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Field Validation of Balanced Mix Design Initial Criteria

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16. Abstract:

The Virginia Department of Transportation (VDOT) initiated efforts to implement balanced mix design (BMD) in 2017, using 11 mixtures from a well-documented previous study in a benchmarking effort to select performance-related tests to use within the BMD framework and develop criteria for those tests. When these mixtures were produced and paved in 2015, sampling for extensive characterization was performed, and mixture locations were documented, providing important information to assess the in-service performance of the mixtures. The field projects associated with these benchmarking mixtures reached 8 years in service in 2023, providing the opportunity to assess performance and evaluate the suitability of the initial BMD cracking test criteria for design and production of 9.5-mm and 12.5-mm surface mixtures having A and D binder designations.

The purpose of this study was to validate the suitability of the initial BMD cracking test criteria for design and reheated production specimens determined from the laboratory benchmark testing of 11 surface mixtures placed in 2015. Pavement condition surveys, falling weight deflectometer testing, field visits, and core testing were conducted to assess the mixture properties and pavement conditions after 8 years in service. Results were analyzed relative to the initial mixture properties and results of BMD benchmark testing to validate VDOT's initial BMD cracking criteria.

The study showed that higher cracking resistance of the asphalt surface mixture, indicated by higher cracking tolerance index values, is associated with a reduced percent cracking in the field. The complex interactions of as-constructed density, pavement structural capacity, traffic loading, and climate complicate the relationship. Mixture quality, construction quality, and traffic loading have a significant influence on the pavement cracking performance, and trends were shown to align with expectations. Asphalt Pavement Analyzer rutting test results were determined to generally indicate field rutting trends. In this study, mixtures with higher laboratory Asphalt Pavement Analyzer rut depths tended to exhibit greater rut depths in service, confirming that the Asphalt Pavement Analyzer remains a useful indicator of rutting susceptibility within BMD projects. Overall, it was concluded that achieving a balanced asphalt mixture, as characterized by VDOT's BMD framework, is critical to optimizing asphalt surface mixture longevity in Virginia. Rutting has generally not been a major concern in Virginia. However, mixtures with increased cracking tolerance index values in this study tended to show greater rut depths, highlighting that improving cracking resistance must be balanced with evaluating rutting potential during mixture design and production to preserve long-term pavement durability.

The study recommends that VDOT's Materials Division continue to implement BMD. The results of this study demonstrate that VDOT's BMD test outcomes align with observed field performance trends. Mixtures meeting the established thresholds exhibited improved cracking resistance and acceptable rut depths when other variables were comparable. Consequently, these findings validate the effectiveness of the current BMD tests and thresholds in indicating in-service asphalt mixture performance and support continued implementation. In addition, it is recommended that the Virginia Transportation Research Council continue monitoring the performance of pavements with BMD surface mixtures to further validate BMD criteria and to quantify the expected life of BMD mixtures.

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FINAL REPORT

FIELD VALIDATION OF BALANCED MIX DESIGN INITIAL CRITERIA

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ABSTRACT

The Virginia Department of Transportation (VDOT) initiated efforts to implement balanced mix design (BMD) in 2017, using 11 mixtures from a well-documented previous study in a benchmarking effort to select performance-related tests to use within the BMD framework and develop criteria for those tests. When these mixtures were produced and paved in 2015, sampling for extensive characterization was performed, and mixture locations were documented, providing important information to assess the in-service performance of the mixtures. The field projects associated with these benchmarking mixtures reached 8 years in service in 2023, providing the opportunity to assess performance and evaluate the suitability of the initial BMD cracking test criteria for design and production of 9.5-mm and 12.5-mm surface mixtures having A and D binder designations.

The purpose of this study was to validate the suitability of the initial BMD cracking test criteria for design and reheated production specimens determined from the laboratory benchmark testing of 11 surface mixtures placed in 2015. Pavement condition surveys, falling weight deflectometer testing, field visits, and core testing were conducted to assess the mixture properties and pavement conditions after 8 years in service. Results were analyzed relative to the initial mixture properties and results of BMD benchmark testing to validate VDOT's initial BMD cracking criteria.

The study showed that higher cracking resistance of the asphalt surface mixture, indicated by higher cracking tolerance index values, is associated with a reduced percent cracking in the field. The complex interactions of as-constructed density, pavement structural capacity, traffic loading, and climate complicate the relationship. Mixture quality, construction quality, and traffic loading have a significant influence on the pavement cracking performance, and trends were shown to align with expectations. Asphalt Pavement Analyzer rutting test results were determined to generally indicate field rutting trends. In this study, mixtures with higher laboratory Asphalt Pavement Analyzer rut depths tended to exhibit greater rut depths in service, confirming that the Asphalt Pavement Analyzer remains a useful indicator of rutting susceptibility within BMD projects. Overall, it was concluded that achieving a balanced asphalt mixture, as characterized by VDOT's BMD framework, is critical to optimizing asphalt surface mixture longevity in Virginia. Rutting has generally not been a major concern in Virginia. However, mixtures with increased cracking tolerance index values in this study tended to show greater rut depths, highlighting that improving cracking resistance must be balanced with evaluating rutting potential during mixture design and production to preserve long-term pavement durability.

The study recommends that VDOT's Materials Division continue to implement BMD. The results of this study demonstrate that VDOT's BMD test outcomes align with observed field performance trends. Mixtures meeting the established thresholds exhibited improved cracking resistance and acceptable rut depths when other variables were comparable. Consequently, these findings validate the effectiveness of the current BMD tests and thresholds in indicating in-service asphalt mixture performance and support continued implementation. In addition, it is recommended that the Virginia Transportation Research Council continue monitoring the

performance of pavements with BMD surface mixtures to further validate BMD criteria and to quantify the expected life of BMD mixtures.

FINAL REPORT

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INTRODUCTION

The Virginia Department of Transportation (VDOT) initiated efforts to implement balanced mix design (BMD) in 2017. The first effort was aimed at selecting performance-related tests to use within a BMD framework and developing criteria for those tests that could be used to identify what should be well-performing mixtures. To achieve those goals, several mixtures from a previous study (Diefenderfer et al., 2018), which had excess material available, were evaluated. The effort included the assessment of several potential performance-related tests and provided benchmark information on mixture response in each test. From this effort, the Cantabro mass loss test, Asphalt Pavement Analyzer (APA) rut test, and indirect tensile cracking test (IDT-CT) at intermediate temperature were selected to use in developing VDOT's initial BMD specifications (Bowers et al., 2022; Diefenderfer and Bowers, 2019). Statistical methods were used to establish initial test criteria from the benchmarked mixtures, based on the assumption that cracking resistance was a priority and that the criteria should result in the design of mixtures that were equal to or improved in performance than the benchmarked mixtures.

The 11 mixtures used for benchmark testing were produced and paved in 2015 (Diefenderfer et al., 2018). During production, sampling for extensive characterization was performed, and mixture locations were documented, providing important information that could be used to assess the in-service performance of the mixtures. Excess loose mixture samples were stored in a climate-controlled environment to minimize any adverse effects and used in 2017 to select performance-related tests for use in BMD and to develop initial criteria for design and production. The field projects associated with the benchmarking mixtures reached 8 years in service in 2023, providing the opportunity to assess performance and evaluate the suitability of the initial BMD cracking test criteria for design and production of 9.5-mm and 12.5-mm surface mixtures having A and D binder designations.

PURPOSE AND SCOPE

The purpose of this project was to assess the effectiveness of VDOT's BMD cracking and rutting test methods and validate the suitability of the initial BMD cracking test criteria for design and reheated production specimens with field validation. The selected test methods and initial criteria were determined from laboratory benchmark testing of 11 surface mixtures placed in 2015 (Bowers et al., 2022; Diefenderfer and Bowers, 2019). The performance of those mixtures in the field after 8 years in service was evaluated. The effort included automated distress surveys to assess surface condition and falling weight deflectometer (FWD) testing to evaluate structural condition. Cores were collected for determination of asphalt content, gradation, and permeability, and for laboratory performance testing. Analyses were undertaken to assess the performance of the field projects after 8 years in service relative to the measured laboratory performance used to develop the initial BMD thresholds.

METHODS

This study's objectives were accomplished through pavement condition surveys, FWD testing, field visits, and core testing to assess the mixture properties and pavement conditions at 8 years in service. Results were analyzed relative to the initial mixture properties and BMD benchmark testing results to validate the initial BMD cracking criteria developed for the design and production of 9.5-mm and 12.5-mm surface mixtures having A and D binder designations.

Field Evaluation

To assess the validity of the initial criteria, pavement condition surveys, FWD testing, and coring were conducted for the field project locations.

Locations

Table 1 summarizes the dates and locations of the field project where each surface mixture was placed, along with mixture and pavement type. Figure 1 shows the distribution of locations across the state.

Table 1. Field Project Locations and Information

Mixture/ Section	Production Date	Location	District	Mixture Type	Pavement Type
A	6/9/2015	US 11N, Lee Hwy.	Bristol	SM-12.5A	Asphalt
B	6/9/2015	SR 685S, Barbershop Rd.	Staunton	SM-12.5A	Asphalt
C	6/16/2015	SR 637N, Potomac View Rd.	Northern Virginia	SM-9.5D	Asphalt
D	6/22/2015	SR 682, Leesville Rd.	Lynchburg	SM-9.5D	Asphalt
E	6/21/2015	US 250W, Ivy Rd.	Culpeper	SM-12.5D	Asphalt
F	6/23/2015	US 211E, Lee Hwy.	Culpeper	SM-9.5A	Asphalt
G	7/1/2015	US 1S, Washington Hwy.	Richmond	SM-12.5E	Composite
H	7/21/2015	US 15S, James Madison Hwy.	Culpeper	SM-12.5D	Asphalt
I	7/28/2015	US 13Bus N, Bayside Dr.	Hampton Roads	SM-9.5A	Composite
J	8/10/2015	SR 2802S, Virginia Ave.	Northern Virginia	SM-9.5A	Asphalt
K	9/9/2015	SR 631N, 5th Street Ext.	Culpeper	SM-9.5D	Asphalt

A and D = mixture produced using PG 64S-22 binder; E = mixture produced using PG 64E-22 binder; SM = surface mixture.

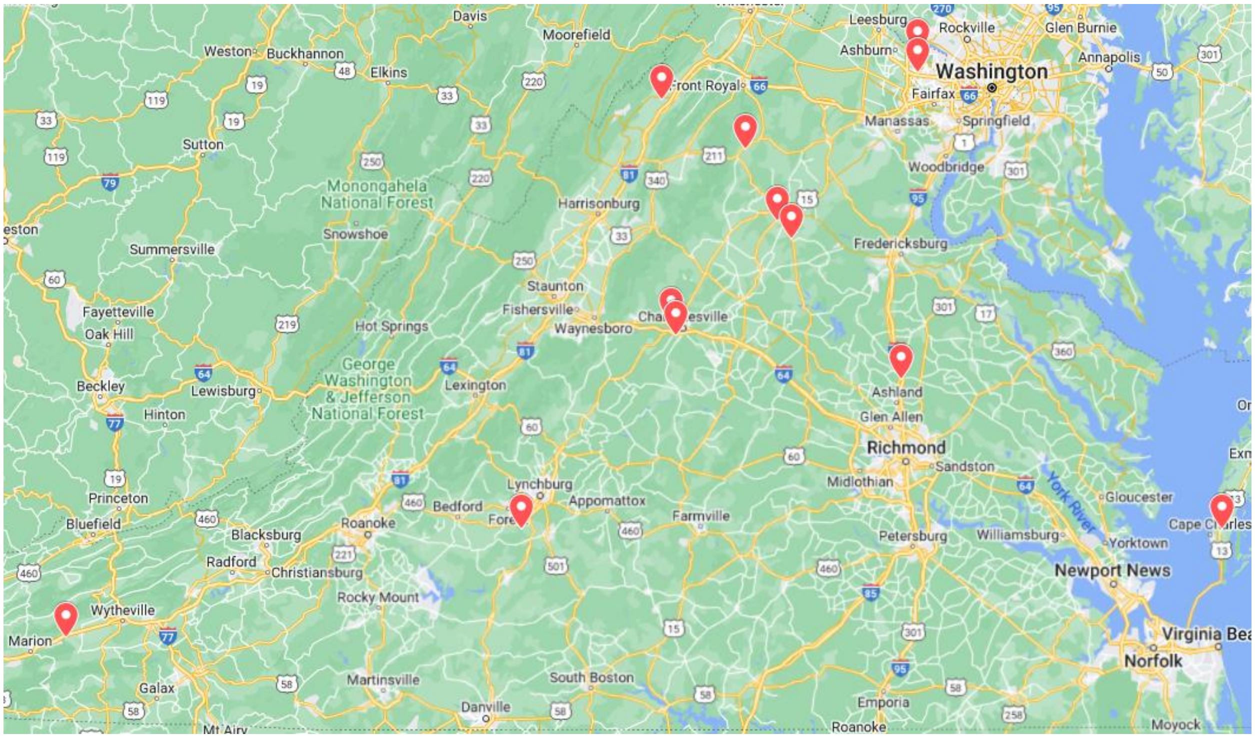

Figure 1. Locations of Field Sections Paved in 2015 and Evaluated after 8 Years in Service to Validate VDOT's Cracking and Rutting Balanced Mix Design Criteria

Mixtures

Eleven mixtures were evaluated to develop the BMD thresholds. The mixtures and field projects are designated with a letter (A–K). All mixtures were plant-produced 9.5-mm or 12.5-mm nominal maximum aggregate size surface mixtures designed using VDOT's initial 50-gyration design specification (Diefenderfer et al., 2018). Mixtures with A or D designations were produced using PG64S-22 binder. The mixture with an E designation was produced using PG64E-22 binder. All mixtures contained reclaimed asphalt pavement.

