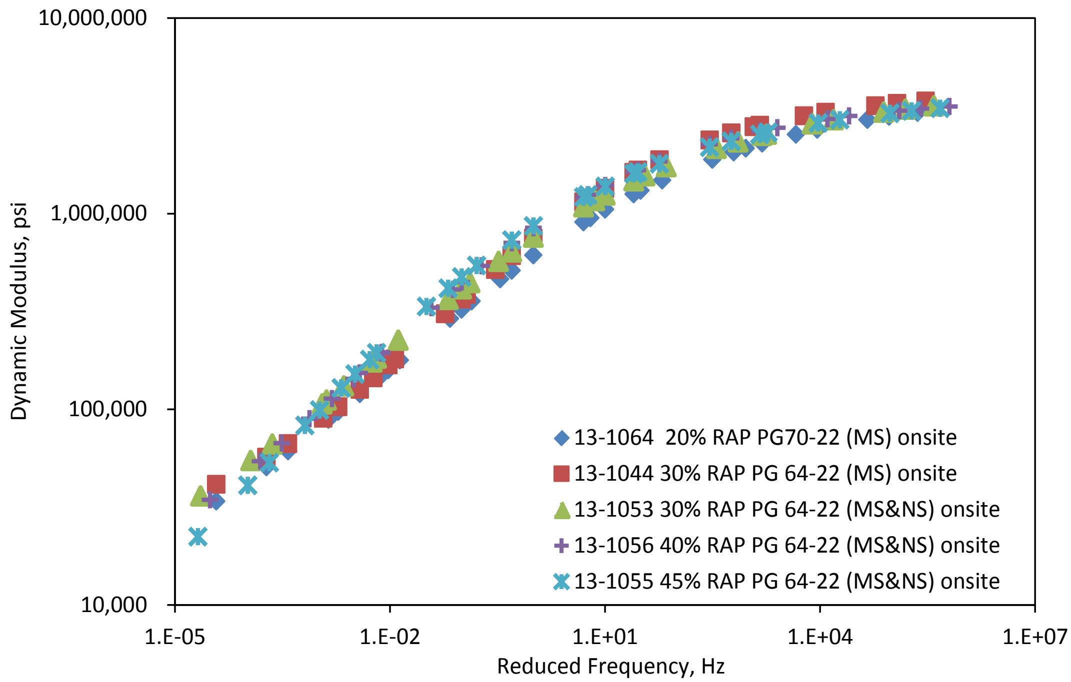
Dynamic modulus curves for samples prepared onsite without reheating are shown in Figure 7. It should be noted that the percent VTM for the prepared specimens ranged from 7.0% to 7.4% with the exception of the 30% RAP (MS & NS) specimen set, which had VTM values of 8.0%, 8.2%, and 8.0%. Despite the differences in air-void content, the 30% RAP (MS & NS) specimens were as expected, relative to the other mixtures.

Figure 8 shows dynamic modulus results for core samples (tested using small-scale specimens), as well as a comparison among laboratory-reheated, onsite-prepared, and core samples. It can be seen that reheated samples showed slightly higher dynamic modulus values compared to others at lower frequencies. This was due to additional stiffening of the mixtures caused by reheating in the laboratory.

Figure 9 shows a comparison of dynamic modulus results for SR 3 reheat, onsite, and core specimens.



(a)



(b)

Figure 7. Dynamic Modulus of SR 3: (a) onsite prepared samples (semi-log scale); (b) onsite prepared samples (log-log scale). RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

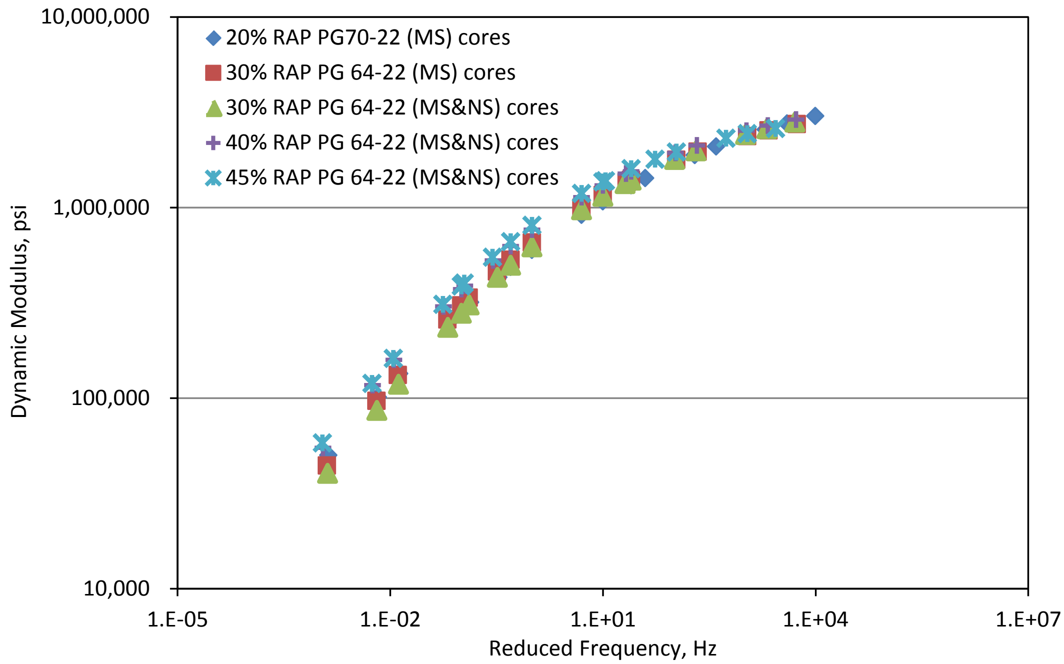


Figure 8. Dynamic Modulus of SR 3 Core Specimens. RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

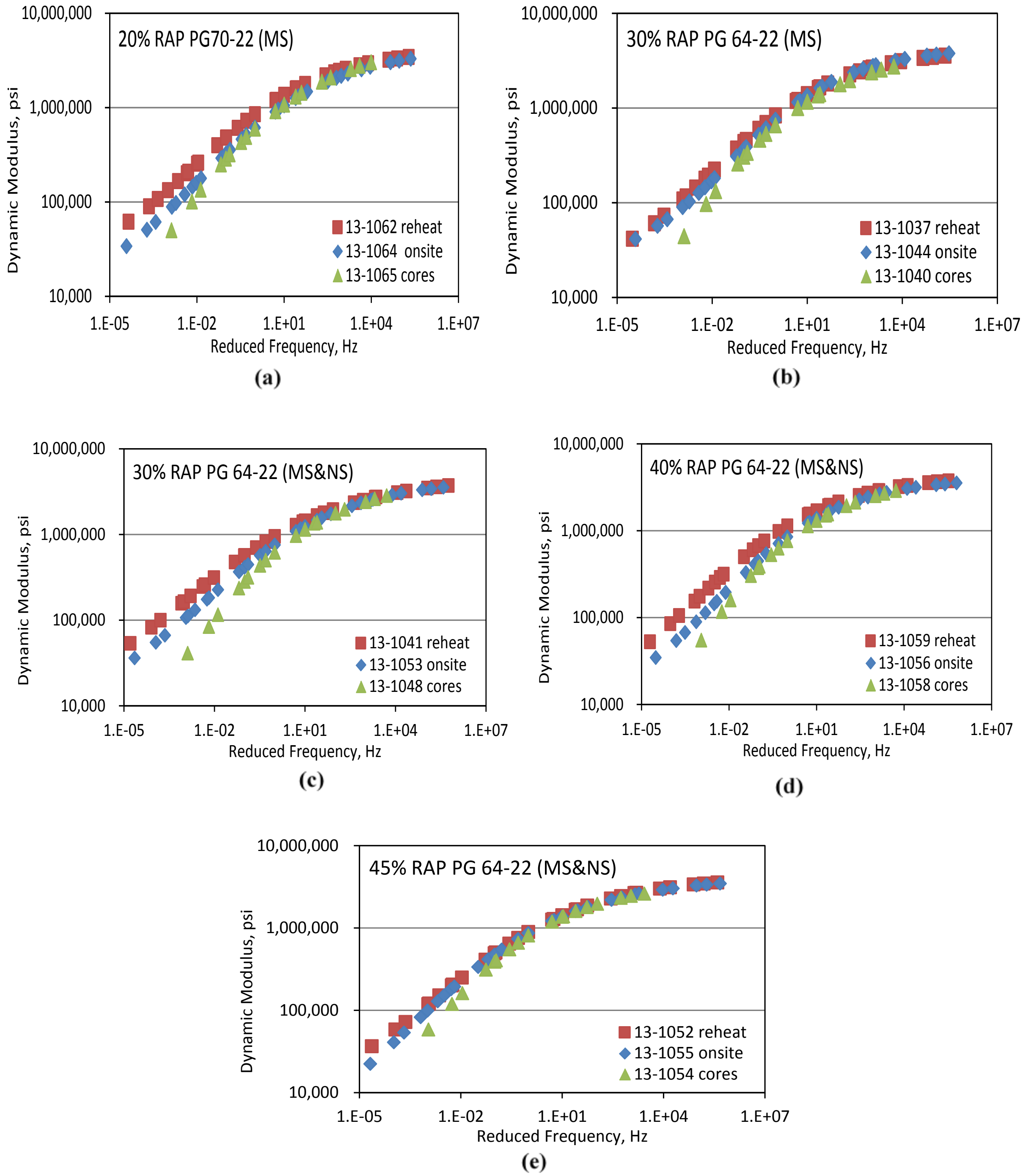


Figure 9. Comparison of Dynamic Modulus Results for SR 3 Reheat, Onsite, and Core Specimens: (a) 20% RAP mixture; (b) 30% RAP (MS) mixture; (c) 30% RAP (MS&NS) mixture; (d) 40% RAP mixture; (e) 45% RAP mixture. RAP = reclaimed asphalt pavement.

Table 15 shows the dynamic modulus and phase angle values for each mixture at the 54.4°C test temperature. In general, a higher dynamic modulus value at higher temperatures is often associated with higher rutting resistance. From Table 15 it may be seen that the stiffness values of all mixtures were comparable. This is reassuring from a practical standpoint, as VDOT uses PG 70-22 mixtures in response to moderate-to-high traffic loading wherein rutting may be a concern; this indicates that the PG 64-22 mixtures containing RAP should provide similar resistance to rutting, which is important reassurance that the rutting performance of these mixtures will not suffer.

