VTRC
Virginia Transportation
Research Council

We Bring Innovation to Transportation

Laboratory and Field Performance Evaluation of Pavement Sections With High Polymer-Modified Asphalt Overlays

http://www.virginiadot.org/vtrc/main/online_reports/pdf/21-r16.pdf

JHONY HABBOUCHE, Ph.D., P.E.
Research Scientist

ILKER BOZ, Ph.D.
Research Scientist

BRIAN K. DIEFENDERFER, Ph.D., P.E.
Principal Research Scientist

Final Report VTRC 21-R16

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454

vtrc.virginiadot.org

Standard Title Page - Report on Federally Funded Project

1. Report No.:
FHWA/VTRC 21-R16

2. Government Accession No.:

3. Recipient's Catalog No.:

4. Title and Subtitle:
Laboratory and Field Performance Evaluation of Pavement Sections With High Polymer-Modified Asphalt Overlays

5. Report Date:
April 2021

6. Performing Organization Code:

7. Author(s):
Jhony Habbouche, Ph.D., P.E., Ilker Boz, Ph.D., and Brian K. Diefenderfer, Ph.D., P.E.

8. Performing Organization Report No.:
VTRC 21-R16

9. Performing Organization and Address:
Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903

10. Work Unit No. (TRAIS):

11. Contract or Grant No.:
115533

12. Sponsoring Agencies' Name and Address:
Virginia Department of Transportation
1401 E. Broad Street
Richmond, VA 23219

Federal Highway Administration
400 North 8th Street, Room 750
Richmond, VA 23219-4825

13. Type of Report and Period Covered:
Final

14. Sponsoring Agency Code:

15. Supplementary Notes:
This is an SPR-B report

16. Abstract:

In 2014, researchers at the Virginia Transportation Research Council initiated a study to evaluate the effectiveness of using high polymer-modified (HP) binders in surface asphalt concrete (AC) mixtures. The results were promising enough to support a field study investigating the use of HP binders in asphalt mixtures over jointed concrete pavement. Since 2015, HP AC overlays have been placed at several sections over existing jointed concrete pavement and cracked asphalt pavements in an effort to mitigate reflective cracking. The purpose of this study was to assess the viability of using HP AC mixtures in Virginia as a reflective crack mitigation technique or when deemed appropriate as a tool for increased crack resistance on higher volume facilities.

Information on the state of the practice and lessons learned from the use of HP AC mixtures in the United States and Canada are also provided. In general, HP AC mixtures have been used in a wide range of applications under heavy traffic on interstates and slow-braking loads at intersections. No major field-related construction issues in terms of mixing temperatures and in-place compaction of HP AC mixtures were reported and standard construction practices and equipment were used. Good communication between the polymer/binder supplier and the contractor and solid planning prior to the work being conducted were important lessons learned with regard to paving with HP AC mixtures. The performance characteristics of conventional polymer-modified asphalt (PMA) and HP field-produced mixtures were evaluated in the laboratory in terms of durability and resistance to rutting and cracking. Based on the mixtures tested in this study, HP AC mixtures showed better performance when compared with PMA mixtures regardless of the mixture type (dense-graded surface mixtures and stone matrix asphalt [SMA]). Moreover, SMA mixtures showed better performance when compared with surface mixtures regardless of the asphalt binder type (PMA and HP). Overall, SMA-HP mixtures showed the most promising performance among all evaluated PMA and HP mixtures.

Distress survey data collected from VDOT's Pavement Management System of HP field sections were compiled, documented, and compared with that of their control PMA sections. The HP sections showed the most promising performance 5 years after construction (2015-2020) regardless of the traffic level and the pre-existing pavement conditions. In general, none of the evaluated mixtures (HP or PMA) was able to stop reflective cracking totally. Moreover, performance evaluations using the network-level pavement management data were conducted to estimate the life expectancy of HP AC overlays. Overall, PMA and HP AC overlays had an average predicted service life of 6.2 and 8.3 years, respectively, indicating a 34% extension of performance life of the AC overlays with HP modification.

The study recommends continued assessment of the as-constructed properties in future HP projects for the purpose of compiling a materials characterization database. Further, the performance of all existing and future HP sections should be monitored. This will help in updating and revising the service life prediction models and the cost-effectiveness of using HP AC mixtures as the existing sections continue to age and more data are available. Finally, the use of the balanced mix design approach should be investigated to promote further the design of more durable and longer-lasting PMA and HP mixtures in Virginia.

17 Key Words:
State of the practice, overlays, high polymer-modified, specifications, implementation, rutting, cracking, durability, performance testing, and dynamic modulus.

18. Distribution Statement:
No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.

19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages: 82	22. Price:

FINAL REPORT

LABORATORY AND FIELD PERFORMANCE EVALUATION OF PAVEMENT SECTIONS WITH HIGH POLYMER-MODIFIED ASPHALT OVERLAYS

Jhony Habbouche, Ph.D., P.E.
Research Scientist

Ilker Boz, Ph.D.
Research Scientist

Brian K. Diefenderfer, Ph.D., P.E.
Principal Research Scientist

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

April 2021
VTRC 21-R16

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

ABSTRACT

In 2014, researchers at the Virginia Transportation Research Council initiated a study to evaluate the effectiveness of using high polymer-modified (HP) binders in surface asphalt concrete (AC) mixtures. The results were promising enough to support a field study investigating the use of HP binders in asphalt mixtures over jointed concrete pavement. Since 2015, HP AC overlays have been placed at several sections over existing jointed concrete pavement and cracked asphalt pavements in an effort to mitigate reflective cracking. The purpose of this study was to assess the viability of using HP AC mixtures in Virginia as a reflective crack mitigation technique or when deemed appropriate as a tool for increased crack resistance on higher volume facilities.

Information on the state of the practice and lessons learned from the use of HP AC mixtures in the United States and Canada are also provided. In general, HP AC mixtures have been used in a wide range of applications under heavy traffic on interstates and slow-braking loads at intersections. No major field-related construction issues in terms of mixing temperatures and in-place compaction of HP AC mixtures were reported and standard construction practices and equipment were used. Good communication between the polymer/binder supplier and the contractor and solid planning prior to the work being conducted were important lessons learned with regard to paving with HP AC mixtures. The performance characteristics of conventional polymer-modified asphalt (PMA) and HP field-produced mixtures were evaluated in the laboratory in terms of durability and resistance to rutting and cracking. Based on the mixtures tested in this study, HP AC mixtures showed better performance when compared with PMA mixtures regardless of the mixture type (dense-graded surface mixtures and stone matrix asphalt [SMA]). Moreover, SMA mixtures showed better performance when compared with surface mixtures regardless of the asphalt binder type (PMA and HP). Overall, SMA-HP mixtures showed the most promising performance among all evaluated PMA and HP mixtures.

Distress survey data collected from VDOT's Pavement Management System of HP field sections were compiled, documented, and compared with that of their control PMA sections. The HP sections showed the most promising performance 5 years after construction (2015-2020) regardless of the traffic level and the pre-existing pavement conditions. In general, none of the evaluated mixtures (HP or PMA) was able to stop reflective cracking totally. Moreover, performance evaluations using the network-level pavement management data were conducted to estimate the life expectancy of HP AC overlays. Overall, PMA and HP AC overlays had an average predicted service life of 6.2 and 8.3 years, respectively, indicating a 34% extension of performance life of the AC overlays with HP modification.

The study recommends continued assessment of the as-constructed properties in future HP projects for the purpose of compiling a materials characterization database. Further, the performance of all existing and future HP sections should be monitored. This will help in updating and revising the service life prediction models and the cost-effectiveness of using HP AC mixtures as the existing sections continue to age and more data are available. Finally, the use of the balanced mix design approach should be investigated to promote further the design of more durable and longer-lasting PMA and HP mixtures in Virginia.

FINAL REPORT

LABORATORY AND FIELD PERFORMANCE EVALUATION OF PAVEMENT SECTIONS WITH HIGH POLYMER-MODIFIED ASPHALT OVERLAYS

Jhony Habbouche, Ph.D., P.E.
Research Scientist

Ilker Boz, Ph.D.
Research Scientist

Brian K. Diefenderfer, Ph.D., P.E.
Principal Research Scientist

INTRODUCTION

Since the early 1900s, asphalt concrete (AC) mixtures have been used as driving surfaces for flexible pavements. The continuous increases in traffic volume, axle loads, and tire pressures have led to a greater demand for high-quality AC mixtures that can resist conflicting distresses such as permanent deformation (i.e., rutting and shoving) and cracking (e.g., fatigue, top-down, block, and reflective) while maintaining long-term durability via resistance to moisture damage and aging. To keep up with these demands, numerous technologies have been introduced over the past 50 years to modify the properties of asphalt binders to accommodate project-specific load and climatic conditions.

When pavement maintenance/rehabilitation has become necessary, AC overlays have been one of the most common treatments used by the Virginia Department of Transportation (VDOT) for maintaining/rehabilitating aged pavements; they are flexible, composite, and rigid. However, when AC overlays are placed on an existing surface where cracks and joints are not properly repaired, differential movements across the underlying cracks or joints attributable to the combined effects of heavy wheel loads, loss of support, and temperature fluctuations result in physical tearing of the AC overlays. The penetration of water and foreign debris into these cracks accelerates the deterioration of the AC overlays and the underlying layers, causing premature failure in the structural and functional performance of a pavement. Thus, the long-term performance of many AC overlays will highly depend on their ability to resist cracking from all sources of distress. Reflective cracking is a serious challenge associated with pavement maintenance, and one way to delay reflective cracking is to increase the resistance of the overlays through enhancement of material properties (Habbouche et al., 2021).

Asphalt binder modification is not a new concept and has become progressively more common over the past several decades. Throughout the past 50 years, asphalt binders have been modified with various components such as polymers, ground tire rubber, chemicals (e.g., acid), and recycled engine oils to enhance the asphalt mixture properties (Habbouche et al., 2020). Several state departments of transportation (DOTs) have recognized the benefits of polymer-modified AC mixtures in resisting multiple modes of load- and climate-induced distresses in flexible pavements (Habbouche et al., 2019). Styrene-butadiene-styrene (SBS) is a well-recognized polymer (elastomer) commonly used in asphalt mixtures because of its performance benefits and resiliency. The most commonly used SBS polymer-modified asphalt (PMA) binders (referred to herein as "PMA binders") have rarely been able to exceed a ~3.5% SBS polymer rate because of practical issues such as mixing, storage, and workability. However, researchers at Delft University developed a new SBS polymer structure that allowed its use in asphalt binders at much higher levels (~7.5%) (referred to herein as "high polymer [HP] binders"). These binders have shown much more elasticity, which may help mitigate some of the pavement failure modes that concern agencies (Bowers et al., 2017).

In 2014, researchers at the Virginia Transportation Research Council (VTRC) initiated a study to evaluate and examine the difference in constructability, laboratory performance, and initial field performance of AC mixtures produced using HP binders compared with AC mixtures produced using conventional PMA binders (Bowers et al., 2018). The work involved the construction of a trial project to compare an AC surface mixture (SM) using an HP binder to one having a PMA binder (as a control). The two mixtures were used in a resurfacing pavement project placed on a milled surface in a subdivision in Northern Virginia (NOVA). The asphalt SM with the HP binder was found to be constructible without major changes in paving operations; in addition, the laboratory performance was equivalent or superior to that of the control mixture. The results were promising enough to support a wider field investigation into the use of HP binders in AC overlays as a reflective crack mitigation technique or when deemed appropriate as a tool for increased crack resistance on higher-volume facilities (Bowers et al., 2018). Since 2015, HP AC overlays have been placed at several sections in Virginia over jointed concrete pavements (JCPs) and cracked asphalt pavements.

PURPOSE AND SCOPE

The purpose of this study was to assess the viability of using HP AC mixtures in Virginia as a reflective crack mitigation technique or when deemed appropriate as a tool for increased crack resistance on higher-volume facilities. This was achieved by the following:

- providing information on the state of the practice with regard to using HP AC mixtures in the United States and Canada
- evaluating the performance characteristics of three PMA and five HP field-produced mixtures placed in Virginia during the 2018 and 2019 paving seasons
- compiling and evaluating routine distress survey data against pre-paving distress survey data for relevant in-service HP pavements constructed from 2015-2018 and comparing them with several control in-service PMA pavements
- conducting performance evaluations using the network-level pavement management data to determine the life expectancy of HP AC overlays.

METHODS

State of the Practice

Information on the state of the practice for using HP AC mixtures was collected through a survey of U.S. and Canadian provincial agencies combined with a search of HP-related specifications, special provisions, and previously constructed field trials or pilot projects. The survey questionnaire included questions related to material specifications and definitions, practice and usage, design, performance, constructability, quality assurance, environmental restrictions, research efforts, costs and benefits, and lessons learned from using the technology. The questionnaire for this survey is presented in Appendix A.

Moreover, VDOT's current state of the practice with regard to using HP paving material was documented by reporting tonnage and types of produced HP AC mixtures. In addition, a survey of asphalt contractors in Virginia who had previously produced and supplied Virginia with HP AC mixtures was initiated to document their experience, lessons learned, and best practices. The questionnaire for this survey is presented in Appendix B.

Laboratory Evaluation of Binders and Mixtures

The properties of the overlying AC layers are important to the performance of the overall system. To this extent, the performance characteristics of three PMA and five HP AC mixtures placed in Virginia during the 2018 and 2019 paving seasons (total of eight mixtures) were evaluated through a series of tests. This included laboratory testing on collected asphalt binders, field cores sampled during construction, and sampled plant-produced mixtures. A summary of the location of the seven field projects and their asphalt binders and mixtures is shown in Table 1. Figure 1 is a flowchart of the laboratory experimental program.

Table 1. Description of Selected PMA and HP Field Projects Placed During 2018 and 2019

Location	VTRC ID	Mix ID	Mix and Binder Type	Cores
I-95, Henry G. Shirley, Memorial Highway	19-1086	A	SM-9.0 (HP)	Yes
	19-1111	F	SMA-9.5 (HP)	Yes
SR 120, South Glebe Road, Arlington	19-1082	B	SM-9.5 (PMA)	Yes
SR 120, South Glebe Road, Arlington	19-1087	C	SM-9.5 (HP)	Yes
I-95, Henry G. Shirley Memorial Highway	19-1062	D	SM-12.5 (PMA)	Yes
I-95	19-1065	E	SM-12.5 (HP)	No
I-495, Annandale	19-1116	F	SMA-9.5 (HP)	Yes
I-95, Fairfax County	19-1063	G	SMA-12.5 (PMA)	Yes

VTRC = Virginia Transportation Research Council; SM = surface mix; HP = high polymer-modified asphalt binder; SMA = stone matrix asphalt; PMA = polymer-modified asphalt binder.

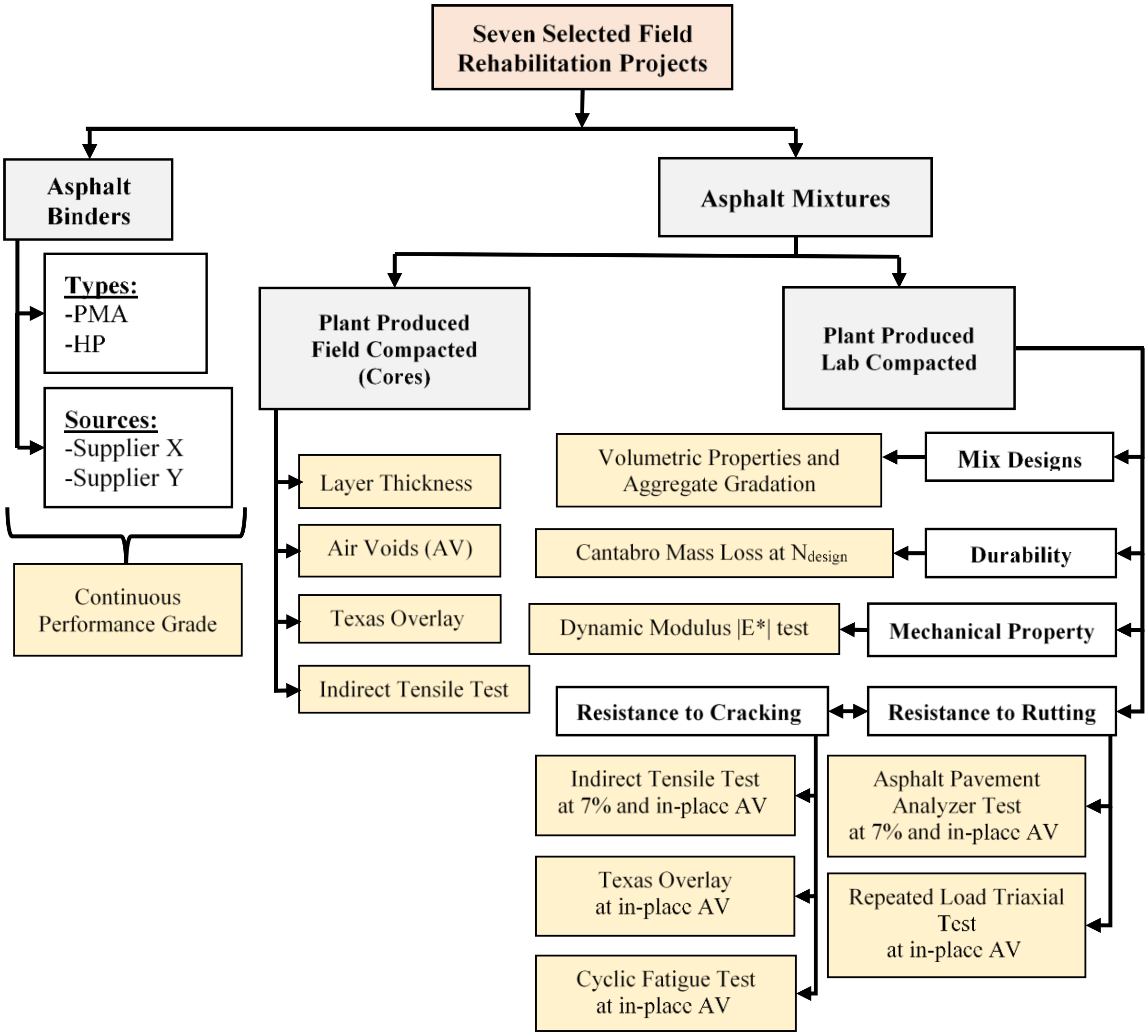


Figure 1. Flowchart of the Experimental Plan. HP = high polymer-modified asphalt binders; PMA = polymer-modified asphalt binders; AV= air voids.

Field Cores

Field core samples were collected from each project during construction. Core locations were randomly stratified along the length and width of the section. The following properties were measured for each core: in-place layer thicknesses; air voids in accordance with AASHTO T 269, Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures (AASHTO, 2014); and the resistance to cracking by means of the Texas overlay test (OT) performed in accordance with Tex-248-F, Test Procedure for Overlay Test (Texas DOT, 2019), and the indirect tensile (IDT) test performed in accordance with ASTM D8225-19, Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature (ASTM, 2019).

Asphalt Binder Testing

Asphalt binder grading was performed in accordance with AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder (AASHTO, 2017), and AASHTO M 332, Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test (AASHTO, 2020).

Moreover, quality assurance testing reports for asphalt binders of all HP AC mixtures placed in Virginia since 2016 were collected. Viscosity values at 135°C measured in accordance with AASHTO T 316, Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer (AASHTO, 2014), were evaluated and compared to the threshold of 3 Pa.s in accordance with AASHTO M 332.

Asphalt Mixture Testing and Characterization

Volumetric Properties and Aggregate Gradations of Mixtures

The theoretical maximum specific gravity of each mixture was determined in accordance with AASHTO T 209, Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Asphalt Mixtures (AASHTO, 2019). The asphalt binder content of each mixture was determined by the ignition method in accordance with AASHTO T 308, Standard Method of Test for Determining the Asphalt Binder Content of Asphalt Mixtures by the Ignition Method (AASHTO, 2018), and Virginia Test Method (VTM) 102, Determination of Asphalt Content from Asphalt Paving Mixtures by the Ignition Method (VDOT, 2013). The size distribution (gradation) of the recovered aggregate was determined in accordance with AASHTO T 11, Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing (AASHTO, 2019), and AASHTO T 27, Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates (AASHTO, 2019). Loose mixtures were conditioned at the compaction temperature and then compacted to N_{design} gyrations using a Superpave gyratory compactor (SGC) in accordance with AASHTO M 323, Standard Specification for Superpave Volumetric Mix Design (AASHTO, 2017). Basic physical characteristics and volumetric parameters in terms of bulk specific gravity (G_{mb}), voids in total mixture, voids in mineral aggregate, voids filled with asphalt, fines to aggregate ratio, aggregate effective specific gravity, aggregate bulk specific gravity, absorbed asphalt binder content, effective asphalt binder content, and effective film thickness were determined.

Cantabro Mass Loss Test

The Cantabro mass loss was determined to evaluate the durability of asphalt mixtures in accordance with AASHTO TP 108, Standard Method of Test for Abrasion Loss of Asphalt Mixture Specimens (AASHTO, 2018). This test has been shown to be useful when evaluating open-graded friction course and dense-graded asphalt mixtures (Cox et al., 2017). The test was performed on specimens fabricated using an SGC that were compacted from loose mixture collected at the plant during production. The loose mixtures were conditioned at the design compaction temperature prior to compaction to N_{design} gyrations. The Cantabro test specimens were 150 mm in diameter by 115 ± 5 mm in height. The test was performed by placing the specimen into an uncharged Los Angeles abrasion machine and rotating it for 300 rotations at a speed of approximately 30 rotations per minute. Three replicates were tested for each mixture, and an average mass loss was reported.

*Dynamic Modulus |E**| Test*

The dynamic modulus of specimens compacted from loose mixtures collected during production was determined using the 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 (HMA) (AASHTO, 2019). Tests were performed on specimens 100 mm in diameter by 150 mm in height cored from the center of specimens 150 mm in diameter by 175 mm in height compacted using an SGC to in-place air voids. Four testing temperatures (4.4, 21.1, 37.8, and 54.4°C) and six testing frequencies ranging from 0.1 to 25 Hz were used. Tests were conducted starting from the coldest temperature to the warmest temperature, and 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 75 to 125 microstrains. All tests were conducted in the uniaxial mode without confinement. Results at each temperature-frequency combination for each mixture type were reported for three replicate specimens.

Asphalt Pavement Analyzer Rut Test

The Asphalt Pavement Analyzer (APA) rut test was performed on specimens prepared from loose mixture collected during construction in accordance with AASHTO T 340, Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA) (AASHTO, 2015). This test simulates rutting in the laboratory by applying a loaded wheel back and forth over a pressurized rubber tube located along the surface of the test specimen at a temperature of 64°C. After 8,000 cycles were applied, the deformation of the specimen was measured. The APA rut test was performed on specimens 150 mm in diameter by 75 ± 2 mm in height compacted using an SGC to in-place and 7 ± 0.5% air voids.

Repeated Load Triaxial Test

The rutting characteristics of specimens prepared from loose mixture collected during construction were evaluated using the repeated load triaxial (RLT) test in accordance with National Cooperative Highway Research Program (NCHRP) Report 719, *Calibration of Rutting Models for Structural and Mix Designs* (Von Quintus et al., 2012). The RLT test specimens were 100 mm in diameter by 150 mm in height and were cored from the center of an SGC specimen 150 mm in diameter by 175 mm in height. All test specimens were compacted to in-place air voids. The RLT test was conducted by applying a repeated deviator stress of 482 kPa, a static confining pressure of 69 kPa, and a contact stress of 24 kPa. The deviator stress was applied through a pulse load with repeated loading and unloading periods. Each loading cycle consisted of 0.1 second of loading followed by a rest period of 0.9 seconds. The axial deformation after each pulse was measured, and the axial resilient strain (ε_r) was calculated. In addition, the cumulative permanent strain (ε_p) was calculated. The RLT test was conducted at 54.4°C. The Franken model, expressed in Equation 1, was used to model numerically the permanent strain-loading cycle relationship. This well-suited mathematical model combines a power model, which characterizes the primary and secondary stages, and an exponential model, which fits the tertiary stage. The flow number (FN) is the number of cycles corresponding to the inflection point at which the second derivative of ε_p is equal to zero.

$$\varepsilon_p(N) = A * N^B + C * (e^{D*N} - 1) \qquad \text{[Eq. 1]}$$

where

$\varepsilon(N)$ = the permanent axial strain expressed in mm/mm
N = the number of loading cycles
A, B, C, and D = regression constants.

Indirect Tensile Test at Intermediate Temperatures

The IDT cracking test was conducted at 25°C on specimens prepared from loose mixture collected during construction in accordance with ASTM D8225-19 (ASTM, 2019). Tests were performed at a loading rate of 50 ± 2 mm/min on specimens 150 mm in diameter by 62 mm in height compacted with an SGC. The IDT test was performed on two sets of specimens: a set compacted to the in-place air voids, and a set compacted to 7.0 ± 0.5% air voids. The cracking tolerance index (CT index) and the fracture strain tolerance (FST) were then calculated from the load-displacement curve of the test using Equation 2 and Equation 4, respectively. Previous studies have shown that these indices are highly correlated, with some showing a better repeatability of characteristics and performance discrimination potential among asphalt mixtures (Diefenderfer et al., 2019; Seitllari et al., 2020). It should be noted that as part of the balanced mix design (BMD) initiative in Virginia, VDOT is currently evaluating the use of the IDT CT index to assess the resistance to cracking of asphalt SMs subjected to a relatively lower traffic level (i.e., <10 million equivalent single axle loads (ESALs]) when compared with those evaluated in this effort (>10 million ESALs).

$$CT_{index} = \frac{G_f}{|m_{75}|} * \left(\frac{l_{75}}{D}\right) * \left(\frac{t}{62}\right) \qquad \text{[Eq. 2]}$$

$$m_{75} = \left|\frac{p_{85} - p_{65}}{l_{85} - l_{65}}\right| \qquad \text{[Eq. 3]}$$

$$FST = \frac{G_f}{S_t} * 10^6 \qquad \text{[Eq. 4]}$$

$$S_t = \frac{2000 P_{max}}{\pi t D} * 10^3 \qquad \text{[Eq. 5]}$$

where

G_f = total area under the load-displacement curve divided by the product of the specimen thickness [t] and diameter [D] in kN/mm
m_{75} = slope of interest expressed in Equation 3
p_{85} = 85% of the peak load (P_{max}) at the post-peak stage in kN

p_{75} = 75% of P_{max} at the post-peak stage in kN
p_{65} = 65% of P_{max} at the post-peak stage in kN
l_{85} = displacement corresponding to p_{85} in mm
l_{75} = displacement corresponding to p_{75} in mm
l_{65} = displacement corresponding to p_{65} in mm
S_t = indirect tensile strength expressed in Equation 5
kPa, D = specimen diameter in mm
t = specimen thickness in mm.

Texas Overlay Test

The OT was performed on cores obtained from the field and on specimens prepared from loose mixture collected during production in accordance with Tex-248-F (Texas DOT, 2019) to evaluate the mixtures' resistance to reflective cracking. The horizontal opening and closing of joints and cracks that exist underneath a new AC overlay were specifically simulated. The OT fixture was designed to increase the functionality of the AMPT by enabling it to determine the reflective cracking susceptibility of asphalt mixtures. The OT specimens were 150 mm long by 75 mm wide by 37.5 mm thick and were trimmed from SGC samples 150 mm in diameter by 115 mm in height that were compacted to in-place air voids. Once prepared, each OT specimen was glued on two metallic plates, well fixed on a mounting wide plate using epoxy. The test was conducted in a controlled displacement mode at a loading rate of 1 cycle per 10 seconds with a maximum displacement of 0.6350 mm at 25 ± 0.5°C. Each cycle consisted of 5 seconds of loading and 5 seconds of unloading. The number of cycles to failure was defined as the number of cycles to reach a 93% drop in initial load, which is measured from the first opening cycle. If a 93% reduction in initial load is not reached within a certain specified number of cycles (5,000), the test stops automatically.

A power function defined in Equation 6 was used to fit the load reduction curve function of the number of loading cycles to determine the crack propagation rate (CPR) (Garcia et al., 2016). The critical fracture energy (Gc) at the maximum peak load of the first loading cycle was determined using Equation 7. G_c was considered the energy required to initiating crack.

$$NL = N^{CPR} \quad \text{[Eq. 6]}$$

$$G_c = \frac{W_c}{b*c} \quad \text{[Eq. 7]}$$

where

NL = normalized crack driving force or load at each loading cycle in kN
N = number of loading cycles
CPR = crack propagation rate
G_c = critical fracture energy in kN-mm^2
W_c = fracture area at the maximum peak load of the first loading cycle
b = specimen width, i.e., 76.2 mm
h = specimen height, i.e., 38.1 mm.

Direct Tension Cyclic Fatigue Test

The simplified viscoelastic continuum damage test, known as the direct tension cyclic fatigue test, was performed using the AMPT in accordance with AASHTO TP 107, Standard Method of Test for Determining the Damage Characteristic Curve and Failure Criterion Using the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test (AASHTO, 2018). The cyclic fatigue test was performed on specimens 100 mm in diameter by 130 mm in height cored from samples 150 mm in diameter by 175 mm in height compacted from loose mixtures collected during construction. All test specimens were compacted to in-place air voids. The developed damage characteristic curves were then used with the viscoelastic material properties (i.e., $|E^*|$) to obtain the fatigue behavior of the asphalt mixtures. To define the asphalt mixtures' fatigue performance, a fatigue cracking index parameter, referred to as apparent damage capacity (Sapp), is usually used. The calculation of Sapp was conducted with FlexMAT for Cracking, an Excel-based tool provided by the Federal Highway Administration (FHWA) (FHWA, 2019).

Field Performance

Distress data were obtained from VDOT's Pavement Management System (PMS) database for all HP and most of the PMA control field-constructed projects. The collected distress data covered one or multiple maintenance and/or rehabilitation cycles of various alternatives prior to the application of HP AC overlays. The asphalt pavement distress data collected from the PMS included transverse cracking, longitudinal cracking, reflective transverse cracking, reflective longitudinal cracking, alligator cracking, longitudinal joint cracking, patching, potholes, delamination, bleeding, and rutting. In the PMS, VDOT uses three condition indices to rate pavement distresses: (1) the load related distress rating; (2) the non-load related distress rating; and (3) the Critical Condition Index (CCI).

The load related distress rating indicates pavement distresses caused by traffic loading; the non-load related distress rating indicates pavement distresses that are not load related, such as those caused by environmental or climatic conditions. These two condition indices are rated on a scale of 0 to 100, where 100 signifies a pavement having no distresses. The CCI is the lower of the load related distress rating and the non-load related distress rating.

In addition to storing the individual distress data, the PMS calculates and stores the load related distress rating, non-load related distress rating, CCI, and International Roughness Index (IRI) for all sections. Additional information regarding how these processes were developed and implemented is available elsewhere (McGhee, 2002; VDOT, 2018).

