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# Laboratory Evaluation of Asphalt Concrete Mixtures Containing High Contents of Reclaimed Asphalt Pavement (RAP) and Binder

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**FINAL REPORT**

**LABORATORY EVALUATION OF ASPHALT CONCRETE MIXTURES  
CONTAINING HIGH CONTENTS OF RECLAIMED ASPHALT PAVEMENT (RAP)  
AND BINDER**

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## ABSTRACT

This study investigated the effect of added asphalt binder content on the performance and volumetric properties of asphalt concrete mixtures containing reclaimed asphalt pavement (RAP) in the amounts of 0%, 20%, and 40%. A laboratory-produced mixture containing 100% RAP was also evaluated. Performance of the mixtures was evaluated based on three criteria: stiffness (dynamic modulus), fatigue resistance, and rutting resistance (flow number and asphalt pavement analyzer).

Results showed that a 0.5% increase in binder content improved both the fatigue and rutting resistance of the 0% and 20% RAP mixtures with only slight (insignificant) decreases in dynamic modulus. However, the addition of various amounts of binder to the 40% RAP mixture led to a significant decrease in rutting resistance with little or no improvement to fatigue resistance. Volumetric analysis was performed on all of the mixtures, and detailed results are presented.

Based on the results of the study, the authors recommend that the Virginia Department of Transportation supplement current asphalt mixture design procedures that are based on mixture volumetric properties with laboratory-mixture performance testing.

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## **INTRODUCTION**

Currently the percentage of reclaimed asphalt pavement (RAP) material permitted for use in asphalt concrete mixtures by the Virginia Department of Transportation (VDOT) is limited to 30% by weight for surface mixtures and 35% for base mixtures. In practice, mixtures with RAP percentages above 25% are considered “high RAP” mixtures, for which some states (not Virginia) require more testing and the use of blending charts to aid in binder selection (Copeland et al., 2010; Daniel et al., 2010). This differs from binder selection for mixtures with lower percentages of RAP, where there is either no change in binder selection when the percentage of RAP is below 15% or a binder “bump” of one performance grade (PG) lower (“softer” binder) for RAP percentages between 15% and 25%. “Softer” binders are used when the percentage of RAP increases in order to mitigate the effects that the stiff aged RAP binder has on the composite mixture. The use of RAP reduces the use of virgin aggregates and asphalt binder, which has positive environmental and economic impacts. In general, it has been found that incorporating RAP improves the dynamic modulus and rutting resistance of mixtures (Hong et al., 2010; Li et al., 2008). On the other hand, one of the disadvantages of high-RAP mixtures is the potential decrease of the mixture’s fatigue cracking resistance (West et al., 2009). Related to this issue, Maupin and Diefenderfer (2006) suggested increasing the asphalt content of underlying layers to produce dense mixtures with improved fatigue and durability characteristics. To prevent mixture instability-related rutting problems, Maupin and Diefenderfer (2006)

incorporated RAP into the mixture to help maintain stiffness as an alternative to using a stiffer binder. The authors found that the increased binder content in the resulting mixture improved, or had the potential to improve, durability, permeability, and fatigue characteristics.

## **PURPOSE AND SCOPE**

The purpose of this study was to quantify the effects of mixture binder content on the design and performance of RAP surface mixtures containing different amounts of RAP (0%, 20%, 40%, and 100% by weight of mixture). Mixture performance was evaluated using the dynamic modulus test, the flow number test, the Asphalt Pavement Analyzer (APA) rutting test and the third-point beam fatigue test. Three different percentages of RAP (0%, 20%, and 40%) were investigated at three different binder contents (design, design + 0.5%, and design + 1.0%) while for the 100% RAP mixture, the binder contents tested were RAP with no added binder, RAP with 0.5% added binder, RAP with 1.0% added binder, and RAP with 1.5% added binder. The specific steps performed in this research were as follows:

1. Conduct a literature review on previous and on-going studies related to the usage of higher percentages of RAP and asphalt binder in asphalt mixtures and the subsequent effects.
2. Determine the effect of binder content on mixture performance: perform dynamic modulus testing, fatigue testing using the flexural beam setup, and rutting testing using the flow number test and the APA test on all mixtures in the study.
3. Determine the effect of binder content on mixture volumetric properties using the Superpave gyratory compactor (SGC) at a compaction effort of 65 gyrations.

## **METHODS**

### **Literature Review**

Many researchers have studied the mechanical properties and performance of RAP mixtures and the results of some studies are summarized here. Additionally, a brief synopsis of the Superpave mix design process including volumetric property requirements is presented and current issues surrounding the Superpave design compaction effort and the effect on design asphalt content and mixture durability are discussed.

### **Dynamic Modulus**

In a study conducted by Li et al. (2004), researchers tested ten Minnesota asphalt mixtures with three percentages of RAP (0%, 20%, and 40%) in order to determine the effect of RAP on the dynamic modulus. The results of the study indicated that as the amount of RAP in the mixture increased, the dynamic modulus also increased (Li et al., 2004). The incorporation of RAP in asphalt concrete was also found to increase the dynamic modulus of mixtures during a

2007 study by the Oklahoma DOT. While performing dynamic modulus testing on Oklahoma asphalt concrete mixtures with the goal of establishing a simpler process for producing dynamic modulus master curves, Cross et al. (2007) found that mixtures incorporating 25% RAP had a higher average stiffness than non-RAP mixtures. This increase in stiffness was equated to the stiffness increase produced by increasing the PG binder grade by one level (Cross et al., 2007). Researchers in Illinois also performed dynamic modulus testing on 0%, 20%, and 40% RAP mixtures in a 2009 study (Al-Qadi et al., 2009). The overall goal of the study was to determine the degree of blending that takes place between the hardened RAP binder and the virgin aggregate in the mix. Dynamic modulus testing indicated that RAP percentage did affect the dynamic modulus of the mix; however, the results also showed that the dynamic modulus of the 20% RAP specimens did not change significantly from the 0% RAP specimens. The mixture containing 40% RAP did show a significant increase in stiffness as compared to the 0% RAP mixture, which researchers felt warranted a double binder bump in PG binder selection (Al-Qadi et al., 2009).

### **Rutting Resistance (Flow Number)**

Rutting resistance of Virginia asphalt concrete mixtures containing RAP was studied by Apeageyi et al. (2011) using the Repeated Load Permanent Deformation (RLPD) test. Eighteen asphalt concrete mixtures commonly used in Virginia containing between 0% and 25% RAP were subjected to a 207 kPa (30 psi) haversine load at 130°F in order to determine the flow number (FN). FNs determined using the Francken model showed that rutting resistance of mixtures containing 0% RAP was similar to those containing 25% RAP. Mixtures containing percentages of RAP between those two levels exhibited the highest rutting resistance. Results also showed that 25% RAP mixtures produced with PG 64-22 binder had unexpectedly low rutting resistance compared to those using PG 70-22 (Apeageyi et al., 2011). Al-Qadi et al. (2012) studied the effects of RAP percentage and binder bumping on the flow number for asphalt concrete mixtures containing 0%, 30%, 40%, and 50% RAP. The researchers found that increasing the RAP resulted in a higher flow number (more rutting resistance) while bumping the binder to a softer grade resulting in a lower flow number (less rutting resistance).

### **Fatigue Resistance**

One of the primary concerns of the use of RAP in asphalt concrete mixtures is a reduction in fatigue resistance. Although this would tend to be the obvious conclusion considering the aged, stiff RAP binder in RAP mixtures, the results of fatigue studies indicate mixed results. Note that in all reviewed studies the mixtures were designed assuming all binder from the RAP is available to mix with the aggregates. McDaniel et al. (2000) investigated the effects of RAP on asphalt concrete as part of NCHRP Project 9-12, Incorporation of Reclaimed Asphalt Pavement in the Superpave System. In the study, mixtures with four different percentages of RAP (0%, 10%, 20%, and 40%) and two binder levels (PG 52-34 and PG 64-22) were evaluated for performance, which included fatigue testing using the four-point beam fatigue test. The results of testing showed that fatigue resistance of asphalt concrete mixtures containing higher amounts of RAP significantly decreases unless the binder is bumped to a softer grade. They also found that there was not a statistically significant difference in the fatigue life for mixtures containing less than 20% RAP as compared to the virgin mixtures (McDaniel et al., 2000). Contrary to this



result, fatigue testing of RAP mixtures performed by Shu et al. (2008) and Al-Qadi et al. (2012) showed that the incorporation of RAP in mixtures actually led to a slight increase in fatigue life. Shu et al. (2008) tested mixtures containing 0%, 10%, 20% and 30% RAP with a PG 64-22 binder using the beam fatigue fixture at  $600\mu\epsilon$  controlled strain. Mixtures containing higher percentages of RAP performed better based on a 50% stiffness reduction criterion. However, the authors also evaluated the incremental damage at each cycle and observed that after a number of cycles, the incremental damage leveled off to a constant value. They defined the plateau value (PV) as the ratio of this constant value to the damage incurred during the first cycle and noticed that the PV was larger for mixtures containing higher percentages of RAP and therefore, based on the PV criterion, mixtures containing higher percentages of RAP perform worse (large PV means relatively larger damage compared to damage during the first cycle). Al-Qadi et al. (2012) also used the four-point beam fatigue test and evaluated fatigue life at six controlled strain levels ( $1000\mu\epsilon$ ,  $800\mu\epsilon$ ,  $700\mu\epsilon$ ,  $500\mu\epsilon$ ,  $400\mu\epsilon$ , and  $300\mu\epsilon$ ). Though results did indicate a slight improvement in fatigue life with the incorporation of RAP, the researchers also stated that single and double bumping of PG binder grade for higher levels of RAP was necessary to achieve those results (Al-Qadi et al., 2012).

### **Superpave Volumetric Properties**

Superpave, short for Superior Performing Asphalt Pavements, was the result of a 1987 Strategic Highway Research Program (SHRP) initiative to create a new system for designing and evaluating asphalt concrete materials (Asphalt Institute, 1996). In addition to traffic- and climate-based binder grade selection and aggregate criteria based on traffic loading, Superpave places requirements on the void structure and void requirements of asphalt concrete mixtures. These properties are considered the asphalt mixture volumetrics and they include voids in the total mix (VTM) or air voids, voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA). The VTM is the “total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture” (Asphalt Institute, 1996). The durability of asphalt concrete is a function of the VTM as it impacts both permeability and a condition known as flushing. If the VTM is too high, there are too many passageways for the entrance of damaging air and water. If the VTM is too low, excess asphalt will squeeze or flush out of the mixture to the surface under traffic loading (Christensen et al., 2006). The VMA is the space available in a compacted asphalt concrete mixture to accommodate both air voids and asphalt. The higher the VMA, the more space is available for a film of asphalt to form and provide sufficient durability to the mixture (Kandhal et al., 1998). VFA is the percentage volume of the void space between the aggregate particles, or VMA, that is occupied by the effective asphalt. VFA is also an indicator of relative durability because if VFA is too low, there is not enough asphalt to provide stability and the mixture is at risk of over-densification under traffic loading (Cominsky et al., 1994).

These Superpave volumetric properties along with the defined aggregate properties provide some indication of how mixtures will perform in the field. Asphalt concrete mixtures are designed by calculating the volumetric properties of trial blends of aggregate and asphalt binder compacted to a design gyratory compaction effort, known as  $N_{\text{design}}$  or  $N_{\text{des}}$ . The intention of compacting to  $N_{\text{des}}$  is to produce lab specimens with the void content that would eventually be reached in the field after densification under real traffic. Superpave specifies that the VTM for a

mixture should be 4% at  $N_{des}$  gyrations (Asphalt Institute, 1996). The allowable range of VMA values for a mixture is based on the nominal maximum aggregate size of the mixture and the minimum VFA level is a function of traffic level. The design asphalt content for a mixture is determined by evaluating trial aggregate blends at several asphalt contents and selecting the asphalt content that meets the volumetric requirements (Asphalt Institute, 1996).

### **Superpave $N_{des}$ Compaction Effort and Asphalt Content**

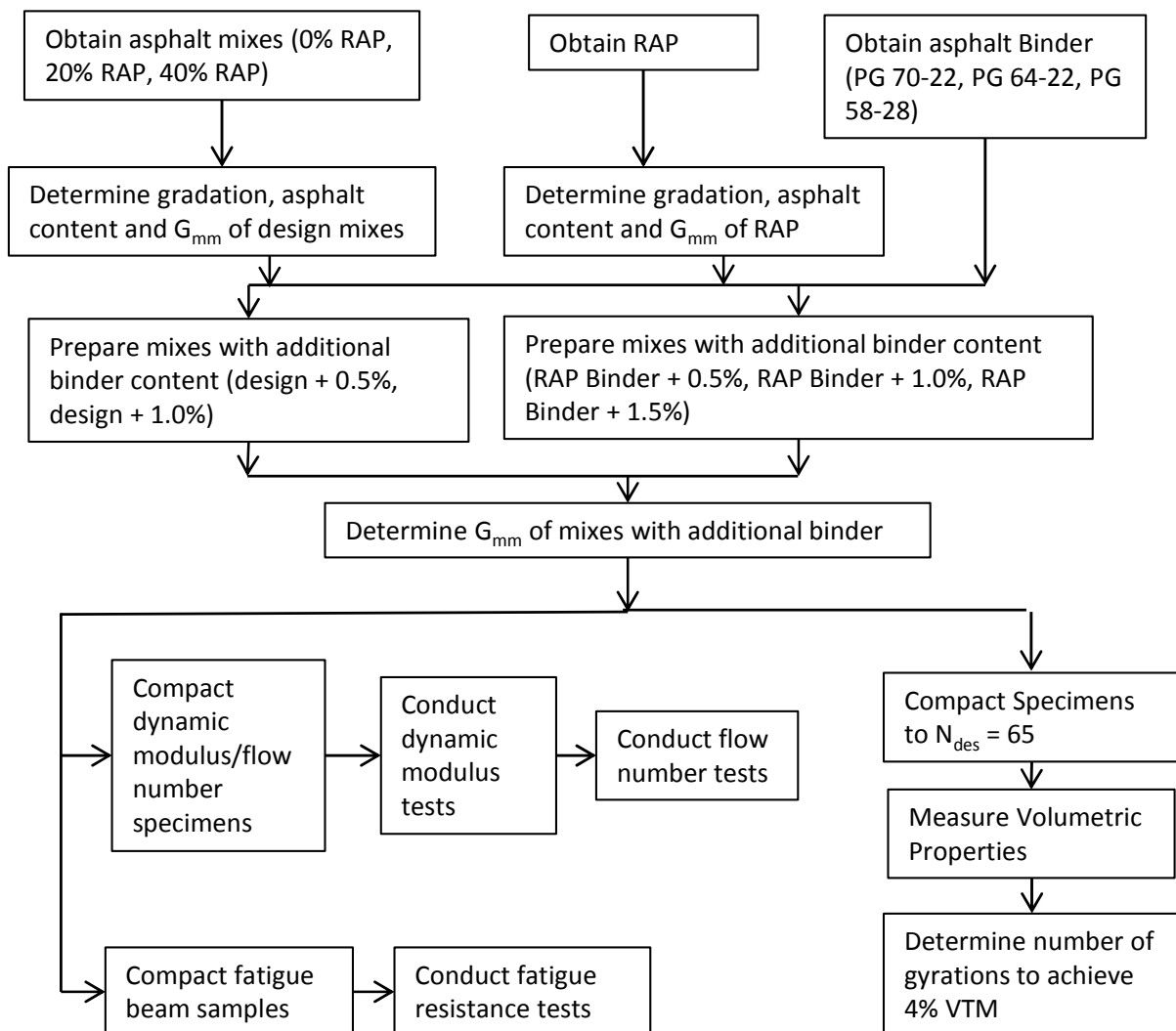
VDOT began using Superpave to design mixtures in 2000, and like many other state highway agencies, there was concern that the Superpave design compaction effort was producing mixtures with low asphalt content and thus lower durability. As a result, Maupin (2003) studied the effects of increasing binder content in Virginia's surface mixtures to determine if durability could be increased. In the study it was determined that as much as 0.5% asphalt could be added to the nine studied mixtures with beneficial results in fatigue life and rutting resistance (Maupin, 2003). As Superpave mixture design specifies that the design asphalt content be determined for a mixture with 4% VTM at  $N_{des}$  compaction effort, the addition of asphalt binder will lead to a lower VTM. Not long after the adoption of Superpave, VDOT changed the  $N_{des}$  compaction effort from the AASHTO-specified level, which was traffic dependent, to 65 gyrations.