Table 15. Dynamic Modulus and Phase Angle at 54.4ºC (130ºF) for All Mixtures

Mix	Property	Value	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
20% RAP	Dynamic Modulus, psi	Average	166,503	124,133	97,465	54,239	48,443	36,801
PG 70-22		Std. Dev.	6,220	6,811	6,094	5,544	5,024	4,594
MS	Phase Angle	Average	29.0	26.6	25.0	23.2	20.7	17.1
		Std. Dev.	1.0	1.0	1.1	1.1	1.0	1.1
30% RAP	Dynamic Modulus, psi	Average	171,676	126,942	101,159	61,815	56,101	45,866
PG 64-22		Std. Dev.	15,957	16,442	16,630	17,375	16,400	15,346
MS	Phase Angle, º	Average	29.9	26.6	24.6	21.5	19.1	16.1
		Std. Dev.	2.1	2.5	2.9	3.6	3.1	2.3
30% RAP	Dynamic Modulus, psi	Average	184,971	135,194	106,037	59,814	52,388	38,870
PG 64-22		Std. Dev.	15,651	15,551	15,871	16,096	15,166	13,614
MS & NS	Phase Angle, º	Average	29.9	28.4	27.0	24.8	22.4	19.3
		Std. Dev.	1.8	2.0	2.3	2.8	2.2	1.2
40% RAP	Dynamic Modulus, psi	Average	199,088	146,338	112,665	60,123	52,402	39,397
PG 64-22		Std. Dev.	4,977	6,890	7,100	7,881	7,727	6,457
MS & NS	Phase Angle, º	Average	30.9	28.6	27.2	25.2	22.6	19.2
		Std. Dev.	0.7	0.8	1.0	1.5	1.1	0.8
45% RAP	Dynamic Modulus, psi	Average	188,017	134,508	102,111	46,127	37,894	24,884
PG 64-22		Std. Dev.	7,787	8,415	7,710	8,103	8,123	7,308
MS & NS	Phase Angle, º	Average	33.0	31.6	30.5	31.0	28.4	24.4
		Std. Dev.	0.7	1.3	1.5	3.3	3.5	3.9

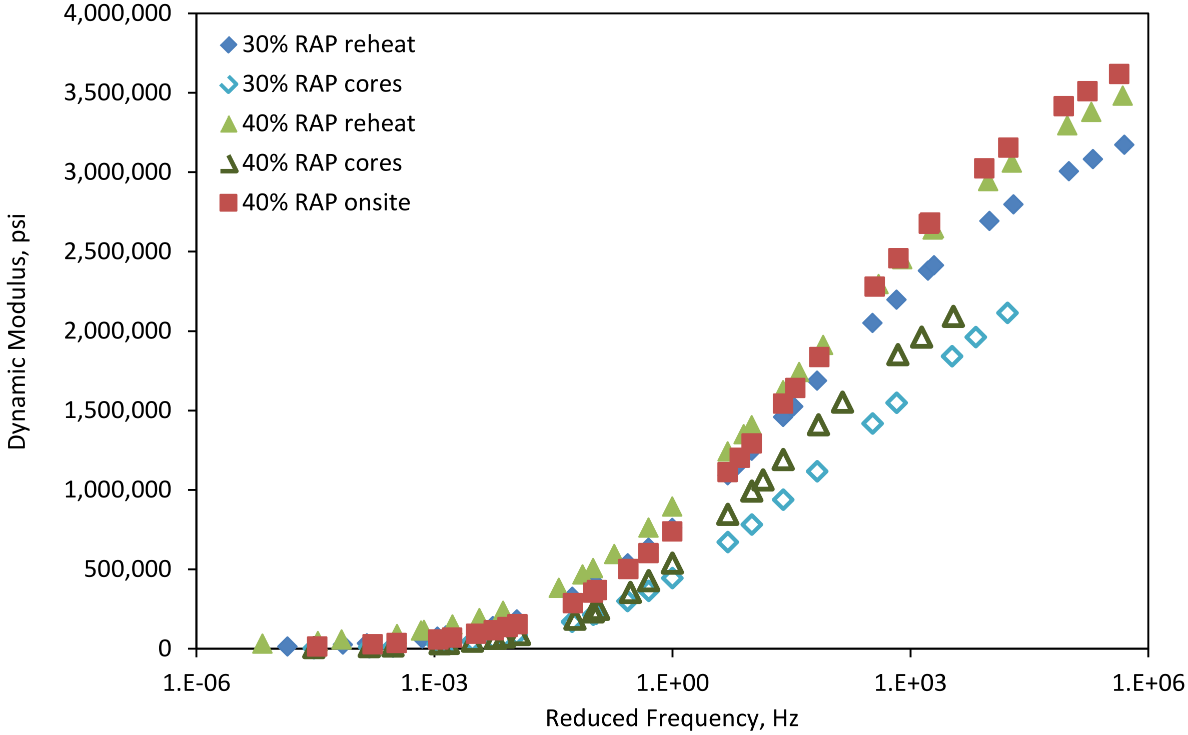
RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

Sherdon Street, City of Hampton

Dynamic modulus results for the 30% and 40% RAP mixture samples from Sherdon Street are shown in Figure 10. In general, the 40% RAP mixture showed higher stiffness compared to the 30% RAP mixture, as expected. Reheating increased the stiffness of the 40% RAP specimens as compared to the specimens prepared onsite without reheating. Both the 30% RAP and 40% RAP cores were less stiff than specimens prepared onsite or after reheating. These findings are similar to those previously shown.

US 60, Cumberland County

Dynamic modulus results for the US 60 mixtures are shown in Figure 11. It can be seen that all the RAP mixtures (produced using PG 64-22 base binder) showed a higher dynamic modulus compared to that of the virgin mixture, which used a PG 70-22 binder. In addition, as RAP percentages increased, stiffness also increased. This may be due to the higher stiffness in RAP binder. Extracted binder results are presented later.



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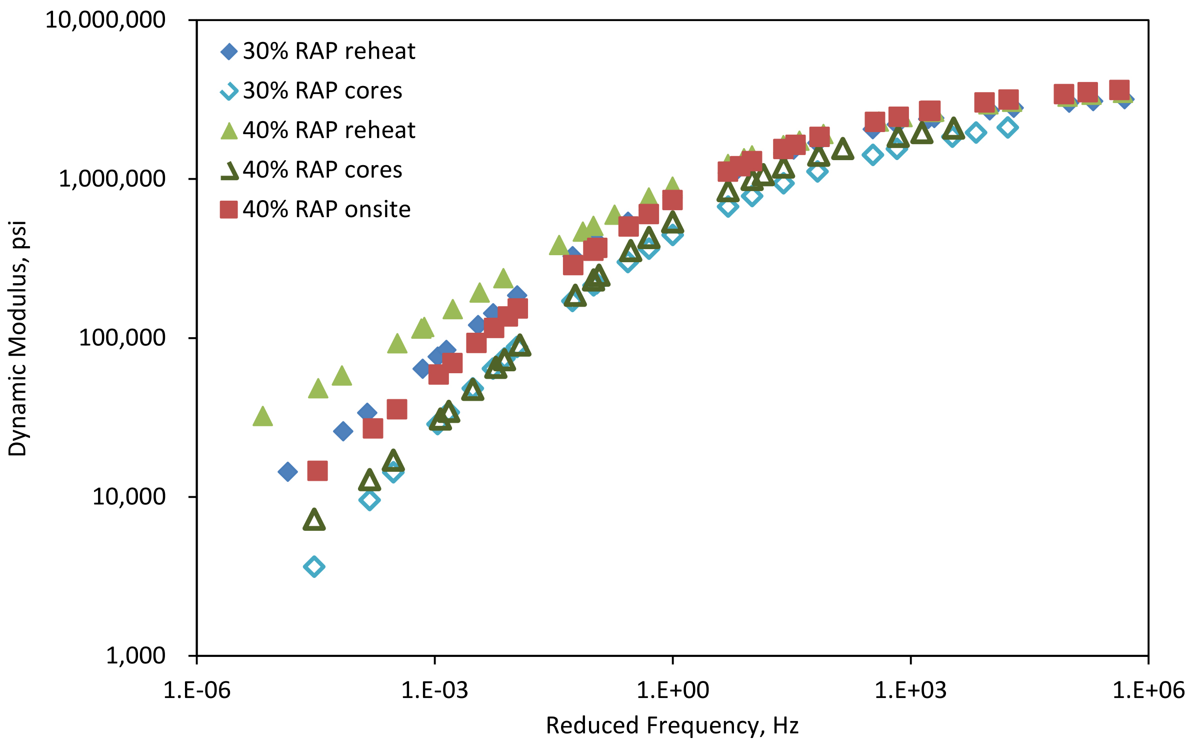
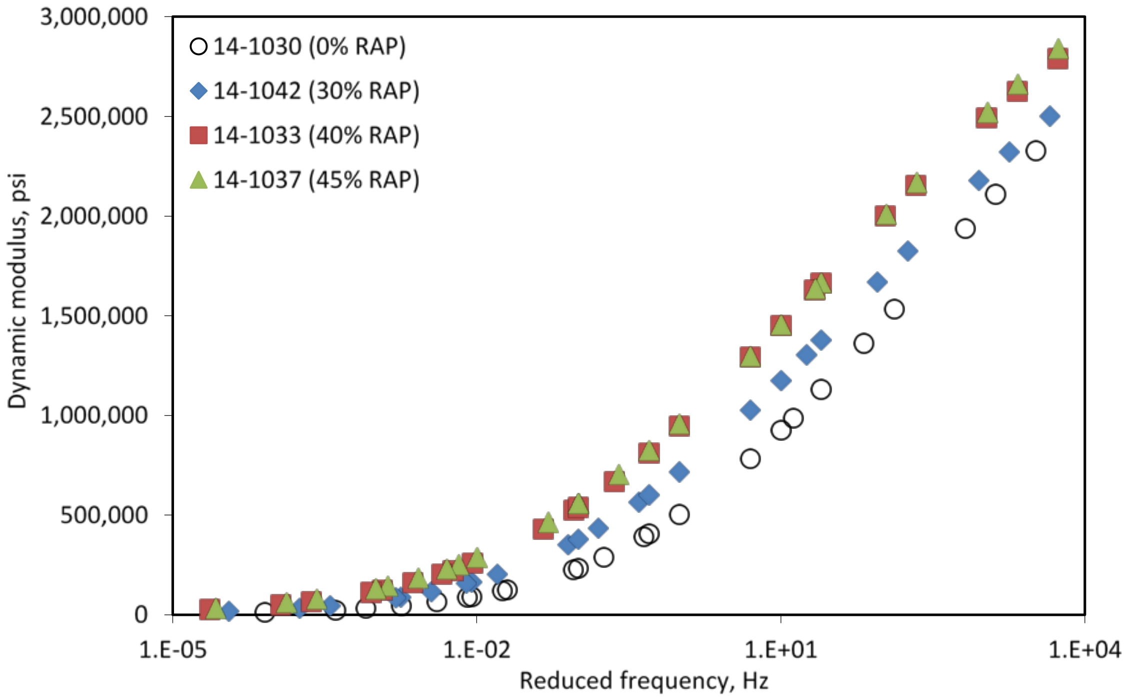


(b)

Figure 10. Dynamic Modulus Results for High RAP Mixtures From Sherdon Street: (a) semi-log scale; (b) log-log scale. RAP = reclaimed asphalt pavement.



