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Ten-Year Assessment of Virginia's First Warm Mix Asphalt Sites

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Final Report VTRC 19-R18

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16. Abstract:

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During the testing performed as part of this study, cores were taken after 3 months, 6 months, 1 year, 2 years, 5 years, and 10 years of service to determine the rate of densification under traffic and to evaluate changes in the performance of the mixtures over time; in addition, binder was recovered from the cores and graded to evaluate the progression of aging. Pavement management data were also collected annually and evaluated for two of the three sites to determine the relative performance of the HMA and WMA sections.

HMA and WMA core air voids were generally similar. Permeability was related to air-void content and appeared to decrease over time. Dynamic modulus results were shown to be mixture dependent, with each mixture showing the effects of aging in a unique manner. Overlay test results indicated no significant differences between the HMA and WMA pairs; however, for two of the three site pairs, this was affected by the test variability. The flexibility index (FI) indicated no significant differences between the HMA and WMA pairs from two sites. The HMA cores from one site showed a significantly higher FI than the WMA cores; however, the WMA core results were similar to the results from the other two sites. Binder testing showed a clear stiffening effect with age for all binders. Evaluation of the ΔT_c cracking parameter indicated that all binders except one HMA binder had exceeded the cracking limit of -5.0ºC by 10 years of service, indicating a potential need for remediation to prevent cracking.

Data extracted from VDOT's Pavement Management System for two of the sections generally indicated that the HMA and WMA mixtures performed similarly. Although individual distress quantities varied over time, the critical condition index, load-related distress index, and non-load related distress index values for each HMA-WMA pair were similar after 10 years of service. Comparison of FI values and overlay test cycles to failure for the 10-year-old cores with deterioration values from the Pavement Management System indicated high correlations in many instances; however, the direction of the correlation was counterintuitive in many cases. These results are limited by the very small dataset evaluated.

Results of the investigation verified that the HMA and WMA mixtures performed similarly over 10 years of service. It was found that binder aging is causing a significant change in binder properties in service for both HMA and WMA that may affect mixture performance. In addition, relationships between performance-based properties of mixtures and in-service pavement performance were found to be promising, but they need further evaluation.

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FINAL REPORT

TEN-YEAR ASSESSMENT OF VIRGINIA'S FIRST WARM MIX ASPHALT SITES

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In Cooperation with the U.S. Department of Transportation
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INTRODUCTION

Warm mix asphalt (WMA) is produced by incorporating additives into asphalt mixtures or by foaming asphalt binder to allow production and placement of the mixture at temperatures below the typical production temperatures of hot mix asphalt (HMA). Benefits such as reduced plant emissions, improved compaction in the field, extension of the paving season into colder weather, longer haul distances, reduced opening time to traffic, and reduced energy consumption at the plant may be realized with different applications.

Research on the uses and benefits of WMA has been promising, and many states, including Virginia, allow several WMA technologies. However, despite gains in the understanding of WMA and predictions of its performance, knowledge of the long-term impact of these technologies on mixture performance is limited, as many early sites have only recently reached the end of their service life. NCHRP Project 09-49, Performance of WMA Technologies: Phase I—Moisture Susceptibility (Martin et al., 2014), found no evidence from in-service pavements to indicate that WMA is more susceptible than HMA to moisture damage, although laboratory test results can indicate potential issues. NCHRP Project 09-49A, Performance of WMA Technologies: Phase II—Long Term Performance (Washington State University et al., 2017), found that pavements containing various WMA technologies exhibited long-term performance comparable with that of the companion HMA pavement sharing a similar pavement structure, climate, and traffic conditions. It benefits the Virginia Department of Transportation (VDOT) to be proactive in evaluating the lifetime performance of in-state WMA installations to verify their performance compared to that of conventional HMA, as the use of some form of WMA has been nearly ubiquitous in the state, with more than 75% of asphalt mixture production reported in 2014 being WMA (Hansen and Copeland, 2015).

VDOT's initial WMA trials were constructed in 2006 and documented in several reports (Diefenderfer and Hearon, 2008, 2010; Diefenderfer et al., 2007). These trials were conducted to assess the Sasobit additive and Evotherm DAT technology, and the studies determined that WMA should perform similarly to HMA, based on initial construction and early performance data. After the trials, VDOT developed a special provision for the use of WMA and in 2009 incorporated the use of approved WMA technologies in its specifications.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the performance over 10 years of WMA trial sections constructed in Virginia in 2006 to assess the hypothesis of equivalent performance of HMA and WMA. The sections were constructed in 2006, and each incorporated an HMA control mixture and a WMA trial mixture.

The pavements were visited and cores were collected at 3 months, 6 months, 1 year, 2 years, 5 years, and 10 years of service to determine the rate of densification under traffic and to evaluate changes in the performance of the mixtures over time by determining core permeability and evaluating the dynamic modulus; in addition, binder was recovered from the cores and graded to evaluate the progression of aging. Ten-year cores were also subjected to testing using the overlay test and the Illinois flexibility index (FI) test. Distress data were also extracted from VDOT's Pavement Management System (PMS) and evaluated for two of the three sites to determine the relative performance of the HMA and WMA sections.

METHODS

Materials

Full information about the materials and methods used during construction are available in Diefenderfer et al. (2007); a summary is presented here.

US Route 211

The mixture used in this trial was an SM-9.5A mixture (9.5 mm nominal maximum surface mixture with PG 64-22 binder) containing 20% recycled asphalt pavement (RAP) with a design asphalt content of 5.5%. Morelife 3300 antistrip additive was used at a dosage of 0.5% by weight of the binder. To produce the WMA, Sasobit was added at a rate of 1.5% by weight of binder; no other changes to the mix design were made. The WMA was produced at a temperature approximately 50ºF cooler than the HMA.

US Route 220

The mixture used in this trial was an SM-12.5A mixture (12.5 mm nominal maximum surface mixture with PG 64-22 binder) containing 10% RAP with a design asphalt content of 5.3%. Hydrated lime was used in the mixture to prevent stripping. Sasobit was added at a rate of 1.5% by weight of binder. No other changes were made to the mix design during the production of WMA. The production temperature of the WMA was approximately 25ºF to 30ºF cooler than that of the HMA.

State Route 143

The mixture used in this trial was an SM-9.5D mixture (9.5 mm nominal maximum surface mixture using PG 70-22 binder) containing 20% RAP and a design asphalt content of 5.7%. The control HMA contained Adhere HP Plus antistrip additive at a dosage rate of 0.3% by weight of the binder. Evotherm DAT emulsion containing antistrip additives with a residual binder content of approximately 70% was used as the binder for the WMA. The base binder used during production of the emulsion was a PG 70-22 binder. The WMA production temperature was approximately 80ºF cooler than that of the HMA.

Laboratory Evaluation

Core Air Voids

Air-void contents were determined in accordance with AASHTO T 269, Percent Air Voids in Compacted Dense and Open Asphalt Mixtures (American Association of State Highway and Transportation Officials [AASHTO], 2017).

Permeability

Permeability testing was performed on cores in accordance with Virginia Test Method 120, Method of Test for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter (VDOT, 2014).

Dynamic Modulus Test

Dynamic modulus tests were performed using an Asphalt Mixture Performance Tester (AMPT) with a 25 to 100 kN loading capacity in accordance with AASHTO T 342, Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures (AASHTO, 2017). Tests were performed on 38-mm-diameter by 110-mm-high specimens cored horizontally from field cores (Bowers et al., 2015; Diefenderfer et al., 2015). Three testing temperatures (4.4°C, 21.1°C, and 37.8°C) and six testing frequencies ranging from 0.1 to 25 Hz were used. Tests were conducted starting from the coldest temperatures to the warmest temperatures. In addition, at each test temperature, the tests were performed starting from the highest to the lowest frequency. Load levels were selected in such a way that at each temperature-frequency combination, the applied strain was in the range of 75 to 125 microstrain. All tests were conducted in the uniaxial mode without confinement. Stress versus strain values were captured continuously and used to calculate dynamic modulus. Dynamic modulus was computed automatically using IPC |E*| software. Results at each temperature-frequency combination for each mixture type are reported for three replicate specimens.

Overlay Test

The overlay test was performed to assess the susceptibility of each mixture to cracking. Testing of field cores having a 150-mm diameter and varying thicknesses was performed generally in accordance with TX-248-F, Test Procedure for Overlay Test (Texas Department of Transportation, 2009), using a universal testing machine with a loading capacity of 25 to 100 kN. Testing was performed at a temperature of 25°C ± 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.

Illinois Flexibility Index Test

For cracking assessment, the Illinois FI test was conducted in accordance with AASHTO TP 124-16, Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperature (AASHTO, 2017).

Binder Extraction and Recovery

Extraction of binder from cores was performed in accordance with AASHTO T 164, Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA), Method A (AASHTO, 2017), using n-propyl bromide as the solvent. Binder was recovered from the solvent using either the Abson recovery procedure specified in AASHTO R 59, Recovery of Asphalt Binder from Solution by Abson Method, or the Rotavap recovery procedure specified in AASHTO T 319, Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures (AASHTO, 2017).

Binder Testing

Binder grading was performed in accordance with AASHTO M 320, Performance-Graded Asphalt Binder (AASHTO, 2017).

Increased scrutiny of the role that aging plays in mixture performance, especially as related to binder aging, has led to the development of additional parameters proposed to be indicative of cracking potential. One of these parameters, ΔT_{cr}, was suggested by Anderson et al. (2011) as an index to predict the thermal cracking potential of binders. ΔT_{cr} is the difference in critical temperature determined using the bending beam rheometer (BBR) stiffness and that determined using the BBR m-value. As binders age, the difference between the critical temperatures is known to increase, as the aging process affects the stiffness and relaxation properties differently. Minimum thresholds for ΔT_{cr} of -2.5 and -5.0 representing the cracking warning and cracking limit, respectively, have been suggested (Anderson et al., 2011; Rowe, 2011). The cracking warning is intended to indicate an accelerated risk of cracking wherein preventative action should be taken. The cracking limit indicates that the materials need immediate remediation to prevent cracking.

Pavement Condition Data

Distress data for available locations were extracted from VDOT's PMS. 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. For the survey, detailed distress data for each 0.1 mi of right-lane or principal-direction pavement surface are collected and summarized. Condition is reported on a scale from 0 to 100, heavily distressed to new or like new, respectively. The overall section rating, the critical condition index (CCI), is the lower of two ratings that summarize the load related and non-load related distresses for a pavement. Distress data were analyzed only for the Rt. 211 and Rt. 143 sites, as only HMA section data were available for the Rt. 220 site.

As the condition surveys of pavements occurred at varying intervals, cumulative degree days were determined based on the actual date that each distress survey was performed to provide an objective measure of when distresses were seen. Climatic data consisting of each daily high temperature from the nearest available weather station were obtained from the National Climatic Data Center (n.d.). Climate data for the Rt. 211 site were obtained from weather station USC00447985, located in Sperryville, Virginia. Climate data for the Rt. 143 site were obtained from weather station USC00449151, Williamsburg 2 N, located in Williamsburg, Virginia. The calculated cumulative degree days were determined as the summation of degrees above 0ºC (32ºF) for each day from initial construction to the date that each pavement condition survey occurred.

Field Sections

US Route 211

The first trial section was constructed on August 11, 2006, as a 1.5-in overlay on Route 211 in Rappahannock County, Virginia. Superior Paving Corp. produced and paved approximately 300 tons of HMA before beginning WMA production. Approximately 775 tons of WMA was paved; the 0.5-mi WMA section evaluated in this study was located within this tonnage in such a manner as to minimize any influences from the beginning and ending of the WMA paving. Once the WMA section was complete, paving continued with conventional HMA and consisted of the placement of approximately 607 tons of material. This conventional HMA served as the control mixture for this evaluation. Testing was conducted on a 0.5-mi segment of the HMA section chosen to minimize transitional effects attributable to the change from paving WMA to paving HMA. Figure 1 indicates the location of the HMA and WMA sections.

US Route 220

The second trial was constructed as a 1.5-in overlay on Route 220 in Highland County, Virginia, on August 14 and 15, 2006, by B&S Construction Inc. Control section paving was performed on August 14 using approximately 634 tons of HMA, and the WMA was placed on August 15 using approximately 320 tons of WMA. Testing was performed on 1,000-ft segments of the HMA and WMA sections, as shown in Figure 2. This project considered the application of WMA to long-haul conditions, as the plant was located approximately 45 mi from the paving site. Because of the mountainous terrain between the plant location in Staunton, Virginia, and the project location in Highland County, this translated to a haul of approximately 1 hr 45 min across several mountains.

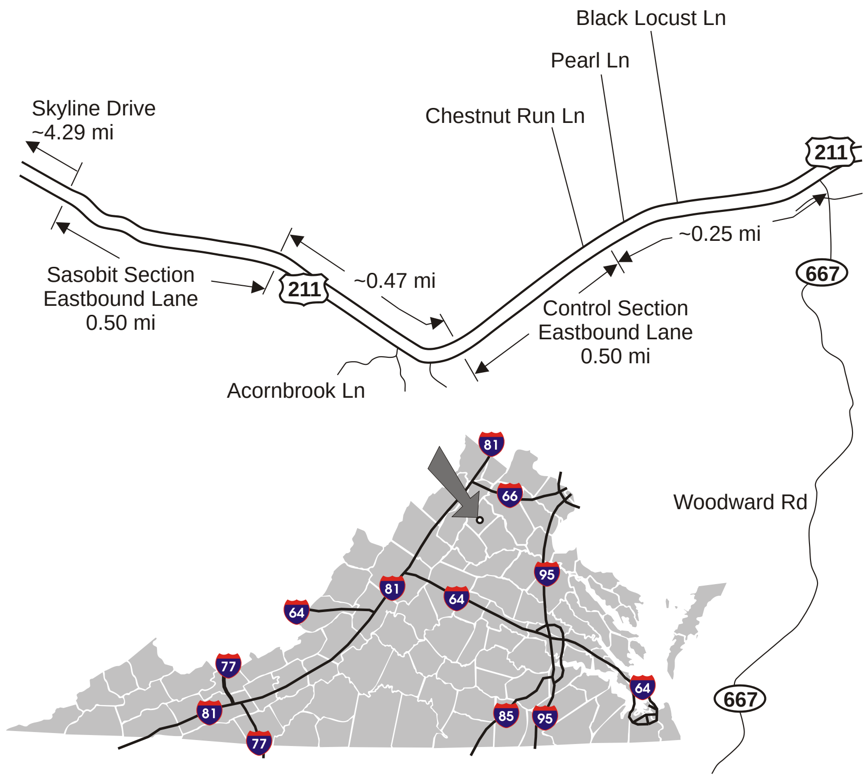


Figure 1. Location of Rt. 211 Trial in Rappahannock County

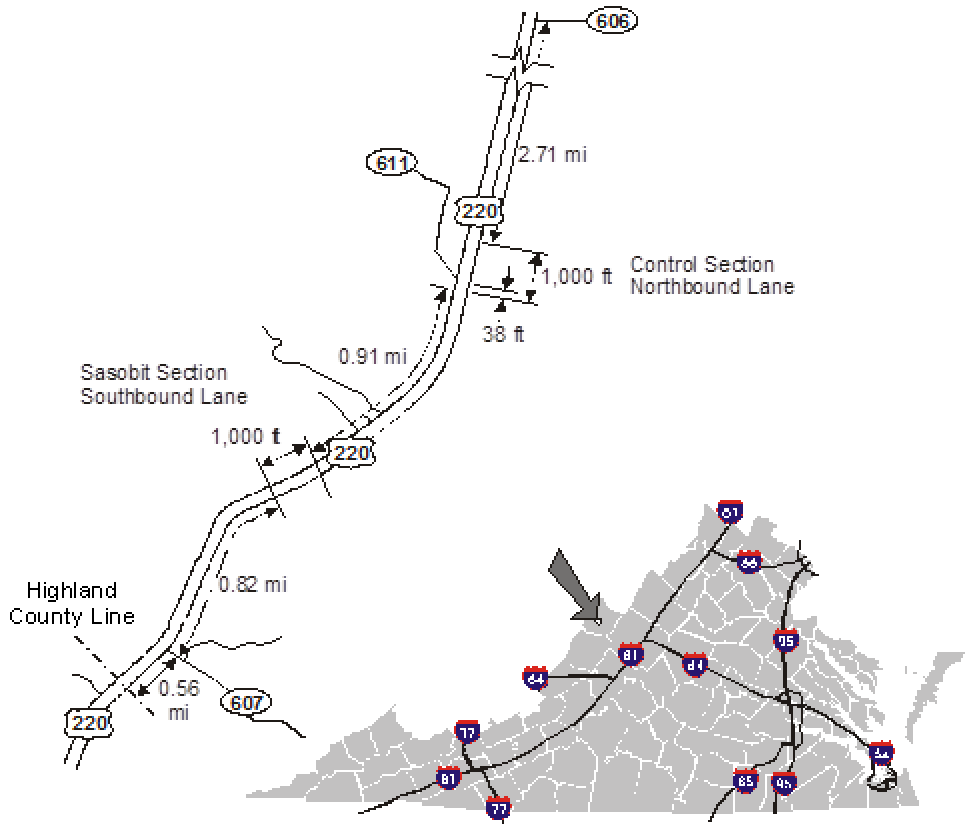


Figure 2. Location of Rt. 220 Trial in Highland County

State Route 143

The third trial was constructed as a 1.5-in overlay on Route 143 in York County, Virginia, by Branscome, Inc., on October 26 and November 2, 2006. Approximately 530 tons of WMA was placed on October 26 in the southbound travel lane, and approximately 1,000 tons of HMA was placed on November 2 in the northbound travel lane. Testing was performed on 1,000-ft segments of this material; the segment locations are described in Figure 3.

Figure 3. Location of Rt. 143 Trial in York County

RESULTS AND DISCUSSION

Laboratory Testing

Air Voids and Permeability

Cores were taken to evaluate the changes in the asphalt mixture density and permeability over time. These cores were taken during construction and at 3 months, 6 months, 1 year, 2 years, 5 years, and 10 years of service. It should be noted that the cores were taken randomly from each section. Permeability testing was performed on the cores to assess changes in the mixture permeability over time, which can indicate the potential for future susceptibility to moisture-related damage.

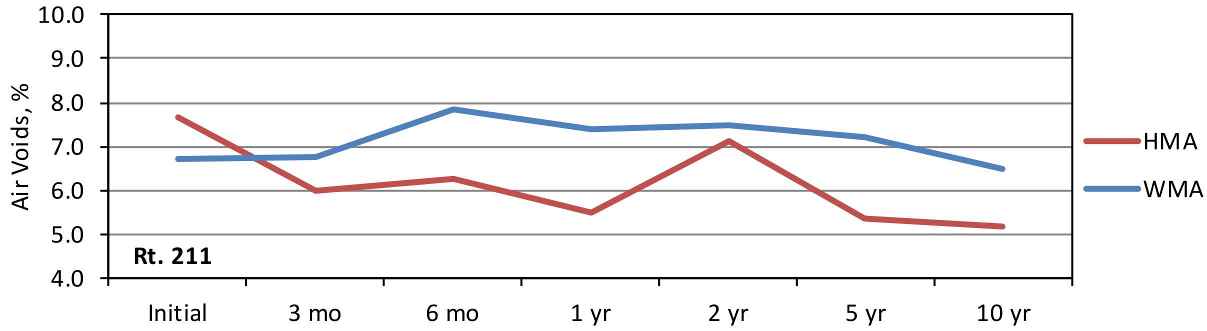
Statistical analyses using Student's two-sample t-test assuming unequal variances were performed to assess if the air-void contents were significantly different between the HMA and WMA cores collected over time. Results are shown in Table 1 and indicate that statistically, air-void contents were comparable between the HMA and WMA for each section, at each time point, except for four comparisons.

Table 1. Summary of Core Air-Void Contents and *p*-Value Results of Student's Two-Sample *t*-Test Assuming Unequal Variances ($\alpha < 0.05$)

Location	Age	HMA		WMA		*p*-value	Comment
		Avg.	Std. Dev.	Avg.	Std. Dev.		
Rt. 211	Initial	7.7	1.1	6.7	1.8	0.3183	
	3-Month	6.0	0.9	6.8	1.9	0.4096	
	6-Month	**6.2**	**0.7**	**7.8**	**1.4**	**0.0465**	**HMA < WMA**
	1-Year	5.5	0.7	7.4	1.9	0.0644	
	2-Year	7.1	1.2	7.5	1.1	0.5972	
	5-Year	**5.4**	**1.4**	**7.2**	**1.3**	**0.0342**	**HMA < WMA**
	10-Year	**5.2**	**1.2**	**6.5**	**1.3**	**0.0285**	**HMA < WMA**
Rt. 220	Initial	9.2	1.3	8.1	2.5	0.3696	
	3-Month	9.4	2.5	8.3	2.7	0.4795	
	6-Month	8.4	2.1	7.9	1.5	0.6754	
	1-Year	6.6	0.9	7.3	0.8	0.1650	
	2-Year	**9.6**	**1.2**	**7.4**	**1.5**	**0.0219**	**HMA > WMA**
	5-Year	6.8	1.5	7.6	1.2	0.3655	
	10-Year	5.9	1.1	6.2	1.0	0.4435	
Rt. 143	Initial	7.6	1.6	9.4	3.5	0.2796	
	3-Month	9.6	1.8	9.2	3.0	0.8119	
	6-Month	7.1	2.4	7.4	2.1	0.8333	
	1-Year	7.0	2.7	7.6	1.9	0.6458	
	2-Year	6.3	0.8	8.6	2.7	0.1305	
	5-Year	6.7	1.4	6.9	2.2	0.8900	
	10-Year	8.5	1.9	7.6	1.9	0.3257	

HMA = hot mix asphalt; WMA = warm mix asphalt. Statistically significant results are in bold type.

Rt. 211 HMA cores were found to have average lower air-void contents than the Rt. 211 WMA cores after the initial specimen set collected during construction, although only the 6-month, 5-year, and 10-year core sets were found to be statistically different. The Rt. 220 HMA cores were found generally to have higher air-void contents than the Rt. 211 WMA cores except at ages 1 year, 5 years, and 10 years, although the results at those times were not statistically different from the WMA core results. With the exception of the 3-month and 10-year results, the Rt. 143 HMA cores indicated lower average air-void contents than the WMA, although none of the differences was statistically significant. Figure 4 shows the average air-void contents for each section over time.