Information from Production

During production and construction in 2015, loose plant mixture samples and cores were collected for evaluation (Diefenderfer et al., 2018). Volumetric properties, asphalt content, and gradation were determined from the loose mixture samples. Layer thickness, density, and permeability were measured for all cores.

Pavement Condition Surveys

Through a contract with a third-party vendor, VDOT collects condition data on the pavement network annually by using continuous digital imaging and performs crack detection through automated image analysis. In addition, pavement surface roughness and rutting data are simultaneously collected by vehicle-mounted sensors (VDOT, 2024). The data are analyzed to quantify the pavement network condition using an index calculation methodology that quantifies the distresses observed in terms of a critical condition index (CCI) (VDOT, 2022). CCI is determined as the lesser (i.e., worse) of the load-related distress rating (LDR) and the non-load-related distress rating (NDR). LDR incorporates load-related distresses, such as wheel-path cracking, patching, and potholes, along with rutting. NDR includes non-load-related distresses, such as transverse and longitudinal cracking, joint cracking, non-wheel path patching, and bleeding. Pavement condition data are available from VDOT's pavement management system (PMS).

Condition data were collected for each of the field projects after 8 years in service. In addition, to evaluate the ability of the 2015 section data to adequately represent statewide conditions, condition data were extracted from VDOT's PMS for primary and secondary routes paved in 2016 with similar surface mixtures after 8 years in service and compiled for comparison. When available, additional condition data at varying ages were extracted for the field projects to assess the rate of deterioration.

Falling Weight Deflectometer Testing

Testing was performed at a service life of 8 years using a Dynatest Model 8012 FWD in the evaluated lane for each section. The FWD load plate was in the right wheel path during testing. The FWD was equipped with nine deflection sensors at radial distances of 0, 8, 12, 18, 24, 36, 48, 60, and 72 inches from the center of the load plate. Testing was conducted at varying intervals, depending on the section length. One load level, 9,000 pounds, was used, and the deflection basin (i.e., the deflection response measured by the array of sensors from a single load application) was recorded. The FWD was calibrated according to its standard calibration procedure and schedule. FWD data were analyzed using VDOT ModTag software (VDOT, 2016) to determine the pavement stiffness modulus (computed by dividing the load applied to the pavement by the average deflection [D1]). The pavement stiffness moduli were normalized by the average value of the pavement stiffness moduli from all sites and were not temperature corrected. Surface layer stiffness moduli were unable to be used as accurate pavement thickness and layer information was not available for all sites.

Cumulative Degree Days

Cumulative degree days (CDD) are defined as the cumulative sum of temperature in degrees above 32ºF experienced each day by a pavement surface over time. CDD was calculated from daily weather data collected from the nearest weather station to each field location. Each degree day was calculated by subtracting 32ºF from the daily high temperature the local weather station reported. CDD was calculated as the sum of all degree days greater than zero and based on the span of time from production to each location's pavement condition survey. The National Centers for Environmental Information (n.d.), National Oceanic and Atmospheric Administration, provided all weather station data.

Coring

Six-inch-diameter road cores were collected from the center of the lane at randomly stratified locations within the length of pavement previously cored in 2015. Full-depth cores were collected at the beginning and end of the section to verify pavement thickness. At least one core was taken through a crack at each section to determine crack origin (the top or bottom of the pavement structure).

Laboratory Testing

Layer thickness, density, and permeability were determined from cores collected from the center of the lane at a service life of 8 years to characterize the in-service mixture and assess changes over time. After this information was collected, test specimens were fabricated from the cores and subjected to IDT-CT and direct tension cyclic fatigue testing. In addition, specimens prepared from cores collected from the wheel path were subjected to the IDT-CT. After testing was completed, the test specimens were broken apart and used to determine mixture properties, including theoretical maximum specific gravity, asphalt content, and gradation.

Air Voids

Air-void contents were determined in accordance with AASHTO T 269-14(2022), *Percent Air Voids in Compacted Dense and Open Asphalt Mixtures* (AASHTO, 2023).

Permeability

Permeability testing was performed on cores according to VTM-120, *Method of Test for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter* (VDOT, 2023).

Theoretical Maximum (Rice) Specific Gravity

The theoretical maximum specific gravity of each mixture was determined in accordance with AASHTO T 209-23, *Standard Method of Test for Theoretical Maximum Specific Gravity (Gmm) and Density of Asphalt Mixtures* (AASHTO, 2023).

Asphalt Content and Gradation

Asphalt content was determined using the ignition furnace in accordance with AASHTO T 308-22, *Determining the Asphalt Binder Content of Hot-Mix Asphalt by the Ignition Method* (AASHTO, 2023). Sieve analysis was performed on the aggregate in accordance with AASHTO T 30-21, *Mechanical Analysis of Extracted Aggregate* (AASHTO, 2023).

Indirect Tensile Cracking Test

The IDT-CT was conducted at 25°C, generally in accordance with American Society for Testing Materials (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 International, 2019). Five replicate field core test specimens—150 mm in diameter and of varying height and air void content—were tested for each mixture. Replicate specimens were selected to be as similar in height and air void content as possible. The cracking tolerance (CT) index was calculated from the test load-displacement curve collected during testing.

Direct Tension Cyclic Fatigue Test

The simplified viscoelastic continuum damage test, known as the direct tension cyclic fatigue test, was performed at 21°C using the Asphalt Mixture Performance Tester in accordance with AASHTO T 411-23, *Standard Method of Test for Determining the Damage Characteristic Curve and Failure Criterion Using Small Specimens in the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test* (AASHTO, 2023). The cyclic fatigue test was performed on 38-mm-diameter by 110-mm-height specimens cored from 150-mm-diameter pavement cores. Specimen air voids differed from the test requirements because of the inconsistency in field density.

During testing, it was found that the specimens produced highly variable test results. This outcome was likely partially due to air void content variability among the cores from which the specimens were fabricated. In addition, the variability may have been due to the presence of small cracks or damage within the cores and specimens that were undetected. Unfortunately, this damage meant that results from the cyclic fatigue test were unable to be used to assess the fatigue behavior of the mixtures.

Analyses

Analyses were performed using data collected in 2015 during production, data collected related to BMD testing in 2018, data collected from the field cores after 8 years in service, condition assessment, and structural assessment to validate the selection of performance-related test criteria for BMD. Statistical evaluation was used to investigate the relationships between mixture properties and performance.

In addition, an independent set of 8-year condition data for primary and secondary routes paved with similar mixtures was obtained from VDOT's PMS with the assistance of the Maintenance Division. This dataset was used as a reference for comparison with the much smaller dataset collected from the field sites. This dataset consisted of 7,388 0.1-mile segments of asphalt pavements and 95 0.1-mile segments of composite pavement. Because of the differences in deterioration mode between asphalt and composite pavements, each was evaluated separately.

Cracking Performance

For this study, cracking performance was evaluated by quantifying the percentage of cracked area relative to the total lane area, following VDOT's methodology as reported for the Moving Ahead for Progress in the 21st Century Act (MAP-21) program (Federal Highway Administration [FHWA], 2025). Cracking performance data were collected during the pavement condition surveys of the field sections after 8 years in service.

The pavement condition surveys identified several types of cracking, including transverse, longitudinal, and alligator (fatigue) cracking, each exhibiting varying severity levels. The methodology for calculating the percentage of crack area differed based on the crack type.

Transverse and Longitudinal Cracks: These linear cracks were measured for their lengths. To account for the area these cracks affected, an "area of influence" was defined, extending 6 inches (0.5 feet) on either side of the crack. The total cracked area for these types was calculated using Equation 1:

$$\text{Cracked Area} = \text{Crack Length} \times 1\ \text{ft (total width)} \qquad \text{[Eq. 1]}$$

Alligator Cracks: These cracks were quantified directly as areas in the condition data. The total crack area was obtained by summing the areas from all crack types. The percent cracking was then determined by dividing the total cracked area by the total lane area of the section, as Equation 2 shows:

$$\text{Percent Cracking} = \frac{\text{Total Cracked Area}}{\text{Total Lane Area}} \times 100 \qquad \text{[Eq. 2]}$$

This metric served as a key indicator in evaluating the cracking performance of asphalt mixtures concerning the parameters considered in this study.

RESULTS AND DISCUSSION

Pavement Condition Surveys

Pavement condition surveys were conducted between August and December 2023 to provide at least one survey covering each trial project. In some cases, when the trial project was such that annual surveys were conducted as part of VDOT's routine condition assessment program, multiple years of condition assessments were available from VDOT's PMS.

Assessment of Representative Data

To verify that the trial projects' 8-year service performance was reasonably representative of statewide pavement performance, an independent set of 8-year condition data for primary and secondary routes paved with similar mixtures was compared with that of the trial sections.

Figures 2 through 4 show the comparisons between primary and secondary asphalt CCI values, which are found to be reasonably similar. Figure 2 indicates that the primary field project 0.1-mile segments perform similarly to the PMS segments, whereas the secondary field 0.1-mile segments perform better than the PMS segments. Figure 3 shows the LDR and NDR occurrences for the primary routes and indicates that the NDR values are influencing the CCI values more than the LDR results. Figure 4 presents the LDR and NDR results for the secondary routes. For these routes, both LDR and NDR appear to similarly influence CCI but not to the same degree as the effect of NDR on primary routes.

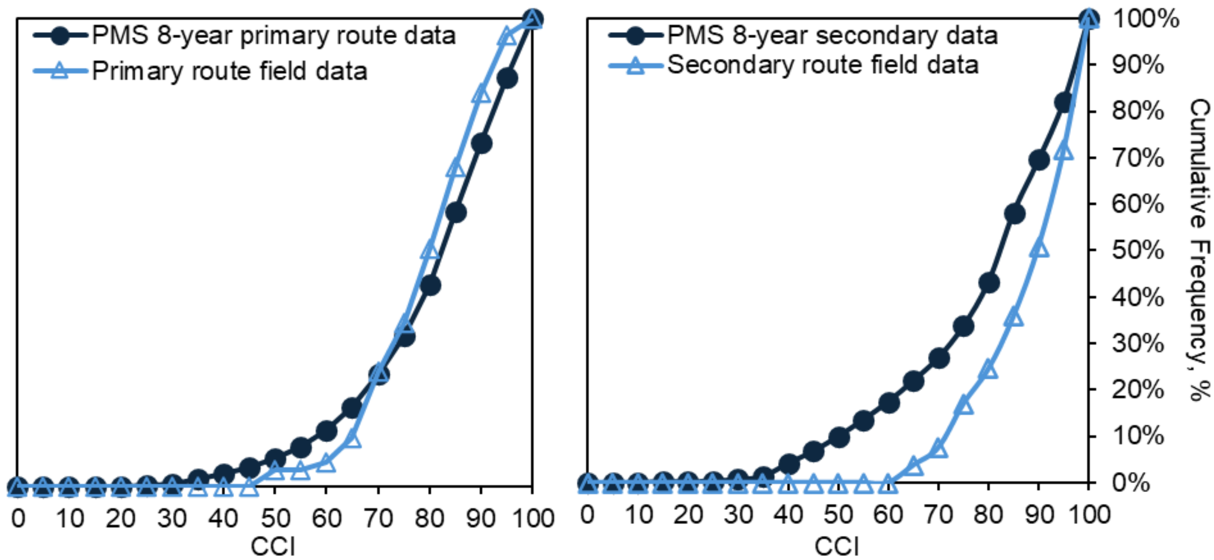

Figure 2. Comparisons of Primary and Secondary Route CCI Values for 0.1-Mile Segments. CCI = critical condition index; PMS = pavement management system.