Several other efforts have been made to calibrate  $N_{des}$ , including a study by Brown and Mallick (1998). The Superpave  $N_{des}$  compaction effort was established for given mixtures at given traffic levels so that they should ultimately result in the laboratory mixture design density (Prowell and Brown, 2007). However, the results of the study indicated that  $N_{des}$  values did not correlate with real field densities from actual traffic and that, at currently specified levels, the Superpave gyratory compactor (SGC) was over-compacting specimens, which results in lower design asphalt contents (Brown and Mallick, 1998). In a subsequent study, Aguiar-Moya et al. aimed to optimize the number of design gyrations based on project requirements. The basis for this study was that Superpave mixture designs were producing mixtures that performed well in rutting, but due to low asphalt binder content they sacrificed fatigue cracking resistance. Three different mixtures were produced at the optimal binder content (4% air voids at 100 gyrations) and three additional asphalt binder contents were selected that produced 4% air voids at 50, 75 and 125 gyrations. Specimens were subjected to four-point bending tests as well as Hamburg Wheel Tracking Device (HWT) tests and results showed that the number of design gyrations could be reduced significantly to optimize performance (Aguiar-Moya et al., 2007). Prowell and Brown (2007) performed a detailed evaluation of the gyratory compaction levels used in the Superpave mixture design method and recommended that compaction levels be reduced.

The FHWA Asphalt Mixture and Construction Expert Task Force (AMCTEF) recognized the concern from many states that the Superpave mixture design gyration levels were producing asphalt concrete mixtures that were too low in asphalt binder. The AMCTEF reviewed the results of published research on gyratory compaction levels and cautioned that reducing the compaction levels could result in reducing the rutting resistance of asphalt mixtures. The AMCTEF recommended that if a reduction in gyrations is proposed, rutting performance tests should be performed on the mixtures resulting from lower compaction gyrations to determine if reductions cause a large change in rutting performance (FHWA, 2010).

## Material Selection and Sampling

A flow chart of the performed study is shown in Figure 1. Three SM-9.5 asphalt concrete surface mixtures typically used in Virginia were obtained from asphalt producers: a control mixture, SM-9.5D, containing 0% RAP (PG 70-22) was obtained from the Sawyer Salem plant, an SM-9.5D mixture containing 20% RAP (PG 70-22), and an SM-9.5A mixture containing 40% RAP (PG 64-22) were obtained from the Superior plant. The 0% and 20% RAP mixtures were both VDOT approved mixtures with the original or design binder content determined by the producer in accordance with VDOT specifications. The 40% RAP mixture, a RAP percentage not approved by VDOT at the time of this study, was obtained from a private project. Additionally, stockpiled RAP used in those asphalt mixtures was also obtained from the producer.



**Figure 1. Test Plan Employed in the Study**

## Source Materials Characterization

The theoretical maximum specific gravity ( $G_{mm}$ ) of each of the three mixtures was determined using the Rice method following AASHTO T 209-94, Standard Method of Test for Theoretical Maximum Specific Gravity ( $G_{mm}$ ) and Density of Hot Mix Asphalt (HMA) (AASHTO, 1994). The ignition oven was used to determine the asphalt content of the plant mixture material. The process followed was adapted from the Virginia Test Method 102, Determination of Asphalt Content From Asphalt Paving Mixtures By the Ignition Method – (Asphalt Lab) (VDOT, 2009). When material was heated and separated to conduct the  $G_{mm}$  testing, three samples exceeding 1500 g (3.3 lb) were taken for use in the ignition oven to determine the asphalt content. An ignition oven correction factor was unable to be developed due to a lack of material. Calculations were therefore performed without a correction factor and with a correction factor obtained from the producer. Sieve analysis following AASHTO T 27-06, Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates (AASHTO, 2006) was then performed on two of the burned samples after asphalt content testing. Gradation curves were produced based on the average of the two sieve analyses for each mixture and the stockpiled RAP material.

## Sample Preparation

The three asphalt concrete mixtures, as well as the 100% RAP collected from the RAP stockpile, were then modified by adding increased amounts of asphalt binder. Two levels of increased binder content were evaluated for the 0% RAP, 20% RAP and 40% RAP mixtures: design, design + 0.5% and design + 1.0%. The original, or design, binder contents for the 0% RAP and 20% RAP mixtures were determined by the producer in accordance with VDOT specifications. Selection of the design binder content for the 40% RAP mixture, which was used on a private project, was not subject to VDOT specifications. The design + 1.0% level was used, as it was suggested by Maupin and Diefenderfer (2006), that one percent might be the additional asphalt content needed to see appreciable improvement in fatigue cracking resistance. Four levels of binder content were evaluated for the mixture containing 100% RAP: RAP with no added binder, RAP + 0.5% added binder, RAP + 1.0% added binder and RAP + 1.5% added binder. PG 70-22 binder was added to both the 0% RAP and 20% RAP mixtures and PG 64-22 binder was added to the 40% RAP mixture, as these were the binder grades used in initial production. PG 58-28 binder was used for the 100% RAP mixture and was chosen because it has been argued that the softer binder would blend and mixture with the aged RAP binder to decrease the stiffness of the overall mixture (McDaniel et al., 2000).

All mixing of the additional binder was performed according to the following procedure. The 0% RAP, 20% RAP, 40% RAP, and 100% RAP materials were placed in ovens preheated to 154°C until the mixing temperature was reached. The PG 70-22, PG 64-22 and PG 58-28 binders were placed in a separate oven and preheated to 160°C, 154°C and 148°C, respectively. Once the mixing temperature of 160°C, 154°C, and 148°C were reached, the material was removed from the oven, placed in a preheated mixing bucket and weighed. The heated binder was then added to the material as a percentage based on the weight of material in the bucket. The materials were then mixed for approximately five minutes using a preheated mixing arm on an electric mixer,

until the aggregates were sufficiently coated with the virgin binder. The  $G_{mm}$  of the mixtures with added binder was determined using the Rice method after mixing was complete.

The scope of this study included preparing one set of three cylindrical specimens for dynamic modulus and flow number testing, one set of three cylindrical specimens for volumetric testing, and one set of three beam specimens for fatigue testing for each mixture. The same specimens that were used for dynamic modulus were also used for the flow number testing once dynamic modulus testing was complete. The dynamic modulus specimens were compacted using the Superpave gyratory compactor at a temperature of 143°C (290°F). All specimens were compacted to a height of 178 mm (7 in) in a 152 mm (6 in) diameter mold. Since the goal was to achieve a target air void level of  $7.0\% \pm 0.5\%$ , the number of gyrations necessary to compact each mixture varied based on the air void target of 7%. Once sufficiently cooled, the specimens were then cut and cored to a length of 152 mm (6 in) and a diameter of 102 mm (4 in). The bulk specific gravity ( $G_{mb}$ ) of the cut and cored specimens was then determined using AASHTO T 166-10, Standard Method of Test for Bulk Specific Gravity ( $G_{mb}$ ) of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens (AASHTO, 2010). Beam fatigue specimens 51 mm (2 in) high, 64 mm (2.5 in) wide, and 381 mm (15 in) long were prepared using the asphalt vibratory compactor (AVC). Three specimens were produced for each RAP and binder content. A maximum compaction time of 35 seconds was used for all specimens at all binder levels, as it was determined sufficient to achieve the target  $7.0 \pm 0.5\%$  air voids.

Samples used for volumetric analysis were prepared and compacted following the procedure specified in AASHTO T 312-04, Preparing Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor (SGC) (AASHTO, 2004). Prior to compacting, the ram pressure and the internal angle of the SGC were calibrated to  $600 \pm 18$  kPa and  $1.16 \pm 0.02^\circ$ , respectively. Samples of approximately 5,000 g were heated in an oven to a temperature of 148°C (300°F) for the 0% and 20% RAP and 143°C (290°F) for the 40% and 100% RAP, then funneled into a preheated mold. Samples were compacted at 30 gyrations per minute with a compactive effort of 65 gyrations, the design compactive effort required for asphalt concrete mixtures produced for VDOT. After compaction, the samples were extracted from the mold and placed on a smooth, flat surface to cool overnight at room temperature. For the most part, the 100% RAP mixture with no added binder held together quite well after removal from the mold; however, the edges and surfaces did become a bit crumbly as the specimens were moved for testing. The height of all compacted samples fell within  $115 \pm 5$  mm, and during compaction; both specimen height and gyration data were continuously collected.

## **Mixture Performance Testing**

### **Dynamic Modulus**

Dynamic modulus testing was conducted according to the testing procedure prescribed in 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) (AASHTO, 2009). Tests were performed at 4.4, 21.1, 37.8, and 54.4°C (40, 70, 100, and 130°F) and at frequencies of 25, 10, 5, 1.0, 0.5, and 0.1 Hz at each temperature using an Interlaken

Technology Corporation (ITC) servo-hydraulic machine. Table 1 displays the specifics of the dynamic modulus test temperatures and conditioning times, frequencies, cycles and pressures. Load levels were chosen such that maximum strain limits for the test would not be exceeded and the same loads were used for all specimens. Three sets of linear variable differential transformers (LVDTs) with gauge lengths of 100 mm (4 in), placed 120 degrees apart, were mounted on aluminum studs to measure displacements in the asphalt specimens under dynamic loading. The dynamic modulus curve was constructed at a reference temperature of 21.1°C (70°F) using the Witzczak sigmoidal model (Witzczak and Fonseca, 1996).

### Flow Number (FN) Test for Rutting Resistance

In this study, the FN test was performed in an environmental chamber at a temperature of 54.4°C (130°F) and an applied stress of 207 kPa (30 psi). All specimens were conditioned at 54.4°C (130°F) for 4 hours prior to testing. The testing was performed according to 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) (AASHTO, 2009) and was considered complete after 10,000 cycles or once the sample began tertiary deformation.

**Table 1. Dynamic Modulus Test Parameters**

Test Temperature, °C (°F) (conditioning time, hours, from room temperature at 25°C)	Frequency, Hz	Pressure, kPa (psi)	Cycles
4.4 (40) (overnight)	25	621 (90)	200
	10	621 (90)	200
	5	552 (80)	100
	1	552 (80)	20
	0.5	483 (70)	15
	0.1	483 (70)	15
21.1 (70) (1 hr)	25	483 (70)	200
	10	483 (70)	200
	5	379 (55)	100
	1	379 (55)	20
	0.5	276 (40)	15
	0.1	276 (40)	15
37.8 (100) (4 hrs)	25	276 (40)	200
	10	276 (40)	200
	5	172 (25)	100
	1	172 (25)	20
	0.5	103 (15)	15
	0.1	103 (15)	15
54.4 (130) (4 hrs)	25	103 (15)	200
	10	103 (15)	200
	5	69 (10)	100
	1	69 (10)	20
	0.5	34 (5)	15
	0.1	34 (5)	15

## APA Rut Test

The APA rut test was conducted in accordance with Virginia Test Method 110, Method of Test For Determining Rutting Susceptibility Using The Asphalt Pavement Analyzer – (Asphalt Lab) (VDOT, 2007). Two replicate beams, 75 mm (3 in) thick by 125 mm (5 in) wide by 300 mm (12 in) long, were tested at a test temperature of 49°C (120°F) and a vertical load of 533 N (120 lbf) applied through a rubber hose filled with compressed air at a pressure of 827 kPa (120 psi). The loading was applied by a wheel traveling at a speed of 0.61 m/sec (2 ft/sec) over 8,000 cycles. The total deformation at the end of the test, which is considered the total rut depth, is measured manually with a specially designed ruler.

## Fatigue Cracking Resistance

In this study, fatigue testing was performed under controlled-strain conditions with a constant strain level of 400 $\mu\epsilon$  at a frequency level of 10 Hz and an ambient air temperature of 20°C (68°F) using an MTS servo-hydraulic machine according to AASHTO T321-03, Standard Method of Test for Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending (AASHTO, 2003). The initial stiffness modulus of the specimen was determined after 50 load cycles and the failure criterion was defined as a 50% reduction from that initial stiffness. Load and deflection data were continually collected throughout the fatigue test in order to calculate the average stiffness modulus for each loading cycle.

## Superpave Volumetric Properties

### Calculation of Volumetric Properties

The volumetric properties of the compacted samples were determined using AASHTO T 166-10, Bulk Specific Gravity of Compacted Hot Mix Asphalt Using Saturated Surface-Dry Specimens (AASHTO, 2010). For the 100% RAP mixture, the aggregate specific gravity,  $G_{sb}$ , of the RAP aggregate was determined using an empirical relationship between the  $G_{sb}$  and the mixture effective specific gravity,  $G_{se}$ , developed and used by the Minnesota Department of Transportation and shown in Equation 1 (MnDOT, 2007).

$$G_{sb} = 0.9397G_{se} + 0.0795 \quad [\text{Eq.1}]$$

Once calculated, the VTM, VMA, and VFA values and the density at  $N_{\text{initial}}$  were compared to the VDOT specifications (VDOT, 2014) shown in Table 2.

**Table 2. Excerpt from 2007 VDOT Road and Bridge Specifications Section 211, Table II-14, Mix Design Criteria**

Mixture Type	VTM (%) Production	VFA (%) Design	VFA (%) Production	Min VMA	Fine/Asphalt Ratio	Number of Gyration N Design
SM-9.5 D	2.0-5.0	73-79	68-84	15	0.6-1.2	65

## Gyrations to Achieve 4% VTM, $N_{4\%}$

In order to determine the number of gyrations that would result in 4% VTM,  $N_{4\%}$ , for each mixture, a method developed by Vavrik and Carpenter (1998) and the Illinois Department of Transportation was utilized. The Illinois method uses statistical regression to determine the number of gyrations at which a mixture is compacted to a specified air voids level. The developers of this method pointed out that the initial portion of the total densification curve, % $G_{mm}$  versus gyrations, follows a logarithmic relationship. It is possible to use this relationship to predict  $N_{4\%}$  for a mixture by using gyratory data up until the “locking point,” or the point at which the mixtures’ aggregate skeleton locks together and subsequent compaction causes only degradation of the aggregate with minimal further compaction (Prowell and Brown, 2007). The locking point was also developed by the Illinois DOT and was first defined as the “first gyration in a set of three gyrations of the same height that was preceded by two gyrations of the same height.” The definition of the locking point was then refined by Vavrik and Carpenter, who said the set of three gyrations at the same height were preceded by two sets of two gyrations at the same height (Prowell and Brown, 2007). The Illinois method has proven to be more accurate than the Superpave procedure for back-calculating gyrations and works especially well for mixtures with smaller maximum nominal aggregate sizes (Vavrik and Carpenter, 1998).

Using the Illinois method, the  $N_{4\%}$  was determined by converting the compaction height data for each gyration to % $G_{mm}$ . This was accomplished using the  $G_{mm}$  of the loose sample and the corrected  $G_{mb}$  following the Superpave mixture design procedure. The  $G_{mb}$  was estimated using Equation 2 (Vavrik and Carpenter, 1998).

$$G_{mb}(\text{estimated}) = \frac{W_m}{V_{mx}} \frac{1}{\gamma_w} \quad [\text{Eq.2}]$$

where:

$G_{mb}(\text{estimated})$  = Estimated bulk specific gravity of specimen during compaction  
 $W_m$  = Mass of specimen  
 $V_{mx}$  = Volume of mold  
 $\gamma_w$  = Density of water

A correction factor was then established because the estimated  $G_{mb}$  assumes a smooth-sided specimen; it must be adjusted due to the fact that in reality, compacted specimens have surface irregularities. The correction factor,  $C$ , was calculated using Equation 3 (Vavrik and Carpenter, 1998).

$$C = \frac{G_{mb}(\text{measured})}{G_{mb}(\text{estimated})} \quad [\text{Eq.3}]$$

The corrected  $G_{mb}$  at any gyration level was then calculated using Equation 4 and the density or % $G_{mm}$  at each gyration was calculated using Equation 5 (Vavrik and Carpenter, 1998). These equations were also used to calculate the density at  $N_{\text{initial}}$  or in the case of this study, the % $G_{mm}$  at 7 gyrations.



$$G_{mb}(\text{corrected}) = C \times G_{mb}(\text{estimated}) \quad [\text{Eq.4}]$$

$$\%G_{mm} \text{ @ gyration } n = \frac{G_{mb}(\text{corrected @ gyration } n)}{G_{mm}} \quad [\text{Eq.5}]$$

A least squares linear statistical regression was then performed on the  $\%G_{mm}$  and the logarithm of the gyrations, truncated to the locking point for each sample. The result of the regression are the compaction slope ( $\alpha$ ) and intercept ( $\beta$ ) given by Equation 6 (Vavrik and Carpenter, 1998).

$$\beta = y - \alpha x \quad \alpha = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad [\text{Eq. 6}]$$

where

- $\beta$  = Intercept of compaction curve
- $\alpha$  = Slope of compaction curve
- $x$  =  $\log(N_{\text{gyr}})$ , independent variable
- $\bar{x}$  = Average value of  $x$
- $y$  =  $\%G_{mm}$ , dependent variable
- $\bar{y}$  = Average value of  $y$

Using the compaction slope and intercept, the number of gyrations to reach 4% VTM or a density of 96% of  $G_{mm}$  was calculated using Equation 7 (Vavrik and Carpenter, 1998).

$$N_{4\%} = 10^{(\%G_{mm} - \beta)/\alpha} \quad [\text{Eq. 7}]$$

## RESULTS

### Sample Preparation

It was noted previously that to achieve the target air void level of  $7.0\% \pm 0.5\%$ , the number of gyrations necessary to compact each mixture varied. Figure 2 indicates that, as the binder content of the mixtures increased, the number of gyrations necessary to achieve the target air void level decreased. The results of testing the specimens for bulk specific gravity,  $G_{mb}$ , and air voids are shown in Table 3.

