Investigation of Binder Aging and Mixture Performance of In-Service RAP Mixtures

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ABSTRACT. *In 2007, the Virginia Department of Transportation piloted a specification allowing up to 30% reclaimed asphalt pavement (RAP) in certain dense-graded asphalt surface mixtures while changing virgin binder grade requirements. The change affected only mixtures requiring an end binder grade of either PG 64-22 or PG 70-22. For mixtures specifying PG 64-22 binder, the virgin binder grade at RAP contents of 30% or less was no longer required to change. For mixtures specifying PG 70-22 binder, the virgin binder grade at RAP contents of 21-30% was no longer required to change from PG 64-22 to PG 64-28. Prior to this, both types of surface mixtures were allowed to contain only up to 20% RAP before binder grade adjustments were required. An initial laboratory study of mixtures produced under the pilot specification indicated that there were no significant differences for fatigue, rutting, and susceptibility to moisture between the higher content (21-30%) RAP mixtures and control mixtures (having 20% RAP or less). The current study evaluated the in-service performance of these mixtures after approximately 7 years and encompassed field visits and a laboratory investigation of a sample of 23 in-service pavement sites used in the initial laboratory evaluation. Cores were collected from each site and used to evaluate the binder and mixture properties. Binder data were compared to data from the original construction when available to assess the changes in properties over time.*

Overall study results revealed no systematic effect on field and laboratory performance with increasing RAP contents up to 30%. Test results from roadway cores showed no conclusive trends in performance with RAP content. Testing of extracted binder indicated that RAP content appears to have an influence on the rate of aging of virgin binder–RAP blends; initial grades were lower for blends having lower RAP contents, although after 7-8 years of service, all blends aged to similar grades. Binder analysis also revealed that depth within the surface layer (in this case, the top half versus the bottom half) significantly affects binder properties, with stiffness decreasing with depth. However, increasing RAP contents appeared to mitigate the difference in failure temperature before and after aging, possibly attributable to the preexisting aged composition of the RAP and its influence on the virgin binder properties.

KEYWORDS: *reclaimed asphalt pavement, asphalt binder, aging, in-service performance.*

The oral presentation was made by Dr. Diefenderfer.

1.0 Introduction

The use of reclaimed asphalt pavement (RAP) in new asphalt mixtures has become increasingly common because of both economic and environmental benefits. The incorporation of RAP gained in popularity in the 1970s because of increasing oil prices (Copeland, 2011), and RAP is often assumed to be both an aggregate and a virgin binder substitution in the mixture. Average RAP contents in asphalt mixtures, according to a 2008 survey, were between 10-20% with a mean of 12%. Much of this is believed to be due to uncertainty regarding how RAP pavements will perform long term (Copeland, 2011). More recently, a 2011 survey indicated that average RAP contents have increased by 5-17% (Hansen and Newcomb, 2011). The Virginia Department of Transportation (VDOT) has been allowing the use of RAP for many years and, like many states, has slowly increased the allowable RAP contents in asphalt mixtures. Currently, up to 30% RAP is allowed in most dense-graded surface mixtures. VDOT also employs a RAP binder adjustment factor, reducing the RAP binder contribution by 0.4% of the total RAP binder content (Babish, 2013).

Unfortunately, there is little understanding of the long-term performance implications of using RAP and RAP binder in asphalt mixtures. Current practice does not reflect consideration of the impact of the already oxidized RAP binder beyond its overall stiffening potential. In an effort to counteract this stiffening, binder grades may be "bumped" (i.e., reduced a high-grade temperature) in some, but not all, cases. However, the complexity of the stiffening phenomenon is exhibited in the research of Apeagyei et al. (2011). This study found that the anticipated stiffening effects may not occur for plant-produced mixtures containing 21-30% RAP and produced in anticipation of using the RAP to increase binder grade from a virgin PG 64-22 to a composite PG 70-22. There are a few studies that investigate the effects of RAP-virgin binder composite on in-service life or long-term performance for asphalt mixtures containing RAP (Al-Khateeb et al., 2005; Al-Azri et al., 2006; Glover et al., 2008; Woo et al., 2008).

Although many test sections have been placed to study the effects of increasing RAP contents, few works have been published that looked at the long-term field performance of the mixtures. In 2009, an examination of the Specific Pavement Studies 5 (SPS5) information in the Long-Term Pavement Performance data base was conducted by the National Center for Asphalt Technology (NCAT) (West et al., 2011). SPS5 consisted of 50-mm and 125-mm overlays constructed from virgin and 30% RAP mixtures. The NCAT study found that the 30% RAP overlays performed as well as the virgin overlays in terms of international roughness index (IRI), rutting, block cracking, and raveling. NCAT has also published work based on trial sections at the NCAT pavement test track (West et al., 2012; Willis et al., 2012). These studies evaluated different binder grades in conjunction with surface mixtures containing 45% RAP and structural sections containing 50% RAP. The RAP and virgin structural sections were designed and constructed to have equivalent binder contents, and all other properties were held within normal production tolerances. The structural sections containing 50% RAP withstood 10 million ESALs of trafficking and their performance was equivalent to that of the control in both cracking and rutting. Anderson and Daniel (2013) examined case studies of roadway sections from across the United States constructed between 1977 and 1999 that contained 20-72% RAP. The analysis used approximately 10 years of in-service pavement condition data to evaluate the performance of the sections versus virgin control sections. Although there were differences in performance, namely, the RAP sections were less crack resistant, of lower ride quality, and more rut resistant than the control sections, these differences were in many cases not statistically significant. None of the distress factors was severe enough to be detrimental to the expected life span of the RAP sections, which was typically less than 5% different than that of the virgin sections.

2.0 Objective

The objective of this study was to investigate the in-service performance of asphalt mixtures containing 0-30% RAP. A total of 22 mixtures were investigated, all of which were placed 7-8 years prior and outlined in a study by Maupin et al. (2008)

The work by Maupin et al. (2008) was undertaken to determine if there were potential adverse impacts from increasing the allowable RAP contents of certain dense-graded mixtures from 20% to 30%. Along with the increase, the requirements for virgin binder grades for these mixtures were changed: for mixtures specifying PG 64-22 binder, changing the virgin binder grade for RAP contents of 30% or less was no longer required, and for mixtures specifying PG 70-22 binder, changing the virgin binder grade from PG 64-22 to PG 64-28 for RAP contents of 21-30% was no longer required. The changes to the PG 70-22 mixtures reflected the expectation that a PG 64-22 virgin binder in combination with 21–30% RAP content in a mixture would result in a net binder grade of PG 70-22. Based on laboratory testing and analysis, the results of the study indicated that the mixtures containing 21-30% RAP with PG 64-22 binders should perform similar to the control mixtures containing 0-20% RAP and PG 70-22 binders.

This paper describes work performed to revisit those installations to investigate the relative performance of the two groups of mixtures after 7-8 years of service. The original test sites were identified, visual surveys of the surface condition were conducted, and cores were collected for laboratory analysis. In addition to the determination of volumetric properties, dynamic modulus and Texas overlay tests were conducted on the cores prior to recovery of the binder for performance grading and molecular weight distribution analysis.

The objectives of this study were to investigate the following:

- Is there any difference in the performance of asphalt mixtures containing varying RAP percentages after 7-8 years of service life?
- What is the effect of 7-8 years of service on the binder grade of the mixtures and how is this affected by varying RAP percentages?
- Does depth within the surface layer impact the aging of the binder?

3.0 Field Evaluation

3.1 Locations

Twenty-three sites were evaluated in this study. These included 11 sites paved with mixtures having RAP contents of 20% or less that were considered the control group (shown in Table 1) and 12 sites paved with mixtures containing RAP contents between 21-30% (shown in Table 2). All sites containing 21-30% RAP were constructed in 2007, as were control sites V and W. All other control sites were constructed in 2006. Figure 1 shows the geographical spread of the site locations around Virginia.

Table 1. *Control sites with RAP contents of 20% or less.*

Site	Route	County	NMAS	Binder	% RAP
E	I-64	Louisa	9.5mm	PG 70-22	0
H, I	SR 211	Rappahannock	9.5mm	PG 64-22	20
K, L	US 220	Highland	12.5mm	PG 64-22	10
M, N	SR 143	York	9.5mm	PG 64-22	20
Q	US 11	Montgomery	9.5mm	PG 70-22	15
T	SR 671	South Hampton	9.5mm	PG 64-22	10
V	I-64	Louisa	9.5mm	PG 70-22	0
W	US 301	Caroline	12.5mm	PG 70-22	20

Table 2. *Sites with RAP contents of 21-30%.*

Site	Route	County	NMAS	Binder	% RAP
A, B	SR 6	Goochland	12.5mm	PG 64-22	25
C	CR 703	Dinwiddie	12.5mm	PG 64-22	25
D	SR 40	Dinwiddie	12.5mm	PG 64-22	25
F	SR 24	Appomattox	9.5mm	PG 64-22	25
J	CR 611	Surry	12.5mm	PG 64-22	25
O	US 29	Pittsylvania	12.5mm	PG 64-22	21
P	CR 988	Pittsylvania	12.5mm	PG 64-22	21
R	US 221	Floyd	12.5mm	PG 64-22	30
S	US 58	Carroll	12.5mm	PG 64-22	30
U	US 29	Nelson	12.5mm	PG 64-22	25
X	I-664	Chesapeake	12.5mm	PG 64-22	30

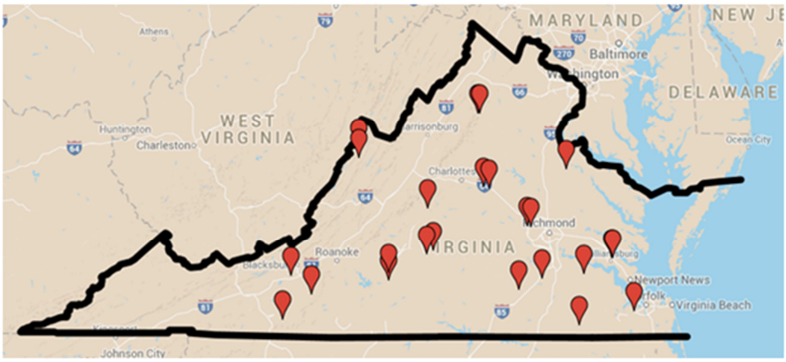

Figure 1. *Site locations.*

3.2 Mixtures

A brief summary of the mixture designs for each evaluated mixture is provided in Table 3. Mixtures A and B were a single production mixture sampled at two locations along the same site. Mixtures C/D, O/P, and R/S were each sampled from two unique sites, although the mixture designs were the same. Mixtures H/I, K/L, and M/N were produced as both hot mix asphalt and warm mix asphalt; both types of mixture were evaluated. Mixtures H and K were produced as warm mix asphalt using Sasobit as an additive; Mixture M was produced as warm mix asphalt using the Evotherm DAT additive system.