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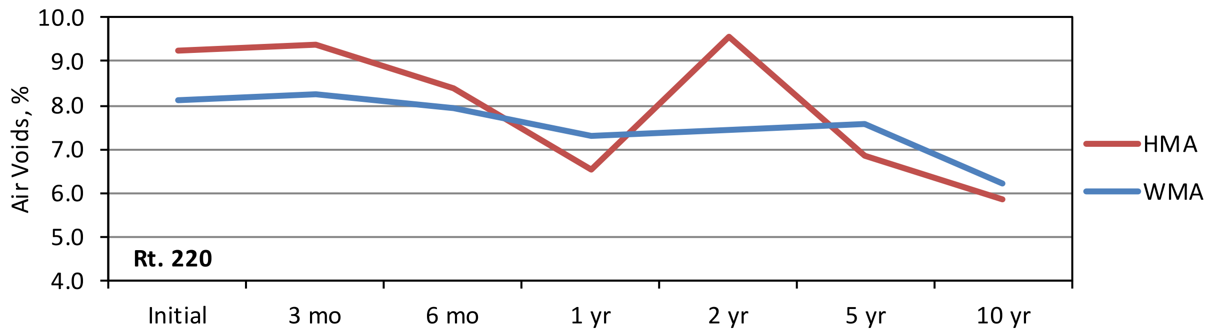

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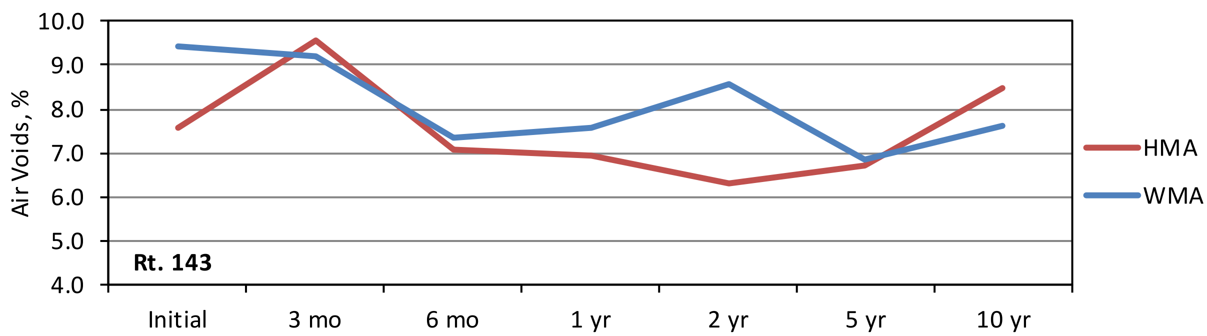
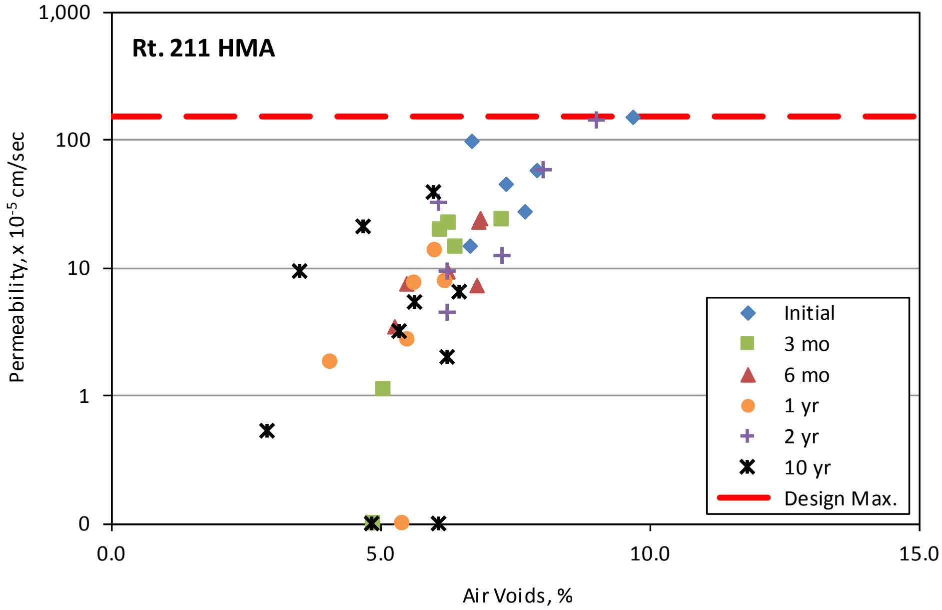


(c)

Figure 4. Average Air-Void Content for Field Cores Collected Over Time From (a) Rt. 211, (b) Rt. 220, and (c) Rt. 143. HMA = hot mix asphalt; WMA = warm mix asphalt.

Results from permeability testing are shown in Figures 5 through 7. These figures indicate that core air-void contents and permeability have a relationship that is fairly well defined, with increasing air voids generally corresponding to higher permeability. In general, the figures show that over time, permeability decreases. In some cases, this is clearly due to decreased air-void content; however, it also appears that perhaps the interconnections between voids are reduced over time, reducing permeability, without necessarily affecting overall void content.



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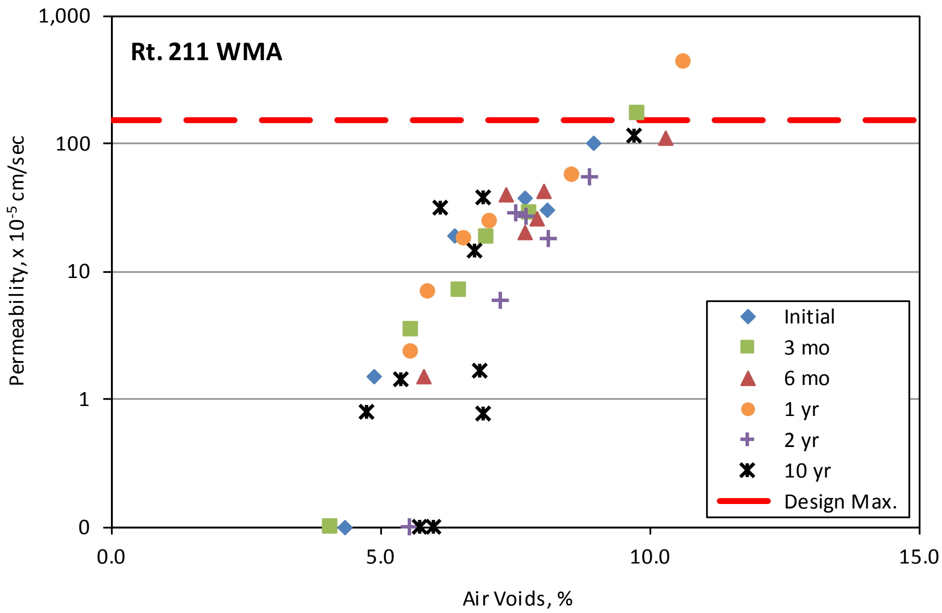
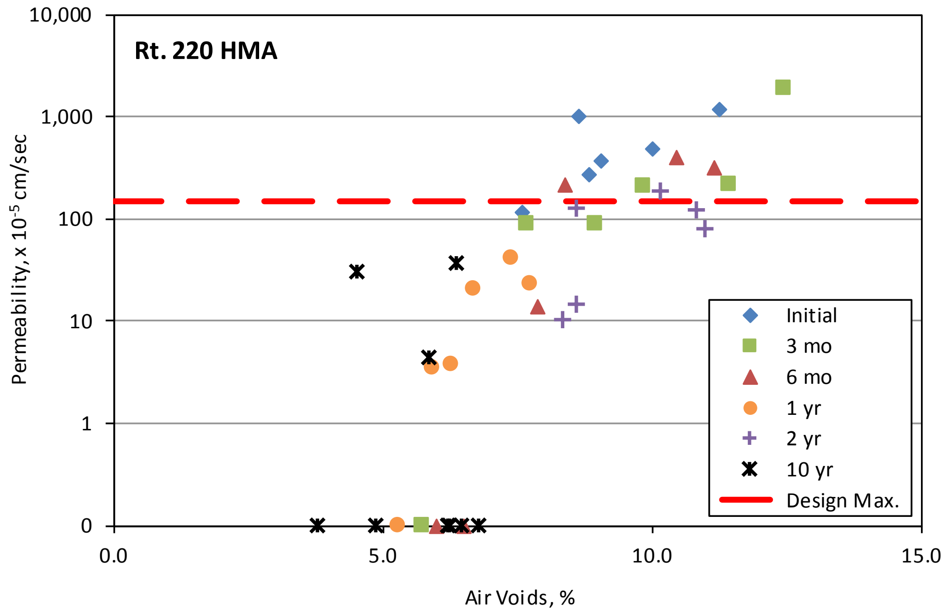


(b)

Figure 5. Permeability Results for Rt. 211 (a) HMA and (b) WMA cores. HMA = hot mix asphalt; WMA = warm mix asphalt.



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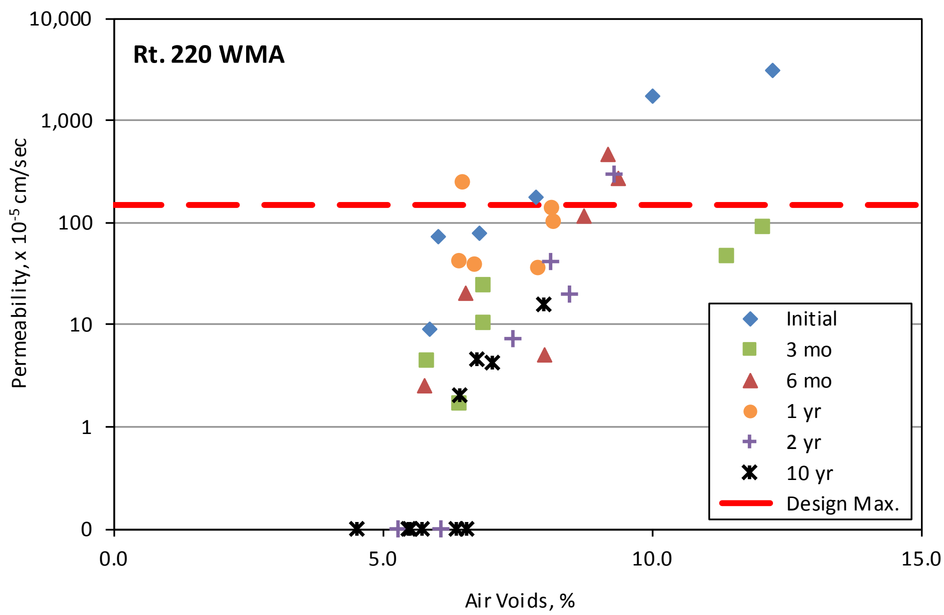
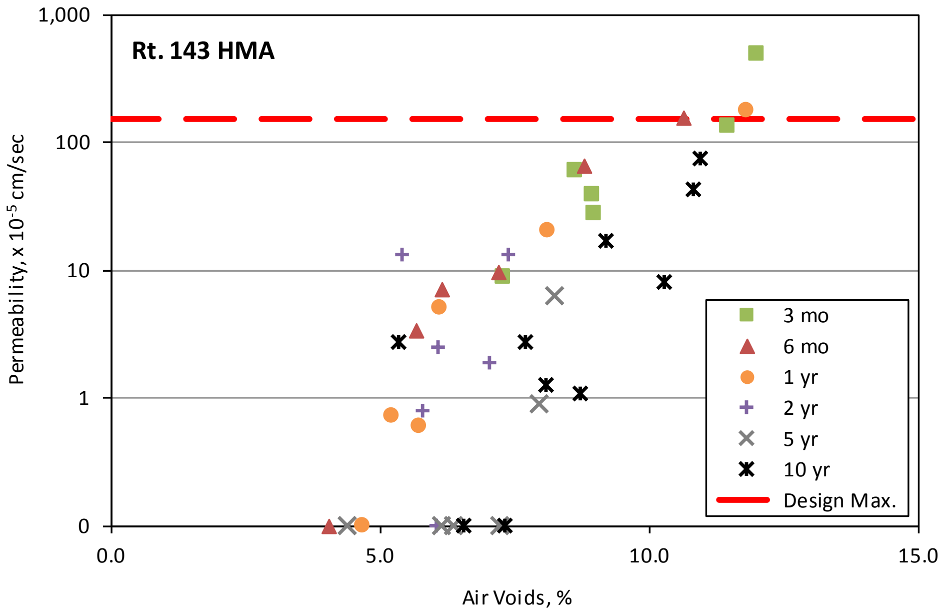


(b)

Figure 6. Permeability Results for Rt. 220 (a) HMA and (b) WMA cores. HMA = hot mix asphalt; WMA = warm mix asphalt.



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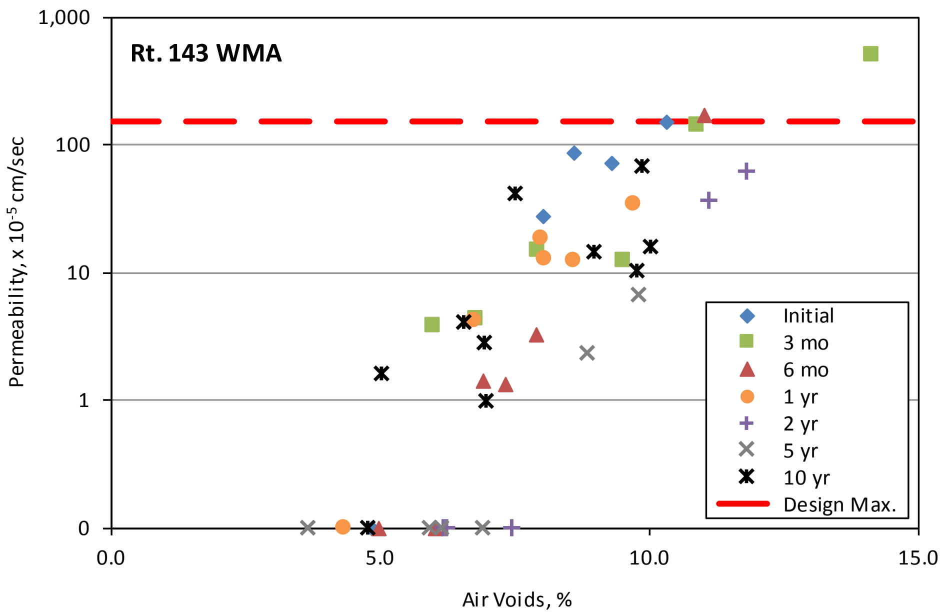


(b)

Figure 7. Permeability Results for Rt. 143 (a) HMA and (b) WMA cores. HMA = hot mix asphalt; WMA = warm mix asphalt.

Dynamic Modulus Test

Dynamic modulus testing was performed on small-scale specimens extracted from field cores, as previously described. Cores collected at 1, 2, 5, and 10 years of service were stored in a climate-controlled area after permeability testing was performed until dynamic modulus specimen preparation and testing commenced. The 1-, 2-, and 5-year specimens were tested in 2015, once small-scale dynamic modulus capability was developed; the 10-year specimens were tested as soon as possible after collection. Dynamic modulus specimen air voids for all locations are shown in Table 2. Specimen air voids affect dynamic modulus values; however, the effect is difficult to quantify, as the modulus values reported in Figures 8 through 13 are averages of the individual specimen results and are influenced by aging and other factors. It should be noted that the specimen void levels do not necessarily meet the requirements of the test method (7.0% ± 0.5% air voids) since they were prepared from road cores. Comparisons are meant to give a sense of as-constructed properties.

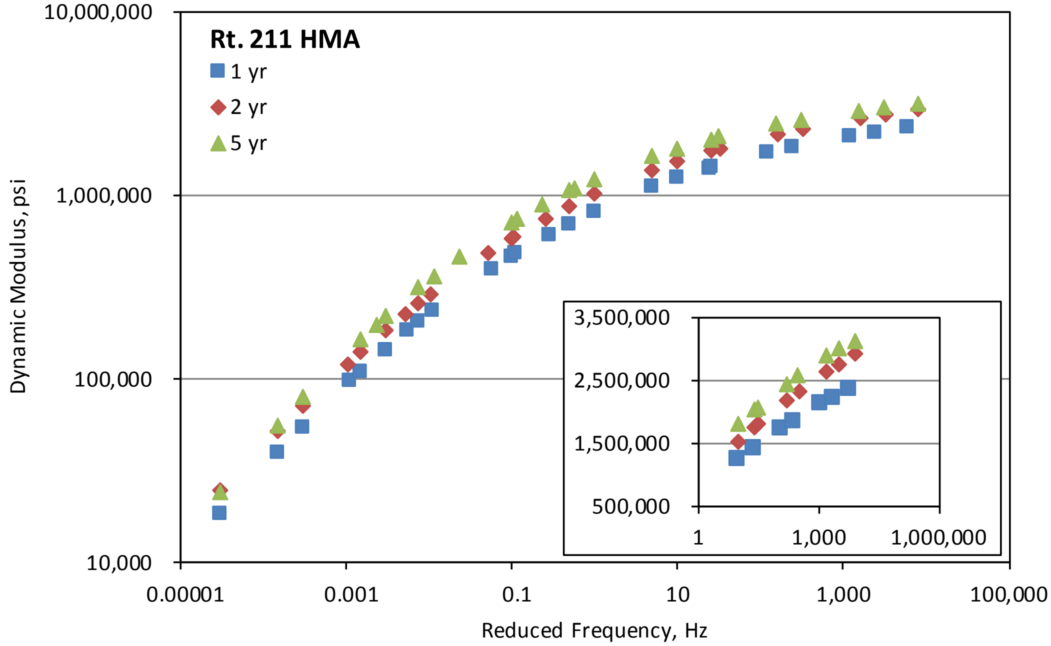
Results for Rt. 211 are shown in Figures 8 and 9. Ten-year cores from Rt. 211 could not be tested as the core thicknesses were not sufficient to allow specimens to be prepared. Figure 8a shows a clear increase in stiffness for the HMA from 1 year to 2 and 5 years, particularly in the central portion of the curve; Figure 8b indicates that the WMA stiffness was fairly consistent after 2 years of service, with the 5-year specimens showing slightly reduced stiffness as compared to the 2-year specimens. Figure 9 compares the stiffness of the HMA and WMA at each service age. This plot indicates that the HMA mixture was slightly stiffer than the WMA mixture at 1 and 5 years of age. Interestingly, the 2-year cores were found to have a similar stiffness response.

Figure 10 presents the dynamic modulus results for cores collected from Rt. 220. These results are quite different from those for Rt. 211. Figure 10a indicates that the 1- and 2-year cores had a similar response below approximately 0.5 Hz reduced frequency, as did the 5- and 10-year cores, which showed lower stiffness over time. At reduced frequencies above 0.5 Hz, the 1- and 5-year cores were similar in stiffness, as were the 2- and 10-year cores. Figure 10b shows a different trend for the WMA cores, with the 10-year cores being the stiffest, as expected, but the 1-year, 5-year, and 2-year cores showing decreasing stiffness, respectively. At higher reduced frequencies, above approximately 100 Hz, the stiffness results seem to converge for all core ages.

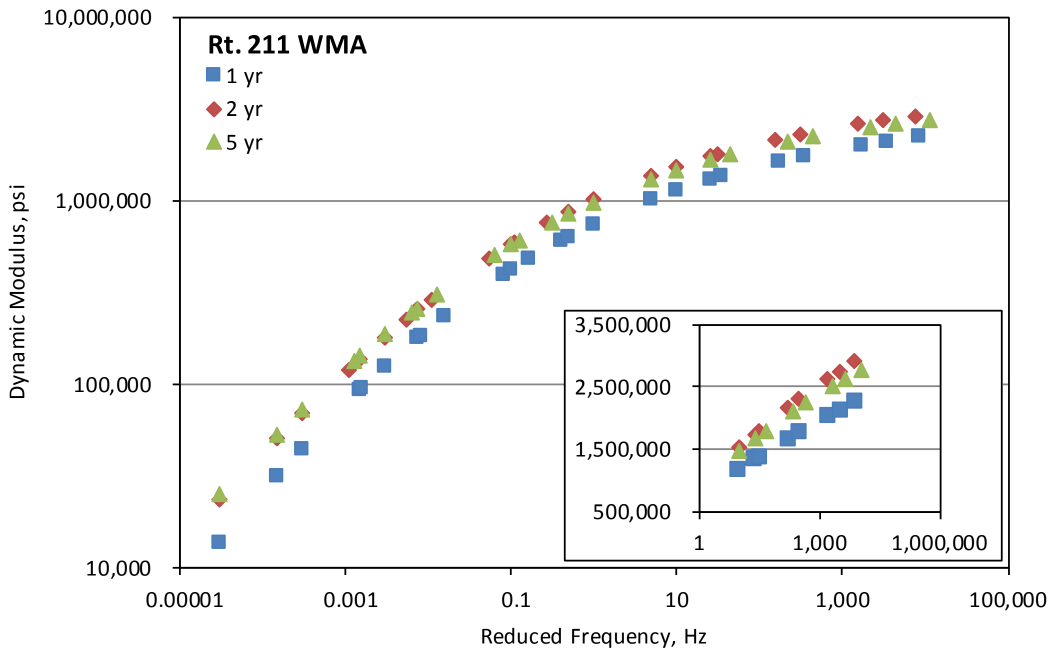
Table 2. Dynamic Modulus Specimen Air Voids

	Rt. 211		**Rt. 220**		**Rt. 143**	
Age	**HMA**	**WMA**	**HMA**	**WMA**	**HMA**	**WMA**
1-yr	6.8	7.1	5.3	7.0	11.3	7.6
	4.5	9.1	5.2	6.1	5.7	4.1
	6.0	6.2	7.3	7.2	4.8	6.2
Average	*5.8*	*7.5*	*5.9*	*6.8*	*7.3*	*6.0*
2-yr	6.6	9.0	8.0	6.3	6.5	5.8
	8.4	6.7	9.1	3.9	5.9	6.8
	6.8	7.9	9.8	6.3	6.0	9.7
Average	*7.3*	*7.9*	*9.0*	*5.5*	*6.1*	*7.4*
5-yr	6.0	5.2	5.6	5.8	5.5	2.8
	6.2	7.2	5.6	5.8	5.4	4.7
	4.7	6.6	6.5	4.2	6.9	5.1
Average	*5.6*	*6.3*	*5.9*	*5.3*	*6.0*	*4.2*
10-yr	-	-	7.7	7.5	9.9	10.2
	-	-	6.6	6.1	11.8	10.1
	-	-	10.9	7.4	11.1	10.8
Average	-	-	*8.4*	*7.0*	*10.9*	*10.4*

HMA = hot mix asphalt; WMA = warm mix asphalt; - = specimens not tested.



(a)



(b)

Figure 8. Dynamic Modulus Mastercurves for Rt. 211 (a) HMA and (b) WMA. Inset graphs show higher reduced frequency results more clearly. HMA = hot mix asphalt; WMA = warm mix asphalt.

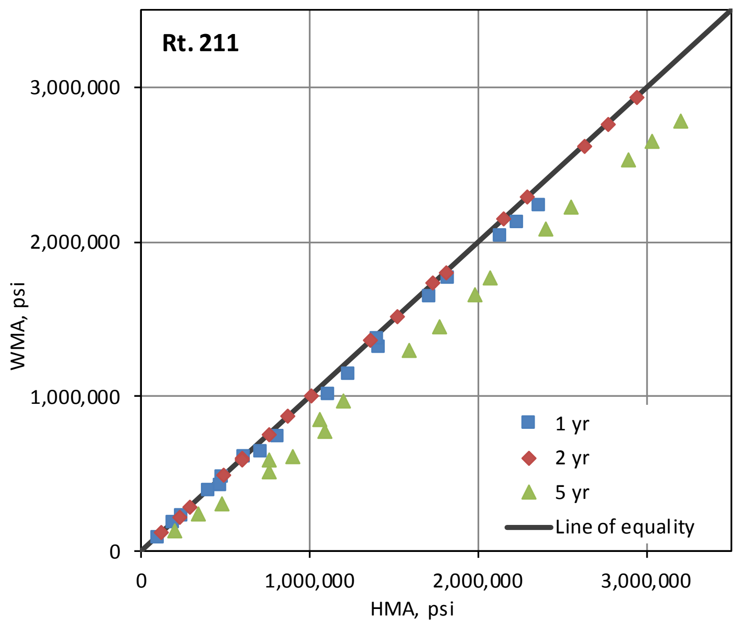
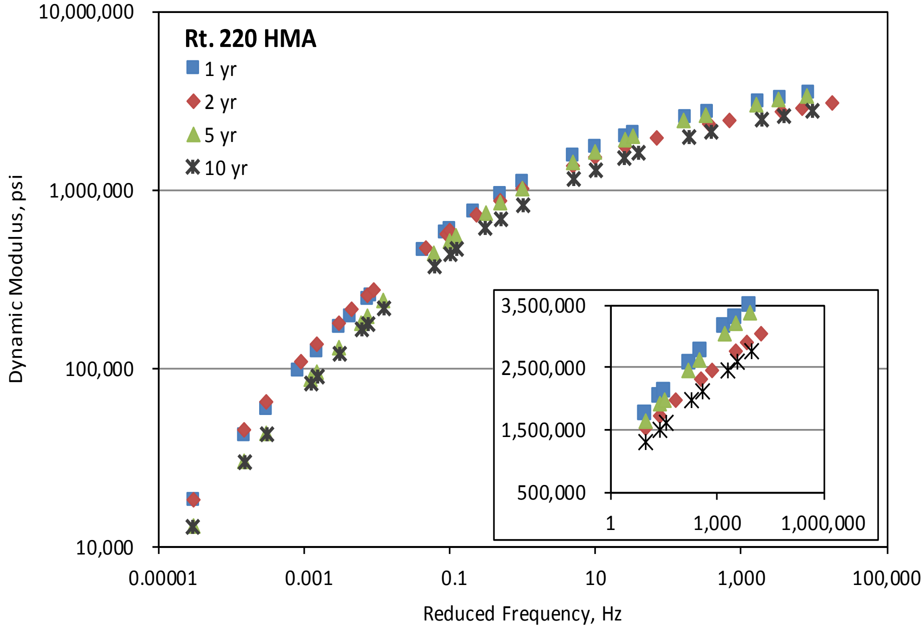


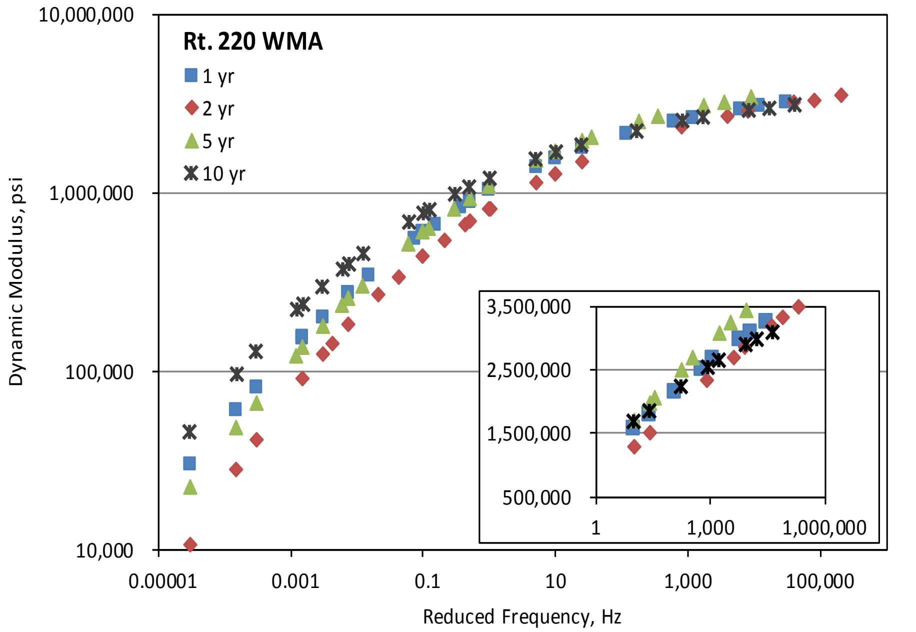
Figure 9. Comparison of Mastercurve values for Rt. 211. HMA = hot mix asphalt; WMA = warm mix asphalt.