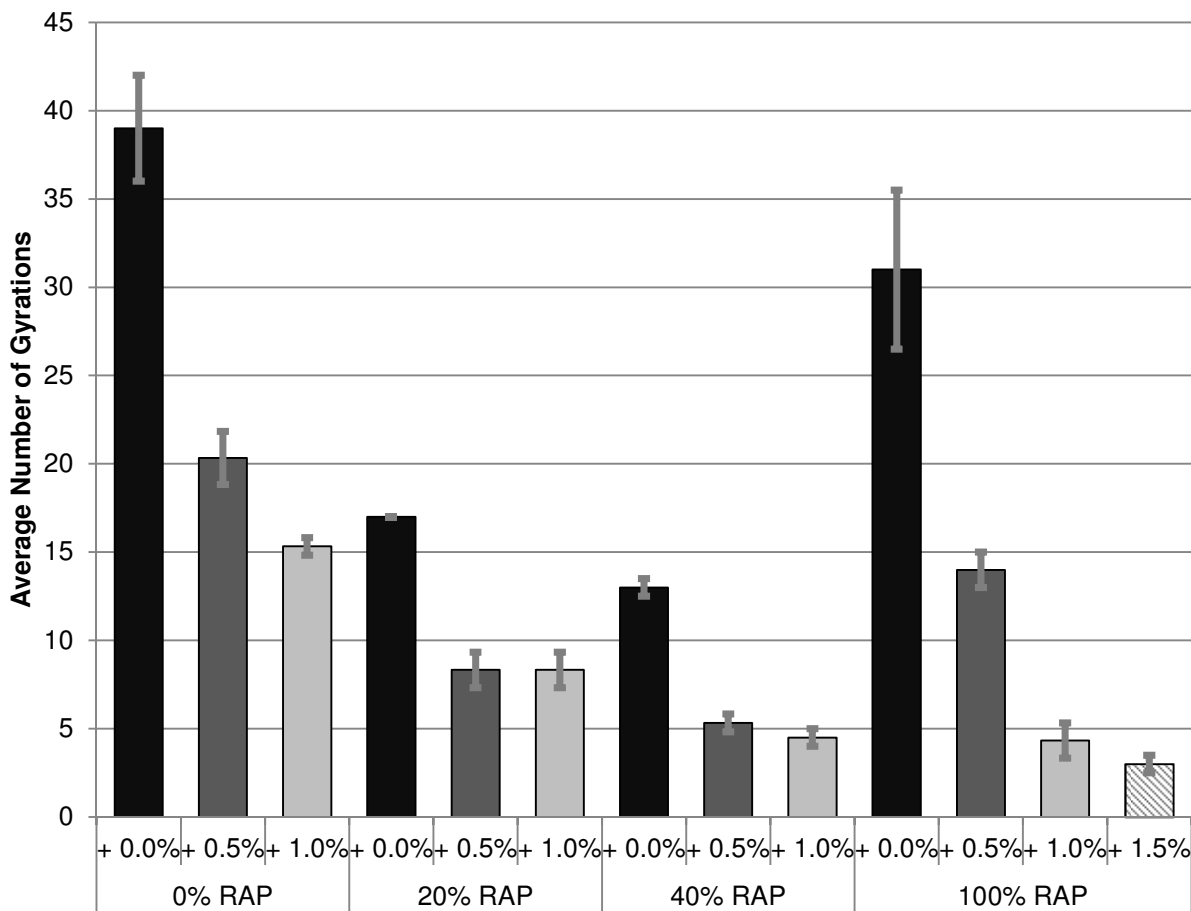
### Mixtures Performance Testing

#### Dynamic Modulus

Figure 3 shows the average sigmoidal dynamic modulus master curves for the three specimens tested at each RAP percentage and binder content. Figure 4 is a summary plot displaying all of the average dynamic modulus master curves at all binder contents for the four RAP mixtures tested. As shown in Figure 3, the dynamic modulus increases with increasing RAP percentage for the 20%, 40% RAP and 100% RAP mixtures. Figure 4 also shows that the 40%

RAP shows increased stiffness at intermediate temperatures (frequencies) relative to the 0% and 20% RAP. The average dynamic modulus of the 100% RAP mixtures is over 400% higher than the average dynamic modulus of the 20% RAP and 40% RAP mixtures at the lowest reduced frequency, gradually decreasing to 125% higher for the highest reduced frequency.

The plot for each mixture illustrates the relationship between binder content and the dynamic modulus. As can be seen in the individual RAP mixture plots in Figure 3(a), (b), (c) and (d), there is less than 1% difference in dynamic modulus values for the 0% RAP, 20% RAP and 40% RAP mixtures between the design (no binder added) and design + 0.5% binder mixtures. However, there is a statistically significant ( $p < 0.5$ ) decrease in dynamic modulus values when comparing the design mixture to the mixture with the additional 1.0% binder for the 0% RAP, 20% RAP and 40% RAP mixtures. On average the dynamic modulus values are approximately 17%, 11% and 21% lower between the design and design + 1.0% binder mixtures for the 0% RAP, 20% RAP and 40% RAP mixtures respectively.



**Figure 2. Average Number of Gyration for Dynamic Modulus and Flow Number Specimen Compaction to Achieve 7% Voids in Total Mixture**

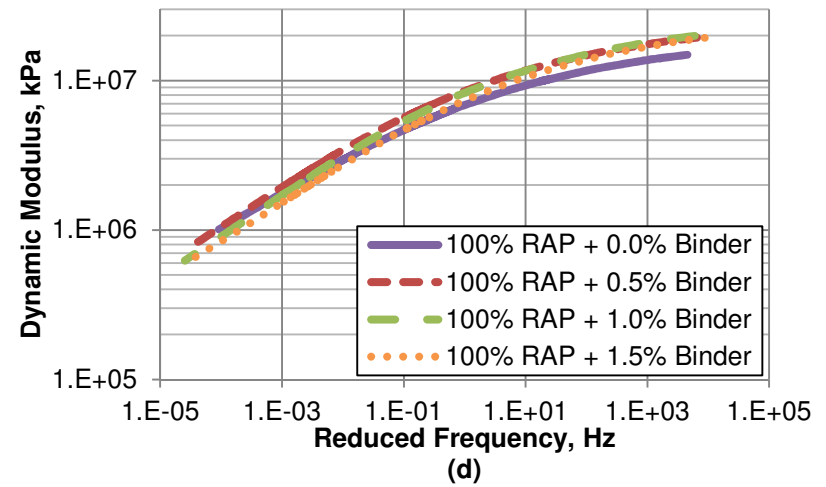
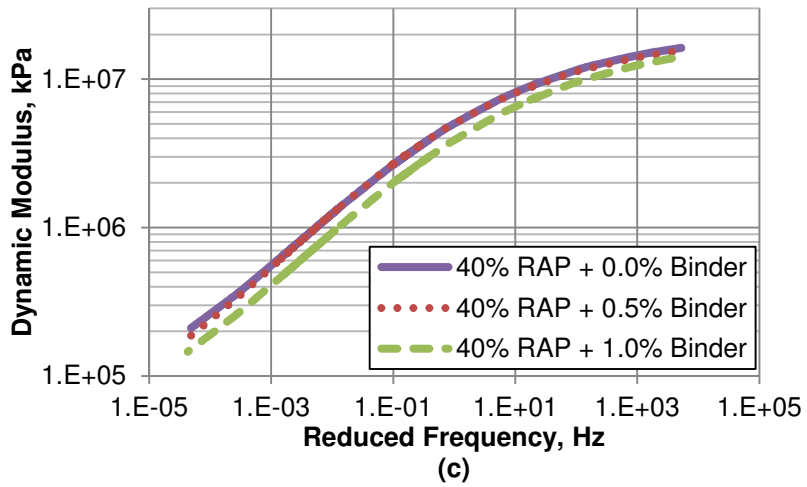
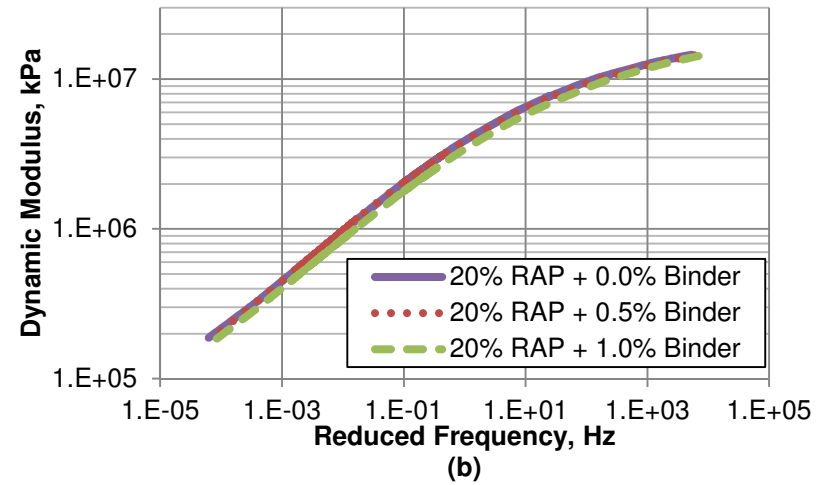
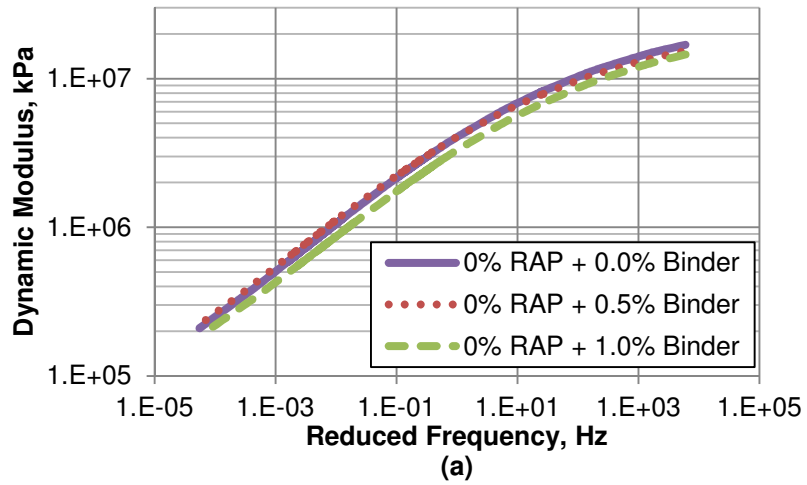


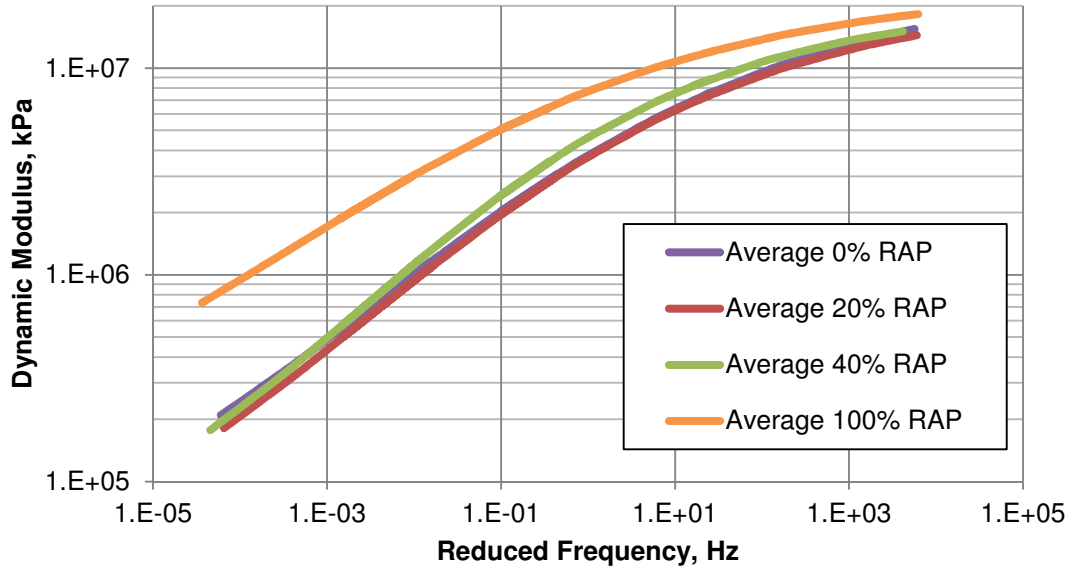
Figure 3. Dynamic Modulus Master Curves for a) 0% RAP mixtures, b) 20% RAP mixtures, c) 40% RAP mixtures, d) 100% RAP Mixtures

**Table 3. Volumetric Data for the Dynamic Modulus and Flow Number Samples**

	$G_{mm}^a$	$G_{mb}^b$	Air Voids (%) <sup>b</sup>
0% RAP + 0.0% Binder	2.686	2.503	6.8
0% RAP + 0.5% Binder	2.668	2.488	6.7
0% RAP + 1.0% Binder	2.648	2.468	6.8
20% RAP + 0.0% Binder	2.614	2.431	7.0
20% RAP + 0.5% Binder	2.595	2.410	7.1
20% RAP + 1.0% Binder	2.576	2.393	7.1
40% RAP + 0.0% Binder	2.603	2.424	6.9
40% RAP + 0.5% Binder	2.584	2.399	7.1
40% RAP + 1.0% Binder	2.565	2.382	7.1
100% RAP + 0.0% Binder	2.626	2.438	7.1
100% RAP + 0.5% Binder	2.623	2.442	6.9
100% RAP + 1.0% Binder	2.598	2.427	6.6
100% RAP + 1.5% Binder	2.586	2.411	6.8

<sup>a</sup> $G_{mm}$  = maximum specific gravity as average of 3 Rice tests

<sup>b</sup>Average of three tested specimens



**Figure 4. Dynamic Modulus Master Curves for Average Dynamic Modulus of Mixtures at Each RAP Percentage**

The relationship between the dynamic modulus and increasing binder content follows the same general trend for the 100% RAP mixtures, except for the case of the 100% RAP mixture with no added binder. There is a statistically significant ( $p < 0.05$ ) increase in the dynamic modulus between the mixture with no additional binder and the mixture with the additional 0.5% binder. This increase becomes increasingly larger as reduced frequency increases. As added binder increases from 0.5% to 1.0%, the dynamic modulus remains relatively unchanged, with only an average 2% difference between the dynamic modulus of the two mixtures. An average decrease of 12% in dynamic modulus values occurs between the 100% RAP mixture with 0.5% additional binder and the mixture with 1.5% additional binder.

## Flow Number

The flow numbers calculated from the RLPD testing for all mixtures are shown in Figure 5. For both the 0% RAP and 20% RAP mixtures, the results show a significant, approximate 100% increase in the flow number between the design + 0.0% binder and the design + 0.5% binder. For both of those mixtures, the addition of 1.0% binder reduced the FN compared to the design + 0.5% mixture; however, the FN was slightly higher than from the FN of the design + 0.0%. The 40% RAP mixture exhibited a different behavior as the addition of binder resulted in a dramatic decrease in the FN. The 100% RAP mixtures exhibited significant resistance to rutting as none of the mixtures reached the tertiary flow region within the 10,000 test cycles. Furthermore, the accumulated strain after 10,000 cycles was very low compared to the other mixtures and this can be seen in Figure 6. However, as shown in the figure, the permanent strain experienced after 10,000 cycles increased for the 100% RAP mixtures as binder content increased.