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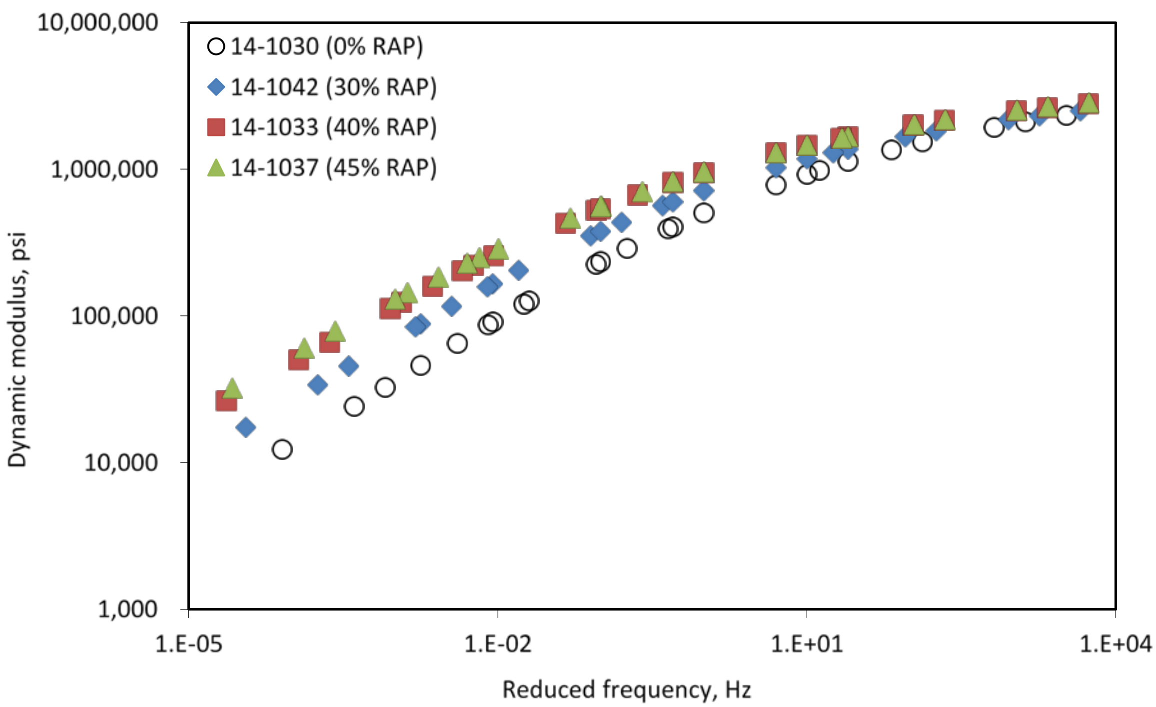

(b)

Figure 11. Dynamic Modulus Results for High RAP Mixtures From US 60: (a) semi-log scale; (b) log-log scale. RAP = reclaimed asphalt pavement.

CR 639, Caroline County

Dynamic modulus results for the CR 639 mixture are shown in Figure 12; this mixture was a 40% RAP mixture with a PG 58-28 binder. Results are compared with those for the 40% RAP mixture from SR 3 that was produced using the same mix design but with PG 64-22 virgin binder. It can be seen that stiffness of the mixture is reduced when a softer binder grade is used.

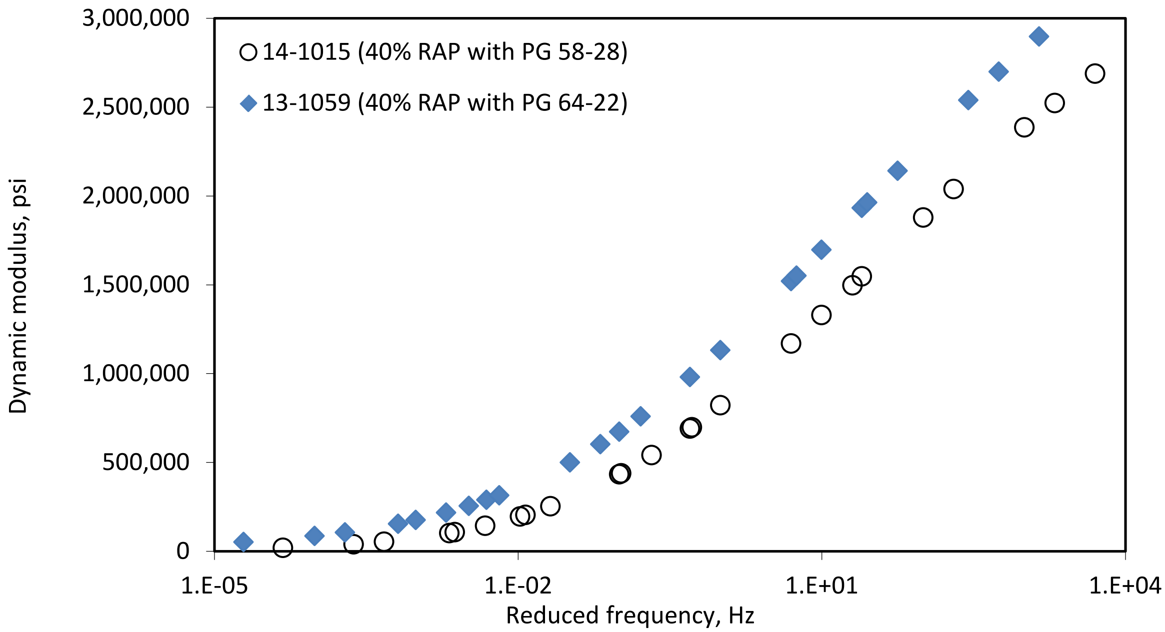

Figure 12. Dynamic Modulus Results for 40% High RAP Mixtures From SR 3 and CR 639 (Semi-Log Scale). RAP = reclaimed asphalt pavement.

Flow Number

The flow number test is used as a laboratory test to evaluate the rutting resistance of asphalt mixtures. It is generally accepted that the higher the flow number, the lower the rutting susceptibility. Table 16 shows the flow number criteria for the unconfined condition developed during NCHRP Project 9-43 for HMA and warm-mix asphalt (WMA) as a function of traffic level (Bonaquist, 2011).

Table 16. Recommended Minimum Flow Numbers for the Unconfined Condition

Traffic Level (million equivalent single-axle loads)	HMA Conditioned at 275°F (135°C)	WMA Conditioned 2 hr at Planned Field Compaction Temperature
<3.0	NA	NA
3.0 < 10.0	50	30
10.0 < 30.0	190	105
>30.0	740	415

HMA = hot-mix asphalt; WMA = warm-mix asphalt; NA =not applicable.
Source: Bonaquist, 2011.

SR 3, King George County

Figures 13 and 14 compare the average flow number values for mixtures with different RAP contents under unconfined and confined conditions. Numerically, the 20% RAP mixture containing PG 70-22 binder had the highest flow number and thus the indication of the highest rutting resistance, followed by mixtures with higher RAP contents using PG 64-22 binder. However, the differences in flow numbers were not statistically significant because of high variability.

The results of the flow number and dynamic modulus tests for SR 3 suggested that the RAP content increase from 30% to 45% did not significantly affect the mixture stiffness. The traffic levels on SR 3 in King George County are in the range of 3 to 10 million ESALs, which according to Table 16 would require a minimum unconfined flow number of 50. The lowest average flow number for any of the mixtures was 219 cycles, so all mixtures tested in this study should perform well against rutting. Figure 14 indicates that all mixtures had similar flow number values when tested in the confined condition.

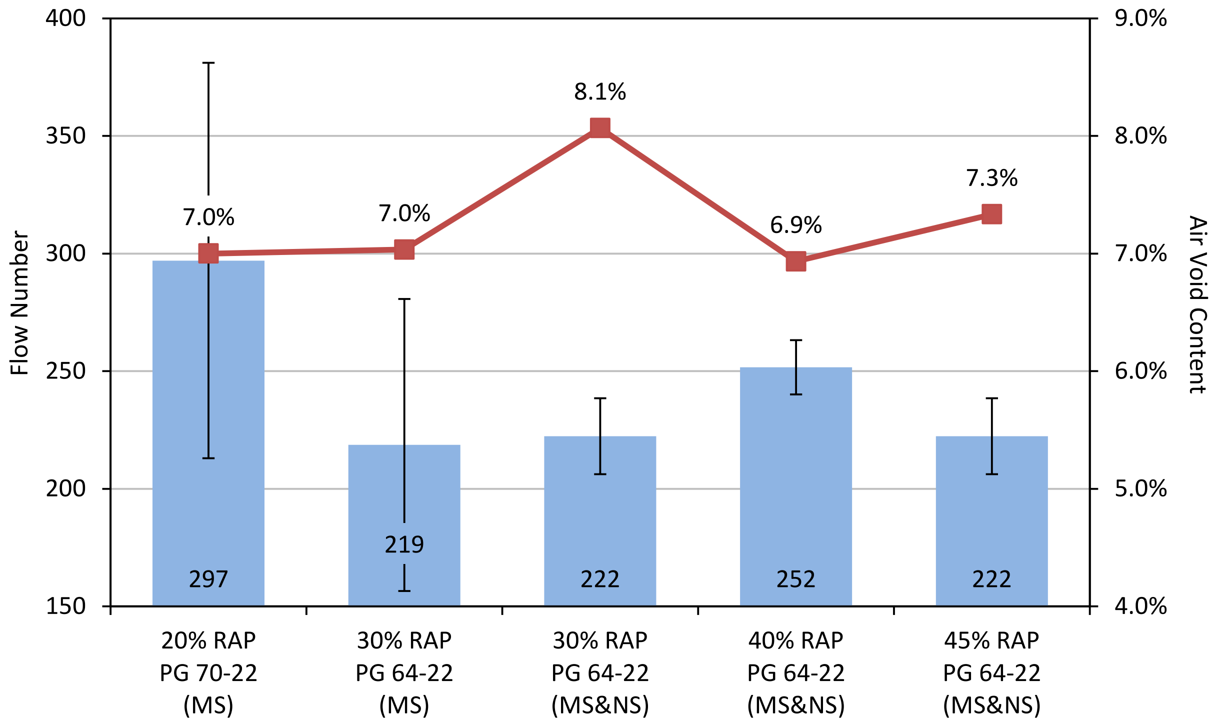

Figure 13. Flow Number Results for Onsite Prepared Specimens for SR 3 Mixtures, Unconfined Condition. I-bars indicate 1 standard deviation in results. RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