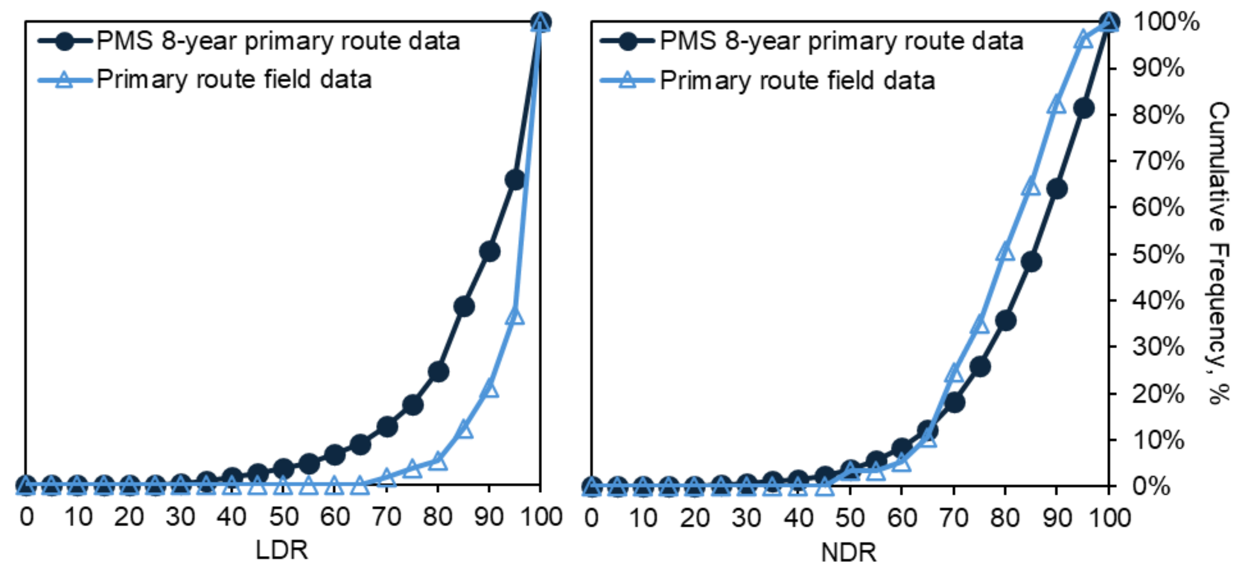

Figure 3. Comparisons of Primary Route LDR and NDR Values for 0.1-mile Segments. LDR = load-related distress index; NDR = non-load-related distress index; PMS = pavement management system.

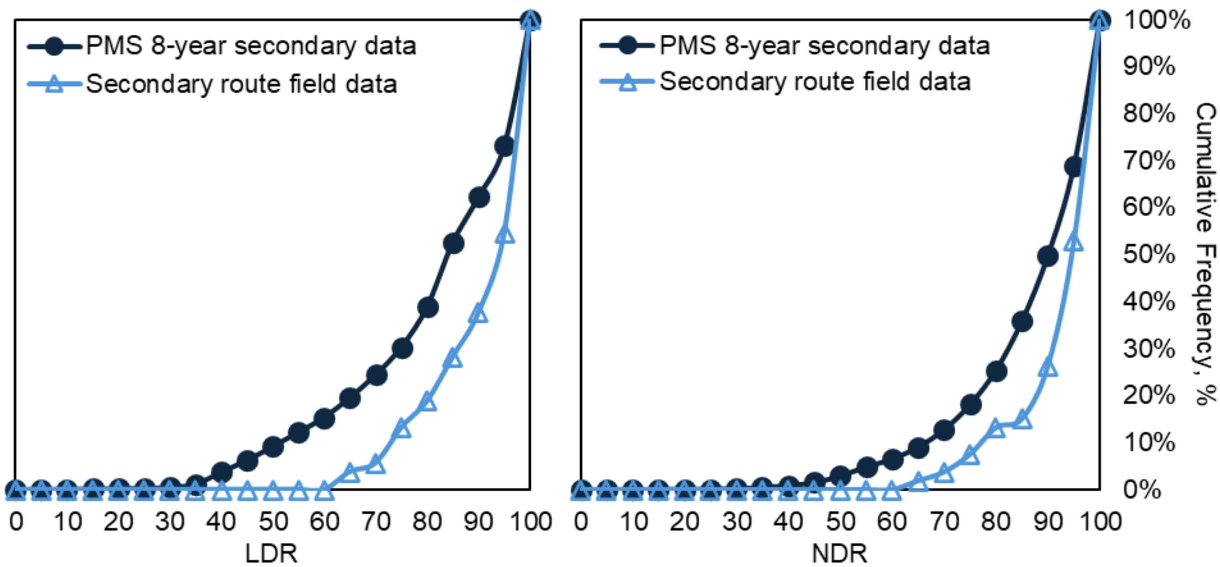

Figure 4. Comparisons of Secondary Route LDR and NDR Values for 0.1-Mile Segments. LDR = load-related distress index; NDR = non-load-related distress index; PMS = pavement management system.

Mixtures G and I were on composite pavements. Although this location did not influence using these mixtures for some comparisons, they were not included in performance evaluations because of the differences in performance between asphalt and composite pavements and the small sample size. PMS data were used to assess that these mixtures did not show unusual behavior by comparing the performance of the two sections with an independent set of data from seven composite pavement sections across the state. Figure 5 shows the distributions of each dataset, indicating that the field section data do not show unusual behavior and fall within the distribution of the PMS dataset. Although field site CCI has a median value less than that of the PMS dataset, the small sample size does not allow for meaningful comparisons.

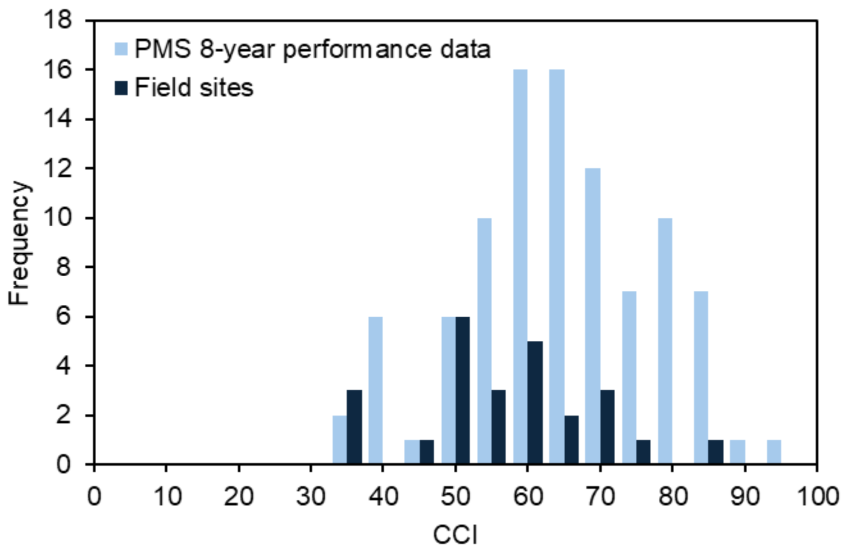

Figure 5. Comparison of CCI Distributions of PMS Performance Data at 8 Years in Service for Composite Pavements and Sections G and I. CCI = critical condition index; PMS = pavement management system.

Overlaid Section

Mixture F was unable to be used in the validation effort because the section was milled and replaced in 2023, before field visits could be arranged. Pavement condition data collected from the right (outer) lane indicated that a section of US 211 inclusive of section F reached replacement conditions between 2020 and 2021, and the surface was replaced in 2023. Mixture F was in the left (inner) lane, so its condition was not directly assessed per VDOT practice. Thus, the exact condition prior to replacement is unknown. However, Figure 6 shows CCI for the replaced segment of US 211. The replaced segment extended beyond the boundaries of the section paved in 2015, indicating that the deterioration was more widespread than the location of the surface mixture paved in 2015 and likely related to other factors than the right-lane surface mixture or mixture F.

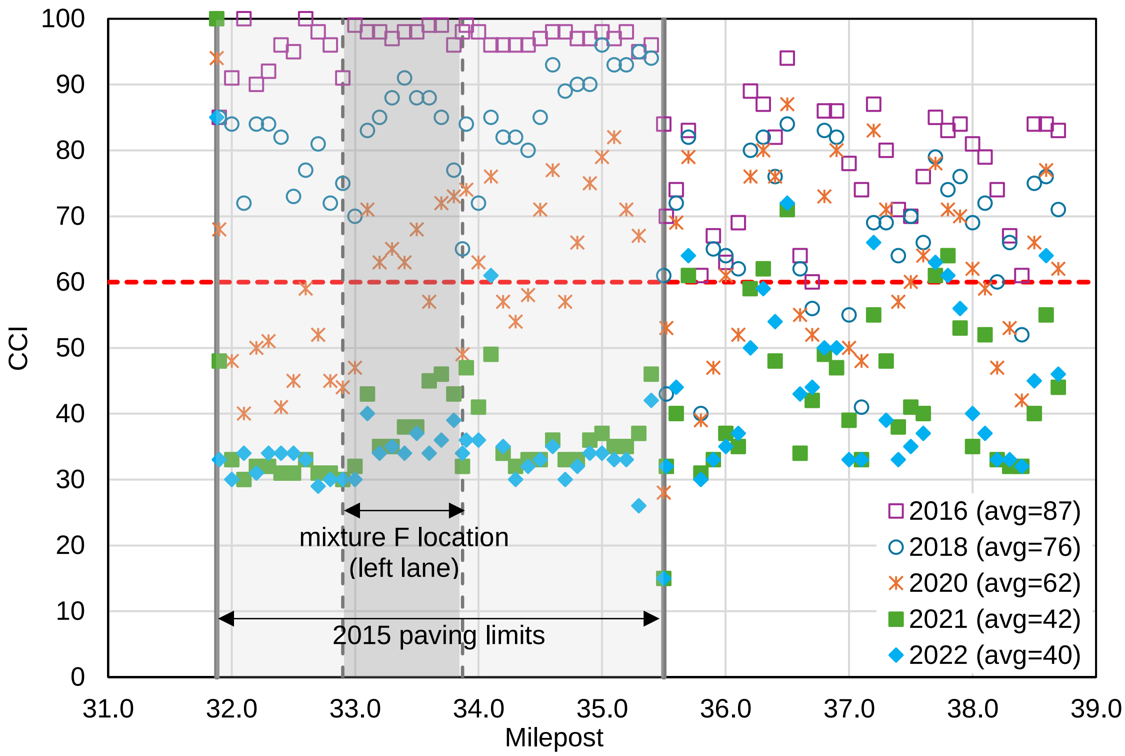

Figure 6. CCI Values over Time for Pavement Segment Milled and Overlaid in 2023. Red dashed line indicates CCI value of 60, below which pavement is considered deficient. Dashed grey lines indicate boundaries of where mixture F is paved in the left (inner) lane. Solid grey lines indicate boundaries of surface mixture paved in 2015. CCI = critical condition index.

Deterioration Rates

Two field sections were such that multiple years of condition data were available from 2016 to 2024. These sections were A, US 11N in Smyth County, and D, SR 682N in Campbell County.

Figure 7 shows the average condition indices for section A from milepost 53.80 to milepost 56.47. The section maintained very good performance through year 6, after which a decline in the indices can be seen, with NDR driving CCI. A linear trend was fit through the CCI values for years 6 through 8 to estimate the rate of deterioration. Based on the trendline, the rate of deterioration is approximately 10.5 CCI units per year, resulting in a surface mixture lifespan of approximately 10 years before reaching a deficient condition. VDOT typically considers a pavement to be deficient when CCI reaches a value of 60.