Figure 11 compares the HMA and WMA at each age, with interesting results. At 1 year in service, the HMA was slightly stiffer than the WMA except at very low stiffnesses. The 2-year cores showed a more scattered response, with some results indicating that the WMA was stiffer and others indicating the HMA was stiffer. At 5 years of service, the results indicated that the two mixtures were similar in terms of stiffness. Finally, the 10-year WMA cores were considerably stiffer than the HMA cores.

Figure 12 shows the dynamic modulus mastercurves for the cores collected from Rt. 143. From Figure 12a, at reduced frequencies below approximately 0.1 Hz, the 1-year HMA cores were clearly the least stiff, with the 2- and 5-year HMA cores showing increasing stiffness with age. At this range of reduced frequency, the 10-year HMA cores fell between the 2- and 5-year cores in terms of stiffness. At reduced frequencies above approximately 0.1 Hz, the 2- and 5-year cores were similar in stiffness and were stiffer than the 1-year cores. The 10-year cores followed a trend of decreasing stiffness compared to the 2- and 5-year cores, and at reduced frequencies above approximately 10 Hz, they were less stiff than the 1-year cores. Figure 12b summarizes the dynamic modulus performance of the WMA cores. Interestingly, the 2-year cores were the least stiff at all reduced frequencies less than approximately 500 Hz, where the 10-year core results converged with the 2-year results. The 1- and 5-year core results were similar throughout the range of frequencies, whereas the 10-year cores were the stiffest at frequencies below 1 Hz.



(a



(b

Figure 10. Dynamic Modulus Mastercurves for Rt. 220 (a) HMA and (b) WMA. Inset graphs show higher reduced frequency results more clearly. HMA = hot mix asphalt; WMA = warm mix asphalt.

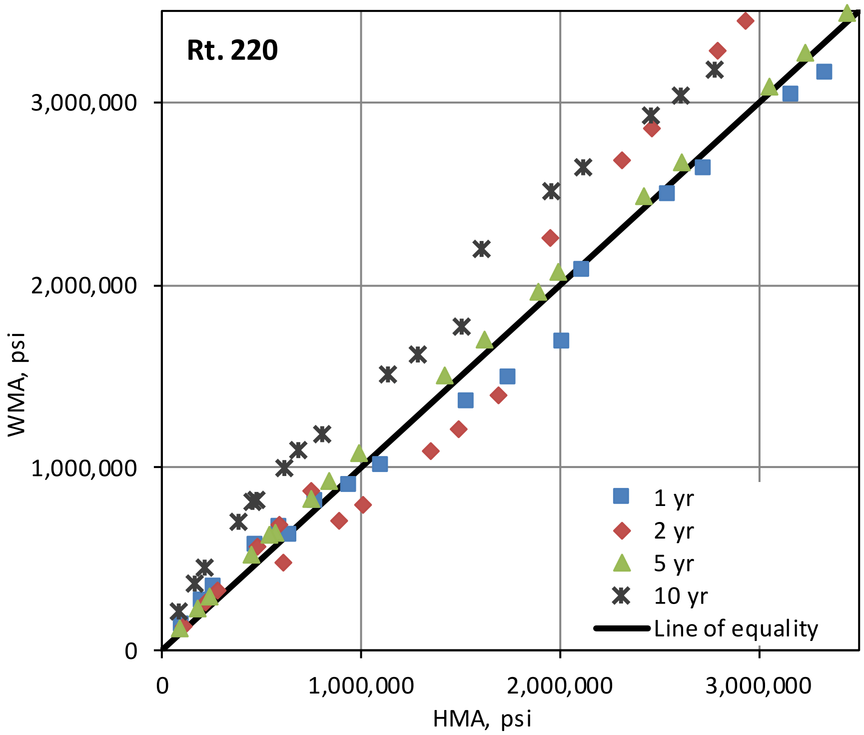
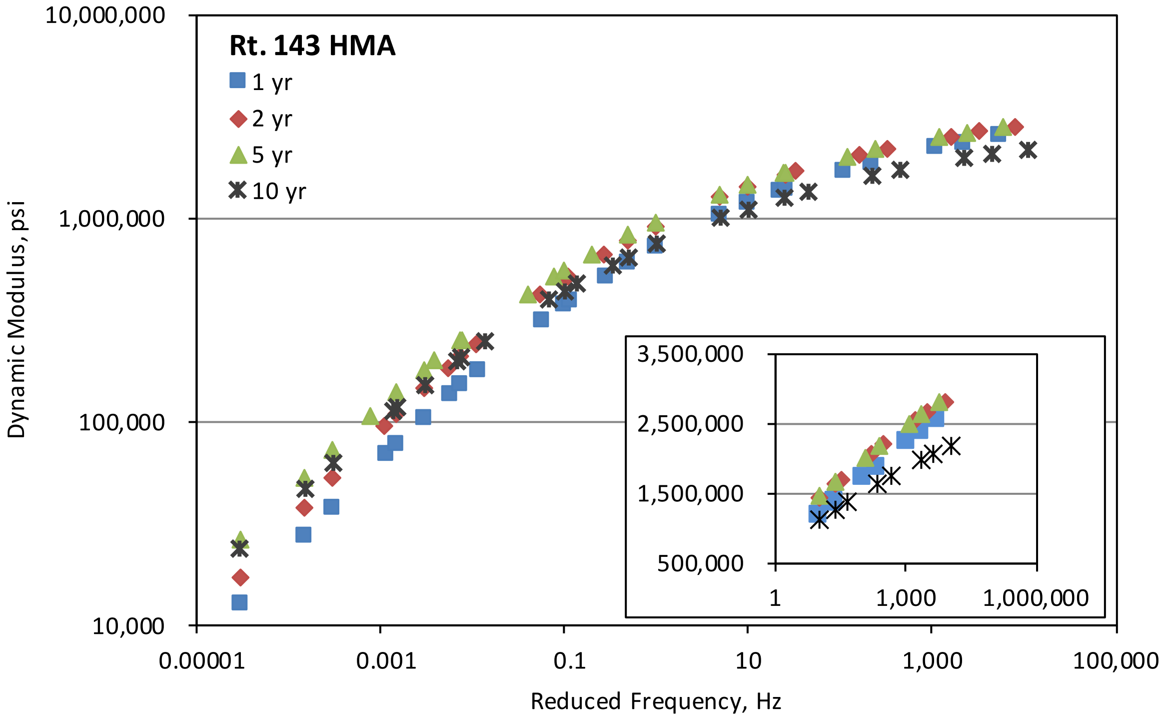


Figure 11. Comparison of Mastercurve values for Rt. 220. HMA = hot mix asphalt; WMA = warm mix asphalt.

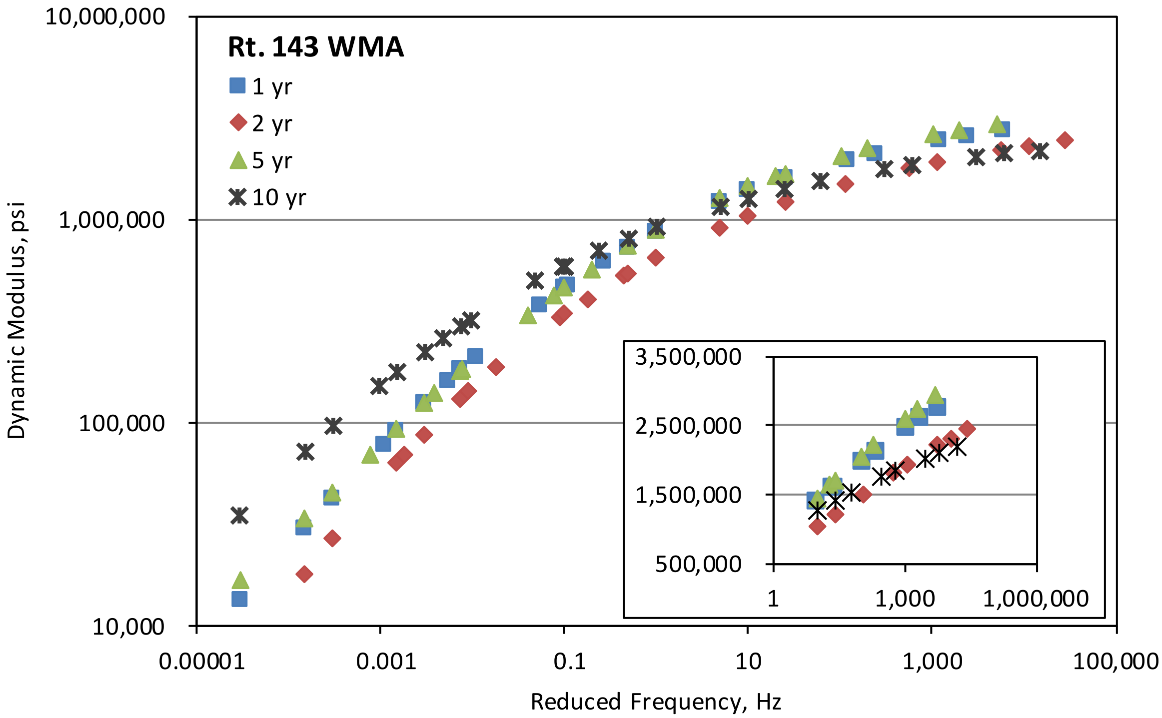
Figure 13 shows the comparison of the HMA and WMA at each age. In general, it can be seen that the WMA at 1 year and 10 years of age was stiffer than the HMA, whereas the 2-year HMA was stiffer than the WMA. At 5 years of age, the trend was mixed, with the HMA being stiffer at high test frequencies (stiffness values below 1,000,000 psi), similar to the WMA at stiffnesses from 1,000,000 psi to 2,250,000 psi, and less stiff than the WMA at higher test frequencies. Overall, there was not a clear distinction between the HMA and WMA with age.

Overlay Test

Overlay test results from 10-year in-service cores are summarized in Table 3. The overlay test was performed on four specimens for all sections except the Rt. 211 WMA section, for which five specimens were tested. In general, the average cycles to failure indicated that the Rt. 220 and Rt. 143 HMA sections performed better than their WMA companions; however, the test variability was such that the differences were not significant. Statistical analysis using Student's two-sample *t*-test assuming unequal variances indicated that there were no significant differences between the HMA and WMA overlay test results for any of the HMA-WMA pairs. This is further shown in Figure 14, where the average and standard deviations of the results are plotted.



(a)



(b)

Figure 12. Dynamic Modulus Mastercurves for Rt. 143 (a) HMA and (b) WMA. Inset graphs show higher reduced frequency results more clearly. HMA = hot mix asphalt; WMA = warm mix asphalt.

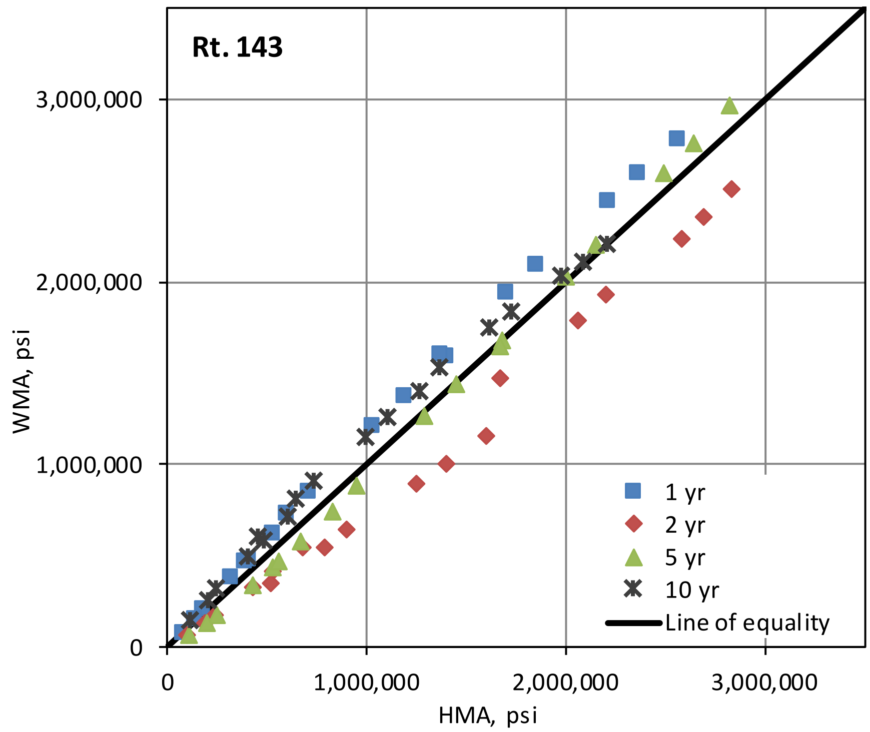


Figure 13. Comparison of Mastercurves for Rt. 143. HMA = hot mix asphalt; WMA = warm mix asphalt.

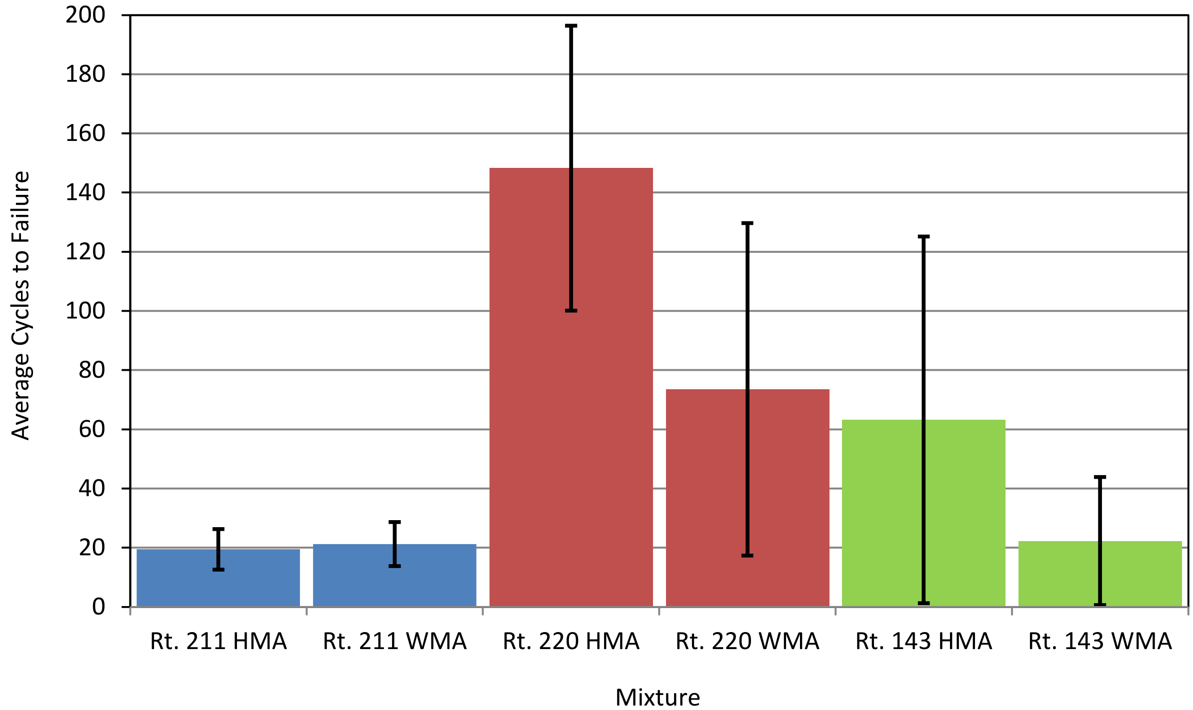


Figure 14. Overlay Test Results for 10-year In-Service Cores. HMA = hot mix asphalt; WMA = warm mix asphalt.

Table 3. Overlay Test Results and Statistical Comparisons Between HMA and WMA 10-Year In-Service Core Specimen Sets

Overlay Test	Rt. 211				Rt. 220				Rt. 143			
	HMA		WMA		HMA		WMA		HMA		WMA	
	%AV	OT cycles	%AV	OT cycles	%AV	OT cycles	%AV	OT cycles	%AV	OT cycles	%AV	OT Cycles
	3.1	28	6.4	16	5.9	110	6.9	139	5.6	47	7.9	20
	3.9	22	5.1	28	5	159	5.7	99	7.6	154	7.3	3
	5.9	13	6.2	13	3.2	112	7	14	6.8	37	5.5	13
	5.2	15	5.6	30	4.3	212	6.6	42	8.2	15	5	53
			6	19								
Average	4.5	19.5	5.9	21.2	4.6	148.3	6.6	73.5	7.1	63.3	6.4	22.3
Std. Dev.	1.3	6.9	0.5	7.5	1.1	48.2	0.6	56.2	1.1	62.0	1.4	21.7
p-value[a]		0.7328				0.0899				0.2797		

HMA = hot mix asphalt; WMA = warm mix asphalt; AV = air voids; OT = overlay test.

[a] *p*-values were determined using the two-sample Student *t*-test assuming unequal variances. *p*-values < 0.05 indicate significant differences between HMA and WMA specimen sets.

Flexibility Index Test

The Illinois FI was used to evaluate the cracking resistance of the mixtures using 10-yr in-service cores. Sets of six (Rt. 211 HMA and WMA) and four (Rt. 220 and Rt. 143 HMA and WMA) specimens were tested, as shown in Tables 4 and 5. Table 4 presents the FI results, and Table 5 shows the specimen air-void contents. The two-sample Student *t*-test was used to compare each HMA and WMA specimen set; results indicated that only the HMA and WMA FI results from Rt. 220 were significantly different. However, the specimen air-void contents were significantly different for all HMA-WMA pairs, even those from Rt. 211 and Rt. 143 for which the FI was not significantly different. Correlation analysis to evaluate the relationship of specimen air voids with FI found a correlation coefficient of -0.39, indicating that the two were not highly correlated. Figure 15 shows the magnitude of difference between the Rt. 220 HMA average result and those from all other sections. This difference in FI would be expected to result in a significantly different performance of the Rt. 220 HMA; however, this was not seen in the field. Visual observation of the performance of the Rt. 211 HMA and WMA during periodic coring indicated generally similar performance from mixtures; unfortunately, PMS data were not available for the Rt. 220 sections to quantify relative performance.

Table 4. Flexibility Index Results From 10-Year In-Service Cores

Flexibility Index	Rt. 211		Rt. 220		Rt. 143	
	HMA	**WMA**	**HMA**	**WMA**	**HMA**	**WMA**
	2.37	0.86	5.34	0.59	0.35	0.60
	0.92	1.07	3.92	0.37	1.20	0.24
	0.28	1.20	4.11	1.16	brittle	1.64
	1.81	0.98	5.34	1.75	brittle	0.72
	0.90	1.28				
	0.20	0.42				
Average	1.08	0.97	4.68	0.97	0.78	0.80
Std. Dev.	0.86	0.31	0.77	0.62	0.60	0.60
p-value[a]	0.7759		0.0003		0.9682	

[a] *p*-values were determined using the two-sample Student *t*-test assuming unequal variances. *p*-values < 0.05 indicate significant differences between HMA and WMA specimen sets.

Table 5. Air-Void Contents (%) for Flexibility Index Test Specimens

Air Void Content	Rt. 211		Rt. 220		Rt. 143	
	HMA	**WMA**	**HMA**	**WMA**	**HMA**	**WMA**
	6.3	6.7	6.2	7.2	9.1	7.7
	6.2	7.2	6.4	8.0	9.3	7.2
	6.4	8.9	6.8	7.3	9.7	7.4
	6.1	6.7	6.2	6.8	8.9	8.4
	6.4	6.8				
	6.2	7.2				
Average	6.27	7.24	6.37	7.32	9.23	7.69
Std. Dev.	0.12	0.85	0.30	0.49	0.38	0.51
p-value	0.0403		0.0223		0.0047	

[a] *p*-values were determined using the two-sample Student *t*-test assuming unequal variances. *p*-values < 0.05 indicate significant differences between HMA and WMA specimen sets.

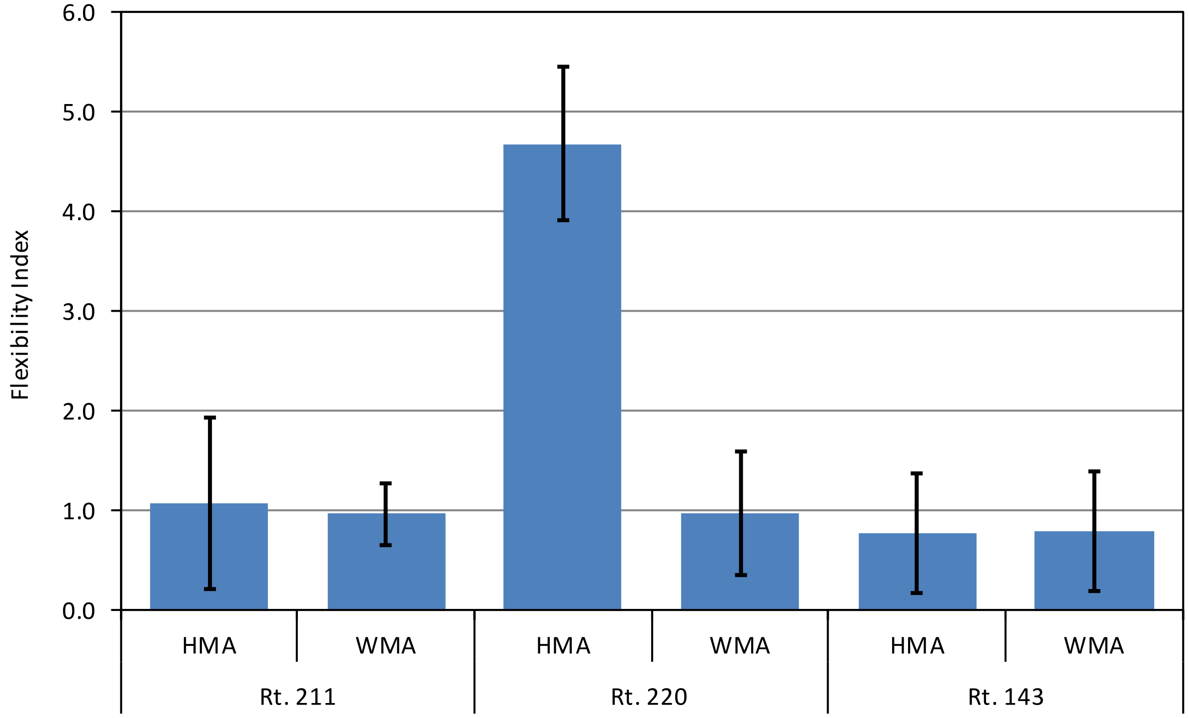


Figure 15. Flexibility Index Results for 10-Year In-Service Cores. The error bars indicate one standard deviation in test results. HMA = hot mix asphalt; WMA = warm mix asphalt.