Assessment of Performance Life

Performance evaluations were conducted using the network-level PMS data to estimate the life expectancy of HP and PMA AC overlays in Virginia using two approaches. The first approach (Approach I) uses the CCI at multiple in-service durations, and the second approach (Approach II) considers only the reflective cracking distress at multiple in-service durations.

Approach I

The VDOT PMS logistic performance deterioration prediction model expressed in Equation 8 was used to fit the reported CCI values at multiple in-service durations and estimate the life expectancy of the PMA and HP AC overlays (Stantec Consulting Services Inc. and H.W. Lochner, Inc., 2007). This model simulates a typical slow deterioration during the first few years of service; followed by a relatively faster deterioration rate expressed through a significant drop in CCI values; and finally followed by a steady reduction in the rate of CCI decrease to approach a low boundary simulating complete failure. The selected performance model was first calibrated using the collected PMS data, which were then used to predict the service life of pavement sections with HP and PMA AC mixtures.

$$CCI = 100 - e^{a-b*c^{\ln(\frac{1}{t})}} \qquad \text{[Eq. 8]}$$

where

CCI = critical condition index
t = pavement age in years
a, b, and c = fitting coefficients.

Approach II

The strain concentration attributable to the movement in the existing pavement in the vicinity of joints and/or cracks constitutes the basic cause of reflective cracking in the AC overlay. The majority of reflective cracking is caused by the combination of bending, shearing, and thermal mechanisms resulting from traffic loads, loss of support, or daily and seasonal temperature changes (Habbouche et al., 2019). Various models have been developed to analyze and/or predict reflective cracking. Lytton et al. (2010) recommended a sigmoidal curve having a finite upper asymptote to simulate the amount and severity of reflective cracking as a function of time (Eq. 9) (Lytton et al., 2010).

$$RFAS = 100 * e^{-(\frac{\rho}{D_{Total}})^{\beta}} \qquad \text{[Eq. 9]}$$

where

RFAS = reflective cracking amount and severity, ranging from 0% to 100%
D_{Total} = total number of days since the overlay construction was completed
ρ, and β = calibration parameters for each severity level.

The calibration parameter ρ is considered a scale factor for reflective cracking amount and severity; a greater ρ value indicates that much accumulated damage must occur to reach a certain amount of reflective cracking. The calibration parameter β indicates the steepness of the rising portion of the model, simulating the propagation rate of reflective cracking.

RESULTS AND DISCUSSION

State of the Practice

Agency Survey and Online Specification Search

In September 2019, an email-based survey of U.S. state and Canadian provincial agencies was conducted to collect key information regarding current practices with regard to HP binders and HP AC mixtures. A total of 23 responses (22 U.S. agencies and 1 Canadian provincial agency) were received, with an overall response rate of 44% from the United States. This survey represented the first look at the use of HP binders and HP AC mixtures across North America (Habbouche et al., 2021).

Of the 22 U.S. agencies that responded to the survey, 11 indicated experience with HP binders and HP AC mixtures. This group is referred to as *Group A,* which included Alabama, Florida, Georgia, Iowa, Maryland, New Jersey, New York, Ohio, Vermont, Virginia, and Wisconsin. After an online search of specifications, special provisions, and field trial or pilot projects, the research team identified another 10 U.S. agencies having experience with HP binders and HP AC mixtures. This group is referred to as *Group B,* which included Alaska, Kentucky, Minnesota, Missouri, New Hampshire, Oklahoma, Oregon, Tennessee, Utah, and Washington. From Groups A and B, 21 agencies use or have constructed field trial and pilot projects using HP AC mixtures, as shown in Figure 2. The majority of these agencies are located in the eastern part of the United States.

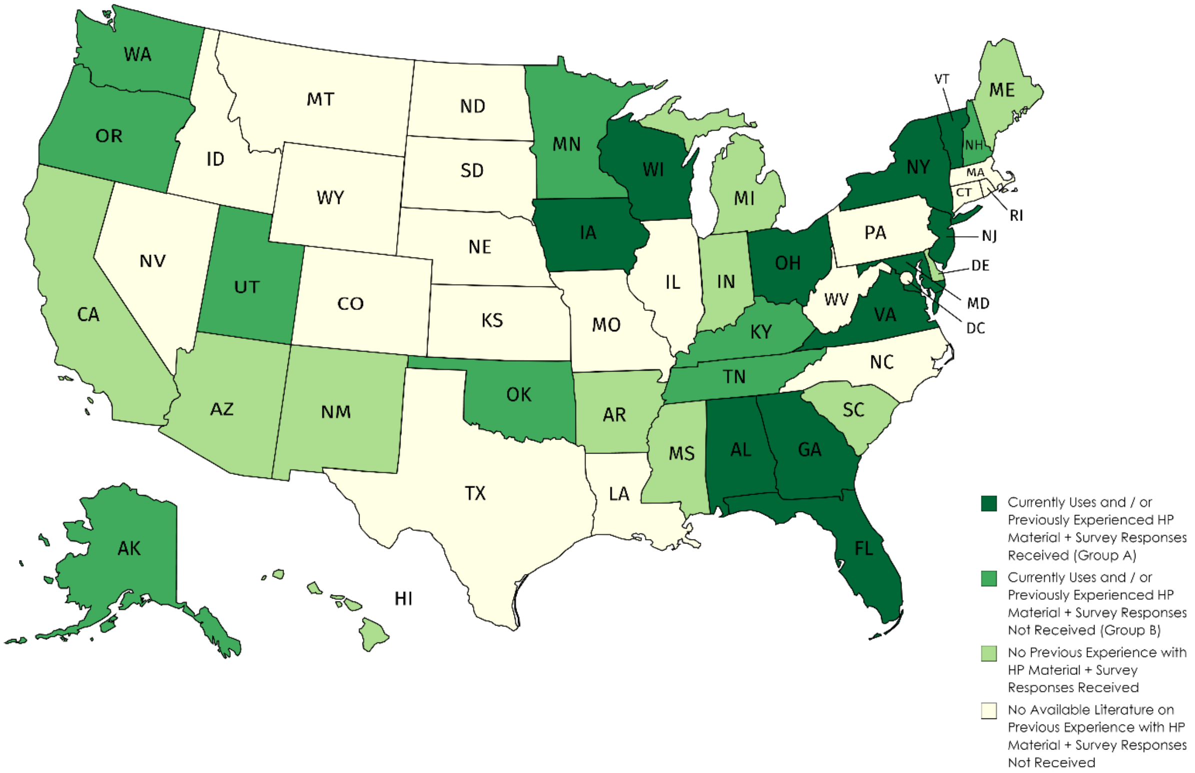


Figure 2. U.S. Map Indicating Agencies' Experience Status with HP AC Mixtures

The survey responses conveyed that the definition and acceptance of these binders are not related to the SBS polymer content but rather to specific binder rheology-related parameters and characteristics, a more performance-oriented viewpoint. Agency special provisions and specifications for properties of HP binders and AC mixtures are summarized in Table 2. As shown, all of the special provisions and specifications rely on a very high elasticity and recovery of the produced asphalt binder to ensure a very good performance by corresponding pavements subjected to heavy, stress-concentrated, or slow-moving traffic loads.

HP binders have been used in numerous applications including structural overlays (29%), functional overlays (21%), interlayers for reflective cracking mitigation (17%), bottom layers for bottom-up fatigue cracking mitigation (8%), and full-depth AC layers (8%). Multiple agencies included “Others” (17%) as part of their response: for example, Florida uses HP binders in open-graded friction course mixtures to improve their resistance to raveling; Iowa uses HP binders to produce high-performance thin-lift overlays; Maryland and Virginia use HP binders in dense-graded SMs and SMA of composite pavements to mitigate reflective cracking. New Jersey uses HP binders in thin overlay mixtures, binder-rich intermediate courses, bottom-rich base courses, bridge deck waterproof surface courses, and a few of the high reclaimed asphalt pavement (RAP) mixtures to meet pre-established performance requirements for the produced mixtures as part of the BMD approach. New York uses HP binders to produce polymer-modified stress-absorbing membrane interlayers and waterproofing bridge deck hot mix AC overlays; Ohio uses mostly HP AC mixtures on bridge decks and at intersections; and Wisconsin allowed the use of HP binders to produce an AC pavement interlayer that meets pre-established performance requirements. Three agencies showed interest in using HP AC mixtures to design thinner pavements (New Jersey and Virginia) or to conduct research (Georgia).

In general, the use of HP AC mixtures by these agencies showed great success in their intended use to prevent rutting and reflective cracking. Alaska (Group B) and the Newfoundland and Labrador Canadian provincial agencies introduced HP binders in AC mixtures as a novel approach to mitigating studded tire abrasion.

No agencies reported any special practices or enforcements of specific safety, health, or environmental restrictions when HP binders were used in AC mixtures. Moreover, numerous factors that are likely to limit the use of HP AC pavements were identified. These factors included lack of project selection criteria (18%), lack of standard specifications (16%), lack of agency experience (16%), relatively higher price (11%), lack of engineering design procedures (7%), lack of local contractors (5%), previous unsuccessful experiences (5%), and reluctance to changes by industries (5%). Other additional factors (11%) were identified by several agencies and included details such as limited supply, shorter storage lifetime, lack of material expertise, and lack of cost-effectiveness information.

Table 2. Summary of Agency Special Provisions and Specifications for HP Binders and AC Mixtures

Agency	Standard / Test Method	Properties/Comments
Alabama	AASHTO M 332 AASHTO T 350	PG 76E-22 reported as PG 88-22 $R_{3.2} \geq 90\%$
Alaska	AASHTO M 320 and M 332 AASHTO T 350 AASHTO T 315 ATM 420	PG 64E-40 $J_{nr,\,3.2} \leq 0.1$ kPa^{-1} and $R_{3.2} \geq 95\%$ at 64°C $G^*.\sin\delta \leq 5{,}000$ kPa at 0°C after PAV Abrasion of HMA by the Prall test; Prall loss < 20 cm^3
Florida	AASHTO T 332 AASHTO T 350 AASHTO T 315	PG 76E-22 $J_{nr,\,3.2} \leq 0.1$ kPa^{-1} and $R_{3.2} \geq 90\%$ at 76°C $G^*/\sin\delta \geq 1{,}0$ kPa and $\delta \leq 75°$ at 76°C on original $G^*.\sin\delta \leq 5{,}000$ kPa at 26.5°C after PAV
Georgia	AASHTO T 332 AASHTO T 350	PG 76E-22 reported as PG 82-28 $J_{nr,\,3.2} \leq 0.1$ kPa^{-1} and $R_{3.2} \geq 90\%$ at 76°C
Iowa	AASHTO M 332 AASHTO T 350	PG 64-34E+ reported as PG 76-34 $R_{3.2} \geq 90\%$ at 64°C
Kentucky	AASHTO M 320 and M 332 AASHTO T 350	PG 76E-22 reported as PG 82-22 $R_{3.2} \geq 90\%$ at 76°C
Maryland	AASHTO T 332 AASHTO T 350	PG 76E-28 $J_{nr,\,3.2} \leq 0.1$ kPa^{-1} & $R_{3.2} \geq 90\%$ at 76°C
Minnesota	AASHTO M 320 AASHTO T 301	PG 76-34 $R_e \geq 90\%$
Missouri	AASHTO T 332 AASHTO T 350	PG 76E-22 $J_{nr,\,3.2} \leq 0.1$ kPa^{-1} & $R_{3.2} \geq 90\%$ at 76°C
Newfoundland and Labrador	AASHTO M 320 AASHTO T 301	PG 64-34 $R_e \geq 60\%$
New Hampshire	AASHTO M 320 AASHTO T 301	PG 76-34 $R_e \geq 90\%$
New Jersey	AASHTO T 332 AASHTO T 350	PG 64E-22 $J_{nr,\,3.2} \leq 0.3\text{-}0.5$ kPa^{-1} at 64°C + depends on the applications and mixture requirements
New York	AASHTO M 332 AASHTO T 350	PG 76E-28 $J_{nr,\,3.2} \leq 0.5$ kPa^{-1} and $R_{3.2} \geq 55\%$ at 76°C
Ohio	AASHTO M 320 OH DOT TM 429 (as AASHTO T 301)	PG 88-22 reported as PG 88-22M $R_e \geq 90\%$
Oklahoma	AASHTO T 332 AASHTO T 350	PG 76E-28 $R_{3.2} \geq 95\%$ at 76°C
Oregon	AASHTO M 320 AASHTO T 301	PG 76-28 $R_e \geq 90\%$
Tennessee	AASHTO M 332 AASHTO T 350	PG 76E-28 $J_{nr,\,3.2} \leq 0.1$ kPa^{-1} and $R_{3.2} \geq 90\%$ at 76°C
Utah	AASHTO M 320 AASHTO T 301	PG 76-34 $R_e \geq 90\%$
Vermont	AASHTO M 320 AASHTO T 301	PG 76-34 $R_e \geq 90\%$
Virginia	AASHTO T 332 AASHTO T 350	PG 76E-28(HP) $J_{nr,\,3.2} \leq 0.1$ kPa^{-1} and $R_{3.2} \geq 90\%$ at 76°C
Washington	AASHTO M 320 AASHTO T 301	PG 76-34 $R_e \geq 90\%$
Wisconsin	AASHTO M 332 AASHTO T 350 AASHTO T 315	PG 58E-34 $J_{nr,\,3.2} \leq 0.5$ kPa^{-1} and $R_{3.2} \geq 75\%$ at 58°C $G^*.\sin\delta \leq 6{,}000$ kPa at 16°C after PAV + depends on the applications and mixture requirements

HP = high polymer-modified asphalt binder; PG = performance grade; PAV = pressure aging vessel; HMA = hot mix asphalt.

Construction Practices: Experience of Virginia Asphalt Contractors

In March 2020, a survey was distributed among asphalt contractors who had previously produced and supplied Virginia with HP AC mixtures. The survey was primarily designed to collect information regarding standard construction practices executed to handle HP material. Four responses from six HP-experienced contractors were received.

Plant-Related Attributes

Temperatures of HP binder must be monitored at the terminal and upon delivery at the plant. The reported practice recommended emptying the liquid binder as quickly as possible upon delivery at the plant. The liquid in the tank is usually kept at a temperature of 330°F to 345°F, with no agitation. The storage time is usually shortened in accordance with the supplier's recommendations. Typically, a duration of not more than 3 days in a storage tank is used. The inventory of liquid asphalt used and HP AC mixtures produced should be tracked on at least a daily basis to make sure the HP binder is not stored longer than its recommended shelf life. The contractors described some challenges and difficulties in managing storage time as production rates of certain jobs may be quite low (especially on a nightly basis) and the binder would not be used within the recommended storage time. In addition, a pump-on-pump transfer system rather than a mass-flow pump system is usually installed, with all unnecessary elbows or excess pipes from the unloading pump to the tank being eliminated. Asphalt contractors reported the use of warm mix additives, sometimes at higher dosages, in an attempt to make the produced HP AC mixtures more workable.

Field-Related Attributes

No contractors reported significant changes from routine established practices in terms of surface preparation or paving operations. However, they reported that additional compaction effort might be required when using the same paving equipment as used for conventional mixtures. Based on their experience, contractors in Virginia recommended running conventional mixtures (or unmodified mixtures) through the paver prior to placing the HP mixture to heat the equipment in order to avoid the mixture sticking in the paver hopper. It is critical to minimize wait time on the job site for loaded trucks since HP AC mixtures cool down and stiffen at a faster rate than conventional mixtures. As for quality control, contractors recommended obtaining liquid samples after draining about 5 gallons of asphalt binder through the sampling valve of the tank. Humidity and moisture during the summer months may affect the mineral filler pile with SMA. Therefore, prior to paving, enough mineral was usually "fluffed" up through the drum/drier and stored in a separate stockpile. This helped minimize clumping in the cold feed bin, conveyor, and chutes. Further, contractors recommended changing the filter basket routinely on the AC pump line. Finally, contractors had not encountered any safety-, health-, or environmental-related concerns specific to HP binders that did not apply to standard conventional asphalt binders.

Lessons Learned and Best Practices

Agencies and asphalt contractors reported many lessons learned and best practices based on their experience with HP paving material. These lessons and practices focused mainly on good communication between the polymer/binder supplier and the contractor and solid planning prior to beginning the paving job.

- Good and frequent communication with the binder supplier is critical during the early planning stages, the production of HP binders, the continuous quality control by the supplier, and the team work to resolve issues when they arise. Good communication with all project stakeholders (supplier, producer, contractor, and owner) to predict changes and respond in a timely manner is very important. Good unloading, storage, and production practices at the plant are critical for success with HP mixtures. A strong focus on quality control will yield success with HP AC mixtures.

- HP binders have a short shelf life; therefore, contractors usually try to receive daily delivery of fresh HP binders and store enough for an upcoming night's production.

- With a reduced shelf life, the contractor has to be aware at all times of the inventory of HP binders at the plant and at the terminal. Extended periods of inclement weather, other job delays, and holidays can mean that changes in plans are needed to adjust properly.

- Contractors have other options if tank storage time becomes an issue, such as the use of HP binders in other applications or blend-down options.

- Conventional mixtures should be run through the material transfer vehicle and paver to heat equipment before paving with HP AC mixture to avoid the mixture sticking in the paver hopper. Aluminum truck beds for hauling the mixture and the use of a good release agent (soap) were noted to prevent sticking and to help mixture slide out when being dumped.

Laboratory Characterization and Performance Evaluation of Binders and Mixtures

The main objective of the laboratory characterization and performance evaluation was to evaluate and compare the performance properties of selected PMA and HP AC mixtures placed on the field projects described earlier in Table 1. This included laboratory testing on collected asphalt binders, sampled plant-produced asphalt mixtures, and field cores collected during construction. It should be noted that throughout the evaluation of plant-produced asphalt mixtures, test specimens were compacted to the initial in-place air-void levels determined through evaluation of corresponding cores sampled from the field. This was performed to ensure a more representative evaluation of the mixtures in the field as their performance characteristics remained highly dependent on the in-place density.

Field Cores: Layer Thickness and In-Place Density

Table 3 summarizes the in-place layer thicknesses and air-void levels. The major change noted among mixtures was that the in-place density of SMA mixtures was higher (air voids lower) compared to SMs regardless of the asphalt binder type (i.e., PMA vs. HP).

Table 3. Summary of In-Place Layer Thickness and Air Voids for Core Samples

Mix ID	VTRC Mix Log ID	Mix Type	VTRC Cores Log ID	Layer Thickness (mm)			In-Place Air Voids (%)		
				Average	CI	Target	Average	CI	Range
A	19-1086	SM-9.0 (HP)	19-1112	20.3	1.7	25.4	7.3	0.6	6.8 to 7.9
B	19-1082	SM-9.5 (PMA)	19-1083	42.9	3.3	38.1	6.3	0.7	5.6 to 7.0
C	19-1087	SM-9.5 (HP)	19-1088	36.6	2.5	38.1	5.5	0.4	5.1 to 5.9
D	19-1062	SM-12.5 (PMA)	19-1056	28.1	2.5	25.4	6.1	0.4	5.7 to 6.5
E	19-1065	SM-12.5 (HP)	--	--	--	--	--	--	6.5 to 7.5[a]
F	19-1111	SMA-9.5 (HP)	19-1113	37.6	3.0	38.1	4.0	0.5	3.5 to 4.5
G	19-1116	SMA-9.5 (HP)	19-1118	42.7	3.1	50.8	4.8	0.6	4.2 to 5.4
H	19-1063	SMA-12.5 (PMA)	19-1064	51.7	4.4	50.8	5.1	0.7	4.3 to 5.8

VTRC = Virginia Transportation Research Council; CI = 95% confidence interval; SM = surface mix; HP = high polymer-modified asphalt binder; PMA = polymer-modified asphalt binders; -- = data not available.

[a] Cores of this mix were not collected; therefore, an in-place density of 93% was estimated for this mix.

Asphalt Binder Testing

Table 4 summarizes the properties of the four evaluated asphalt binders. Testing was performed on original PMA and HP binders. All four binders met the corresponding VDOT specifications (VDOT, 2018). It should be highlighted that typical HP binders show common viscosity values of 4 to 5 Pa.s in the laboratory at a testing temperature of 135°C with the rotational viscometer. These binders are still accepted in practice with no potential clogging issues when pumped (as reported by asphalt contractors) since they are mixed at a temperature much higher than 135°C (around 165°C). At that temperature, the viscosity of HP binders drops significantly to values much lower than 3 Pa.s. Although the viscosity Superpave criterion for asphalt binders was developed without the nature of such paving materials being taken into consideration, additional research is needed either to refine the testing temperature when the rotational viscosity test is conducted (i.e., 165°C instead of 135°C) or to adjust the accept/reject criterion (in this case 3 Pa.s) at 135°C for HP binders. For that purpose, testing reports were collected for HP binders used in Virginia since 2016. The reports included viscosity values at 135°C measured in accordance with AASHTO T 316.

The dataset included 66 viscosity measurements for HP binders produced by two suppliers, denoted here as supplier X and supplier Y for anonymity. Supplier X had 24 measurements and supplier Y had 42 measurements over a period of 5 years: 2016, 5 measurements; 2017, 22 measurements; 2018, 4 measurements; 2019, 25 measurements; and 2020, 10 measurements. Figure 3 shows a box plot of measured viscosities for HP binders. The box plot represents the spread of the viscosity measurements per year and per supplier. The line in the box indicates the median, and the interquartile range (IQR) box represents the middle 50%. In addition, the whisker bars extending from either side of the box represent the ranges for the bottom 25% and the top 25% of the viscosity measurements, not including outliers, which are represented by asterisks (*). The average (mean) of the viscosity measurements per year and per supplier was identified by the circle in the box.

Table 4. Properties of Evaluated PMA and HP Binders

Property	Test Results				Specification	Test Method
	PMA-B1	**PMA-B2**	**HP-B1**	**HP-B2**		
Original Binder						
Flash Point, °C	300	332	340	319	Min. 230	AASHTO T 48
Viscosity at 135°C, Pa.s	1.134	1.250	4.107	3.575	Max. 3.000[a]	AASHTO T 136
Dynamic Shear, G*/sinδ at 76°C and 10 rad/s, kPa	1.165	1.298	3.875	3.524	Min. 1.000	AASHTO T 315
Rolling Thin Film Oven (RTFO) Residue, AASHTO T 240						
Mass Loss, %	-0.23	-0.24	-0.25	-0.14	|Max.| 1.00	AASHTO T 240
Non-Recoverable Creep Compliance,[b] $J_{nr\ 3.2}$ at 3.2 kPa at 64°C for PMA and 76°C for HP, kPa^{-1}	0.349	0.240	0.093	0.059	Max. 0.5 for PMA Max 0.1 for HP	AASHTO T 350
Non-Recoverable Creep Compliance Difference,[b] $J_{nr\ diff}$ at 3.2 kPa at 64°C for PMA and 76°C for HP, %	19.2	17.0	10.4	6.3	--	AASHTO T 350
Creep Recovery,[b] $R_{3.2}$ at 3.2 kPa at 64°C for PMA and 76°C for HP, %	46.8	53.3	91.5	92.2	No spec. for PMA Min. 90 for HP	AASHTO T 350
Pressure Aging Vessel (PAV) Residue, AASHTO R 28						
Dynamic Shear G*sinδ, max. 6,000 kPa, test temp. at 10 rad/s, °C	22	25	16	16	--	AASHTO T 315
Creep Stiffness[c] at 60 s, S, test temp. -12°C for PMA and -18°C for HP, MPa	195	212	176	196	Max. 300	AASHTO T 313
Creep Relaxation[c] at 60 s, m-value, test temp. -12°C for PMA and -18°C for HP, MPa	0.309	0.308	0.314	0.330	Min. 0.300	AASHTO T 313
Continuous Grade						
Performance Grade	77.5-23.1	78.6-23.0	84.9-30.5	84.9-30.7	--	AASHTO M 320
Performance Grade	64E-22	64E-22	76E-28	76E-28	--	AASHTO M 322

B = batch; HP = high polymer-modified asphalt binders; PMA = polymer-modified asphalt binders; -- = data not available.

[a] The viscosity must be less than or equal to 3.0 Pa.s; however, the Engineer may increase the viscosity limit to 5.0 Pa.s if the binder supplier and contractor agree that the binder is suitably workable.

[b] The Multiple Stress Creep Recovery (MSCR) test on RTFO residue should be performed at the PG grade based on the environmental high pavement temperature (i.e., 64°C for PMA and 76°C for HP).

[c] Testing temperature is 10°C warmer than the actual low performance grade.

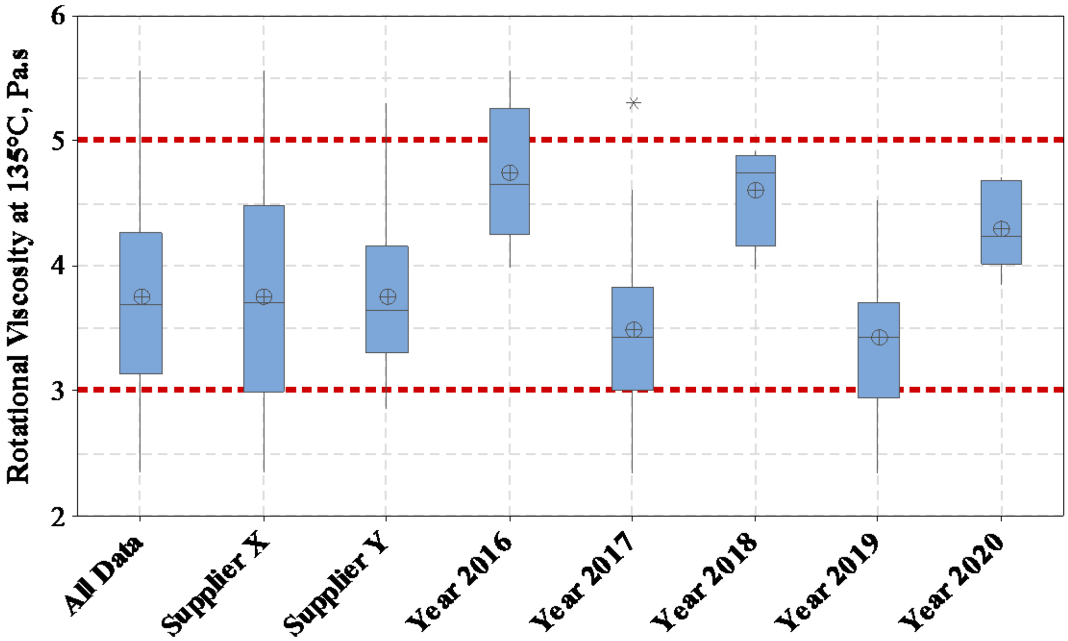


Figure 3. Box Plots of Measured Rotational Viscosities at 135°C for HP Binders Used From 2016-2020. HP = high polymer-modified.

Table 5 lists the descriptive statistics of the measured rotational viscosities for all HP binders including the IQR that was used to evaluate the spread of the measured viscosity. The mean viscosity for all HP binders at 135°C ranged from 2.338 to 5.563 Pa.s (all datasets). Viscosities greater than 5 Pa.s were reported only for years 2016 (by supplier X) and 2017 (by supplier Y).

As opposed to the standard deviation, the IQR is known as a resistant measure in that extreme values (or outliers) do not affect the IQR. By definition, the IQR is calculated as the difference between the 75th percentile (Quartile 3, Q3) and the 25th percentile (Quartile 1, Q1) of a given dataset. The IQR of supplier X was significantly higher than the IQR of supplier Y. Moreover, no consistent trend was observed for the IQR of viscosities throughout the years. It can be seen that the highest IQR values were for 2017 and 2019. When the mean and variability of the measured viscosities for the HP dataset were used, more than 95% of the test values were lower than 5 Pa.s; therefore, the 3 Pa.s threshold viscosity limit measured for asphalt binders (in general) at 135°C could be changed to a 5 Pa.s threshold viscosity limit for HP binders measured at 135°C. HP binders with viscosity values greater than 5 Pa.s at the terminal or mix plant should be rejected. This would help VDOT guarantee a better workability and compactibility of HP AC mixtures when produced and placed in the field. Moreover, no consistent and clear trends showing an increase in viscosity values were observed for HP binders sampled from suppliers' tanks vs. the same HP binders sampled after delivery to the contractors' tanks during production. Therefore, according to the viscosity measurements, and in line with the reported experience of asphalt contactors, the 5 Pa.s cutoff threshold viscosity at 135°C for HP binders could be considered to avoid jeopardizing safety and workability during production at the plant.

Table 5. Descriptive Statistics of Rotational Viscosities for HP Binders

Variable	Components	Rotational Viscosity at 135°C (Pa.s) Mean	Minimum	Quartile 1	Median	Quartile 3	Maximum	Range	IQR
All Data		3.732	2.338	3.191	3.682	4.241	5.563	3.225	1.050
Supplier	X	3.735	2.338	3.038	3.700	4.366	5.563	3.225	1.328
	Y	3.730	2.838	3.353	3.632	4.122	5.287	2.449	0.769
Year	2016	4.725	3.975	4.500	4.650	4.938	5.563	1.588	0.438
	2017	3.473	2.338	3.022	3.419	3.791	5.287	2.949	0.769
	2018	4.588	3.963	4.516	4.744	4.815	4.900	0.937	0.299
	2019	3.405	2.338	2.963	3.425	3.675	4.525	2.187	0.712
	2020	4.280	3.838	4.056	4.232	4.591	4.713	0.875	0.535

IQR = interquartile range.

Asphalt Mixture Testing and Characterization Results

Volumetric Properties and Aggregate Gradations of Mixtures

Volumetric properties and aggregate gradations for the evaluated PMA and HP AC mixtures are shown in Tables 6 and 7, respectively. These results compared well with the quality control and acceptance data available from the producers and VDOT districts, although those data are not shown. The major change noted among mixtures was that the effective binder content of SMA mixtures was higher compared to SMs regardless of the asphalt binder type (i.e., PMA vs. HP), which could be attributed to the gap gradation of SMA mixtures with the intent of having higher design binder contents.

Cantabro Mass Loss

Figure 4 shows the Cantabro mass loss for PMA and HP AC mixtures. The mean mass loss ranged from 1.6% to 9.8%, with an average coefficient of variation (COV) of 10%. As seen, HP AC mixtures had a lower mass loss than PMA AC mixtures. This can be attributed to the ductility induced with the use of high polymer binders. Moreover, SMA mixtures had a lower mass loss than SMs regardless of the asphalt binder type (i.e., PMA vs. HP), which could be attributed to the higher asphalt binder contents of SMA mixtures compared to SMs. Overall, SMA-HP mixtures had the lowest mass loss among all evaluated mixtures, indicating a potential greater durability and resistance to abrasion when subjected to loading.

Dynamic Modulus and Phase Angle Master Curves

The dynamic modulus (|E*|) and phase angle (δ) of the PMA and HP AC mixtures are presented in Figures 5 and 6, respectively. The data in these figures were constructed at a reference temperature of 21°C using the generalized logistic models (for both |E*| and δ data) and the polynomial shift factor. These models and the shift factor result in a better fit to the measured data compared to a conventional sigmoidal function used in the current mechanistic empirical pavement design software (Boz et al., 2017; Oshone et al., 2017; Tavassoti-Kheiry et al., 2017). A higher |E*| value at higher temperatures (and lower frequencies) is often attributed to a potential higher rutting resistance of asphalt mixtures.