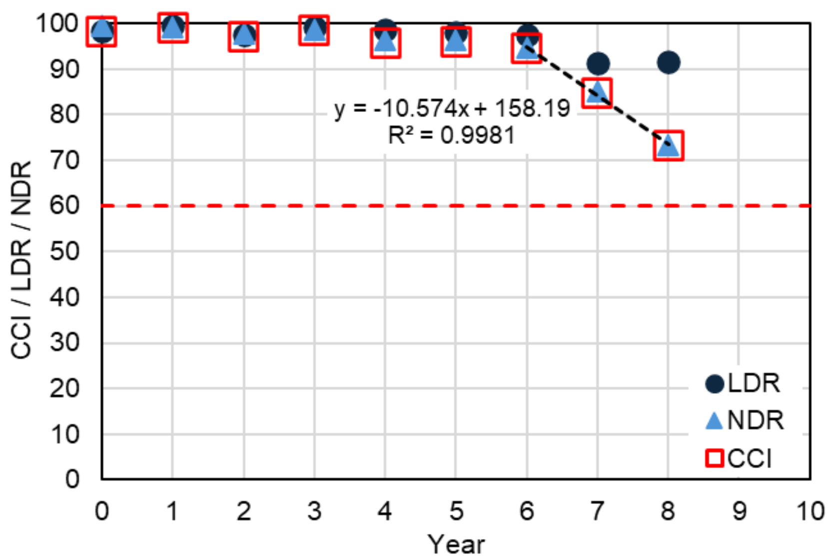

Figure 7. Deterioration Curve for Section A, US 11N in Smyth County. Red dashed line indicates CCI value of 60, below which pavement is considered deficient. CCI = critical condition index; LDR = load-related distress index; NDR = non-load-related distress index.

The second section for which multiple years of condition data were available is section D, SR 682N in Campbell County, from milepost 18.4 to milepost 19.1. Figure 8 presents the condition indices for this section. A slow but continuous rate of deterioration of approximately 1.4 CCI units per year that appears to be load-related is shown to date. It is difficult to predict the expected lifespan for this section with this trend because the typical pavement will eventually undergo an increased rate of deterioration that is not yet evident.

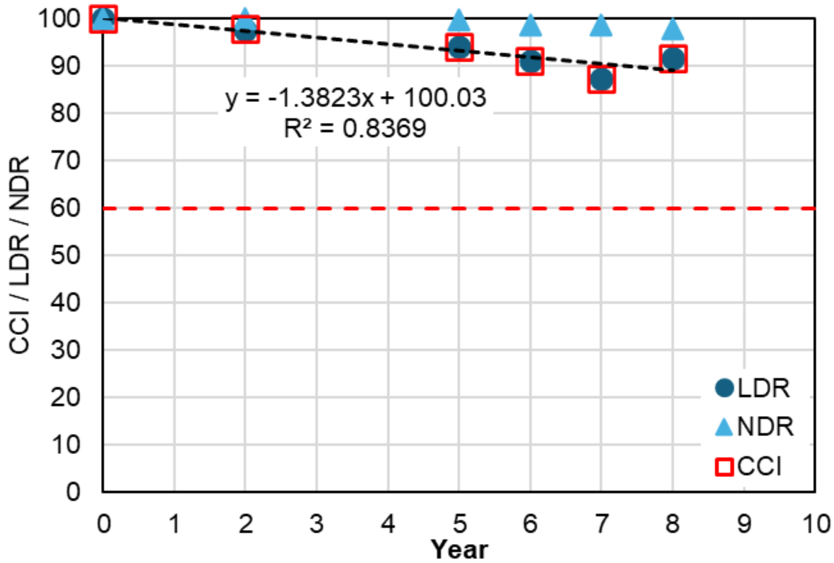

Figure 8. Deterioration Curve for Section D, SR 682N in Campbell County. Red dashed line indicates CCI value of 60, below which pavement is considered deficient. CCI = critical condition index; LDR = load-related distress index; NDR = non-load-related distress index.

Falling Weight Deflectometer

FWD testing was performed prior to section visits to assess the underlying pavement structure condition and determine if the structure properties were generally continuous throughout each field section. Because detailed information regarding each pavement structure was not available, the pavement stiffness modulus was used as an indicator of structural condition. Figure 9 shows a typical graph of the stiffness modulus for section H. Table 2 summarizes the average stiffness modulus for each section except I, which was not tested.

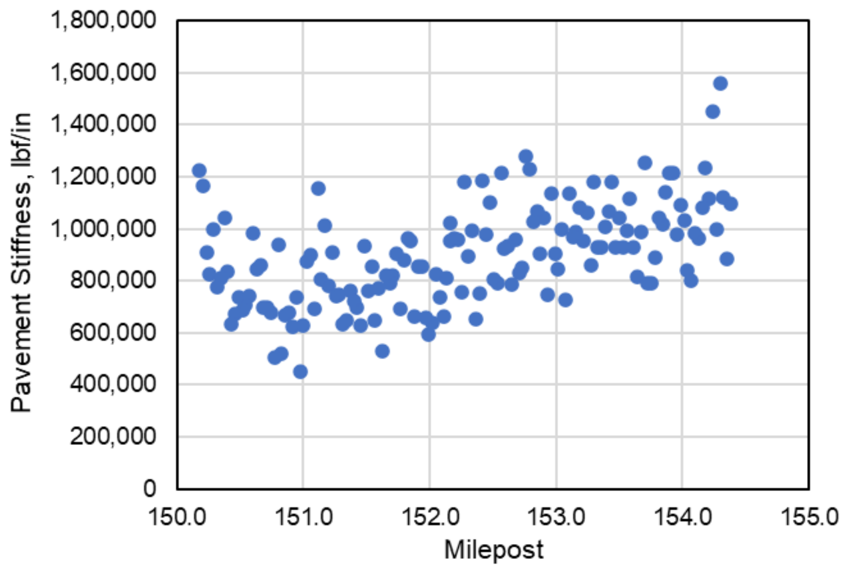

Figure 9. Example of Stiffness Modulus Calculated from Falling Weight Deflectometer Test Results for Section H, US 15S

Table 2. Average Pavement Stiffness Values from Falling Weight Deflectometer Testing

Section	Location	Avg. Pavement Stiffness, lbf/in	Number of Tests	Milepost from	Milepost to	Distance, miles	Pavement Type
A	US 11N	987,626	140	53.80	56.43	2.63	Asphalt
B	SR 682S	644,049	116	0.00	2.18	2.18	Asphalt
C	SR 637N	1,485,416	94	0.00	0.90	0.90	Asphalt
D	SR 682N	1,133,424	62	18.25	18.83	0.58	Asphalt
E	US 250W	1,020,029	149	91.10	92.67	1.57	Asphalt
G	US 1S	1,351,159	95	113.91	114.80	0.89	Composite
H	US 15S	897,472	150	150.18	154.38	4.20	Asphalt
I	US 13Bus N	-	-	0.0	1.58	1.58	Composite
J	SR 2802E	337,414	66	0.00	0.62	0.62	Asphalt
K	SR 631N	1,087,290	58	10.70	11.24	0.54	Asphalt

"-" = falling weight deflectometer testing not performed.

Cumulative Degree Days

CDD values were calculated for each section from the nearest weather station. Based on a study of more than 80 pavement sections, NCHRP 09-47A found that cracking developed in pavements after approximately 70,000 CDD (Shen et al., 2017). Diefenderfer (2019) found that 70,000 CDD is reached between 6 and 7 years in service, depending on the location in Virginia. Table 3 summarizes the CDD values for each field section.

Table 3. CDD for Each Field Section Based on Production Date and Date of Pavement Condition Assessment

Section	Location	District	County	Production Date	Assessment Date	Total Days	Weather Station	CDD	Missing Days	Missing Days, %
A	US 11N	Bristol	Smythe	6/9/2015	9/22/2023	3005	Wytheville	97,901	48	1.6
B	SR 682S	Staunton	Shenandoah	6/9/2015	11/30/2023	2298	Woodstock 2 NE	75,810	82	3.6
C	SR 637N	Northern Virginia	Loudoun	6/16/2015	12/7/2023	3096	Dulles Int'l Airport	112,576	0	0
D	SR 682	Lynchburg	Campbell	6/22/2015	8/1/2023	2963	Lynchburg Reg Airport	111,692	7	0.2
E	US 250W	Culpeper	Albemarle	6/21/2015	10/8/2023	3024	Charlottesville 2	103,279	10	0.3
G	US 1S	Richmond	Hanover	7/1/2015	8/15/2023	2967	Ashland Hanover Reg Airport	115,227	4	0.1
H	US 15S	Culpeper	Culpeper	7/21/2015	11/30/2023	3006	Charlottesville 2	100,869	10	0.3
I	US 13Bus N	Hampton Roads	Northampton	7/28/2015	10/20/2023	3006	Cape Charles 5 ENE	107,464	10	0.3
J	SR 2802N	Northern Virginia	Fairfax	8/10/2015	10/22/2022	2630	Dulles Int'l Airport	94,643	0	0
K	SR 631N	Culpeper	Albemarle	9/9/2015	12/3/2023	3000	Charlottesville 2	100,951	10	0.3

CDD = cumulative degree days.

Field Section Visits

Field locations were visited for coring and general visual assessment. During coring, full-depth cores were taken at the beginning and end of each section, and often at the mid-point, to validate the pavement thickness. This extraction was necessary because the pavement structural data in PMS is not always fully accurate. Full-depth cores were unable to be collected for composite pavement section I because the drill bit was unable to cut through the underlying concrete slabs. Table 4 provides a summary of the structure at each location.

Table 4. Pavement Structural Information

Location	Core Asphalt Thickness, in.	PMS Asphalt Thickness, in.	Core Concrete Thickness, in.	PMS Concrete Thickness, in.
A	5.7–7.3	6.0	-	-
B	4.1–5.6	1.75	-	-
C	7.2–10.0	0.0 [a]	-	-
D	8.8–9.6	No information in PMS	-	-
E	Not available	6.8	-	-
G	7.8–8.7	[a]	15.1	JRCP [a]
H	5.0–5.1	8.2–8.5	-	-
I	4.5–4.8	2.2–5.7	[b]	8.0 JRCP [c]
J	3.5–3.9	0.0 [a]	-	-
K	4.7–9.0	[a]	-	-

[a] missing some or all layers or thicknesses in PMS; [b] Unable to core through JRCP slab; [c] JCRP layer isolated to one segment after segmentation of larger section, so layer appears to be missing; - = material not present in pavement; JRCP = jointed reinforced concrete pavement; PMS = pavement management system.

Figures 10 through 13 provide examples of various distresses seen during the field visits. Figure 10 shows delamination at section B, SR 685S. Figure 11 shows a composite pavement core from section G, US 1S with stripping in one of the underlying asphalt layers. When extracted, the bottom of most cores from section G appeared to have broken loose in this darker colored stripped layer, indicating that the layer is likely moisture-susceptible and could be causing a widespread issue. Figures 12 and 13 show cores from section K, SR 631N. Figure 12 illustrates bottom-up fatigue cracking, and Figure 13 is an example of top-down cracking.

Figure 10. Section B, SR 685S, Core 21 Showing Delamination.

Figure 11. Section G, US 1S, Composite Pavement Core 1 Showing Stripping and Delamination. Most cores were extracted with the bottom surface in the dark delaminated layer, likely indicating that the layer has a stripping issue.

Figure 12. Section K, SR 631N, Core 4 Showing Bottom-up Fatigue Cracking.

Figure 13. Section K, SR 631N, Core 5 Showing Top-down Cracking

Laboratory Evaluation

During production and construction in 2015, loose plant mixture samples and cores were collected for evaluation (Diefenderfer et al., 2018). Table 5 summarizes the as-produced mixture properties. Cores were collected to assess performance after 8 years in service. Table 6 summarizes the mixture properties measured from this core material. Tables 7 through 9 present test data for the reheated fabricated specimens, cores collected at construction, and cores collected after 8 years in service. Table 7 compares the average core thickness and average air voids of the cores collected at construction and after 8 years in service. Table 8 shows average permeability for each set of cores, where, as expected, permeability decreased over time. Table 9 presents the CT index for the reheated loose mixture specimens and cores collected after 8 years in service.