Binder Testing

Binder grading was performed on base binder samples at the time of construction and on extracted and recovered binder samples taken over the 10-year period. Binder recovery was performed using the Abson method on cores collected at construction through 24 months of service; the Rotavap method of recovery was used on cores collected from 12 months through 10 years of service.

Tables 6 and 7 present the binder data for the Rt. 211 HMA and WMA mixtures, respectively. The data show a clear binder stiffening effect as the pavement ages. This is further shown in Figures 16 through 19. Figures 16 and 17 indicate that the binder high temperature grade is increasing; Figure 18 shows the increase in the low temperature grade. Figure 19 shows ΔT_c, the difference in the critical cracking temperature based on BBR values; this figure shows that at 10 years in service, the WMA has a greater magnitude ΔT_c than the HMA and exceeds the cracking limit, indicating cracking susceptibility.

Table 6. Binder Data for Rt. 211 HMA

Property	Base Binder	0 mo Abson	6 mo Abson	12 mo Abson	12 mo Rotavap	24 mo Abson	24 mo Rotavap	5 yr Rotavap	10 yr Rotavap
Dynamic Shear, 10 rad/sec, specification: G*/sin delta >2.20 kPa									
RTFO G*/sin delta, 64ºC	4.817								
RTFO G*/sin delta, 70ºC	2.226	3.98	4.925						
RTFO G*/sin delta, 76ºC		1.914	2.376	5.461	3.857	4.67	5.813	6.408	9.414
RTFO G*/sin delta, 82ºC				2.769	1.837	2.274	2.733	3.056	4.456
RTFO G*/sin delta, 88ºC				1.24			1.332	1.51	2.182
RTFO G*, 76ºC					3.819	4.608	5.738	6.308	9.211
RTFO G*, 82ºC					1.827	2.256	2.713	3.029	4.399
RTFO G*, 88ºC							1.327	1.503	2.166
RTFO phase angle, 76ºC					81.95	80.7	80.79	79.9	78.07
RTFO phase angle, 82ºC					84.06	83	83.13	82.37	80.82
RTFO phase angle, 88ºC							85.07	84.43	83.14
RTFO failure temperature	70.06	75.17	76.41	84.08	80.54	82.27	83.88	84.83	87.88
Dynamic Shear, 10 rad/sec, specification: G* sin delta < 5000 kPa									
PAV G* sin delta, 22.0ºC	4520								
PAV G* sin delta, 25.0ºC	3028	4952	4409	5011	6320				
PAV G* sin delta, 28.0ºC		3428	3032	3616	4551	5359	5822	5418	5117
PAV G* sin delta, 31.0ºC					3215	3974	4150	3868	3705
PAV G*, 25.0ºC					9.63E +06				
PAV G*, 28.0ºC					6.59E +06	7.84E +06	8.59E +06	7.90E +06	7.68E +06
PAV G*, 31.0ºC					4.44E +06	5.61E +06	5.83E +06	2.38E +06	5.30E +06
PAV phase angle, 25.0ºC					41.03				
PAV phase angle, 28.0ºC					43.7	43.1	42.66	43.33	41.79
PAV phase angle, 31.0ºC					46.4	45.1	45.38	45.99	44.38
PAV failure temperature	21.03	24.91	23.71	25.02	27.11	28.76	29.34	31.72	31.22
Creep stiffness, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300									
Stiffness, 0ºC									
M-value, 0ºC									
Stiffness, -6ºC					137	172	178	179	256
M-value, -6ºC					0.334	0.329	0.324	0.313	0.302
Stiffness, -12ºC	210	235	235	252	270	350	320	362	374
M-value, -12ºC	0.339	0.332	0.32	0.315	0.275	0.27	0.275	0.264	0.254
Stiffness, -18ºC				494					
M-value, -18ºC				0.277					
ΔT_c, ºC				1.2	-3.9	-1.4	-2.2	-2.4	-2.0
Stiffness failure temperature	NA	NA	NA	-23.2	-23.4	-20.3	-21.2	-20.0	-18.2
M-value failure temperature	NA	NA	NA	-24.4	-19.5	-18.9	-18.9	-17.6	-16.3
Performance Grade	64-22	70-22	76-22	82-22	76-16	82-16	82-16	82-16	82-16

HMA = hot mix asphalt; red text = Abson method of recovery was used; black text = Rotavap method of recovery was used; RTFO = rolling thin film oven; PAV = pressure aging vessel; NA = data not available.

Table 7. Binder Data for Rt. 211 WMA

Property	Base Binder	0 mo Abson	6 mo Abson	12 mo Abson	12 mo Rotavap	24 mo Abson	5 yr Rotavap	10 yr Rotavap
Dynamic Shear, 10 rad/sec, specification: G*/sin delta > 2.20 kPa								
RTFO G*/sin delta, 64ºC	4.817	12.88						
RTFO G*/sin delta, 70ºC	2.226	5.886	4.834	6.657				
RTFO G*/sin delta, 76ºC		2.778	2.293	3.115	3.794	2.638	7.176	5.921
RTFO G*/sin delta, 82ºC				1.524	1.809	1.293	3.391	2.776
RTFO G*/sin delta, 88ºC							1.65	1.329
RTFO G*, 76ºC					3.755	2.619	7.057	5.838
RTFO G*, 82ºC					1.799	1.288	3.358	2.755
RTFO G*, 88ºC							1.641	1.324
RTFO phase angle, 76ºC					81.72	83.1	79.55	80.43
RTFO phase angle, 82ºC					83.94	84.9	82.08	82.86
RTFO phase angle, 88ºC							84.21	84.86
RTFO failure temperature	70.06	77.12	76.22	79.45	80.41	77.53	85.61	83.92
Dynamic Shear, 10 rad/sec, specification: G* sin delta < 5000 kPa								
PAV G* sin delta, 22.0ºC	4520			8260				
PAV G* sin delta, 25.0ºC	3028	4893	4255	5796	6776			6185
PAV G* sin delta, 28.0ºC		3445	2968	4128	4849	4425	6101	4503
PAV G* sin delta, 31.0ºC		2379		2819		3097	4343	
PAV G*, 25.0ºC					1.03E+07			9.54E+06
PAV G*, 28.0ºC					7.00E+06	4.18E+06	8.96E+06	6.60E+06
PAV G*, 31.0ºC						6.26E+06	6.06E+06	
PAV phase angle, 25.0ºC					43.82			40.41
PAV phase angle, 28.0ºC					41	47.8	42.94	4307
PAV phase angle, 31.0ºC						45	45.74	
PAV failure temperature	21.03	24.78	23.26	26.43	27.73	26.97	32.76	29.98
Creep Stiffness, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300								
Stiffness, 0ºC								
M-value, 0ºC								
Stiffness, -6ºC				150	144	132	199	162
M-value, -6ºC				0.347	0.318	0.336	0.301	0.312
Stiffness, -12ºC	210	244	229	308	280	294	414	274
M-value, -12ºC	0.339	0.31	0.302	0.299	0.281	0.28	0.259	0.23
Stiffness, -18ºC								
M-value, -18ºC								
ΔT_c, ºC	NA	NA	NA	0.2	-4.0	-2.4	-2.7	-6.5
Stiffness failure temperature	NA	NA	NA	-21.7	-22.9	-22.2	-18.8	-23.4
M-value failure temperature	NA	NA	NA	-21.9	-18.9	-19.9	-16.1	-16.9
Performance Grade	64-22	76-22	76-22	76-16	76-16	76-16	82-16	82-16

WMA = warm mix asphalt; red text = Abson method of recovery was used; black text = Rotavap method of recovery was used; RTFO = rolling thin film oven; PAV = pressure aging vessel; NA = data not available.

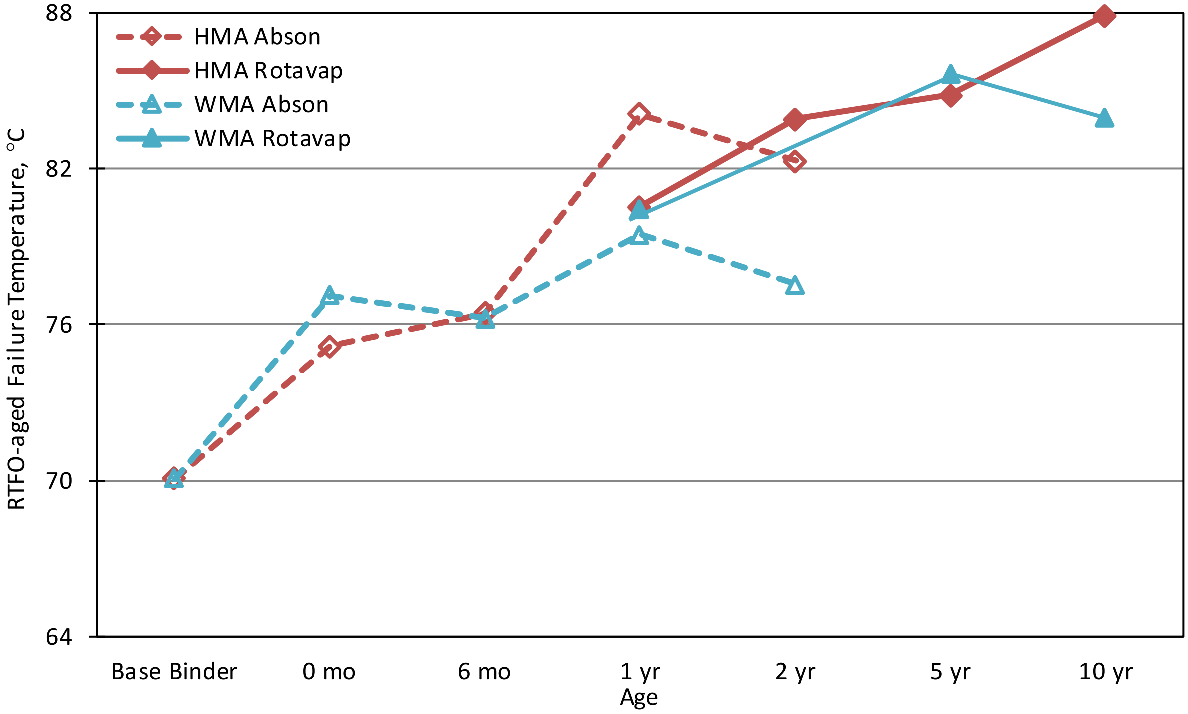


Figure 16. RTFO-aged Binder Failure Temperatures Over Time for Rt. 211. RTFO = rolling thin film oven; HMA = hot mix asphalt; WMA = warm mix asphalt.

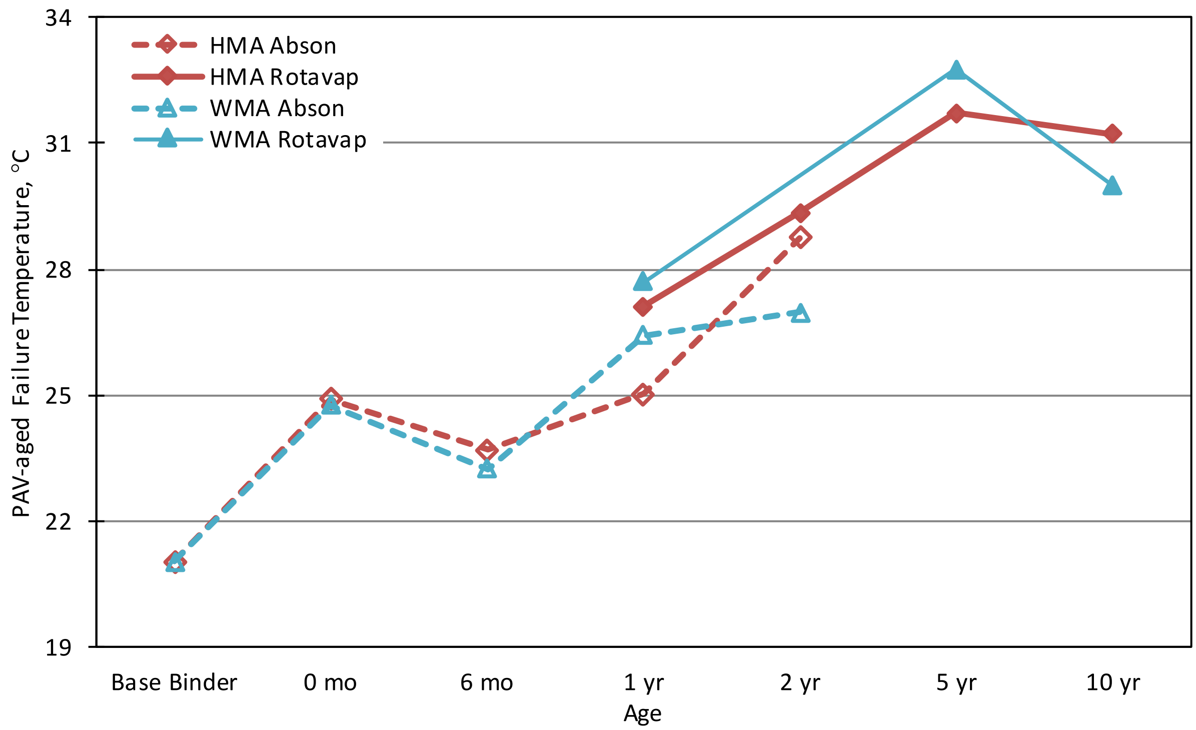


Figure 17. PAV-aged Binder Failure Temperatures Over Time for Rt. 211. PAV = pressure aging vessel; HMA = hot mix asphalt; WMA = warm mix asphalt.

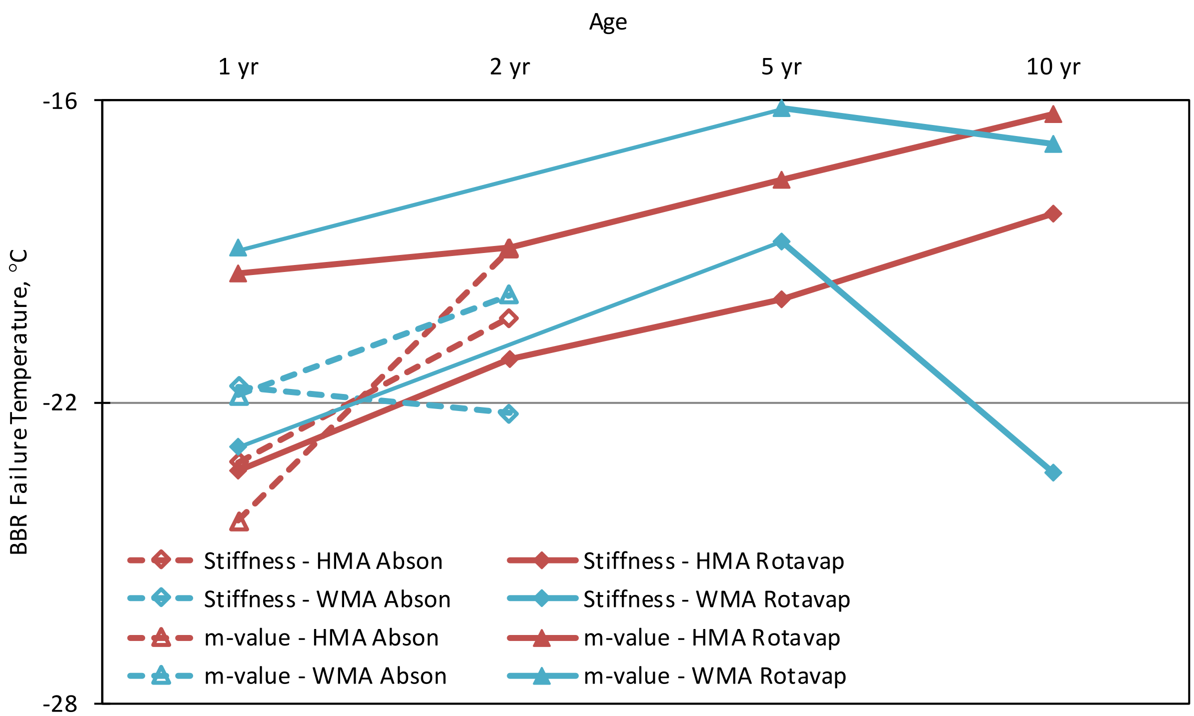


Figure 18. BBR Stiffness and m-value Binder Failure Temperatures Over Time for Rt. 211. BBR = bending beam rheometer; HMA = hot mix asphalt; WMA = warm mix asphalt.

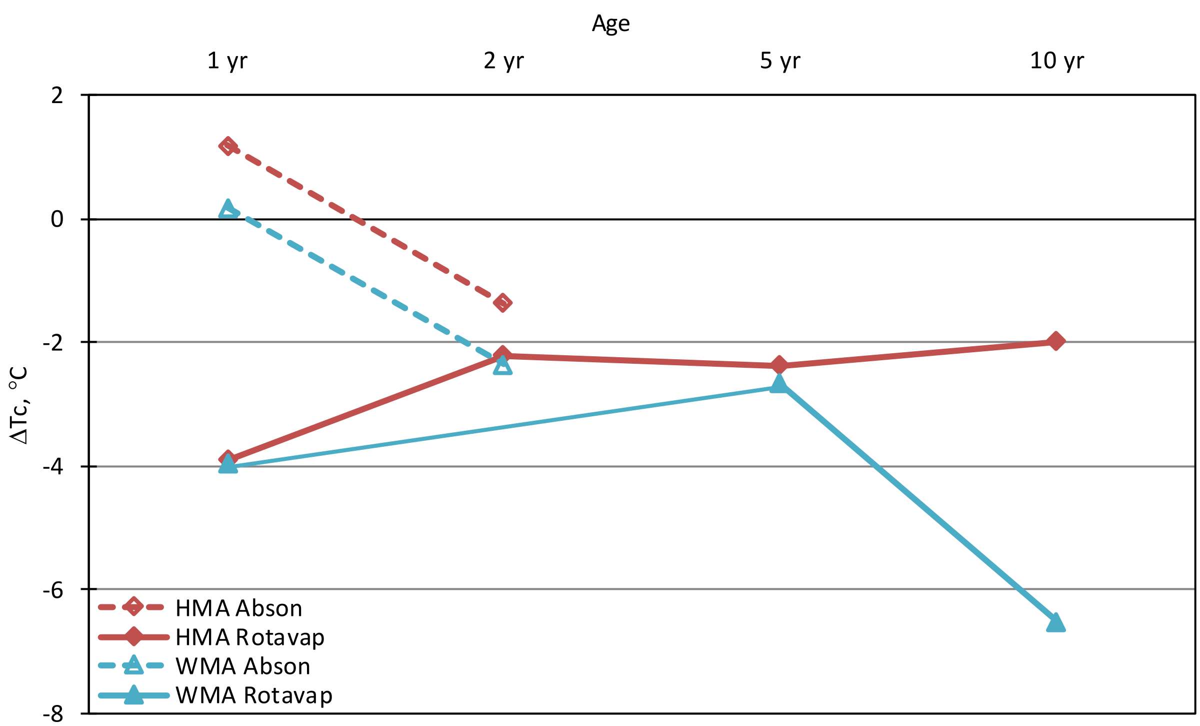


Figure 19. ΔT_c Over Time for Rt. 211. HMA = hot mix asphalt; WMA = warm mix asphalt.

Tables 8 and 9 show the binder grading data for the Rt. 220 HMA and WMA mixtures, respectively. As expected, the binders are shown to increase in grade and stiffness with age except for the 10-year HMA sample, which was unexpectedly softer. The impact of the softer binder was shown in the higher FI results for the Rt. 220 HMA discussed previously. Data were not available for the WMA mixture at 10 years of service to provide a comparison.

Figures 20 through 22 show the trends in failure temperature for the Rt. 220 HMA and WMA mixtures. The Abson recovery results through year 2 indicate that the HMA and WMA trended together in terms of the RTFO-aged and PAV-aged failure temperatures; however, the trends diverged more for the Rotavap recovery results. The BBR stiffness and m-value failure temperatures in Figure 22 show the HMA and WMA trending together although the HMA failure temperatures are higher than the WMA failure temperatures. Figure 23 presents the ΔT_c results and indicates that both mixtures may be highly susceptible to cracking as the difference in the m-value and stiffness failure temperatures well exceeds the recommended cracking limit of 5.0º.

Tables 10 and 11 show the binder grading data for the Rt. 143 HMA and WMA mixtures, respectively. As with all other mixtures, the binders increased in grade and stiffness with age. Binder data were unavailable for the WMA mixture at 5 years in service.

Figures 24 through 26 show the failure temperatures for the extracted Rt. 143 HMA and WMA binders. The trends of the binders generally are similar. The ΔT_c data presented in Figure 27 indicate that both binders exceeded the recommended difference of |5.0º| and should be considered cracking susceptible at all ages except for the Abson-recovered HMA binder at 2 years of age.

Pavement Condition Data

Pavement condition data were obtained from VDOT's PMS for the HMA sections located on Rt. 211 and Rt. 143. Data for the Rt. 220 sections are not presented as data are available only for the HMA section located in the northbound lane; PMS data were not collected for Rt. 220 in the southbound direction. The date of collection of the PMS data was recorded; in addition, since condition surveys took place at varying intervals for the different routes, cumulative degree days (CDD) were calculated to provide an objective measure of when distresses were seen. CDD were calculated as a summation of degrees above 0ºC (32ºF) for each day from the initial construction date to the date on which each condition survey occurred.

Table 8. Binder Data for Rt. 220 HMA

Property	Base Binder	0 mo Abson	6 mo Abson	12 mo Abson	12 mo Rotavap	24 mo Abson	24 mo Rotavap	5 yr Rotavap	10 yr Rotavap
Dynamic Shear, 10 rad/sec, specification: G*/sin delta > 2.20 kPa									
RTFO G*/sin delta, 64ºC	3.56								
RTFO G*/sin delta, 70ºC	1.652	3.257	3.594	5.627					7.551
RTFO G*/sin delta, 76ºC		1.567	1.71	2.668	3.177	3.329	6.157	4.410	3.570
RTFO G*/sin delta, 82ºC				1.304	1.513	1.632	2.705	2.061	1.720
RTFO G*/sin delta, 88ºC							1.423		
RTFO G*, 70ºC									7.436
RTFO G*, 76ºC					3.155	3.302	6.07	4.371	3.539
RTFO G*, 82ºC					1.508	1.625	2.684	2.051	1.712
RTFO G*, 88ºC							1.416		
RTFO phase angle, 70ºC									79.99
RTFO phase angle, 76ºC					83.30	82.7	80.33	82.37	82.49
RTFO phase angle, 82ºC					85.28	84.8	82.97	84.49	84.62
RTFO phase angle, 88ºC							84.62		
RTFO failure temperature, ºC	68.28	73.75	74.44	77.67	78.97	79.49	84.14	81.48	79.98
Dynamic Shear, 10 rad/sec, specification: G* sin delta < 5000 kPa									
PAV G* sin delta, 22.0ºC	4325	7097							
PAV G* sin delta, 25.0ºC	2959	4909	3871	7015				6454	
PAV G* sin delta, 28.0ºC			2652	4876	6366	5366	5431	4590	5115
PAV G* sin delta, 31.0ºC					4448	3870	3984	3203	3721
PAV G*, 25.0ºC								9.61E+06	
PAV G*, 28.0ºC					9.51E+06	7.86E+06	7.97E+06	6.47E+06	7.40E+06
PAV G*, 31.0ºC					6.36E+06	5.43E+06	5.59E+06	4.30E+06	5.16E+06
PAV phase angle, 25.0ºC								42.18	
PAV phase angle, 28.0ºC					42	43	42.98	45.18	43.75
PAV phase angle, 31.0ºC					45.06	45.7	45.48	48.15	46.2
PAV failure temperature, ºC	20.52	24.88	22.22	27.79	30.09	28.66	31.8	30.21	28.21
Creep Stiffness, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300									
Stiffness, 0ºC							102		
M-value, 0ºC							0.339		
Stiffness, -6ºC				153	152	162	175	177	164
M-value, -6ºC				0.343	0.31	0.314	0.273	0.308	0.319
Stiffness, -12ºC	178	225	187	304	303	307	363	349	300
M-value, -12ºC	0.304	0.285	0.281	0.293	0.275	0.257	0.243	0.255	0.271
ΔT_c, ºC	NA	NA	NA	-0.7	-4.2	-4.2	-9.4	-3.4	-3.6
Stiffness failure temperature, ºC	NA	NA	NA	-21.8	-21.9	-21.7	-20.0	-20.3	-22.0
M-value failure temperature, ºC	NA	NA	NA	-21.2	-17.7	-17.5	-10.6	-16.9	-18.4
Performance Grade	64-22	70-16	70-16	76-16	76-16	76-16	82-10	82-16	76-16

HMA = hot mix asphalt; red text = Abson method of recovery was used; black text = Rotavap method of recovery was used; RTFO = rolling thin film oven; PAV = pressure aging vessel; NA = data not available.