Table 6. Volumetric Properties for Evaluated PMA and HP AC Mixtures

Mix Type	HP **SM-9.0**	**Control PMA SM-9.5**	**HP SM-9.5**	**Control PMA SM-12.5**	**HP SM-12.5**	**HP SMA-9.5**		**Control PMA SMA-12.5**
Mixture ID	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
VTRC Log No.	**19-1086**	**19-1082**	**19-1087**	**19-1062**	**19-1065**	**19-1111**	**19-1116**	**19-1063**
Composition								
RAP Content, %	15	15	15	15	15	15	15	15
Asphalt Binder ID	HP-B1	PMA-B2	HP-B1	PMA-B1	HP-B1	HP-B1	HP-B2	PMA-B2
Property								
N_{design}, gyrations	50	50	50	50	50	75	75	75
NMAS, mm	9.0	9.5	9.5	12.5	12.5	9.5	9.5	12.5
Asphalt Content, %	5.94	5.39	5.46	5.51	5.22	6.46	6.68	6.57
Rice SG (G_{mm})	2.445	2.576	2.477	2.555	2.456	2.625	2.595	2.604
VTM, %	4.7	3.2	4.0	3.1	3.3	1.9	2.4	2.5
VMA, %	18.1	15.8	16.5	16.1	14.9	17.9	17.9	18.3
VFA, %	73.9	79.6	75.7	80.8	77.6	89.5	86.6	86.1
FA Ratio	1.00	1.19	0.85	1.18	1.97	1.52	0.37	1.55
Mixture Bulk SG (G_{mb})	2.330	2.493	2.377	2.476	2.374	2.576	2.533	2.538
Aggregate Effective SG (G_{se})	2.678	2.816	2.696	2.796	2.659	2.940	2.912	2.918
Aggregate Bulk SG (G_{sb})	2.675	2.801	2.691	2.789	2.645	2.935	2.879	2.902
Absorbed Asphalt Content (P_{ba}), %	0.04	0.20	0.07	0.09	0.20	0.06	0.41	0.19
Effective Asphalt Content (P_{be}), %	5.90	5.20	5.39	5.42	5.03	6.40	6.30	6.39
Effective Film Thickness (F_{be}), µm	8.1	8.7	9.7	8.3	6.1	9.4	10.5	9.2

B = batch; HP = high polymer-modified asphalt binder; Ndesign = number of Superpave design gyrations; NMAS = nominal maximum aggregate size; PMA = polymer-modified asphalt binder; RAP = reclaimed asphalt pavement; SG = specific gravity; SM = surface mix; SMA = stone matrix asphalt; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate ratio; H, V, and E = high, very high, and extremely high traffic.

Table 7. Aggregate Gradations for Evaluated PMA and HP AC Mixtures

Mix Type	**HP SM-9.0**	**Control PMA SM-9.5**	**HP SM-9.5**	**Control PMA SM-12.5**	**HP SM-12.5**	**HP SMA-9.5**		**Control PMA SMA-12.5**
Mix ID	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
VTRC Log No.	**19-1086**	**19-1082**	**19-1087**	**19-1062**	**19-1065**	**19-1111**	**19-1116**	**19-1063**
Gradation/Sieve Size	**% Passing**							
¾ in (19.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
½ in (12.5 mm)	99.8	99.6	100.0	97.8	100.0	100.0	100.0	83.1
3/8 in (9.5 mm)	97.3	96.9	94.6	90.2	88.9	72.8	61.6	61.1
No. 4 (4.75 mm)	77.1	60.1	60.8	63.0	58.2	27.6	22.6	27.4
No. 8 (2.36 mm)	58.4	39.2	43.5	45.1	46.2	20.4	12.9	20.8
No. 16 (1.18 mm)	45.6	30.6	33.1	35.9	38.3	18.2	10.5	18.6
No. 30 (600 µm)	33.7	22.6	24.2	26.8	29.0	16.5	9.0	17.0
No. 50 (300 µm)	21.1	14.5	15.4	16.8	19.5	14.9	7.5	15.0
No. 100 (150 µm)	11.7	9.2	8.6	9.9	13.1	12.9	5.5	13.0
No. 200 (75 µm)	5.9	6.2	4.6	6.4	9.9	9.7	2.3	9.9

HP = high polymer-modified asphalt binder; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt.

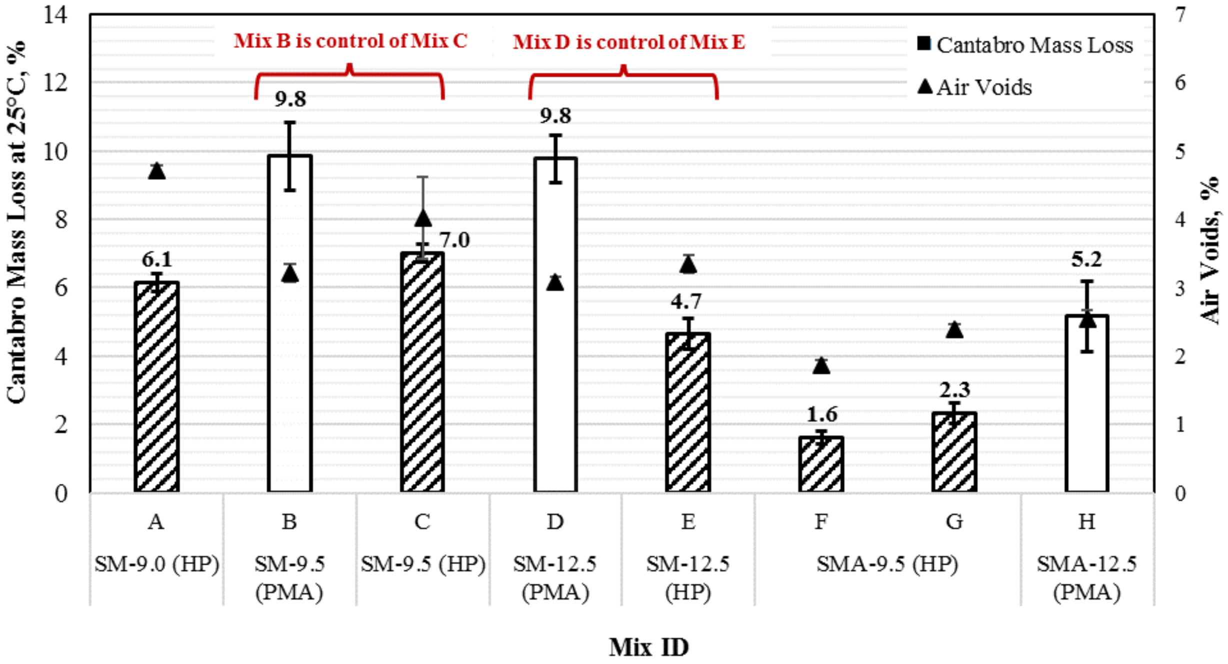
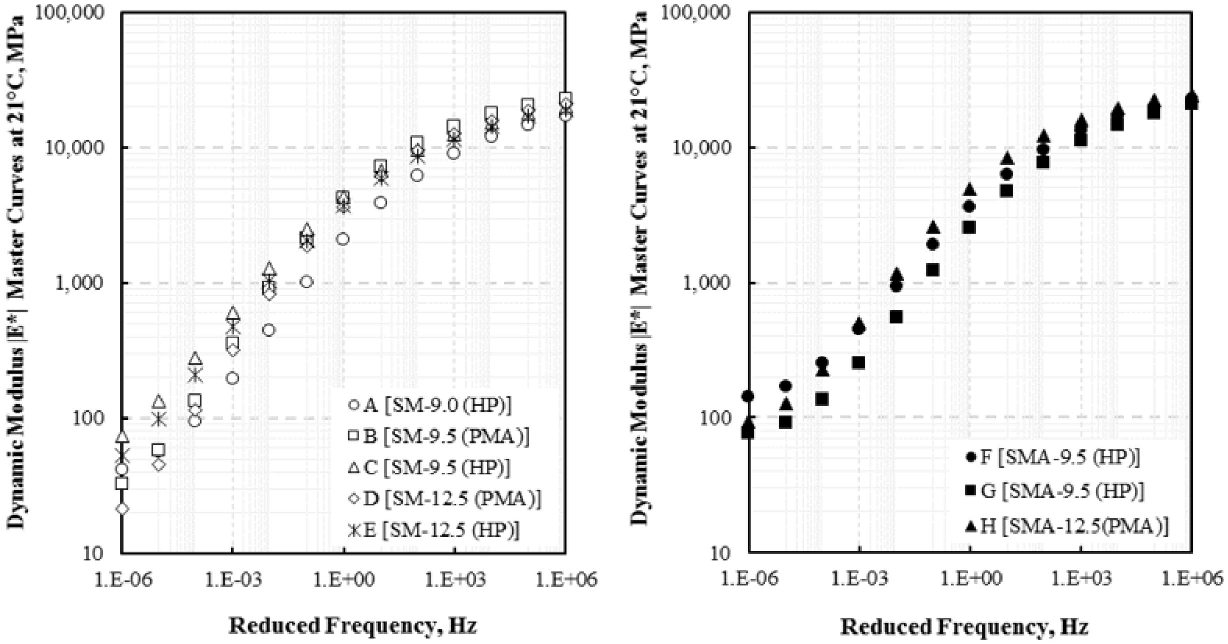
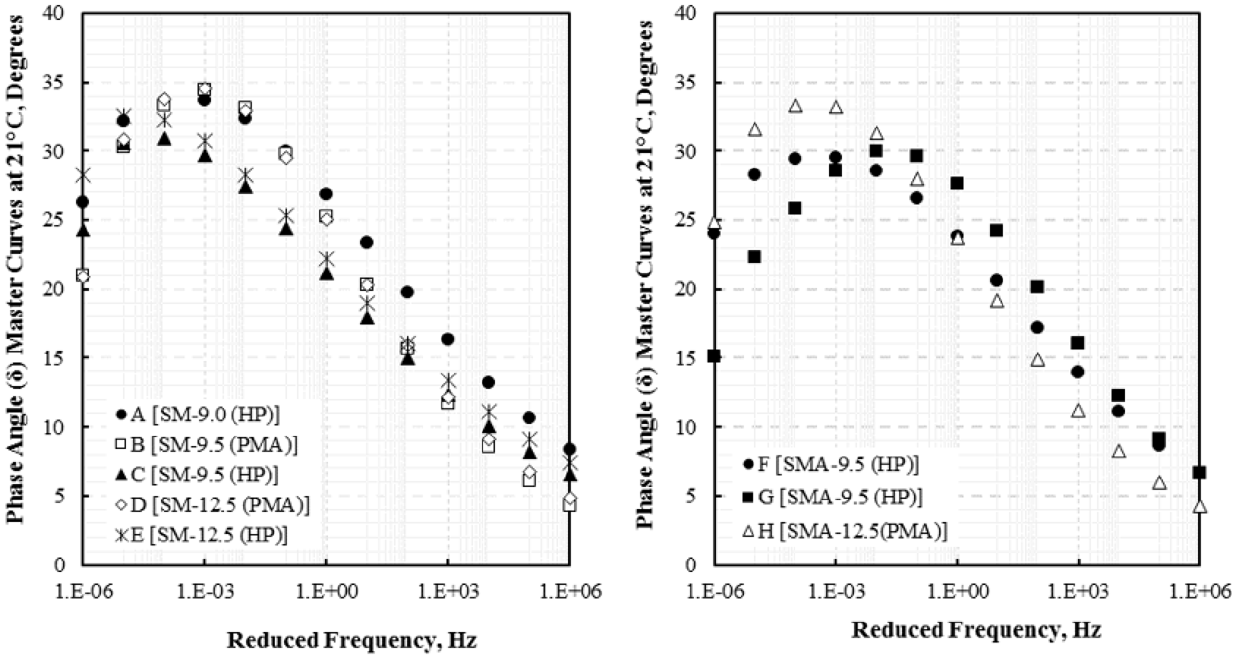


Figure 4. Performance Test Data for Cantabro Mass Loss of PMA and HP Mixtures. I-bars indicate mass loss variability plus/minus standard deviation. HP = high polymer-modified asphalt binder; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt.



(a) **(b)**

Figure 5. Dynamic Modulus |E*| Master Curves for PMA and HP AC Mixtures: (a) SM; (b) SMA. HP = high polymer-modified asphalt binder; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt.



(a) **(b)**

Figure 6. Phase Angle (δ) Master Curves for PMA and HP AC Mixtures: (a) SM; (b) SMA. HP = high polymer-modified asphalt binder; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt.

The data in Figure 5 showed that SMA mixtures had a higher |E*| values at lower frequencies than SMs, regardless of the binder type, indicating a potential higher resistance to rutting and shoving. A higher |E*| value and lower δ at lower temperatures (and higher frequencies) are often associated with a potential higher cracking susceptibility of asphalt mixtures. All mixtures had similar |E*| values at higher frequencies. No clear trends were observed for the |E*| values among SM-PMA, SM-HP, SMA-PMA, and SMA-HP mixtures. This could be attributed to the interaction of multiple factors affecting the |E*| measurements, including the nominal maximum aggregate size (NMAS) of the mixture, mineralogy and morphological characteristics of the aggregates, binder content, variability of the RAP material incorporated, and in-place air voids. It should be noted that all E* specimens were compacted to the in-place air-void range of corresponding field sections. Also, all HP and PMA mixtures included 15% RAP regardless of the mixture type (SM vs. SMA). Figure 6 showed that the majority of HP mixtures had lower δ values than the PMA mixtures, indicating the potential for higher cracking resistance among the six mixtures. Overall, SMA-HP mixtures had the highest |E*| at high temperature and the lowest δ values across the loading spectrum, indicating a promising performance of this type of mixture at low, intermediate, and high temperatures.

Rutting Performance

Two performance tests were considered to assess the resistance of PMA and HP AC mixtures to rutting. These tests represent two levels of testing: intermediate and advanced. The intermediate level included the APA rut test, which needs longer times for specimen preparation and testing. The advanced level included the RLT test, which requires more specimen preparation, including cutting and/or coring, and more test/analysis time, including multiple days to complete and analyze the test results.

APA Rut Test. Figure 7 shows the APA rut depths measured after application of 8,000 loading cycles at 64°C for all PMA and HP AC mixtures. Two sets of specimens were considered for the APA rut test: Set I included specimens compacted to the in-place air-void range (see Table 3), and Set II included specimens compacted to the 7.0 ± 0.5% air-void level in accordance with AASHTO T 340. The mean APA rut depths of Set I ranged from 1.2 to 4.7 mm, with an average COV of 9.2%. For Set II, relatively greater mean APA rut depths ranging from 2.6 to 6.0 mm, with an average COV of 16.7%, were found. The specimens of Set I were compacted to an air-void level relatively lower than for the specimens of Set II, indicating a decrease in the APA rut depth with the decrease in specimen air-void level. Overall, HP mixtures had less rutting when compared with PMA mixtures regardless of mixture type (i.e., SM vs. SMA), which can be attributed to the high polymer modification. Moreover, SMA-HP mixtures had the lowest rut depth among all evaluated mixtures, indicating a promising rutting performance at high temperatures and/or under heavy/slow traffic.

VDOT does not specify a pass/fail criterion for the APA rut depth of mixtures subjected to heavy traffic. However, the APA testing protocol followed in this study matched the protocol provided as part of NCHRP Report 673, *A Manual for Design of Hot-Mix Asphalt With Commentary* (Advanced Asphalt Technologies, 2011). As part of that effort, the guidelines generated for highly trafficked mixtures recommended a maximum allowable APA rut depth of 3 mm for specimens compacted to an air-void level of 4.0 ± 0.5%. Highly trafficked mixtures were defined as mixtures designed to withstand a traffic level of more than 30 million ESALs.

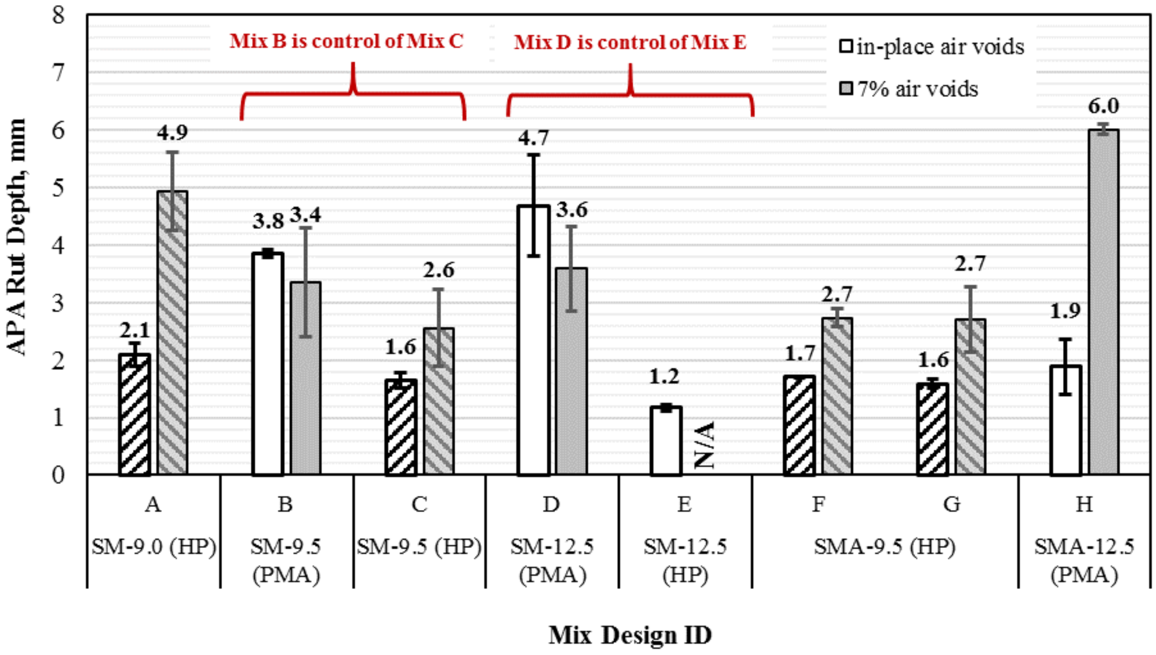
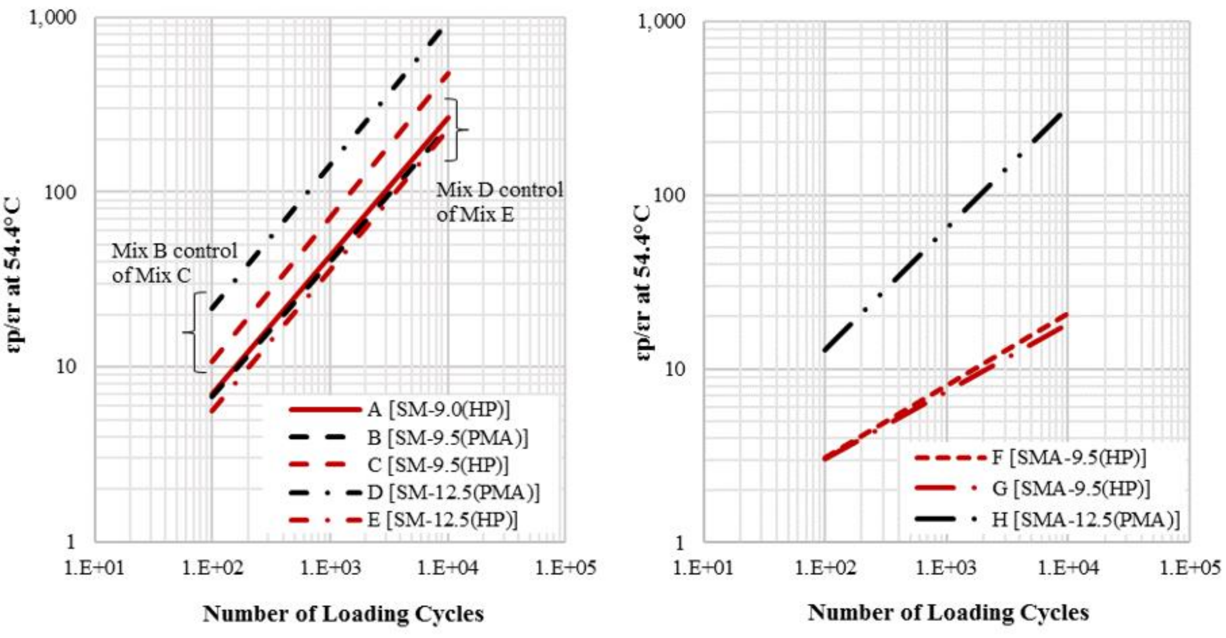


Figure 7. Performance Test Data for APA Rut Depth at 64°C and 8,000 Loading Cycles of PMA and HP Mixtures. I-bars indicate rut variability: plus/minus standard deviation. HP = high polymer-modified asphalt binders (hatched bars); N/A = data not available; PMA = polymer-modified asphalt binders (plain bars); SM = surface mix; SMA = stone matrix asphalt.

In this study, the APA test results indicated that the evaluated mixtures are not expected to exhibit excessive rutting in the field with the exception of two SM-PMA AC mixtures. Mixture B and Mixture D had relatively higher APA rut depths. However, the in-place air-void ranges of these two mixtures significantly exceeded the 4 ± 0.5% considered in NCHRP Report 673. Therefore, it is possible that these two mixtures may not exhibit excessive rutting in the field if placed at lower air-void contents. It is noteworthy that some HP mixtures/specimens (e.g., Mixture A) that were compacted to an air-void level significantly greater than 4 ± 0.5% still had an APA rut depth less than 3 mm.

Repeated Load Triaxial Test. Figure 8 shows the rutting relationship at 54.4°C for all PMA and HP AC mixtures. The rutting relationship was defined as the resulting cumulative permanent axial strain (ε_p) over the resilient strain (ε_r) function of the number of load repetitions (N). The rutting characteristic (i.e., $\varepsilon_p/\varepsilon_r$ vs. N) indicates the response of the asphalt mixture to repeated loading at high temperatures. A lower characteristic indicates lower accumulated permanent strains with loading, thus indicating a better resistance to rutting. Further, a flatter curve indicates a lower susceptibility of the asphalt mixtures to rutting by repeated loading. It should be noted that the test has been proven to be sensitive to the air-void level of the asphalt mixtures where, in general, a better resistance to rutting is expected with the decrease in air-void level, to a certain minimum value. Table 8 summarizes the FN values, ε_p, at the number of cycles corresponding to the FN ($\varepsilon_{p \text{ at FN}}$) and the FN index, defined as the ratio between $\varepsilon_{p \text{ at FN}}$ and FN expressed as a percentage (Zhang et al., 2013).



(a) **(b)**

Figure 8. Rutting Characteristic at 54.4°C for PMA and HP AC Mixtures: (a) SM; (b) SMA. HP = high polymer-modified asphalt binders; PMA = polymer-modified asphalt binders; SM = surface mix; SMA = stone matrix asphalt.

Table 8. Summary of Rutting Performance for Evaluated PMA and HP AC Mixtures

Mix Type	**SM-9.0 (HP)**	**SM-9.5 (PMA)**	**SM-9.5 (HP)**	**SM-12.5 (PMA)**	**SM-12.5 (HP)**	**SMA-9.5 (HP)**		**SMA-12.5 (PMA)**
Mixture ID	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Asphalt Content, %	5.9	5.4	5.5	5.5	5.2	6.5	6.7	6.6
FN, cycles	774	860	335	176	925	10000	7942	497
$\varepsilon_{p \text{ at FN}}$, %	5.1	9.2	7.4	9.8	6.9	3.5	2.7	13.5
FN Index, %	0.0065	0.0107	0.0221	0.0559	0.0075	0.0004	0.0003	0.0272

PMA = polymer-modified asphalt binders; HP = high polymer-modified asphalt binders; AC = asphalt concrete; FN = flow number.

Based on the data presented in Figure 8, HP AC mixtures had lower rutting relationships when compared with their PMA control AC mixtures regardless of the mixture type (SM vs. SMA), indicating a better rutting resistance, which can be attributed to the impact of high polymer modification. Moreover, SMA mixtures showed lower and flatter rutting curves when compared with SMs regardless of the asphalt binder type (PMA vs. HP). Overall, SMA-HP mixtures showed the lowest and flattest rutting curves associated with the lowest FN index values among all evaluated mixtures, indicating a very promising rutting resistance during the life of the pavement.

A significant difference in the laboratory rutting resistance among asphalt mixtures will not necessarily translate into the same difference in rutting performance of the AC pavement in the field. Many factors may greatly affect the rutting life of an AC pavement such as stiffness, the developed compressive strain in each of the AC sublayers under field loading, the rutting characteristic of the evaluated asphalt mixture, and the interaction of all these factors. In a mechanistic pavement analysis, an AC layer with higher stiffness and a lower laboratory rutting life (i.e., PMA AC mixtures when compared with HP AC mixtures) may have lower compressive strains in the AC sublayers under field-loading conditions and thus have a better pavement rutting life. Therefore, a full mechanistic analysis coupled with laboratory-measured engineering and performance properties would be necessary to quantify and evaluate effectively the impact of HP binder on the rutting performance of the corresponding AC pavement.

Cracking Performance

Three performance tests were considered to assess the resistance of PMA and HP AC mixtures to cracking. These tests belong to three levels of testing: basic, intermediate, and advanced. The basic level included the IDT test characterized by a short time for specimen preparation and testing without requiring any specific cutting, coring, and gluing. The intermediate level included the OT that needs a longer time for specimen preparation and testing. The advanced level included the direct tension cyclic fatigue test that required operations of cutting and/or coring to prepare the specimens and multiple days to complete and analyze the test results.

Indirect Tensile Test. Two sets of specimens were considered for the IDT test: Set I included specimens compacted to the in-place air-void range (see Table 3), and Set II included specimens compacted to a 7.0 ± 0.5% air-void level in accordance with ASTM D8225-19. Figures 9 and 10 show the results of CT and FST indices for all PMA and HP AC mixtures, respectively. The data presented in these figures did not include any outliers.

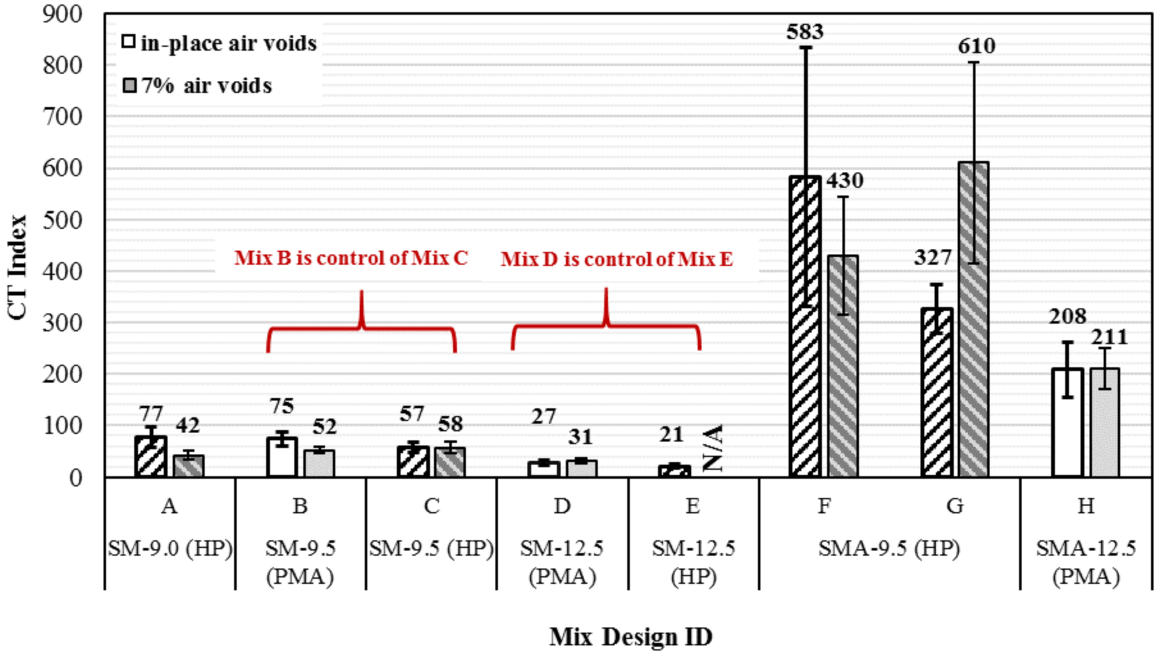


Figure 9. Performance Test Data for IDT CT Index of PMA and HP Mixtures at 25°C. I-bars indicate CT index variability: plus/minus one standard deviation. IDT = indirect tensile; CT = cracking tolerance; HP = high polymer-modified asphalt binders (hatched bars); N/A = not available; PMA = polymer-modified asphalt binders (plain bars); SM = surface mix; SMA = stone matrix asphalt.

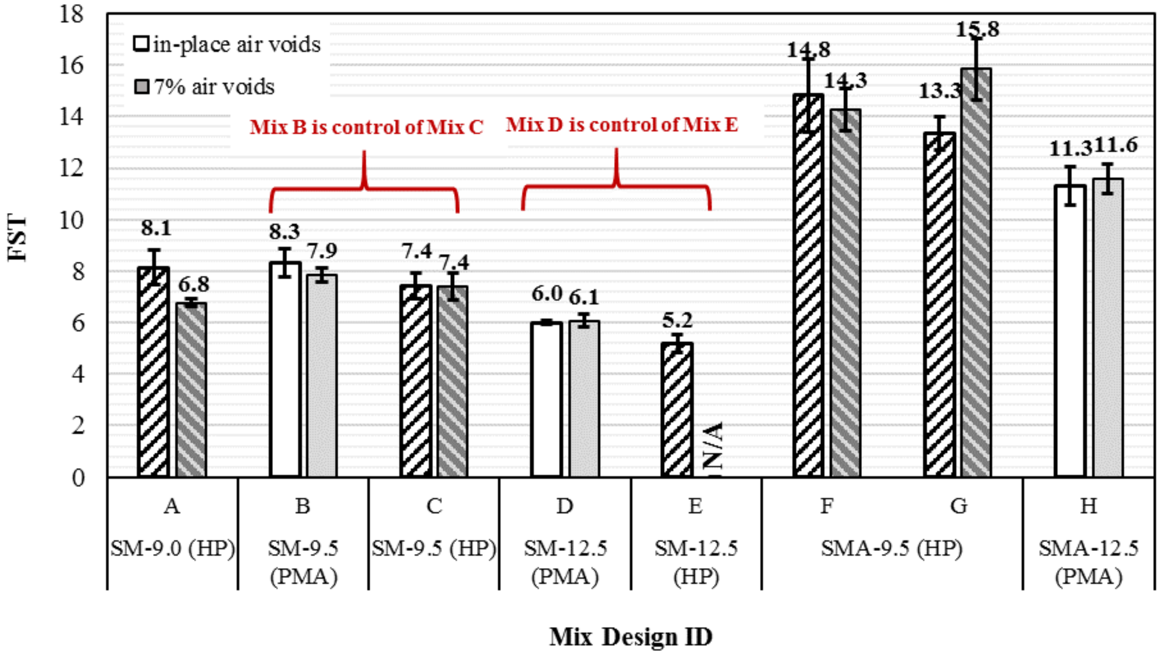


Figure 10. Performance Test Data for IDT FST of PMA and HP Mixtures at 25°C. I-bars indicate FST variability: plus/minus one standard deviation. IDT = indirect tensile; FST = fracture strain tolerance; HP = high polymer-modified asphalt binders (hatched bars); N/A = data not available; PMA = polymer-modified asphalt binders (plain bars); SM = surface mix; SMA = stone matrix asphalt.