Table 5. Production Mixture Information

Mixture/Section	A	B	C	D	E	F	G	H	I	J	K
Mixture Type	SM-12.5A	SM-12.5A	SM-9.5D	SM-9.5D	SM-12.5D	SM-9.5A	SM-12.5E	SM-12.5D	SM-9.5A	SM-9.5A	SM-9.5D
Binder Type	PG 64S-22	PG 64S-22	PG 64S-22	PG 64S-22	PG 64S-22	PG 64S-22	PG E-22	PG 64S-22	PG 64S-22	PG 64S-22	PG 64S-22
RAP Content, %	30	30	30	26	25	30	15	30	30	30	25
Asphalt content, %	5.49	5.64	5.44	5.50	6.87	5.3	6.58	5.52	5.94	5.74	6.13
Rice specific gravity, G_{mm}	2.513	2.627	2.695	2.527	2.556	2.663	2.486	2.749	2.513	2.702	2.545
VTM, %	6.6	6.1	3.7	4.3	1.6	4.7	4.9	4.5	3.5	3.8	2.5
VMA, %	18.7	18.6	16.9	16.7	17.4	17.4	19.3	16.9	17.0	18.3	15.8
VFA, %	64.7	67.3	78.0	73.9	90.6	72.8	74.5	73.5	79.4	79.0	84.1
FA ratio	1.26	1.59	1.20	1.21	0.93	1.08	1.28	1.04	0.85	1.13	1.00
Mixture bulk specific gravity, G_{mb}	2.347	2.467	2.595	2.417	2.514	2.537	2.364	2.626	2.425	2.598	2.481
Aggregate effective specific gravity, G_{se}	2.743	2.895	2.971	2.760	2.869	2.922	2.761	3.046	2.764	2.998	2.815
Aggregate bulk specific gravity, G_{sb}	2.729	2.860	2.954	2.741	2.835	2.908	2.737	2.986	2.748	2.998	2.766
Absorbed binder content, P_{ba}, %	0.19	0.44	0.20	0.26	0.43	0.17	0.33	0.68	0.22	0.00	0.65
Effective binder content, P_{be}, %	5.31	5.22	5.25	5.26	6.47	5.14	6.27	4.88	5.74	5.74	5.52
Effective film thickness, F_T, microns	10.0	7.3	8.8	8.8	12.3	9.0	9.8	9.2	11.6	10.1	9.7
Sieve Size	Percent Passing										
¾ in (19.0 mm)	100.0	100.0	99.7	100.0	100.0	100.0	100.0	100.0	99.7	100.0	100
½ in (12.5 mm)	93.0	95.7	98.8	99.5	98.6	99.9	93.7	98.6	98.3	99.0	99.5
3/8 in (9.5 mm)	83.8	86.1	95.6	95.5	88.6	94.1	79.7	89.7	95.4	88.9	93.8
No. 4 (4.75 mm)	54.7	64.6	60.0	60.0	54.7	61.2	52.2	56.1	57.1	58.1	66.7
No. 8 (2.36 mm)	33.3	49.6	41.5	41.1	36.3	38.6	33.7	37.2	39.2	37.3	47.2
No. 16 (1.18 mm)	21.0	33.8	31.5	30.8	26.3	28.0	23.3	26.7	30.1	24.3	33.7
No. 30 (600 µm)	14.1	23.1	22.7	22.3	18.1	21.1	16.5	19.4	19.9	17.4	22.5
No. 50 (300 µm)	10.4	16.1	14.6	14.6	11.0	14.8	11.5	13.7	11.1	13.1	12.9
No. 100 (150 µm)	8.2	11.2	8.7	9.0	7.9	9.0	8.0	8.5	6.9	9.5	8.3
No. 200 (75 µm)	6.7	8.3	6.3	6.3	6.0	5.5	5.7	5.1	4.9	6.5	5.5

FA = fines to asphalt; PG = performance grade; RAP = reclaimed asphalt pavement; SM = surface mixture; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mix.

Table 6. Surface Mixture Information from Cores Collected After 8 Years in Service

Mixture/Section	A	B	C	D	E	G	H	I	J	K
Location	US 11N	SR 682S	SR 637N	SR 682N	US 250W	US 1S	US 15S	US 13Bus N	SR 2802E	SR 631N
Mixture Type	SM-12.5A	SM-12.5A	SM-9.5D	SM-9.5D	SM-12.5D	SM-12.5E	SM-12.5D	SM-9.5A	SM-9.5A	SM-9.5D
RAP Content, %	30	30	30	26	25	15	30	30	30	25
Asphalt content, %	5.67	6.06	6.06	5.65	6.50	6.40	5.78	5.93	6.13	6.47
Rice specific gravity, G_{mm}	2.601	2.625	2.704	2.507	2.573	2.513	2.743	2.517	2.709	2.565
Sieve Size	Percent Passing									
3/4" (19.0mm)	100	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100
1/2" (12.5mm)	96.0	94.7	100.0	99.3	97.7	95.1	98.5	99.2	98.1	98.2
3/8" (9.5mm)	86.8	84.1	94.0	95.6	86.4	84.8	92.2	95.7	88.1	93.5
No.4 (4.75mm)	58.6	59.0	61.0	56.4	54.1	57.8	60.2	59.8	59.2	68.2
No.8 (2.36mm)	37.2	44.9	40.9	37.3	36.4	38.9	40.6	42.6	38.6	47.4
No.16 (1.18mm)	24.6	31.3	29.4	29.0	26.8	27.2	29.6	32.9	26.4	34.0
No.30 (600µm)	17.1	21.8	21.2	21.8	18.6	19.4	21.8	21.4	19.4	22.6
No.50 (300µm)	13.0	15.4	14.9	14.7	11.7	13.9	15.7	11.8	14.9	13.1
No.100 (150µm)	10.3	10.7	10.0	9.1	8.4	9.7	10.2	7.5	11.1	8.3
No.200 (75µm)	8.4	7.4	6.8	6.5	6.3	6.9	6.3	5.3	7.8	5.3

RAP = reclaimed asphalt pavement; SM = surface mixture.

Table 7. Average Surface Layer Thickness and Voids at Construction and After 8 Years in Service

	Mixture/Section Location	A US 11N	B SR 682S	C SR 637N	D SR 682	E US 250W	G US 1S	H US 15S	I US 13Bus N	J SR 2802E	K SR 631N
2015	Avg. Thickness, mm	44.1	42.3	34.0	44.0	45.0	53.7	50.1	36.3	40.1	40.7
	Std. Dev.	6.0	7.8	5.3	4.3	7.8	3.9	3.4	3.6	5.7	2.5
	Avg. Voids, %	9.0	5.8	5.3	6.0	7.6	7.9	4.5	5.6	6.5	9.1
	Std. Dev.	1.5	1.6	0.8	1.4	2.3	1.6	0.9	1.1	1.9	1.8
2024	Avg. Thickness, mm	35.5	37.1	45.7	43.7	36.0	55.4	47.6	34.0	45.0	39.1
	Std. Dev.	4.2	6.1	13.4	7.9	6.9	5.5	5.6	6.4	6.3	6.2
	Avg. Voids, %	7.1	7.0	4.6	7.2	4.2	7.8	4.2	7.1	5.1	7.0
	Std. Dev.	2.1	1.6	1.4	1.0	0.9	0.5	1.0	1.5	2.0	1.0

Avg. = average; RAP = reclaimed asphalt pavement; SM = surface mixture; Std. Dev. = standard deviation.

Table 8. Average Surface Mixture Permeability at Construction and After 8 Years in Service

Mixture	Location	At Construction: Average Permeability x 10-5 cm/sec	At Construction: Standard Deviation	After 8 Years in Service: Average Permeability x 10-5 cm/sec	After 8 Years in Service: Standard Deviation
A	US 11N	197.1	552.9	0.9	0.8
B	SR 682S	27.0	67.4	2.6	5.4
C	SR 637N	1.9	4.7	0.7	1.8
D	SR 682	17.3	32.3	0.8	0.9
E	US 250W	226.1	275.8	0.5	0.5
G	US 1S	13.4	12.7	4.7	3.1
H	US 15S	4.1	9.9	0.5	1.0
I	US 13Bus N	2.4	4.3	1.2	1.6
J	SR 2802E	145.9	317.6	0.8	1.9
K	SR 631N	147.2	225.7	1.0	0.8

Table 9. Average CT Index, Specimen Thickness, and Voids for Reheated Loose Mixture Specimens and Cores Collected After 8 Years in Service

	Reheated Loose Mixture Specimens				Cores After 8 Years in Service			
Mixture	Average Voids	Average CT Index	Standard Deviation	COV, %	Average Voids	Average CT Index	Standard Deviation	COV, %
A	6.8	52	16.0	30.8	7.2	23	7.8	33.8
B	7.0	38	7.7	20.5	7.0	24	18.1	75.3
C	6.7	45	12.4	27.6	4.1	56	10.2	18.3
D	6.7	37	7.1	19.3	6.8	42	15.9	37.8
E	6.8	155	1.2	0.8	4.7	96	33.3	34.7
G	7.1	74	19.6	26.3	7.5	41	33.0	81.3
H	7.0	74	8.9	12.1	5.5	171	24.0	14.0
I	7.1	62	2.2	3.6	6.7	25	14.5	56.7
J	7.4	136	33.7	24.8	4.5	158	83.2	52.7
K	6.8	82	2.5	3.0	7.0	29	7.6	25.6

COV = coefficient of variation; CT = cracking tolerance.

Figure 14 illustrates the relationship between reheat CT index values and CT index values measured from the cores collected after 8 years in service. Most fail the initial VDOT minimum allowable CT index value of 70, which is unsurprising because all mixtures were designed and produced under volumetric specifications prior to the introduction of BMD. Some of the paired values are in relative agreement. The remaining values either have considerable differences (mixtures H and E) or show the reheat value passing the initial criterion while the core value fails.

Figure 15 shows the test specimen air voids for the reheat and 8-years-in-service core specimens. Reheat specimens were fabricated to meet the test requirements of 7.0 ± 0.5% voids, and core specimens were selected to be as close to the requirements as possible. Interestingly, three of the core specimen sets that failed the air void requirement (specimen sets H, J, and E) were also shown to have considerably higher core CT index values.

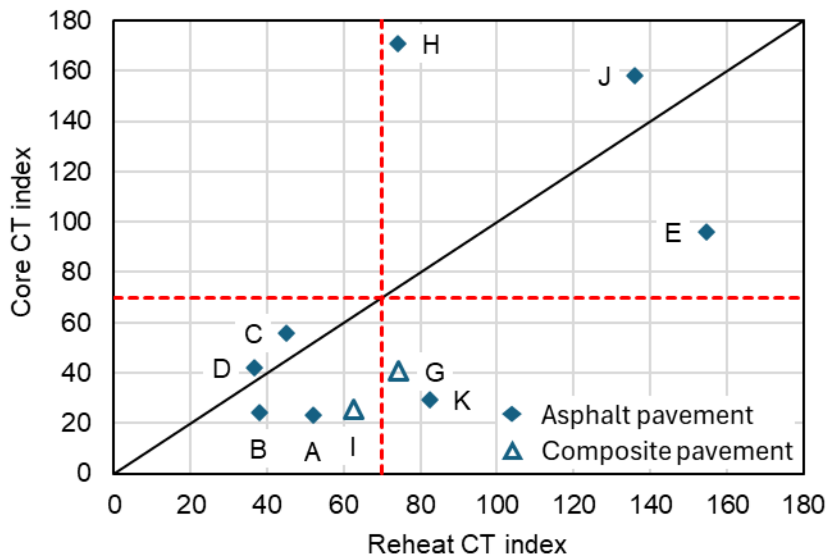

Figure 14. Reheat CT Index Values versus Core CT Index Values at 8 Years of Service Life. Red dashed lines indicate initial VDOT minimum allowable CT index values. CT = cracking tolerance.

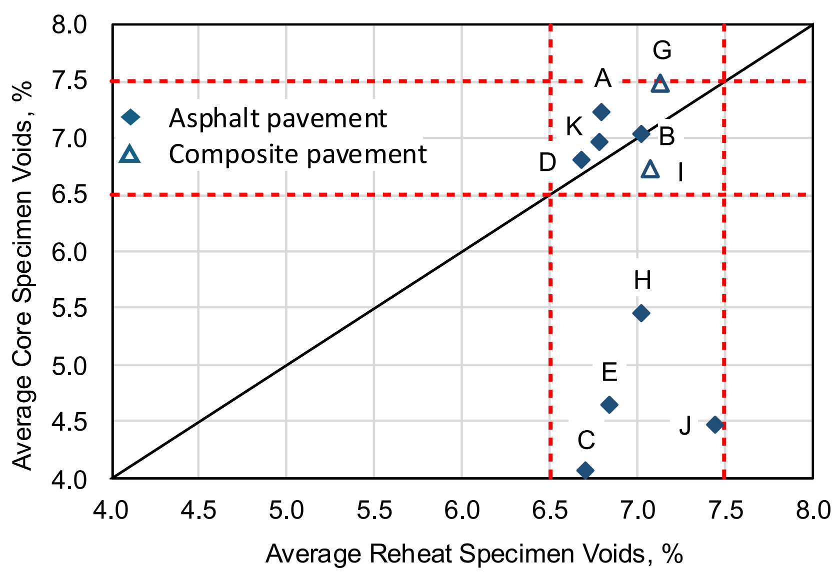

Figure 15. Reheat Air Voids versus Core Air Voids at 8 Years of Service Life. Red dashed lines indicate permissible air void percentages for fabricated specimens.