Table 4 presents production data for each mixture; these data were compiled from quality control and assurance data collected by VDOT during each project. Film thickness is not included, despite its desirability, as VDOT collects only selected sieve data, precluding the calculation. Despite the variation in mixture sources, RAP contents, and other factors, the production asphalt contents (determined by ignition) were fairly consistent, with averages from 5.22-5.92%. Air voids averaged 2.36-4.38% at 65 gyrations. Pearson correlation analysis indicated no significant correlation between RAP content and production volumetric properties.

3.3 Coring

Ten cores 6 in. (150mm) in diameter were taken from each pavement site for evaluation. Core locations were randomized along the length and width of the pavement site.

Table 3. *Mixture design summary.*

Site	NMAS	Binder	Design AC	RAP Content
A, B	12.5mm	PG 64-22	5.6%	25%
C, D	12.5mm	PG 64-22	5.5%	25%
E	9.5mm	PG 70-22	5.6%	0%
F	9.5mm	PG 64-22	5.5%	25%
H, I	9.5mm	PG 64-22	5.5%	20%
J	12.5mm	PG 64-22	5.8%	25%
K, L	12.5mm	PG 64-22	5.2%	10%
M, N	9.5mm	PG 64-22	5.7%	20%
O, P	12.5mm	PG 64-22	5.9%	21%
Q	9.5mm	PG 70-22	5.7%	15%
R, S	12.5mm	PG 64-22	5.5%	30%
T	9.5mm	PG 64-22	5.5%	10%
U	12.5mm	PG 64-22	5.7%	25%
V	9.5mm	PG 70-22	5.7%	0%
W	12.5mm	PG 70-22	5.4%	20%
X	12.5mm	PG 64-22	5.4%	30%

NMAS = Nominal maximum aggregate size. AC = Asphalt content. RAP = Reclaimed asphalt pavement.

3.4 Visual Survey and Distress Data

A visual survey was conducted at each pavement site in accordance with the guidelines for distress identification by Miller and Bellinger (2003). The survey distances varied depending on the length of the pavement section and the traffic control setup, vehicle traffic volumes, and roadway geometry for safety purposes. The minimum survey distance was 1,000 ft, and the maximum was 3,500 ft. Most surveys were conducted on sections of 1,000 or 1,500 ft.

Distress data were extracted from VDOT's Pavement Management System (PMS) where possible. VDOT's Maintenance Division acquires and maintains the results of an annual condition survey of all interstates, all primaries, and approximately 20% of secondary pavements. The survey collects and summarizes detailed distress data for each 0.1 mile of right-lane or principal direction pavement surface. As the distress data are collected in 0.10-mile increments based on county mileposts, the data extracted for each mixture did not correspond directly to the visual survey locations; instead, all data collected over the entire project length were aggregated to provide an average indication of performance for each mixture. Distresses investigated included rutting and IRI.

Table 4. *Mixture production data.*

Site		AC, %	VTM, %	VMA, %	VFA, %	F/A Ratio	Pbe, %	Gmm
A, B	Average	5.61	3.29	14.88	77.90	1.27	4.97	2.487
	Std. Dev.	0.07	0.43	0.32	2.43	0.04	0.08	0.003
C, D	Average	5.50	2.99	15.33	80.70	0.98	5.34	2.453
	Std. Dev.	0.15	0.88	0.88	4.21	0.08	0.15	0.023
E	Average	5.57	4.33	16.81	74.46	1.09	NA	2.468
	Std. Dev.	0.29	0.89	0.49	4.98	0.00	NA	0.014
F	Average	5.68	2.99	15.82	81.09	0.81	5.23	2.614
	Std. Dev.	0.11	0.57	0.40	3.33	0.09	0.13	0.055
H, I	Average	5.74	2.97	15.33	80.70	1.05	5.25	2.503
	Std. Dev.	0.20	0.46	0.55	2.52	0.12	0.16	0.005
J	Average	5.67	2.88	15.68	81.67	0.98	5.54	2.447
	Std. Dev.	0.14	0.80	0.42	4.74	0.04	0.17	0.018
K, L	Average	5.36	NA	NA	NA	NA	NA	NA
	Std. Dev.	0.18	NA	NA	NA	NA	NA	NA
M, N	Average	5.92	2.64	16.10	83.80	0.93	5.68	2.479
	Std. Dev.	0.22	1.15	1.19	5.76	0.05	0.22	0.014
O, P	Average	5.89	3.06	15.63	80.58	1.12	5.49	2.432
	Std. Dev.	0.20	0.70	0.44	3.95	0.07	0.20	0.014
Q	Average	5.97	3.14	16.19	80.71	1.20	5.56	2.489
	Std. Dev.	0.13	0.74	0.37	4.19	-	0.17	0.005
R, S	Average	5.72	3.33	16.45	79.80	1.02	5.60	3.142
	Std. Dev.	0.22	0.96	0.72	5.17	0.27	0.27	3.862
T	Average	5.56	3.44	16.04	78.64	1.04	5.40	2.466
	Std. Dev.	0.17	1.05	0.55	5.79	0.06	0.20	0.005
U	Average	5.71	3.53	15.46	76.75	1.08	5.07	2.531
	Std. Dev.	0.19	1.04	0.84	7.07	0.09	0.21	0.011
V	Average	5.58	4.38	15.90	72.33	1.15	3.60	2.601
	Std. Dev.	0.06	0.31	0.29	1.28	0.06	2.40	0.003
W	Average	5.26	2.36	14.68	83.99	1.07	5.09	2.555
	Std. Dev.	0.02	0.39	0.54	2.07	0.02	0.08	0.009
X	Average	5.38	3.06	14.24	72.50	1.01	4.66	2.454
	Std. Dev.	0.21	1.03	4.29	21.99	0.05	1.83	0.012

NA = information not available. - = Single observation.

4.0 Laboratory Evaluation

4.1 Core Air Voids and Permeability

Core air void contents were determined in accordance with AASHTO T 269: Percent Air Voids in Compacted Dense and Open Asphalt Mixtures (American Association of State Highway and Transportation Officials [AASHTO], 2013). Permeability testing was performed on cores in accordance with VTM 120: Method of Test for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter (VDOT, 2014).

4.2 Dynamic Modulus Test

Dynamic modulus tests were performed with an asphalt mixture performance tester generally in accordance with AASHTO T 342: Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures (AASHTO, 2013). Tests were performed on specimens 38mm in diameter by 110mm tall cored horizontally from field cores (Diefenderfer et al., 2015; Bowers et al., 2015b). Three testing temperatures (4.4°C, 21.1°C, and 37.8°C) and six testing frequencies from 0.1-25 Hz were used. Tests were conducted starting from the coldest to the warmest temperatures. In addition, at each test temperature, the tests were performed starting from the highest to the lowest frequency. Load levels were selected in such a way that at each temperature-frequency combination, the applied strain was in the range of 75-125 microstrain. All tests were conducted in the uniaxial mode without confinement. Stress versus strain values were captured continuously and used to calculate dynamic modulus. The results at each temperature-frequency combination for each mixture type are reported for three replicate specimens.

4.3 Overlay Test

The Texas overlay test was performed to assess the susceptibility of each mixture to cracking. Testing was performed using a universal testing machine with a 25-100 kN loading capacity generally in accordance with TX-248-F: Test Procedure for Overlay Test (Texas Department of Transportation, 2009) on field cores having a 150-mm diameter and varying thicknesses. Testing was performed at a temperature of 25 ± 0.5°C. Loading was applied for a total of 1,200 cycles or until a reduction of 93% or more of the maximum load was reached.

4.4 Binder Extraction, Recovery, and Testing

Extraction of binder from cores was performed in accordance with AASHTO T 164: Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA), Method A

(AASHTO, 2013), using n-propyl bromide as the solvent. Binder was recovered from the solvent in accordance with the Rotavap recovery procedure specified in AASHTO T 319: Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures (AASHTO, 2013). Binder grading was performed in accordance to AASHTO M 320: Performance-Graded Asphalt Binder (AASHTO, 2013).

4.5 Gel Permeation Chromatography

Gel permeation chromatography (GPC) was performed to analyze the molecular weight distribution of the asphalt binder after the recovery process. Testing was performed using an EcoSEC GPC by Tosoh Biosciences, which had a guard column, one TSKgel SuperHZ2500 column with a mean pore size of 30 Å, two TSKgel SuperHZ3000 columns with a mean pore size of 75 Å, and one TSKgel SuperHZ4000 column with a mean pore size of 200 Å in series. Columns were calibrated using polystyrene standards. The elution solvent was tetrahydrofuran stabilized with butylated hydroxytoluene.

Analysis of the data consisted of calculating the percentage of large molecules present within the molecular weight distribution of the binder. This process involves taking the area of the first 5/13s of the chromatogram and dividing it by the total area beneath the chromatogram. This ratio, converted to a percentage, relates to the stiffness of the binder and its oxidative properties (Bowers et al., 2014; Bowers et al., 2015a; Doh et al., 2008; Kim et al., 2006; Lee et al., 2006; Zhao et al., 2014). A higher percentage of large molecular sizes (LMS) equates to a stiffer binder.