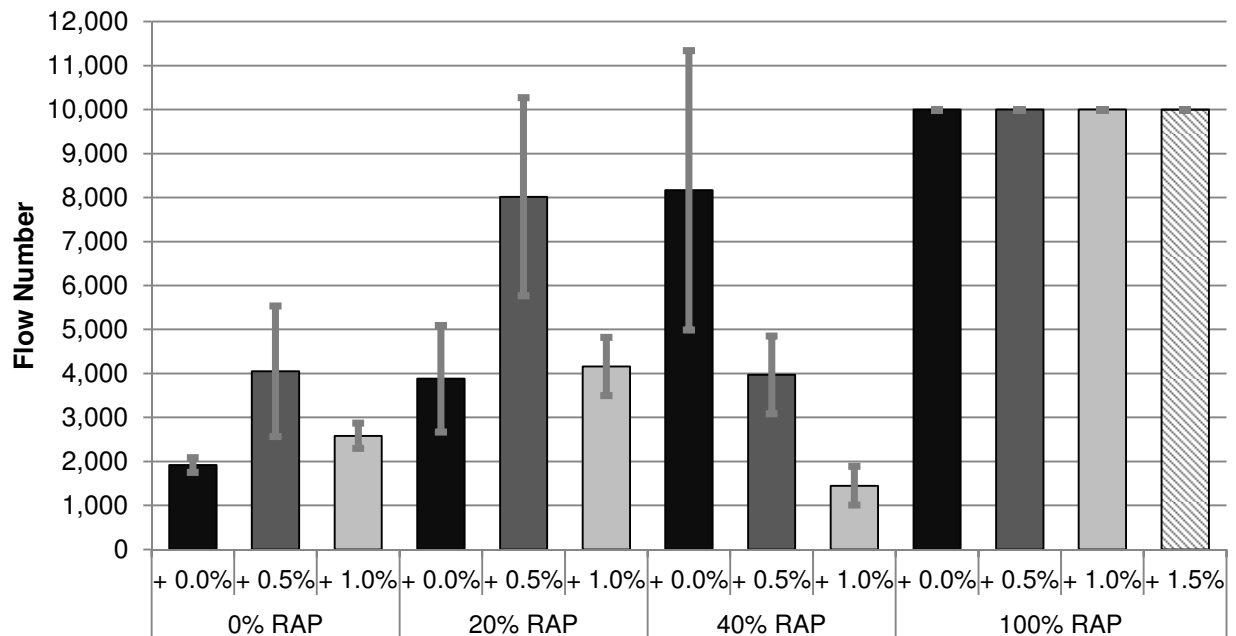


Figure 5. Flow Number of All Mixtures

## APA Rutting Test

The results of the APA rut test are presented in Table 4. Results for the 20% and 40% RAP mixtures with 0% added binder are not available because of insufficient loose material (the APA test requires more material than the other tests). Each of the 20% and 40% mixtures was produced for a single day, which is the reason an additional amount of material could not be collected. For the 20% RAP mixtures, unlike the FN test, the APA test did not show a difference between the mixture with design + 0.5% binder and the mixture with design + 1% binder. For the 40% RAP mixtures, although the results of the mixture with design + 1% binder showed a higher rutting susceptibility than the results of the mixture with design + 0.5% binder, this is mainly due to the significantly large deformation of one specimen. Note also that the specimen

that resulted in lower rutting had an air voids content of 5.4%, which is 1.5% lower than the specimen that resulted in high rutting, and this 1.5% difference in air voids could have been the cause for the large difference in rutting performance. The specimen's total deformation was about 4 times as large as that of the other specimen. Disregarding this "outlier" specimen, the results showed that rutting resistance for the mixture with design + 1% binder was better than that for the mixture with design + 0.5% binder. This is in contradiction to the results of the FN test and with what would be expected. For the 0% RAP mixtures, the results seem to better agree with the FN test, where rutting performance improved with 0.5% added binder and then deteriorated with 1% added binder. However, the results of the mixture with 0.5% added binder are based on a single specimen and the results of the 0% added binder mixture are highly variable, such that the difference between 0% and 0.5% added binder is not statistically significant. In a previous study, Apeageyi and Diefenderfer (2011) noted that the FN test seemed to be sensitive to different mixture parameters, whereas the APA rut depth was not. The results in this study, although much more limited, seem to confirm the observation of Apeageyi and Diefenderfer (2011).

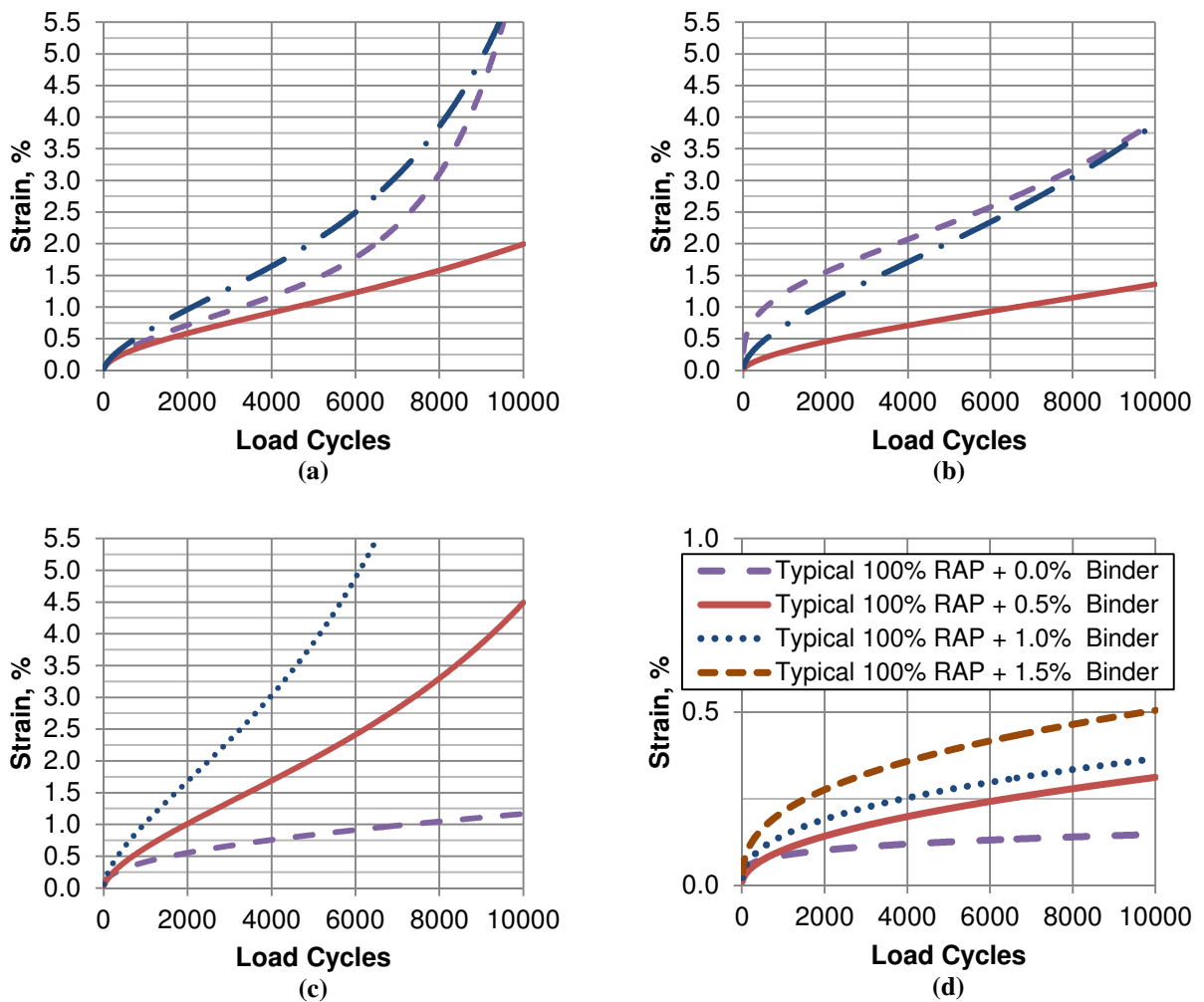


Figure 6. Typical Flow Behavior of (a) 0% RAP Mixtures; (b) 20% RAP Mixtures; (c) 40% RAP Mixtures; and (d) 100% RAP Mixtures

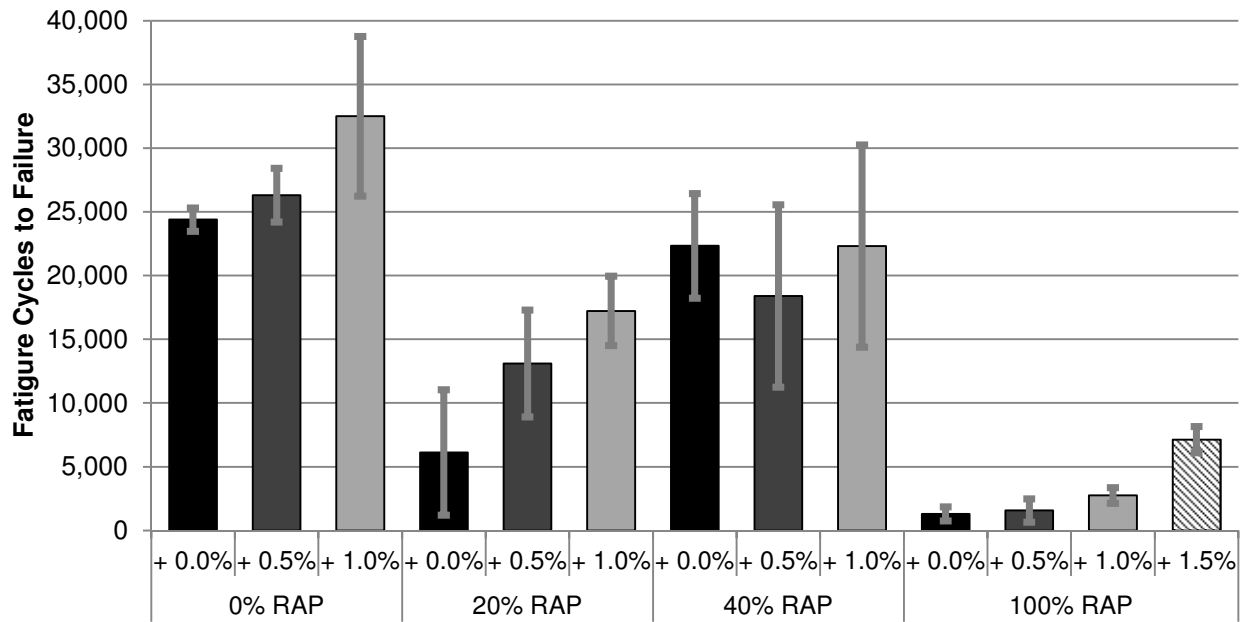
**Table 4. Results of the APA Rut Depth Test**

Log Number	Mix Type	Air Voids	Left (mm)	Center (mm)	Right (mm)	Average (mm)	
						Specimen	Mix
12-1057	20% RAP + .5%Binder	7.3	1.011	1.119	0.946	1.025	1.216
12-1057	20% RAP + .5%Binder	7.4	1.205	1.795	1.221	1.407	
12-1057	20% RAP + 1%Binder	7.3	1.42	0.969	1.35	1.246	1.222
12-1057	20% RAP + 1%Binder	7.5	1.507	0.927	1.161	1.198	
12-1058	40% RAP + .5%Binder	6.3	1.254	1.739	1.493	1.495	1.417
12-1058	40% RAP+ .5%Binder	8.0	1.482	1.164	1.371	1.339	
12-1058	40% RAP + 1%Binder	5.4	1.24	1.042	0.981	1.088	2.675
12-1058	40% RAP + 1%Binder	6.9	4.27		4.253	4.262	
13-1016	0% RAP+ 0%Binder	7.9	1.447	0.893	1.235	1.192	0.827
13-1016	0% RAP + 0%Binder	6.6	0.671	0.243	0.475	0.463	
13-1015	0% RAP + 1%Binder	7.1	1.504	1.924	1.031	1.486	1.337
13-1015	0% RAP+ 1%Binder	7.1	1.228	1.155	1.179	1.187	
13-1014	0% RAP + .5%Binder	7.9	0.433	0.342	0.518	0.431	0.431

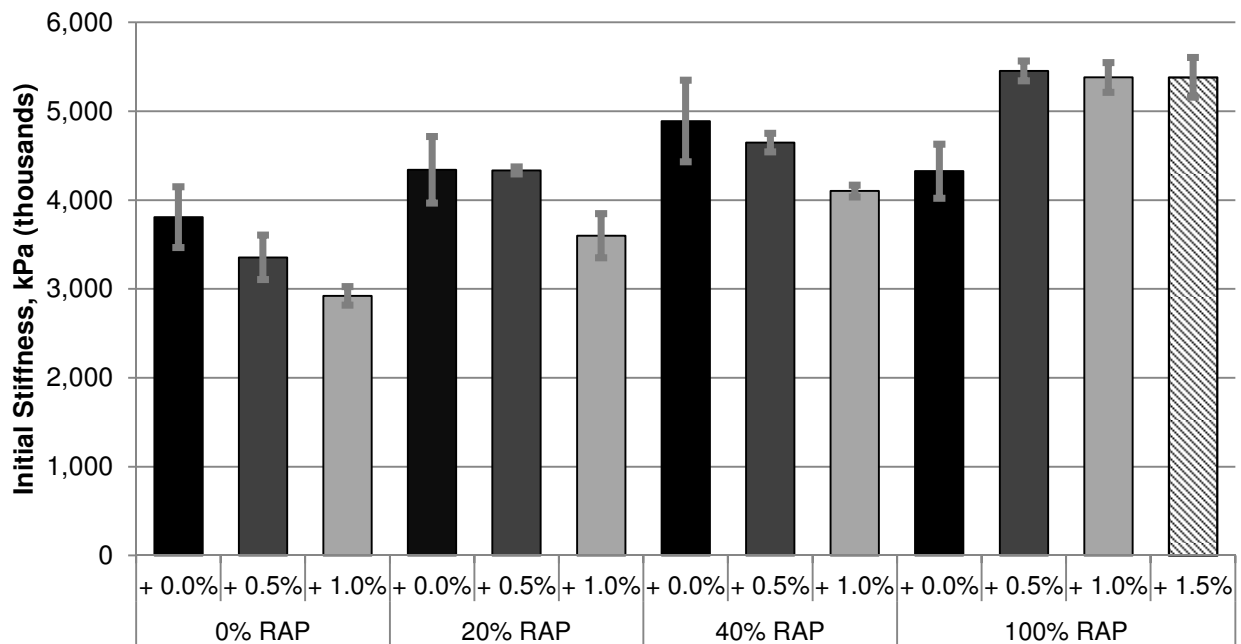
## Fatigue Resistance

The average and standard deviation of the fatigue cycles to failure and the initial stiffness during fatigue testing are shown in Figure 7. The results of fatigue testing show that, for the original mixtures (no added binder), the mixture with 0% RAP had the longest fatigue life, while the mixture with 20% RAP had a significantly lower fatigue life. The 100% RAP mixture had a fatigue life that is significantly lower than the other three mixtures; however, with the addition of 1.5% binder to the 100% RAP mixture, the number of cycles to fatigue failure became similar to the original 20% RAP mixture. For all but the 40% RAP mixture, an increase in binder content led to an increase in fatigue life. An analysis of variance was performed and it showed that the percentage of RAP had a statistically significant impact on the fatigue resistance at the 95% confidence level ( $p < 10^{-7}$ ). The binder content did not have a statistically significant impact at the 95% confidence level ( $p = 0.065$ ). Similarly, the VTM did not have a statistically significant impact at the 95% confidence level ( $p = 0.651$ ). Note that the target VTM for all samples was  $7.0\% \pm 0.5\%$ , which could be a small range to observe an effect of VTM on the mixture performance. For the effect of the binder content on fatigue performance, Figure 7a shows that for the 0%, 20% and 100% RAP mixtures, the addition of binder improved fatigue performance while for the 40% RAP mixture, the addition of binder did not lead to increase in fatigue performance. An analysis of variance was performed with only the 0%, 20%, and 100% RAP mixtures. In this case, the binder content and percentage of RAP had a significant effect on fatigue performance at the 95% confidence level ( $p = 0.0008$  and  $p < 10^{-12}$ , respectively).