The Dixon Q outlier test (Minitab, 2018) was performed at a significance level of 5% on both indices to identify and remove outlier(s) from the datasets. The CT index and FST values are indicators of cracking performance for asphalt mixtures. Higher CT index and FST values generally indicate a better cracking resistance of the evaluated mixture and, hence, less cracking potential in the field. The mean (i.e., average) CT index of Set I ranged from 21 to 583, with a COV ranging from 14.3% to 43.1%. For Set II, mean CT index values were similar, ranging from 31 to 610 with a COV ranging from 11.2% to 32.0%. The mean FST for Set I ranged from 5.2 to 14.8 with a COV ranging from 1.4 to 9.5%. For Set II, the mean FST values were similar, ranging from 6.1 to 15.8 with a COV ranging from 1.9% to 7.5%. It should be remembered that the specimens of Set I were compacted to an air-void level relatively lower than the specimens of Set II. Overall, the CT index showed a significantly greater variability when compared with the FST, which could be attributed to the calculation of a slope as part of the CT index (Seitllari et al., 2020).

For VDOT practices, there are currently no pass/fail criteria for the CT or FST index when PMA and HP mixtures are evaluated. It is evident from Figures 9 and 10 that the differences in the magnitude of CT index and FST values between SMs and SMA mixtures were large and unexpectedly high regardless of asphalt binder type (i.e., PMA vs. HP). SMA mixtures had much higher CT index and FST values when compared with those of SMs. However, as noted in ASTM D8225-19, the range for an acceptable CT index value is highly dependent on mixture type and associated specific application. Therefore, a quantitative evaluation of cracking performance should be performed only among mixtures of the same type (i.e., SM vs. SMA). The SM-PMA and SM-HP mixtures had statistically similar CT index and FST values, indicating that the IDT test could not detect the expected impact of high polymer modification in improving the cracking resistance of SMs. The SMA-HP mixtures had statistically greater CT index and FST values when compared with those of SMA-PMA mixtures, indicating a better resistance to cracking, which could be attributed to the compatibility of the expansion effect of polymers in HP binders and the differences in volumetric properties and aggregate gradation characteristics of SMA mixtures. Overall, SMA-HP mixtures indicated the most promising cracking performance among all evaluated mixtures based on laboratory testing.

Previous studies also showed numerous limitations of using the IDT test and its associated indices to evaluate the cracking performance of asphalt mixtures (Boz et al., 2020, 2021; Seitllari et al., 2020). These limitations included the lack of sensitivity to air-void level and stiffness. Although higher densities of pavements would result in better cracking performance, CT index values were higher with the increase in air-void level regardless of the asphalt mixture and binder type. Moreover, the use of higher RAP contents would result in a decrease of the cracking performance life for pavements. However, for a given design, mixtures with higher RAP contents had greater CT index and FST values regardless of binder type. In this study, the IDT test had inconsistent results when the impact of high polymer modification on the cracking performance of SMs and SMA mixtures was evaluated. Although various factors including the differences in mixture compositions could have led to such inconsistent results, it is expected that mixtures with a higher polymer content would be more resistant to cracking (Habbouche et al., 2020). Future efforts should be considered by VDOT to assess the feasibility of using the IDT test at intermediate temperatures to evaluate the cracking resistance of PMA and HP mixtures.

Texas Overlay Test. Figure 11 shows the number of cycles at 25°C at which each evaluated AC mixture reached a 93% reduction in initial load. A higher number of OT cycles to failure indicates a better resistance to reflective cracking. Specimens compacted to an in-place air-void range were evaluated only by the OT. In general, confounding effects of asphalt binder type (PMA vs. HP) and other factors such as morphological characteristics of aggregates had a significant impact on the reflective cracking behavior of the evaluated AC mixtures. For all HP AC mixtures, a similar or greater number of OT cycles to failure were observed when compared with the respective PMA AC control mixtures regardless of the mixture type (SM vs. SMA), thus indicating an increased flexibility and resistance to reflective cracking of the HP AC mixtures under different environmental conditions. In addition, a significantly greater number of OT cycles to failure were observed for SMA mixtures. Further, SMA-HP mixtures had the greatest number of OT cycles to failure among all evaluated AC mixtures.

The OT data were further analyzed to quantify the resistance of the evaluated mixtures to cracking initiation and cracking propagation in accordance with the approach of Garcia et al. (2016). The crack initiation is represented and evaluated using the critical fracture energy (G_c), and the resistance to cracking during the propagation of the crack is evaluated using the CPR. A greater G_c value indicates that the evaluated AC mixture is tough and requires high initial energy to initiate a crack. On the other hand, a greater CPR value indicates that the evaluated AC mixture is more susceptible to cracking (a fast crack propagation indicates a shorter reflective cracking life).

Figure 12 shows a design interaction graph plotting G_c vs. CPR for all PMA and HP AC mixtures. Four categories were identified on this interaction plot:

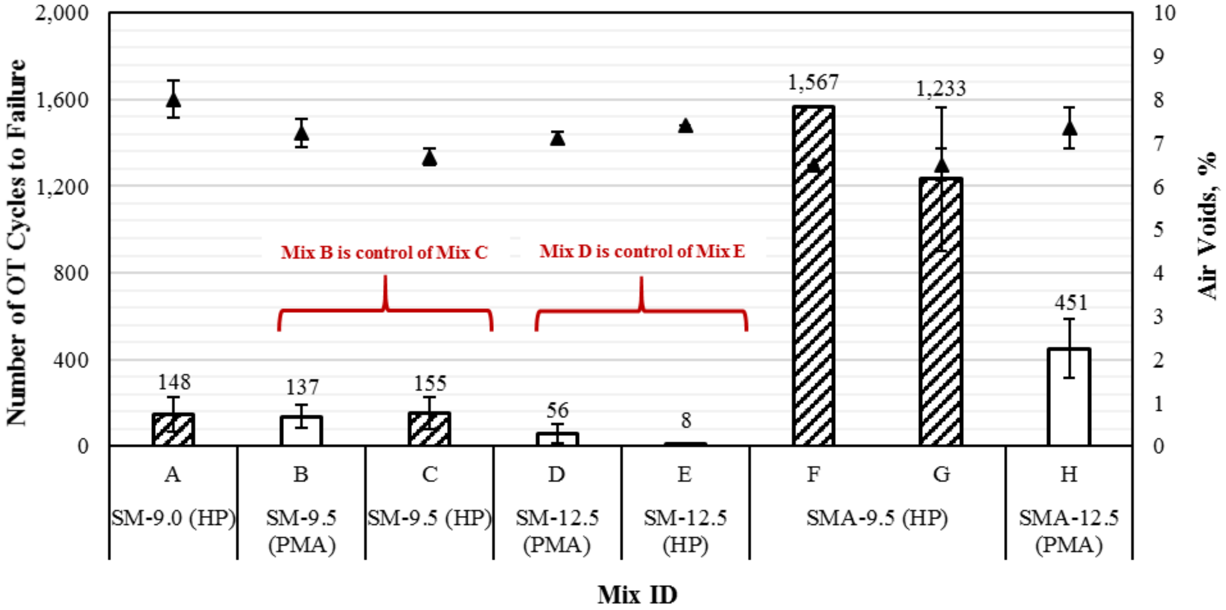
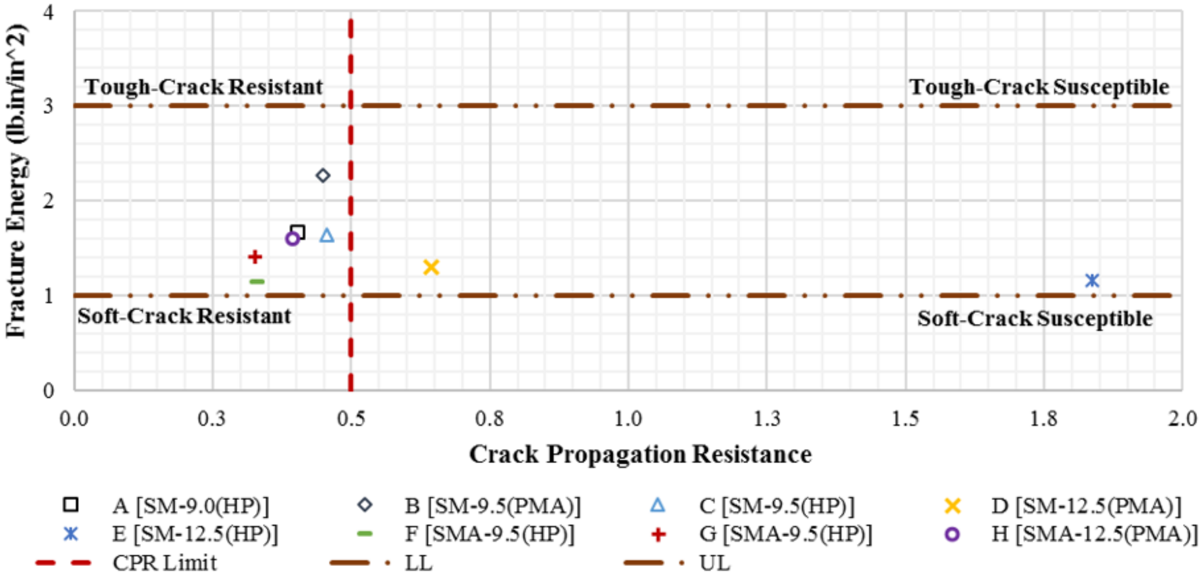


Figure 11. Performance Test Data for OT of PMA and HP Mixtures at 25°C. I-bars indicate the variability of OT cycles: plus/minus one standard deviation. OT = overlay test; HP = high polymer-modified asphalt binders; PMA = polymer-modified asphalt binders; SM = surface mix; SMA = stone matrix asphalt.



*1 lb.in/in^2 = 17.86 kg.m/m^2

Figure 12. Cracking Resistance Interaction Plot for PMA and HP AC Mixtures. HP = high polymer-modified asphalt binders; LL = lower limit; N/A = data not available; PMA = polymer-modified asphalt binders; SM = surface mix; SMA = stone matrix asphalt; UL = upper limit.

1. *Tough-crack resistant:* simulating a good resistance in both crack initiation (i.e., higher G_c values) and crack propagation (flexible or crack resistant) (i.e., lower CPR values).

2. *Tough-crack susceptible:* simulating a good resistance in crack initiation (i.e., higher G_c values) but susceptible to crack propagation (brittle) (i.e., higher CPR values).

3. *Soft-crack resistant:* simulating softness and susceptibility to crack initiation (i.e., lower G_c values) but a slow-down of the propagation of the crack (flexible) (i.e., lower CPR values).

4. *Soft-crack susceptible:* simulating a significantly poor resistance to both crack initiation (i.e., lower G_c values) and crack propagation (brittle) (i.e., higher CPR values).

A preliminary threshold for a CPR of 0.5 was proposed (Garcia et al., 2016). Moreover, preliminary limits for the G_c were identified: an upper limit of 3 to screen the evaluated AC mixtures with high brittleness potential and a lower limit of 1 to guarantee a minimum stability under traffic of the evaluated mixtures. It should be noted that these thresholds were used for comparison purposes only. Independent efforts should consider defining new thresholds specifically for PMA and HP AC mixtures. As seen in Figure 12, all mixtures except Mixtures D and E had a CPR value lower than 0.5, indicating good cracking resistance. Moreover, all mixtures had a G_c from 1 to 3, indicating good resistance to crack initiation. SMA-HP mixtures (Mixtures F and G) showed the most soft-crack-resistant behavior among the evaluated mixtures, and Mixture D showed the most soft-crack-susceptible behavior.

Direct Tension Cyclic Fatigue Test. Figure 13 shows the fatigue characteristics at 25°C of all PMA and HP AC mixtures. A fatigue characteristic for each mixture was developed by fitting a power regression function between the number of cycles to failure and the applied strain levels. A higher and flatter fatigue curve indicates a better resistance to fatigue cracking. Fatigue performance was better for the HP AC mixtures than for the PMA AC mixtures at all strain levels, thus indicating increased flexibility under different environmental conditions regardless of the mixture type (SM vs. SMA). The noticeably better fatigue performance for HP AC mixtures can be mainly attributed to the dominant behavior of the additional polymer. Fatigue performance was better for SMA mixtures than for SMs regardless of the binder type (PMA vs HP). However, a difference in the laboratory fatigue resistance will not necessarily translate into the same difference in fatigue performance of the AC pavement in the field.

The Sapp index, developed by the FHWA, can be used as another parameter to indicate cracking performance (FHWA, 2019). This index accounts for the material's modulus and its toughness with regard to its potential to resist fatigue cracking. After testing, it was found that none of the PMA and HP specimens had failed even after being subjected to the maximum number of loading cycles at the selected strain levels. In other words, PMA and HP specimens should have been evaluated at higher strain levels to induce failure. Therefore, the Sapp indices were not reported as part of this study.

As stated previously, a difference in the laboratory cracking resistance will not necessarily translate into the same difference in cracking performance of the AC pavement in the field. Many factors affect the cracking life of an AC pavement such as stiffness, the developed tensile strain under field loading, the cracking performance characteristic of the evaluated asphalt mixture, and the interaction of all of these factors. Therefore, a full mechanistic analysis would be necessary to evaluate effectively the impact of HP binder on the cracking performance of the corresponding AC pavement.

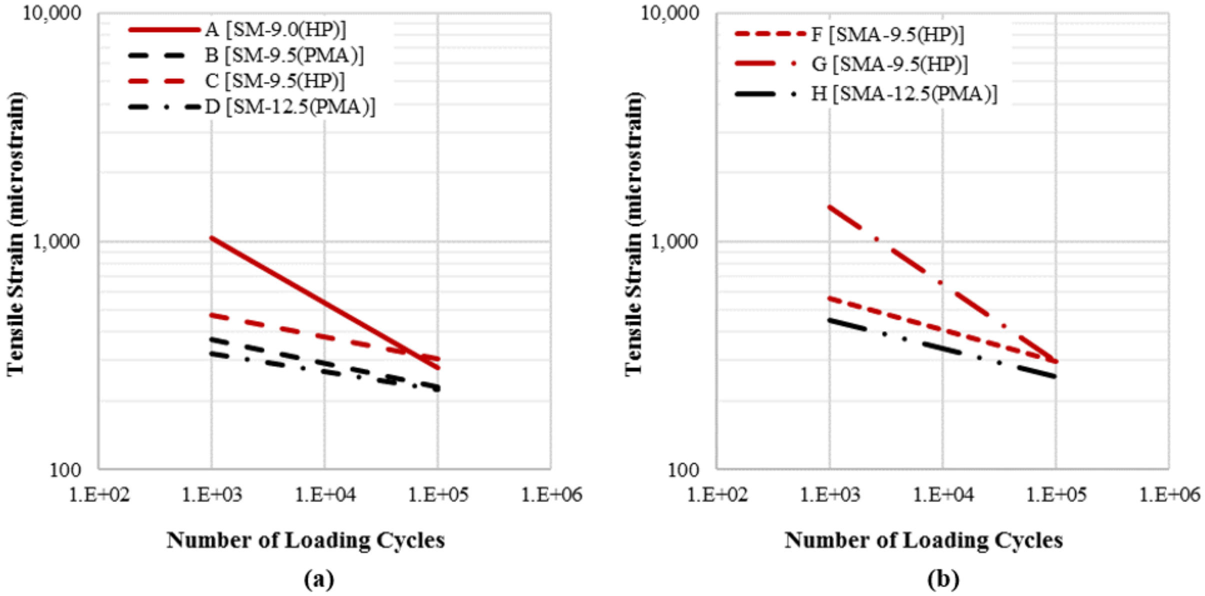


Figure 13. Fatigue Characteristics for All PMA and HP AC Mixtures at 25°C: (a) SM; (b) SMA. HP = high polymer-modified asphalt binders; AC = asphalt concrete; PMA = polymer-modified asphalt binders; SM = surface mix; SMA = stone matrix asphalt.

Performance Evaluation of Field Cores

Field core samples collected just after pavement construction were used to measure in-place layer thickness and air voids (see Table 5). In addition, the cracking resistance of these cores was evaluated by means of the IDT test and OT at 25°C. These 150-mm-diameter cores had a thickness less than the 62-mm and 37.5-mm thickness set forth for typical IDT test and OT specimens, respectively. The research team acknowledges the variation that might be induced with high variations from the target heights; therefore, the data generated were used for comparison purposes especially with plant-produced laboratory-compacted specimens to assess the impact of specimen preparation type (laboratory vs. field compaction) and other components such as in-place densities. No cores were sampled for Mixture E; therefore, no data are available. Figure 14 shows the CT and FST indices of all cores by mixture type. Similar observations could be made: SM-PMA and SM-HP mixtures had statistically similar CT and FST values, whereas SMA-HP mixtures had greater index values when compared with SMA-PMA mixtures. Figure 15 shows the number of cycles to failure and an interaction plot determined by the OT. All mixtures had a CPR value lower than 0.5, indicating good cracking resistance. Moreover, all mixtures had a G_c closer to 1, indicating a promising resistance to crack initiation that can be induced because of the polymer modification. It can also be seen that CPR and G_c decreased with the increase of polymer content (PMA vs. HP), indicating the positive impact of HP on the resistance to reflective cracking.

Evaluation of In-Service Field Performance

Since 2015, HP AC overlays have been placed at several sections over cracked JCPs and composite (BOJ) and flexible (BIT) pavements in Virginia, as shown in Table 9. These routes were mainly located in three VDOT districts: NOVA, Richmond, and Hampton Roads, with a majority in the NOVA District on I-95 and I-495. Currently, HP mixtures are not differentiated from other dense-graded mixtures (e.g., “E” mixtures) in the PMS. This makes identifying their use and performance more difficult. To support their identification for future study, beginning and end mileposts were provided in Table 9 to document the locations of HP projects. The approximate quantity of each type of HP AC mixture per district per year is summarized in Table 10. Few selected PMA control field projects were considered under this effort. Distress data for the selected pavement sections were obtained from the PMS database for all HP and PMA control sections. The collected distress data covered one or multiple maintenance and/or rehabilitation cycles of various alternatives prior to the application of HP or PMA AC overlays. A quantification of the condition trend was carried out through calculation of the CCI loss rate for each treatment cycle of every considered field section. These values are summarized in Table 11.

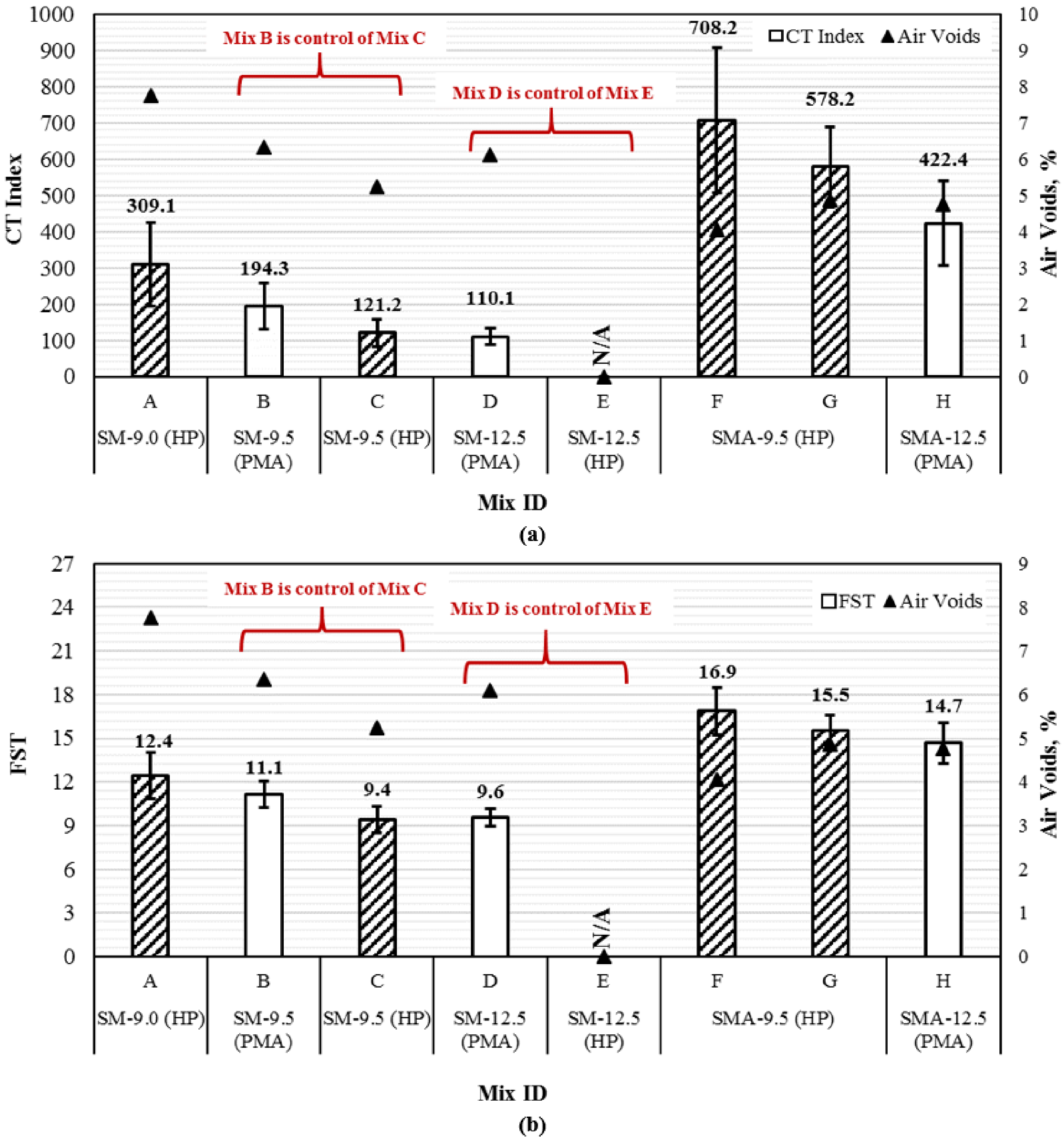
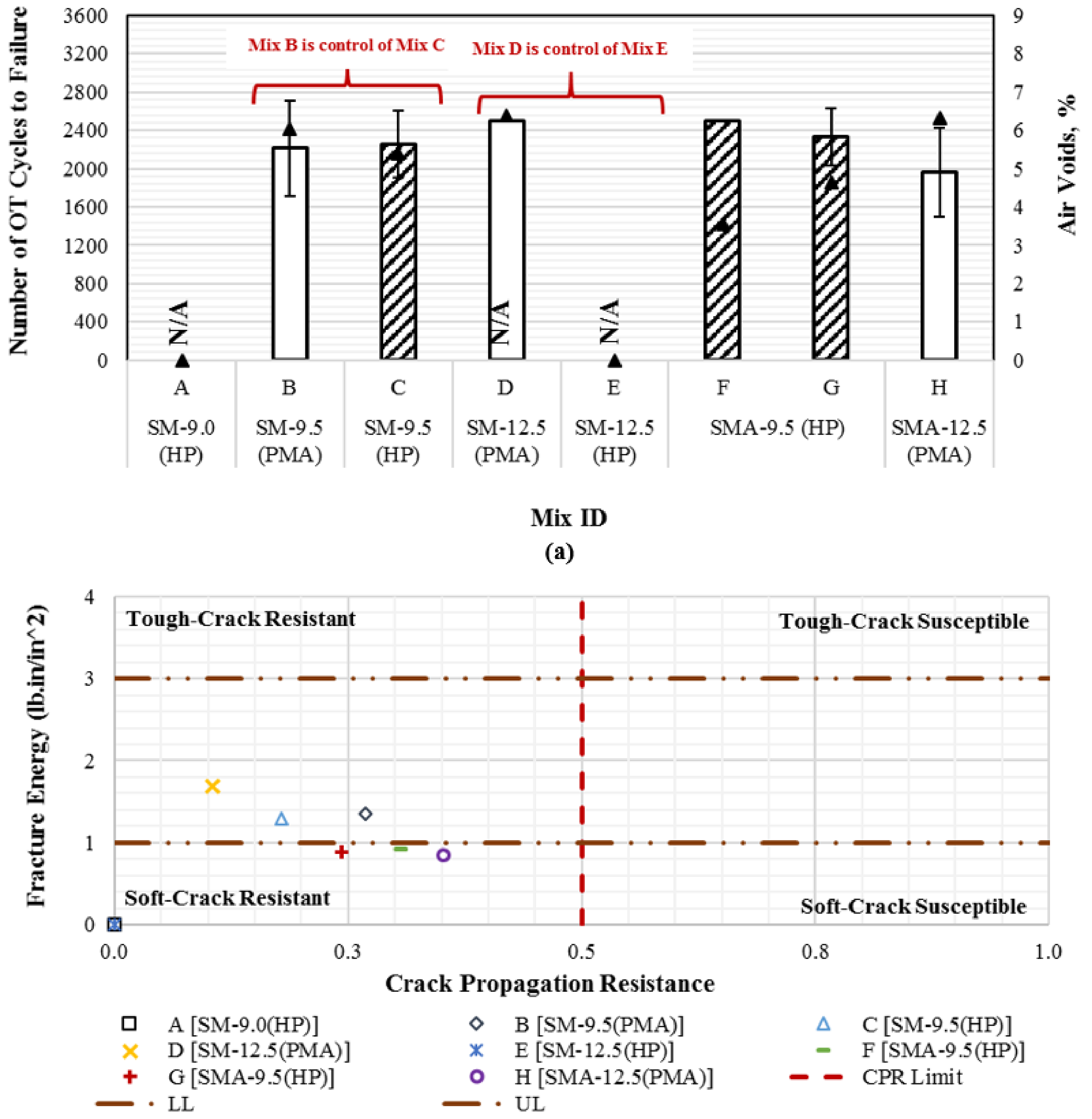


Figure 14. Performance Test Data for IDT Test of PMA and HP Mixtures at 25°C: (a) CT index; (b) FST. I-bars indicate CT index variability: plus/minus standard deviation. IDT = indirect tensile; CT = cracking tolerance; FST = fracture strain tolerance; HP = high polymer-modified asphalt binders; N/A = not available; PMA = polymer-modified asphalt binders; SM = surface mix; SMA = stone matrix asphalt.



(b)

Figure 15. Performance Test Data for OT of PMA and HP Mixtures at 25°C: (a) number of cycles to failures; (b) interaction plot. I-bars indicate the variability of the test cycles: plus/minus standard deviation. HP = high polymer-modified asphalt binders; LL = lower limit; N/A = not available; PMA = polymer-modified asphalt binders; SM = surface mix; SMA = stone matrix asphalt; UL = upper limit.

Table 9. Summary of Selected Route Sections With HP and a Few Control PMA Overlays in Virginia

No.	Route	County / County Mileposts	Pavement Type	Activity		Year of Prior Rehabilitation
				Details	Year	
1	I-95SB	Prince William, 0.02-3.89	BOJ	Milling 2.0 in SM-12.5 E(HP) 2.0 in	2015	2009
2	I-95SB	Prince William, 10.98-13.12	BOJ	Milling 2.5 in SMA-9.5 E(HP) 1.5 in SMA-9.0 E(HP) 1.0 in	2015	2007
3	I-95NB	Prince William, 0.07-3.92	BOJ	Milling 2.0 in SM-12.5 E(HP) 2.0 in	2015	2008
4	I-495NB	Fairfax, 5.56-6.63	BOJ	Milling 2.0 in SM-12.5 E(HP) 2.0 in	2016	2012
5	I-95SB	Hanover, 2.76-5.63	BOJ	Milling 3.5 in SMA-19.0 E 2.0 in SMA-12.5 E(HP) 1.5 in	2016	2002
C6	I-95NB	Henrico, 7.33-9.55	BOJ	Milling 3.5 in SMA-9.5 E 1.5 in SMA-19.0 E 2.0 in	2015	2004
7	I-64EB	York, 14.81-20.55	BOJ	New Construction THMACO 0.75 in SMA-12.5 E(HP) 2.0 in	2017	N/A (new construction)
8	I-64WB	York, 14.98-20.33	BOJ	New Construction THMACO 0.75 in SMA-12.5 E(HP) 2.0 in	2017	N/A (new construction)
9	I-95NB	Fairfax, 3.41-4.45	BIT	Milling 2.0 in SM-12.5 E(HP) 2.0 in	2017	2010
10	I-495NB	Fairfax, 1.194-3.66	BOJ	Milling 4.0 in SM-9.0 E(HP) 1.0 in SMA-9.5 E(HP) 1.5 in	2018	2014
11	I-95NB	Prince William, 11.121-12.64	BOJ	Milling 2.0 in SM-12.5 E(HP) 2.0 in	2018	2011

PMA AC = polymer-modified asphalt binders; BIT = bituminous pavement; BOJ = bituminous over jointed concrete pavement; CRC = continuously reinforced concrete; HP = high polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt; THMACO = thin hot mix asphalt concrete overlay; E = binder designation for heavy traffic defined as PG 64E-22 equivalent to PG 76-22.