5.0 Analysis and Discussion of Results

5.1 Visual Survey and Distress Data

Visual survey data were compiled and evaluated for all sites. Table 5 presents a summary of the data. Overall, the performance of the control sites and RAP sites was similar based on the visual assessment. Statistical analysis using two-tailed paired Student's *t*-tests was performed to compare the percentage of sites with each type of distress. Pairings were made by each distress severity. At a level of significance of $\alpha=0.05$, no significant differences were found between the percentages of control and RAP sites exhibiting each severity of each distress.

In addition to the visual survey, Tables 6 and 7 summarize roughness and rutting data from 2014 extracted from VDOT's PMS. In some cases, project limit mileposts did not correlate with PMS mileposts, resulting in missing data. Most of the pavements are in acceptable ride condition although IRI varied from 60-128. All sites showed low rut depths of less than 0.16 in., with the exception of site A/B, which had a rut depth of 0.23 in.

Table 5. *Summary of visual survey data.*

	Control Sites (≤20% RAP)				**RAP Sites (21-30% RAP)**			
	Number of Sites		11		Number of Sites		12	
	Total Length		11,500 ft		Total Length		17,600 ft	
	Total Lane Area		138,000 sq ft		Total Lane Area		211,200 sq ft	
Severity	**Quantity**	**No. Sites**	**% Sites**	**% Total Lane Area**	**Quantity**	**No. Sites**	**% Sites**	**% Total Lane Area**
Fatigue Cracking, sq ft								
Low	1240	1	9.1%	0.90%	7473	5	41.7%	3.54%
Medium	3669.3	8	72.7%	2.66%	2079.3	4	33.3%	0.99%
High	5800	1	9.1%	4.20%	249	2	16.7%	0.12%
Longitudinal Cracking - Wheelpath , ft								
Low	387.3	3	27.3%	-	2080	8	47.1%	-
Medium	4699.3	6	54.5%	-	9723.9	6	35.3%	-
High	0	0	0.0%	-	0	0	0.0%	-
Longitudinal Cracking - Non-Wheelpath, ft								
Low	0	0	0.0%	-	315.7	4	23.5%	-
Medium	6600.5	8	72.7%	-	2017.8	6	35.3%	-
High	44	1	9.1%	-	1000	2	11.8%	-
Transverse Cracking - Unsealed, ft								
Low	347	4	36.4%	-	52.5	3	17.6%	-
Medium	355	9	81.8%	-	387	5	29.4%	-
High	228	1	9.1%	-	50	1	5.9%	-
Transverse Cracking - Sealed, ft								
Low	0	0	0.0%	-	0	0	0.0%	-
Medium	64	1	9.1%	-	0	0	0.0%	-
High	553	1	9.1%	-	0	0	0.0%	-
Raveling, sq ft								
Low	0	0	0.0%	-	66	2	11.8%	-
Medium	407.4	3	27.3%	-	117	2	11.8%	-
High	0	0	0.0%	-	0	0	0.0%	-
Patching, number / sq ft								
Low	1 / 222	1	16.7%	-	2 / 1500	1	5.9%	-
Medium	10 / 1352	2	33.3%	-	0	0	0.0%	-
High	0	0	0.0%	-	0	0	0.0%	-
Pothole, number / sq ft								
Low	2 / 2	1	16.7%	-	0	0	0.0%	-
Medium	4 / 15	2	33.3%	-	2 / 6	2	12.0%	-
High	0	0	0.0%	-	0	0	0.0%	-

No sealed longitudinal cracking, bleeding, or reflection cracking was observed.

Table 6. *Roughness and rutting data for sites having RAP contents of 20% or less.*

Site	% RAP	IRI, in/mile	Rut Depth, in	Traffic, AADTT
E	0	NA	NA	NA
H, I	20	60	0.11	54
K, L	10	78	0.09	17
M, N	20	106	0.08	82
Q	15	90	0.13	81
T	10	NA	NA	NA
V	0	NA	NA	NA
W	20	NA	NA	NA

RAP = Reclaimed asphalt pavement; IRI = International roughness index; AADTT = Average annual daily truck traffic; NA = Data not available.

Table 7. *Roughness and rutting data for sites having RAP contents of 21-30%.*

Site	% RAP	IRI, in/mile	Rut Depth, in	Traffic, AADTT
A, B	25	109	0.23	121
C	25	128	0.15	48
D	25	90	0.12	67
F	25	75	0.09	189
J	25	NA	NA	NA
O	21	75	0.15	889
P	21	NA	NA	NA
R	30	114	0.11	60
S	30	113	0.14	57
U	25	73	0.16	806
X	30	81	0.16	2163

RAP = Reclaimed asphalt pavement; IRI = International roughness index; AADTT = Average annual daily truck traffic; NA = Data not available.

4.2 Core Air Voids and Permeability

Air voids and permeability were measured for all undamaged cores. The results are shown in Tables 8 and 9. Individual measurements were variable, as typically expected. Average air void contents for each site ranged from 4.6-8.9%. All mixtures except those from sites N, Q, and S met VDOT design permeability criteria, despite the variability in air void contents, indicating that permeability should not be a concern. Section 211.03 of VDOT's *Road and Bridge Specifications* (VDOT, 2007) requires a maximum design permeability of 150 x 10^{-5} cm/sec at 7.5% air voids for mixtures.

Table 8. *Air void content and permeability for cores from control sites having RAP contents of 20% or less.*

Site	Property	1	2	3	4	5	6	7	8	9	10	Avg.
E	VTM, %	11.9	10.5	8.1	6.4	6.2	8.1	6.3	5.7	6.2	6.8	7.6
0% RAP	Permeability x 10^{-5} cm/sec	117.4	66.9	17.3	0.7	0.5	18.6	0.7	0.0	0.3	1.9	22.4
V	VTM, %	8.1	9.6	-[a]	8.8	8.6	8.3	10.0	7.6	7.0	6.9	8.3
0% RAP	Permeability x 10^{-5} cm/sec	17.1	85.2	-	29.2	10.2	30.4	93.6	13.0	5.9	11.6	32.9
K	VTM, %	6.5	4.7	4.1	6.8	4.0	5.6	8.8	8.2	6.2	5.3	6.0
10% RAP	Permeability x 10^{-5} cm/sec	0.0	0.0	0.0	22.9	0.0	0.0	3.6	4.1	0.2	1.0	3.2
L	VTM, %	7.5	4.6	5.0	7.3	6.3	4.6	7.9	6.6	6.5	6.0	6.2
10% RAP	Permeability x 10^{-5} cm/sec	48.9	0.0	0.0	33.4	20.3	0.5	49.0	20.7	547.8	0.3	72.1
Q	VTM, %	6.1	8.2	-	9.9	9.0	11.4	8.6	7.1	8.4	9.5	8.7
15% RAP	Permeability x 10^{-5} cm/sec	8.9	48.1	-	292.2	157.5	606.2	84.7	14.4	59.5	182.8	161.6
H	VTM, %	6.8	7.4	6.5	-	3.6	5.6	6.8	7.0	3.6	4.9	5.8
20% RAP	Permeability x 10^{-5} cm/sec	3.1	3.9	0.9	-	0.0	0.5	1.4	3.0	0.0	0.1	1.4
I	VTM, %	6.4	5.3	6.0	5.7	5.8	6.0	5.8	5.8	7.0	7.6	6.1
20% RAP	Permeability x 10^{-5} cm/sec	55.3	0.2	4.2	0.6	2.7	3.4	2.2	1.4	1.3	0.9	7.2
M	VTM, %	5.5	-	7.7	5.7	6.3	10.0	7.6	7.9	7.7	8.4	7.4
20% RAP	Permeability x 10^{-5} cm/sec	0.0	-	1.5	0.0	0.0	6.2	1.3	2.4	1.4	3.3	1.8
N	VTM, %	7.4	10.6	-	8.4	9.5	10.1	8.9	7.6	7.9	8.1	8.7
20% RAP	Permeability x 10^{-5} cm/sec	68.6	499.7	-	98.3	194.9	462.2	143.1	72.1	86.2	135.0	195.6
W	VTM, %	10.0	8.6	9.6	12.8	7.5	6.0	5.7	3.2	3.9	4.3	7.2
20% RAP	Permeability x 10^{-5} cm/sec	NA	0.8	2.3	370.8	1.7	0.0	0.0	0.0	0.0	0.0	41.7

VTM = Voids in total mix.

[a] *- indicates that core was broken or damaged.*

Table 9. *Air void content and permeability for cores from sites having RAP contents of 21-30%.*