Laboratory rut testing was not conducted on the field cores collected after 8 years in service because little indication of field rutting was seen in the pavement condition data. However, APA rut testing was performed on reheated loose mixture specimens during the benchmarking effort (Bowers et al., 2022; Diefenderfer and Bowers, 2019). Table 10 shows a summary of APA test results.

Table 10. Asphalt Pavement Analyzer Rut Test Results for Reheated Loose Mixture Specimens

Mixture	Location	Mix Type	Binder	RAP, %	Average Voids, %	Average Rut Depth, mm	Standard Deviation
A	US 11N	SM-12.5A	PG 64S-22	30	8.0	3.9	0.1
B	SR 685S	SM-12.5A	PG 64S-22	30	8.0	3.1	0.8
C	SR 637N	SM-9.5D	PG 64S-22	30	8.0	4.3	1.5
D	SR 682	SM-9.5D	PG 64S-22	26	7.8	6.3	1.3
E	US 250W	SM-12.5D	PG 64S-22	25	7.8	7.9	0.2
G	US 1S	SM-12.5E	PG 64E-22	15	7.8	2.2	0.1
H	US 15S	SM-12.5D	PG 64S-22	30	7.6	3.0	0.1
I	US 13Bus N	SM-9.5A	PG 64S-22	30	8.3	6.5	1.3
J	SR 2802E	SM-9.5A	PG 64S-22	30	8.4	5.4	1.9
K	SR 631N	SM-9.5D	PG 64S-22	25	7.7	8.5	0.5

PG = performance grade; RAP = reclaimed asphalt pavement; SM = surface mixture.

Balanced Mix Design Field Validation

Multiple interrelated factors influence asphalt mixture performance in the field. This study focuses on evaluating the effect of four primary parameters: mixture quality, construction quality, traffic loading, and pavement structural capacity. Mixture quality was assessed through performance indices obtained from laboratory tests. Specifically, the CT index was utilized to quantify the cracking resistance of asphalt mixtures, and APA rut depth was used to quantify the rutting susceptibility of asphalt mixtures. Construction quality was evaluated based on as-constructed air void content. Traffic loading was quantified by annual average daily traffic (AADT), and pavement structural capacity was quantified using pavement stiffness values obtained from FWD testing.

The individual and combined effects of these factors on pavement distresses, specifically cracking and rutting, were analyzed to understand their influence on long-term performance—in this case, the performance metrics at 8 years of service life.

Cracking Performance Evaluation

Influence of Individual Factors on Cracking Performance

The influence of individual factors identified in this study was evaluated with regard to the percent cracking performance. The CT index values of the plant-produced mixtures, after reheating, ranged from 37 to 154. As-constructed air void contents, determined from field cores taken during construction, ranged from 4.5 to 9.1%. AADT for the sections ranged from 498 to 26,227 vehicles per day. FWD stiffness values, measured at 8 years of service life and normalized by the average FWD stiffness value across all sections, ranged from 0.3 to 1.7. These ranges indicate substantial variability in the factors considered, suggesting that the evaluated sections likely encompass the spectrum of conditions encountered by VDOT asphalt surface mixtures with A and D designations designed using the BMD approach.

Figure 16 illustrates the relationship between the percent cracking and four key factors considered: CT index, as-constructed air void content, AADT, and normalized FWD stiffness. Linear regression lines are superimposed on each scatter plot to depict the general trends.

Although the data exhibit considerable scatter, likely because of the multifactorial nature of pavement performance and the interplay of various influencing parameters, the observed trends align with overall expectations. Specifically, an increase in the CT index corresponds with a decrease in the percent cracking. Conversely, higher as-constructed air void contents and elevated AADT levels are associated with increased percent cracking.

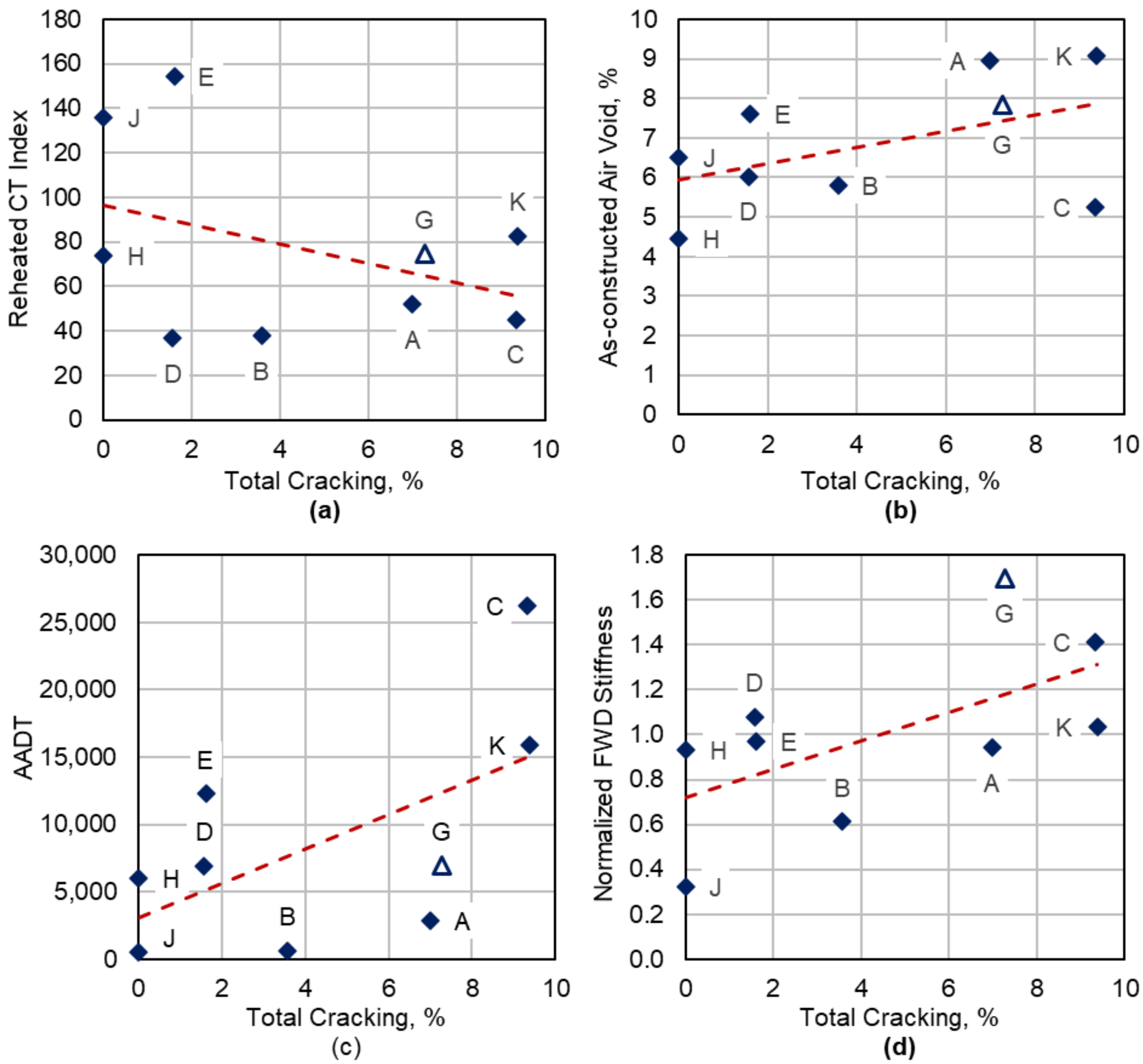

Figure 16. General Trends between the Percent Cracking Calculated at 8 Years of Service Life and: (a) CT Index; (b) As-Constructed Air Voids; (c) AADT; and (d) Normalized FWD Stiffness. Section G, indicated by a hollow triangle, includes a concrete layer. CT index values represent plant-produced mixtures after reheating. As-constructed air void contents were determined from field cores obtained during construction. FWD stiffness values were measured at 8 years of service life and normalized by the average FWD stiffness value for all sections. The red dashed line indicates the linear regression fit to the data. AADT = annual average daily traffic; CT = cracking tolerance; FWD = falling weight deflectometer.

Figure 16d shows the relationship between pavement structural capacity and cracking performance, illustrating the correlation between normalized FWD stiffness values and the percent cracking. The data exhibit a general trend wherein sections with higher normalized FWD stiffness values tend to demonstrate increased percent cracking. This trend is influenced by confounding factors, such as traffic loading and the properties of individual pavement layers within each section. For example, Figure 17 presents the correlation between normalized FWD stiffness and AADT for the evaluated sections. The analysis reveals a positive correlation between these two parameters, suggesting that sections with higher stiffness values are subjected to greater traffic loads. Notably, when section G—which includes a concrete layer and thus exhibits atypical structural characteristics compared with the rest of the full-depth asphalt sections—is excluded from the dataset, the coefficient of determination (R^2) increases to 0.82. This improvement in correlation indicates that traffic loading may be a significant contributing factor to the observed increase in cracking for sections with higher stiffness values.

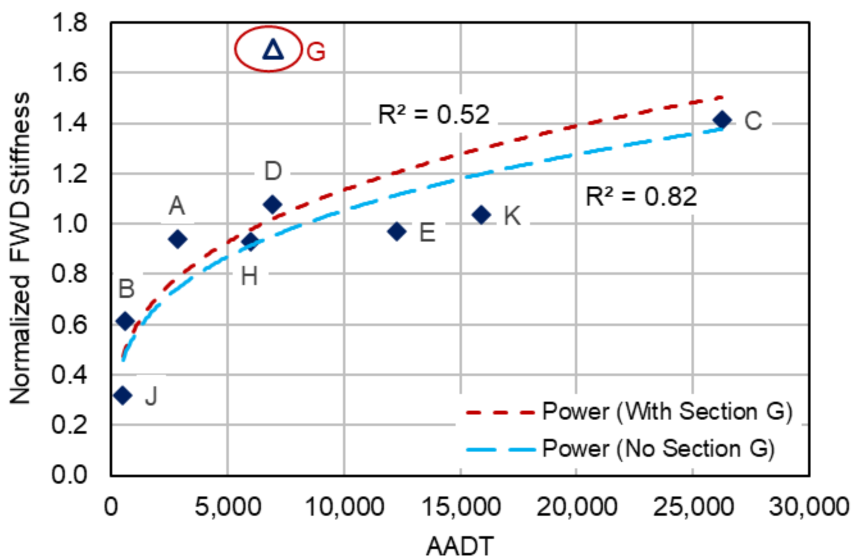

Figure 17. Relationship between Normalized FWD Stiffness at 8 Years of Service Life and AADT. FWD stiffness values were normalized by the average FWD stiffness value across all sections. Section G includes a concrete layer. AADT = annual average daily traffic; FWD = falling weight deflectometer.

Statistical Evaluation and Modeling of Factors Influencing Cracking Performance

To systematically assess the influence of key factors on the cracking performance, an analysis of covariance was conducted at a 95% confidence level. This statistical approach was employed to determine the significance of the four primary variables considered. The initial analysis of covariance encompassed all pavement sections, including section G which incorporates a concrete layer, and all four variables. The results indicated that none of the variables exhibited a statistically significant effect on the percent cracking at the 95% confidence level. The p-values for each factor in this scenario are as follows: CT index: 0.331; as-constructed air void content: 0.079; AADT: 0.337; and normalized FWD stiffness: 0.128.