Table 10. Type and Quantity of HP Mixtures per Mix Type per District

Year	Comments: Mix Type / District	Quantity of HP AC Mixes Produced (tons)	
		Specific per Mix Type and District	Total
2014	SM-9.5 / NOVA (trial section)	N/A	N/A
2015	SM-9.0 / NOVA	4,808	44,084
	SM-12.5 / NOVA	31,972	
	SMA-9.5 / NOVA	7,304	
2016	SM-12.5 / NOVA	5,643	11,848
	SMA-9.5 / Richmond	6,205	
2017	SM-12.5 / Hampton Roads	11,726	69,744
	SMA-12.5 / Hampton Roads	24,005	
	SM-9.5 / NOVA	3,904	
	SM-12.5 / NOVA	25,954	
	SM-12.5 / Richmond	4,155	
2018	SM-9.5 / NOVA	974	12,635
	SM-12.5 / NOVA	11,661	
2019	SM-9.0 / NOVA	17,724	65,923
	SM-9.5 / NOVA	6,598	
	SMA-9.5 / NOVA	41,601	

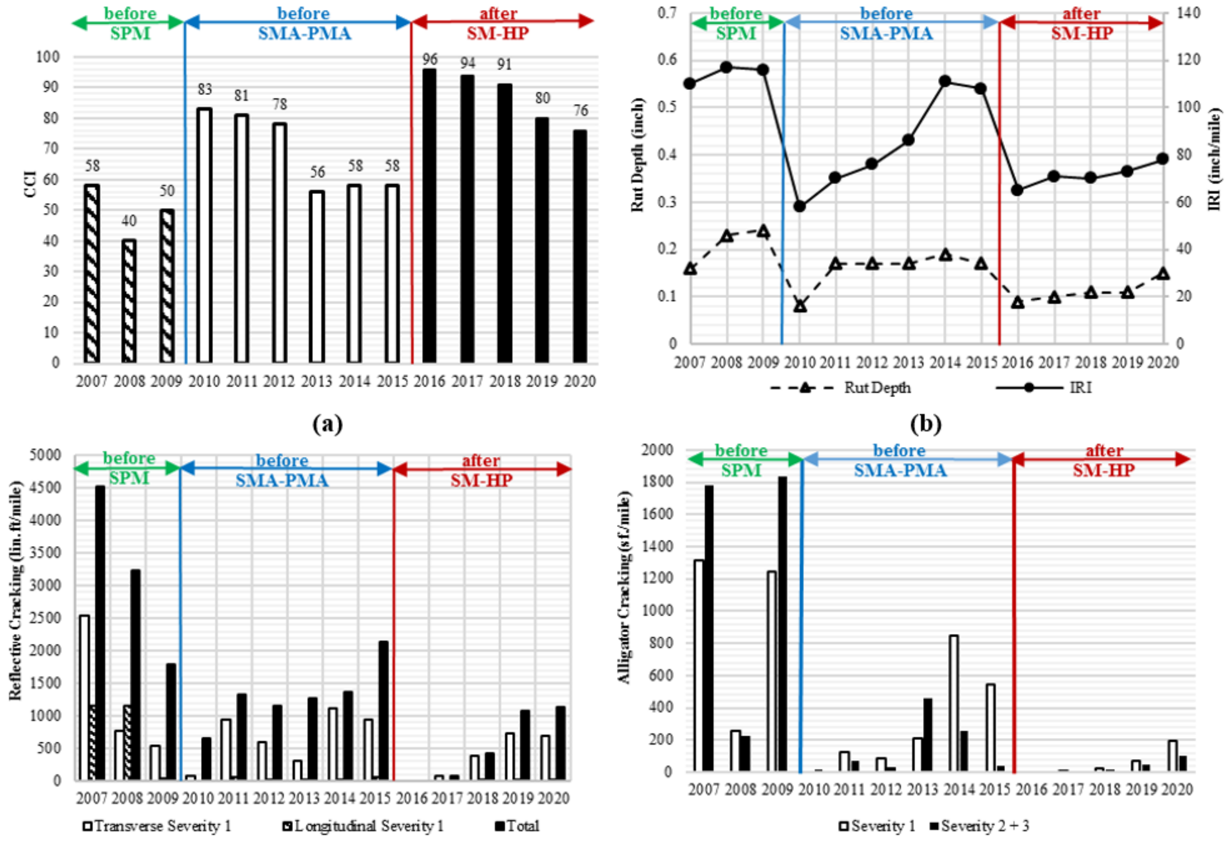
HP = high polymer-modified asphalt binder; N/A = not available; SM = surface mix; NOVA = Northern Virginia; SMA = stone matrix asphalt.

Table 11. Quantitative Evaluation of CCI for All Considered Pavement Sections

Project ID	Route, County, Mileposts	Pavement Type	Treatment Cycle: Time	Treatment Cycle: Overlay Mix Type	Treatment Cycle: Loss Rates (CCI units/year)
1	I-95SB, Prince William, 0.02-3.89	BOJ	2010-2015	SMA-PMA	6.2
			2016-2020	SM-HP	5.4
2	I-95SB, Prince William, 10.98-13.12	BOJ	2008-2015	SMA-PMA	6.7
			2016-2020	SMA-HP	2.9
3	I-95NB, Prince William, 0.07-3.92	BOJ	2009-2015	SMA-PMA	9.5
			2016-2020	SM-HP	5.0
4	I-495NB, Fairfax, 5.56-6.63	BOJ	2013-2016	Latex Modified	6.5
			2017-2020	SM-HP	5.5
5	I-95SB, Hanover, 2.76-5.63	BOJ	2007-2016	Latex Modified	2.4
			2017-2018	SMA-HP	1.6
C6	I-95NB, Henrico, 7.33-9.55	BOJ	2008-2015	SM-D	5.5
			2016-2020	SMA-PMA	2.3
7	I-64EB, York, 14.81-20.55	BOJ	2018-2020	SMA-HP + THMACO	--
8	I-64WB, York, 14.98-20.33	BOJ	2018-2020	SMA-HP + THMACO	--
9	I-95NB, Fairfax, 3.41-4.45	BIT	2007-2017	SM-D	4.0
			2018-2020	SM-HP	--
10	I-495NB, Fairfax, 1.194-3.66	BOJ	2012-2019	SM-PMA	8.3
			2019-2020	SMA-HP	--
11	I-95NB, Prince William, 11.121-12.64	BOJ	2012-2018	SM-PMA	6.9
			2019-2020	SM-HP	--

CCI = Critical Condition Index; -- = CCI loss rate was not calculated because of limitations in data; BIT = bituminous; BOJ = bituminous over jointed; HP = high polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt; SM-D = surface mixture with D designation (using unmodified asphalt binder PG 64H-22); THMACO = thin hot mix asphalt concrete overlay; Latex Modified = surface treatment; E = binder designation for heavy traffic defined as PG 64E-22 equivalent to PG 76-22.

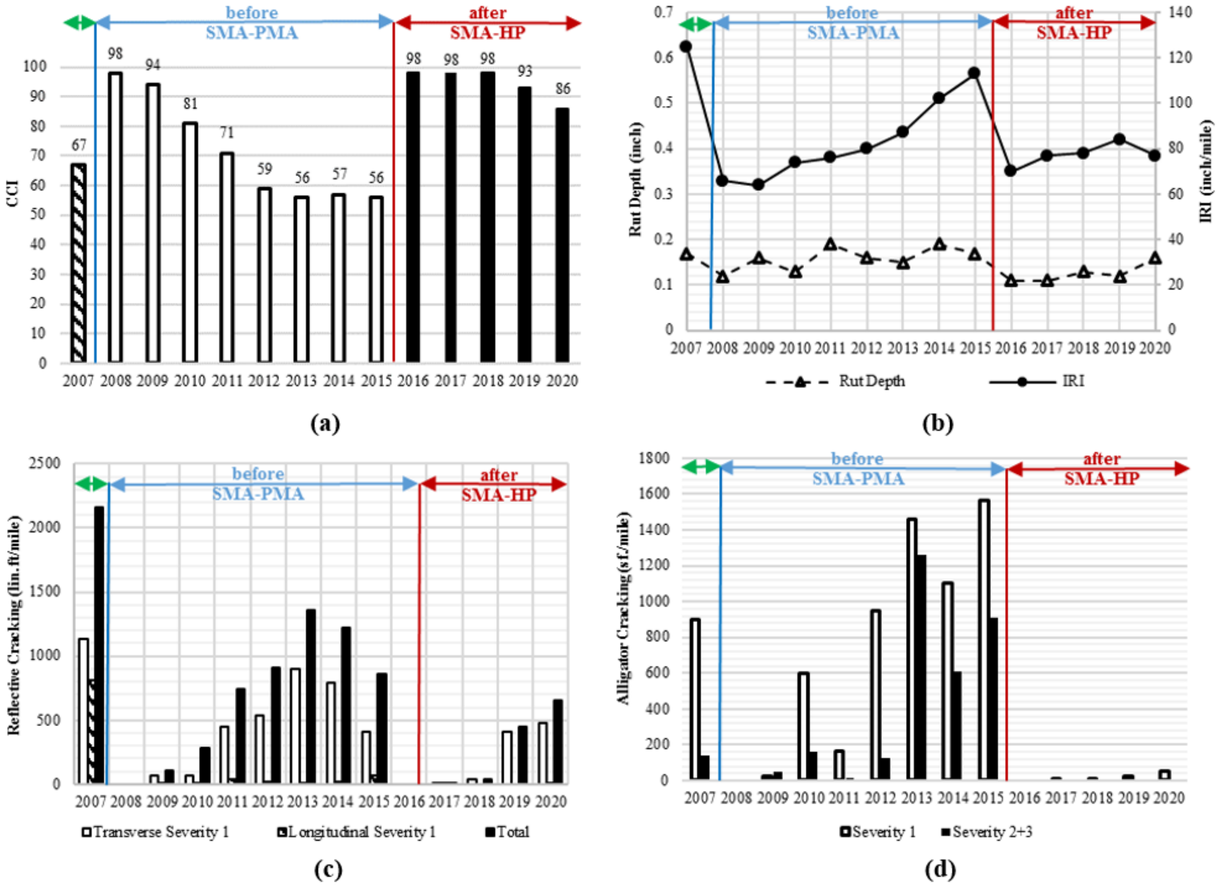
Figure 16 shows some of the distress data before and after placement of an HP AC overlay for field project 1 (details shown in Table 9). CCI values varied considerably with respect to time as a function of the treatment applied, as shown in Figure 16a. There was a negligible decrease in the CCI from 2016 to 2018 followed by a slightly greater decrease in 2019 and 2020. CCI values were higher at the first few years of service life for the SM-HP overlay (CCI loss rate of 5.4 units per year) when compared with the SMA-PMA overlay (produced using a conventional PMA PG 76-22 binder) applied during the previous maintenance cycle (CCI loss rate of 6.2 units per year). As seen in Figure 16b, rut depths were lower (~0.1 in) for the SM-HP overlay when compared with the SMA-PMA overlay placed in the prior treatment cycle (~0.18 in). As can also be seen in Figure 16b, IRI values were less than 80 in/mi, indicating a relatively smooth pavement even after 5 years of service. The increase rate of IRI for SM-HP pavement was lower than for the SMA-PMA surface. Less reflective cracking and alligator cracking were reported for the 2016-2020 period when compared with the 2010-2015 period (Figures 16c and 16d). This can be attributed to the improvement in mixture performance properties because of high polymer modification.



(a) (b) (c) (d)

Figure 16. Distress Data Before and After HP Treatment for BOJ Project 1: (a) CCI; (b) rut depth and IRI; (c) reflective cracking; (d) alligator cracking. HP = high polymer-modified asphalt binder; BOJ = bituminous over jointed; CCI = Critical Condition Index; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt; SPM = Superpave plant mix.

Figure 17 shows some of the distress data before and after placement of an HP AC overlay for field section 2 (details are shown in Table 9). CCI values varied considerably throughout time as a function of the treatment applied, as shown in Figure 17a. There was a negligible decrease in CCI from 2016 to 2019 followed by a slightly greater decrease in 2020. Similar to field section 1, CCI values were greater during the first few years of service for the SMA-HP overlay when compared with the SMA-PMA overlay applied during the previous maintenance cycle (2008-2015). Moreover, the SMA-HP overlay had a CCI loss rate of 2.9 units per year, compared to 6.7 units per year for the SMA-PMA overlay, indicating a potential much longer expected service life of the overlay, which is attributable to the increase in polymer content for the same mixture type. Rut depths were lower for the SMA-HP overlay when compared with the SMA-PMA overlay (Figure 17b). IRI values were less than 85 in/mi, indicating a relatively smooth pavement even after 5 years in service. The increase rate of IRI for SMA-HP pavement was lower than for the SMA-PMA surface (Figure 17b). A negligible amount of top-down and bottom-up fatigue cracking was reported for the 2016-2020 period (when SMA-HP was applied) when compared with the 2008-2015 period (when SMA-PMA was applied). A negligible amount of reflective cracking was reported during the first 2 years of service for SMA-HP (i.e., 2017 and 2018). The amount of reflective transverse cracking increased slightly for SMA-HP overlay during 2019 and 2020.



(a)

(b)

(c)

(d)

Figure 17. Distress Data Before and After HP Treatment for BOJ Project 2: (a) CCI; (b) rut depth and IRI; (c) reflective cracking; (d) alligator cracking. HP = high polymer-modified asphalt binder; BOJ = bituminous over jointed; CCI = Critical Condition Index; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt.

Figure 18 shows some of the distress data before and after placement of an HP AC overlay for field section 3 (details are shown in Table 9). CCI values also varied considerably throughout time as a function of the treatment applied for this section (Figure 18a). There was a negligible decrease in CCI from 2016 to 2018 followed by a slightly greater decrease in 2019 and 2020. Likewise, CCI values were greater at the first few years of service life for the SM-HP overlay (CCI loss rate of 5.0 units per year) when compared with the 9.5 units per year for the SMA overlay applied during the previous maintenance cycle. Both overlay types (i.e., SMA-PMA and SM-HP) showed a similar rutting performance through their in-service years (Figure 18b). IRI values ranged from 60 to 80 in/mi, indicating a relatively smooth pavement, even after 5 years of service. The rate of change of IRI for SM-HP pavement was less than that for SMA-PMA pavement (Figure 18b). Less reflective cracking, top-down cracking, and bottom-up fatigue cracking were reported for the 2016-2020 period when compared with the 2010-2015 period (Figures 18c and 18d), which can be attributed to the improvement in mixture performance properties because of high polymer modification. It is noteworthy that the amount of some of the distresses (i.e., reflective cracking) increased considerably during 2019 and 2020.

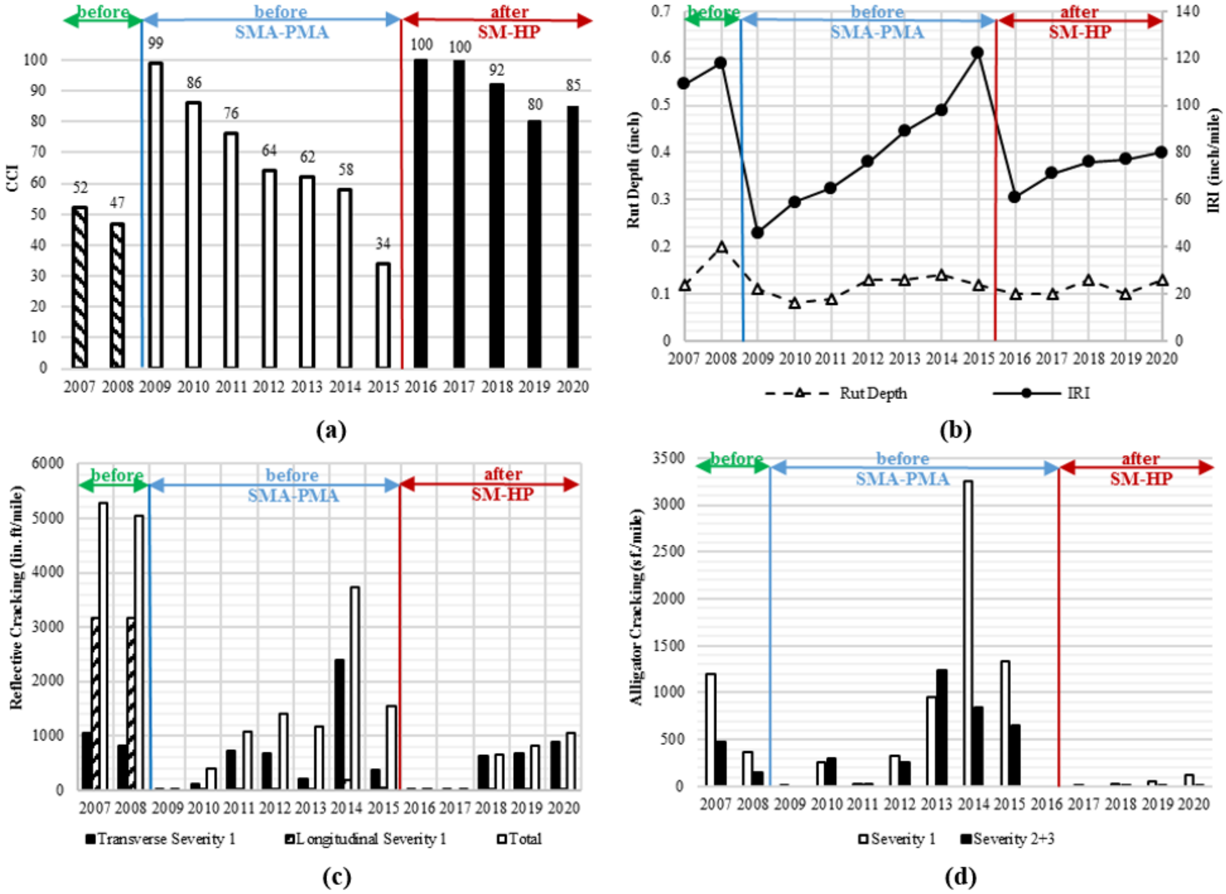


Figure 18. Distress Data Before and After HP Treatment for BOJ Project 3: (a) CCI; (b) rut depth and IRI; (c) reflective cracking; (d) alligator cracking. HP = high polymer-modified asphalt binder; BOJ = bituminous over jointed; CCI = Critical Condition Index; IRI = International Roughness Index; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt.

Figure 19 shows some of the distress data before and after placement of an HP AC overlay for field section 4 (details are shown in Table 9). Figure 19a shows that CCI values varied in a similar way throughout the SM-HP overlay cycle when compared with the previous cycle during which latex modified surface treatment was applied. Both cycles showed a steep decrease in CCI from 100 to ~80 through the first 3 to 4 years of service life, indicating a potential controlling effect of the joint condition of the underlying JCP layer. The CCI loss rate was 6.5 and 5.5 units per year for the latex modified surface treatment and SM-HP overlay, respectively. IRI values (90 to 100) were higher for the HP cycle when compared with the latex modified surface treatment cycle (80 to 90), indicating a relatively less smooth surface. Rut depths were lower during the HP overlay cycle (Figure 19b), which can be attributed to the high polymer modification in enhancing the mixtures' overall performance properties. Although IRI and rut depth values increased, as expected, with the increase of service life for the most recent cycle, CCI values and amounts of reflective and alligator cracking were lower for 2020 when compared with the period 2017-2019 (Figures 19c and 19d). It should be mentioned that no maintenance activities were reported in 2019.

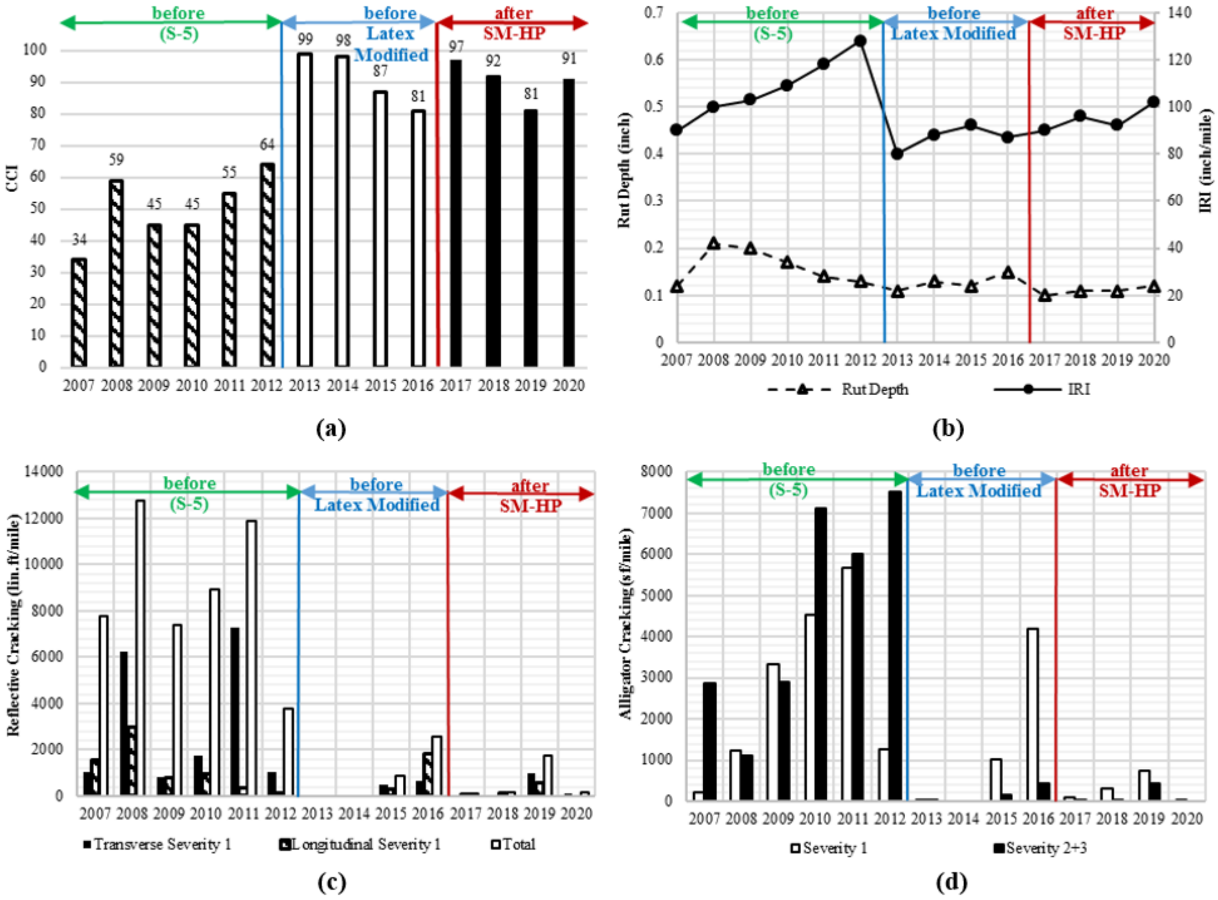
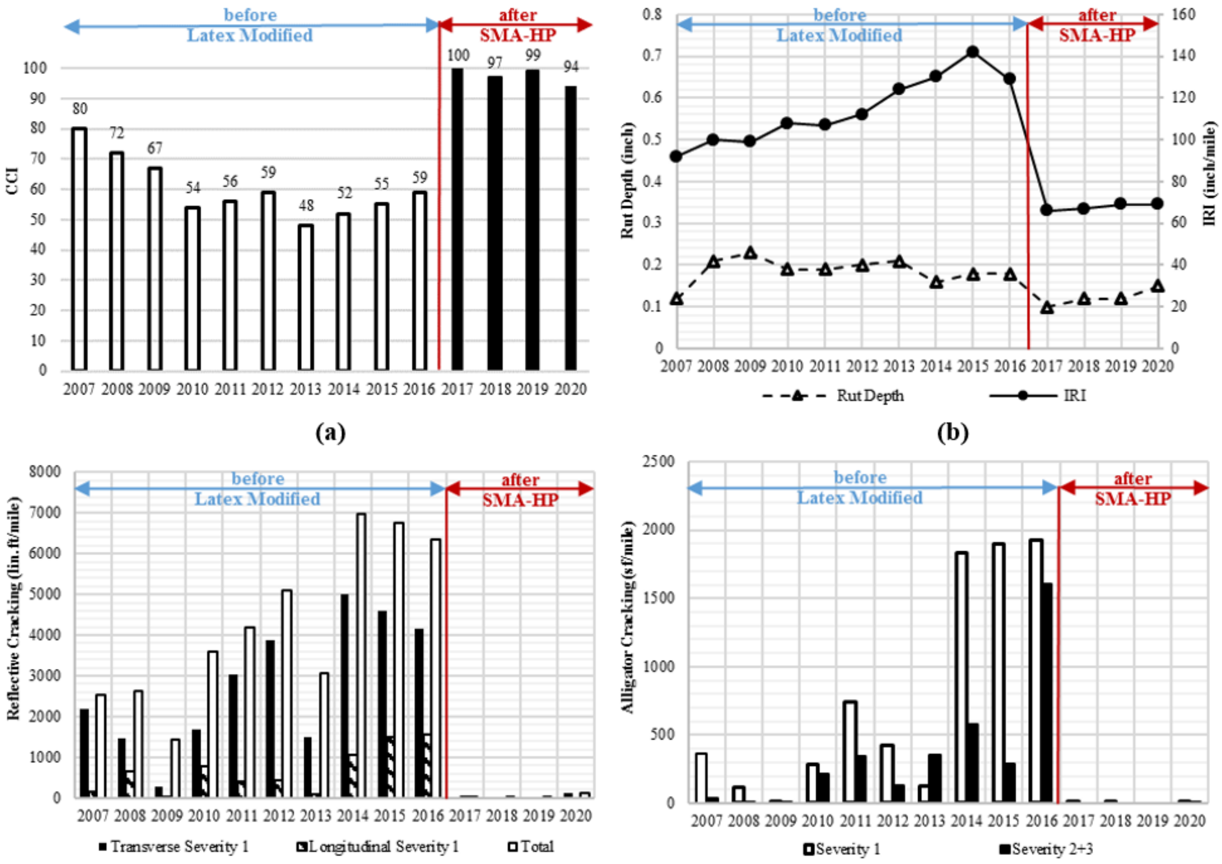


Figure 19. Distress Data Before and After HP Treatment for BOJ Project 4: (a) CCI; (b) rut depth and IRI; (c) reflective cracking, (d) alligator cracking. HP = high polymer-modified asphalt binder; BOJ = bituminous over jointed; IRI = International Roughness Index; PMA = polymer-modified asphalt binder; SM = surface mix; S-5 = surface mix designed following the Marshall procedure.

Figure 20 shows some of the distress data before and after placement of an HP AC overlay for BOJ field section 5 (details are shown in Table 9). There was no large decrease in CCI values during the 4 years of service for the SMA-HP overlay (Figure 20a), confirming a promising field performance when such a technology (HP modification) is used with SMA mixtures (a CCI loss rate of 1.6 units per year). The latex modified surface treatment applied during the previous treatment cycle was placed in 2002; therefore, it took this treatment only 5 years to reach a CCI of 80, which is significantly faster than for the SMA-HP treatment (CCI of 94) after 4 years in service. This observation was made based on the assumption that no significant changes in traffic occurred and that there were no significant structural changes to the underlying structure, which may not hold true. The latex modified treatment had a CCI loss rate of 2.4 units per year. Rut depths were lower during the SMA-HP cycle when compared with the latex modified surface treatment cycle (Figure 20b). IRI values for the SMA-HP treatment cycle were less than 70 in/mi, indicating a relatively smooth pavement even after 4 years in service (Figure 20b). Minor amounts of reflective and alligator cracking were reported throughout the 4 years in service of the SMA-HP overlay treatment (Figures 20c and 20d).

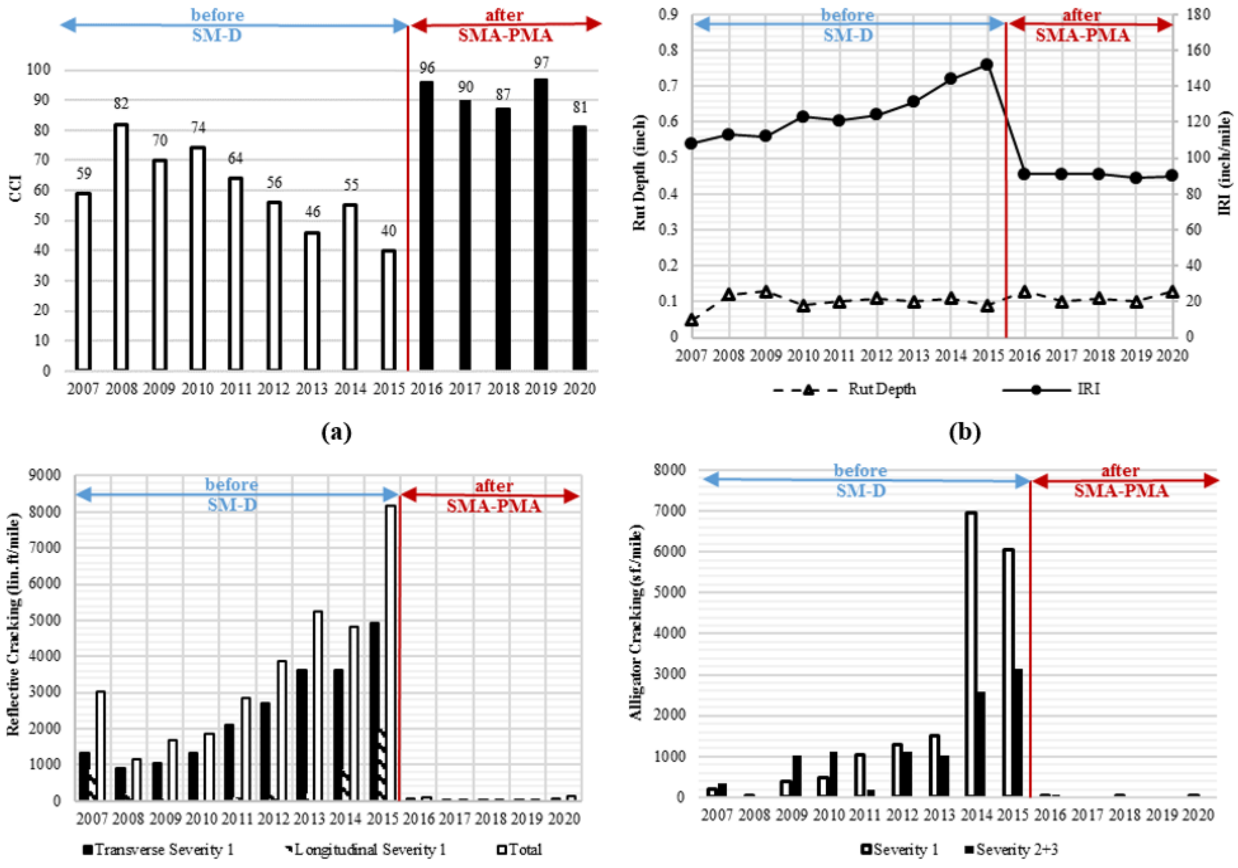


(a) (b)

(c) (d)

Figure 20. Distress Data Before and After HP Treatment for BOJ Project 5: (a) CCI; (b) rut depth and IRI; (c) reflective cracking; (d) alligator cracking. HP = high polymer-modified asphalt binder; BOJ = bituminous over jointed; CCI = Critical Condition Index; IRI = International Roughness Index; PMA = polymer-modified asphalt binder; SMA = stone matrix asphalt.

Figure 21 shows some of the distress data before and after placement of a PMA AC overlay for BOJ field section C6. It should be noted that section C6 was constructed to serve as a PMA control for HP field section 5 in Richmond (details are shown in Table 9). CCI values varied considerably throughout time as a function of the treatment applied (Figure 21a). Data are for two consecutive cycles: a cycle featuring the use of a conventional SMA-PMA mixture, and a cycle featuring the use of an asphalt mixture with an unmodified asphalt binder (SM-12.5D). The SMA-PMA overlay had a CCI loss rate of 2.3 units per year, much lower than for the SM-D overlay (i.e., 5.5 units per year), which can be attributed to the impact of polymer modification of asphalt binders in general. Both overlays (i.e., SM-D vs. SM-HP) showed a similar rutting performance through their in-service years (Figure 21b). IRI values for the SMA-PMA treatment cycle were constant and in the range of 95 in/mi throughout the 4 years in service (Figure 21b). However, significantly lower amounts of reflective cracking, top-down cracking, and bottom-up fatigue cracking were reported for the 2016-2020 period when compared with the 2007-2015 period (Figures 21c and 21d), which can be attributed to the improvement in mixture performance properties because of the polymer modification.