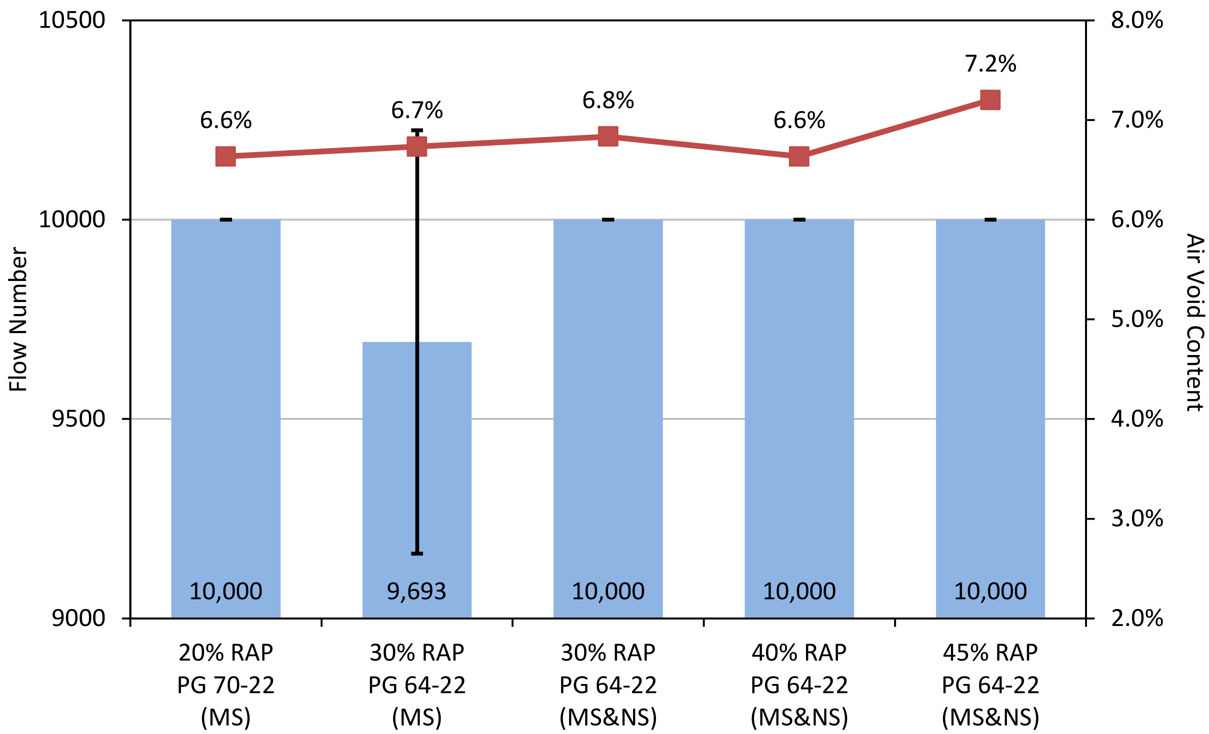

Figure 14. Flow Number Results for Reheated Specimens for SR 3 Mixtures, Confined Condition. I-bars indicate 1 standard deviation in results. RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

US 60, Cumberland County

Flow number results for US 60 are shown in Figure 15. The mixture without RAP (virgin mixture) had lower flow numbers (average value of 295) compared to the high RAP mixtures even though the virgin mixture used a PG 70-22 binder. As the RAP percentage increased, the flow number value also increased. This is due to the stiffening contribution of the increasing RAP as demonstrated earlier with the dynamic modulus results (Figure 11). All mixtures performed similarly in confined flow number testing (flow number values of 10,000), although the data are not shown. Even though the virgin mixture had lower flow numbers, it met minimum flow number criteria as recommended for the traffic levels of US 60.

CR 639, Caroline County

The 40% RAP mixture with PG 58-28 had an average flow number value in the unconfined condition of 883 (standard deviation of 240), indicating excellent rutting resistance.

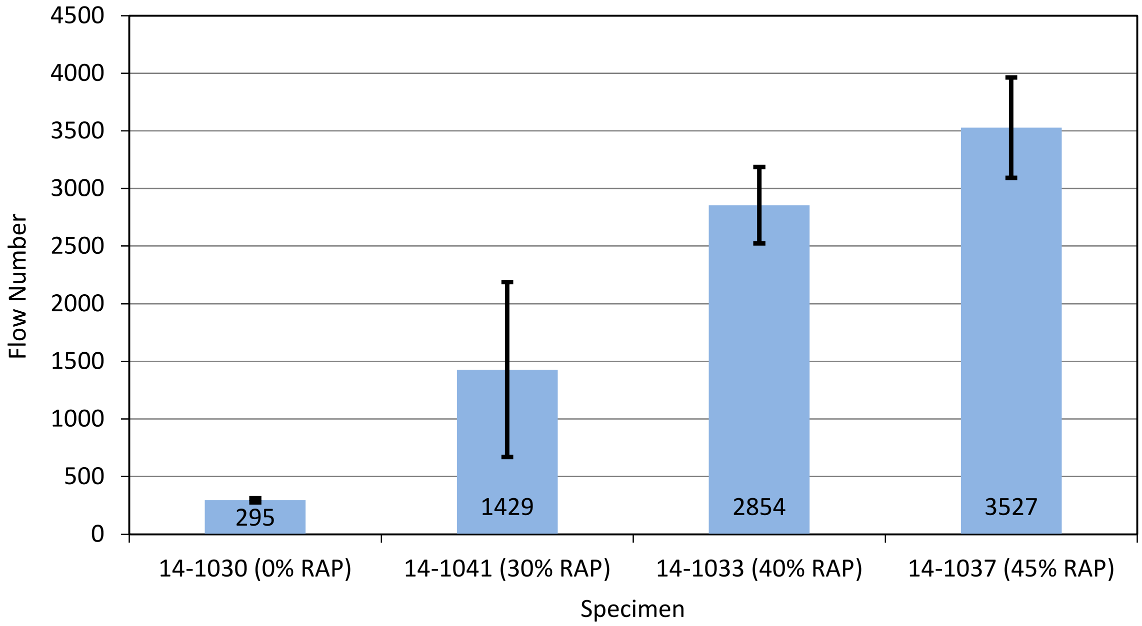

Figure 15. Flow Number of Different RAP Mixtures, Unconfined Condition, US 60. I-bars indicate 1 standard deviation in results. RAP = reclaimed asphalt pavement.

APA Rut Test Results

APA rut test results for all mixtures in the study are shown in Table 17. VDOT specifications limit deformation in the APA rut test to 7 mm and 5.5 mm, respectively, for surface mixtures designated A and D (generally, having PG 64-22 and PG 70-22 as-produced binder grades). All mixtures used in this study showed excellent rut resistance.

Table 17. Asphalt Pavement Analyzer Rut Test Results for All Mixtures

Sample ID	Air Voids, %	Specimen No.			Average
		1	2	3	
SR 3, King George County					
13-1062 (20% RAP, PG 70-22, MS)	8.4	0.94	2.07	1.10	1.37
13-1037 (30% RAP, PG 64-22, MS)	7.7	0.82	1.03	1.15	1.00
13-1041 (30% RAP, PG 64-22, MS & NS)	8.3	0.87	2.77	1.78	1.80
13-1059 (40% RAP, PG 64-22, MS & NS)	8.5	1.77	1.77	1.94	1.83
13-1052 (45% RAP, PG 64-22, MS & NS)	9.1	3.34	2.46	2.14	2.65
Sherdon Street, City of Hampton					
13-1087 (30% RAP)	8.1	2.28	1.54	1.75	1.86
13-1088 (40% RAP)	7.2	0.96	1.24	1.31	1.17
CR 639, Caroline County					
14-1014 (30% RAP)	7.5	0.43	0.68	-	0.56
14-1015 (40% RAP with PG 58-28)	8.1	2.06	1.97	2.35	2.13
US 60, Cumberland County					
14-1030 (0% RAP)	-	-	-	-	-
14-1042 (30% RAP)	8.2	3.27	2.72	2.49	2.83
14-1033 (40% RAP)	7.7	0.83	0.60	0.88	0.77
14-1037 (45% RAP)	7.8	0.16	0.60	0.59	0.45

RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

Beam Fatigue Test

Reduced resistance to fatigue cracking is a common concern with mixtures that contain higher levels of RAP. Beam fatigue test results for the SR 3 trial mixtures, along with the CR 639 (40% RAP with PG 58-28) mixture, are shown in Figure 16. It can be seen that fatigue performance was comparable except for the 40% RAP mixture from SR 3. The decreased expected fatigue life for the 40% RAP mixture is likely due in part to lower binder content. Extracted binder results (Table 19) also showed higher binder stiffness, indicating a stiffer binder in the RAP compared to the other mixtures. The 40% RAP mixture with PG 58-28 binder from CR 639 showed a higher fatigue life when compared with the 40% RAP mixture from SR 3 (which used a PG 64-22 virgin binder), indicating that improved fatigue life can be obtained using a softer binder with higher RAP mixtures.

Beam fatigue test results for high RAP mixtures from Sherdon Street are shown in Figure 17. The 30% RAP mixture showed a higher fatigue life than the 40% RAP mixture. Dynamic modulus and extracted binder values (Table 19) likewise showed a higher stiffness for 40% RAP mixtures as compared to the 30% RAP mixture.

Beam fatigue test results for US 60 are shown in Figure 18. Consistent with the dynamic modulus and binder test results, as RAP content increased, fatigue life of the mixtures decreased. As expected, the virgin mixtures showed a very high fatigue life compared to the other mixtures.