Subsequent analyses explored various combinations of included and excluded variables and sections to identify scenarios in which factors significantly influenced cracking performance. Notably, when section G was excluded from the dataset, the analysis of covariance results revealed that the CT index ($p = 0.042$), as-constructed air void content ($p = 0.022$), and AADT ($p = 0.033$) had statistically significant effects on percent cracking. In contrast, normalized FWD stiffness did not exhibit a significant effect ($p = 0.288$). The lack of significance for pavement structural capacity may be attributed to its confounding relationship with traffic loading because higher stiffness values often correspond to sections with greater traffic volumes or vice versa.

Following the statistical significance assessment, efforts were directed toward developing a predictive model that balances simplicity and accuracy in estimating the percent cracking based on the identified factors. Various modeling approaches were considered, including linear regression, nonlinear models, and machine learning techniques. Among these approaches, a multiple linear regression model demonstrated the most favorable balance, achieving an R^2 of 87.5% and an adjusted R^2 of 78.1%. Equation 3 is the resulting regression equation.

$$\text{Percent Cracking} = -4.25 + 1.386 \times \text{Va} - 0.0448 \times \text{CT index} + 0.000277 \times \text{AADT} \quad \text{[Eq. 3]}$$

Where percent cracking is calculated at 8 years in service and where:
Va = as-constructed air void content (%), determined from field cores taken during construction.
CT index = cracking tolerance index, obtained from testing of reheated plant-produced mixtures at a target air void content of 7%.
AADT = annual average daily traffic.

This model highlights the significant influence of mixture quality, construction quality, and traffic loading on the cracking performance, with trends aligning with expectations. Specifically, the negative coefficient for the CT index indicates that higher cracking resistance of the asphalt mixture is associated with reduced percent cracking. Conversely, positive coefficients for as-constructed air void content and AADT suggest that increased air voids and higher traffic volumes contribute to elevated levels of cracking.

Sensitivity Analysis of Factors Influencing Cracking Performance

To systematically assess the influence of individual factors on cracking performance, a sensitivity analysis was conducted using Equation 3. This approach involved varying one parameter at a time while holding the others constant, thereby isolating and quantifying the effect of each factor on the percent cracking. Such an approach allows for a clearer understanding of how specific variables affect pavement performance within the observed data range.

For this assessment, the CT index values varied between 50 and 150. Three levels of as-constructed air void content were selected: 7.5%, corresponding to VDOT’s specification limit; 6.2%, reflecting the average as-constructed air void content of BMD sections paved during the 2024 construction season; and 5.2%, representing a potential improvement level to evaluate the benefits of improved compaction practices. Traffic loading was represented by AADT levels of 1,000, 10,000, and 25,000 vehicles per day, corresponding to low, medium, and high traffic conditions for the sections considered in this study, respectively.

It is important to note that the ranges for these factors were selected to ensure that the sensitivity analysis remained within the bounds of the existing dataset, thereby avoiding extrapolation beyond observed conditions. This approach ensures the validity and applicability of the analysis outcomes.

Figure 18 presents the percentage improvement in predicted cracking performance at a service life of 8 years resulting from a 10-unit increase in CT index with all other variables held constant. The predicted improvement per 10-unit increase in CT index ranged from 4.5% to 45.1%, depending on the traffic level and the as-constructed air void content. For example, at an AADT level of 10,000 vehicles per day, the model predicts a 7.8% improvement in cracking performance when the as-constructed air void content is 7.5%, which corresponds to VDOT's current specification limit. When the air void content is reduced to 6.2%, which reflects the average value observed in BMD projects constructed during the 2024 paving season, the predicted improvement increases to 11.3%. A further reduction in air void content to 5.2% yields a 17.3% improvement in cracking performance. These results demonstrate that the benefit of increasing mixture cracking resistance becomes more pronounced under lower traffic loading and tighter compaction conditions. As traffic volume increases, the incremental benefit associated with improving the CT index diminishes, suggesting that the effects of traffic loading may outweigh the gains achieved through mixture-level improvements. Similarly, lower as-constructed air void contents not only enhance compaction quality but also amplify the positive effect of improved cracking resistance.

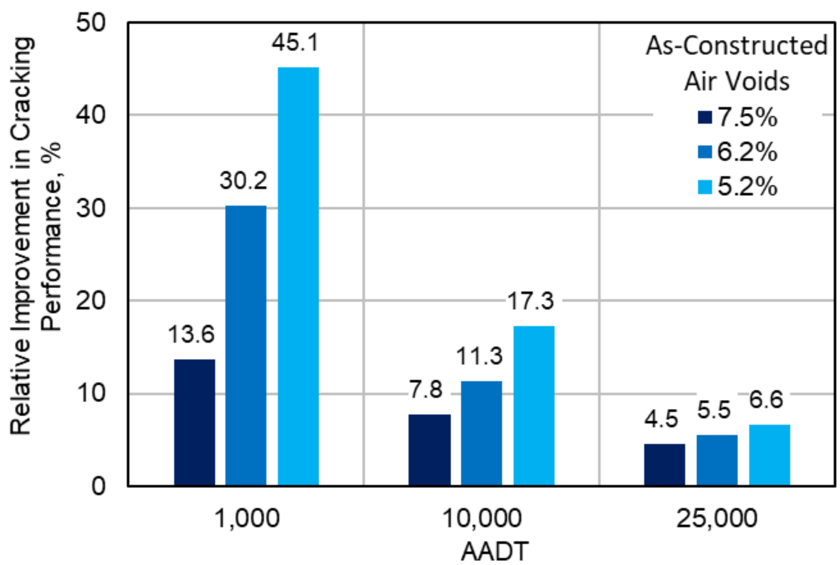

Figure 18. Percentage Improvement in Predicted Cracking Performance at 8 Years of Service Life per 10-Unit Increase in Cracking Tolerance Index. Improvements are shown for three levels of as-constructed air void content and three traffic loading conditions. AADT = annual average daily traffic.

Figure 19 builds on the prior analysis by quantifying the percentage improvement in predicted cracking performance at 8 years of service life resulting from a CT index increase from 70 to 100. This scenario reflects VDOT's proposed revision to the minimum CT index requirement for BMD mixtures, which is to be implemented starting with the 2026 construction season. The findings indicate that increasing the CT index from 70 to 100 has a substantial and positive effect on predicted cracking performance, with the magnitude of improvement varying as a function of both traffic level and construction quality. For instance, at a traffic level of

10,000 vehicles per day, the corresponding improvements ranged from 23.3% to 51.9%, depending on the as-constructed air void content.

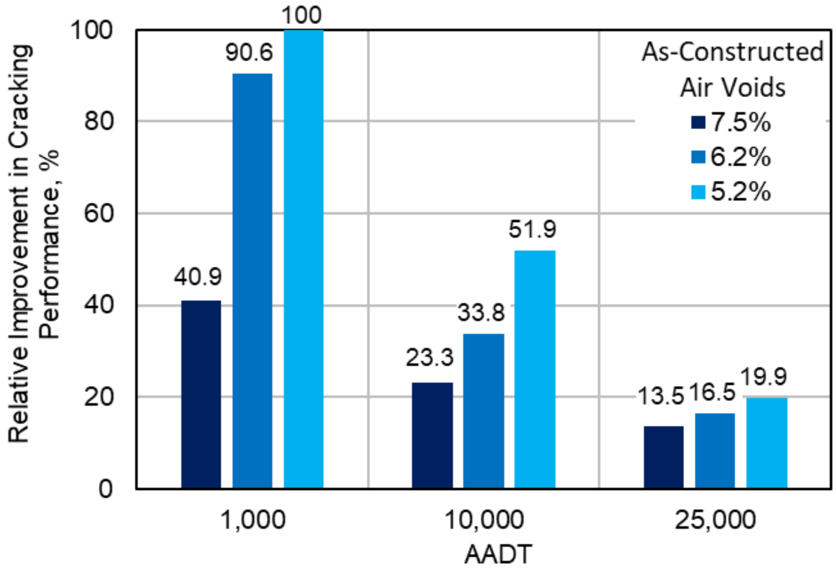

Figure 19. Predicted Percentage Improvement in Cracking Performance at 8 Years of Service Life Resulting from Increasing the Cracking Tolerance Index from 70 to 100. Improvements are shown for three levels of as-constructed air void content and three traffic loading conditions. AADT = annual average daily traffic.

Figure 20 presents the predicted percentage improvement in cracking performance at 8 years of service life resulting from a 1% decrease in as-constructed air void content. The analysis was conducted across three levels of CT index—70, 100, and 125—and for three traffic loading conditions represented by AADT values of 1,000, 10,000, and 25,000 vehicles per day. Consistent with the analysis described in the preceding paragraphs, the results were generated using the developed multiple linear regression model, with all other variables held constant to isolate the effect of air void content.

The results indicate that the benefit of reducing air void content on cracking performance. At an AADT of 10,000 vehicles per day, a 1% reduction in air voids results in a predicted improvement in cracking performance of 24.0% when the CT index is 70. This benefit increases to 31.3% for a CT index of 100 and reaches 41.8% for a CT index of 125, demonstrating a synergistic effect between improved compaction and higher mixture cracking resistance. At lower traffic levels (AADT = 1,000), the benefits are even more pronounced, with predicted improvements of 42.2% and 71.1% for CT index values of 70 and 100, respectively. For the CT index of 125, the model did not predict any cracking at this traffic level, and therefore, the percentage improvement could not be calculated. This case is denoted as “N/A” in Figure 20. Under high traffic conditions (AADT = 25,000), the improvements are smaller but still meaningful, ranging from 14.0% to 18.6%, depending on the CT index. These findings underscore the critical role of construction quality—specifically, achieving lower in-place air voids—in enhancing long-term cracking performance. Moreover, the effectiveness of improved compaction is amplified when paired with mixtures exhibiting higher resistance to cracking, particularly under low to moderate traffic loading conditions.

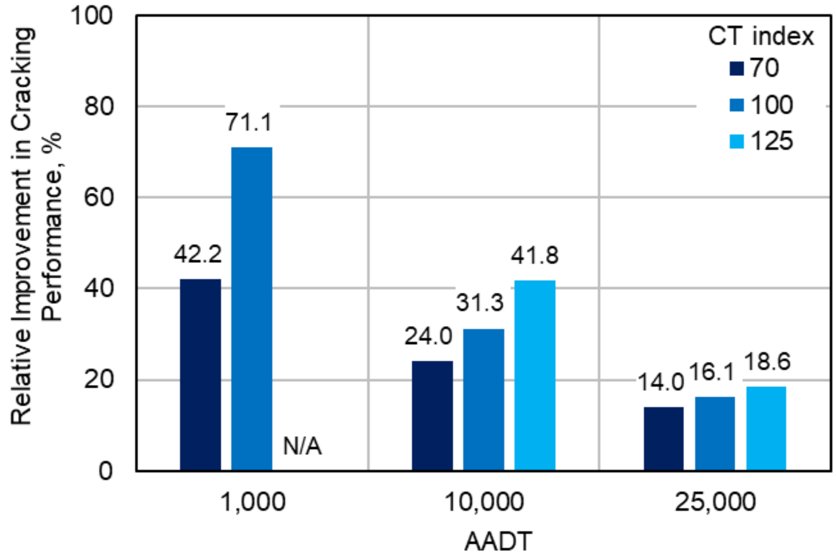

Figure 20. Predicted Percentage Improvement in Cracking Performance at 8 Years of Service Life Resulting from a 1% Decrease in As-constructed Air Void Content. "N/A" indicates that no cracking was predicted for the given combination of parameters, and therefore, improvement could not be quantified. AADT = annual average daily traffic; CT = cracking tolerance.

To conceptualize the influence of CT index thresholds on field performance, an analysis was conducted to quantify the traffic levels in terms of AADT corresponding to a specific predicted level of cracking. This evaluation considered two CT index thresholds: 70, which represents VDOT's current specification, and 100, the revised minimum threshold to be adopted beginning with the 2026 construction season. The analysis was performed using the developed multiple linear regression model by varying predicted cracking values between 0% and 10%, and corresponding AADT levels were estimated using the regression model while holding as-constructed air void contents at three levels (7.5%, 6.2%, and 5.2%) and CT index values at two levels (70 and 100). Figures 21a and 21b illustrate the resulting AADT-cracking relationships for CT index values of 70 and 100, respectively.

In addition, the analysis identifies the AADT level at which the model predicts 5% cracking, a threshold of particular relevance under federal performance classifications. According to MAP-21 guidance (FHWA, 2025), asphalt pavements with less than 5% cracking are categorized as in "good" condition, those with cracking between 5% and 20% are considered "fair," and pavements with greater than 20% cracking are classified as "poor." As such, the 5% cracking threshold serves as a practical benchmark for evaluating the relative performance benefits of CT index specifications.