Increasing binder content resulted in a decrease in initial stiffness (the stiffness measured during the 50<sup>th</sup> load cycle, which was the average of the 10 cycles between 5 and 6 seconds of testing) for all mixtures except the 100% RAP mixtures. In the case of the 100% RAP mixtures, the stiffness initially increased approximately 25% from 0.0% added binder to 0.5% added binder and leveled off (with negligible decrease) with increasing binder content of 1.0% and 1.5%.



(a)



(b)

**Figure 7. Fatigue Resistance: (a) Average Cycles to Failure of All Mixtures and (b) Average Initial Stiffness of All Mixtures**

The initial stiffness of the beams increased with increasing RAP percentage, excluding the 100% RAP mixture with 0.0% added binder. Similar to the results of the dynamic modulus testing, the addition of 0.5% binder to the 100% RAP mixture with no added binder led to an increase in stiffness.



Figure 8 shows the average stiffness of each mixture throughout the fatigue test. Focusing on the 0% RAP mixtures, by visual inspection of the figure, it is observed that as the binder content increases, the beams fail in a more gradual manner, i.e., the slope of the stiffness versus fatigue cycle is less steep. This same behavior is exhibited by the 20% and 40% RAP mixtures as binder content is increased. Again, upon visual inspection of the stiffness curves, it is observed that as the RAP percentage increases, the slope of the curves becomes steeper, with the 100% RAP beams exhibiting the most abrupt reduction of stiffness and the 0% RAP the most gradual reduction.

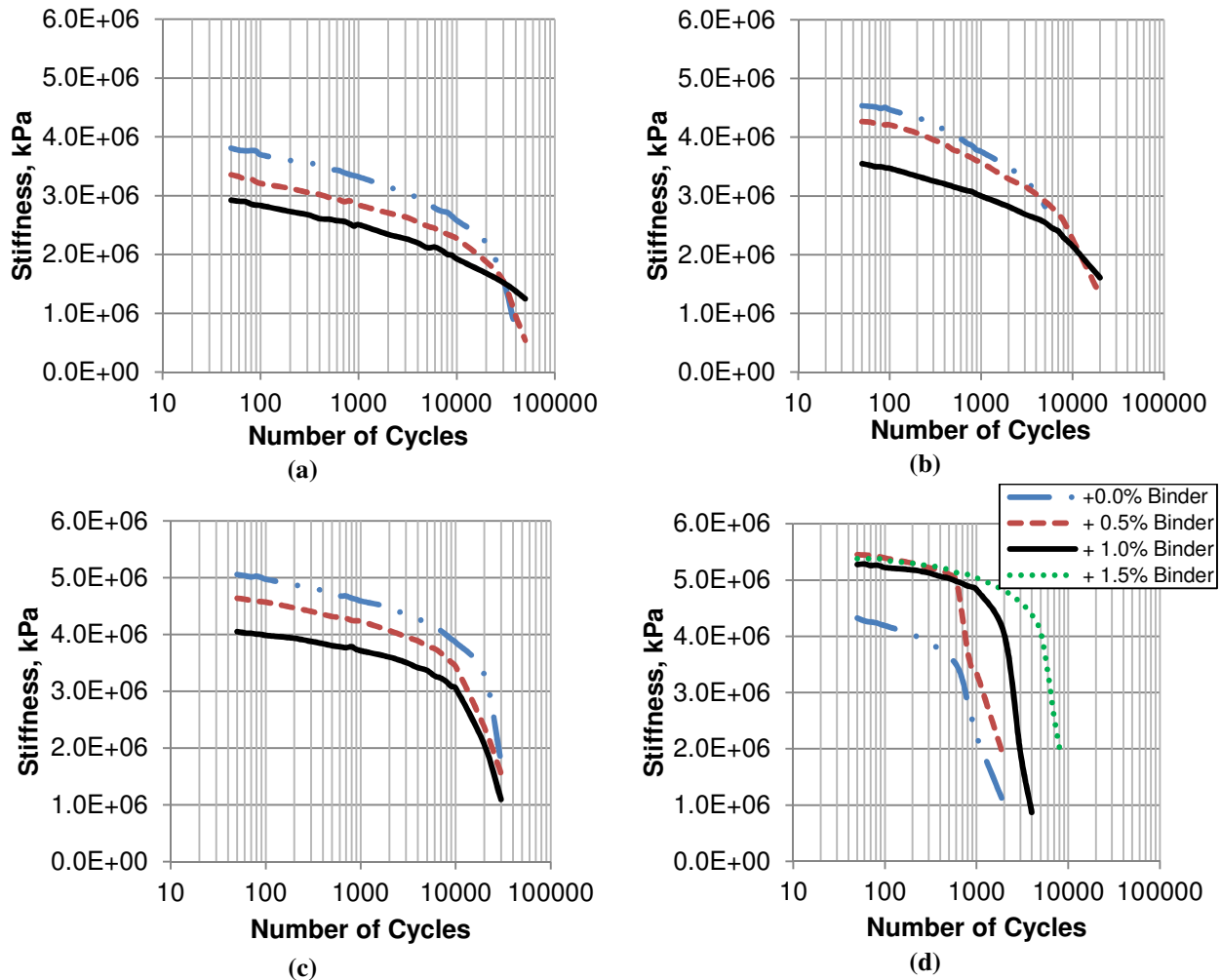
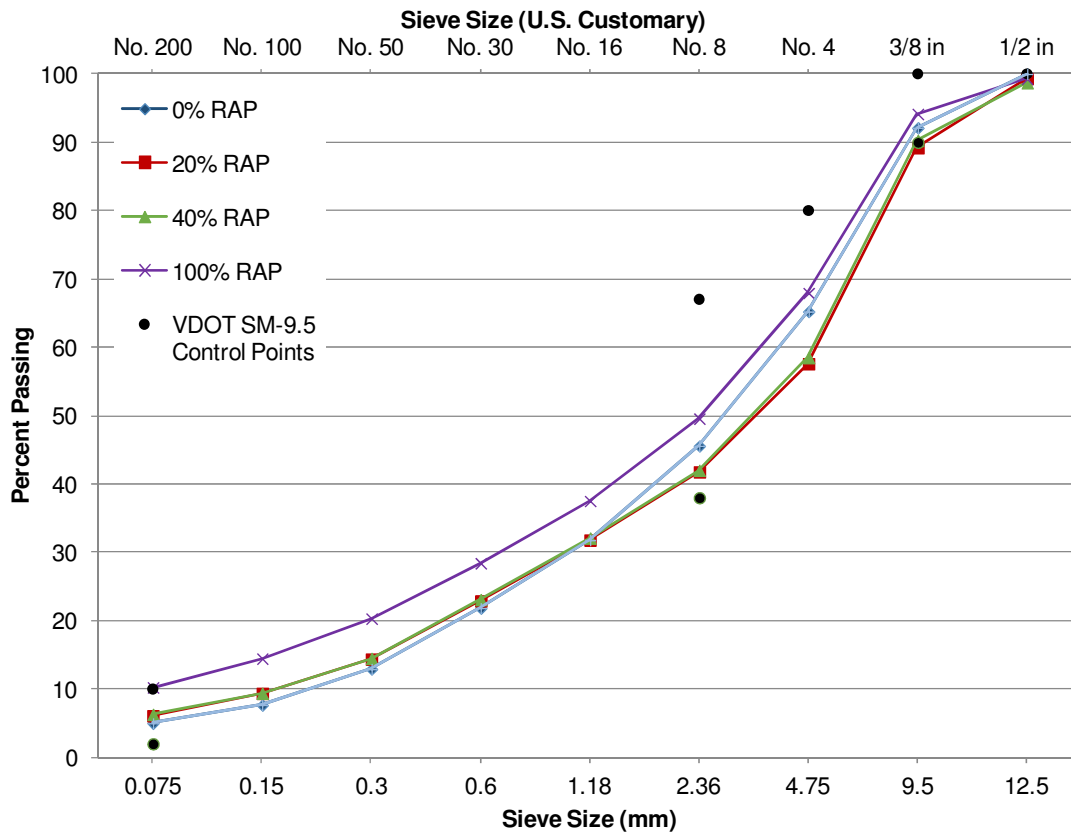


Figure 8. Fatigue Resistance, Stiffness Versus Load Cycles for (a) 0% RAP Mixtures, (b) 20% RAP Mixtures, (c) 40% RAP Mixtures, and (d) 100% RAP Mixtures

## Superpave Volumetric Properties

### Calculation of Volumetric Properties

The aggregate gradations of the mixtures are shown in Figure 9. The 20% RAP and 40% RAP mixtures were both obtained from the Superior plant and had the same gradations (this was verified with the producer supplied gradation). The 0% RAP mixture was obtained from the Sawyer plant and had a slightly different gradation.



**Figure 9. Gradation of the Mixtures and RAP**

The results of the volumetric testing are displayed in Table 5 for all of the mixtures and binder contents. The VTM at  $N_{design}$  for each RAP percentage decreased as binder was added for all of the mixtures in the study. This reduction in VTM is obvious upon visual inspection of the mixture curves displaying the VTM versus gyrations, which are shown in Figure 10.

The VTM of the 0% RAP and 20% RAP design mixtures were within VDOT production limit standards, between 2.0% and 5.0%, while the VTM of the 40% RAP design mixture was below the specified level at 1.9%. Note that the 40% RAP mixture was not a mixture supplied to VDOT but rather to a private customer. Additionally, the binder content of the 40% RAP mixture was approximately the same as those of the 0% RAP and 20% RAP with 0.5% added binder, or about 6%. As 0.5% binder was added to the three mixtures, the VTM decreased significantly by 44%, 69%, and 67% for the 0% RAP, 20% RAP and 40% RAP mixtures, respectively. Adding 1.0% binder led to a reduction in VTM of 69% for the 0% RAP, 86% for the 20% RAP, and 93% for the 40% RAP. The VTM of the 40% RAP mixture at design binder content, 1.9%, was between the VTM values for the 0% and 20% RAP at design + 0.5% binder. A plot showing the VTM of each mixture and binder content as well as the VDOT VTM specifications is shown in Figure 11.

**Table 5. Mixtures Volumetric Data**

		Design		Design + 0.5%	Design + 1.0%
		Producer <sup>b</sup>	Lab (VTTI)		
0% RAP	Binder Content (%) <sup>a</sup>		5.63	6.13	6.63
	G <sub>mm</sub>		2.69	2.67	2.65
	VTM (%)		4.1	2.3	1.3
	VMA (%)		17.2	16.8	17.9
	VFA (%)		76.1	86.4	92.9
	Density @ N <sub>initial</sub> (%)		88.4	89.9	90.6
20% RAP	Binder Content (%) <sup>a</sup>	5.18	5.54 (5.14)	6.04 (5.64)	6.54 (6.14)
	G <sub>mm</sub>	2.619	2.61	2.60	2.58
	VTM (%)	3.1	3.0	0.9	0.4
	VMA (%)	15.2	16.1 (15.7)	16.1	17.8
	VFA (%)	79.7	81.0 (80.6)	94.1	97.7
	Density @ N <sub>initial</sub> (%)	89.3	89.4	91.5	92.3
40% RAP	Binder Content (%) <sup>a</sup>	5.42	5.99 (5.59)	6.49 (6.09)	6.99 (6.59)
	G <sub>mm</sub>	2.599	2.60	2.57	2.56
	VTM (%)	1.9	1.9	0.6	0.1
	VMA (%)	14.7	16.2 (15.7)	17.0	18.3
	VFA (%)	86.9	88.0 (87.6)	96.2	99.3
	Density @ N <sub>initial</sub> (%)	90.6	90.7	92.9	93.9
		RAP	RAP + 0.5%	RAP + 1.0%	RAP + 1.5%
100% RAP	Binder Content (%) <sup>a</sup>	5.77	6.27	6.77	7.27
	G <sub>mm</sub>	2.63	2.62	2.59	2.59
	VTM (%)	5.6	1.6	0.5	0.2
	VMA (%)	16.8	14.5	14.6	15.7
	VFA (%)	66.7	88.7	96.9	98.5
	Density @ N <sub>initial</sub> (%)	86.7	91.8	94.4	95.7

<sup>a</sup>Binder content at VTTI was determined using the ignition oven without applying a correction factor. Producer binder content is calculated using the producer correction factor for the ignition oven. The values in parenthesis are obtained by applying the producer correction factor to the binder content measured at VTTI.

<sup>b</sup>Producer data for the 0% RAP mixture was not available.

Addition of asphalt binder to the design mixtures also led to significant increases in VFA as VTM decreased and VMA generally increased. A plot of the VFA at N<sub>design</sub> for each mixture as well as the VDOT VFA range specification is shown in Figure 12. The 0% RAP at design binder content and design + 0.5% binder and the 20% RAP at design binder content were the only mixtures that fell within VDOT production specifications for VFA. The 40% RAP mixture at design binder content was already at 88% VFA, above the VDOT threshold of 84%. At design + 0.5% binder, the 20% RAP and 40% RAP mixtures were well above the limits of 94% and 95%, increasing to 98% and 99% at design + 1.0% binder. Asphalt binder was visibly bleeding out of 20% and 40% RAP design + 1.0% binder specimens, coating both the top and bottom specimen papers upon extraction from the SGC molds.

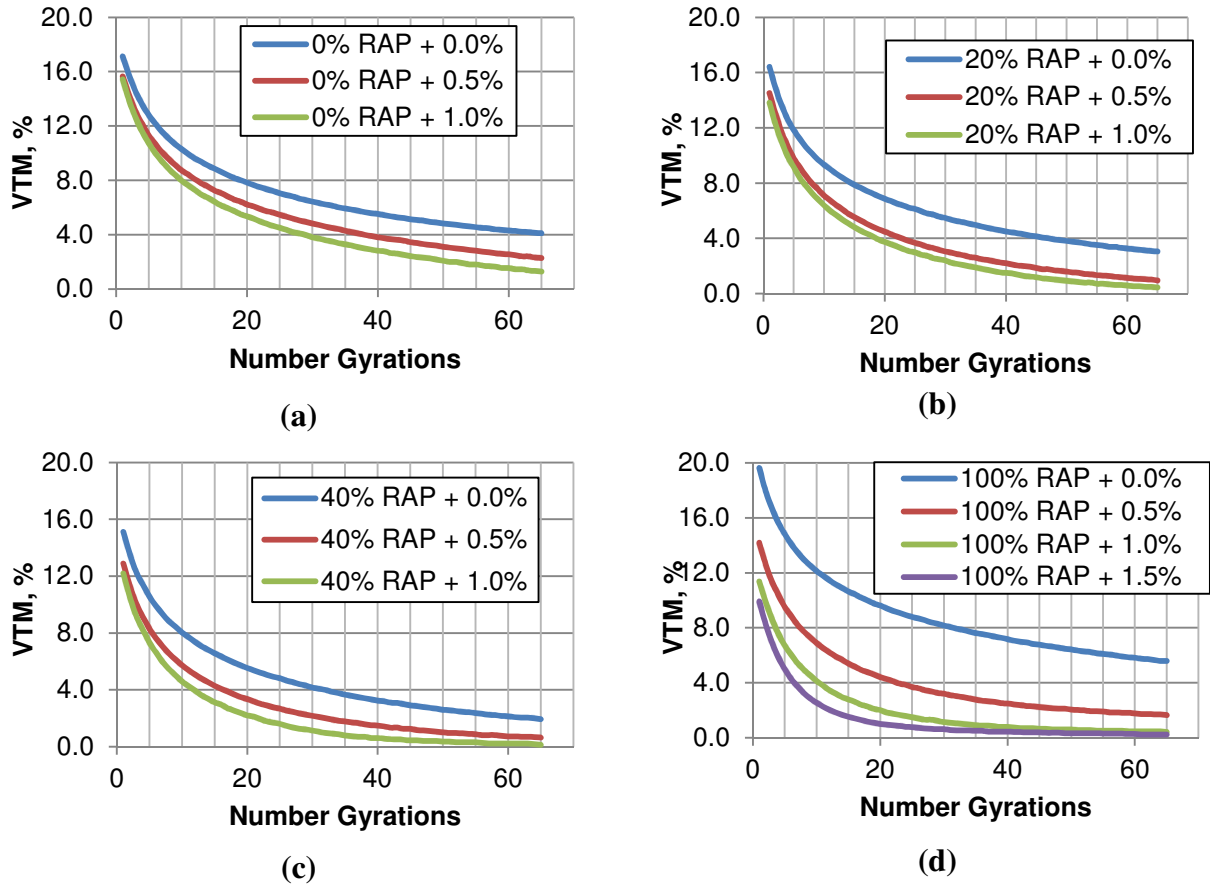


Figure 10. Voids in Total Mix Versus Gyration for (a) 0% RAP, (b) 20% RAP, (c) 40% RAP, and (d) 100% RAP