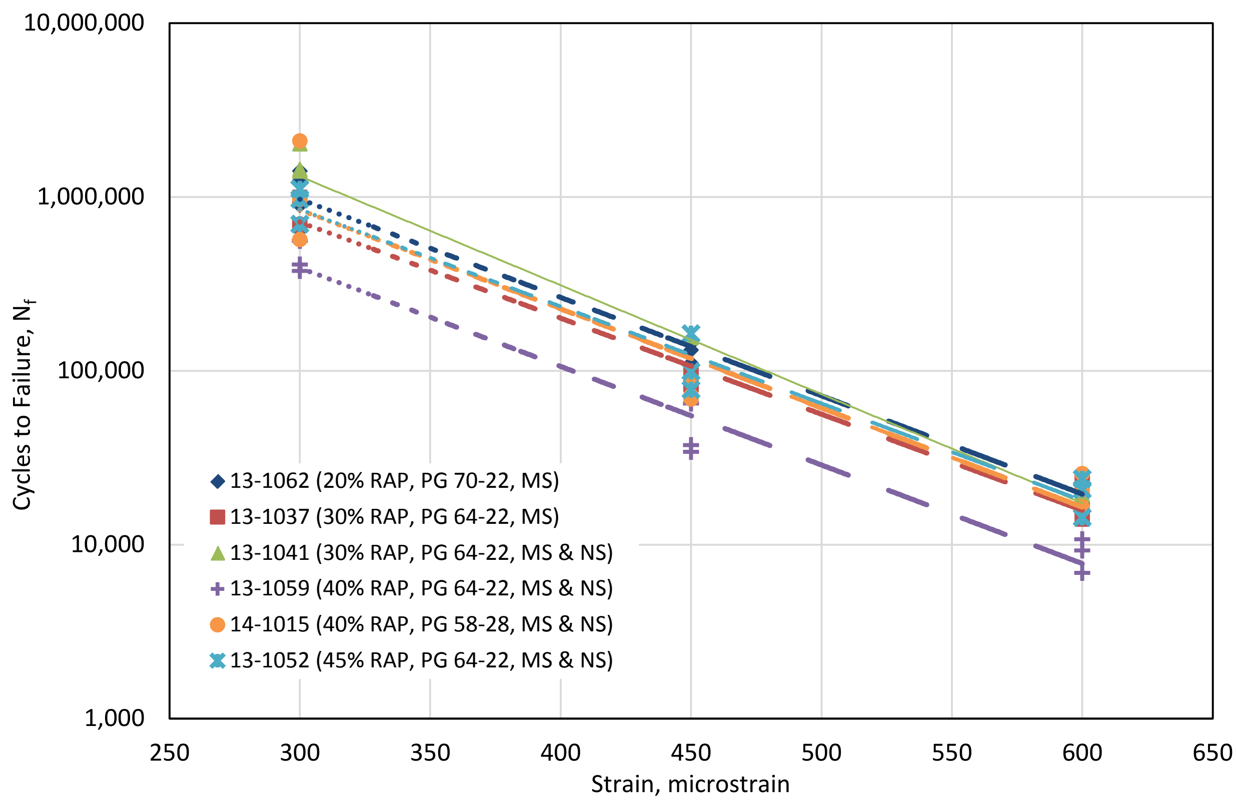

Figure 16. Beam Fatigue Test Results for Mixtures Used on SR 3 and CR 639, 40% RAP With PG 58-28. RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

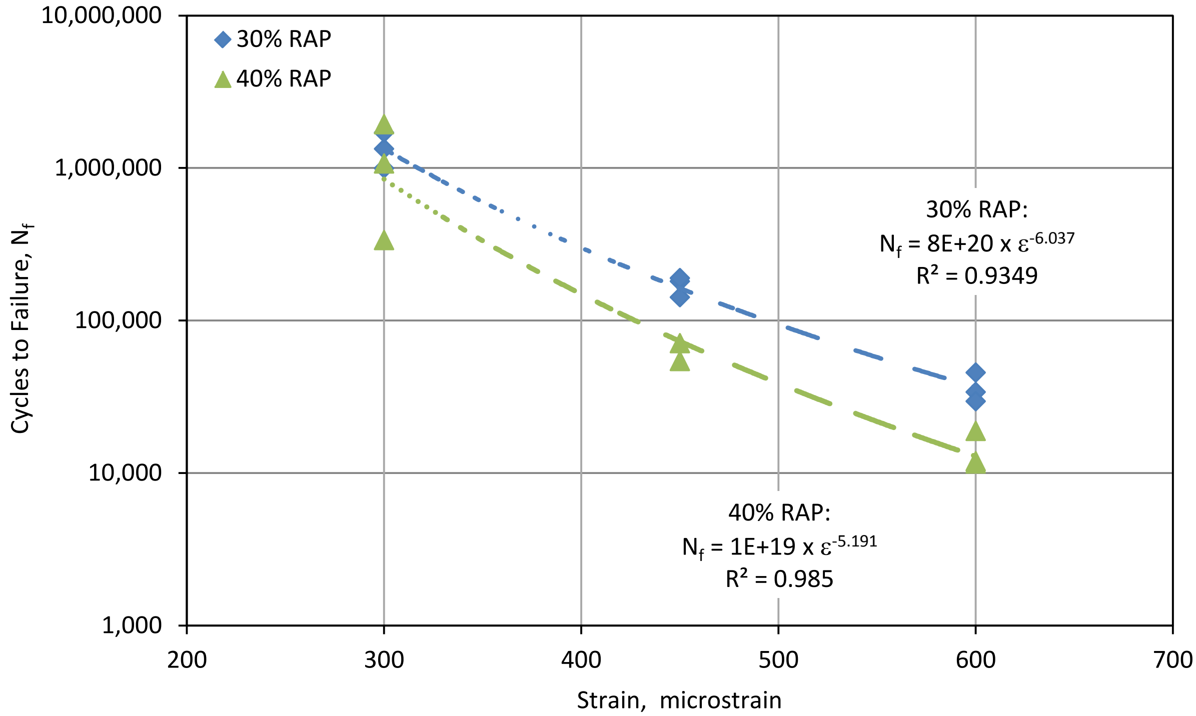

Figure 17. Beam Fatigue Test Results for Mixtures Used in Sherdon Street. RAP = reclaimed asphalt pavement.

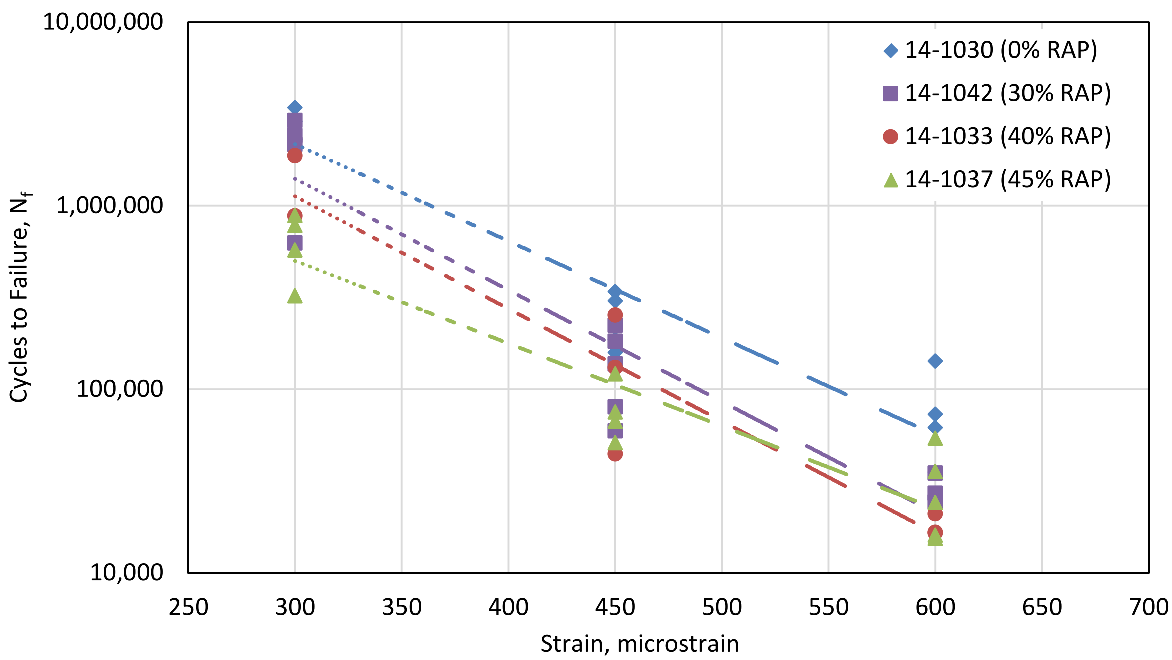

Figure 18. Beam Fatigue Test Results for Mixtures Used in US 60. RAP = reclaimed asphalt pavement.

Texas Overlay Test Results

Texas overlay test results for the SR 3 mixtures, along with the CR 639 mixtures, are shown in Figure 19 for laboratory-prepared specimens. Similar to the beam fatigue test results, the 40% RAP PG 64-22 mixture showed lower cycles to failure compared to other mixtures, indicating heightened susceptibility to reflective cracking.

The 30% RAP PG 64-22 MS mixture also showed lower cycles to failure and an increased susceptibility to reflective cracking. However, when cores were tested for this project (Figure 20), results were comparable across all mixtures except for the 20% RAP PG 70-22 mixture, which showed low cycles to failure. This may be due to higher air voids in the specimens (8.9%) compared to other mixtures.

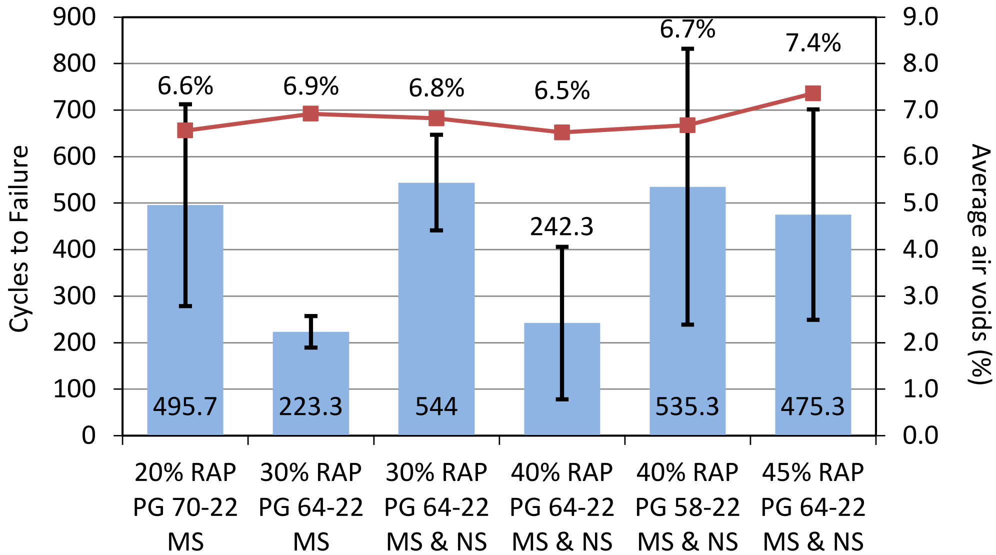

Figure 19. Texas Overlay Test Results and Air-Void Contents of Laboratory-Produced Specimens for Mixtures Used in SR 3 and CR 639. I-bars indicate 1 standard deviation in results. RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

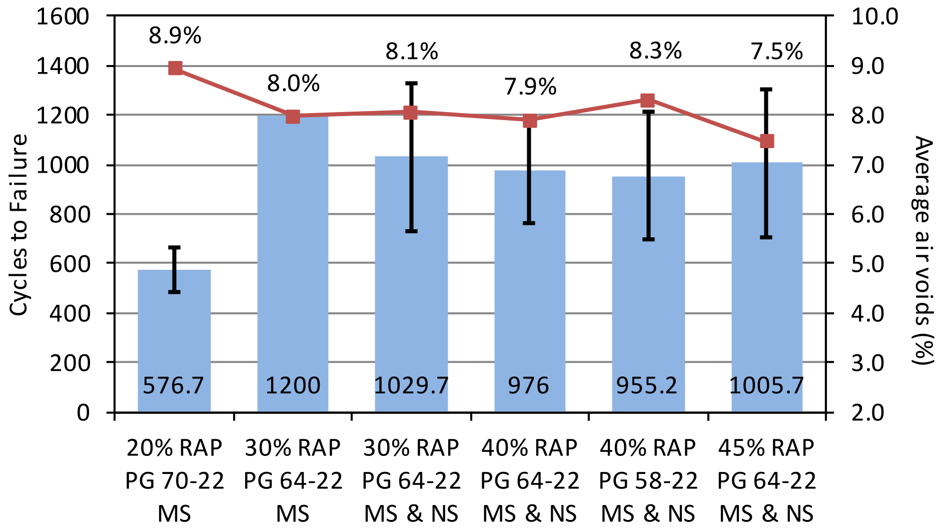

Figure 20. Texas Overlay Test Results From Field Cores for SR 3 and CR 639. I-bars indicate 1 standard deviation in results. RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand.