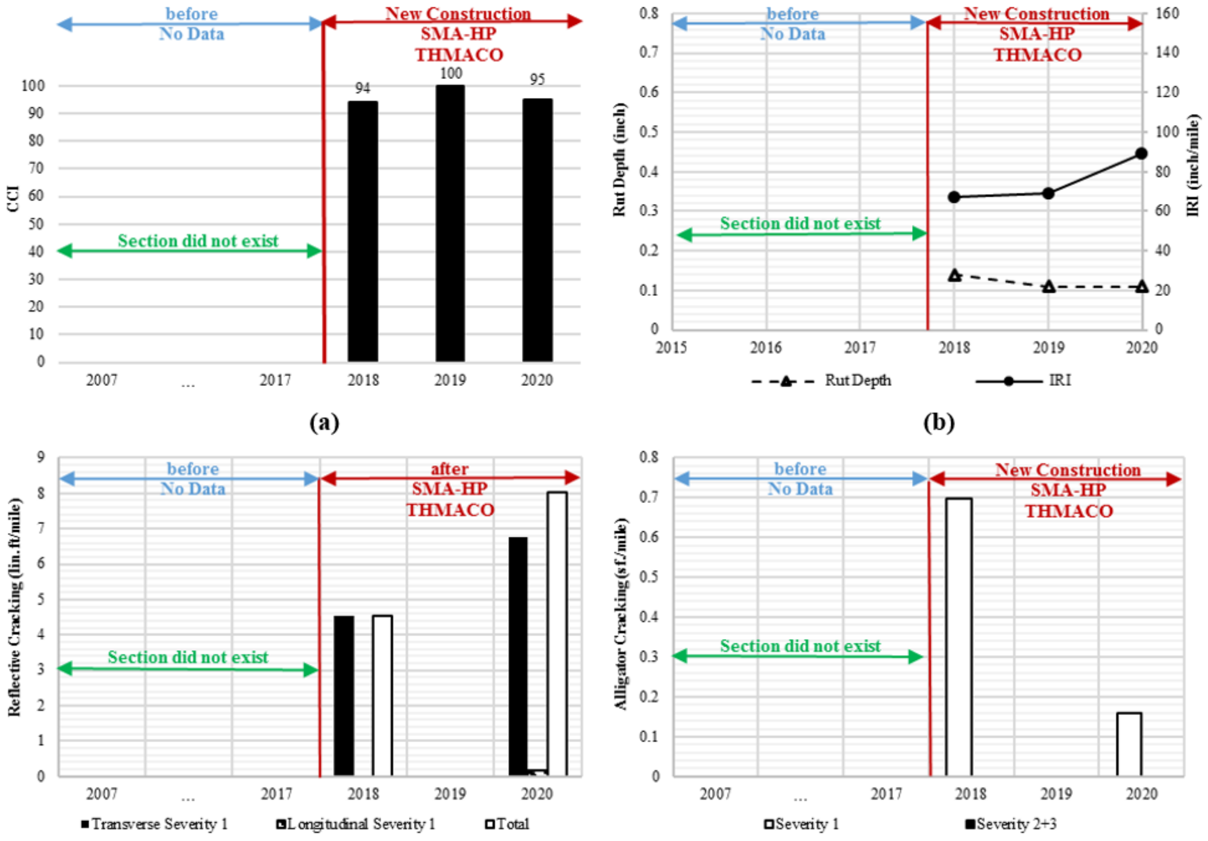
(a) (b)

(c) (d)

Figure 21. Distress Data Before and After PMA Treatment for BOJ Project C6: (a) CCI; (b) rut depth and IRI; (c) reflective cracking; (d) alligator cracking. BOJ = bituminous over jointed; CCI = Critical Condition Index; IRI = International Roughness Index; D = designation for a mix with unmodified asphalt binders; HP = high polymer-modified asphalt binder; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt.

The SMA-HP overlay of HP field section 5 had a CCI loss rate of 1.60 units per year, which is much less than the 2.3 units per year for the SMA-PMA overlay of PMA control section C6, indicating a potential extension of the performance life for AC overlays when HP binders are employed. IRI values were lower for the SMA-HP overlay of HP field section 5, indicating a much smoother surface when compared with the SMA-PMA overlay of PMA control field section C6. Both sections had similar rut depths and negligible amounts of cracking during the last treatment cycle.

Figures 22 and 23 show some of the distress data for field projects 7 and 8, respectively (details are shown in Table 9). These sections were recently constructed as part of the widening of I-64 Segment I on a patched concrete pavement that was constructed more than 50 years ago. Therefore, the performance of HP mixtures placed on these sections at an early age was not compared to any previous treatment cycles since these sections were recently constructed.



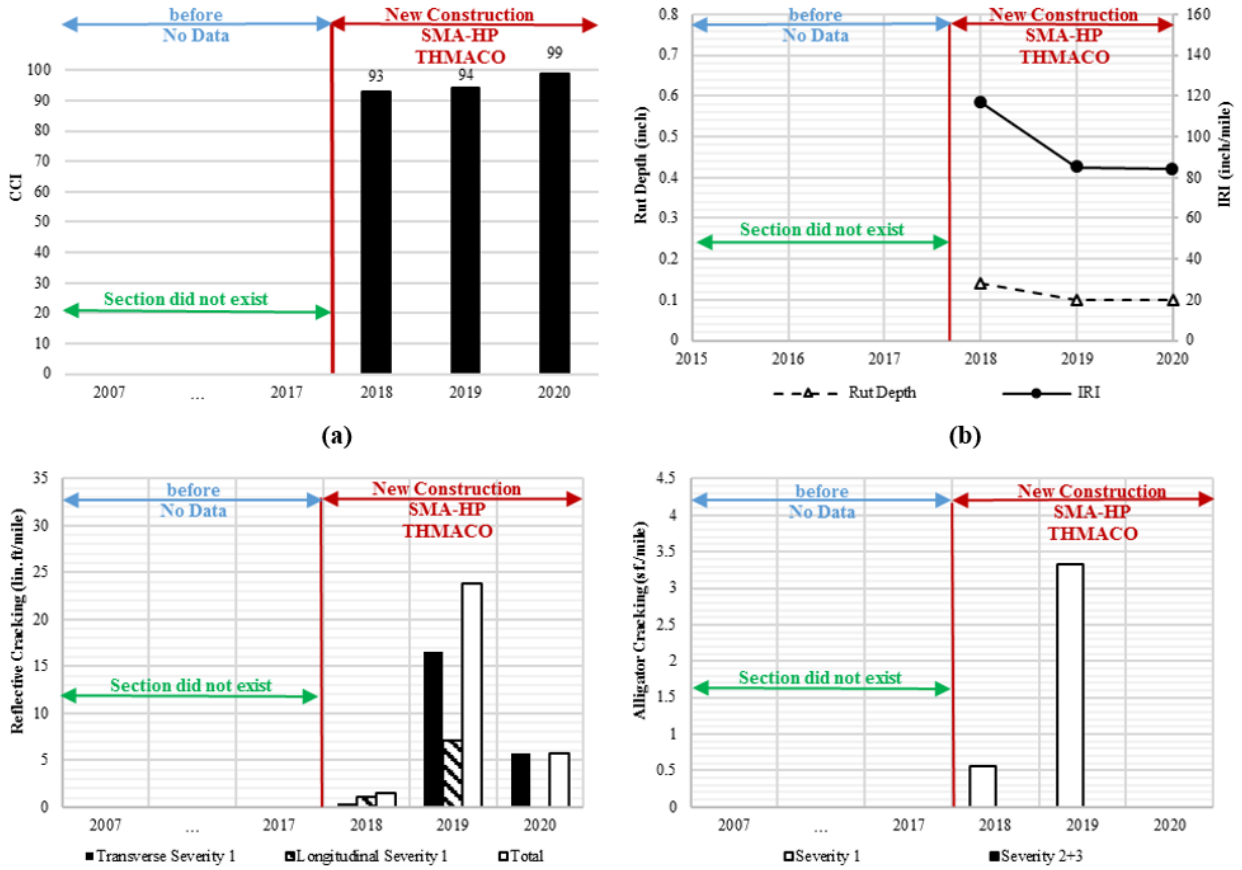
(a) (b)

(c) (d)

Figure 22. Distress Data Before and After HP Treatment for BOJ Project 7: (a) CCI; (b) rut depth and IRI; (c) reflective cracking; (d) alligator cracking. HP = high polymer-modified asphalt binder; BOJ = bituminous over jointed; CCI = Critical Condition Index; IRI = International Roughness Index; SMA = stone matrix asphalt; THMACO = thin hot mix asphalt concrete overlay.

CCI values were higher throughout the first 3 years of in-service life. IRI values ranged from 65 to 90 in/mi for both sections, indicating a relatively smooth pavement after 3 years in service. The IRI value (117 in/mi) was relatively high for the eastbound direction (field section 7) in 2018 followed by a significant decrease in 2019 and 2020. A very low amount of reflective cracking, top-down cracking, and bottom-up fatigue cracking was reported for the 2018-2020 period. It should be noted that considerable patching in the wheel and non-wheel path occurred during 2018 and 2020 on both field sections.

Figure 24 shows some of the distress data before and after placement of an HP AC overlay for field section 9 (details are shown in Table 9). The CCI values (i.e., 100) were highest for the SM-HP overlay during the 3 years of in-service life. Although there was no CCI loss for the SM-HP overlay, the CCI values varied considerably throughout time as a function of the SM-D overlay applied during the previous cycle (Figure 24a). The CCI loss rate was 4.0 units per year for the SM-D overlay treatment. Rut depths were low during the 3 years of the SM-HP cycle (Figure 24b). These values were similar to the ones reported during the SM-D cycle. IRI values were less than 60 in/mi, indicating a relatively smooth pavement even after 3 years in service (Figure 24b). Negligible top-down and bottom-up fatigue cracking was reported for the 2018-2020 period (Figure 24c).

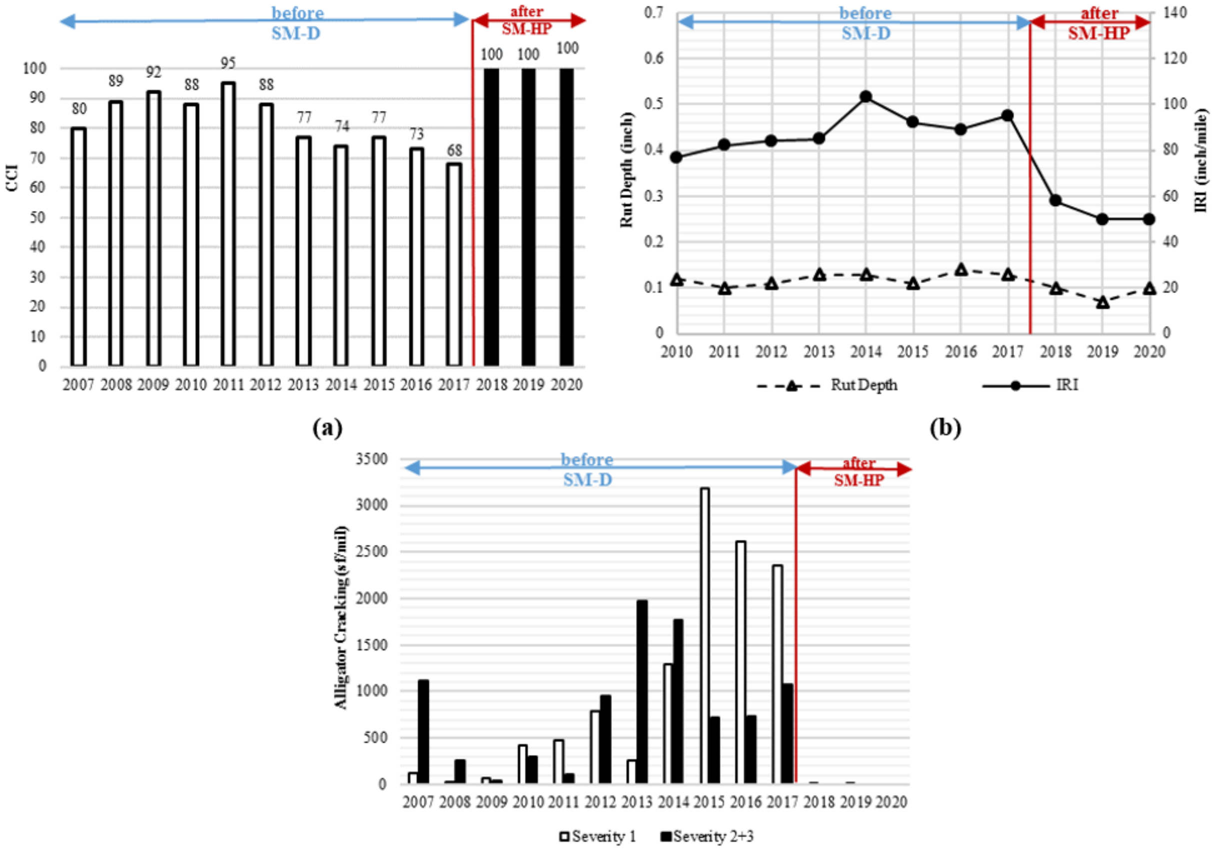


(a) (b)

(c) (d)

Figure 23. Distress Data Before and After HP Treatment for BOJ Project 8: (a) CCI; (b) rut depth and IRI; (c) reflective cracking; (d) alligator cracking. HP = high polymer-modified asphalt binder; BOJ = bituminous over jointed; CCI = Critical Condition Index; IRI = International Roughness Index; SMA = stone matrix asphalt; THMACO = thin hot mix asphalt concrete overlay.

The reflective cracking data were missing for 2012-2018; therefore, no data or analyses were reported. Figure 25 shows some of the distress data before and after placement of an HP AC overlay for field section 10 (details are shown in Table 9). The CCI was 99 for the SMA-HP overlay during its first year of service. CCI values varied considerably throughout time as a function of the SM-PMA overlay applied during the previous cycle. The CCI loss rate of 8.3 units per year was high for the SM-PMA overlay treatment. IRI values and rut depths were in the same range for both overlay cycles. Negligible reflective, top-down, and bottom-up fatigue cracking was reported for the SMA-HP overlay in 2020, which is expected at an early stage of the overlay performance life. Despite the early-age performance of the HP cycle, the data collected for the SM-PMA cycle (2012 -2019) will be used as a PMA control dataset.

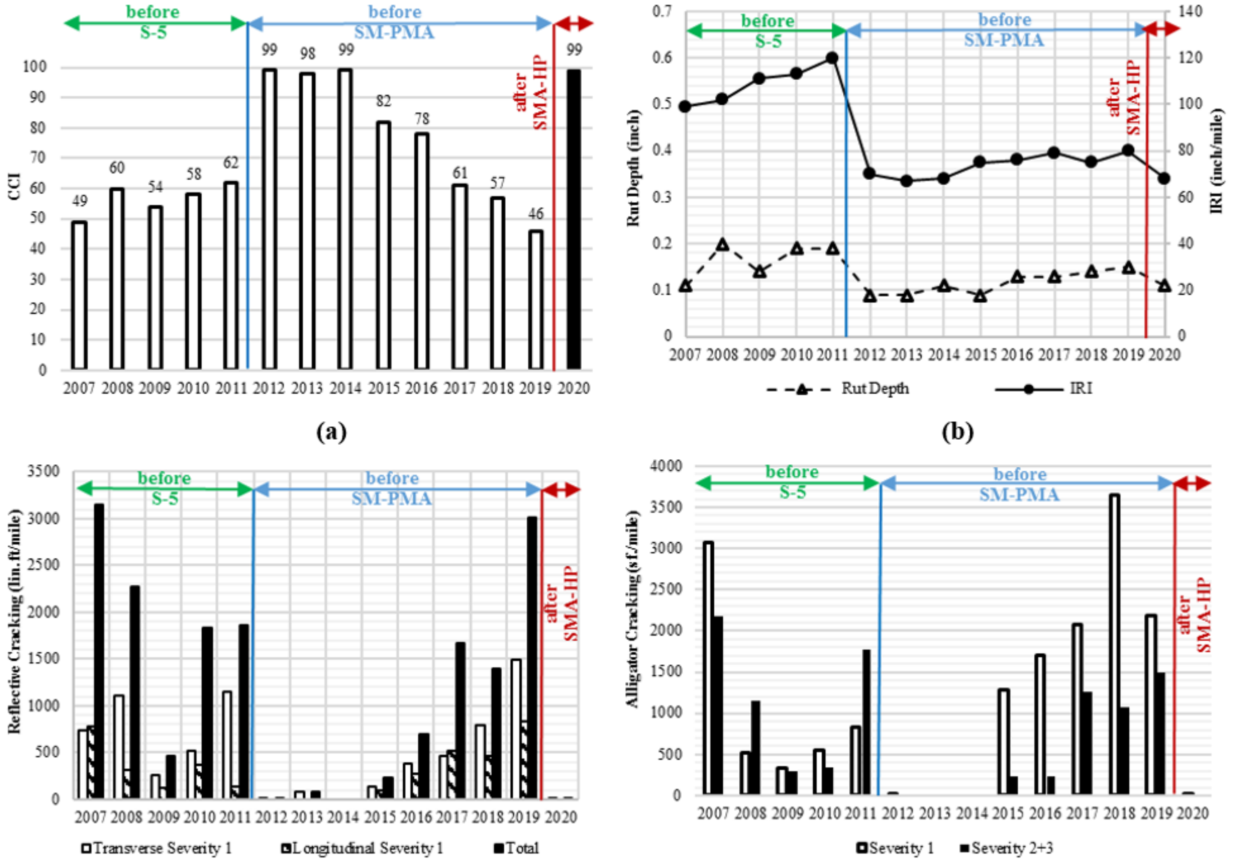


(a) (b)

(c)

Figure 24. Distress Data Before and After HP Treatment for BIT Project 9: (a) CCI; (b) rut depth and IRI; (c) alligator cracking. HP = high polymer-modified asphalt binder; BIT = bituminous; CCI = Critical Condition Index; IRI = International Roughness Index; SM = surface mix.

Figure 26 shows some of the distress data before and after placement of an HP AC overlay for field section 11 (details are shown in Table 9). As shown in Figure 26a, a CCI value of 84 was followed by a much higher CCI value (i.e., 95) for the SM-HP overlay during the 2 years of service life. After a review of all the distress data and patching efforts done on this section for the SM-HP cycle, the research team believes that the relatively lower CCI value of 84 might be a typographical error. CCI values varied considerably throughout time as a function of the SM-PMA overlay applied during the previous cycle. The CCI loss rate of 6.9 units per year was high for the SM-PMA overlay treatment. Rut depths were in the same range for both overlay cycles (Figure 26b). However, relatively lower IRI values were reported for SM-HP overlay when compared with SM-PMA, indicating a smoother pavement surface (Figure 26b). Negligible reflective, top-down, and bottom-up fatigue cracking was reported for the SM-HP overlay in 2019 and 2020 (Figures 26c and 26d), which is expected at the early stage of the overlay performance life. Despite the early-age performance of the HP cycle, the data collected for the SM-PMA cycle (2012-2018) were used as a PMA control dataset.



(a)

(b)

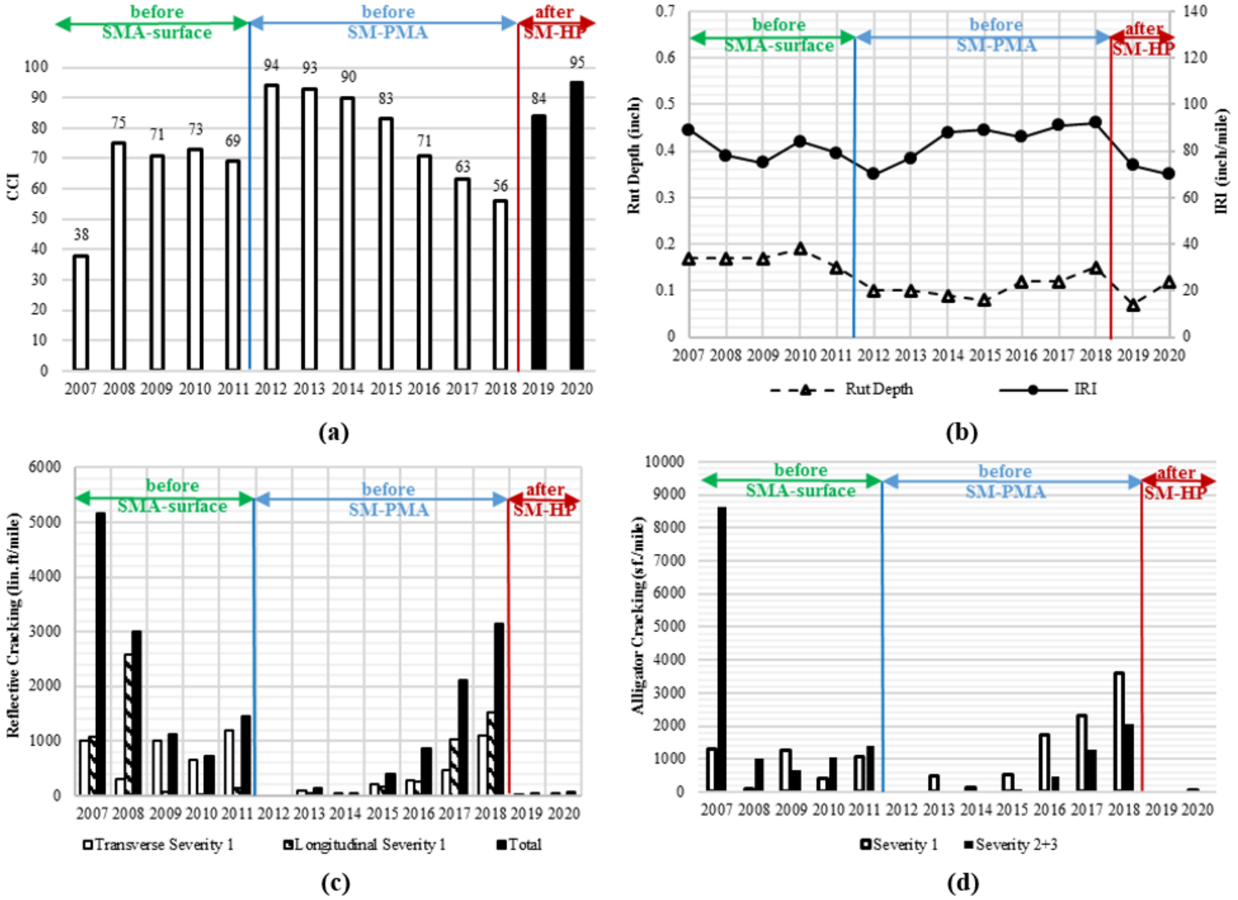
(c)

(d)

Figure 25. Distress Data Before and After HP Treatment for BOJ Project 10: (a) CCI; (b) rut depth and IRI; (c) reflective cracking; (d) alligator cracking. HP = high polymer-modified asphalt binder; BOJ = bituminous over jointed; CCI = Critical Condition Index; IRI = International Roughness Index; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt; S = Superpave mix.

Evaluation of In-Service Performance Life

Most of the pavement sections evaluated in this study were constructed within the past 5 years; therefore, their long-term performance data are not yet available. As indicated earlier, two different approaches were undertaken to estimate the life expectancy of HP and some PMA AC overlays using the performance data of the sections. Approach I uses the CCI measurement at multiple in-service durations, and Approach II considers only the reflective cracking distress at multiple in-service durations. The in-service performance evaluations through the two approaches were carried out through three levels of analysis: (i) considering the data of each treatment cycle on a project level basis; (ii) after data were dissected into four separate groups based on mixture type (SM vs. SMA) and binder type (PMA vs. HP), labeling the four groups as SM-HP, SM-PMA, SMA-HP, and SMA-PMA; and (iii) after dissecting data into two separate groups based solely on the binder type (PMA and HP), labeling the two groups as HP mixtures and PMA mixtures.



(a) (b) (c) (d)

Figure 26. Distress Data Before and After HP Treatment for BOJ Project 11: (a) CCI; (b) rut depth and IRI; (c) reflective cracking; (d) alligator cracking. HP = high polymer-modified asphalt binder; BOJ = bituminous over jointed; CCI = Critical Condition Index; IRI = International Roughness Index; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt.

Analysis (i)

Numerous models for each of the sections considered in this study were generated as part of Analysis (i); however, a few detailed examples are shown here for brevity. The details of predictive models obtained following Approach I are provided in Appendix C. The outcomes of all prediction models are summarized in Table 12.

Figure 27 shows the predictive models for both approaches for the PMA and HP overlay cycles of project 1, as an example. For Approach I, the VDOT model was first used to fit the measured CCI data vs. pavement age. The pavement service life was then predicted on the basis of a minimum CCI threshold of 60. As shown in Figure 27a, the HP AC overlay had a predicted service life of 6.6 years, which was 2.3 years longer than that of the PMA AC overlay (i.e., 4.3 years), indicating a 54% extension in performance life when high polymer modification was used. The predicted service lives of all overlays discussed in this section were determined based on extrapolation of a non-linear performance model using limited data in terms of observed service life in the field and are subject to revision as the existing sections continue to age.

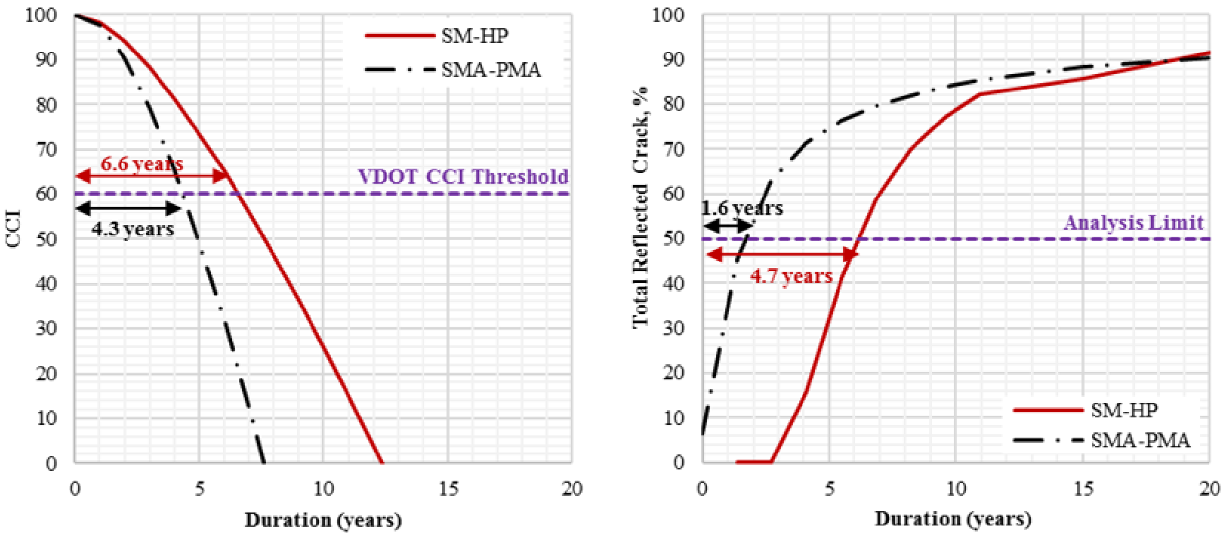
Table 12. Quantitative Evaluation of Performance Life for All Considered Pavement Sections

Project ID	Route, County, and Mileposts	Treatment Cycle		Performance Life Following Approach I	
		Time	Overlay Mix Type	No. of Years	% increase
1	I-95SB, Prince William, 0.02-3.89	2010-2015	SMA-PMA	4.3	53.4
		2016-2020	SM-HP	6.6	
2	I-95SB, Prince William, 10.98-13.12	2008-2015	SMA-PMA	6.4	73.4
		2016-2020	SMA-HP	11.1	
3	I-95NB, Prince William, 0.07-3.92	2009-2015	SMA-PMA	5.0	56.0
		2016-2020	SM-HP	7.8	
4	I-495NB, Fairfax, 5.56-6.63	2013-2016	Latex Modified	5.0	14.0
		2017-2020	SM-HP	5.7	
5	I-95SB, Hanover, 2.76-5.63	2007-2016	Latex Modified	8.5	36.5
		2017-2018	SMA-HP	11.6	
C6	I-95NB, Henrico, 7.33-9.55	2008-2015	SM-D	5.4	35.2
		2016-2020	SMA-PMA	7.3	
7	I-64EB, York, 14.81-20.55	2018-2020	SMA-HP + THMACO	--	--
8	I-64WB, York, 14.98-20.33	2018-2020	SMA-HP + THMACO	--	--
9	I-95NB, Fairfax, 3.41-4.45	2007-2017	SM-2C	8.1	--
		2018-2020	SM-HP	--	
10	I-495NB, Fairfax, 1.194-3.66	2012-2019	SM-PMA	6.5	--
		2019-2020	SMA-HP	--	
11	I-95NB, Prince William, 11.121-12.64	2012-2018	SM-PMA	6.1	--
		2019-2020	SM-HP	--	

-- = property of interest was not calculated because of limitations in data; BIT = bituminous; BOJ = bituminous over jointed; HP = high polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt; SM-D = surface mix with D designation (using unmodified asphalt binder PG 64H-22); THMACO = thin hot mix asphalt concrete overlay; E = binder designation for heavy traffic defined as PG 64E-22 equivalent to PG 76-22.

Figure 27b illustrates the development of total reflective cracking for AC overlay on top of concrete pavements (i.e., cycles 1 and 2) of project 1 (Approach II) after preliminary calibration of the reflective cracking model to the observed respective field performance. The total reflective cracking includes reflective transverse cracking and reflective longitudinal cracking at all severities (i.e., 1, 2, and 3).

Total reflective cracking was selected because it showed the shortest predicted performance life. The preliminary analysis depicted that cracks appeared on the AC surface within 2.7 years for the HP AC overlay; it took less than 1 year for such cracks to appear when the SMA-PMA overlay was placed. It took almost 4.7 years for 50% of the cracks to propagate to the surface with the HP AC overlay, approximately 3 times longer than for the PMA AC overlay. Based on typical behavior of conventional dense-graded asphalt mixtures on top of JCP, reflective cracks would typically start to appear at the surface of the AC overlay within 1 to 2 years after construction at a rate of about 1 in per year.