Table 9. **Binder Data for Rt. 220 WMA**

Property	Base Binder	0 mo Abson	6 mo Abson	12 mo Abson	12 mo Rotavap	24 mo Abson	24 mo Rotavap	5 yr Rotavap
Dynamic Shear, 10 rad/sec, specification: G*/sin delta > 2.20 kPa								
RTFO G*/sin delta, 64ºC	3.56							
RTFO G*/sin delta, 70ºC	1.652	3.405	4.032	4.58				
RTFO G*/sin delta, 76ºC		1.569	1.951	2.121	4.275	2.645	3.988	5.306
RTFO G*/sin delta, 82ºC					1.999	1.269	1.837	2.458
RTFO G*/sin delta, 88ºC								1.172
RTFO G*, 76ºC					4.232	2.627	3.951	5.246
RTFO G*, 82ºC					1.988	1.265	1.828	2.443
RTFO G*, 88ºC								1.169
RTFO phase angle, 76ºC					81.87	83.3	82.21	81.43
RTFO phase angle, 82ºC					83.99	85.1	84.27	83.67
RTFO phase angle, 88ºC								85.54
RTFO failure temperature, ºC	68.28	73.94	75.28	75.81	81.24	77.54	80.61	82.96
Dynamic Shear, 10 rad/sec, specification: G* sin delta < 5000 kPa								
PAV G* sin delta, 22.0ºC	4325	6051						
PAV G* sin delta, 25.0ºC	2959	4256	5292	5862	0			
PAV G* sin delta, 28.0ºC			3659	4103	5223	5033	5732	6547
PAV G* sin delta, 31.0ºC					3848	3534	4254	4670
PAV G*, 28.0ºC					7.78E+06	7.40E+06	8.55E+06	9.84E+06
PAV G*, 31.0ºC					5.47E+06	7.92E+06	6.07E+06	6.63E+06
PAV phase angle, 28.0ºC					42.19	42.3	42.11	41.69
PAV phase angle, 31.0ºC					44.76	45.9	44.53	44.81
PAV failure temperature, ºC	20.52	23.76	25.54	26.47	28.43	28.06	29.37	30.39
Creep Stiffness, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300								
Stiffness, 0ºC							78	85
M-value, 0ºC							0.353	0.322
Stiffness, -6ºC			136	132	159	143	157	174
M-value, -6ºC			0.343	0.321	0.287	0.309	0.295	0.276
Stiffness, -12ºC	178	246	269	281	298	244		354
M-value, -12ºC	0.304	0.268	0.29	0.28	0.257	0.233		0.248
ΔT_c, ºC	NA	NA	-2.5	-3.7	-8.7	-8.6	-11.4	-9.3
Stiffness failure temperature, ºC	NA	NA	-23.4	-22.8	-22.1	-25.3	-26.9	-20.2
M-value failure temperature, ºC	NA	NA	-20.9	-19.1	-13.4	-16.7	-15.5	-10.9
Performance Grade	64-22	70-16	70-16	70-16	76-10	76-16	76-10	82-10

WMA = warm mix asphalt; red text = Abson method of recovery was used; black text = Rotavap method of recovery was used; RTFO = rolling thin film oven; PAV = pressure aging vessel; NA = data not available.

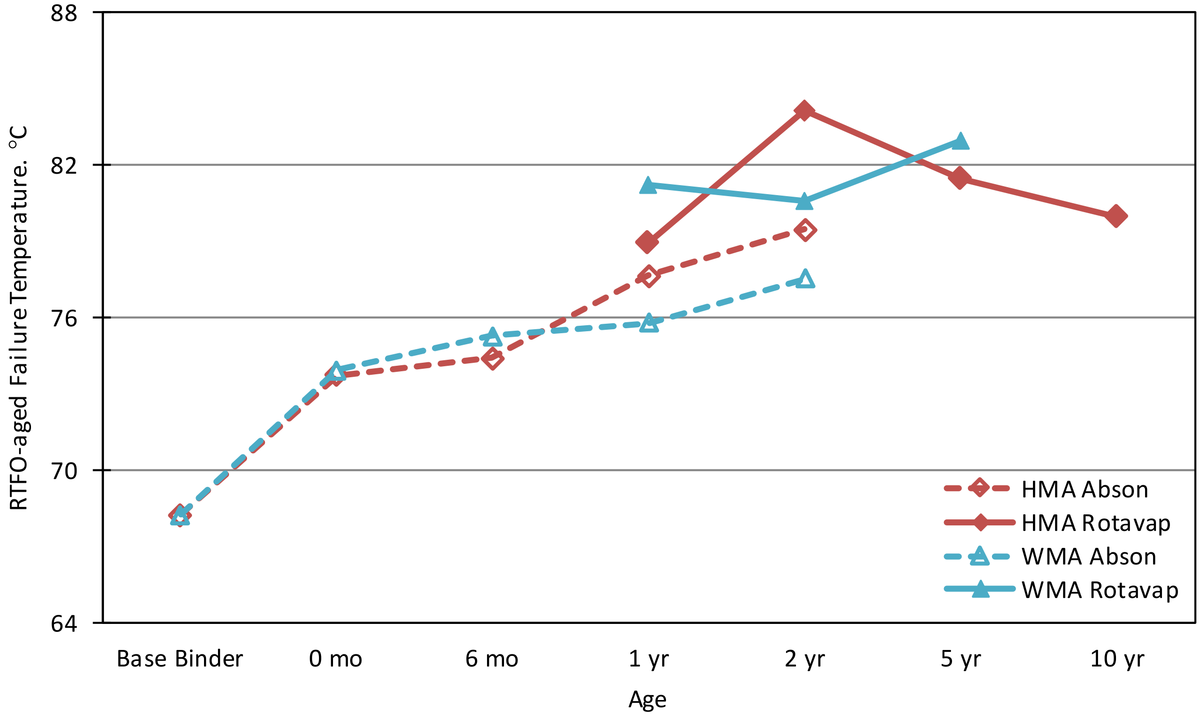


Figure 20. RTFO-aged Binder Failure Temperatures Over Time for Rt. 220. RTFO = rolling thin film oven; HMA = hot mix asphalt; WMA = warm mix asphalt.

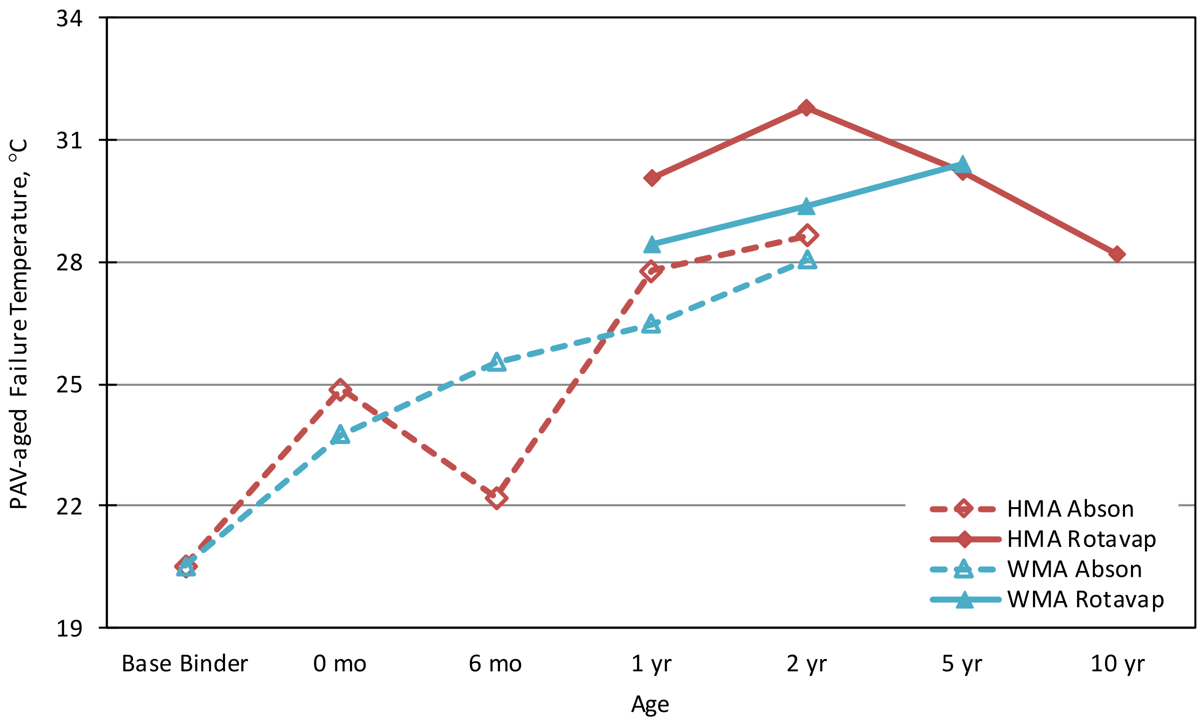


Figure 21. PAV-aged Binder Failure Temperatures Over Time for Rt. 220. PAV = pressure aging vessel; HMA = hot mix asphalt; WMA = warm mix asphalt.

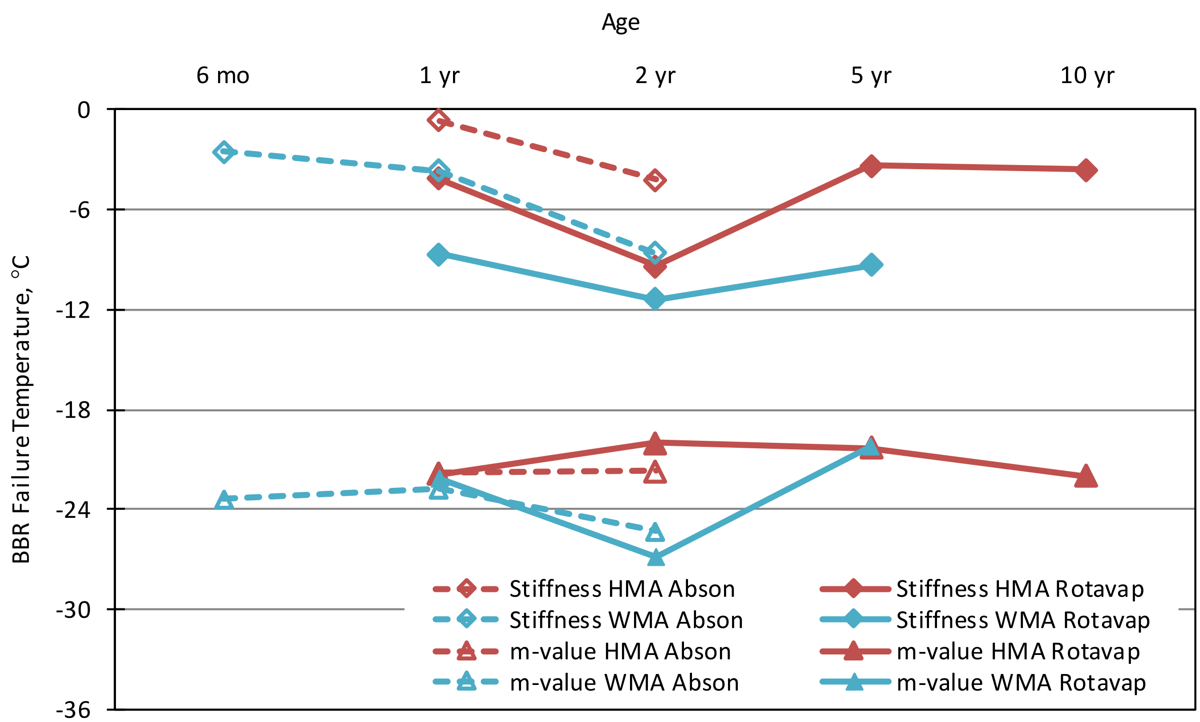


Figure 22. BBR Stiffness and m-Value Binder Failure Temperatures Over Time for Rt. 220. BBR = bending beam rheometer; HMA = hot mix asphalt; WMA = warm mix asphalt.

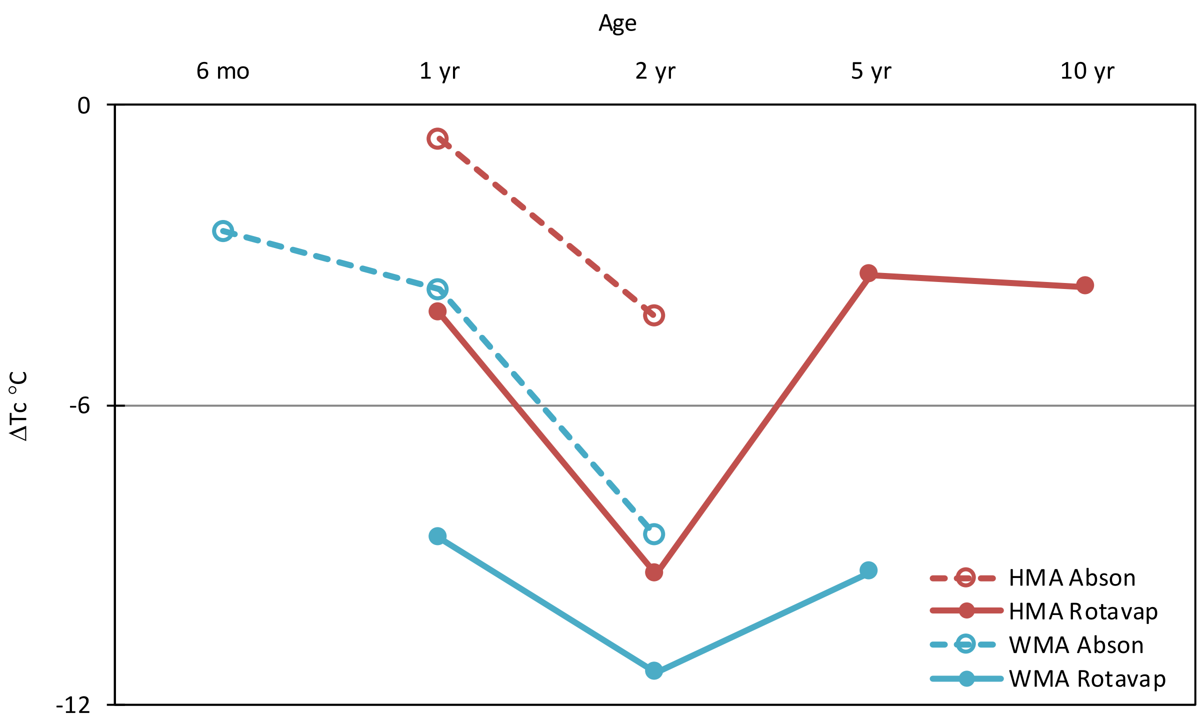


Figure 23. ΔT_c Over Time for Rt. 220. HMA = hot mix asphalt; WMA = warm mix asphalt.

Table 10. Binder Data for Rt. 143 HMA

Property	0 mo Abson	3 mo Abson	6 mo Abson	12 mo Rotavap	24 mo Abson	5 yr Rotavap	10 yr Rotavap
Dynamic Shear, 10 rad/sec, specification: G*/sin delta > 2.20 kPa							
RTFO G*/sin delta, 70ºC	5.209	4.782	4.724				
RTFO G*/sin delta, 76ºC	2.59	2.344	2.335	4.778	2.205	5.832	5.93
RTFO G*/sin delta, 82ºC		1.14		2.299	1.118	2.809	2.972
RTFO G*/sin delta, 88ºC				1.148		1.396	1.526
RTFO G*, 76ºC				4.698	2.187	5.737	5.792
RTFO G*, 82ºC				2.277	1.113	2.78	2.929
RTFO G*, 88ºC				1.142		1.389	1.513
RTFO phase angle, 76ºC				79.5	82.6	79.59	77.61
RTFO phase angle, 82ºC				81.99	84.5	82.03	80.27
RTFO phase angle, 88ºC				84.12		84.11	82.58
RTFO failure temperature, ºC	76.89	76.72	76.34	82.47	76.02	84.14	90.68
Dynamic Shear, 10 rad/sec, specification: G* sin delta < 5000 kPa							
PAV G* sin delta, 25.0ºC	5183	4100	4117	5418	4285		6616
PAV G* sin delta, 28.0ºC	3614	2866	2857	3927	3032	5197	4934
PAV G* sin delta, 31.0ºC	2493			2808		3776	
PAV G*, 25.0ºC				8.43E+06	6.23E+06		1.08E+07
PAV G*, 28.0ºC				5.82E+06	4.22E+06	7.53E+06	7.64E+06
PAV G*, 31.0ºC				3.98E+06		5.26E+06	
PAV phase angle, 25.0ºC				39.98	43.4		37.87
PAV phase angle, 28.0ºC				42.47	46	43.65	40.23
PAV phase angle, 31.0ºC				44.94		45.89	
PAV failure temperature, ºC	25.35	22.81	22.9	25.75	23.66	28.36	30.81
Creep Stiffness, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300							
Stiffness, -6ºC				110		148	187
M-value, -6ºC				0.333		0.327	0.308
Stiffness, -12ºC	240	198	198	218	202	294	316
M-value, -12ºC	0.327	0.313	0.319	0.289	0.302	0.278	0.261
Stiffness, -18ºC					406		
M-value, -18ºC					0.264		
ΔT_c, ºC	NA	NA	NA	-12.1	-2.6	-8.9	-10.2
Stiffness failure temperature, ºC	NA	NA	NA	-32.6	-24.9	-28.2	-27.3
M-value failure temperature, ºC	NA	NA	NA	-20.5	-22.3	-19.3	-17.0
PG Grade	76-22	76-22	76-22	82-16	76-22	82-16	82-16

HMA = hot mix asphalt; red text = Abson method of recovery was used; black text = Rotavap method of recovery was used; RTFO = rolling thin film oven; PAV = pressure aging vessel.

Table 11. Binder Data for Rt. 143 WMA

Property	0 mo Abson	3 mo Abson	6 mo Abson	12 mo Rotavap	24 mo Abson	24 mo Rotavap	10 yr Rotavap
Dynamic Shear, 10 rad/sec, specification: G*/sin delta > 2.20 kPa							
RTFO G*/sin delta, 70ºC		5.504	6.871				
RTFO G*/sin delta, 76ºC	2.683	2.687	3.363	4.819	2.874	3.674	5.905
RTFO G*/sin delta, 82ºC	1.395		1.704	2.395	1.468	1.807	2.991
RTFO G*/sin delta, 88ºC				1.231			1.526
RTFO G*, 76ºC				4.741	2.841	3.632	5.782
RTFO G*, 82ºC				2.372	1.459	1.795	2.952
RTFO G*, 88ºC				1.224			1.514
RTFO phase angle, 76ºC				79.73	81.4	81.39	78.31
RTFO phase angle, 82ºC				82.05	83.5	83.51	80.75
RTFO phase angle, 88ºC				84.04			82.96
RTFO failure temperature, ºC	78.25	77.04	80.21	82.84	78.39	80.34	90.74
Dynamic Shear, 10 rad/sec, specification: G* sin delta < 5000 kPa							
PAV G* sin delta, 25.0ºC	4204	4443	4918	6393	6295	6712	
PAV G* sin delta, 28.0ºC	2868	3088	3416	4592	4511	4805	5729
PAV G* sin delta, 31.0ºC				3258		3378	4234
PAV G*, 25.0ºC				9.67E+06	9.45E+06	1.02E+07	
PAV G*, 28.0ºC				6.63E+06	6.45E+06	6.93E+06	8.48E+06
PAV G*, 31.0ºC				4.51E+06		4.65E+06	6.03E+06
PAV phase angle, 25.0ºC				41.41	41.8	41.18	
PAV phase angle, 28.0ºC				43.87	44.8	43.9	42.49
PAV phase angle, 31.0ºC				46.3		46.62	44.56
PAV failure temperature, ºC	23.21	23.77	24.84	30.21	27.7	27.6	32.35
Creep Stiffness, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300							
Stiffness, -6ºC				151	129	131	207
M-value, -6ºC				0.322	0.332	0.335	0.307
Stiffness, -12ºC	271	224	279	284	277	270	407
M-value, -12ºC	0.316	0.317	0.308	0.277	0.29	0.293	0.265
Stiffness, -18ºC							
M-value, -18ºC							
ΔT_c, ºC	NA	NA	NA	-9.8	-8.4	-8.3	-7.8
Stiffness failure temperature, ºC	NA	NA	NA	-28.7	-28.9	-29.3	-24.8
M-value failure temperature, ºC	NA	NA	NA	-18.9	-20.6	-21.0	-17.0
PG Grade	76-22	76-22	76-22	82-16	76-16	76-16	82-16

WMA = warm mix asphalt; red text = Abson method of recovery was used; black text = Rotavap method of recovery was used; RTFO = rolling thin film oven; PAV = pressure aging vessel.

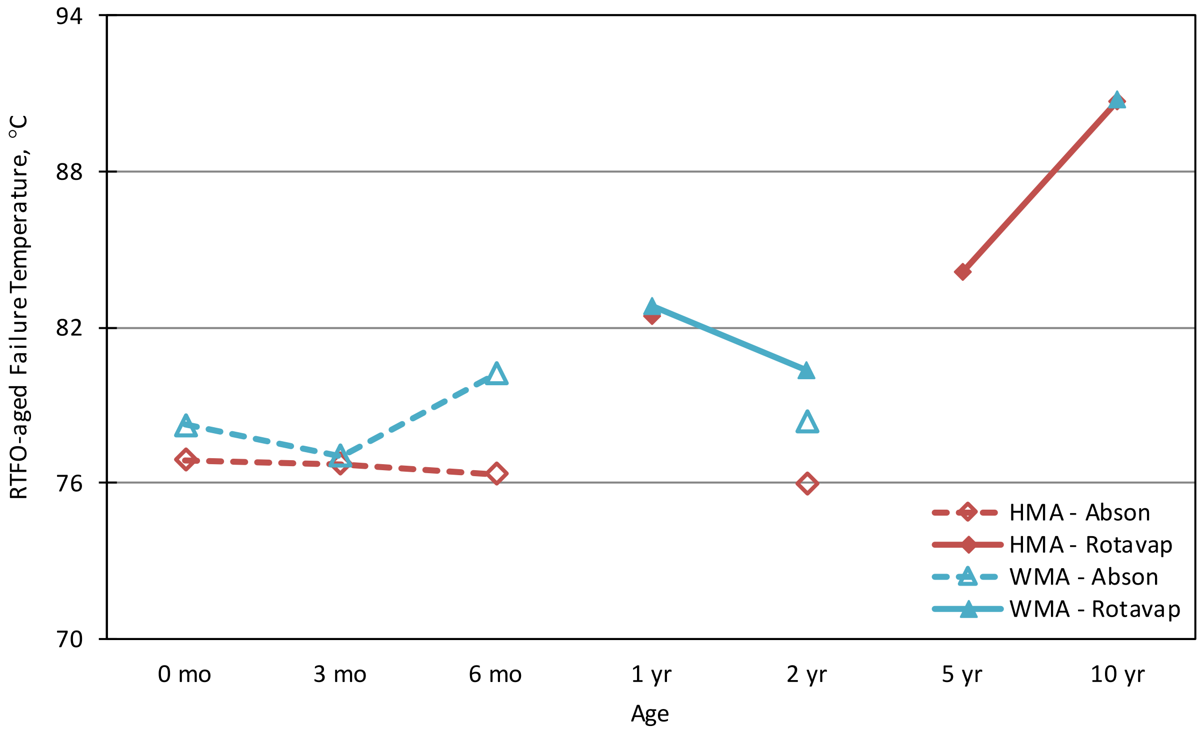


Figure 24. RTFO-aged Binder Failure Temperatures Over Time for Rt. 143. RTFO = rolling thin film oven; HMA = hot mix asphalt; WMA = warm mix asphalt.