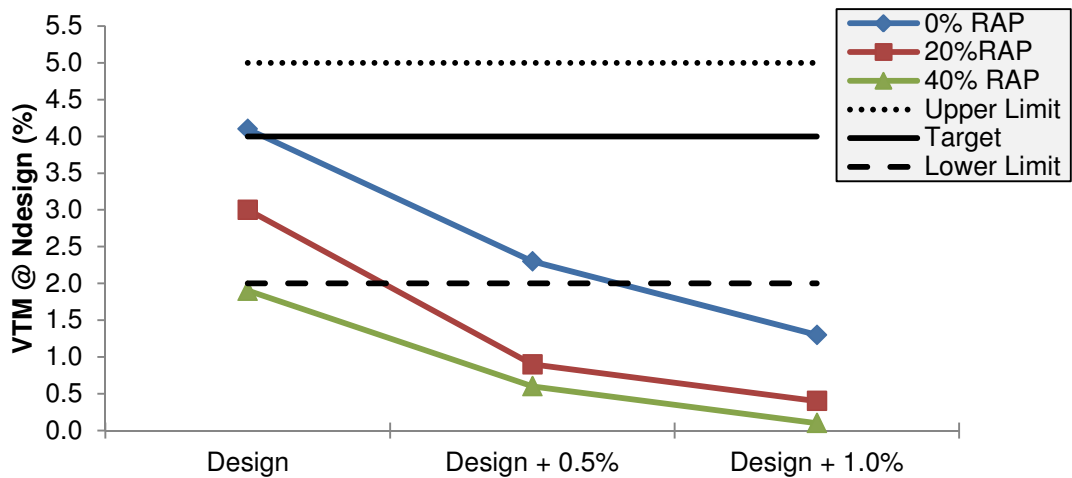


Figure 11. Voids in Total Mix at  $N_{design}$  for All Mixtures (With VDOT Specifications)

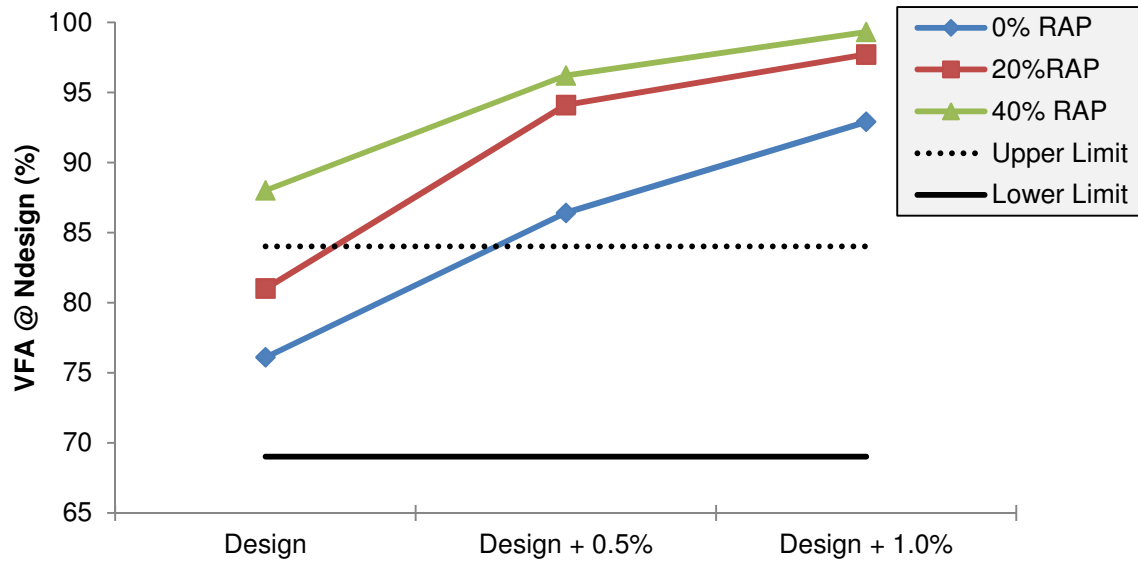


Figure 12. Voids Filled With Asphalt at  $N_{design}$  for All Mixtures (With VDOT Specifications)

### Gyrations to Achieve 4% VTM, $N_{4\%}$

The number of gyrations to achieve 4% VTM,  $N_{4\%}$ , for each mixture and binder content is shown in Figure 13. Visual inspection of Figure 13 indicates that  $N_{4\%}$  decreases as binder is added for all mixtures with only the  $N_{4\%}$  of the 0% RAP mixture at design binder content above the VDOT design compactive effort of 65 gyrations. For the 20% and 40% RAP mixtures at design binder content, it was predicted that only 47 and 33 gyrations would be necessary to yield 4% air voids, respectively. For the 40% RAP mixture, this is approximately half of the specified design compactive effort. At design + 0.5% binder the predicted  $N_{4\%}$  for the 0% RAP mixture

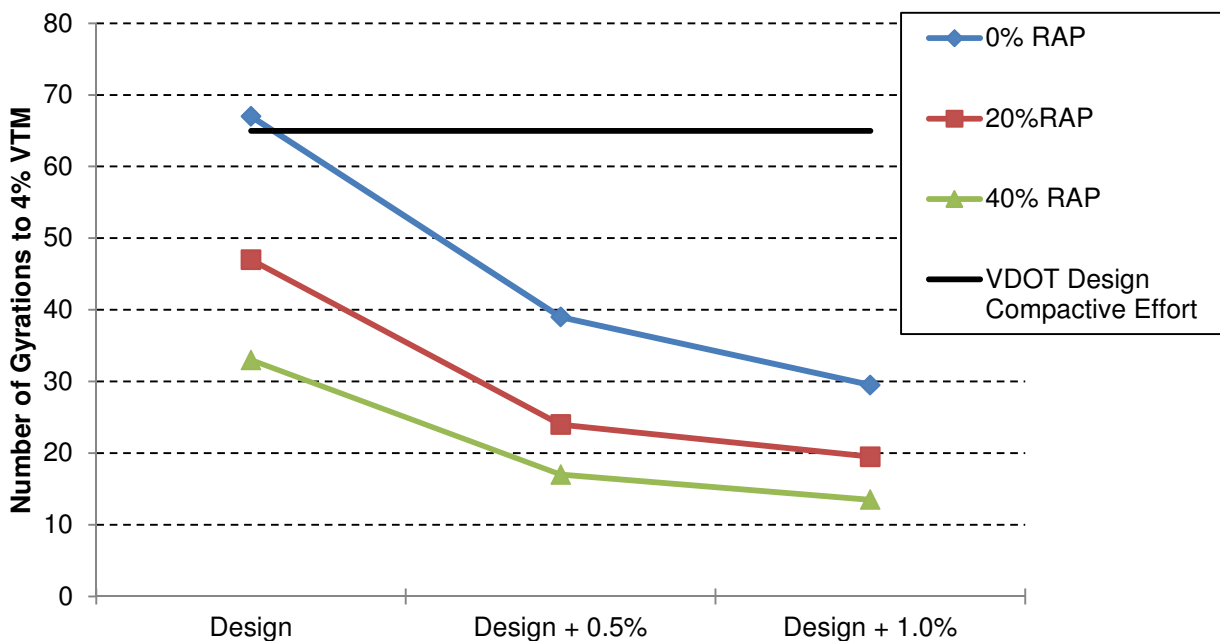


Figure 13. Predicted Number of Gyrations to 4% Voids in Total Mix,  $N_{4\%}$

was reduced by approximately 40% and at 1.0% added binder the  $N_{4\%}$  was 55% less than that of the design mixture. The 20% RAP and 40% RAP mixtures followed a similar trend, with reductions in  $N_{4\%}$  of 49% and 25% respectively when 0.5% binder was added. Adding 1.0% to both these mixtures led to a 60% reduction in  $N_{4\%}$ . The gyratory height data for the 0% RAP mixtures showed none of them experienced “locking points” during the 65 gyrations of compaction. The 20% RAP mixture at design binder content also did not have a locking point; however, the other two 20% RAP mixtures and all three of the 40% RAP mixtures did have locking points, with the average locking point decreasing with additional binder.

## DISCUSSION

### Mixture Performance Testing

This study confirmed that it is possible to improve the performance of asphalt concrete mixtures with RAP by adding additional binder. This holds especially true for the 20% RAP mixture where the addition of 0.5% or 1.0% binder improves both the fatigue cracking resistance and rutting resistance with only a slight decrease in the dynamic modulus. For the 20% RAP mixture specifically, the addition of 0.5% binder led to a 200% increase in fatigue resistance, a 200% increase in rutting resistance and only a 1% decrease in dynamic modulus.

Although both the 0% RAP and 20% RAP mixture exhibited similar performance behavior as the percentage of binder was increased, the behavior of the 40% RAP, or “high” RAP mixture, was somewhat different. As both the fatigue and rutting resistance of the 0% and 20% RAP mixtures improved when comparing the mixtures at design binder content to those with the additional 0.5% binder, the 40% RAP exhibited a significant decrease in rutting resistance with added binder while the fatigue resistance remained relatively unchanged. Volumetric mixture design data was requested and provided by the asphalt concrete producer for both the 20% RAP and 40% RAP mixtures in order to help identify the source of the disparity in performance. As shown in Table 5, the air voids of the plant-produced 40% RAP mixture was 1.9%, just below the VDOT’s lower limit for production of 2.0%. However, as stated earlier, this project required collecting a 40% RAP mixture from a private customer as VDOT did not authorize the use of RAP above 30% at the beginning of this study. Asphalt content data from the producer, also shown in Table 5, showed only a difference of approximately 0.2% in binder levels for the 20% and 40% RAP. Further AC testing by ignition oven in this study showed a larger difference in asphalt content between the two mixtures, 5.539% and 5.994% for the 20% RAP and 40% RAP mixtures, respectively. The volumetric and AC data suggest that the 40% RAP mixture had initially been designed with more binder and was already at the optimal binder level, as incorporating even higher levels of binder to the 40% RAP mixture led to poorer performance. This could be a cause for the different performance between the 20% RAP mixture and the 40% RAP mixture and would need to be further investigated.

As shown in Figure 4, at intermediate temperatures (represented by intermediate frequencies based on TTS) the 40% RAP showed increased dynamic modulus relative to the 0% and 20% RAP mixtures, but this effect was diminished at high temperatures (low frequencies).

The addition of 1.0% binder to the 40% RAP led to the highest average decrease in dynamic modulus at 21%, and a decrease of over 80% in FN determined using the RLPD test, which is run at a high temperature of 54.4°C (130 °F). This stiffness behavior is also in accordance with the higher initial stiffness of the 40% RAP mixtures during fatigue resistance testing, run at 20°C (68 °F) or intermediate temperature. This behavior further suggests that the 40% RAP mixture incorporated a higher binder percentage, which was confirmed by the volumetric analysis of the mixture (see Table 5).

Another explanation for the reduced rutting resistance of the 40% RAP mixtures with added binder is the softer PG binder used in the mixture; in this case the PG 64-22 relative to the PG 70-22 binder used in the 0% and 20% RAP mixtures. In a 2011 study of 18 asphalt concrete mixtures commonly used in Virginia by Apeageyi and Diefenderfer (2011), results of FN testing indicated that 25% RAP mixtures fabricated with PG 64-22 binder had unexpectedly low rutting resistance compared to those using PG 70-22. The use of different binders for the 20% RAP and 40% RAP mixtures must be taken into account and the effects should be further studied.

Results of this study also indicate that it is possible to create an asphalt concrete mixture in a laboratory setting using 100% RAP that can perform relatively well in dynamic modulus, fatigue resistance and rutting resistance by adding as little as 1.5% virgin binder. 100% RAP alone has the advantage of being extremely stiff with particularly high dynamic modulus and rutting resistance. The shortfall of the 100% RAP material is low fatigue resistance; however, with the addition of 1.5% binder, the 100% RAP had a fatigue resistance comparable to the 20% RAP mixture at the design binder level currently used in Virginia. Although these results suggest possible good performance of the 100% RAP mixture, they are based on only one strain level. Further investigation at different strain levels would be needed to validate these results. The same 100% RAP mixture with 1.5% additional binder also had a dynamic modulus between 125% and 300% higher along the range of reduced frequencies and exhibited under 0.6% permanent strain after 10,000 cycles of loading during RLPD testing. Of course, the dynamic modulus, fatigue resistance and rutting resistance, while very important, are not the only performance measures of a mixture and the fact that the 100% RAP mixture with 1.5% added binder outperforms the original 20% RAP mixture should not be interpreted as evidence that the 100% RAP mixture will perform well in the field. For example, the high dynamic modulus can be a drawback for resistance to low-temperature cracking. Furthermore, although the fatigue life of the 20% original RAP mixture and the 100% RAP mixture with 1.5% added binder are similar, Figure 8(d) shows that accumulation of fatigue damage in the 100% RAP mixture is very sudden, which is not desirable for cracking resistance.

### **Superpave Volumetric Properties**

The volumetric analysis can help explain the results of the previously completed performance tests as well as determine if the currently utilized design procedure results in asphalt contents that are less than optimal for RAP mixtures. Dynamic modulus testing indicated that there were only slight decreases in stiffness when binder was added to the 0%, 20% and 40% RAP mixtures. As well, the addition of binder generally improved the fatigue cracking resistance

of all three mixtures. Unexpectedly, the 40% RAP mixture at the design binder content showed higher fatigue resistance relative to the 20% RAP mixtures at all three binder contents.

The 0% RAP and 20% RAP mixtures also saw increased FNs at the design + 0.5% and design + 1.0% binder levels. However, when binder was added to the 40% RAP mixture, the flow number decreased significantly. One of the explanations for this decrease is the use of the softer PG64-22 binder in the 40% RAP mixture; however, the volumetric properties also offer an explanation to this behavior. A plot depicting FNs and VTM at  $N_{design}$  for all of the mixtures is shown in Figure 14. The VTM of the 40% RAP mixture at design binder content was 1.9%, significantly lower than that of the 0% RAP and 20% RAP design mixtures, but in between the VTM values for the 0% and 20% RAP mixtures with 0.5% added binder. With the addition of 0.5% binder, the 0% RAP and 20% RAP exhibited an increase in FN as well as a decrease in VTM from 4.1% to 2.3% and 3.0% to 0.9%, respectively. For the 0% RAP and 20% RAP, the design + 0.5% binder level proved to be the optimal mixture for the three binder levels tested across all three performance tests. With the addition of 0.5% binder, the 40% RAP mixture experienced a decrease in VTM from 1.9% to 0.6% and a subsequent decrease in FN and this decrease in VTM and FN continued with the addition of 1.0% binder. At design + 1.0% binder, both the 0% RAP and 20% RAP mixtures exhibited decreases in both VTM and FN from the design + 0.5% binder mixtures. It is likely that this trend would have continued if these mixtures had been tested with even higher additional binder levels, which would have also resulted in lower VTM values. Whereas the addition of 0.5% binder led to an increase in FN for the 0% RAP and 20% RAP mixtures before FN was reduced with the addition of 1.0% binder, FN for the 40% RAP mixtures steadily decreased with additional binder. This relationship shows that the 40% RAP mixture was most probably already at optimal binder content when tested with no additional binder, which is the reason for the lower initial VTM.