Overlay test results for the high RAP mixtures from Sherdon Street are shown in Figure 21. Laboratory-prepared specimens for the 30% and 40% RAP mixtures showed comparable results. However, variability in the test results was exceptionally high. When cores were tested, though, the 40% RAP mixture showed higher cycles to failure; again, test results were also highly variable.

Texas overlay test results for US 60 are shown in Figure 22. As RAP content increased, cycles to failure decreased. Beam fatigue results also showed a similar trend. As expected, the virgin mixture withstood many more cycles than the other mixtures. As explained before, lower cycles to failure for high RAP mixtures are due to the higher stiffness of the mixtures (increased stiffness in the RAP binder as shown in the binder test results) (Table 19).

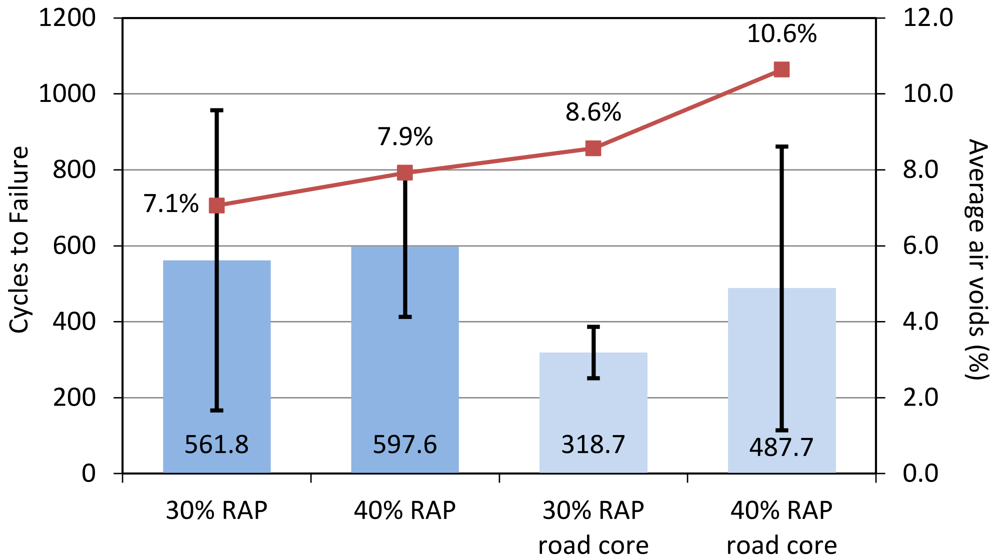

Figure 21. Texas Overlay Test Results for Mixtures Used in Sherdon Street. I-bars indicate 1 standard deviation in results. RAP = reclaimed asphalt pavement.

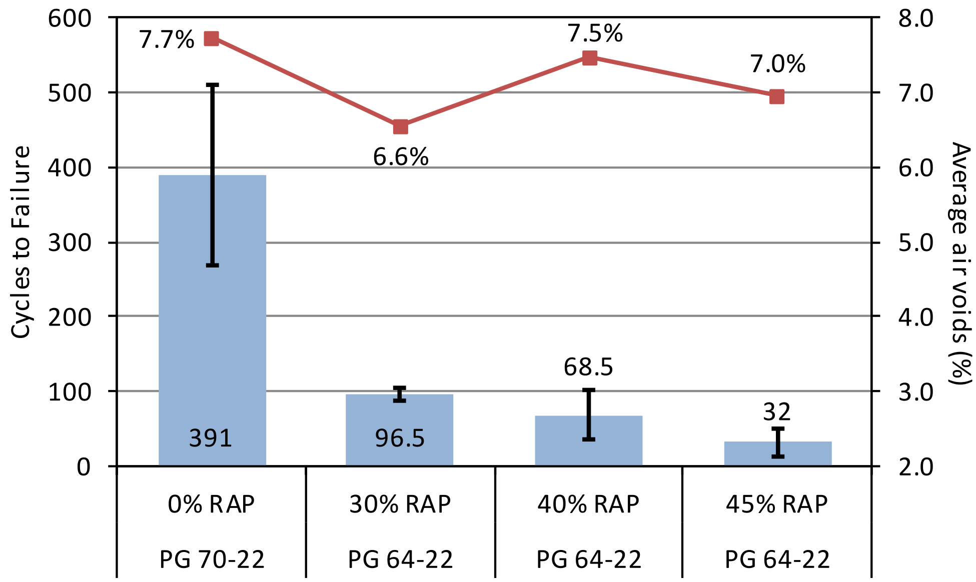

Figure 22. Texas Overlay Test Results for Mixtures Used in US 60. I-bars indicate 1 standard deviation in results. RAP = reclaimed asphalt pavement.

SCB Test

Al-Qadi et al. (2015) introduced the flexibility index (FI), which is derived from the load-displacement curves obtained from the IL-SCB test using parameters of fracture energy and slope at the post-peak inflection point to capture cracking resistance of mixtures. Their test results showed that FI values varied from 15 to 1 for the best and poorest performing laboratory-produced mixtures. The researchers also developed a correlation between the IL-SCB test method and the FI values obtained for field cores, which ranged from 1 to 25. They found that good-performing sections had FI values greater than 10 and sections with an FI less than 6 showed premature cracking (Al-Qadi et al., 2015).

SCB test results using laboratory-prepared samples are shown in Figure 23. Test results of SCB testing of field cores are shown in Figure 24. For SR 3, 20%, 30%, and 40% RAP mixtures had similar FI values. These values were much lower than the Illinois FI criteria for good-performing pavements. The virgin mixture from US 60 had higher FI numbers, using both laboratory-prepared specimens (average FI value of 7) and specimens prepared from field cores (average FI value of 16). The difference in FI values for laboratory and field cores may be due to additional stiffening of the laboratory-prepared samples because of the reheating necessary to make the specimens. Differences may also result from variability in air voids and thickness with the field cores. The FI results for US 60 indicated brittle behavior (lower failure strain and lower mixture fracture energy) for the 40% and 45% RAP mixtures.

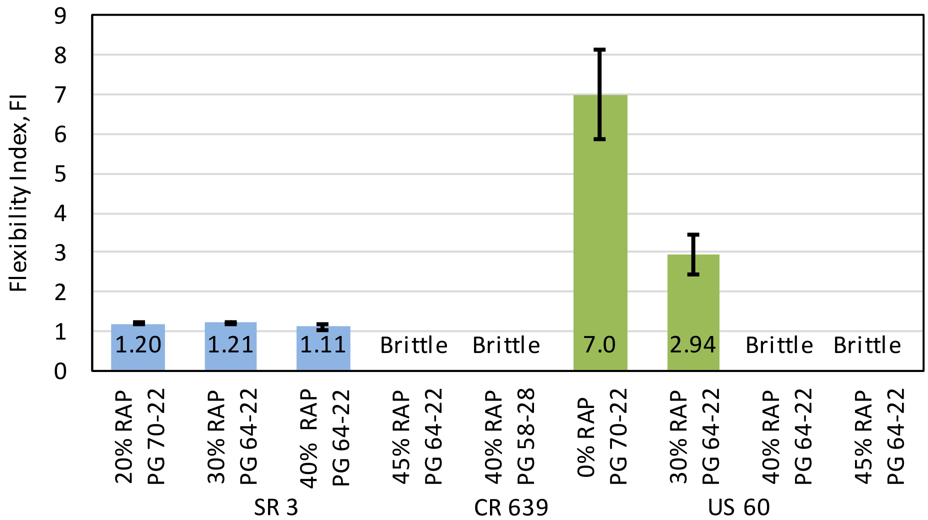

Figure 23. Semi-Circular Bend Test Results for All Mixtures. I-bars indicate 1 standard deviation in results. RAP = reclaimed asphalt pavement.

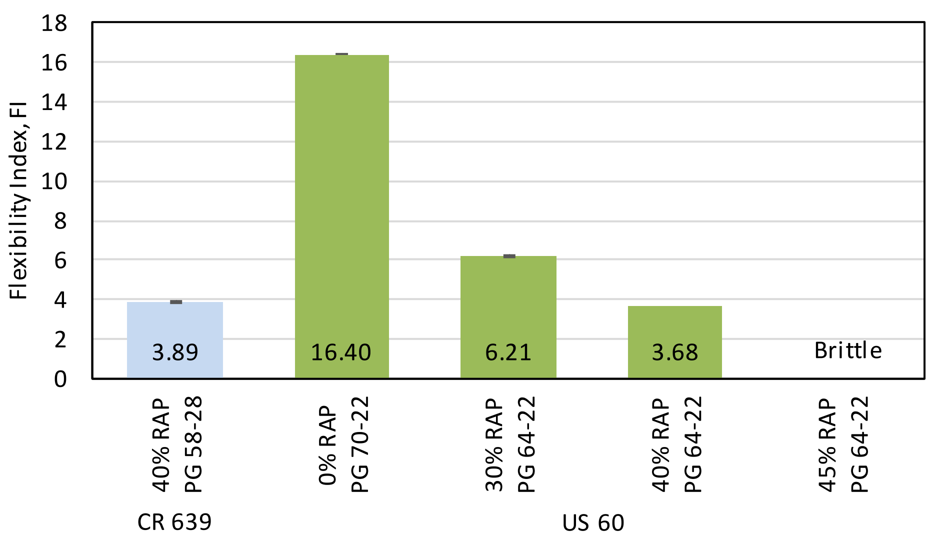

Figure 24. Semi-Circular Bend Test Results for CR 639 and US 60 From Field Cores. I-bars indicate 1 standard deviation in results. RAP = reclaimed asphalt pavement.