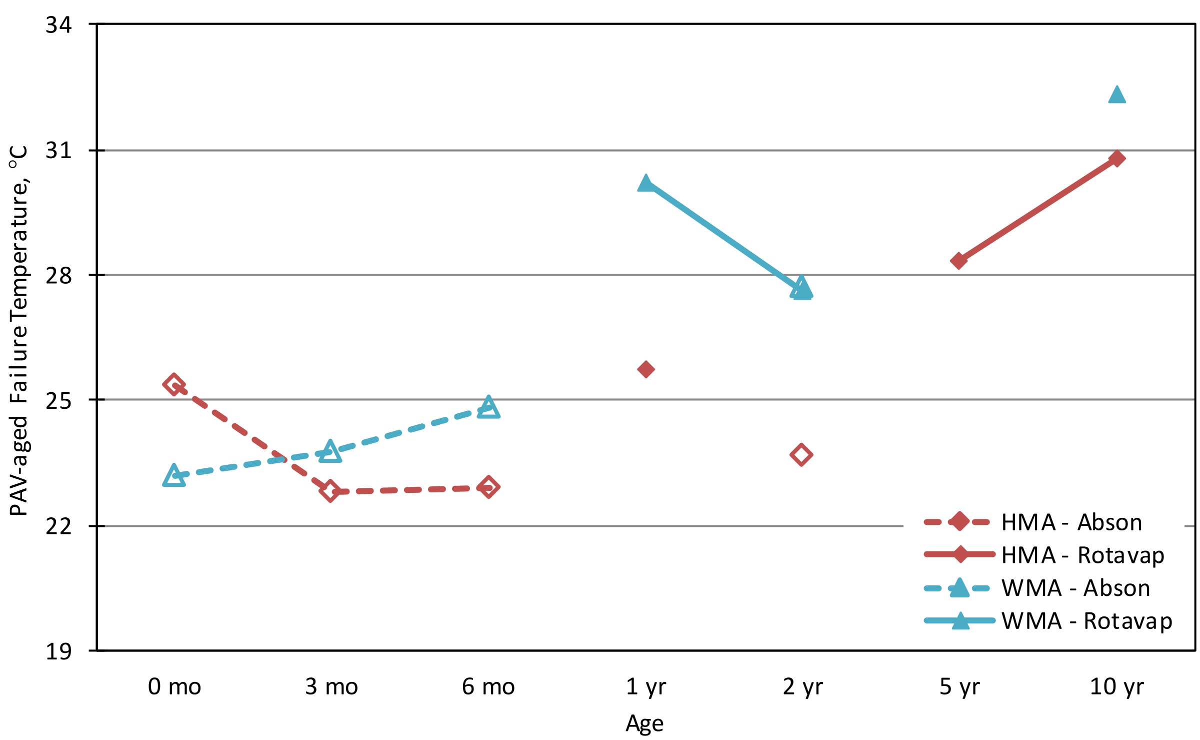


Figure 25. PAV-aged Binder Failure Temperatures Over Time for Rt. 143. PAV = pressure aging vessel; HMA = hot mix asphalt; WMA = warm mix asphalt.

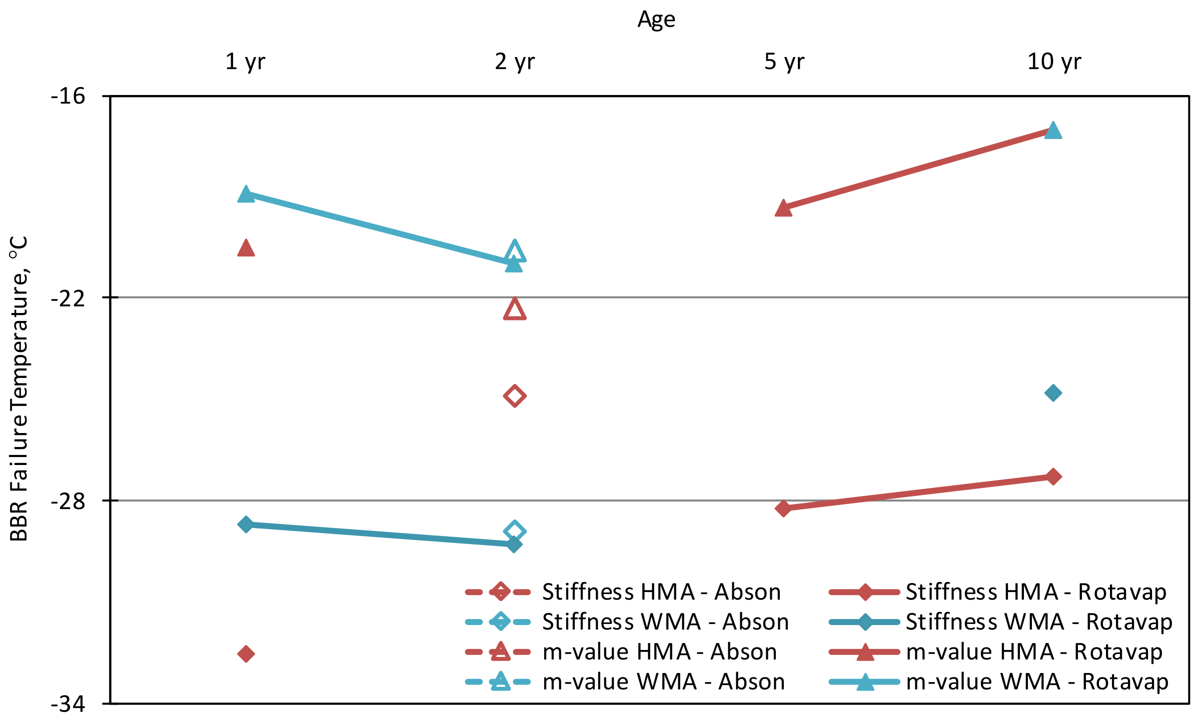


Figure 26. BBR Stiffness and m-Value Binder Failure Temperatures Over Time for Rt. 143. BBR = bending beam rheometer; HMA = hot mix asphalt; WMA = warm mix asphalt.

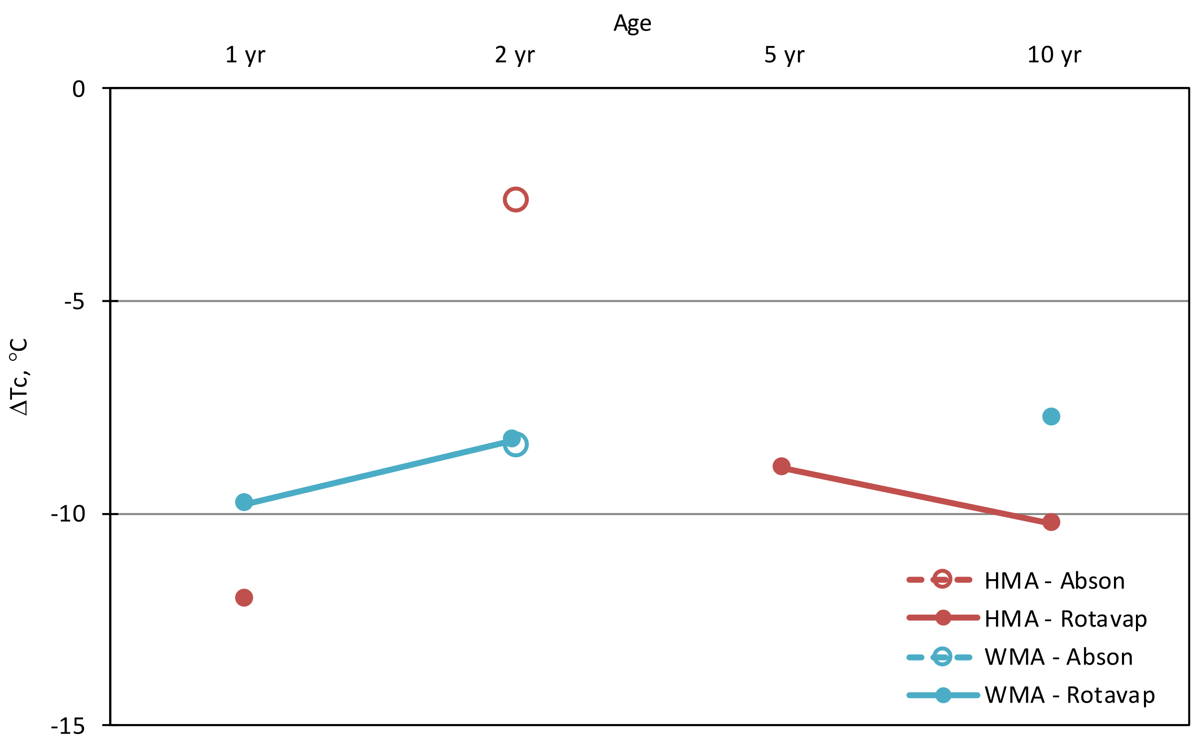


Figure 27. ΔT_c Over Time for Rt. 143. HMA = hot mix asphalt; WMA = warm mix asphalt.

Tables 12 and 13 summarize the PMS condition indices and distress data, respectively, for the Rt. 211 HMA and WMA sites. These data were obtained over a 0.5-mi distance based on milepost data in the PMS most closely approximating the physical location of the trial sites. The values shown for each section were averaged from five 0.1-mi segments. Figures 28 through 33 present graphical comparisons of indices and distresses over the 10-year performance period. It should be noted that the HMA and WMA sections were each 0.5-mi sections located along a continuous stretch of eastbound Rt. 211 and separated by approximately 0.47 mi. In general, this should result in very comparable sections, as the traffic application is uniform and the pavement substructure should also be uniform.

Figure 28 shows the CCI; fitted trend lines indicate that the CCI of the HMA section is decreasing more rapidly than that of the WMA section. Interestingly, Figure 29 indicates that the WMA international roughness index (IRI) is considerably higher than that of the HMA, with a 10-year average value of 81 in/mi, compared to a value of 65 in/mi for HMA. Figure 30 indicates that both sections had similar incidences of transverse cracking. Longitudinal cracking is shown in Figure 31, with a defined increase seen in Severity Level 1 cracking beginning at approximately 60,000 + CDD; this increase appears to level off for the HMA section after approximately 72,000 CDD but continues to increase for the WMA section throughout the remaining assessment period. Interestingly, this figure also shows a cyclic trend in the Severity Level 2 longitudinal cracking wherein the cracking seems to increase and decrease. Fatigue cracking, expressed in the PMS data as alligator cracking, is shown in Figure 32 to follow similar trends for the HMA and WMA sections. Rutting is also shown to be similar for both sections in Figure 33.

Tables 14 and 15 summarize the PMS condition indices and distress data, respectively, for the Rt. 143 HMA and WMA sites. These data were obtained over a 0.4-mi distance based on milepost data in the PMS most closely approximating the physical location of the trial sites. The values shown for each section were averaged from four 0.1-mi segments. Figures 28 through 33 present graphical comparisons of indices and distresses over the 10-year performance period. It should be noted that the HMA and WMA sections were located in the travel lanes in different directions on Rt. 143, a divided four-lane highway. Although this arrangement is not ideal, the locations were found to have a similar traffic application and uniform pavement structure.

Figure 34 shows the CCI, the load related distress index (LDR), and non-load related distress index (NDR); fitted trend lines indicate that the HMA has a greater rate of reduction in the CCI than the WMA, although initially, the HMA CCI was reported as higher. CCI ratings for both the HMA and WMA sections are primarily due to the NDR, which is determined from distresses such as transverse and longitudinal cracking, among others, considered to be primarily non-load related and caused by climatic factors or material and/or construction deficiencies (VDOT, 2016). In this case, the contributing factor is transverse cracking.

Figure 35 shows that the IRI trend for the WMA section was much higher post-construction than that of the HMA; however, the WMA IRI did not change much over the 10-year period, whereas the HMA IRI steadily increased.

Table 12. Average Condition Index Values for Rt. 211 HMA and WMA Sections Over a 0.5-mi Distance

PMS Year		**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Date Survey Conducted		**8/11/06[a]**	**2/20/07**	**2/11/08**	**4/24/09**	**3/25/10**	**12/3/10**	**3/23/12**	**11/30/12**	**4/20/14**	**10/6/14**	**12/8/16**
Cumulative Degree Days[b]		**0**	**5083**	**17828**	**30764**	**41119**	**52023**	**66205**	**76227**	**88636**	**94829**	**117773**
CCI	HMA	-[c]	98.8	95.6	69.6	85.4	71.8	56.2	48.6	27.8	29.8	35.6
	WMA	-	98	82.2	82.2	92.6	71.6	75.2	51.2	54	42.6	40.8
LDR	HMA	-	98.8	95.6	69.6	92.6	71.8	56.2	48.6	27.8	29.8	35.6
	WMA	-	98	82.2	82.6	100	71.6	78	51.2	55.6	42.6	40.8
NDR	HMA	-	100	99.8	89.8	85.4	94.2	81.4	70.2	69.2	83.2	78.2
	WMA	-	99.2	98	94.8	92.6	95	87	76.2	68.6	75.4	78.8
Average IRI	HMA	-	56	54.4	58	61.2	60	63.6	63.4	63.6	65.4	65
	WMA	-	76.2	76.6	78.6	72.6	74.2	78.6	77.6	87.6	82	81.6
IRI Right WP	HMA	-	61.2	59.2	61.6	67.6	67.2	70	70.2	68.8	72.6	71.8
	WMA	-	85.6	84.8	86.6	79.8	81	87	87.4	99.8	94.2	89.6
IRI Left WP	HMA	-	50.4	49.2	53.6	54.6	53.2	57	56.4	57.8	57.8	57.8
	WMA	-	66.2	67.8	70	64.6	66.6	69.6	67.4	75	69.4	73

Condition index data were collected in 0.1-mi increments. Five increments each were averaged for the HMA and WMA sections.
HMA = hot mix asphalt; WMA = warm mix asphalt; PMS = Pavement Management System; CCI = critical condition index; LDR = load related distress index; NDR = non-load related distress index; IRI = international roughness index; WP = wheelpath.
[a] Date of construction
[b] Determined from 0ºC (32ºF) base.
[c] As condition surveys were not performed immediately after construction, measured condition indices were not available.

Table 13. Distress Values for Rt. 211 HMA and WMA Sections Over a 0.5- mi Distance

PMS Year		**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Date Survey Conducted		**8/11/06[a]**	**2/20/07**	**2/11/08**	**4/24/09**	**3/25/10**	**12/3/10**	**3/23/12**	**11/30/12**	**4/20/14**	**10/6/14**	**12/8/16**
Cumulative Degree Days[b]		**0**	**5083**	**17828**	**30764**	**41119**	**52023**	**66205**	**76227**	**88636**	**94829**	**117773**
Transverse Cracking, Severity 1, ft	HMA	0[c]	0	5	43	244	124	617	720	3169	1047	3511
	WMA	0	2	41	66	132	163	613	772	2601	885	3236
Transverse Cracking, Severity 2, ft	HMA	0	0	0	8	16	4	57	120	113	13	34
	WMA	0	0	2	2	9	10	41	125	136	13	19
Longitudinal Cracking, Severity 1, ft	HMA	0	0	6	98	143	65	2	148	155	138	122
	WMA	0	15	12	13	76	32	6	109	212	265	431
Longitudinal Cracking Severity 2, ft	HMA	0	0	0	124	116	29	71	215	100	26	0
	WMA	0	0	11	55	48	10	30	87	142	189	0
Longitudinal Joint Severity 1, ft	HMA	0	0	0	0	0	0	0	0	0	0	0
	WMA	0	0	0	0	0	0	0	0	119	0	28
Alligator Cracking: Severity 1, sq ft	HMA	0	112	352	2351	1109	2237	803	2266	3352	6996	3612
	WMA	0	71	1631	2508	1403	2617	982	2529	3475	5364	2607
Alligator Cracking: Severity 2, sq ft	HMA	0	0	45	2017	2645	471	2953	2455	3868	1640	2433
	WMA	0	0	206	880	764	362	1213	1958	1356	1207	2564
Alligator Cracking: Severity 3, sq ft	HMA	0	0	0	56	22	0	31	5	0	44	0
	WMA	0	0	3	43	1	0	11	5	0	34	0
Patching Area: Wheelpath, sq ft	HMA	0	0	0	0	0	1	1	1	0	0	0
	WMA	0	140	0	0	0	0	0	0	0	0	0
Patching Area: Non-wheelpath, sq ft	HMA	0	0	0	0	0	1	2	2	0	0	0
	WMA	0	57	0	0	0	0	0	0	0	0	0
Rutting, in	HMA	0	0.040	0.076	0.08	0.078	0.086	0.094	0.092	0.102	0.092	0.096
	WMA	0	0.040	0.076	0.062	0.078	0.072	0.086	0.070	0.084	0.090	0.086

Zero distress was assumed to be present at construction. Condition index data were collected in 0.1-mi increments. Five increments were averaged each for the HMA and WMA sections.

HMA = hot mix asphalt; WMA = warm mix asphalt; PMS = Pavement Management System.

[a] Date of construction.

[b] Determined from 0ºC (32ºF) base.

[c] Condition surveys were not performed immediately after construction; however, it can be assumed that immediately post-construction no distresses were present.

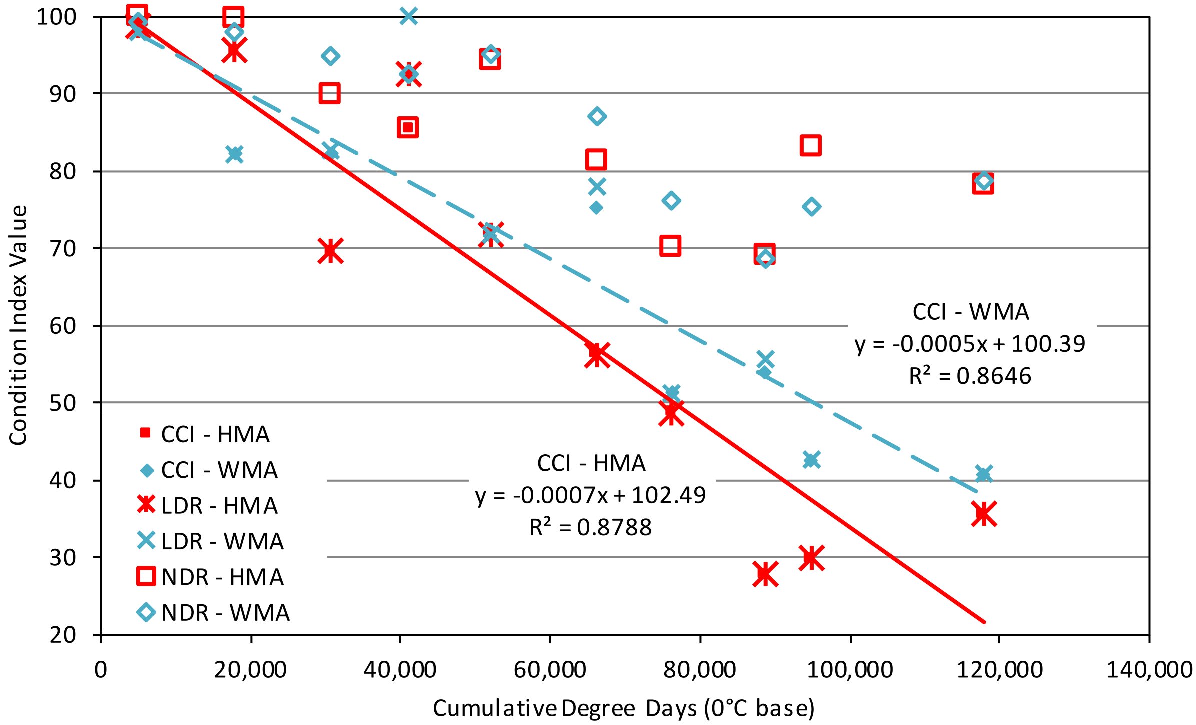


Figure 28. Condition Indices vs. Cumulative Degree Days for Rt. 211 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt; CCI = critical condition index; LDR = load-related distress index; NDR = non-load-related distress index.

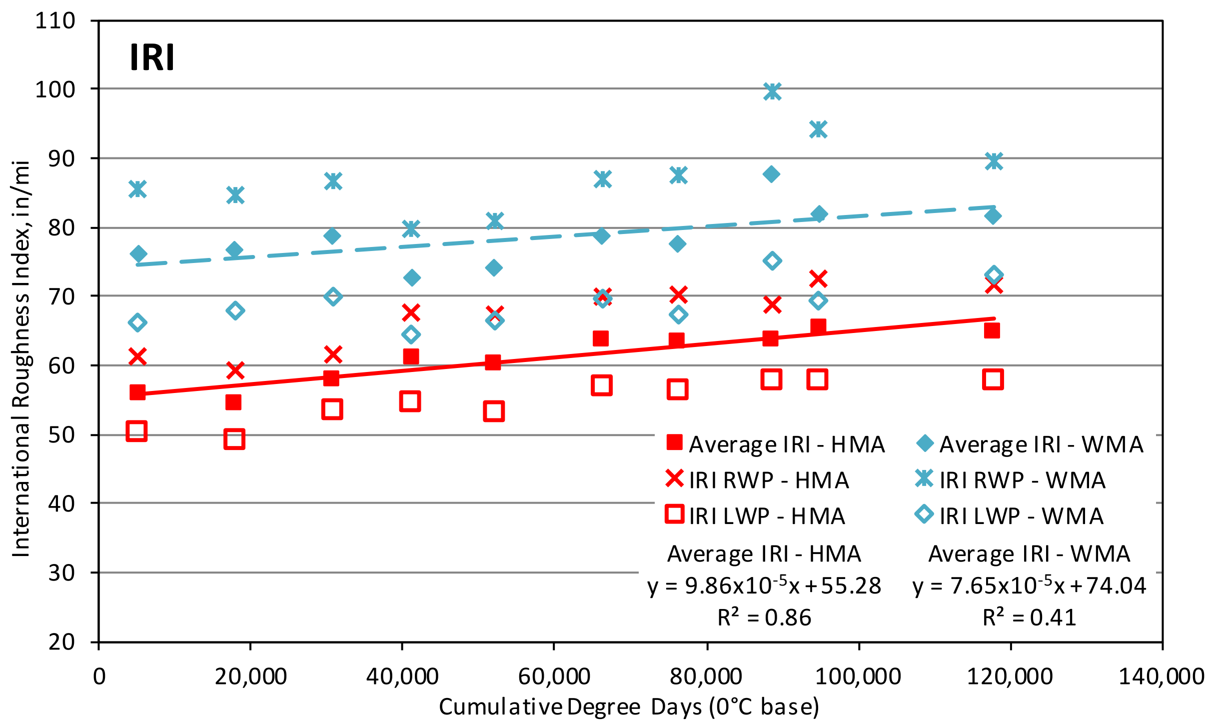


Figure 29. International Roughness Index vs. Cumulative Degree Days for Rt. 211 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt; RWP = right wheelpath; LWP = left wheelpath.

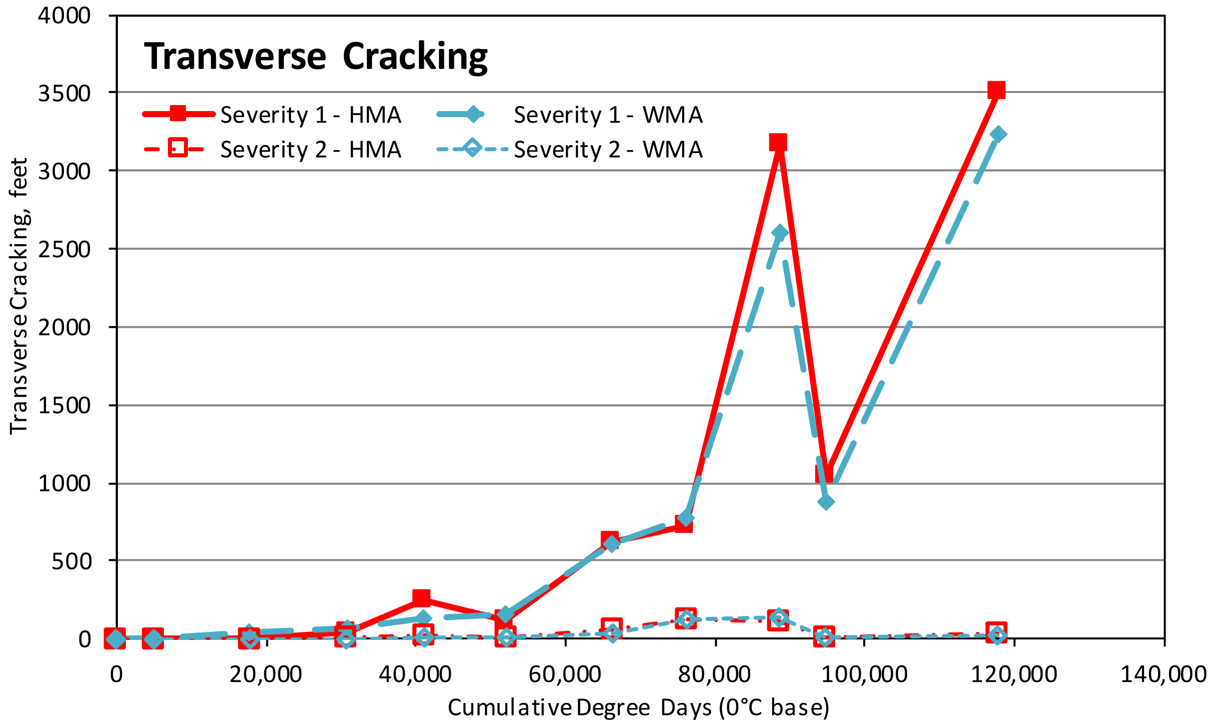


Figure 30. Transverse Cracking vs. Cumulative Degree Days for Rt. 211 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt.