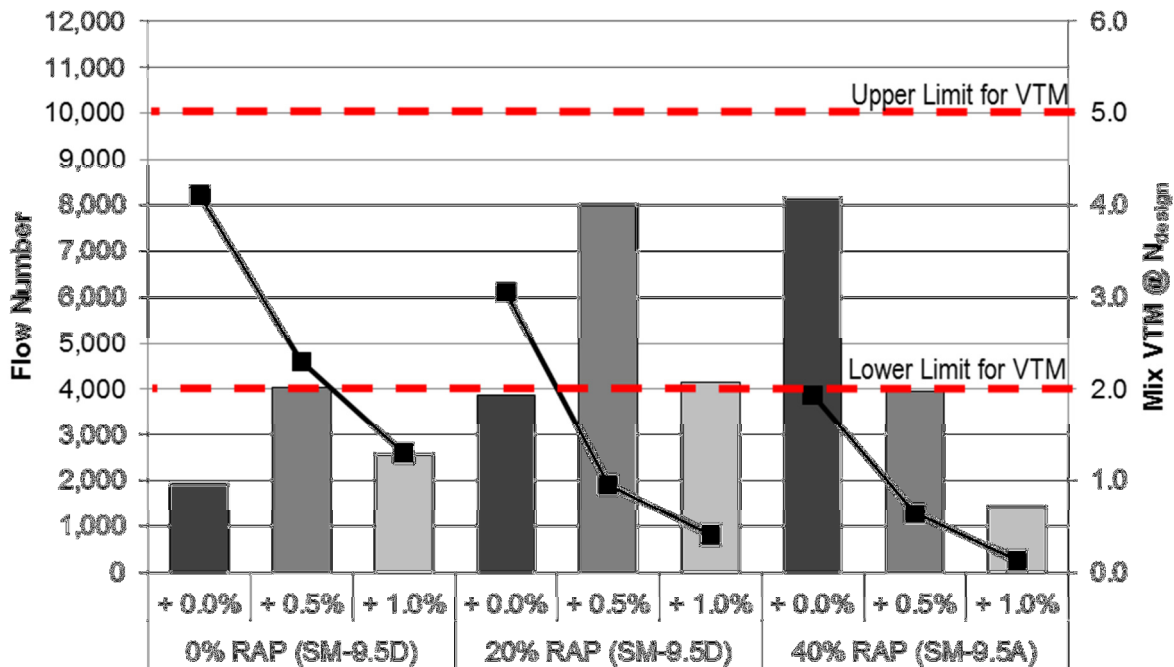


Figure 14. Flow Number and Voids in Total Mix at  $N_{design}$  for All Mixtures. Bars Indicate Flow Number; Points Indicate Voids in Total Mix at  $N_{design}$ .



As stated earlier, the general consensus is that too low VTM, less than 2.0%, will result in mixtures with lower rutting resistance (Huang 1993). The results of this study indicate that for the 20% RAP, the greatest rutting resistance, or highest FN, was the design + 0.5% binder mixture with 0.9% VTM at  $N_{design}$ . The 40% RAP mixture at design binder content and 1.9% VTM at  $N_{design}$  exhibited the highest rutting resistance overall. For both the 20% and 40% RAP, once the VTM fell below 0.5%, the rutting resistance decreased.

Figure 15 shows the FN and asphalt content for all mixtures. Upon visual inspection of the plot it can be seen that the optimal FN for all mixtures occurs at an AC of approximately 6%. For the case of the 0% and 20% RAP, this was the AC resulting from adding 0.5% binder and for the 40% RAP, this was the initial asphalt content of the design mixture received from the producer.

As recommended by the FHWA, any consideration for reduction in design gyrations in order to achieve mixtures with higher asphalt binder must be combined with an evaluation of the rutting resistance of mixtures resulting from lower design compaction effort (FHWA 2010). Figure 16 shows the FN and predicted  $N_{4\%}$  for the 0%, 20% and 40% RAP mixtures. Upon visual inspection it is obvious that the mixtures for which rutting resistance was highest would have yielded 4% VTM at significantly lower design gyrations than currently specified. In the case of the 20% RAP and 40% RAP, the mixture with the highest FN had asphalt binder contents that would have resulted in 4% VTM with 25 and 33 gyrations, respectively, which is approximately 50% or less than the 65 gyrations currently used. Additionally, the optimally performing RAP mixtures, the 20% design + 0.5% binder and 40% at design binder content, both had average locking points of 61. This means that additional gyrations past 61 mainly result in degradation of the aggregate skeleton.

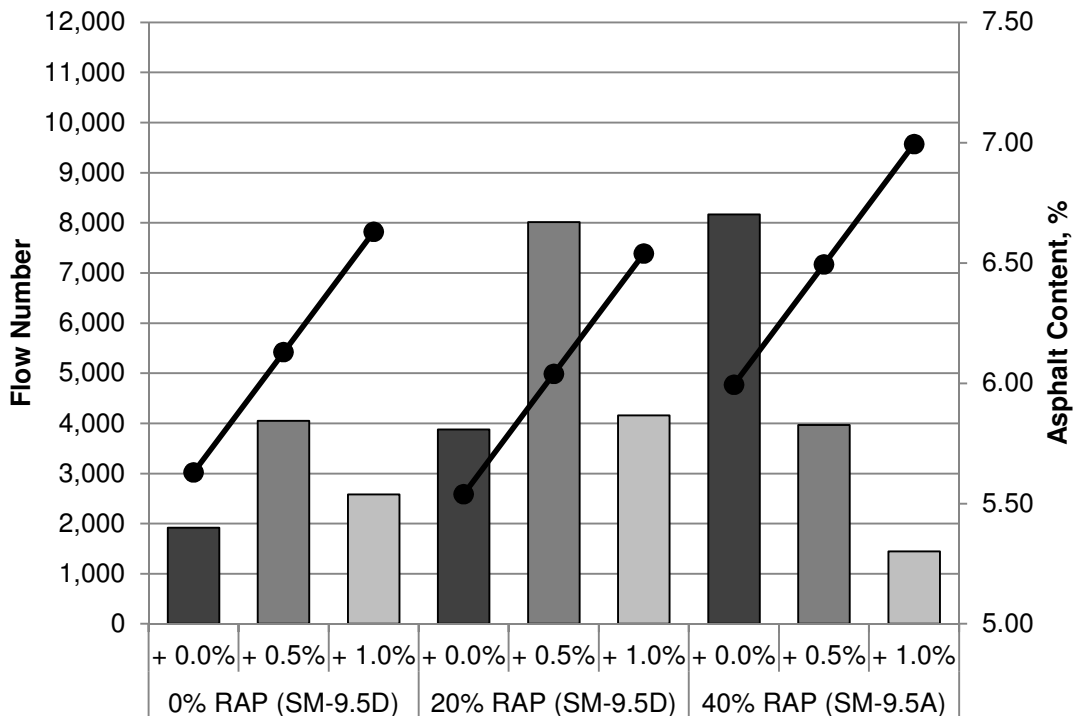
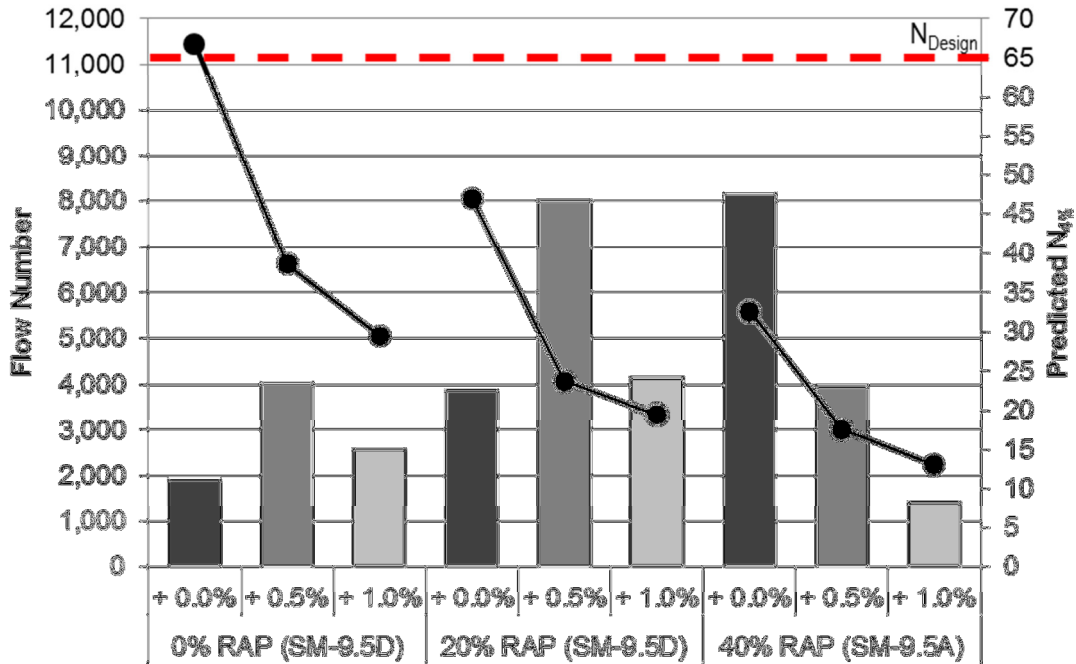


Figure 15. Flow Number and Asphalt Content for All Mixtures. Bars Indicate Flow Number; Points Indicate Asphalt Content

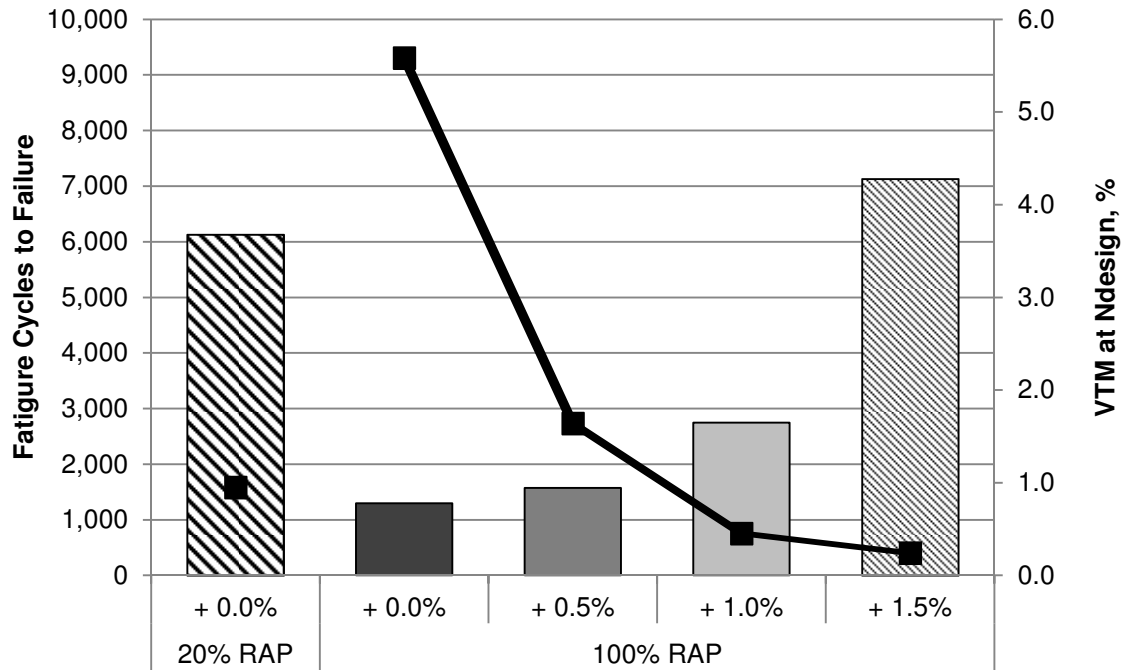


**Figure 16. Flow Number and Gyration to  $N_{4\%}$  for All Mixtures. Bars Indicate Flow Number; Points Indicate Predicted Number of Gyration to 4% Air Voids.**

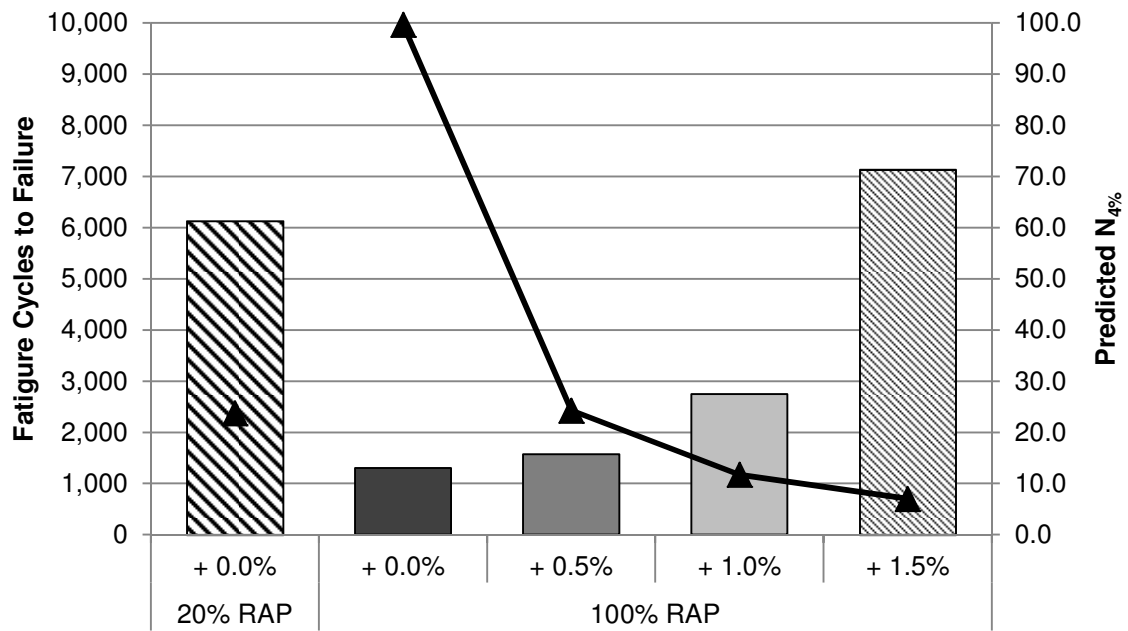
One of the concerns of excessive binder is producing mixtures that could possibly become tender during construction. However, a study performed as part of NCHRP Report 573 determined that 36% of 40 HMA samples with design traffic between 0.3 million and 3 million ESALs (the same design traffic level as the mixtures in this study) failed the  $N_{initial}$  requirement, with only one of the mixtures actually being tender in the field. In that study all of the mixtures exhibited exceptional rutting resistance (Prowell and Brown, 2007). This suggests that the optimally performing mixtures in this study would not necessarily become tender due to added binder; however, this would require further evaluation in the field.

### 100% RAP

The 100% RAP mixtures at the four added binder levels (0.0%, 0.5%, 1.0%, 1.5%) all exhibited extremely high stiffness (dynamic modulus) and rutting resistance (FN). In fact, none of the mixtures exhibited more than 0.5% strain during the Repeated Load Permanent Deformation (RLPD) test. However, the 100% RAP mixtures did not perform well during fatigue resistance testing, with the exception of the 1.5% added binder mixture. The fatigue cycles to failure for the 100% RAP + 1.5% binder mixture was greater than that of the 20% RAP mixture at design binder content. As shown in Figure 17(a), the higher fatigue resistance of the 100% RAP + 1.5% binder mixture was achieved with VTM at  $N_{design}$  dropping to 0.2%. Figure 17(b) shows that the predicted design gyrations to achieve 4% VTM for 100% RAP mixture with 1.5% added binder is only 7 gyrations. So for 1.5% added binder content, the design VTM is achieved at  $N_{initial}$ . The volumetric analysis of the 100% RAP samples proved that improving the fatigue resistance of 100% RAP by adding binder creates mixtures with poor volumetric properties. The extremely low VTM and the extremely high density at  $N_{initial}$  along with the gradation of the 100% RAP could be of concern for an unstable mixture during construction.



(a)



(b)

**Figure 17. Fatigue Cycles to Failure and (a) Voids in Total Mix at  $N_{design}$  for 100% RAP Mixtures and (b) Predicted  $N_{4\%}$  for 100% RAP Mixtures. Bars Indicate Cycles to Failure; Points Indicate Voids in Total Mix and Predicted Gyration, Respectively.**

## SUMMARY OF FINDINGS

### 0% and 20% RAP Mixtures

- Increasing binder content resulted in increased fatigue and rutting resistance for the 0% and 20% RAP mixtures with only slight decreased in dynamic modulus. Specifically, adding 0.5% binder to the 20% RAP mixture resulted in 200% increase in fatigue resistance, a 200% increase in rutting resistance and only a 1% decrease in dynamic modulus. The optimally performing 20% RAP mixture had 0.5% added binder and had a VTM of 2.3% at  $N_{\text{design}}$ . The predicted gyrations to achieve VTM of 4% or  $N_{4\%}$  for the 20% RAP + 0.5% binder mixture was 24 gyrations. The optimally performing 0% RAP mixture had a VTM of 2.3 at  $N_{\text{design}}$  and  $N_{4\%}$  of 39 gyrations.
- Both the 0% and 20% RAP were plant-produced mixtures designed to meet VDOT specifications. The VTM, VFA and VMA for these mixtures at design binder content were within VDOT production specifications. As binder was added to these mixtures, performance improved; however, the mixtures with added binder no longer met the current volumetric specifications, except for the VMA.