Cantabro Test Results

Cantabro test results for all mixture are shown in Figure 25. Most mixtures showed lower mass loss (approximately 7% or less), which may indicate better durability. Exceptions included the 30% and 40% RAP mixtures from SR 3 and Sherdon Street and the 45% RAP material from US 60.

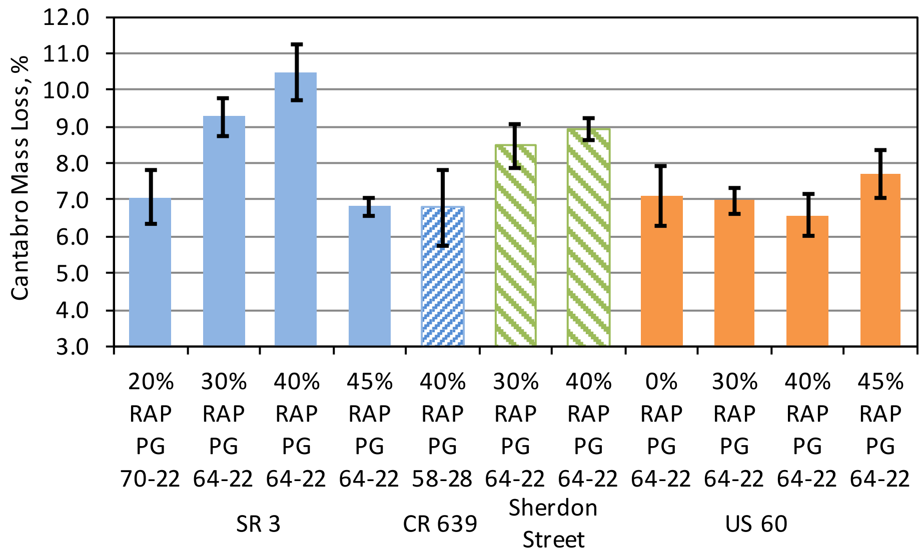

Figure 25. Cantabro Mass Loss Results for All Mixtures. I-bars indicate 1 standard deviation in results. RAP = reclaimed asphalt pavement.

Asphalt Binder Testing

RAP samples were collected during different mixture production days for SR 3. The corresponding extracted RAP binder test results are shown in Table 18. In general, RAP stockpiles used on different days showed consistent binder test results (high temperature grades were similar with only two RAP samples showing different low temperature grades).

Table 19 shows test results for the virgin binder and the binder as extracted from the mixture. With the exception of the 40% RAP mixture, the SR 3 mixtures showed similar binder grades, even with 45% RAP. All mixtures met VDOT's specification for binders in the mixture. For US 60, both the 40% and 45% RAP mixtures showed higher extracted binder stiffness. This was also reflected in the cracking test results. Percentage recovery for all mixtures was lower, as none of the mixtures used polymer-modified binder.

Table 18. Test Results of Extracted RAP Binder for SR 3

Test	**Sampling Date**						
	6/12	**6/13**	**6/14**	**6/17**	**6/18**	**6/19**	**6/25**
High Failure Temperature, °C	86.1	85.3	89.3	87.6	88.5	89.0	88.5
Intermediate Failure Temperature, °C	29.8	28.6	33.6	30.5	32.0	32.9	32.0
Stiffness Low Failure Temperature, °C	-9.5	-9.7	-7.5	-9.9	-8.3	-7.8	-8.6
m-value Low Failure Temperature, °C	-6.7	-6.4	-1.5	-6.7	-7.0	-6.6	-5.6
Performance Grade	82-16	82-16	82-10	82-16	82-16	82-16	82-10

RAP = reclaimed asphalt pavement.

Table 19. Base and Extracted Binder Test Results for All Projects

Sample Source	Binder Property	SR 3, King George County					Sherdon Street, City of Hampton		CR 639, Caroline County	US 60, Cumberland County			
		20% RAP MS 13-1062	30% RAP MS 13-1037	30% RAP MS & NS 13-1041	40% RAP MS & NS 13-1059	45% RAP MS & NS 13-1052	30% RAP 13-1087	40% RAP 13-1088	40% RAP 14-1015	0% RAP	30% RAP	40% RAP	45% RAP
Base Binder (tank sample)	Performance Grade	70-22	64-22	64-22	64-22	64-22	70-22	70-22	58-28	70-22	64-22	64-22	64-22
	Non-Recoverable $J_{nr100Pa}$	0.6645	2.368	2.383	2.39	2.327	1.162	1.162	2.015	1.36	2.103	1.899	2.171
	Non-Recoverable $J_{nr3200Pa}$	0.7514	2.562	2.587	2.58	2.521	1.304	1.304	2.218	1.529	2.369	2.138	2.441
	Avg. % Recovery R_{100Pa}	22.43	4.262	4.439	4.313	4.424	11.74	11.74	5.339	10.24	6.866	7.715	6.679
	Avg. % Recovery R_{3200Pa}	14.81	1.598	1.627	1.553	1.604	5.46	5.46	1.925	4.373	2.32	2.699	2.253
	ΔT_c, ºC	-1.8	-0.6	-0.2	-0.1	-1.2	0.7	0.7		0.5	0.9	0.5	0.5
Extracted Binder	Performance Grade	76-22	76-16	76-16	82-16	76-16	70-22	76-22	-	70-22	76-22	82-16	82-16
	Non-Recoverable $J_{nr100Pa}$	0.3924	0.4065	0.5915	0.1566	0.3354	0.8324	0.6579	-	0.8366	0.6884	0.207	0.288
	Non-Recoverable $J_{nr3200Pa}$	0.4219	0.4296	0.6322	0.1622	0.3517	0.9003	0.7101	-	0.9136	0.7516	0.2182	0.3052
	Avg. % Recovery R_{100Pa}	24.46	18.92	14.24	33.32	19.71	11.7	13.93	-	13.03	15.01	27.07	23.5
	Avg. % Recovery R_{3200Pa}	19.38	14.76	10.03	30.43	16.05	6.842	8.974	-	7.788	9.752	23.4	19.44
	ΔT_c, ºC	-2.3	-11.5	-12.2	-11.4	-9.9	-1.6	-1.7	-	-2.6	-2.4	-8.6	-10.1

RAP = reclaimed asphalt pavement; MS = manufactured sand; NS = natural sand; - = not tested.

The relationship of the MSCR test specification parameter (J_{nr}) to in-service rutting has been documented elsewhere (FHWA, 2011). With the MSCR test specification, the maximum J_{nr} requirement for standard traffic is 4.0 kPa^{-1}. For heavy, very heavy, and extremely heavy traffic, the required J_{nr} is 2.0, 1.0, and 0.5 kPa^{-1}, respectively. MSCR tests for this study were performed at 64°C. For all mixtures, the J_{nr} value for extracted binder was <1, indicating more than adequate rutting resistance for the relevant traffic levels for these routes. Rut test results from the APA and flow number tests also showed adequate rutting resistance for all mixtures used in this study.

ΔTc is an indicator of non-load related cracking susceptibility and is calculated as the difference between the critical temperature for stiffness and m-value for a binder (i.e., the numerical difference between the low continuous grade temperature determined from the bending beam rheometer stiffness criteria, the temperature where stiffness, S, equals 300 MPa) and the low continuous grade temperature determined from the m-value (the temperature where m equals 0.300). Minimum thresholds for ΔT_{cr} of -2.5 and -5.0 representing the cracking warning and cracking limit, respectively, have been recommended in previous work (Anderson et al., 2011).

From Table 19 it can be seen that there can be considerable differences between the ΔTc values for the base binder (determined from tank samples) and those determined from binder extracted from the mixtures. This difference is due to a combination of changes in the base binder during production as well as the incorporation of the aged RAP binder into the mixture. The properties of the RAP binder are particularly influential and change based on the properties of the RAP source. Evaluation of the ΔTc values indicated that RAP content has varying impacts on ΔTc. The US 60 mixture containing 0% RAP had a ΔTc value of -2.6, falling into the cracking warning area, and the US 60 and SR 3 20% RAP mixture, both Sherdon Street mixtures (containing 30% and 40% RAP), and the US 60 30% RAP mixture fell below the warning limit and should not be susceptible to non-load related cracking. The SR 3 30%, 40%, and 45% RAP mixtures all had ΔTc values exceeding the 5.0 cracking limit, as did the US 60 45% RAP mixture, indicating susceptibility to non-load related cracking.

Field Performance

Data on early-age field performance for SR 3 were extracted from VDOT's PMS. Table 20 shows the international roughness index, rut depth, and critical condition index for this project for the last 3 years. Based on the results, the early-age performance of this section was excellent. Sections with higher RAP mixtures did not show any premature cracking. Figure 26 shows part of the section after 3 years in service.

Table 20. PMS Data for SR 3

Mile Marker From	Mile Marker To	After Paving		
		IRI (in/mile)	Rut Depth (in)	CCI (year of data collection)
12.61	19.73	63	0.07	100 (2014)
		67	0.10	99 (2015)
		66	0.10	98 (2016)
		64	0.11	96 (2017)

PMS = VDOT's Pavement Management System; IRI = international roughness index; CCI = critical condition index.

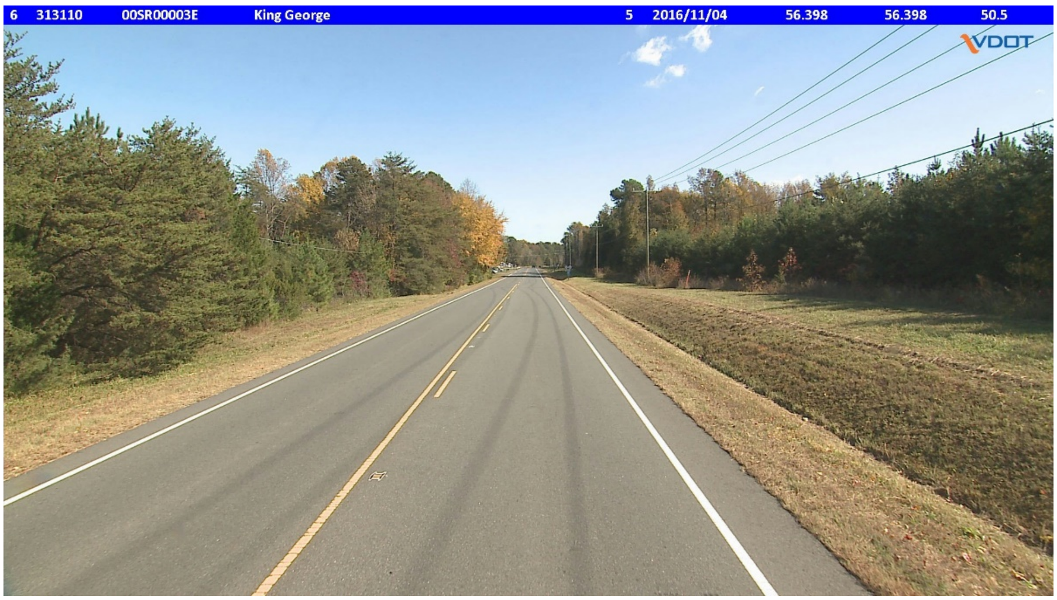

Figure 26. SR 3 Project After 3 Years

The 2-year performance of US 60 is shown in Table 21, and Figure 27 shows a view of the pavement. The early-age performance of this section was also excellent and did not appear to vary with RAP content in the surface mixture.