Site	Property	1	2	3	4	5	6	7	8	9	10	Avg.
O	VTM, %	7.8	6.0	6.0	6.5	8.7	7.8	7.1	-[a]	7.9	6.2	7.1
21% RAP	Permeability x 10^{-5} cm/sec	4.39	0	0	0	9.76	4.59	2.86	-	5.39	0	3.0
P	VTM, %	7.3	-	7.1	6.5	9.8	7.7	6.1	7.7	6.2	6.8	7.3
21% RAP	Permeability x 10^{-5} cm/sec	2.3	-	1.9	0.6	32.9	5.7	0.0	4.7	0.0	1.0	5.4
A[b]	VTM, %	4.4	7.3	4.8	6.5	6.4	5.2	6.8	5.7	6.2	6.7	6.0
25% RAP	Permeability x 10^{-5} cm/sec	0.0	8.7	0.8	8.6	3.8	0.6	22.7	9.7	0.5	0.5	5.6
B	VTM, %	7.9	8.9	6.8	5.5	8.4	9.6	10.6	11.1	8.6	12.0	8.9
25% RAP	Permeability x 10^{-5} cm/sec	-	14.9	0.0	0.0	13.8	17.8	29.7	80.3	22.3	93.1	30.2
C	VTM, %	6.0	10.6	2.1	2.7	3.6	3.9	2.9	4.0	4.3	5.7	4.6
25% RAP	Permeability x 10^{-5} cm/sec	0.0	9.0	12.4	20.3	28.8	9.4	97.5	6.0	23.4	137.7	34.5
D	VTM, %	8.0	7.5	8.3	6.7	8.2	7.7	10.3	8.4	7.3	11.5	8.4
25% RAP	Permeability x 10^{-5} cm/sec	3.0	0.0	4.3	0.0	5.0	0.0	23.5	4.3	0.0	57.4	9.8
F	VTM, %	6.8	4.1	8.4	-	4.8	3.7	4.5	4.0	4.5	4.6	5.0
25% RAP	Permeability x 10^{-5} cm/sec	0.3	0.0	0.7	-	0.0	0.0	0.0	0.0	0.0	0.0	0.1
J	VTM, %	6.4	7.3	10.5	7.8	10.3	8.6	8.2	8.5	8.9	8.3	8.5
25% RAP	Permeability x 10^{-5} cm/sec	1.0	0.0	48.2	24.6	NA	24.8	15.4	65.7	55.3	0.0	26.1
U	VTM, %	8.1	7.1	7.8	5.6	6.1	5.3	7.8	5.1	5.3	6.8	6.5
25% RAP	Permeability x 10^{-5} cm/sec	2.3	3.1	0.3	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.7
R	VTM, %	8.0	-	9.1	7.0	8.3	9.4	10.3	9.3	8.4	8.6	8.7
30% RAP	Permeability x 10^{-5} cm/sec	12.0	-	44.0	10.8	15.1	77.9	143.3	57.6	18.5	19.0	44.2
S	VTM, %	6.6	-	10.7	6.3	9.1	8.4	9.2	9.4	7.5	9.0	8.5
30% RAP	Permeability x 10^{-5} cm/sec	0.0	-	384.2	0.0	182.5	44.5	205.9	210.9	12.1	167.7	134.2
X	VTM, %	6.4	6.0	5.1	6.0	5.5	4.6	5.5	4.9	4.5	4.8	5.3
30% RAP	Permeability x 10^{-5} cm/sec	NA	1.6	0.8	3.1	5.1	0.4	1.6	0.9	0.0	0.0	1.5

VTM = Voids in total mix.

[a] *- indicates that core was broken or damaged.*

[b] *Sites A and B were composed of a single contiguous surface mixture; two sets of cores were collected.*

4.3 Performance Test Results

Performance testing was conducted using small-scale dynamic modulus testing and Texas overlay testing to identify differences in modulus and cracking potential for mixtures.

4.3.1 Dynamic Modulus

Because of insufficient core thickness, dynamic modulus testing was not performed on specimens from sites A, F, H, I, and Q. Tables 10 and 11 show summaries of the test results for evaluated mixtures having RAP contents of 20% or less and those having RAP contents of 21-30%, respectively.

To identify any obvious trends in modulus with RAP content, dynamic modulus values at all temperatures and three selected frequencies, 0.1 Hz, 1.0 Hz, and 10 Hz, were graphed for all mixtures. Figures 2, 3, and 4 show the results; all mixtures were ordered by increasing RAP content. The results indicated that neither the RAP content nor virgin binder grade appeared to have meaningful or trending influences on the measured modulus.

This visual assessment was further investigated using *t*-tests to evaluate significant differences between individual mixture test results at each temperature and frequency combination. The two-tailed, two-sample *t*-test was employed assuming unequal variance for analysis. The results indicated that differences were present at a level of significance of $\alpha=0.05$ between data sets for individual mixtures; however, there were no consistent trends in the significant differences that indicated any dependence on mixture properties. Table 12 presents an example of the analysis results for all mixtures at a temperature of 21.1°C (70°F) and test frequencies of 1 Hz and 5 Hz.

Statistical comparisons of the modulus values were performed to determine if significant differences existed between mixtures with RAP contents less than or equal to 20% and those with RAP contents between 21-30%. No significant differences were found using the two-tailed *t*-test assuming unequal variance at a level of significance of $\alpha=0.05$ for any combination of temperature and frequency.

Table 10. *Dynamic modulus results for mixtures having RAP contents of 20% or less. Modulus values are expressed in psi.*

Temp., °C	**Freq., Hz**	**E** **9.5mm** **PG 70-22** **0% RAP**	**V** **9.5mm** **PG 70-22** **0% RAP**	**K** **12.5mm** **PG 64-22** **10% RAP**	**L** **12.5mm** **PG 64-22** **10% RAP**	**T** **9.5mm** **PG 64-22** **10% RAP**	**M** **9.5mm** **PG 64-22** **20% RAP**	**N** **9.5mm** **PG 64-22** **20% RAP**	**W** **12.5mm** **PG 70-22** **20% RAP**
37.8	0.1	166,387	94,328	101,231	123,587	60,836	62,042	50,098	64,493
	0.5	309,027	179,460	194,829	220,022	122,107	116,771	96,425	127,188
	1	391,408	232,640	252,544	275,427	160,919	150,345	125,487	169,539
	5	645,611	413,261	443,960	451,889	296,457	263,362	223,469	320,292
	10	777,886	514,981	550,418	544,230	374,995	326,264	279,060	412,149
	25	968,175	666,690	705,898	661,662	492,113	418,586	360,503	550,418
21.1	0.1	773,341	521,942	574,688	573,527	368,178	327,129	280,976	375,309
	0.5	1,100,933	802,929	863,845	813,758	584,429	495,879	426,642	630,576
	1	1,255,205	940,521	1,005,256	922,440	693,715	578,519	497,931	762,657
	5	1,644,582	1,317,861	1,383,611	1,208,744	1,010,115	797,995	690,127	1,150,149
	10	1,817,661	1,491,568	1,559,107	1,332,606	1,164,145	899,824	778,626	1,334,540
	25	2,041,309	1,723,676	1,781,111	1,491,471	1,377,351	1,036,410	896,966	1,590,097
4.4	0.1	2,163,769	1,787,010	1,865,523	1,541,944	1,457,774	1,047,058	943,554	1,568,583
	0.5	2,509,829	2,173,100	2,237,255	1,793,246	1,813,479	1,266,577	1,131,342	2,009,159
	1	2,657,574	2,337,524	2,398,150	1,894,096	1,973,455	1,364,092	1,212,165	2,200,367
	5	2,988,067	2,702,633	2,763,548	2,125,721	2,348,088	1,583,556	1,404,301	2,643,215
	10	3,120,389	2,850,378	2,913,421	2,214,339	2,508,500	1,675,124	1,485,113	2,827,268
	25	3,280,124	3,035,204	3,100,036	2,316,736	2,710,682	1,788,460	1,583,953	3,053,914

Table 11. *Dynamic modulus test results for mixtures having RAP contents of 21-30%. All mixtures were produced with PG 64-22 virgin binders. Modulus values are expressed in psi.*

Temp., °C	Freq., Hz	O 9.5mm 21% RAP	P 9.5mm 21% RAP	B 12.5mm 25% RAP	C 12.5mm 25% RAP	D 12.5mm 25% RAP	J 9.5mm 25% RAP	U 9.5mm 25% RAP	R 9.5mm 30% RAP	S 9.5mm 30% RAP	X 12.5mm 30% RAP
37.8	0.1	103,243	98,331	41,940	93,675	71,924	75,555	39,871	128,706	99,133	150,172
	0.5	193,770	188,481	84,678	171,352	141,426	150,462	77,300	241,343	193,384	270,350
	1	249,271	242,020	116,209	216,503	187,195	197,831	103,755	304,918	251,350	341,274
	5	432,792	414,179	236,702	362,111	343,063	352,006	200,200	500,912	440,915	564,245
	10	534,947	507,632	315,844	440,915	433,808	436,322	260,826	602,922	544,907	683,224
	25	681,242	644,112	430,810	549,499	564,390	558,830	348,622	747,089	695,794	849,631
21.1	0.1	536,301	533,352	267,014	439,077	417,564	431,294	246,467	647,110	556,365	684,868
	0.5	802,155	782,140	476,255	645,805	658,810	652,766	415,678	909,435	829,326	981,567
	1	930,175	902,618	589,046	746,509	777,015	760,868	504,683	1,030,976	958,361	1,121,770
	5	1,275,123	1,221,991	921,134	1,023,821	1,107,846	1,056,600	766,524	1,338,408	1,291,802	1,488,764
	10	1,433,069	1,369,059	1,082,416	1,151,551	1,262,311	1,194,627	893,771	1,475,614	1,441,095	1,653,188
	25	1,644,099	1,566,987	1,306,113	1,326,998	1,471,021	1,379,550	1,069,750	1,568,293	1,638,684	1,868,327
4.4	0.1	1,720,486	1,697,715	1,281,408	1,403,627	1,521,736	1,446,364	1,068,203	1,779,371	1,743,861	1,949,887
	0.5	2,056,731	2,012,930	1,666,193	1,696,216	1,875,144	1,747,753	1,372,975	2,049,866	2,051,848	2,291,886
	1	2,202,978	2,149,314	1,838,788	1,824,671	2,026,612	1,880,269	1,509,214	2,164,059	2,179,699	2,436,730
	5	2,534,002	2,457,374	2,241,074	2,125,963	2,373,204	2,190,601	1,833,808	2,424,499	2,469,339	2,761,856
	10	2,670,434	2,586,409	2,407,481	2,254,708	2,517,226	2,320,507	1,971,546	2,532,890	2,588,923	2,893,212
	25	2,836,406	2,745,467	2,276,947	2,431,750	2,692,722	2,481,015	2,143,851	2,670,289	2,735,411	3,076,588

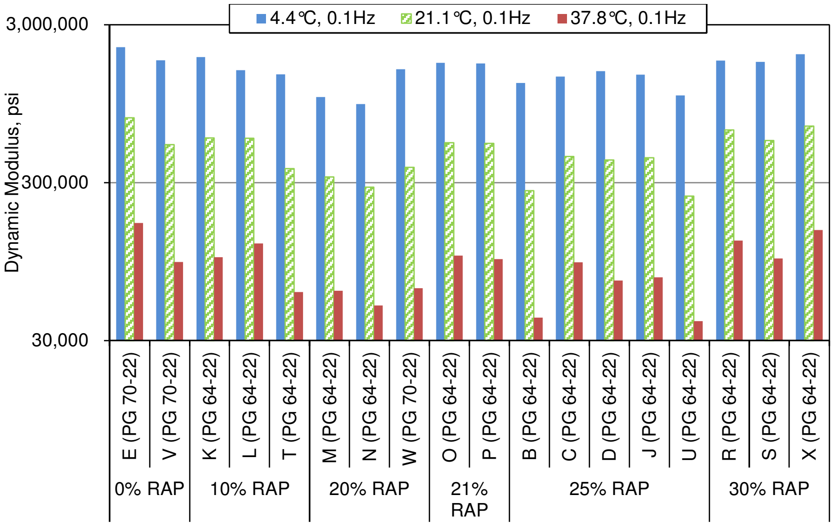

Figure 2. *Dynamic modulus values at all test temperatures and 0.1 Hz frequency.*