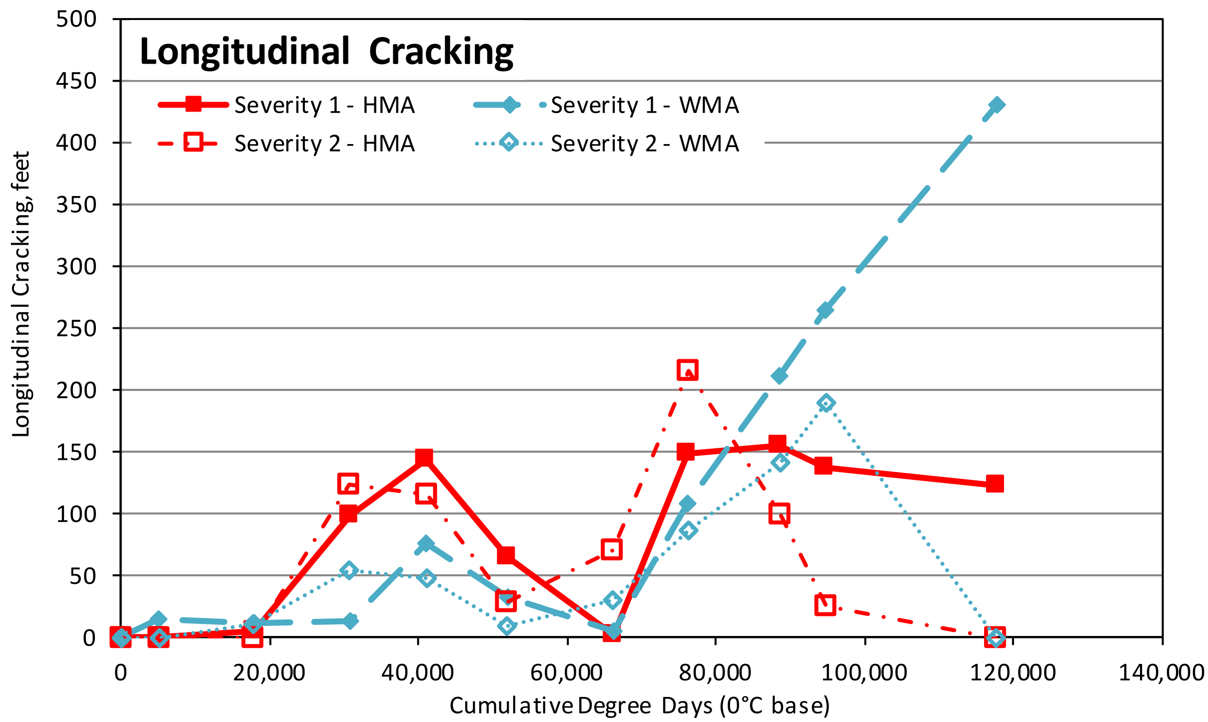


Figure 31. Longitudinal Cracking vs. Cumulative Degree Days for Rt. 211 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt.

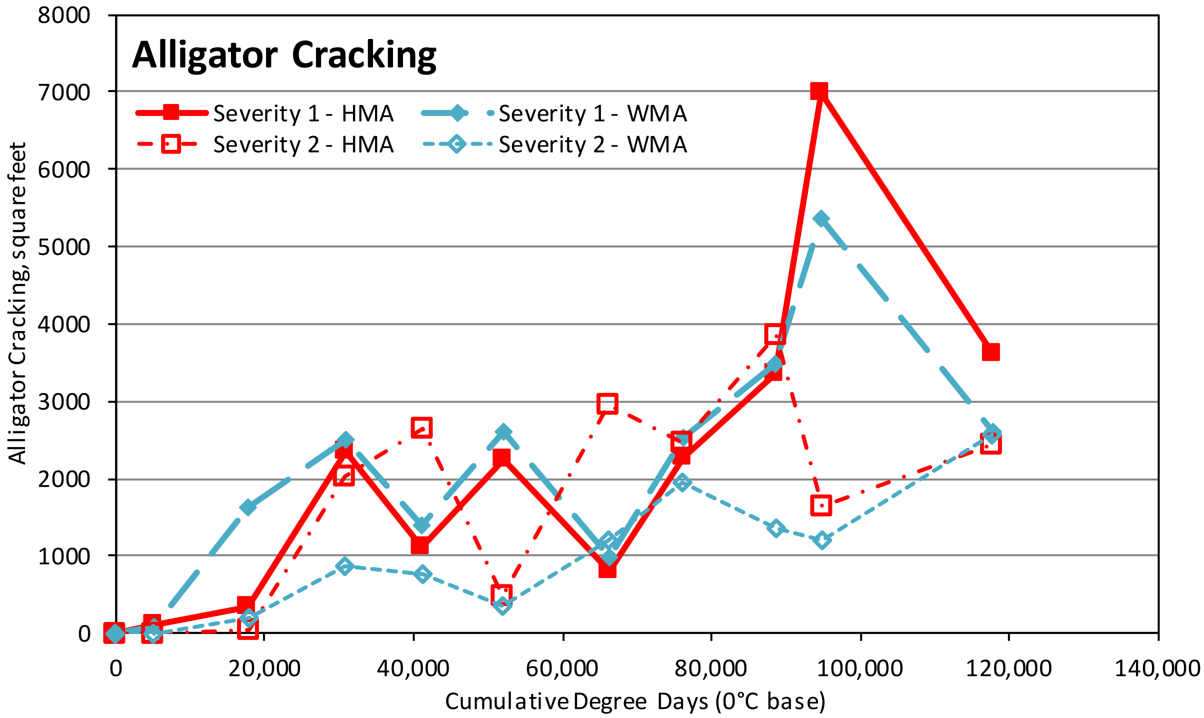


Figure 32. Alligator Fatigue Cracking vs. Cumulative Degree Days for Rt. 211 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt.

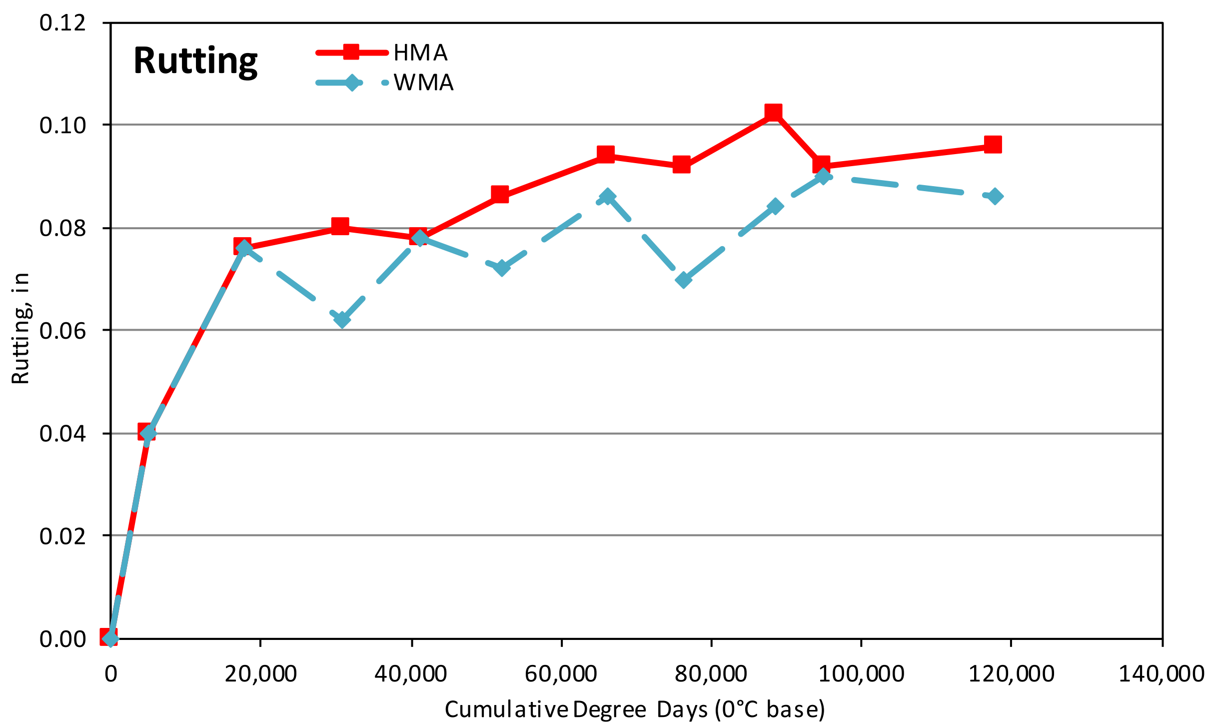


Figure 33. Rutting vs. Cumulative Degree Days for Rt. 211 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt.

Table 14. Average Condition Index Values for Rt. 143 HMA and WMA Sections Over a 0.4-mi Distance

PMS Year		**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Date Survey Conducted		**11/2/06**[a]	**2/8/07**	**1/23/08**	**1/20/09**	**1/20/10**	**11/22/10**	**1/20/12**	**2/18/13**	**12/13/13**	**11/22/14**	**1/7/16**
Cumulative Degree Days[b]		**0**	**2360**	**15777**	**29515**	**43113**	**55599**	**70440**	**85367**	**97346**	**110197**	**124882**
CCI	HMA	-[c]	100	92.5	97	84.25	80.5	78	42.75	45	43.75	56.25
	WMA	-	94.75	98.25	97.25	72.75	83.5	72.5	70.25	68	45.75	55.25
LDR	HMA	-	100	99.25	99.25	97.25	96.75	96.5	94.5	94.75	90.75	91
	WMA	-	94.75	98.75	98.25	93.25	95.25	89.25	85.5	92.75	91.5	90
NDR	HMA	-	100	92.5	97	84.25	80.5	77.75	42.75	45	43.75	56.25
	WMA	-	100	99	98	72.75	83.5	74.75	73	68	45.75	55.25
Average IRI	HMA	-	91.67	90.5	86.25	94.75	101.5	103.5	104.25	112.5	115.75	116
	WMA	-	108.25	124	128	125.75	120	123.5	131.25	124	130.25	120.75
IRI Right WP	HMA	-	93.67	87.25	89.25	98	102.5	103.75	104.75	114	117.75	116.25
	WMA	-	102	119.5	129.5	122.5	116.75	120.25	127.75	123	127.25	120.75
IRI Left WP	HMA	-	89.33	93.5	82.75	90.75	100	102.25	103.25	110.5	112.75	115.25
	WMA	-	115	128	126.25	128.25	123	126	134.25	124.5	132.75	120.5

Condition index data were collected in 0.1-mi increments. Five increments each were averaged for the HMA and WMA sections.
HMA = hot mix asphalt; WMA = warm mix asphalt; PMS = Pavement Management System; CCI = critical condition index; LDR = load related distress index; NDR = non-load related distress index; IRI = international roughness index; WP = wheelpath.
[a] Date of construction.
[b] Determined from 0ºC (32ºF) base.
[c] As condition surveys were not performed after construction, measured condition indices were not available.

Table 15. Distress Values for Rt. 143 HMA and WMA Sections Over a 0.4-mi Distance

PMS Year		**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Date Survey Conducted		**11/2/06[a]**	**2/8/07**	**1/23/08**	**1/20/09**	**1/20/10**	**11/22/10**	**1/20/12**	**2/18/13**	**12/13/13**	**11/22/14**	**1/7/16**
Cumulative Degree Days[b]		**0**	**2360**	**15777**	**29515**	**43113**	**55599**	**70440**	**85367**	**97346**	**110197**	**124882**
Transverse Cracking, Severity 1, ft	HMA	0[c]	0	3	35	231	255	270	34	77	33	455
	WMA	0	0	9	18	126	177	226	303	326	33	470
Transverse Cracking, Severity 2, ft	HMA	0	0	15	0	21	63	102	962	1121	1001	30
	WMA	0	0	0	0	248	45	155	14	270	640	0
Longitudinal Cracking, Severity 1, ft	HMA	0	0	4	0	1	1	11	14	51	29	75
	WMA	0	0	0	0	13	0	4	2	5	8	0
Longitudinal Cracking, Severity 2, ft	HMA	0	0	84	0	0	3	1	26	0	2	0
	WMA	0	0	0	0	0	0	0	0	0	2	0
Longitudinal Joint, Severity 1, ft	HMA	0	0	0	0	0	24	0	17	38	1376	0
	WMA	0	0	0	0	35	172	345	196	0	508	539
Longitudinal Joint, Severity 2, ft	HMA	0	0	0	0	0	0	0	0	0	0	0
	WMA	0	0	0	0	0	0	0	30	0	0	0
Alligator Cracking, Severity 1, sq ft	HMA	0	0	4	47	169	217	225	123	293	524	370
	WMA	0	462	29	11	160	42	218	193	286	321	257
Alligator Cracking, Severity 2, sq ft	HMA	0	0	31	5	28	7	34	186	48	11	156
	WMA	0	0	0	0	107	5	139	549	54	24	174
Alligator Cracking, Severity 3, sq ft	HMA	0	0	0	0	0	0	0	0	0	0	0
	WMA	0	0	0	2	0	0	0	0	0	0	0
Patching Area: Wheelpath, sq ft	HMA	0	0	0	0	0	0	5	0	15	0	24
	WMA	0	0	0	0	0	0	0	0	0	0	0
Patching Area: Non-wheelpath, sq ft	HMA	0	0	0	0	0	0	2	1026	19	0	17
	WMA	0	0	0	0	0	0	0	896	0	769	3
Delamination Area, sq ft	HMA	0	0	6	0	0	0	0	2	0	0	0
	WMA	0	0	0	0	0	0	0	0	0	0	0
Rutting, in	HMA	0	0.063	0.055	0.058	0.068	0.080	0.075	0.095	0.088	0.125	0.110
	WMA	0	0.085	0.100	0.118	0.118	0.148	0.148	0.125	0.125	0.135	0.135

Zero distress is assumed to be present at construction. Distress data were collected in 0.1-mi increments and summed over 0.4 mi.
HMA = hot mix asphalt; WMA = warm mix asphalt; PMS = Pavement Management System.
[a] Date of construction.
[b] Determined from 0ºC (32ºF) base.
[c] Condition surveys were not performed after construction; however, it can be assumed that immediately post-construction no distresses were present.

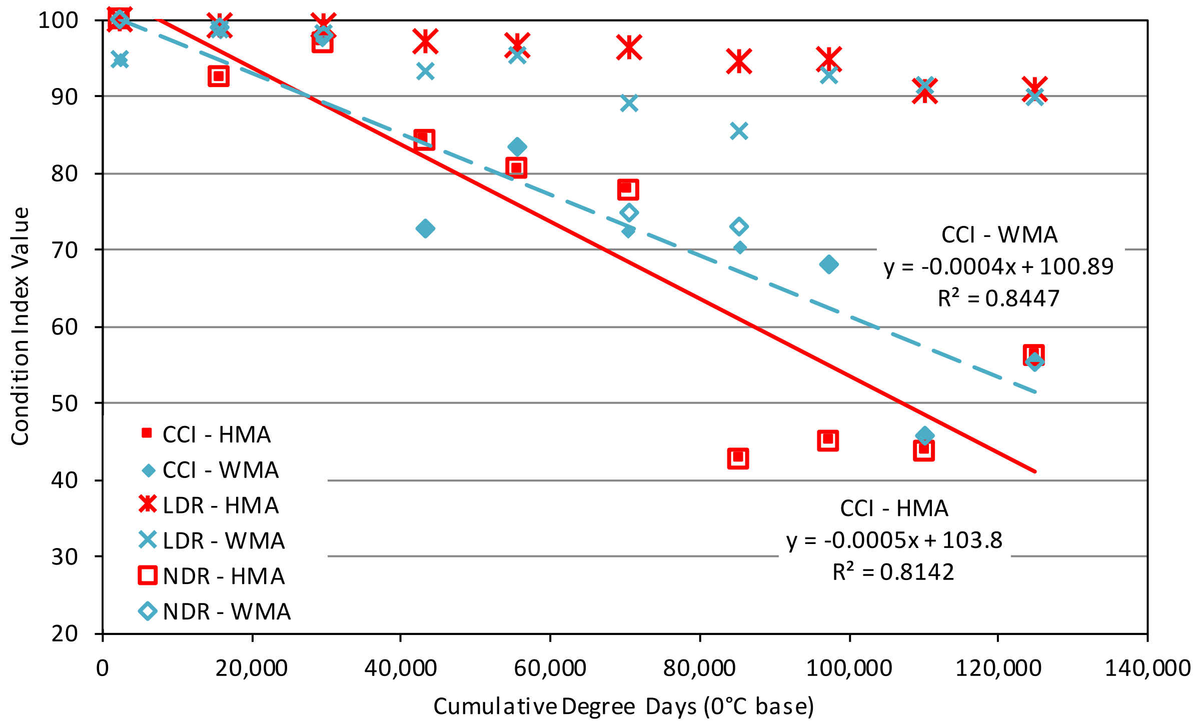


Figure 34. Condition Indices vs. Cumulative Degree Days for Rt. 143 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt; CCI = critical condition index; LDR = load related distress index; NDR = non-load related distress index.

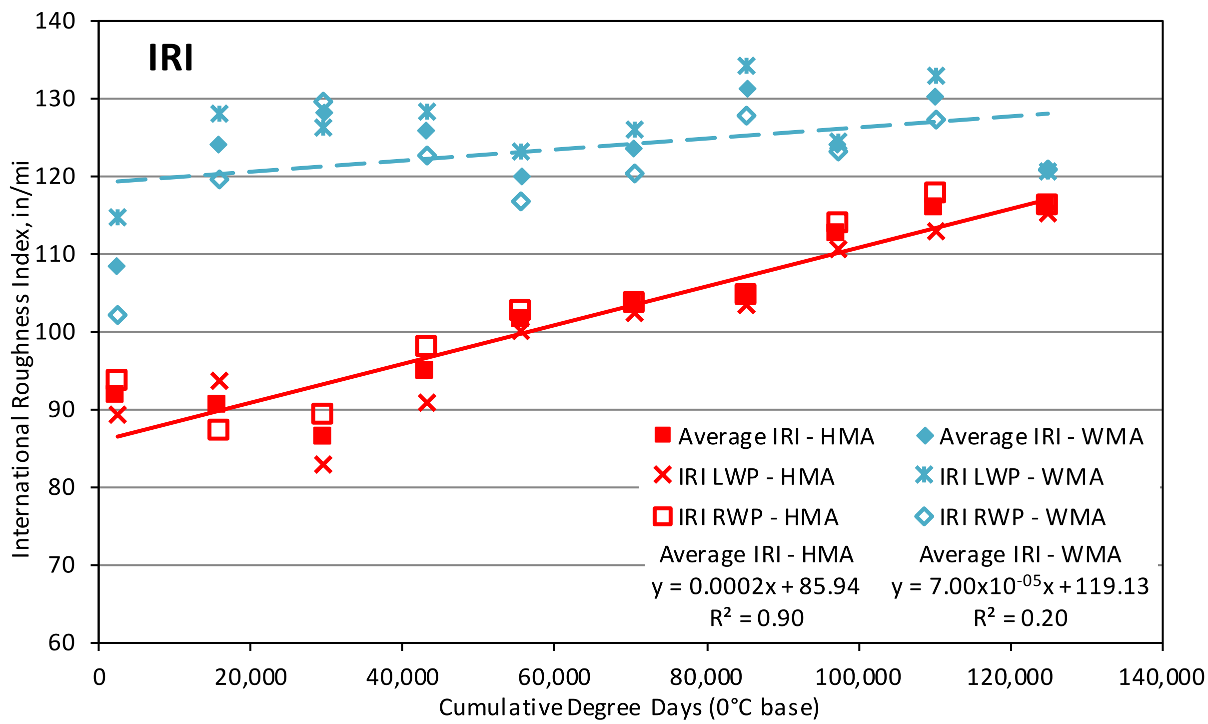


Figure 35. International Roughness Index vs. Cumulative Degree Days for Rt. 143 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt; LWP = left wheelpath; RWP = right wheelpath.

The transverse cracking that contributed to the dominating NDR rating is shown in Figure 36. The measured cracking begins to increase after approximately the first 2 years, at approximately 30,000 cumulative degree days. Figure 37 shows the incidence of longitudinal cracking, which is less for the WMA. Fatigue, or alligator, cracking is shown in Figure 38. Similar to the transverse cracking, fatigue cracking is shown to begin generally around the second year with the exception of the unusual data point at the first pavement survey for the WMA Severity 1 cracking, which disappears at subsequent inspections. Observances of patching and delamination are shown in Figure 39. These data are questionable, as it appears unlikely that patches or delaminated areas that are present at one inspection are no longer present at subsequent surveys. Figure 40 presents the observed rutting in each section. The WMA section is shown to have a slightly greater depth of rutting than the HMA section.

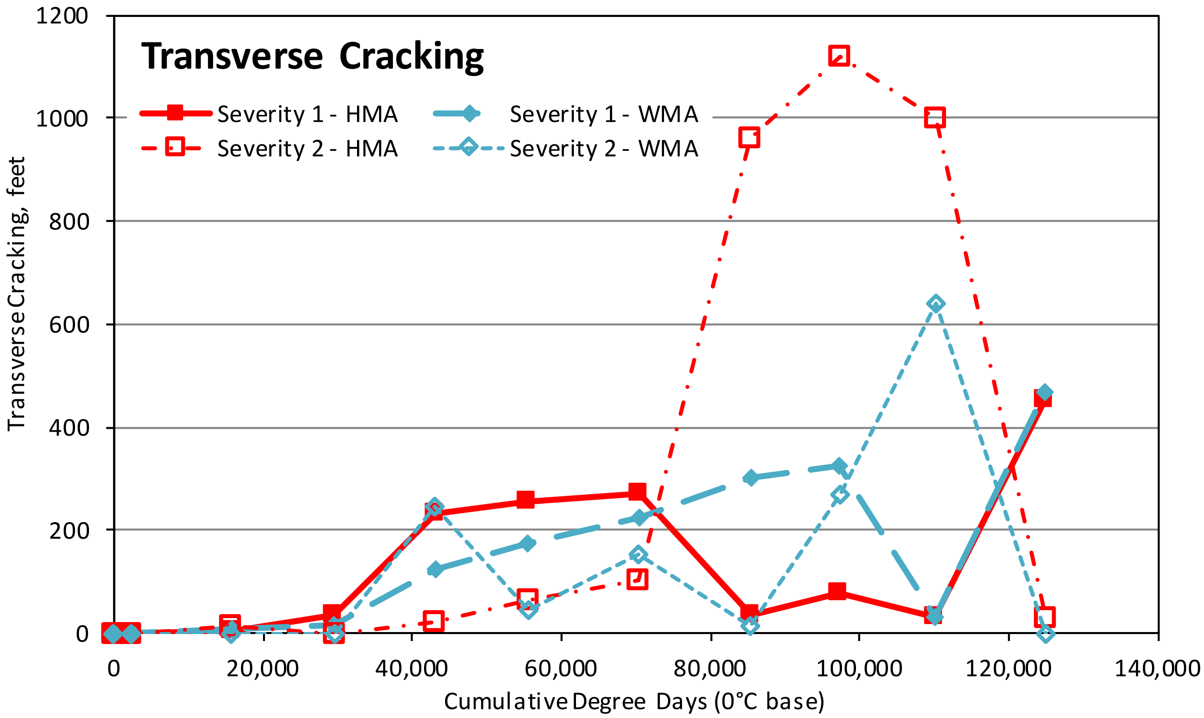


Figure 36. Transverse Cracking vs. Cumulative Degree Days for Rt. 143 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt.