Performance data for Sherdon Street and CR 639 were not available in VDOT's PMS.

Table 21. PMS Data for US 60

Mile Marker From	Mile Marker To	After Paving		
		IRI (in/mi)	Rut Depth (in)	CCI (year of data collection)
20.13	25.51	77	0.07	100 (2015)
		76	0.09	99 (2016)
		78	0.12	95 (2017)

PMS = VDOT's Pavement Management System; IRI = international roughness index; CCI = critical condition index.

Figure 27. US 60 Project After 2 Years

Summary of Findings

SR 3 and CR 639 Trials

- Dynamic modulus results indicated that the PG 64-22 binder used in RAP-containing mixtures was being stiffened by the RAP binders, resulting in dynamic modulus values greater than those with the PG 70-22 mixture.

- Comparison of the 40% RAP mixtures produced with PG 58-28 and PG 64-22 binders showed that stiffness of the mixture was reduced when a softer binder grade was used.

- All SR 3 mixtures had similar flow number results when tested in the confined condition. When tested in the unconfined condition, all mixtures had flow numbers sufficient to resist rutting under the expected traffic levels (i.e., higher than recommended minimums).

- APA rut test results indicated excellent rutting resistance.

- Beam fatigue results indicated that the SR 3 and CR 639 mixtures had similar fatigue performances with the exception of the SR 3 40% RAP mixture, which showed a lower fatigue life as well as higher binder and mixture stiffness. The 40% RAP mixture with PG 58-28 binder from CR 639 showed a higher fatigue life when compared with the 40% RAP mixture from SR 3 (which used a PG 64-22 virgin binder).

- Texas overlay test results for laboratory-prepared specimens indicated that the 30% and 40% RAP PG 64-22 mixtures survived fewer cycles to failure, indicating heightened susceptibility to reflective cracking. However, testing of field cores indicated that all mixtures were comparable except the 20% RAP PG 70-22 mixture, which showed lower cycles to failure (with higher air voids in the core specimens).

- Laboratory-prepared specimens of the 20%, 30%, and 40% RAP mixtures had similar FI values. These values were much lower than the Illinois FI criteria for good-performing pavements. Laboratory-prepared specimens for the 45% RAP mixture and the CR 639 40% RAP mixture showed brittle behavior.

- Results of SCB testing of field cores from the CR 639 40% RAP mixture showed higher FI values compared to laboratory-prepared samples, although they were still lower than the Illinois FI criteria.

- Cantabro testing indicated good durability for the 20% RAP and 45% RAP mixtures from SR 3 and the 40% RAP mixture from CR 639. The 30% and 40% RAP mixtures from SR 3 had mass losses exceeding that recommended for better durability (i.e., more than 7.5%).

- Extracted binder results for the SR 3 mixtures showed lower binder stiffness.

- PMS data indicated that the early-age performance of the SR3 sections was excellent, with no indications of premature cracking.

Sherdon Street Trial

- In general, the 40% RAP mixture showed higher stiffness compared to the 30% RAP mixture, as expected.

- APA rut test results indicated excellent rutting resistance.

- The 30% RAP mixture showed a higher fatigue life than the 40% RAP mixture. Dynamic modulus and extracted binder test results likewise showed higher stiffness for 40% RAP mixtures as compared to the 30% RAP mixture.

- Laboratory-prepared specimens for the 30% and 40% RAP mixtures had comparable overlay test results. However, variability in the test results was exceptionally high. When cores were tested, though, the 40% RAP mixture showed higher cycles to failure; again, test results were highly variable.

- Cantabro testing indicated comparable mass losses for both mixtures; however, those losses slightly exceeded the value recommended for good durability.

US 60 Trial

- A higher compaction effort was required for the 45% RAP mixture compared to the 0%, 30%, and 40% RAP mixtures.

- All RAP mixtures (produced using PG 64-22 base binder) had higher dynamic modulus values compared to the virgin mixture, which used a PG 70-22 binder.
- For these mixtures, as RAP percentages increased, stiffness also increased.
- As RAP content increased, the unconfined flow number for the mixtures also increased; however, even the minimum flow number (in the virgin mixture with PG 70-22 binder) exceeded the minimum flow number criteria as recommended for the traffic levels for US 60.
- APA rut test results indicated excellent rutting resistance.
- The 0% RAP mixture showed a very high fatigue life compared to the other mixtures. As RAP content increased, fatigue life decreased compared to the virgin mixture.
- Texas overlay test results indicated that as RAP content increased, cycles to failure decreased. This corresponded with the increasing stiffness of the mixtures and extracted binders.
- The 0% RAP mixture had higher FI numbers than the RAP-containing mixtures, using both laboratory-prepared specimens and specimens prepared from field cores. With the exception of the lone virgin mixture tested (0% RAP), the Illinois FI criteria would indicate that all the mixtures were cracking susceptible. FI results showed brittle behavior for the laboratory-prepared specimens from the 40% and 45% RAP mixtures and the 45% RAP mixture field cores.
- Cantabro testing indicated similar mass losses for all mixtures; the 45% RAP mixture slightly exceeded the maximum loss recommended for better durability.
- Binder stiffness (dynamic modulus, etc.) increased as the percentage of RAP in the mixture increased.
- The early-age performance of the US 60 high RAP mixtures was excellent and did not appear to vary with RAP content in the surface mixture.

General Findings

- With the exception of one 45% RAP mixture (SR 3), all tested mixtures met VDOT specification requirements for volumetrics and gradation.
- Isolated segregation was observed on some of the high RAP mixtures.

- All high RAP mixtures met VDOT's requirement for in-place density.

- In general, mixtures met VDOT's requirement for permeability. The presence of natural sand in some mixtures was coincident with lower permeability.

- All other things held equal, as RAP content increased, dynamic modulus also increased.

- All mixtures showed excellent rutting resistance based on flow number testing, regardless of RAP content. In general and as expected, mixtures with higher percentages of RAP showed better rutting resistance. The presence of natural sand (<11% in this study) did not affect the rutting characteristics of the mixtures.

- Confined flow number tests did not differentiate mixtures used in this study.

- APA rut test results showed excellent rutting resistance for all mixtures used in this study. Mixtures with higher RAP percentages showed very low APA rut depths.

- Texas overlay test results were consistent with beam fatigue results. In general, when the dynamic modulus and binder stiffness increased, fewer cycles to failure were observed.

- As expected, SCB test results showed higher FI numbers for virgin mixtures compared to higher RAP mixtures. Based on SCB testing, all 45% RAP mixtures showed brittle behavior. With the exception of the lone virgin mixture tested (0% RAP), the Illinois FI criteria would indicate that all mixtures were cracking susceptible.

- In general, the Cantabro test results showed adequate durability for most of the mixtures in this study. The highest mass losses occurred with the 30% and 40% RAP mixtures.

- For all mixtures, the J_{nr} value of the extracted binder was <1, indicating more than adequate rutting resistance for the relevant traffic levels for these routes. APA rut test results and flow number results also indicated adequate rutting resistance for all mixtures used in this study.

- Evaluation of the ΔTc values indicated that RAP content had a varying impact on ΔTc, which indicated that some of the high RAP mixtures may be susceptible to non-load related cracking.

- There were considerable differences between the ΔTc values for the base binder (determined from tank samples) and those determined from binder extracted from the mixtures.

- The 2- to 3-year field performance showed that all sections were performing well with no premature failures regardless of the RAP content. The international roughness index and rut test results also indicated a good early-age performance for these sections.

CONCLUSIONS

- *Mixtures containing up to 45% RAP can be designed, produced, and placed provided that proper procedures are followed and attention to detail is paid during design, production, and construction. Excellent rutting resistance can be achieved with high RAP mixtures.*

- *Beam fatigue testing suggests that improved fatigue life can be obtained using a softer binder with higher RAP mixtures.*

- *Cracking resistance of high RAP mixtures (as determined through laboratory performance tests) is associated with mixture and binder stiffness: lower stiffness is associated with better cracking resistance.*

- *Laboratory performance tests of both the mixture and extracted binder show promise for discriminating the cracking susceptibility of asphalt mixtures.*

RECOMMENDATIONS

1. *VTRC should continue to monitor the high RAP projects in this study to evaluate their long-term field performance*. Actual field performance will be key to assessing the practical discriminating power of the laboratory performance tests.

2. *VTRC and VDOT's Materials Division should work together to install more field projects with high RAP mixtures*. To encourage mixture durability, a performance-based specification should be used to design, produce, and accept further trial mixtures.

IMPLEMENTATION AND BENEFITS

Implementation

Recommendation 1 will be implemented by VTRC through a technical assistance project to monitor the field performance of the 2014 higher RAP trials. Field visits will be conducted periodically to collect cores, which will be used to assess material aging and to conduct laboratory performance testing. These data will be coupled with surface condition state data from VDOT's PMS.

For Recommendation 2, several high RAP field trials are planned for the 2019 construction season. VTRC and VDOT's Materials Division have developed a performance-related specification for these trials.

Benefits

The results of this study provided a greater understanding of the production and placement impacts, as well as the resulting performance implications, of using increasing amounts of RAP in asphalt mixtures. This improved insight may influence future specifications and assist in the proper design of mixtures to optimize performance.

Implementing Recommendation 1 will help VDOT identify laboratory tests that best relate laboratory performance with long-term field performance. Correlation of field and laboratory performance will provide a basis for design, acceptance, and perhaps even payment decisions for use in performance-oriented specifications.

Implementing Recommendation 2 will develop more experience with increased use of reclaimed material, which will reduce growing RAP stockpiles and promote lower material prices. Concurrent development and application of performance-based specifications will help ensure that VDOT does not sacrifice performance for higher levels of reuse and lower pricing.

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