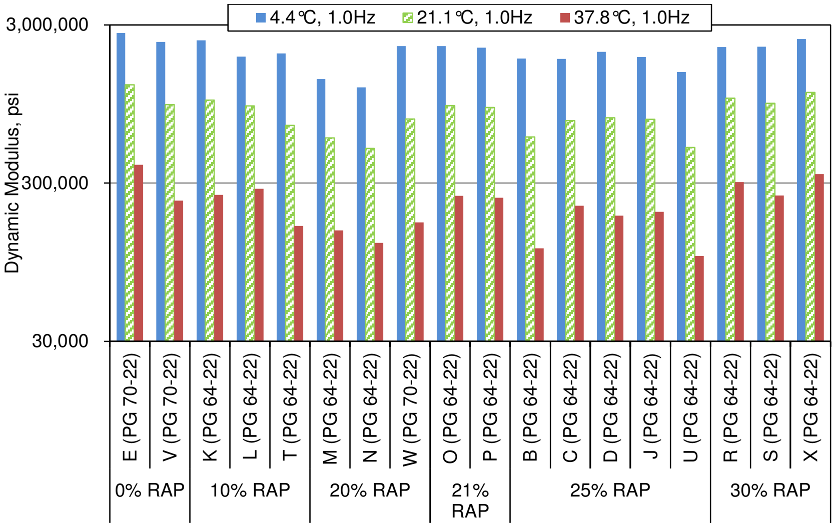

Figure 3. *Dynamic modulus values at all test temperatures and 1.0 Hz frequency.*

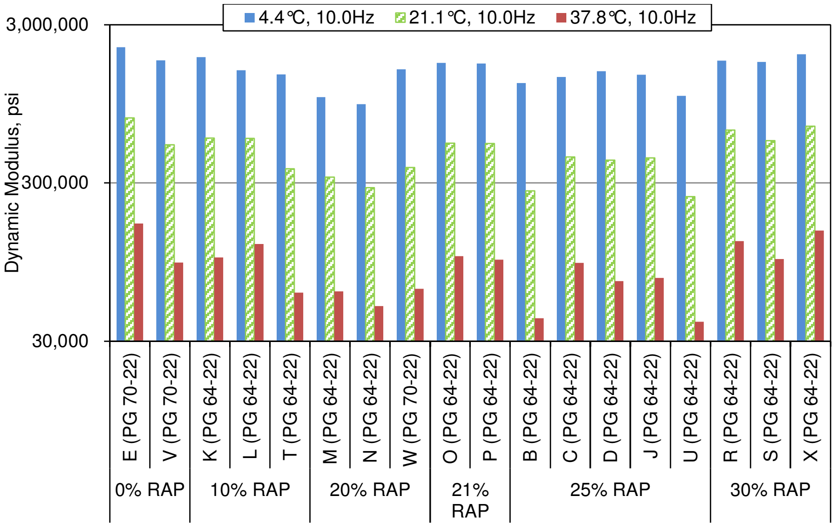

Figure 4. *Dynamic modulus values at all test temperatures and 10.0 Hz frequency.*

Table 12. *T-test comparisons of mixtures at 21.1°C (70°F) and 1 Hz (lower left half of table) and 5 Hz (upper right half of table). Shaded cells indicate significant differences between modulus results of compared site pairs at a level of significance of α=0.05.*

Site (%RAP)	E (0%)	V (0%)	K (10%)	L (10%)	T (10%)	M (20%)	N (20%)	W (20%)	O (21%)	P (21%)	B (25%)	C (25%)	D (25%)	J (25%)	U (25%)	R (30%)	S (30%)	X (30%)
E (0%)		0.0331	0.3005	0.0259	0.0241	0.0238	0.0103	0.0081	0.0314	0.0379	0.7502	0.0791	0.0087	0.0100	0.0088	0.0734	0.0424	0.4695
V (0%)	0.0325		0.7562	0.8089	0.1668	0.3797	0.0417	0.1069	0.9007	0.7171	0.0976	0.3719	0.1194	0.0210	0.0045	0.1336	0.7024	0.3342
K (10%)	0.3315	0.7800		0.6989	0.2249	0.5284	0.2858	0.3114	0.7273	0.6454	0.3849	0.3558	0.3349	0.3073	0.1089	0.9007	0.8203	0.6416
L (10%)	0.0179	0.3215	0.4937		0.1521	0.5420	0.0883	0.1571	0.9362	0.8618	0.0791	0.4140	0.1822	0.0960	0.0187	0.2083	0.6248	0.3007
T (10%)	0.0396	0.1854	0.2097	0.2676		0.2427	0.6443	0.5803	0.1421	0.1891	0.0290	0.7997	0.5082	0.5622	0.2607	0.1132	0.1658	0.0846
M (20%)	0.0212	0.2654	0.4607	0.9084	0.2976		0.2258	0.3245	0.5188	0.7491	0.0578	0.5608	0.3785	0.2556	0.0903	0.1386	0.3076	0.2130
N (20%)	0.0066	0.0476	0.2265	0.1729	0.8611	0.1931		0.8455	0.1022	0.2106	0.0310	0.9976	0.7135	0.7909	0.0864	0.0172	0.0415	0.1132
W (20%)	0.0123	0.1760	0.3781	0.6473	0.4006	0.6970	0.3266		0.1596	0.2810	0.0246	0.9361	0.8888	0.9830	0.0634	0.0419	0.0909	0.1138
O (21%)	0.0251	0.6420	0.6589	0.5860	0.1778	0.4810	0.0766	0.3322		0.8165	0.0862	0.3990	0.1846	0.1144	0.0236	0.2792	0.7294	0.3191
P (21%)	0.0272	0.4240	0.5286	0.9216	0.2521	0.8326	0.1848	0.6027	0.6846		0.0792	0.4740	0.3220	0.2416	0.0441	0.2777	0.5954	0.2765
B (25%)	0.5749	0.0459	0.4400	0.0278	0.0510	0.0301	0.0080	0.0183	0.0409	0.0425		0.0924	0.0271	0.0332	0.0185	0.1992	0.1147	0.6320
C (25%)	0.0813	0.2890	0.2835	0.4745	0.9568	0.4986	0.9641	0.6154	0.3494	0.4511	0.1015		0.8795	0.9410	0.2906	0.2332	0.3382	0.1692
D (25%)	0.0079	0.1016	0.3106	0.4290	0.5335	0.4522	0.4913	0.7334	0.2000	0.4094	0.0113	0.7329		0.8446	0.0542	0.0441	0.0993	0.1237
J (25%)	0.0051	0.0109	0.2485	0.2034	0.7401	0.2179	0.7678	0.3989	0.0811	0.2179	0.0056	0.8897	0.6092		0.0148	0.0052	0.0125	0.1219
U (25%)	0.0043	0.0004	0.0931	0.0272	0.2500	0.0676	0.0773	0.0382	0.0152	0.0352	0.0042	0.3384	0.0413	0.0104		0.0030	0.0020	0.0500
R (30%)	0.0413	0.6614	0.8465	0.2555	0.1798	0.2300	0.0519	0.1460	0.4967	0.3451	0.0590	0.2657	0.0870	0.0091	0.0001		0.1735	0.5962
S (30%)	0.0242	0.6432	0.7002	0.4370	0.1956	0.3420	0.0483	0.2318	0.8569	0.5517	0.0339	0.3227	0.1305	0.0171	0.0012	0.3976		0.3739
X (30%)	0.4275	0.3783	0.7030	0.2019	0.0817	0.1874	0.0853	0.1432	0.2992	0.2243	0.6191	0.1502	0.1127	0.0949	0.0392	0.4280	0.3239	

4.3.2 Overlay Test

In an effort to compare lateral cracking potential of mixtures containing varying amounts of RAP, the Texas overlay test was conducted on 13 of the specimen sets. Replicate tests were performed on each mixture, and the number of replicates ranged from four to six. As demonstrated in Figure 5, the target coefficient of variation between cores of below 30% (Texas Department of Transportation, 2009) was difficult to achieve, most likely because of specimen variability. A test of reasonableness was applied in an effort to remove potential outliers from the data. This reduced the coefficient of variability, which sometimes reached levels as high as 90%, to below 30% for all but two mixtures, as shown in Figure 6. These two mixtures, P and X, are believed to maintain such high COVs in part because of the few number of cycles required to reach failure. Overall there was no evidence of a conclusive trend between RAP content and cracking susceptibility as measured by this specific test.