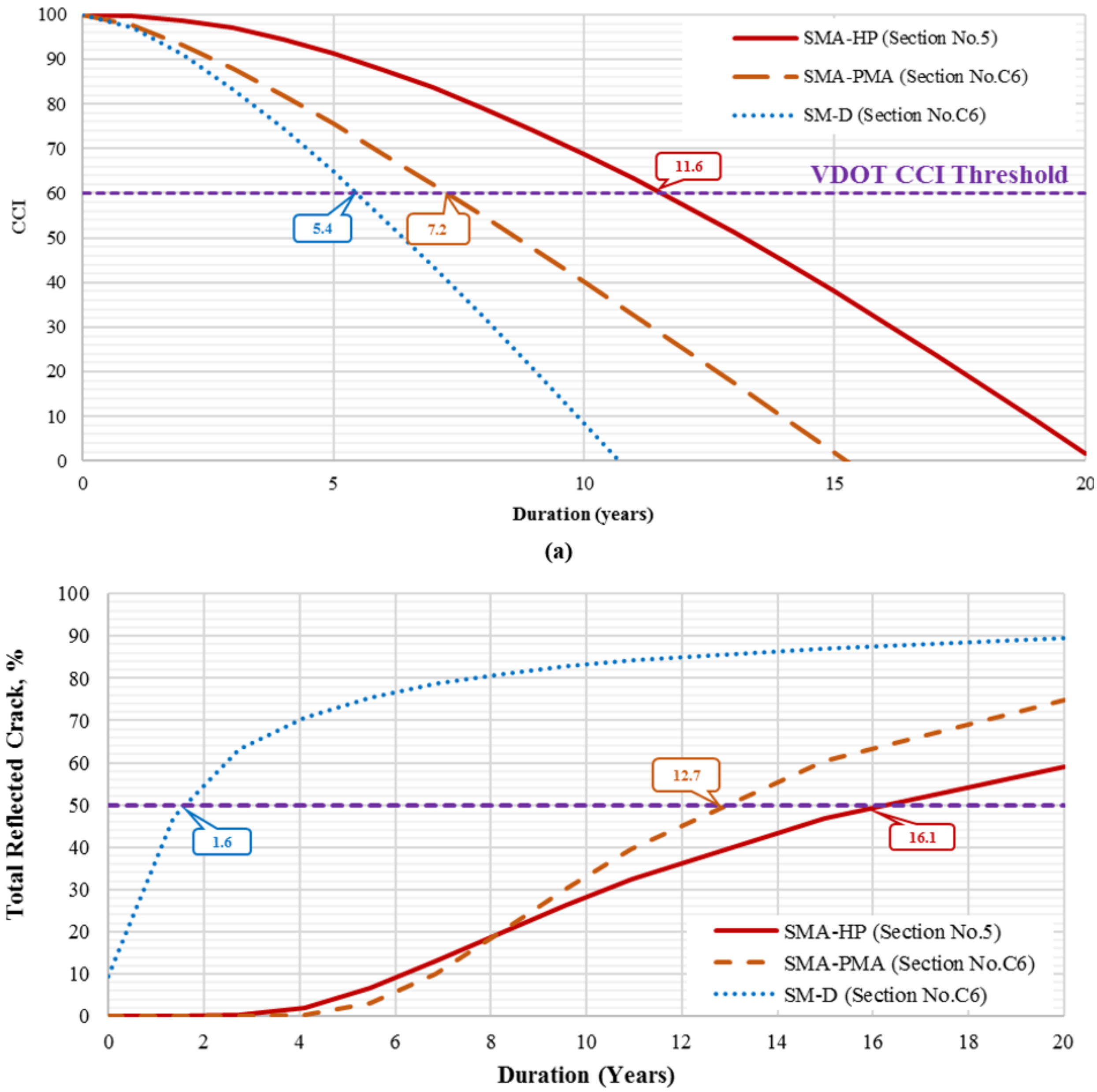
(a) (b)

Figure 27. In-Service Predictive Performance Models for PMA and HP AC Overlays of Project 1: (a) Approach I; (b) Approach II. PMA = polymer-modified asphalt binder; HP = high polymer-modified asphalt binder; AC = asphalt concrete; SM = surface mix; SMA = stone matrix asphalt.

Figure 28a shows the predictive models for HP, PMA, and SM-D overlays for project 5 and its designated control section C6 following Approach I. The SMA-HP AC overlay of section 5 had a predicted service life of 11.6 years, which was 4.4 years longer than for the PMA AC overlay (i.e., 7.2 years) and 6.2 years longer than for the unmodified overlay (SM-D performance life of 5.4 years), both placed on control section C6. Figure 28b shows the reflective cracking performance curves for the HP, PMA, and SM-D overlays for projects 5 and C6 estimated following Approach II. The models indicated an average service life of 16.1, 12.7, and 1.6 years for the SMA-HP, SMA-PMA, and SM-D overlays, respectively.

Analysis (ii)

As part of Analysis (ii), the compiled data were dissected into groups to represent four general types of placed mixtures: SM-HP, SM-PMA, SMA-HP, and SMA-PMA. Figure 29a shows the predictive models for these types of AC overlays determined following Approach I. Each model in Figure 29a was developed by combining all of the existing data from the field projects for a given mixture type. As shown, the SM-HP, SM-PMA, SMA-HP, and SMA-PMA overlays had an average predicted service life of 6.1, 6.3, 8.6, and 5.6 years, respectively. Figure 29b presents the reflective cracking performance curves for the mixture types determined following Approach II. The models indicated an average service life of 4.7, 5.2, 6.9, and 5.9 years for the SM-HP, SM-PMA, SMA-HP, and SMA-PMA overlays, respectively. The results revealed that the service life for SMA-HP mixture types was longer than for the other three mixture types as classified in this part of the study, and these other mixture types are expected to have similar service lives. Such an increase in service life of SMA-HP mixture types was attributed to the combined effects of the higher binder content incorporated into SMA mixtures and the resiliency of the HP binders.



(a)

(b)

Figure 28. In-Service Predictive Performance for AC Overlays of Projects 5 and C6: (a) Approach I; (b) Approach II. AC = asphalt concrete; HP = high polymer-modified asphalt binder; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt.

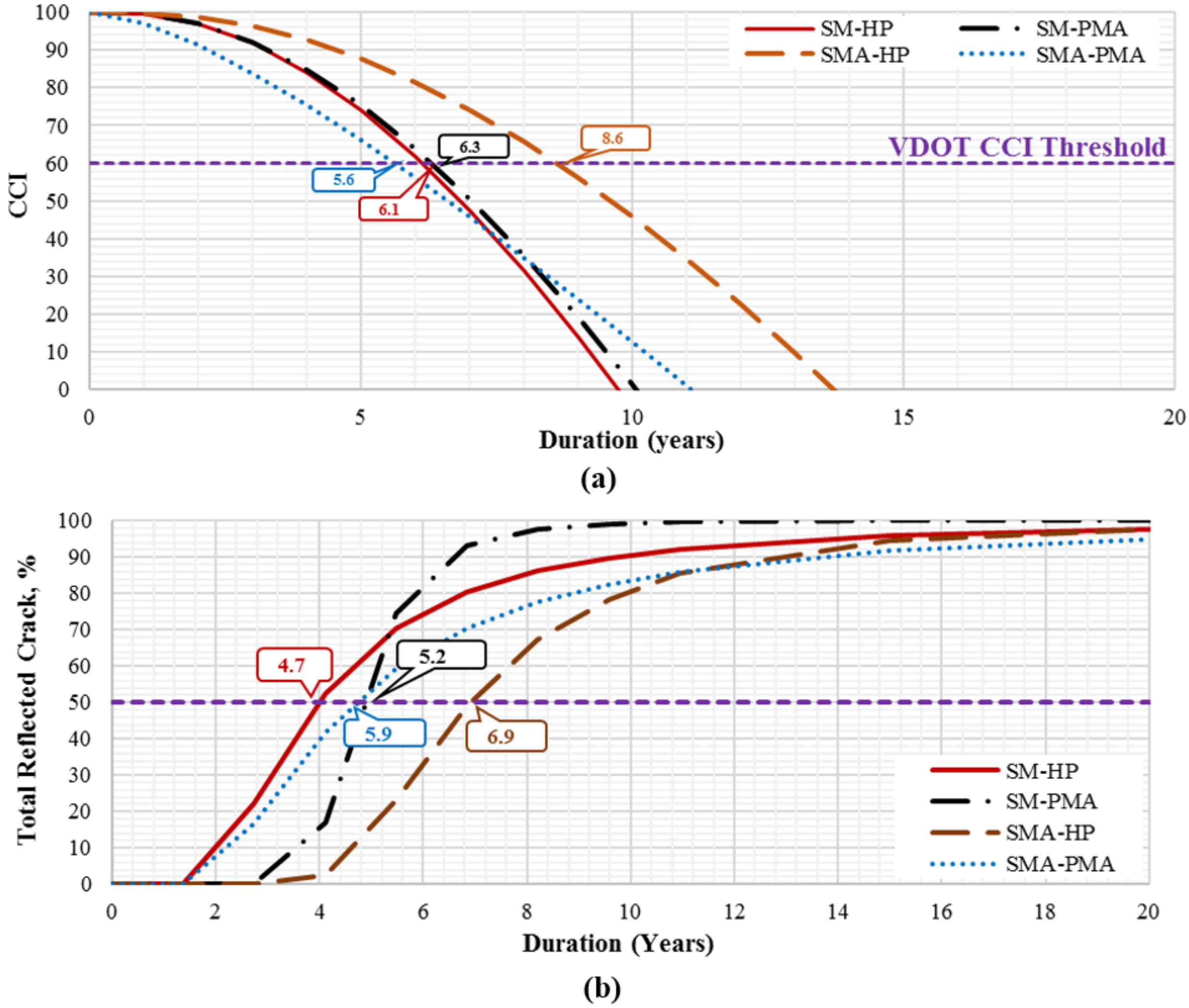


Figure 29. In-Service Predictive Performance for SM-HP, SM-PMA, SMA-HP, and SMA-PMA Overlay Mixtures: (a) Approach I; (b) Approach II. HP = high polymer-modified asphalt binder; PMA = polymer-modified asphalt binder; SM = surface mix; SMA = stone matrix asphalt.

Analysis (iii)

As part of Analysis (iii), the compiled data were dissected into two groups to represent the two types of asphalt binders (PMA vs. HP). Figure 30a shows the predictive models of PMA and HP AC overlays determined with Approach I and after the combined data of all selected field projects for a given mixture type as classified in this part of the study were considered. The HP and PMA AC overlays had an average predicted service life of 8.3 and 6.2 years, respectively, indicating a 34% extension of performance life of the AC overlay with high polymer modification, which confirmed the findings reported in previous studies (Habbouche et al., 2020). Shorter performance lives were estimated with Approach II when compared with Approach I regardless of the analysis level. This may indicate that condition indices such as the CCI alone may not capture the increase in reflective cracks over time and do not isolate other deterioration factors such as rutting and fatigue cracking. The HP and PMA AC overlays had an average predicted service life of 6.0 and 4.7 years, respectively (as shown in Figure 30b).

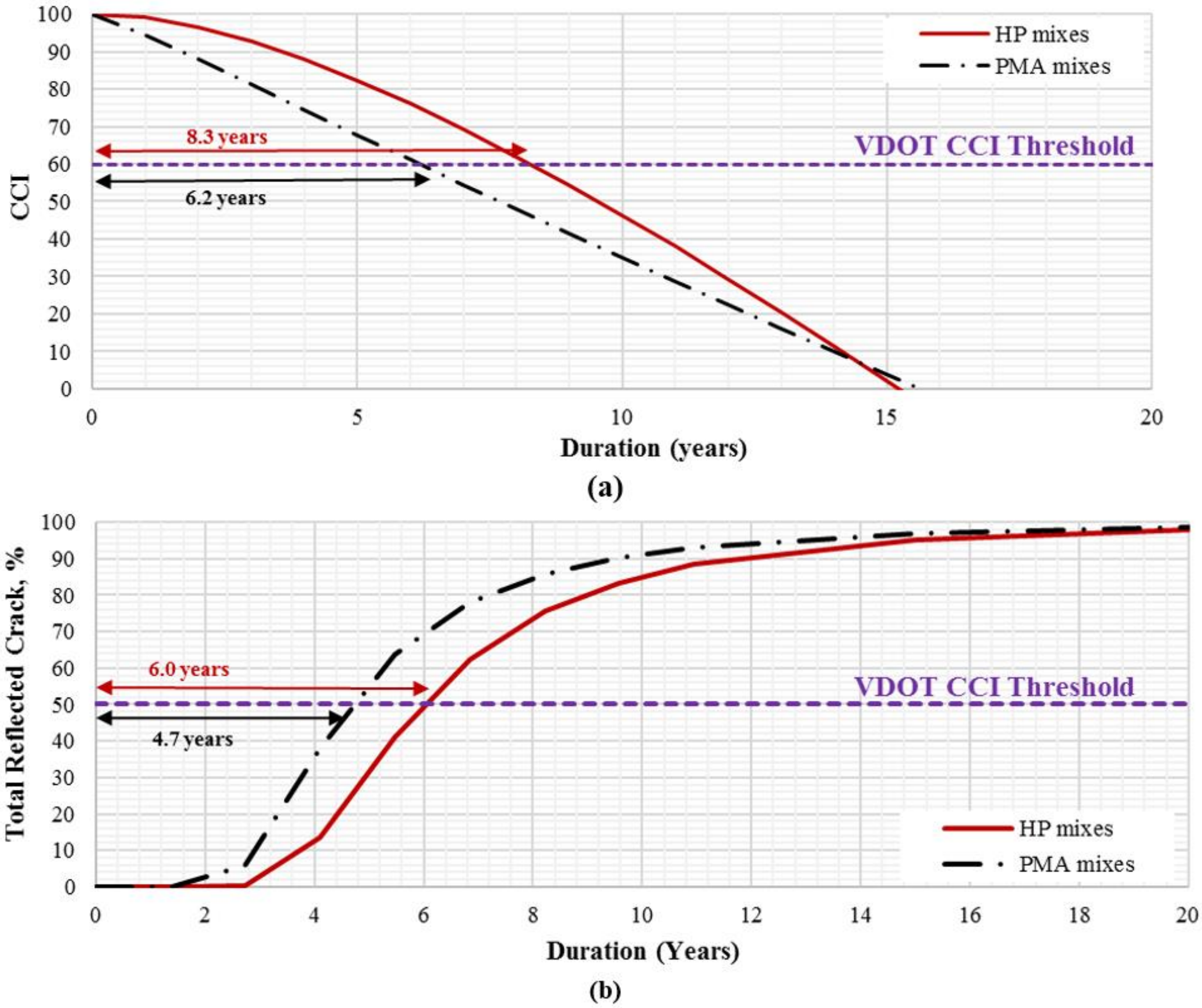


Figure 30. In-Service Predictive Performance for HP and PMA Overlays: (a) Approach I; (b) Approach II. HP = high polymer-modified asphalt binder; PMA = polymer-modified asphalt binder.

Overall, the results revealed that the service life for the HP overlays was estimated to be longer than for the PMA overlays. Such increases in service life could be mainly attributed to the resiliency of the HP binders.

Cost Analysis

A preliminary life cycle cost analysis to assess potential savings in using HP AC overlays was not carried out as part of this effort since the researchers thought that an accurate assessment of the HP unit cost was not available. This is because of the limited tonnage applied to date, modified storage requirements, and realities of a newly employed specialty product. Approximate unit material costs of $82.00 per ton for SM-PMA, $86.20 for SMA-PMA, $131.60 for SM-HP, and $135.00 for SMA-HP were obtained from VDOT bid documents for contracts PM9I-96A-F15, N501, and PM9I-029-F16, N501. The research team believes that any cost analysis performed using these prices and the fairly limited performance life database would be highly subjective and its outcomes might be misleading to local and national stakeholders.

This study documented and evaluated the early-life (up to 5 years) field performance of HP mixtures used as overlays on existing JCPs or cracked AC pavements in Virginia. Although the data presented and discussed indicated promising performance, there remains a definite need to continue monitoring the performance of existing and newly constructed sections. This will help in updating and revising the service life prediction models and cost-effectiveness of using HP AC mixtures as the existing sections continue to age and more data are available.

SUMMARY OF FINDINGS

State of the Practice

- HP AC mixtures have been used over a wide range of applications ranging from full-depth AC layers to thin AC overlays under heavy traffic ranging from interstates to slow-braking loads at intersections.

- SBS polymers used to produce HP binders have a different chemical structure than those used to produce conventional PMA binders.

- The need for good communication between the polymer/binder supplier and the contractor and solid planning prior to the paving work being conducted were important lessons learned by agencies when paving HP AC mixtures.

- No practices or enforcements of specific safety, health, or environmental restrictions and no changes to current quality control / quality assurance routine practices were identified by agencies with regard to using HP binders in AC mixtures.

Laboratory Characterization and Performance Evaluation of Binders and Mixtures

Asphalt Binder Testing

- The evaluated HP binders typically had viscosity values of 4 to 5 Pa.s in the laboratory at a testing temperature of 135°C using the rotational viscometer.

- For the mean and variability of the measured viscosities for all HP binders used in Virginia since 2016, more than 95% of the test values were less than 5 Pa.s.

Cantabro Mass Loss

- HP AC mixtures had lower mass loss than PMA AC mixtures.

- SMA mixtures had lower mass loss than SMs, regardless of the asphalt binder type (i.e., PMA vs. HP).

- SMA-HP mixtures had the lowest mass loss among all evaluated mixtures, indicating a potential greater durability and resistance to abrasion when subjected to loading.

Dynamic Modulus

- The visual inspection of dynamic modulus master curves showed that the SMA mixtures had higher |E*| values at lower frequencies than SMs, regardless of the binder type, indicating a potential higher resistance to rutting and shoving.

- The visual inspection of phase angle master curves showed that the majority of HP mixtures had lower δ values than the PMA mixtures, indicating the potential for higher cracking resistance among the six mixtures.

- The dynamic modulus test showed that SMA-HP mixtures had the highest |E*| at high temperatures and the lowest δ values across the loading spectrum, indicating a promising performance of this type of mixture at low, intermediate, and high temperatures.

Rutting Performance

APA Rut Test

- The APA rut test results indicated that HP mixtures had less rutting than PMA mixtures, regardless of the mixture type (i.e., SM vs. SMA).

- The APA rut test results indicated that SMA-HP mixtures had the lowest rut depth among all evaluated mixtures, indicating a promising rutting performance of this mixture type at high temperatures and/or under heavy/slow traffic.

- Overall, rut depth decreased with the decrease in specimen air-void level.

Repeated Load Triaxial Test

- The RLT test results indicated that HP AC mixtures had lower rutting relationships when compared with their PMA control AC mixtures regardless of the mixture type (SM vs. SMA), indicating a better rutting resistance.

- SMA mixtures showed lower and flatter rutting curves when compared with SMs regardless of the asphalt binder type (PMA vs. HP) when evaluated by the RLT test, indicating a better rutting resistance.

- The RLT test results indicated that SMA-HP mixtures had the lowest and flattest rutting curves associated with the lowest FN index values among all evaluated mixtures, indicating a very promising rutting resistance during the life of the pavement.

Cracking Performance

Indirect Tensile Test

- The CT index had a significantly greater variability when compared with the FST index, which could be attributed to the calculation of a slope as part of the CT index.

- The FST index provided a similar performance ranking and better performance discrimination potential among evaluated PMA and HP mixtures when compared with the CT index.

- SMA mixtures had significantly higher CT index and FST values when compared with SMs. However, as per ASTM D8225-19, evaluation of cracking performance among different mixture types (SM vs. SMA) on the basis of the CT index is not advised.

- The SM-PMA and SM-HP mixtures evaluated in this study had statistically similar CT index and FST values, indicating that the IDT test may not detect the expected impact of high polymer modification in improving the cracking resistance of SMs.

- SMA-HP mixtures indicated the most promising cracking performance among all evaluated mixtures based on laboratory testing despite the limitations of the IDT test.

Texas Overlay Test

- The number of OT cycles to failure was similar to or greater for HP AC mixtures than for the respective PMA AC control mixtures regardless of the mixture type (SM vs. SMA), indicating an increased flexibility and resistance to reflective cracking of the HP AC mixtures under different environmental conditions.

- The number of OT cycles to failure was significantly greater for SMA mixtures than for SMs.

- The majority of HP AC mixtures had low Gc and CPR values, indicating a good resistance to cracking initiation and propagation, respectively.

- SMA-HP mixtures had the greatest number of OT cycles to failure and showed the most soft-crack–resistant behavior among all evaluated AC mixtures.

Direct Tension Cyclic Fatigue

- Fatigue performance was better for HP AC mixtures than for PMA AC mixtures (at all strain levels).

- Fatigue performance was better for SMA mixtures than for SMs regardless of the binder type (PMA vs HP).

Evaluation of In-Service Field Performance

- Since 2015, HP AC overlays have been placed at several sections over existing JCPs and cracked asphalt pavements to mitigate reflective cracking.

- According to the PMS distress data, all of the evaluated mixtures (HP or PMA) had some degree of reflective cracking.

- CCI values were higher and CCI loss rates were lower during the service life of HP overlays compared with the PMA overlays applied during the previous maintenance cycles of a given project or selected control section.

- Based on the collected and documented PMS data, HP sections showed very promising performance after 5 years (2015-2020) regardless of the traffic level and pre-existing pavement conditions.

- The PMS data for the sections reviewed indicated a potential controlling effect of the joint condition of the underlying JCP layer regardless of the asphalt mixture type employed (PMA or HP).

Evaluation of In-Service Performance Life

Analysis (i)

- The numerous models generated for each of the projects/sections considered in this study revealed that the service life for HP overlays was estimated to be longer than for PMA overlays.

Analysis (ii)

- With Approach I, the SM-PMA, SM-HP, SMA-PMA, and SMA-HP overlays had an average predicted service life of 6.3, 6.1, 5.6, and 8.6 years, respectively.

- With Approach II, the SM-PMA, SM-HP, SMA-PMA, and SMA-HP overlays had an average predicted service life of 5.2, 4.7, 5.9, and 6.9 years, respectively.

Analysis (iii)

- With Approach I, the HP and PMA AC overlays had an average predicted service life of 8.3 and 6.2 years, respectively, indicating a 34% extension of performance life of the AC overlay with high polymer modification.

- With Approach I, the HP and PMA AC overlays had an average predicted service life of 6.0 and 4.7 years, respectively, indicating a 28% extension of performance life of the AC overlay with high polymer modification.

CONCLUSIONS

- *HP AC mixtures can be used as a reflective crack mitigation technique or when deemed appropriate as a tool for increased crack resistance on higher volume facilities in Virginia. This was proven with the positive feedback reported by fellow state DOTs and local asphalt contractors, the improved performance of HP AC mixtures when evaluated in the laboratory, the promising in-service field performance of HP sections, and the longer estimated service life of HP AC overlays when compared with the service life of PMA AC overlays.*

- *The definition and acceptance of HP binders are not directly related to the SBS polymer content but rather to specific binder rheology-related parameters and characteristics, a more performance-oriented viewpoint.*

- *The HP binders with viscosities greater than 3 Pa.s but lower than 5 Pa.s at 135°C are still acceptable in practice with no potential clogging issues when pumped (as reported by asphalt contractors) since they are mixed at the asphalt plant at a much higher temperature (around 165°C).*

- *Based on results from the mixtures tested in this study, the Cantabro mass loss test was able to capture the impact of high polymer modification on the durability performance of asphalt mixtures. Moreover, there is a need to develop performance threshold criteria in terms of Cantabro mass loss for the four types of mixtures (SM-PMA, SM-HP, SMA-PMA, and SMA-HP). In addition, there is a need to evaluate the acceptable levels of test variability and develop precision statements.*

- *Based on results from the mixtures tested in this study, the APA and RLT tests were able to capture the impact of high polymer modification on the rutting performance of asphalt mixtures. Therefore, both tests could be used to evaluate the rutting properties of PMA and HP AC mixtures in Virginia. There is a need to develop corresponding performance threshold criteria for the four types of mixtures (SM-PMA, SM-HP, SMA-PMA, and SMA-HP). Moreover, comparisons and establishment of correlations with rut depths obtained from mechanistic-empirical pavement design simulations and field performance are still needed.*

- *Based on results from the mixtures tested in this study, the IDT test revealed contradicting observations when the impact of high polymer modification on the cracking performance of asphalt mixtures was evaluated. Therefore, the feasibility of using the IDT test at intermediate temperatures to evaluate the cracking resistance of PMA and HP mixtures remains unsure and unclear. However, the OT and direct tension cyclic fatigue test revealed similar observations and were able to capture the impact of high polymer modification. There is a need to develop corresponding performance threshold criteria for the four types of mixtures (SM-PMA, SM-HP, SMA-PMA, and SMA-HP). Moreover, comparisons and establishments of correlations to predicted cracking obtained from mechanistic-empirical pavement design simulations and field performance are still needed.*

- *A significant difference in performance was observed for HP AC mixtures when compared with PMA AC mixtures. A similar improvement was found for SMA mixtures when compared with dense-graded mixtures. The existing mechanistic-empirical distress predictions are based on dense-graded non-modified mixtures and a few selected modified mixtures and therefore do not accurately reflect these differences in the field. Therefore, revised distress prediction models are still warranted.*

- *All of the HP sections are in very good condition. Since most of the evaluated sections were placed from 2015 to 2017, performance data can still be considered preliminary. However, this study showed that the use of HP overlays can help mitigate reflective cracking and can extend the in-service life, which is a worthwhile effort.*

- *The CCI loss rate was lower for HP sections than for PMA sections.*

- *Currently, HP mixtures are not differentiated from other dense-graded mixtures (e.g., "E" mixtures) in VDOT's PMS, making their identification more difficult.*

- *Continued monitoring of the performance of the HP sections will be needed to quantify accurately any potential cost-savings of using HP overlays to mitigate reflective cracking, especially on top of JCPs.*

RECOMMENDATIONS

1. *VDOT's Materials Division should encourage the VDOT districts to continue using HP AC overlays as a reflective crack mitigation technique or when deemed appropriate as a tool for increased crack resistance on higher volume facilities.* The preliminary data presented and discussed previously showed promising laboratory and field performance when this technology was employed.

2. *VDOT's Materials Division should consider keeping the maximum allowable viscosity of HP binders at 135°C as 5 Pa.s for samples collected from binder suppliers and/or contractor tanks.* Additional research is needed to refine and determine a more representative testing temperature and threshold limit when the rotational viscosity test is conducted on HP binders.

3. *VTRC should continue assessing the as-constructed properties of future HP projects for the purpose of compiling a materials characterization database to be used as an input for pavement designs performed with AASHTOWare Pavement ME software.*

4. *VTRC should submit a research need statement (RNS) to VTRC's Pavement Research Advisory Committee to investigate the use of the BMD approach for PMA and HP mixtures in Virginia.* This effort should include selection of suitable performance tests and assessment of their capability to capture the impact of polymer modification on the performance properties of asphalt mixtures. Moreover, the effort should include determining corresponding performance-based threshold criteria in an appropriate manner to guarantee a longer performance life of these mixtures in the field.

5. *VDOT's Maintenance Division should include a separate label for HP mixtures in VDOT's PMS database.* Currently, HP mixtures are still added to the database as regular "E" mixtures.

6. *VTRC should continue to monitor the performance of the HP projects/sections evaluated in this study, the sections recently constructed and not incorporated into this study, and the sections to be constructed in the future.* The predicted service life models of all PMA and HP AC overlays developed and discussed in this study should be updated and revised as the existing sections continue to age.

7. *VTRC should evaluate the cost-effectiveness of using HP AC mixtures as part of future projects when a more accurate representation of material costs is expected.*

IMPLEMENTATION AND BENEFITS

Implementation

With regard to Recommendation 1, further communication with the VDOT districts in the form of a webinar could be used to present and discuss the early-age field performance of HP projects/sections placed in Virginia and to provide lessons learned and best practices by no later than the end of Fiscal Year 2022.

With regard to Recommendation 2, VDOT's Materials Division should keep the viscosity threshold of 5 Pa.s for HP binders in the current specifications.

With regard to Recommendation 3, VTRC will maintain close contact with state and district materials officials who are most likely to prescribe HP mixtures in upcoming projects (e.g., NOVA, Richmond, Hampton Roads). As projects are identified, VTRC's lead researcher will coordinate with district materials staff to arrange for the necessary sampling during mixture production activities. VTRC will perform the relevant materials characterization and performance testing and then add the corresponding properties to Virginia's materials characterization database for HP mixtures. This effort will be documented through technical memoranda that will be circulated within 6 to 12 months of material placement.

With regard to Recommendation 4, VTRC will draft and submit separate RNSs to the appropriate VTRC Pavement Research Advisory Subcommittee by no later than Fiscal Year 2023.

With regard to Recommendation 5, VDOT's Maintenance Division and Construction Division will adjust the mixture designation of existing HP sections and use a revised mixture designation for future HP projects before the start of the 2021 paving season.

With regard to Recommendations 6 and 7, VTRC will monitor the performance of HP sections in Virginia for the next 3 to 5 years in order to guarantee a more representative documentation of field performance for this type of paving material. This effort will help address the cost-effectiveness of using HP paving material, perhaps to include recommendations concerning a more systematic use. This effort will be documented as part of a technical assistance project.

Benefits

This effort thoroughly assessed the viability of using HP AC mixtures in Virginia as a reflective crack mitigation technique or when deemed appropriate as a tool for increased crack resistance on higher volume facilities. Timely and practical information on the state of the practice and lessons learned with regard to using HP AC mixtures in the United States and Canada were provided. This information is expected to be particularly helpful to any owner and/or agency looking to use this material for the first time.

The as-constructed properties of HP projects constructed in 2018 and 2019 were evaluated in the laboratory for the purpose of compiling a materials characterization database. This database will constitute an accurate input for pavement designs performed using AASHTOWare Pavement ME software. Moreover, the field performance of HP pavement sections constructed since 2015 was documented. Preliminary models assessing the in-service performance life of HP paving material were developed. Findings from both aspects, the laboratory and the field, will constitute a sound performance basis for quantifying the cost-effectiveness of using HP mixtures in the future.

ACKNOWLEDGMENTS

The authors thank Andrew Barbour, Christopher Burns, Troy Deeds, Donnie Dodds, Scott Hodgson, Derek Lister, Danny Martinez Rodriguez, and Jennifer Samuels of VTRC for their outstanding efforts in sample collection and testing. The authors thank Liliya Fedzhora of VDOT's Maintenance Division; Andrew McGilvray of VDOT's Hampton Roads District; Candice Entwisle, Michael Nuckols, and Bryan Smith of VDOT's Materials Division; and Harihar Shiwakoti of VDOT's Northern Virginia District for their assistance in this project. Appreciation is also extended to Linda Evans of VTRC for her editorial assistance. The authors are also appreciative of the technical review panel for their expertise and guidance: Thomas Schinkel, David Shiells, and Sungho Kim of VDOT and Jason Provines of VTRC. Thanks are also given to all agency and industry survey respondents.

REFERENCES

Advanced Asphalt Technologies, LLC. *NCHRP Report 673: A Manual for Design of Hot Mix Asphalt With Commentary*. Transportation Research Board, Washington, DC, 2011.

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.

ASTM International. *ASTM D8225-19: Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature.* West Conshohocken, PA, 2019.