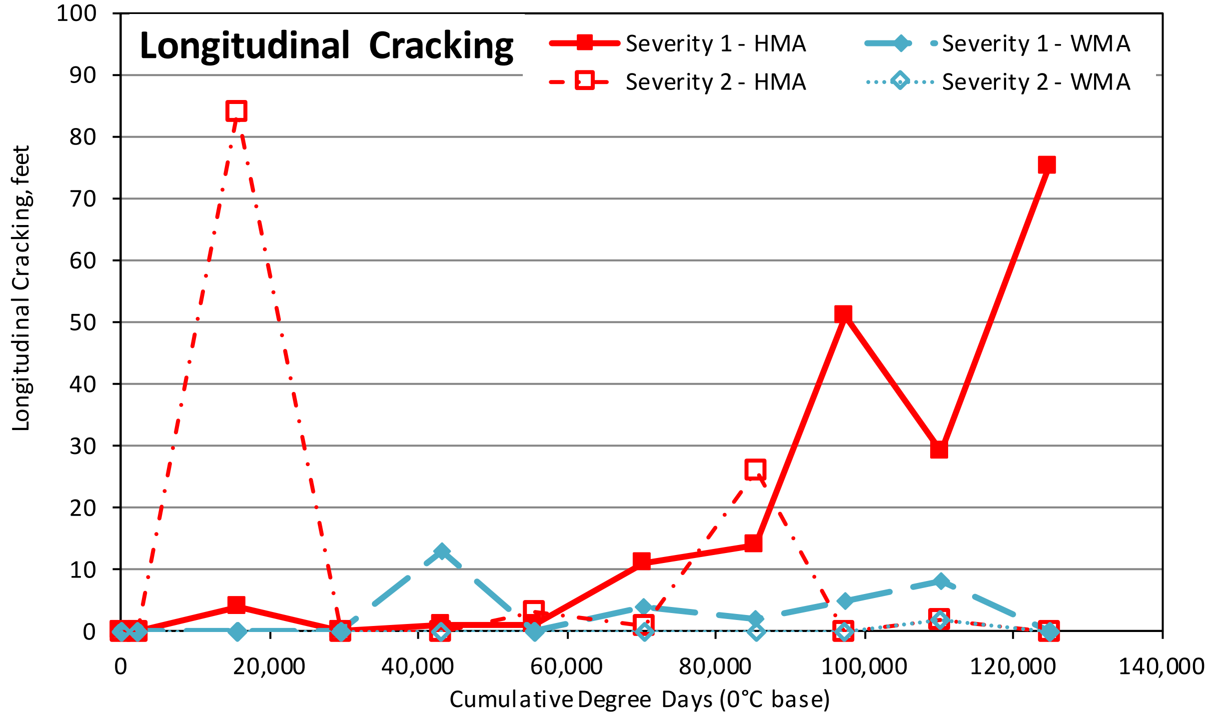


Figure 37. Longitudinal Cracking vs. Cumulative Degree Days for Rt. 143 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt.

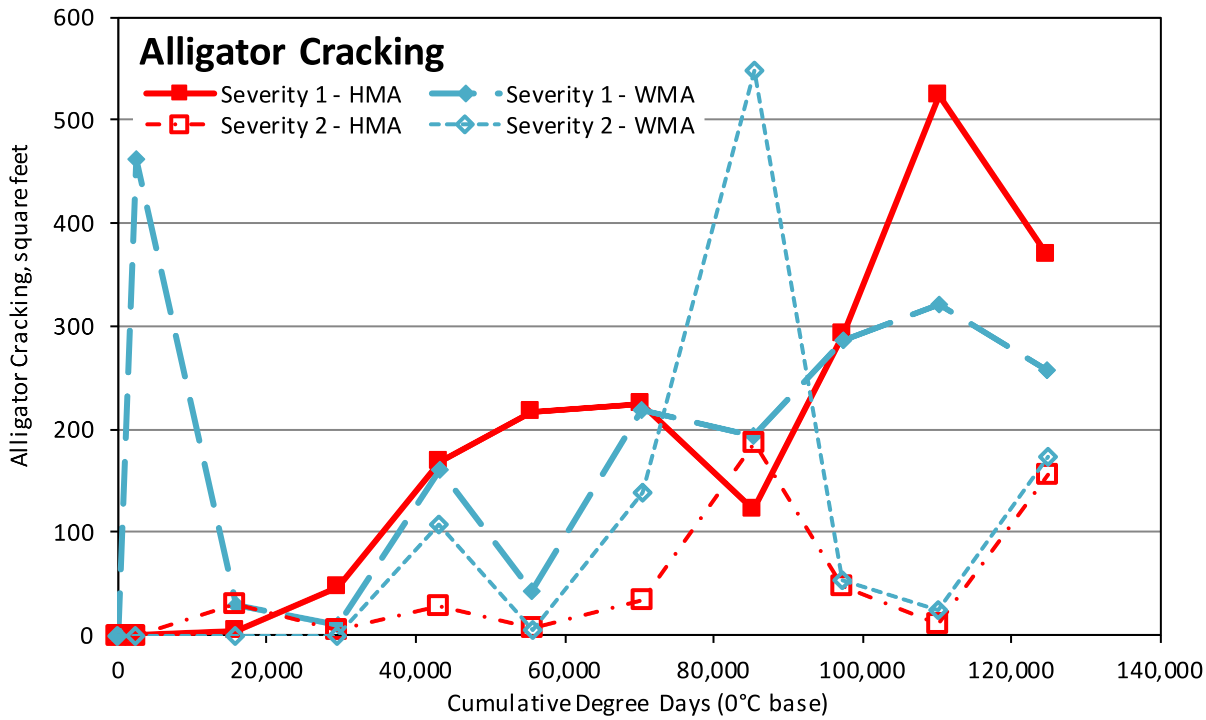


Figure 38. Alligator Fatigue Cracking vs. Cumulative Degree Days for Rt. 143 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt.

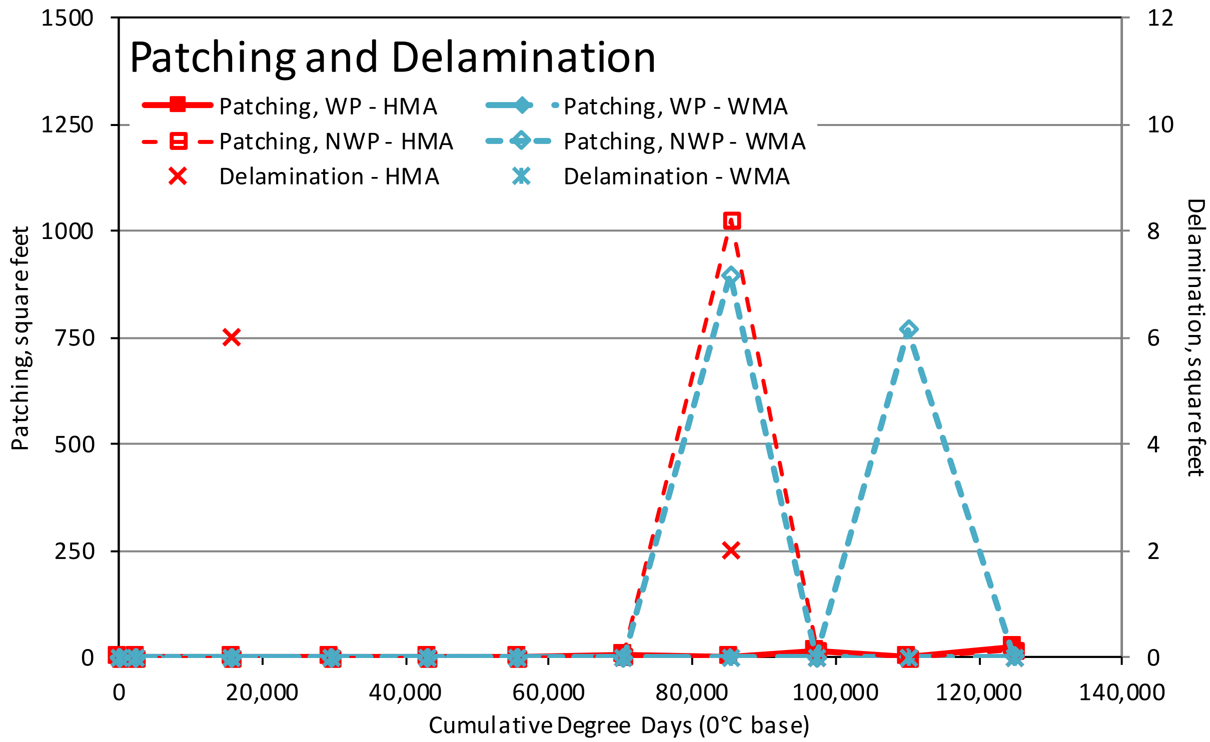


Figure 39. Patching and Delamination vs. Cumulative Degree Days for Rt. 143 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt; WP = wheelpath; NWP = non-wheelpath.

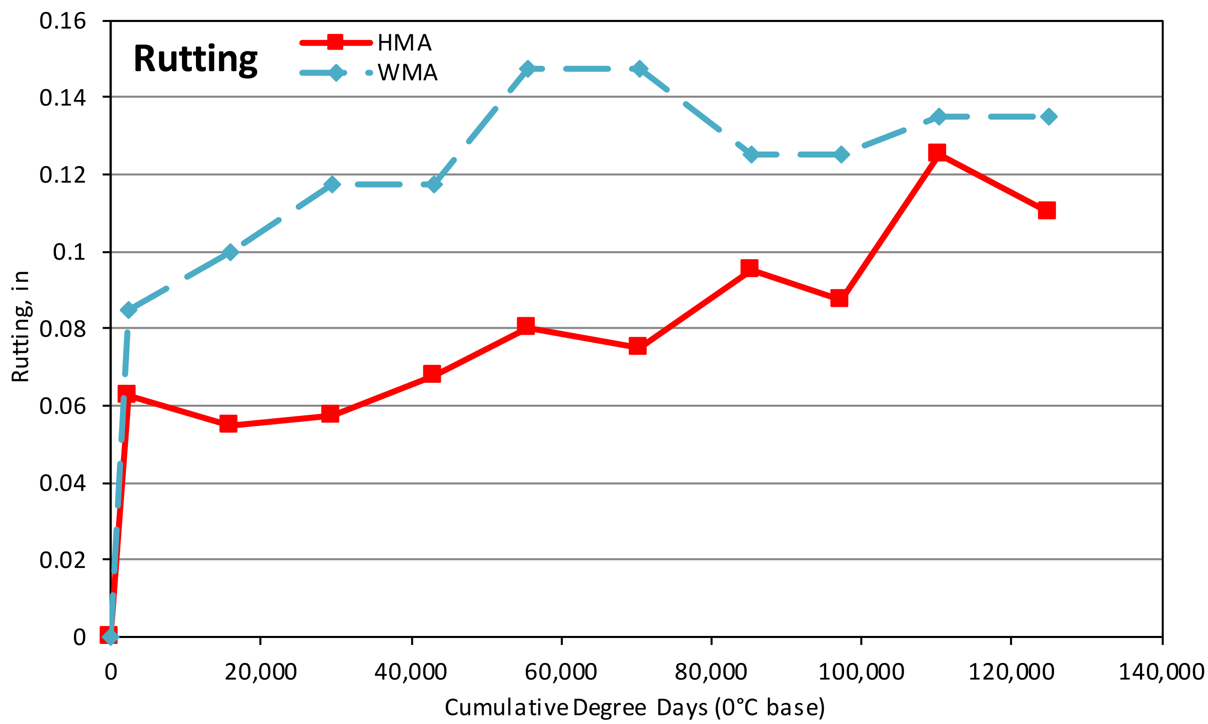


Figure 40. Rutting vs. Cumulative Degree Days for Rt. 143 HMA and WMA. HMA = hot mix asphalt; WMA = warm mix asphalt.

Performance Testing Correlation With PMS Data

Results of the overlay and FI performance tests were compared with the PMS data collected at an age of 10 years. The values compared are shown in Table 16. Analyses were performed to determine the correlation coefficient between each performance test and each of the measured distress parameters; results are shown in Table 17 and are quite interesting. For this very limited dataset, the overlay test and FI results are shown to have a moderate negative correlation, such that as one increases, the other decreases; this is contrary to common logic, as both test results should increase in tandem, as mixtures tend to perform increasingly well in either test.

Table 16. Average Performance Test Results for 10-year Cores and Pavement Distress Data at 10 years in Service

Data	Rt. 211 HMA	Rt. 211 WMA	Rt. 143 HMA	Rt. 143 WMA
OT	19.5	21.2	63.25	22.25
FI	1.08	0.97	0.78	0.80
CCI	35.6	40.8	56.25	55.25
LDR	35.6	40.8	91	90
NDR	78.2	78.8	56.25	55.25
Average IRI, in/mi	65	81.6	116	120.75
Transverse Cracking, Severity 1, ft	3511	3236	454.75	470.25
Transverse Cracking, Severity 2, ft	34	19	30	0
Longitudinal Cracking, Severity 1, ft	122	431	75	0
Longitudinal Joint, Severity 1, ft	0	28	0	539
Alligator, Severity 1, sq ft	3612	2607	370	257
Alligator, Severity 2, sq ft	2433	2564	156	174
Patching Area: Wheelpath, sq ft	0	0	24	0
Patching Area: Non-wheelpath, sq ft	0	0	17	3
Rutting, in	0.10	0.09	0.11	0.14

HMA = hot mix asphalt; WMA = warm mix asphalt; OT = overlay test; FI = flexibility index; CCI = critical condition index; LDR = load related distress index; NDR = non-load related distress index; IRI = international roughness index.

Table 17. Correlation Coefficients for Overlay Test Cycles and Flexibility Index With Pavement Distress Data

Parameter	OT	FI
OT	1.0	-0.6414
FI	-0.6414	1.0
CCI	0.6355	-0.9934
LDR	0.6225	-0.9680
NDR	-0.5855	0.9391
Average IRI, in/mi	0.5412	-0.9885
Transverse Cracking, Severity 1, ft	-0.6149	0.9666
Transverse Cracking, Severity 2, ft	0.3567	0.4862
Longitudinal Cracking, Severity 1, ft	-0.2954	0.4715
Longitudinal Joint, Severity 1, ft	-0.3150	-0.4860
Alligator, Severity 1, sq ft	-0.5782	0.9932
Alligator, Severity 2, sq ft	-0.6136	0.9348
Patching Area: Wheelpath, sq ft	0.9986	-0.6009
Patching Area: Non-wheelpath, sq ft	0.9907	-0.7198
Rutting, in	0.1368	-0.7193

OT = overlay test; FI = flexibility index; CCI = critical condition index; LDR = load related distress index; NDR = non-load related distress index; IRI = international roughness index.

The correlations shown in Table 17 indicate that the FI results have greater correlations with pavement distress data except patching area, which was highly correlated with the overlay test. The FI was found to be highly correlated (having coefficients greater than |0.9|) with CCI, LDR, NDR, average IRI, Severity 1 transverse cracking, and both levels of alligator cracking. However, the direction of correlation was not logical for CCI, LDR, Severity 1 transverse cracking, and both levels of alligator cracking. For CCI and LDR, an increase in FI should correlate with increasing values, resulting in less deteriorated pavements, i.e., not have the negative relationship indicated in the analysis. In the same manner, cracking, such as the Severity 1 transverse cracking and alligator cracking, should decrease with an increase in the FI and not be positively correlated. Moderate correlations (correlation coefficient greater than |0.5|) were found between the FI and patching area and rutting. Interestingly, although these relationships were not as strong, they were more appropriate in terms of direction than many of the highly correlated relationships, with increases in the FI being related to decreases in distress.

The OT results showed much more moderate correlation coefficients than did the FI results with the exception of the correlation to patching; however, in several cases the direction of correlation was more appropriate than that of the FI. In the cases of the CCI, LDR, Severity 1 transverse cracking, and both severity levels of alligator cracking, an increase in OT cycles to failure was correlated with a decrease in the distress rating.

Correlation coefficients of less than |0.5| were seen for both performance tests with respect to Severity 2 transverse cracking, Severity 1 longitudinal cracking, and Severity 1 longitudinal joint cracking. These indicated weak relationships and were not further considered.

It is not clear if these confounding relationships were due to the limited dataset, use of 10-year in-service cores to perform the testing, or other factors, but the causes should be investigated further in future work.

SUMMARY OF FINDINGS

- HMA and WMA core air voids were generally similar. Statistically significant differences were found in only 4 of 21 comparisons. Three of the significant comparison pairs, all cores collected from Rt. 211, indicated that the HMA void content was significantly less than the WMA void content. The fourth significant comparison pair was collected from Rt. 220 and indicated that the HMA void content was greater than the WMA void content.

- Permeability results indicated that, as expected, permeability is related to air-void content; permeability also appeared to decrease over time.

- Dynamic modulus results were shown to be mixture dependent, with each mixture showing the effects of aging in a unique manner.

  — The Rt. 211 HMA was shown to increase in stiffness from Year 1 to Years 2 and 5, whereas the WMA stiffness was fairly consistent after 2 years in service; in addition, the

HMA was slightly stiffer than the WMA at 1 and 5 years of age but similar in stiffness at 2 years of age.

— The Rt. 220 HMA and WMA cores indicated that stiffness varied across age with testing temperature and frequency. The only clear trend observed was that the 10-year WMA cores were considerably stiffer than the HMA cores.

— The Rt. 143 HMA and WMA cores indicated that stiffness varied across age with testing temperature and frequency. At 1 year and 10 years of age, the WMA cores were stiffer than the HMA cores; the trend was reversed for the 2-year-old cores, and the 5-year-old cores showed similar stiffness.

- Overlay test results indicated no significant differences between the HMA and WMA pairs; however, for the Rt. 220 and Rt. 143 pairs, this was affected by the test variability.

- The FI indicated no significant differences between the HMA and WMA pairs from Rt. 211 and Rt. 143. The HMA cores from Rt. 220 showed a significantly higher FI than the WMA cores; however, the WMA core results were similar to the results seen from the other two sites.

- Binder testing showed a clear stiffening effect with age for all binders. Evaluation of the ΔT_c cracking parameter indicated that all binders except the Rt. 211 HMA binder exceeded the cracking limit of -5.0 by 10 years of service, indicating a potential need for remediation to prevent cracking.

- Data extracted from VDOT's PMS for the Rt. 211 and Rt. 143 sections generally indicated that the HMA and WMA mixtures performed similarly. Whereas individual distress quantities varied over time, the CCI, LDR, and NDR values for each HMA-WMA pair were similar after 10 years of service.

- Comparison of FI values and overlay test cycles to failure for the 10-year-old cores with cracking values indicated good correlations in many instances; however, the direction of the correlation was counterintuitive in many cases. The overlay test cycles to failure measurement was found to be highly correlated with patching and to be moderately correlated with CCI, LDR, Severity 1 transverse cracking, and alligator cracking. The FI had much higher correlations with a number of distresses; however, of the highly correlated relationships, only the correlations with NDR and average IRI were rational. These results were limited by the very small dataset evaluated.

CONCLUSIONS

- *Based on the sections and technologies evaluated in this study, HMA and WMA mixtures perform similarly over 10 years in service.*

- *Binder aging is causing a significant change in binder properties in service for both HMA and WMA that may affect mixture performance.* In general, there were slight differences in the aging paths between HMAs and WMAs; however, the binders showed similar properties after 10 years in service.

- *Relationships between performance-based properties of mixtures and in-service pavement performance are promising but need further evaluation.*

RECOMMENDATIONS

1. *VDOT's Materials Division should continue to allow WMA as currently permitted in the specifications.* There are no indications that HMA and WMA perform differently and no impediments to continued use.

2. *The Virginia Transportation Research Council (VTRC) should continue to investigate the impact of aging on binder properties and mixture performance for both HMA and WMA.* Binder aging can significantly affect the performance of asphalt mixtures and unless addressed may compromise the lifespan of Virginia mixtures. Further work is needed to validate the impact of aging and consider means to mitigate it if necessary.

3. *VTRC should monitor the performance of additional asphalt sections to assess their lifetime performance and changes in material properties related to performance.* This study evaluated 10 years of performance for a limited number of sites; data from additional sites are needed to assess the validity of predicting pavement performance with laboratory mixture performance tests. These relationships will be vital to understanding the design of well-performing mixtures in the future.

IMPLEMENTATION AND BENEFITS

Implementation

With regard to Recommendation 1, no further implementation is necessary at this time.

With regard to Recommendations 2 and 3, VTRC will continue to focus efforts on identifying the factors that influence binder aging and its impact on mixture performance. VTRC will also focus efforts on identifying the relationships between mixture test performance and in-service pavement performance properties. Both of these efforts are integral to current work in the area of performance mixture design and are already underway through a project titled "Performance Mix Design—Phase I."

Benefits

The study provides a greater understanding of the impact WMA technologies have on material properties as well as pavement performance over time. This improved insight may influence future specifications and assist in the selection of WMA technologies for the design of mixtures to optimize performance.

With regard to Recommendation 1, the benefit is that reassurance is provided to VDOT that the use of WMA does not adversely affect mixture or pavement performance.

With regard to Recommendation 2, the benefit is that VDOT will be provided help to identify and address the impacts of aging on mixture and pavement performance. Understanding and mitigating the effects of aging may result in the extension of mixture life and improvements in pavement performance.

With regard to Recommendation 3, the benefit is additional understanding of the relationship between material properties and overall pavement performance. This effort supports the development of performance-based specifications by providing the links between material properties and performance that are a basis for specifying well-performing materials.

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REFERENCES

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, and AASHTO Provisional Standards.* Washington, DC, 2017.

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

Bowers, B.F., Diefenderfer, B.K., and Diefenderfer, S.D. Evaluation of Dynamic Modulus in Asphalt Paving Mixtures Utilizing Small-Scale Specimen Geometries. *Journal of the Association of Asphalt Paving Technologists,* Vol. 84, 2015, pp. 497-526.

Diefenderfer, B.K., Bowers, B.F., and Diefenderfer, S.D. *Asphalt Mixture Performance Characterization Using Small-Scale Cylindrical Specimens*. VTRC 15-R26. Virginia Center for Transportation Innovation and Research, Charlottesville, 2015.

Diefenderfer, S.D., and Hearon, A.J. *Laboratory Evaluation of a Warm Asphalt Technology for Use in Virginia*. VTRC 09-R11. Virginia Transportation Research Council, Charlottesville, 2008.

Diefenderfer, S.D., and Hearon, A.J. *Performance of Virginia's Warm Asphalt Trial Sections*. VTRC 10-R17. Virginia Transportation Research Council, Charlottesville, 2010.

Diefenderfer, S.D., McGhee, K.K., and Donaldson, B.M. *Installation of Warm Mix Asphalt Projects in Virginia*. VTRC 07-R25. Virginia Transportation Research Council, Charlottesville, 2007.

Hansen, K.R., and Copeland A. *Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2014.* Information Series 138 (5th edition). National Asphalt Pavement Association, Lanham, MD, 2015.

Martin, A.E., Arambula, E., Yin, F., Garcia Cucalon, L., Chowdhury, A., Lytton, R., Epps, J., Estakhri, C., and Park, E.S. *NCHRP Report 763: Evaluation of the Moisture Susceptibility of WMA Technologies.* Transportation Research Board, Washington, DC, 2014.

National Climatic Data Center. Climate Data Online. n.d. https://www.ncdc.noaa.gov/cdo-web/. Accessed September 4, 2018.

Rowe, G.M. Prepared Discussion for Paper by Anderson et al.: Evaluation of the Relationship Between Asphalt Binder Properties and Non-Load Related Cracking. *Journal of the Association of Asphalt Paving Technologists,* Vol. 80, 2011, pp. 649-662.

Texas Department of Transportation. *Test Procedure for Overlay Test Tex-248-F. Effective Dates: January 2009–October 2013.* http://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/200-F_series/archives/248-0109.pdf. Accessed July 1, 2018.

Virginia Department of Transportation. *Virginia Test Methods.* Richmond, 2014. http://www.virginiadot.org/business/resources/materials/bu-mat-vtms.pdf. Accessed April 20, 2017.

Virginia Department of Transportation. *State of the Pavement—2016*. Richmond, 2016. http://www.virginiadot.org/info/resources/State_of_the_Pavement_2016.pdf. Accessed July 1, 2018.

Washington State University, Pennsylvania State University–Altoona, and Louisiana Transportation Research Center. *NCHRP Report 843: Long-Term Field Performance of Warm Mix Asphalt Technologies.* Transportation Research Board, Washington, DC, 2017.