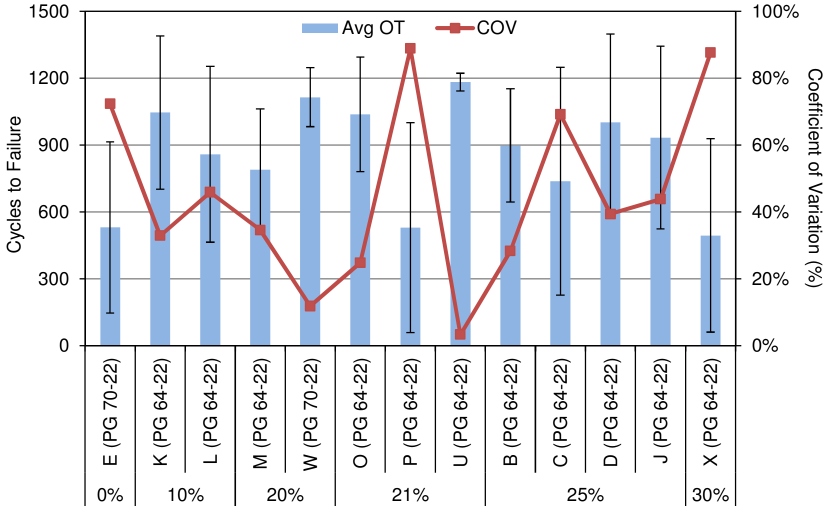

Figure 5. *Overlay test results prior to removal of outlier data.*

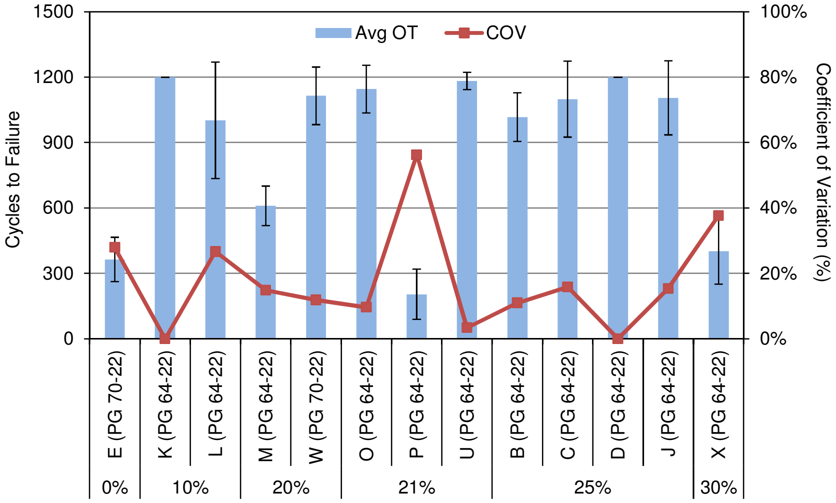

Figure 6. *Overlay test results after removal of outlier data.*

4.4 Binder Testing Results

Binders were extracted and recovered from cores collected for each surface mixture and site. Cores from 10 sites were sliced in half horizontally and binder was extracted and recovered separately from the top half and bottom half of these cores to investigate the impact of depth within the surface layer on binder grade. Binder samples for the remaining sites were extracted from the entire core and were considered representative of the entire surface layer. Binders were tested after recovery and after aging in a pressure aging vessel (PAV).

4.4.1 Performance Grading

Table 13 summarizes the performance grade obtained for binder from each site. Of interest, most of the binders graded to a PG 82-XX with the exception of two full surface and two bottom-half specimens that graded as PG 76-XX and one top-half specimen that graded as PG 88-XX. In addition, the top-half specimen from site B did not meet the PG criteria as specified in AASHTO M 320, as the failure temperatures exceeded the limits of the specification. Failure temperatures varied more widely than did the binder grades, as expected.

Table 13. *Summary of performance grading results for recovered binders.*

% RAP	Site	Specimen Type[a]	Grade	Failure temperature, °C			
				High	Intermed.	Stiffness	M-value
0	E	Full	82-10	89.29	35.20	-16.0	-14.6
	V	Bottom	82-16	84.26	30.31	-19.3	-18.8
		Top	82-10	92.06	36.42	-15.9	-13.2
10	K	Full	76-16	82.89	31.60	-20.7	-16.6
	L	Full	82-10	84.84	33.26	-18.7	-12.0
15	Q	Bottom	76-10	84.76	29.15	-24.9	-15.6
		Top	82-10	92.33	34.64	-23.0	-11.8
20	H	Bottom	76-16	81.15	28.46	-22.1	-18.5
		Top	82-16	83.52	29.22	-21.3	-17.2
	I	Bottom	82-16	86.38	31.57	-19.6	-16.5
		Top	88-10	88.71	33.06	-18.5	-14.3
	M	Full	82-16	83.03	28.37	-24.0	-18.7
	N	Bottom	82-16	88.79	31.84	-19.0	-16.0
		Top	82-16	88.94	29.26	-22.4	-17.7
	W	Full	82-16	82.72	30.73	-20.9	-17.6
21	O	Full	82-10	89.00	36.60	-17.8	-10.7
	P	Full	82-10	84.29	32.58	-20.3	-13.0
25	A	Bottom	82-16	78.47	26.50	-22.6	-21.7
		Top	82-16	82.81	29.67	-20.5	-18.5
	B	Bottom	82-10	89.42	34.62	-16.2	-14.7
		Top	NA[b]	103.9	40.43	-14.4	-4.9
	C	Full	82-10	87.21	30.9	-19.8	-15.6
	D	Full	82-16	84.55	29.74	-21.0	-19.3
	F	Bottom	82-16	80.35	27.10	-22.9	-18.6
		Top	82-10	84.77	27.76	-22.2	-15.2
	J	Full	82-10	84.27	31.70	-20.8	-15.6
	U	Full	76-16	77.79	27.33	-23.2	-18.5
30	R	Bottom	82-10	83.88	31.85	-21.4	-14.0
		Top	82-10	85.65	32.06	-21.2	-13.2
	S	Bottom	82-16	84.27	29.08	-20.5	-16.5
		Top	82-10	88.33	34.52	-19.4	-12.0
	X	Full	82-16	86.25	30.81	-19.8	-17.1

Note: Sites A and B contain a contiguous surface mixture.

[a] *Selected cores were split into top and bottom halves for evaluation.*

[b] *Did not meet requirements for standard performance grade according to AASHTO M 320.*

Table 14 shows the comparison of failure temperatures for binder recovered from the top and bottom halves of cores. The results indicated that in nearly every case, the binder recovered from the top half of the core was stiffer than that obtained from the bottom half. This is expected, as the surface of the cores undergoes UV exposure; in addition, the rate of diffusion of oxygen would be expected to be higher at the upper portion of the core, leading to increased aging, as compared to the lower portions (Glover et al., 2014). Figure 7 shows that the trends are generally the same for all failure temperatures. The influence of factors such as core air void contents was not evaluated, as multiple cores were required to be combined to acquire sufficient recovered binder for grading.

Table 14. *Comparison of failure temperatures for binder recovered from the top and bottom halves of cores*

Site		**V**	**Q**	**H**	**I**	**N**	**A**	**B**	**F**	**R**	**S**
RAP Content		**0%**	**15%**	**20%**	**20%**	**20%**	**25%**	**25%**	**25%**	**30%**	**30%**
High failure temp., °C	Top	92.1	92.3	83.5	88.7	88.9	82.8	103.9	84.8	85.7	88.3
	Bottom	84.3	84.8	81.2	86.4	86.8	78.5	89.4	80.4	83.9	84.3
Difference		7.8	7.6	2.4	2.3	2.1	4.3	14.5	4.4	1.8	4.1
Intermediate failure temp., °C	Top	36.4	34.6	29.2	33.1	29.3	29.7	40.4	27.8	32.1	34.5
	Bottom	30.3	29.2	28.5	31.6	31.8	26.5	34.6	27.1	31.9	29.1
Difference		6.1	5.5	0.8	1.5	-2.6	3.2	5.8	0.7	0.2	5.4
Stiffness failure temp., °C	Top	-15.9	-23.0	-21.3	-18.5	-22.4	-20.5	-14.4	-22.2	-21.2	-19.4
	Bottom	-19.3	-24.9	-22.1	-19.6	-19.0	-22.6	-16.2	-22.9	-21.4	-20.5
Difference		3.5	1.9	0.8	1.0	-3.5	2.1	1.8	0.7	0.2	1.1
M-value failure temp., °C	Top	-13.2	-11.8	-17.2	-14.3	-17.7	-18.5	-4.9	-15.2	-13.2	-12.0
	Bottom	-18.8	-15.6	-18.5	-16.5	-16.0	-21.7	-14.7	-18.6	-14.0	-16.5
Difference		5.6	3.8	1.3	2.2	-1.7	3.2	9.8	3.4	0.9	4.5

Difference = Top - Bottom.

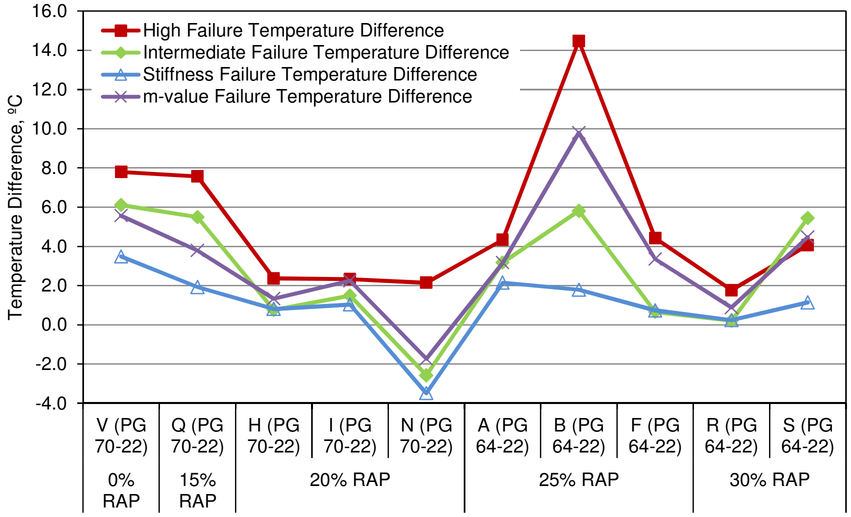

Figure 7. *Failure temperature difference between top and bottom halves of cores.*

Table 15 presents the results of binder grading performed during this study on recovered binder from cores at 6–7 years of service as compared to the binder grading performed on virgin binders, RAP stockpile samples, and loose mixtures sampled during construction in 2006 and 2007. Table 15 indicates that all mixtures, regardless of RAP content, gained one to two high-temperature performance grades over the in-service period evaluated. Low-temperature grades were similarly affected, with only one site (site W) found to retain the as-constructed low-temperature grade in-service. The results from sites Q and R, wherein cores were split into top and bottom halves for evaluation, indicated that the increase in temperature was influenced by proximity to the surface of the pavement. Figure 8 indicates that the mixtures containing less RAP aged over the 6-year period to a greater extent than those containing higher RAP contents, although the trend is less pronounced for the low failure temperatures. Sites V and Q (top half) had the highest high-temperature failure differences and the lowest RAP contents, and the sites containing 25-30% RAP resulted in lower differences in failure temperatures. Of interest, results for the difference in failure temperature for the top and bottom halves of site Q were very different, with the top half showing a significantly greater change. Site W, containing 20% RAP and a PG 70-22 binder was also unusual in that very little change in temperature occurred at either the high or low failure temperature.