Bowers, B.F., Diefenderfer, S.D., and Diefenderfer, B.K. Laboratory Evaluation of a Plant-Produced High Polymer–Content Asphalt Mixture. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2631, 2017, pp. 144-152.

Bowers, B.F., Diefenderfer, B.K., and Diefenderfer, S.D. *Evaluation of Highly Polymer-Modified Asphalt Mixtures: Phase I.* VTRC 18-R14. Virginia Transportation Research Council, Charlottesville, 2018.

Boz, I., Tavassoti-Kheiry, P., and Solaimanian, M. The Advantages of Using Impact Resonance Test in Dynamic Modulus Master Curve Construction Through the Abbreviated Test Protocol. *Journal of Materials and Structures*, Vol. 50, No. 3, 2017.

Boz, I., Sherif, M., Ozbulut, O.E., and Diefenderfer, S. A Modified Moisture Damage Test for Use in Balanced Mixture Design Procedure. Technical Assistance Memorandum. Virginia Transportation Research Council, Charlottesville, 2020.

Boz, I., Habbouche, J., and Diefenderfer, S.D. The Use of Indirect Tensile Test to Evaluate the Resistance of Asphalt Mixtures to Cracking and Moisture-Induced Damage. In *Airfield and Highway Pavements 2021*, in press, 2021.

Cox, B.C., Smith, B.T., Howard, I.L., and James, R.S. State of Knowledge for Cantabro Testing of Dense Graded Asphalt. *Journal of Materials in Civil Engineering,* Vol. 29, No. 10, 2017.

Diefenderfer, B.K., Boz, I., and Bowers, B.F. Evaluating Cracking Tests for Performance-Based Design Concept for Cold Recycled Mixtures. In *Airfield and Highway Pavements 2019: Design, Construction, Condition Evaluation, and Management of Pavements*, pp. 220-229. American Society of Civil Engineers, Reston, VA, 2019.

Federal Highway Administration. *Cyclic Fatigue Index Parameter (Sapp) for Asphalt Performance Engineered Mixture Design*. FHWA-HIF-19-091. Washington, DC, 2019.

Garcia V., Miramontes A., Garibay J., Abdallah I., and Nazarian, S. *Improved Overlay Tester for Fatigue Cracking Resistance of Asphalt Mixtures.* TxDOT 0-6815-1. University of Texas at El Paso, 2016.

Habbouche, J., Hajj, E.Y., and Sebaaly, P.E. *Structural Coefficient of High Polymer Modified Asphalt Mixes.* WRSC-UNR-FDOT-BE321-DEL6. Florida Department of Transportation, Tallahassee, 2019.

Habbouche, J., Hajj, E.Y., Sebaaly, P.E., and Piratheepan, M. A Critical Review of High Polymer-Modified Asphalt Binders and Mixtures. *International Journal of Pavement Engineering*, Vol. 21, 2020, pp. 686-702.

Habbouche, J., Boz, I., Diefenderfer, B.K., Smith, B.C., and Adel, S.H. State of the Practice for High Polymer-Modified Asphalt Binders and Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, 2021.

Lytton, R.I., Tsai, F.L., Lee, S.I., Luo, R., Hu, S., and Zhou, F. *NCHRP Report 669: Models for Predicting Reflection Cracking of Hot-Mix Asphalt Overlays*. Transportation Research Board, Washington, DC, 2010.

McGhee, K.H. *Development and Implementation of Pavement Condition Indices for the Virginia Department of Transportation, Phase I: Flexible Pavements.* Virginia Department of Transportation, Materials Division, Richmond, 2002.

Minitab. Software for Statistics, 2018. https://support.minitab.com/en-us/minitab/18/help-and-how-to/statistics/basic-statistics/how-to/outlier-test/perform-the-analysis/select-the-analysis-options/?SID=95354. Accessed December 22, 2020.

Oshone, M., Dave, E., Daniel, J.S., and Rowe, G.M. Prediction of Phase Angles From Dynamic Modulus Data and Implications for Cracking Performance Evaluation. *Road Materials and Pavement Design*, Vol. 18 (Supp. 4), 2017, pp. 491-513.

Seitllari, A., Boz, I., Habbouche, J., and Diefenderfer, S.D. Assessment of Cracking Performance Indices of Asphalt Mixtures at Intermediate Temperatures. *International Journal of Pavement Engineering*, 2020.

Stantec Consulting Services Inc. and H.W. Lochner, Inc. *Development of Performance Prediction Models for Virginia Department of Transportation Pavement Management System.* Virginia Department of Transportation, Richmond, 2007.

Tavassoti-Kheiry, P., Boz, I., Chen, X., and Solaimanian, M. Application of Ultrasonic Pulse Velocity Testing of Asphalt Concrete Mixtures to Improve the Prediction Accuracy of Dynamic Modulus Master Curve. In *Airfield and Highway Pavements, 2017*, pp. 152-164. American Society of Civil Engineers, Reston, VA, 2017.

Texas Department of Transportation. *Test Procedure for Overlay Test Tex-248-F. Effective Date: July 2019.* https://ftp.txdot.gov/pub/txdot-info/cst/TMS/200-F_series/pdfs/bit248.pdf. Accessed June 15, 2020.

Virginia Department of Transportation. *Virginia Test Methods*. Richmond, 2013. http://www.virginiadot.org/business/resources/materials/bu-mat-vtms.pdf. Accessed September 29, 2019.

Virginia Department of Transportation. *Road and Bridge Specifications*. Richmond, 2018.

Von Quintus, H.L., Mallela, J., Bonaquist, R., Schwartz, C.W., and Carvalho, R.L. *NCHRP Report 719: Calibration of Rutting Models for Structural and Mix Design*. Transportation Research Board, Washington, DC, 2012.

Zhang, J., Alvarez, A.E., Lee, S.I., Torres, A., and Walubita, L.F. Comparison of Flow Number, Dynamic Modulus, and Repeated Load Tests for Evaluation of HMA Permanent Deformation. *Journal of Construction and Building Material*, Vol. 44, 2013, pp. 391-398.

APPENDIX A

U.S. STATE AND CANADIAN PROVINCIAL AGENCIES' SURVEY

This survey was designated to collect key information from agencies regarding current practices of high-polymer modified (HP) asphalt mixes. This questionnaire includes 10 modules of questions related to materials, design, constructability, performance, challenges, and advantages / disadvantages of using this technology.

Q1- Contact Information

Name	
Position / Title	
Agency	
Address (City, State & Zip Code)	
Phone	
Email	

May we contact you for more information?

- ○ Yes.
- ○ Please contact this person instead (please provide name, phone number, and / or email address).
- ○ No.

Q2- Practice and Usage

a- Does your organization currently specify or allow the use of *high polymer* content in asphalt binders and mixtures?

- ○ Yes, currently use / allow.
- ○ No.
- ○ Not sure.

[If "No" is selected, please skip to Question 3]

b- Your organization defines *high polymer* content asphalt binder as a binder containing polymers by total weight of the binder at the rate of:

- ○ 4 to 6%.
- ○ 6 to 8%.
- ○ Greater than 8%.
- ○ Other.

c- At what stage do you consider checking the quality of the supplied high polymer content asphalt binder meeting the specification requirements:

- ○ At the terminal.
- ○ At the plant.
- ○ In the field.
- ○ Does not check for the quality.

d- How long you have been using high-polymer modified asphalt mixes?

○ Less than 2 years.
○ 2 to 4 years.
○ More than 4 years.

e- In which application (s) do you specify / allow the use of high polymer-modified asphalt mixtures?

○ Structural overlays.
○ Functional Overlays.
○ Interlayers for reflective cracking mitigation.
○ Bottom layer for bottom-up fatigue cracking mitigation.
○ Full-depth AC layer.
○ Others.

f- Indicate the extent of your *annual* high polymer-modified paving program in lane miles.

g- Approximately how many tons of high polymer-modified asphalt mix are placed each year? What is an approximate price for a ton of high polymer-modified asphalt mix ($/ton)? What is an approximate offset price from a regular conventional HMA mix ($/ton)? To answer this section, please consider filling the table below.

Year	**Approximate quantity of HP asphalt mixes placed (tons)**	**Approximate price for high-polymer modified asphalt mixture ($ per ton)**	**Approximate *offset* price from a regular conventional HMA mix ($ per ton)**	**Comments *(if needed)***

Q3- Practice and Usage

a- Why does / did your organization use high polymer-modified asphalt binder / mixes? (Select all that apply)

○ Does not use high polymer-modified asphalt binder / mixes at all.
○ To prevent bottom-up fatigue cracking.
○ To prevent top-down fatigue cracking.
○ To prevent reflective cracking.
○ To prevent rutting.
○ To design thinner AC layers.
○ For research purposes.
○ Others, please indicate your reasons.

b- Did your organization use high polymer-modified asphalt binder / mixes in the past and discontinue its use in some or all pavement applications?

○ Yes
○ No.
○ Not sure.

[If "No" is selected, skip to Question 4]

c- Why are high polymer-modified asphalt mixes no longer used in these applications?

Q4- Specifications

a- Does your organization have any specifications, test methods, mix design methods or acceptance criteria for high polymer-modified asphalt binders and / or mixtures?

○ Yes
○ No.

[If "No" is selected, skip to Question 5]

b- How does your organization accept high polymer modified asphalt binder for a project (or your program by Approval Product) since it may have shorter time to maintain the binder properties before mixing?

c- Please provide links in the space below or email copies to Jhony.habbouche@vdot.virginia.gov **of these specifications, test methods, mix design methods or acceptance criteria for high polymer-modified asphalt binders and / or mixtures**

d- Which properties do you measure / control (i.e., Mix design or field acceptance)?

Q5- Design and Performance

a- Mix Design Testing: Which of the following methods does your agency or your contractor use to design high polymer-modified asphalt mixes?

○ Do not use high polymer-modified mixes at all ***(if selected, please skip to Q6)***.
○ Do not do any formal mix designs.
○ Hveem mix design.
○ Marshall mix design.
○ Superpave gyratory compactor.
○ Balanced mix design
○ Bailey design
○ Other mix design methodology.

b- Structural Design: During project development, does your agency consider the structural capacity of the high polymer-modified layer using:

○ Falling Weight Deflectometer (FWD) testing.
○ Established structural coefficients.

- Mechanistic and / or mechanistic-empirical designs.
- Other.

c- During project development, what criteria do you consider and action (s) do you perform for surface preparation prior to laying down high polymer-modified asphalt layer?

- Subgrade stabilization.
- Applying a leveling course (for overlay applications).
- Milling (for overlay applications).
- Applying a tack coat.
- Rubblizing or cracking and seating an underlying rigid pavement (for overlay applications).
- Replacing localized areas of extreme damage.
- Other.

d- What performance measures (different than a conventional regular HMA mix) would you recommend for evaluating the quality of high polymer-modified asphalt pavements?

Q6- QC / QA

a- Quality Control: briefly indicate *all changes* of current quality control programs and / or practices executed specifically for high polymer-modified field projects (changes from regular conventional HMA field projects).

b- Quality Assurance: briefly indicate *all changes* of current quality assurance programs and / or practices executed specifically for high polymer-modified field projects. What types of acceptance testing do you specify?

Q7- Environmental Restrictions

a- Are you aware of / does your organization practice or enforce any safety / health / environmental restrictions specific to high polymer when high polymer-modified asphalt binders are used in asphalt mixtures?

- Yes.; if so please specify them:

  At the plant (where these mixes are being produced):
  In the field:

- No.
- Rely on manufacturers' recommendations; if so please specify if provider of the polymer, or binder supplier. Please sate some of these recommendations if they exist.

b- Please indicate all of the factors you think are likely to limit the use of high polymer-modified asphalt pavement.

○ Lack of standard specifications.
○ Lack of mix design methods.
○ Price
○ Lack of project selection criteria.
○ Lack of engineering design procedures.
○ Lack of agency experience.
○ Lack of local contractors.
○ Previous unsuccessful experiences.
○ Opposition from competing industries.
○ Reluctance to changes by industries.
○ Others, please specify below (if selected).

Q8- Research Projects

a- Does your organization have any current or completed research projects (laboratory and field) or performance histories (laboratory or field) on high polymer-modified asphalt mixes?

○ Yes
○ No.

[If "No" is selected, skip to Question 9]

b- If yes, please provide links in the space below or email copies to Jhony.habbouche@vdot.virginia.gov **of these current or completed research projects (laboratory and field) or performance histories (laboratory or field) on high polymer-modified asphalt mixes.**

Q9- Costs and Benefits

a- Does your organization have information on costs (initial or life cycle) or benefit-cost ratios for high polymer-modified asphalt mixes?

○ Yes.
○ No.

[If "No" is selected, skip to Question 10]

b- If yes, please provide links below or email copies to Jhony.habbouche@vdot.virginia.gov**. Is there anyone we could contact for more information? (Please provide name and contact information.)**

Q10- Additional Information and Acknowledgment

a- Please provide any *"lessons learned"*, good or bad that you may have, regarding the use of high polymer modified asphalt binders and mixtures in your State?

b- Do you have any additional information, current or historical, that you would like to share? If yes, please outline the information in the space provided below or provide links or contact information for more details.

○ Yes; if yes, please provide links below or email copies to Jhony.habbouche@vdot.virginia.gov. Is there anyone we could contact for more information? (Please provide name and contact information.)

○ No.

Acknowledgment-

The research team acknowledges your time, effort, and information.
This completes the survey.

APPENDIX B

SURVEY FOR ASPHALT CONTRACTORS IN VIRGINIA

This survey was primarily designated to collect information regarding standard construction practices executed to handle high-polymer modified (HP) material. The survey included plant-related questions covering specific practices from supply of HP binders to contractors' tanks (special pumps, larger pipes, special tools, etc.); specific practices for storage of HP binders (temperatures, shelf life, specific continuous mixing/shearing effort, etc.); and specific practices for production of HP AC mixtures (mixing time, mixing temperature, special additives [warm mix additive or any specific liquid anti-strip agent], etc.). In addition, the survey included field-related questions covering potential changes in current conventional practices for typical asphalt concrete (AC) mixtures in terms of surface preparation before paving; placement of HP AC mixtures (adjustment for thickness, compaction effort, paving equipment, etc.); quality control programs; and safety, health, and environmental restrictions. Finally, contractors were asked to provide any lessons learned based on their experience in placing HP binders and AC mixtures.

Q1- Please provide your contact information.

Name	
Position / Title	
Agency	
Address (City, State & Zip Code)	
Phone	
Email	

May we contact you for more information?

☐Yes.

☐Please contact this person instead (please provide name, phone number, and / or email address).

☐No.

Q2- Please specify any specific practices for suppling HP binders to your plant (e.g., special pumps, bigger pipes, special tools, and so on)?

Q3- Please specify any specific practices for storage of HP binders at your plant (temperatures, duration, specific continuous mixing / shearing effort, and so on).

Q4- Please indicate *<u>all changes</u>* of current practice in terms of <u>producing HP asphalt mixture at the plant</u> (e.g., mixing time, mixing temperature, special additives [Warm mix additive and / or specific liquid anti-strip being used], and so on)?

Q5- Please indicate *all changes* of current practice / action / criteria in terms of surface preparation prior to laying down HP asphalt layer (especially if it is used as an overlay)?

Q6- Please indicate *all changes* of current practice in terms of placement of HP asphalt mixtures (e.g., any adjustment for thickness, compaction effort, and so on)? Can the same paving equipment still be used for HP asphalt mixes?

Q7- Please indicate *all changes* of current quality control programs and / or practices executed specifically for HP field projects (changes from regular conventional HMA field projects).

Q8- Does your organization practice or enforce any safety / health / environmental restrictions specific to when HP binders are used in asphalt mixtures?

☐Yes.; if so please specify them:

At the plant:
In the field:

☐No.

☐Rely on manufacturers' recommendations; if so please specify if provider of the polymer, or binder supplier. Please sate some of these recommendations if they exist.

Q10- Please provide any *"lessons learned"*, good or bad that you may have, regarding the use of HP binders and mixtures in your organization?

Acknowledgment-

The research team acknowledges your time, effort, and information.
This completes the survey.

APPENDIX C

ESTIMATION OF IN-SERVICE PERFORMANCE LIFE OF PMA AND HP PAVEMENTS

Analysis (i)

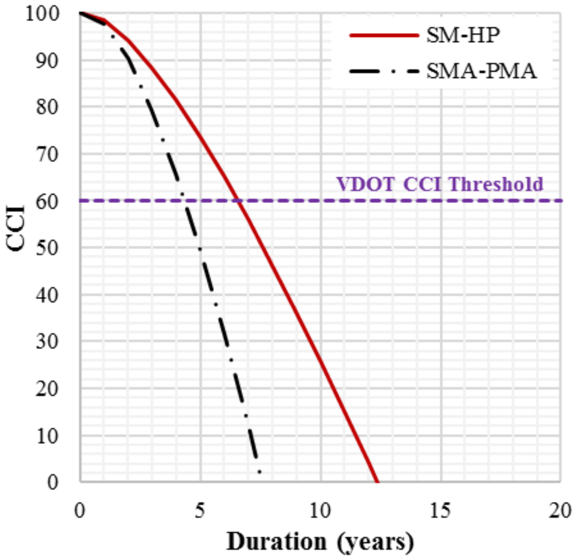


Figure C1. In-Service Predictive Performance Models for PMA and HP AC Overlays of Project 1 Using Approach I. PMA = polymer-modified asphalt binder; HP = high polymer-modified asphalt binder; AC = asphalt concrete.

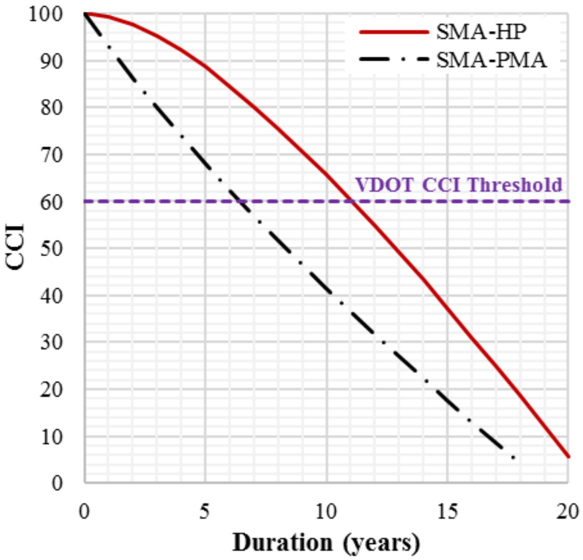


Figure C2. In-Service Predictive Performance Models for PMA and HP AC Overlays of Project 2 Using Approach I. PMA = polymer-modified asphalt binder; HP = high polymer-modified asphalt binder; AC = asphalt concrete.

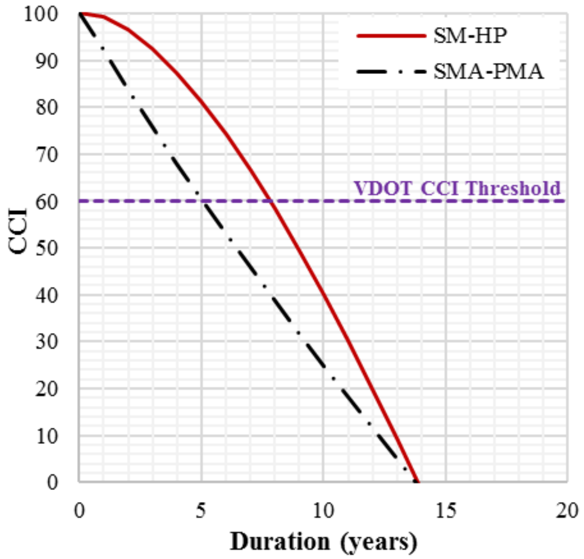


Figure C3. In-Service Predictive Performance Models for PMA and HP AC Overlays of Project 3 Using Approach I. PMA = polymer-modified asphalt binder; HP = high polymer-modified asphalt binder; AC = asphalt concrete.

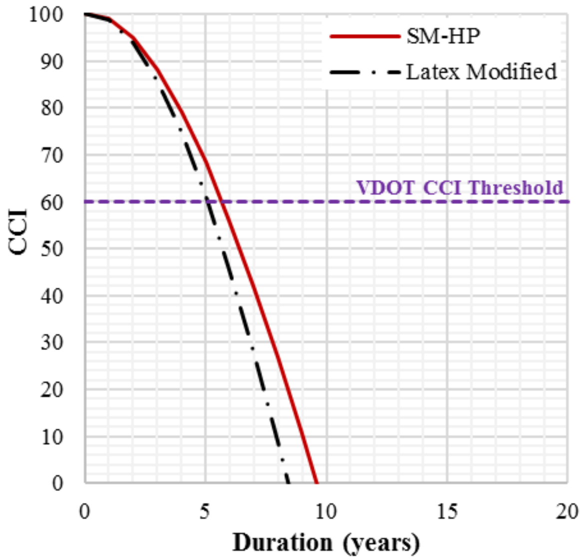


Figure C4. In-Service Predictive Performance Models for HP AC Overlay and Latex modified of Project 4 Using Approach I. HP = high polymer-modified asphalt binder; AC = asphalt concrete.

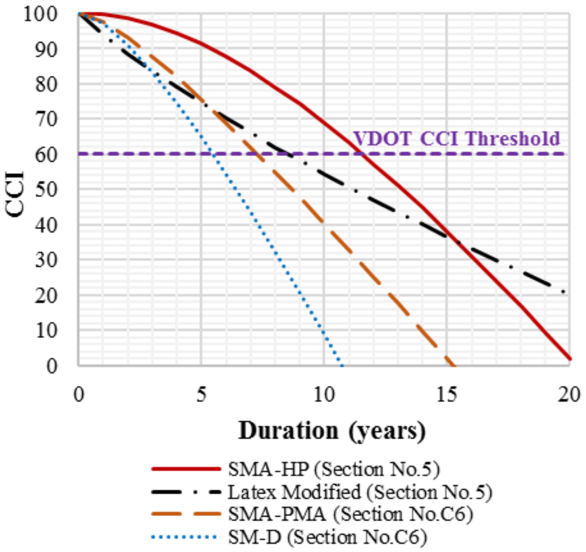


Figure C5. In-Service Predictive Performance Models for PMA and HP AC Overlays of Projects 5 and C6 Using Approach I. PMA = polymer-modified asphalt binder; HP = high polymer-modified asphalt binder; AC = asphalt concrete.

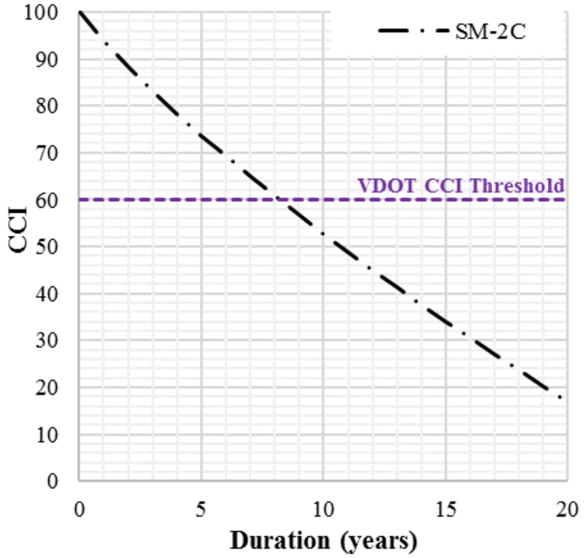


Figure C6. In-Service Predictive Performance Models for AC Overlay of Project 9 Using Approach I. AC = asphalt concrete.

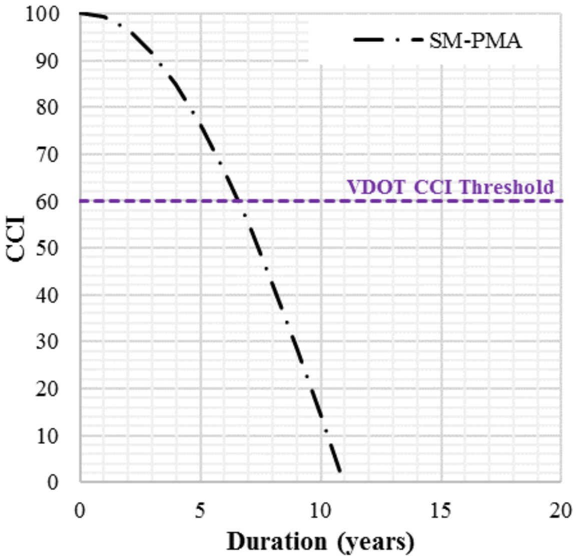


Figure C7. In-Service Predictive Performance Models for PMA AC Overlay of Project 10 Using Approach I. PMA = polymer-modified asphalt binder; AC = asphalt concrete.

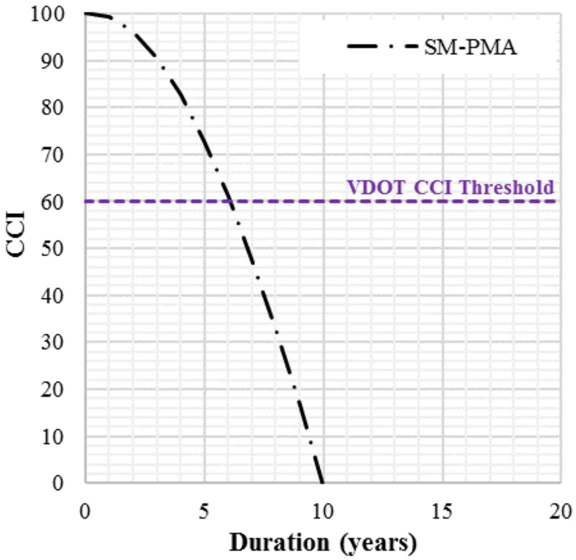


Figure C8. In-Service Predictive Performance Models for PMA AC Overlay of Project 11 Using Approach I. PMA = polymer-modified asphalt binder; AC = asphalt concrete.

Table C1. Prediction Model Coefficients (Approach) for Projects as Part of Analysis (i)

			Treatment Cycle		Prediction Model Coefficients			
Project ID	**Route, County, and Milepost**	**Pavement Type**	**Time Period**	**Overlay Mix Type**	**a**	**b**	**c**	**o**
1	I-95SB, Prince William, 0.02-3.89	BOJ	2010-2015	SMA-PMA	15.82	14.95	1.15	100
			2016-2020	SM-HP	15.61	15.12	1.13	100
2	I-95SB, Prince William, 10.98-13.12	BOJ	2008-2015	SMA-PMA	17.11	15.16	1.06	100
			2016-2020	SMA-HP	15.60	16.12	1.13	100
3	I-95NB, Prince William, 0.07-3.92	BOJ	2009-2015	SMA-PMA	17.17	15.11	1.07	100
			2016-2020	SM-HP	15.76	15.99	1.14	100
4	I-495NB, Fairfax, 5.56-6.63	BOJ	2013-2016	Latex Modified	16.00	15.77	1.16	100
			2017-2020	SM-HP	15.93	15.83	1.16	100
5	I-95SB, Hanover, 2.76-5.63	BOJ	2007-2016	Latex Modified	17.55	15.77	1.06	100
			2017-2018	SMA-HP	14.15	15.61	1.17	100
C6	I-95NB, Henrico, 7.33-9.55	BOJ	2008-2015	SM-D	17.22	16.15	1.11	100
			2016-2020	SMA-PMA	17.11	16.23	1.10	100
7	I-64EB, York, 14.81-20.55	BOJ	2018-2020	SMA-HP + THMACO	--	--	--	--
8	I-64WB, York, 14.98-20.33	BOJ	2018-2020	SMA-HP + THMACO	--	--	--	--
9	I-95NB, Fairfax, 3.41-4.45	BIT	2007-2017	SM-D	17.56	15.76	1.06	100
			2018-2020	SM-HP	--	--	--	--
10	I-495NB, Fairfax, 1.194-3.66	BOJ	2012-2019	SM-PMA	15.15	15.61	1.17	100
			2019-2020	SMA-HP	--	--	--	--
11	I-95NB, Prince William, 11.121-12.64	BOJ	2012-2018	SM-PMA	15.2	15.58	1.18	100
			2019-2020	SM-HP	--	--	--	--

BOJ = bituminous over jointed; SMA = stone matrix asphalt; PMA = polymer-modified asphalt binder; SM = surface mix; HP = high polymer-modified asphalt binder; latex modified = surface treatment; SM-D = SM with D designation (using unmodified asphalt binder PG 64H-22); THMACO = thin hot mix asphalt concrete overlay; BIT = bituminous; -- = critical condition index (CCI) loss rate was not calculated because of limitations in the data.

Analysis (ii)

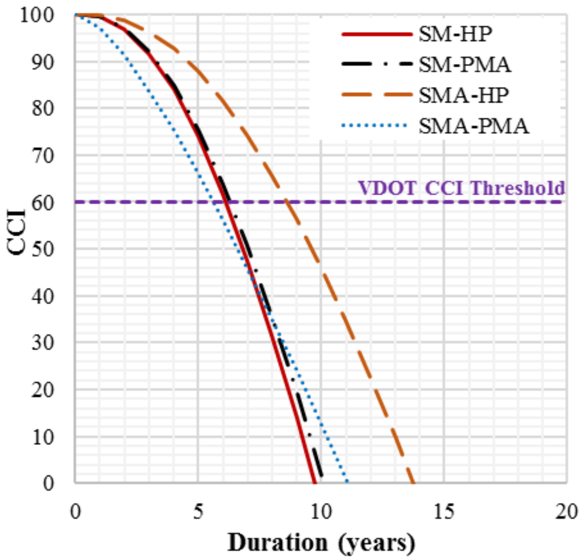


Figure C9. In-Service Predictive Performance for SM-HP, SM-PMA, SMA-HP, and SMA-PMA Overlay Mixes Using Approach I. SM = surface mix; HP = high polymer-modified asphalt binder; PMA = polymer-modified asphalt binder; SMA = stone matrix asphalt.

Analysis (iii)

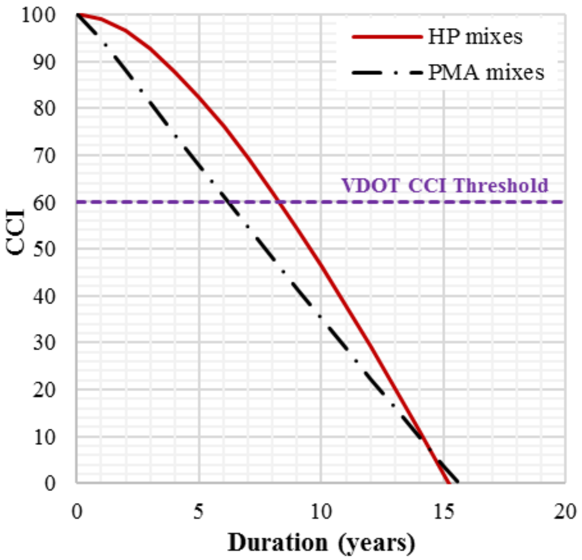


Figure C10. In-Service Predictive Performance for HP and PMA Overlays Using Approach I. HP = high polymer-modified asphalt binder; PMA = polymer-modified asphalt binder.