### 40% RAP Mixtures

- Increasing binder content resulted in a decrease in rutting resistance with little change to fatigue resistance for the 40% RAP mixture. The addition of 0.5% binder and 1.0% binder to the 40% RAP mixture resulted in a 60% and 80% decrease in FN, respectively. The addition of 1.0% binder resulted in a 21% decrease in dynamic modulus for the 40% RAP mixture. The optimally performing 40% RAP mixture had no added binder and had a VTM of 1.9% at  $N_{\text{design}}$ .  $N_{4\%}$  for the 40% RAP + 0.0% binder mixture was predicted to be 33 gyrations.
- The 40% RAP mixture used in this study was collected from a private customer as VDOT did not authorize 40% RAP at the time of this study and, therefore, the mixture did not have to meet VDOT design and production specifications. Nevertheless, the VTM and VFA of the mixture would not have met VDOT production standards. However, the VMA of the mixture would have met specifications indicating that sufficient volume was available for both asphalt binder and air voids. The low VTM and high VFA indicates that additional binder had already been added to the 40% RAP mixture compared to the 0% and 20% RAP mixtures. This also corresponds to ignition oven asphalt content testing that showed the 40% RAP mixture contained almost 0.5% more asphalt binder than the 20% RAP mixture. As binder was added to the 40% RAP mixture, the performance decreased, indicating that the initial binder content provided for the optimal performance (for the performed tests).

### 100% RAP Mixtures

- Both stiffness and rutting resistance of the 100% RAP mixtures were considerably higher than all other mixtures, while the fatigue resistance was significantly lower until 1.5% binder

was added to the mixture. On average, the dynamic modulus of the 100% RAP mixtures was 400% higher than the other mixtures at the lowest reduced frequency and 125% higher at the highest reduced frequency. None of the 100% RAP mixtures exhibited tertiary flow during RLPD testing with all mixtures experiencing less than 0.5% strain. The 100% RAP mixtures with 0%, 0.5% and 1.0% added binder had the lowest average fatigue cycles to failure at 1300, 1572 and 2746 cycles, respectively. Only the 100% RAP + 1.5% binder mixture had an average fatigue cycles to failure comparable to the other mixtures, at 7131 cycles, which was higher than the 20% RAP + 0.0% binder, but lower than all other tested mixtures. The optimally performing 100% RAP mixture had 1.5% added binder and had a VTM of 0.2% at  $N_{design}$ . The predicted gyrations to achieve VTM of 4%, or  $N_{4\%}$ , for the 20% RAP + 0.5% binder mixture was only 7 gyrations.

- Although the 100% RAP mixture showed extremely high stiffness and rutting resistance, the fatigue resistance only reached an acceptable level once 1.5% binder was added. At this binder level, the 100% RAP mixture had only 0.2% VTM, a VFA of 98.5%, and a density at  $N_{initial}$  of 95.7%, indicating that this would not be a stable mixture in the field.

## CONCLUSIONS

- *The percentage of RAP and the percentage of binder have significant effects on the performance and volumetric properties of the mixtures investigated in this study.*
- *The addition of 0.5% virgin binder to the existing RAP-containing mixtures improves rutting and fatigue resistance with minimum effect on dynamic modulus, at least as measured in the laboratory. Unfortunately, binder addition to these existing mixtures produces volumetric properties that do not meet VDOT specifications (and may indicate a tender or unstable mixture during construction).*

## RECOMMENDATIONS

1. *VDOT's Materials Division should incorporate asphalt mixture performance testing as part of the asphalt mixture design methodology. In general, the best performing mixtures in this study did not meet current VDOT volumetric requirements, which suggests that the current mixture design procedure, which is based on volumetric properties, is not enough to ensure good mixture performance measured in the laboratory.*
2. *VCTIR should evaluate additional performance measures to determine the effects of RAP percentage and binder content. This study was limited to four performance tests: dynamic modulus, flow number, rutting resistance, and fatigue resistance. Additional tests that should be considered include moisture susceptibility and low temperature cracking.*

3. *VCTIR should include mixtures that were designed to meet VDOT design and production specifications in future research on mixtures with a high RAP content. The “high RAP” mixture used in this study was not a VDOT-approved mixture as VDOT did not allow 40% RAP mixtures at the time of this study.*
4. *VCTIR should initiate a study to evaluate the effect of binder performance grade on mixtures containing varying RAP percentages. Three different performance grades of asphalt binder were used in this study with only one performance grade per RAP percentage. Results of testing and the true effects of high RAP percentage and high binder content could be better distinguished if mixtures were tested using all three performance grades.*
5. *VCTIR should investigate the use of a softer binder (such as PG 58-28) to provide a better balance between the extreme stiffness and rutting resistance provided by the RAP material and optimize fatigue resistance without such an adverse effect on volumetric properties.*
6. *VCTIR and VDOT’s Materials Division should evaluate whether current design and volumetric specifications need to be altered so that asphalt concrete mixtures containing RAP are designed with the optimal level of binder.*

## **BENEFITS AND IMPLEMENTATION PROSPECTS**

This study evaluated the effect of increasing the mixture binder content on laboratory performance of mixtures containing currently allowable RAP contents (0% and 20% RAP) and a higher RAP content (40% RAP). Results of the 40% RAP mixture performance were encouraging, which has prompted VDOT to initiate a field evaluation of mixtures containing RAP contents greater than the 30% maximum currently specified. Results of the 0% and 20% RAP mixture performance testing have shown that performance can still be improved with changes to mixture design. This result along with the current voiced concerns (of VDOT district engineers and Virginia asphalt producers) that Superpave mixtures are not providing the necessary durability compared to some of the mixtures placed prior to the implementation of Superpave has led to initiation of a research project to evaluate different mixture designs with laboratory mixture performance testing. All these efforts will together lead to better and longer lasting mixtures that are economically and environmentally more sustainable.

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## REFERENCES

- American Association of State Highway and Transportation Officials. *AASHTO T 209-94: Standard Test Method for Theoretical Maximum specific Gravity and Density of Bituminous Paving Mixtures*. Washington, DC, 1994.
- American Association of State Highway and Transportation Officials. *AASHTO T321-03: Standard Test Method for Determining the Fatigue Life of Compacted Hot Mix Asphalt (HMA) Subjected to Repeated Flexural Bending*. Washington, DC, 2003.
- American Association of State Highway and Transportation Officials. *AASHTO T312-04: Standard Test Method for Preparing and Determining Density of Hot Mix Asphalt (HMA) Specimens by Mean of the Superpave Gyrotory Compactor*. Washington, DC, 2004.
- American Association of State Highway and Transportation Officials. *AASHTO T27-06: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. Washington, DC, 2006.
- American Association of State Highway and Transportation Officials. *AASHTO TP 79: Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*. Washington, DC, 2009.
- American Association of State Highway and Transportation Officials. *AASHTO T166-10: Standard Test Method for Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface Dry Specimens*. Washington, DC, 2010.
- Aguiar-Moya, J.P., Prozzi, J.A., and Tahmoressi, M. Optimum Number of Superpave Gyration Based on Project Requirements. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2001. Transportation Research Board of the National Academies, Washington, DC, 2007, pp. 84-92.
- Al-Qadi, I.L., Carpenter, S.H., Roberts, G.L., Ozer, H., Aurangzeb, Q., Elseifi, M.A., and Trepanier, J. *Determination of Usable Residual Asphalt Binder in RAP*. FHWA-ICT-09-031. Illinois Center for Transportation, Rantoul, 2009.
- Al-Qadi, I.L., Aurangzeb, Q., Carpenter, S.H., Pine, W.J., and Trepanier, J. *Impact of High RAP Contents on Structural and Performance Properties of Asphalt Mixtures*. FHWA-ICT-12-002. Illinois Center for Transportation, Rantoul, 2012.
- Apeageyi, A.K., Diefenderfer, B.K., and Diefenderfer, S.D. Rutting Resistance of Asphalt Concrete Mixtures That Contain Recycled Asphalt Pavement. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2208. Transportation Research Board of the National Academies, Washington, DC, 2011, pp. 9-16.

- Apeageyi, A., and Diefenderfer, S. *Asphalt Material Design Inputs for Use With the Mechanistic Empirical Pavement Design Guide*. VCTIR 12-R6. Virginia Center for Transportation Innovation and Research, Charlottesville, 2011.
- Apeageyi, A.K., and Diefenderfer, B.K. Development of Dynamic Modulus Master Curves for Hot-Mix Asphalt with Abbreviated Testing Temperatures. *International Journal of Pavement Engineering*, Vol. 13, No. 2, 2012, pp. 98-109.
- Applied Research Associates. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*. Transportation Research Board of the National Academies, Washington, DC, 2004.
- Asphalt Institute. *Superpave Mix Design Superpave Series No. 2 (SP-2)*. Lexington, KY, 1996.
- Biligiri, K.P., Kaloush, K.E., Mamlouk, M.S., and Witczak, M.W. Rational Modeling of Tertiary Flow for Asphalt Mixtures. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2001. Transportation Research Board of the National Academies, Washington, DC, 2007, pp. 63-72.
- Biligiri, K.P., Kaloush, K., and Uzan, J. Evaluation of Asphalt Mixtures' Viscoelastic Properties Using Phase Angle Relationships. *International Journal of Pavement Engineering*, Vol. 11, No. 2, 2010, pp. 143-152.
- Bonaquist, R., and Christensen, D.W. Practical Procedure for Developing Dynamic Modulus Master Curves for Pavement Structural Design. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1929. Transportation Research Board of the National Academies, Washington, DC, 2005, pp. 208-217.
- Brown, E.R., and Mallick, R.B. An Initial Evaluation of N-design Superpave Gyrotory Compactor. In *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 67, 1998, pp. 101-116.
- Christensen, D.W., and Bonaquist, R.F. *Volumetric Requirements for Superpave Mix Design*. NCHRP Report 567. Transportation Research Board of the National Academies, Washington, DC, 2006.
- Cominsky, R.J. *The Superpave Mix Design Manual for New Construction and Overlays*. SHRP-A-407. Transportation Research Board of the National Academies, Washington, DC, 1994.
- Copeland, A., D'Angelo, J., Dongré, R., Belagutti, S., and Sholar, G. Field Evaluation of High Reclaimed Asphalt Pavement-Warm-Mix Asphalt Project in Florida. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2179. Transportation Research Board of the National Academies, Washington, DC, 2010, pp. 93-101.



- Cross, S.A., Yatish, J., and Sumesh, K.C. *Determination of Dynamic Modulus Master Curves for Oklahoma HMA Mixtures*. FHWA-OK-07-05. Oklahoma Department of Transportation, Oklahoma City, 2007.
- Daniel, J.S., Pochily, J.L., and Boisvert, D.M. Can More Reclaimed Asphalt Pavement Be Added? In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2180. Transportation Research Board of the National Academies, Washington, DC, 2010, pp. 19-29.
- Diefenderfer, S. *Investigation of Fatigue Properties of Superpave HMA at the Virginia Smart Road*. Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, 2009.
- Dougan, C.E., Stephens, J.E., Mahoney, J., and Hansen, G. *E\*-DYNAMIC MODULUS: Test Protocol-Problems and Solutions*. Connecticut Transportation Institute, Connecticut Advanced Pavement Lab, Hartford, 2003. [http://www.caplab.uconn.edu/pdfs/e-final\\_report\\_3-26-03.pdf](http://www.caplab.uconn.edu/pdfs/e-final_report_3-26-03.pdf).
- Hong, F., Chen, D.H., and Mikhail, M.M. Long-Term Performance Evaluation of Recycled Asphalt Pavement Results from Texas. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2180. Transportation Research Board of the National Academies, Washington, DC, 2010, pp. 58-66.
- Huang, Y.H. *Pavement Analysis and Design*. Prentice Hall, Upper Saddle River, NJ, 1993.
- Kandhal, P.S., Foo, K.Y., and Mallick, R.B. Critical Review Of Voids in Mineral Aggregate Requirements in Superpave. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1609. Transportation Research Board of the National Academies, Washington, DC, 1998, pp. 21-27.
- Li, X., Clyne, T.R., and Marasteanu, M.O. *Recycled Asphalt Pavement (RAP) Effects on Binder and Mixture Quality*. MN/RC-2005-02. University of Minnesota, Twin Cities, 2004. <http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=973>.
- Li, X., Marasteanu, M.O., Williams, R.C., and Clyne, T.R. Effect of Reclaimed Asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2051. Transportation Research Board of the National Academies, Washington, DC, 2008, pp. 90-97.
- Maupin, G.W. *Additional Asphalt to Increase the Durability of Virginia's Superpave Mixtures*. VTRC 03-R15. Virginia Transportation Research Council, Charlottesville, 2003.
- Maupin, G.W., and Diefenderfer, B. *Design of High-Binder High-Modulus Asphalt Mixture*. VTRC 07-R15. Virginia Transportation Research Council, Charlottesville, 2006.

- McDaniel, R.S., Soleymani, H., Anderson, R.M., Turner, P., and Peterson, R. *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method*. NCHRP Web Document 30, 2000. [http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp\\_w30-a.pdf](http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w30-a.pdf). Accessed October 2, 2014.
- MnDOT Materials Lab. *1815: Determination of RAP Aggregate Bulk Specific Gravity, Laboratory Testing Manual*. Minnesota Department of Transportation, 2007. <http://www.dot.state.mn.us/materials/manuals/laboratory/1815.pdf>. Accessed September 2014.
- Prowell, B.D., and Brown, E. *Superpave Mix Design: Verifying Gyration Levels in the Ndesign Table*. NCHRP Report 573. Transportation Research Board of the National Academies, Washington, DC, 2007.
- Shu, X., Huang, B., and Vukosavljevic, D. Laboratory Evaluation of Fatigue Characteristics of Recycled Asphalt Mixture. *Construction and Building Materials*, Vol. 22, No. 7, 2008, pp. 1323-1330.
- Federal Highway Administration. *TechBrief: Superpave Mix Design and Gyrotory Compaction Levels*. FHWA-HIF-11-031, 2010. <http://www.fhwa.dot.gov/pavement/materials/pubs/hif11031/tb00.cfm>. Accessed September 2014.
- Vavrik, W.R., and Carpenter, S.H. Calculating Air Voids at Specified Number of Gyration in Superpave Gyrotory Compactor. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1630. Transportation Research Board of the National Academies, Washington, DC, 1998, pp. 117-125.
- Virginia Department of Transportation. *Division II – Materials, Special Provision Copied Notes (SPCNs), Special Provision (SPs) and Supplemental Specifications (SSs)*. Richmond, 2014. [http://www.virginiadot.org/business/resources/const/07RevDiv\\_II.pdf](http://www.virginiadot.org/business/resources/const/07RevDiv_II.pdf). Accessed September 2014.
- Virginia Department of Transportation. *VTM Determination of Asphalt Content from Asphalt Mixtures by the Ignition Method (Asphalt Lab)*. 2009. <http://www.virginiadot.org/business/resources/bu-mat-VTMs070704.pdf>. Accessed April 2014.
- West, R., Kvasnak, A., Tran, N., Powell, B., and Turner, P. Testing of Moderate and High Reclaimed Asphalt Pavement Content Mixtures. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2126. Transportation Research Board of the National Academies, Washington, DC, 2009, pp. 100-108.
- Witczak, M.W. *Specification Criteria for Performance Tests for Rutting, Volume I: Dynamic Modulus (E\*), Volume II: Flow Number and Flow Time*. NCHRP Report 465. Transportation Research Board of the National Academies, Washington, DC, 2007.

Witczak, M.W., and Fonseca, O.A. Revised Predictive Model for Dynamic (Complex) Modulus of Asphalt Mixtures. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1540.1. Transportation Research Board of the National Academies, Washington, DC, 1996, pp. 15-23.

Witczak, M.W., Kaloush, K., Pellinen, T., El-Basyouny, M., and von Quintus, H. *Simple Performance Test for Superpave Mix Design*. NCHRP Report 465. Transportation Research Board of the National Academies, Washington, DC, 2002.

Washington State Department of Transportation. *WSDOT Pavement Guide*. (Cited October 8, 2012). <http://classes.engr.oregonstate.edu/cce/winter2012/ce492/>.