Table 15. *Comparison of performance grading results from samples collected at construction and after 6 years in-service*

Site	RAP	Virgin Binder (At Construction)		Abson (At Construction)			Recovery	Rotavap (6-7 Years In-Service)	Recovery
				RAP Stockpile		Loose Mix		Core	
		PG Grade	True Grade	PG Grade	True Grade	PG Grade	True Grade	PG Grade	True Grade
V	0%	PG 70-22	PG 72-23	NA	NA	PG 70-22	PG 73-25	PG 82-10	PG 92-13
Q	15%	PG 70-22	PG 71-24	PG 71-24	PG 85-27	PG 70-22	PG 73-23	Top: PG 82-10	PG 92-11
		PG 70-22	PG 71-23	PG 71-23	PG 85-27	PG 76-22	PG 76-22	Bottom: PG 82-10	PG 84-15
W	20%	PG 70-22	PG 72-24	PG 72-24	PG 94-16	PG 76-16	PG 79-16	PG 82-16	PG 82-17
O	21%	PG 64-22	PG 65-24	PG 65-24	PG 95-14	PG 76-16	PG 77-21	PG 82-10	PG 89-10
		PG 64-22	PG 66-24	PG 66-24	PG 95-14	PG 70-22	PG 72-22		
		PG 64-22	PG 66-25	PG 66-25	PG 95-14	PG 70-22	PG 74-22		
D	25%	PG 64-22	PG 67-24	PG 67-24	PG 88-13	PG 76-22	PG 76-22	PG 82-16	PG 84-19
F	25%	PG 64-22	PG 66-24	PG 66-24	PG 90-18	PG 70-22	PG 71-22	PG 82-10	PG 84-15
J	25%	PG 64-22	PG 67-24	PG 67-24	PG 96-13	PG 70-22	PG 71-23	PG 82-10	PG 84-15
U	25%	PG 64-22	PG 65-24	PG 65-24	PG 94-17	PG 70-22	PG 73-23	PG 76-16	PG 77-18
		PG 64-22	PG 64-24	PG 64-24	PG 94-17	PG 64-22	PG 69-25		
		PG 64-22	PG 65-24	PG 65-24	PG 94-17	PG 70-22	PG 74-22		
R	30%	PG 64-22	PG 64-24	PG 64-24	PG 83-18	PG 76-16	PG 76-20	Top: PG 82-10	PG 85-13
								Bottom: PG 82-10	PG 83-14
X	30%	PG 64-22	PG 67-26	PG 67-26	PG 93-17	PG 76-22	PG 76-25	PG 82-16	PG 86-17

Note: Several samples were collected over multiple days of construction for sites O, Q, and U.

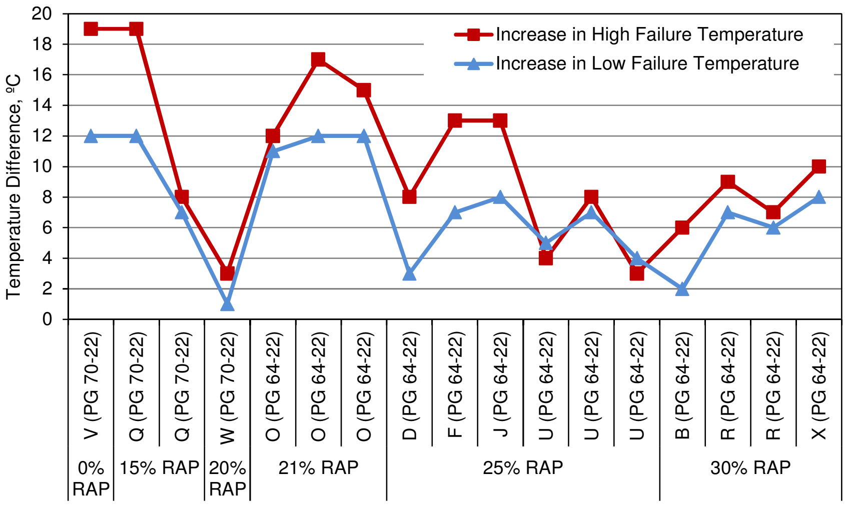

Figure 8. *Increase in high and low failure temperatures with RAP content.*

The observed trends of increased aging, as measured by changes in failure temperatures, in mixtures having lesser percentages of RAP may support the hypothesis that since RAP has already undergone significant aging (assuming the RAP source is from milled pavement and not from plant waste), it will not continue to stiffen and further age extensively. This may have further implications on the effects of mixture aging when the use of rejuvenators is considered, insofar as rejuvenating the RAP provides a new mechanism for aging to occur and thus may impact the long-term grade of the binder.

4.4.2 Gel Permeation Chromatography

In an effort to investigate further the trend shown in Table 13 and Figure 7 as it relates to the stiffness levels of the tops and bottoms of the cores, GPC was employed to investigate the percentage of LMS in the mixture. During the PG grading process of the top half and bottom half of the cores, a corresponding sample of binder was tested after binder recovery (shown in Figure 9) and after the recovered binder was PAV-aged (shown in Figure 10).

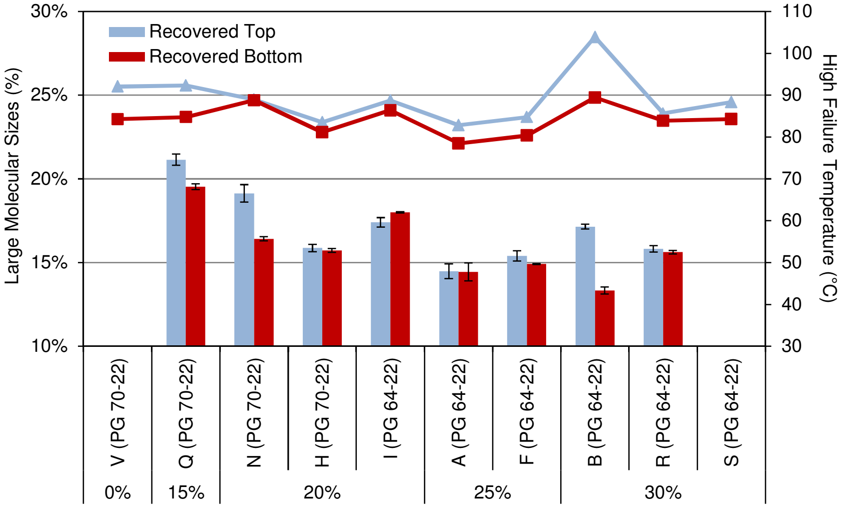

Figure 9. *LMS and failure temperature for recovered binders. Bars indicate LMS values, and lines indicate failure temperature. Error bars indicate one standard deviation. Recovered LMS data were not available for samples V and S.*

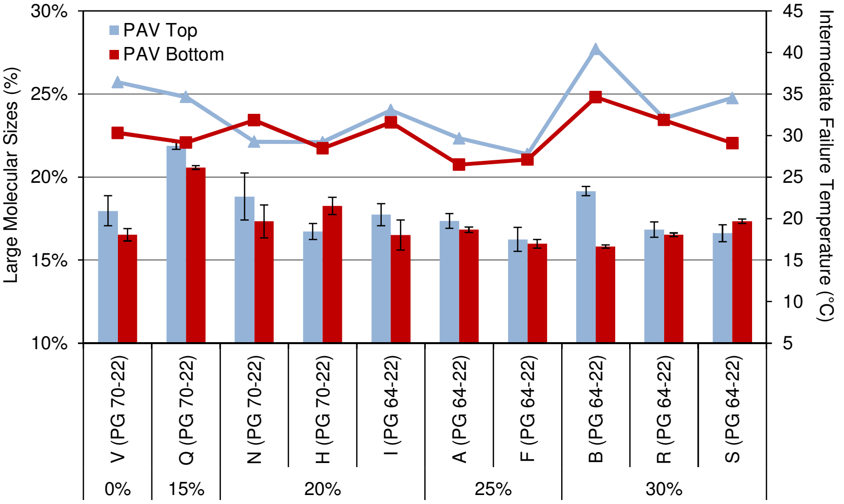

Figure 10. *LMS and failure temperature for recovered binders after PAV aging. Bars indicate LMS values, and lines indicate failure temperature. Error bars indicate one standard deviation.*

The percentages of LMS for each sample were generally in agreement with the trends found through the binder grading process. Increased LMS percentages for the top of the core as compared to the bottom of the core were indicative that the top of the core was stiffer than the bottom of the core, which was the case described earlier. However, there are cases such as sample I in the recovered binder and H and S in the PAV-aged binders where the LMS percentages were not in agreement with the failure temperature. In the case of PAV-aged binder N, the bottom half of the core had a higher temperature grade than the top, which was also not represented within the LMS percentages. The cause of these differentiations between failure temperature and LMS percentage is not known conclusively.

5.0 Findings and Conclusions

Few studies have been conducted to investigate the long-term performance of RAP-containing mixtures in-service, but those that are available indicate that similar performance can be expected from virgin and RAP-containing mixtures. This study of the in-service performance of 22 asphalt mixtures containing percentages of RAP from 0-30% was conducted after 7-8 years of service. The findings were as follows:

- No significant differences were found in the performance of asphalt mixtures containing varying percentages of RAP based on the visual survey.
- No significant differences were found in the performance of asphalt mixtures containing varying percentages of RAP based on small-scale dynamic modulus and Texas overlay testing of roadway core specimens.
- Performance grading of recovered binders showed high temperature grade increases after 7-8 years of service, regardless of RAP content. The measured high temperature grades were similar regardless of RAP content and initial virgin binder grade.
- Performance grading of recovered binders indicated that asphalt mixtures having higher RAP contents may have decreased rates of aging. This is likely due to a decrease in the oxidation rates of RAP binders.
- Performance grading and GPC analysis of the top half and bottom half of core specimens indicated that the top half is generally more highly oxidized than the bottom half.

In conclusion, the study found no systematic effect on field and laboratory performance with increasing RAP contents up to 30%. Based on the sites and mixtures evaluated in this study, it appears that increasing the allowable RAP content from a maximum of 20% to 30% without binder grade bumping has not adversely affected the performance of the dense-graded surface mixtures evaluated in this study. The RAP content does impact the degree of aging, as lower RAP-content mixtures indicated a greater differential in failure temperature over their life than did higher RAP-content mixtures. However, as the failure temperatures for all mixtures were within a relatively small span of temperatures for this study, and the performances were not found to be significantly different, it was not clear what impact the rate of aging may ultimately have on mixture performance. Further work to consider wider ranges in binder and mixture properties and climatic effects may provide more insight.

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8.0 Discussion

JOHN D’ANGELO: Stacey, a very interesting presentation. Nice, nice job with that. And I could actually see most of the slides, so it was pretty good.

STACEY DIEFENDERFER: I was trying for slide visibility after seeing the setup.

JOHN D’ANGELO: I do have a question. You seem to be concentrating significantly on high temperature stiffness in RAP mixes, and I’m wondering why? With RAP, you're not typically worried about the high temperature properties as it will be stiffer. It’s really the low temperature properties that’s a more significant indicator of performance issues. And I have another question after this one.

STACEY DIEFENDERFER: Okay. Actually, in Virginia, we’re less worried about low temperature, simply because we don’t see what we think is an incident of low temperature cracking. What we do see as we put these higher stiffness mixtures out on rural secondary routes that have low support is a potential for cracking. They're not highly trafficked routes, but if it happens to be a farm route, there’s some potential loading, a pavement structure that could use improvement, and since we’re placing a stiff mix over the top of it, we’re more worried about the stiffness. Anecdotally, from our districts, that’s what they are seeing. They see premature fatigue and some premature cracking that they think may be top-down cracking, simply because we don’t have the support structure underneath of what is perceived as an exceptionally stiff mix. So we were trying to address that perception.

JOHN D’ANGELO: That’s great, and I think that’s the right thing to do, but, again, let me recommend that you go from the bottom up on the low temperature stiffness to address that, not from top down on the high temperature stiffness. Because my other thought, and I don’t know if you can do this, you saw in yesterday’s presentations significant amount of effort was put into addressing not low temperature cracking but actual fatigue and other cracking tied to the delta Tc data. I’m assuming that you probably have quite a bit of data available to make those calculations, and it would be truly interesting to see. Because there were some relatively significant changes you had there going from minus 20s and 25s up to 16s, 17, and 13s, so that would significantly affect that fatigue cracking, top down cracking.

STACEY DIEFENDERFER: That’s absolutely in the works.

ERV DUKATZ: Stacey, excellent job. It is nice to see some real world data being presented. Some of my questions you’ve already answered. One comment that I have is that on the rate of aging, if you check in some of the past proceedings of AAPT, this was first reported on Marshall testing probably back in the ‘70s, and if

Professor Monismith is here, he probably has research that goes back even farther than that that shows aging effects. I do have one question. Did you look at what the binder ratio was of extracted asphalt content compared to the virgin asphalt content in any of these mixes?

STACEY DIEFENDERFER: Unfortunately, I don't have any of the RAP stockpile info. That's not something that was collected originally, so I don't have a RAP asphalt content to go back to. I've got a RAP percentage from the mix design as that is reported, but that's the limit of the data I've got on the RAP.

ERV DUKATZ: So it isn't required to report that?

STACEY DIEFENDERFER: Unfortunately, no. It's becoming more available because now we have a deduction applied to the RAP binder content during design. Currently, the RAP binder content has a 0.4% deduction applied before it's entered into design calculations, so for verification the asphalt contents are available. But when this work was performed, we were allowing 100% contribution from the RAP and did not require asphalt content data to be reported in the mix design. The contractors might have it still if requested, but, due to the time frame that has elapsed, it's not very accessible.

ERV DUKATZ: Basically the reason for asking is that for some of your rare jumps in the data what we found is that you may say that you have 30% RAP but the actual binder replacement could be as low 10% and vice versa.

STACEY DIEFENDERFER: Yes. I was hoping to be able to look at that but then I was unable to find the data.

GALE PAGE: We've been recycling in Florida since the '70s. When we first started, our target for recovered binder was viscosity. And I think we were probably using a micrometer to try and measure what was acceptable. With the PG binder, I think we've got a yardstick, so we have a little more play or less sensitivity for our target. A couple of things. One is the RAP PG binder grade, you didn't mention that.

STACEY DIEFENDERFER: It's in the paper.

GALE PAGE: Okay. I figured it was around 80-16, 82-16, somewhere around there.

STACEY DIEFENDERFER: Somewhere around the mid-80s to mid-90s.

GALE PAGE: Okay. And in the effort of simplicity, it's really good to see that somebody is using a deduction to total RAP binder to get an effective RAP binder. I would have preferred to use a percent deduction because of the varied RAP contents that do occur, rather than just a brute force 0.4%, just to comment. And, in addition, because of simplicity, we want to use a common binder with RAP, assuming all RAP is the same, which it is not, in most cases. But we need to follow up as agencies or as researchers to make sure that those simple assumptions are, in fact, being met in the field. And I'm glad that somebody is following up and verifying that we are getting, in fact, what we are paying for. So thank you very much, and I know other agencies are doing the same thing. I know we are in Florida. Thank you.

STACEY DIEFENDERFER: Thanks, Gale. Just to comment on that 0.4%. Yes, it's a brute force. That particular number was derived a few years ago in response to a study that indicated that, of course, we were not getting 100% contribution from the RAP. The question was—how do you address it in a way in a low-bid state that keeps the playing field level for all of the contractors? We had contractors at the time that were using their own deduction, and you could sort of see it in their mix results, but we had to develop a universal method. So the study surveyed industry for RAP contents from burns and from extractions and evaluated the results to determine an average number from RAP stockpiles across the state and determined the 0.4% deduction as a state-wide average to apply.

MICHAEL DUNNING: Were there any polymer modified samples being used out there?

STACEY DIEFENDERFER: Not in this study. Currently we do allow polymer modified binders with RAP although amounts are limited to 15% for both dense-graded and SMA mixtures. The modified mixtures are considered premium mixtures because of the polymer, and we don't want to compromise their performance.

MICHAEL DUNNING: I appreciate your presentation. Very good for us. We have been using 15% recycled for years. We had it up to 40% recycled about five years ago, and it prompts me now to go back and look. At that time, we tested after placement using recovery for binder. The binder tests for PG all came out very good after the first use. I'm glad you stirred up my memory. I'll go back and check our five-year-old pavements and see how they look. That's very good. Thank you.

STACEY DIEFENDERFER: Thank you.

PAVEL KRIZ: Thank you for your presentation. I quite enjoyed it. I've one comment and maybe one question. We did some work on the binder diffusion and how the RAP can get activated. We had a paper here couple years ago on binder diffusion and we also had a paper on binder diffusion in mixes at CTAA in 2014. I think your data make a lot of sense. For instance, you don't see more raveling with higher RAP mixes when local climate PG 64-22 is used as virgin binder, right? So if you would have RAP behaving as a black rock, then you probably should see more raveling because your active binder content would be much lower, but it's indeed much higher. I don't know if you can activate 100% of RAP binder by diffusion, but you're getting close to complete blending between virgin and RAP binders over several months or several years of service. So I was glad to see your field data, with very high RAP content and without great bumping on the low side for the virgin binder. So my question goes more to what I saw in your Superpave data obtained for binders recovered from mixes. Did you PAV age the recovered binders when you did your grading?

STACEY DIEFENDERFER: Yes.

PAVEL KRIZ: Right. So we saw grades like 72-20, perhaps -22. That's what I saw generally in your data. After six years of field aging, I saw for example 93-15 and similar much harder grades. So what I'm trying to say is that PAV is clearly not capturing the extent of field aging, it's not even close for six years of performance. This is a big concern, if you could please comment on that.

STACEY DIEFENDERFER: I think that ties into our concern about how we specify binder based off of our current testing ability using the PAV and RTFO. What we're actually getting after that longer term is anybody's guess, because we know it's not accurate. So how well are our specifications working on the front end to give us what we want in the long term? We've had a lot of discussion with some of our engineers looking at some of this. The question becomes—if we end up with a PG 92 over time in service despite whether we begin by specifying a PG 64 or PG 70, why are we paying for the 70? Theoretically, we're likely to get similar long-term performance on the road. So it's bringing up more discussion. We wish we'd had even more variety in binders, but assessing 22 sites was a challenge as it was. We'd like look at more variety in binders and in the lower RAP contents as well to see how those binders are aging.

PAVEL KRIZ: Thank you very much.

STACEY DIEFENDERFER: Thank you.

ESHAN DAVE: Very good presentation, excellent work, Stacey. It's really interesting to see this. Just two very quick questions. One, did you look at gradation differences between these mixes and especially how they compared to one thing interesting to me was permeability?

STACEY DIEFENDERFER: We haven't yet. I've got construction sample gradations that we will look at, but because our cores were so limited, we had just enough material to perform extractions and recoveries but not enough to look at gradations. In some cases, in order to extract enough binder, we were using our overlay specimens for extractions. We would slice off anything that was contaminated, allowing us to run the extractions, but because of cut surfaces, could not assess gradation.

ESHAN DAVE: And the reason I ask is we recently finished a project looking at 16 field sites, and in that study we were looking at gradation effects on performance. And one thing that was really interesting to me was how well permeability correlated to performance test results. So if you want to read that, that might be interesting too.