Figure 21a presents the relationship between AADT and the predicted percent cracking for mixtures with a CT index of 70. As shown, at 8 years of service life, the model predicts that pavements constructed with 7.5% as-constructed air void content and a mixture CT index of 70 are expected to remain in "good" condition—per MAP-21 guidelines—for traffic volumes up to approximately 7,188 vehicles per day. In other words, under these conditions, the model predicts that the pavement will meet acceptable performance thresholds for this traffic level during the 8-year period. Improving compaction by reducing the as-constructed air void content to 6.2% and

5.2% extends the allowable traffic volume before reaching the 5% cracking threshold to approximately 13,692 and 18,696 vehicles per day, respectively.

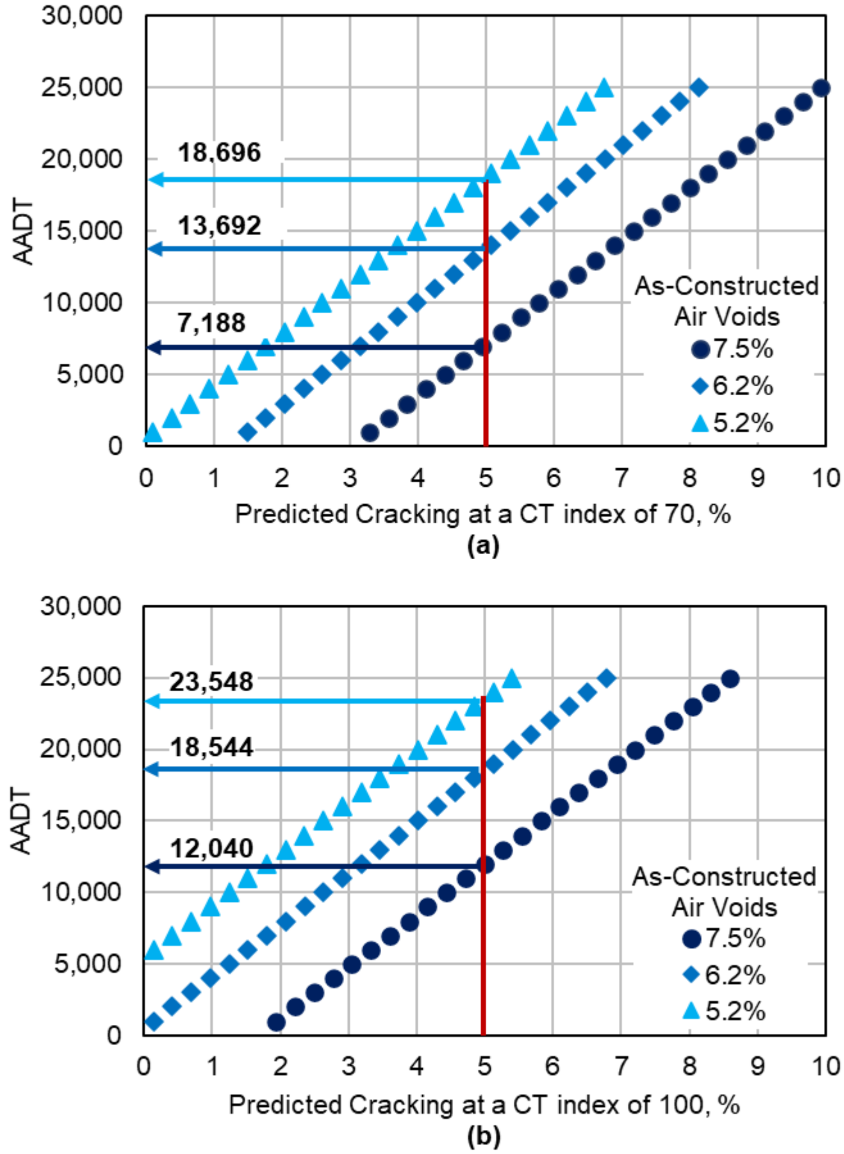

Figure 21. Predicted Percent Cracking at 8 Years of Service Life as a Function of AADT for CT Index Values of (a) 70 and (b) 100, Evaluated across Three As-Constructed Air Void Contents. The vertical red line denotes the 5% cracking threshold, which corresponds to the "good" condition category under Moving Ahead for Progress in the 21st Century Act pavement performance guidelines. Horizontal arrows indicate the AADT level at which the predicted cracking reaches 5% for each compaction level. AADT = annual average daily traffic; CT = cracking tolerance.

Similarly, Figure 21b presents the relationship between AADT and the predicted percent cracking for mixtures with a CT index of 100. As shown, at 8 years of service life, the model predicts that pavements constructed with 7.5% as-constructed air void content and a CT index of 100 are expected to remain in "good" condition, per MAP-21 guidelines, for traffic volumes up to approximately 12,040 vehicles per day. When compaction is improved, lowering the as-constructed air void content to 6.2%, the cracking threshold of 5% is reached at a higher AADT of about 18,544. Further improvement in compaction to 5.2% increases the allowable traffic volume to approximately 23,548 vehicles per day before 5% predicted cracking is exceeded.

A comparison of Figures 21a and 21b demonstrates the substantial performance benefits associated with increasing the CT index requirement from 70 to 100. At any given level of as-constructed air void content, pavements with a CT index of 100 can accommodate significantly higher traffic volumes while maintaining predicted cracking levels below the 5% threshold. For example, at 7.5% air voids, increasing the CT index from 70 to 100 raises the AADT limit for remaining in "good" condition from approximately 7,188 to 12,040 vehicles per day—a 67% increase in traffic capacity. Similarly, for as-constructed air void contents of 6.2% and 5.2%, the increases in allowable AADT before reaching 5% predicted cracking are approximately 35% and 26%, respectively.

Rutting Performance Evaluation

Rutting performance was evaluated using rut depth measurements reported in VDOT's PMS for the sections considered at 8 years of service life. An extensive effort was undertaken to model and evaluate the rutting potential of these pavements concerning the key variables identified in this study. However, no meaningful model was identified that could adequately explain the observed field rutting using the available variables.

Consequently, the trend between the APA rut depth and the observed field rutting after 8 years of service life was examined. Figure 22 presents this general trend. As depicted, an overall trend appears, although not very strong due to the minimal presence of field rutting, indicating that as the APA rut depth increases, the field-measured rut depth also increases, suggesting that the APA test provides a reasonable indication of field rutting performance.

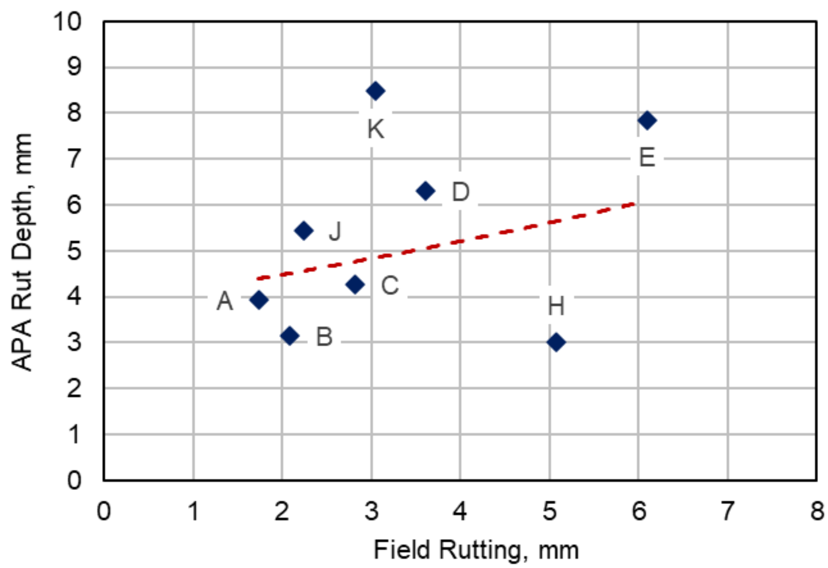

Figure 22. General Trend between APA Rut Depth and Field-Measured Rut Depth at 8 Years of Service Life. APA = Asphalt Pavement Analyzer.

Anecdotal observations from field conditions across Virginia, along with this study's findings, suggest that rutting has not posed a substantial performance issue for asphalt pavements in the state. The growing emphasis on improving cracking resistance, particularly through achieving higher CT index values, may shift the balance of mixture performance toward increased rutting susceptibility. Figure 23 illustrates the general trend between the CT index and field-measured rut depth for the sections evaluated in this study. As shown, a general trend indicates that pavements with higher CT index values tend to have greater rut depths observed after 8 years in service. This trend underscores the importance of maintaining performance equilibrium within the BMD framework. As improved cracking resistance is pursued, it is essential that the rutting potential of asphalt mixtures be concurrently evaluated during both the design and production phases. Ensuring that asphalt mixtures remain truly "balanced" requires continued attention to both cracking and rutting performance metrics to avoid unintended trade-offs that may compromise long-term pavement durability.

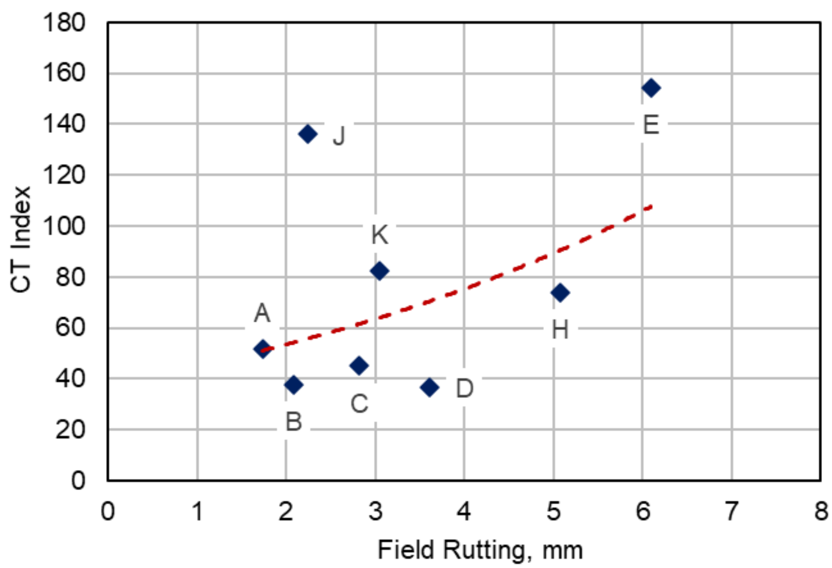

Figure 23. General Trend between CT Index and Field-Measured Rut Depth at 8 Years of Service Life. CT = cracking tolerance.

CONCLUSIONS

- *Because pavement conditions did not reach the critical failure condition defined by VDOT as a CCI of 60 by 8 years of age, the BMD initial criteria assessed in this study could not be truly validated.* Evaluated field sections contained varying structures, traffic loads, and as-constructed air void contents, preventing the direct comparison of performance to date. Additional field monitoring is necessary to reach terminal life for validation.

- *Higher cracking resistance of asphalt mixtures, indicated by higher CT index values, is associated with reduced percent cracking in the field.* The complex interactions of as-constructed density, pavement structural capacity, traffic loading, and climate complicates this relationship.

- *Mixture quality, construction quality, and traffic loading have significant influence on the pavement cracking performance, and trends align with expectations.* Higher as-constructed air void contents (i.e., reduced pavement density) contribute to increased levels of cracking. Higher traffic volumes contribute to elevated levels of cracking.

- *APA test results generally indicate field rutting trends.* In this study, mixtures with higher laboratory APA rut depths tended to exhibit greater rut depths in service, confirming that APA remains a useful indicator of rutting susceptibility within BMD projects.

- *Overall, achieving a balanced asphalt mixture, as characterized by VDOT's BMD framework, is critical to optimizing asphalt mixture longevity in Virginia.* Rutting has generally not been a major concern in Virginia. However, mixtures with increased CT index values in this study tended to show greater rut depths, highlighting that improving cracking resistance must be balanced with evaluating rutting potential during mixture design and production to preserve long-term pavement durability.

RECOMMENDATIONS

1. *VDOT's Materials Division should continue to implement BMD.* The results of this study demonstrated that VDOT's BMD test outcomes align with observed field performance trends. Mixtures meeting the established thresholds exhibited improved cracking resistance and acceptable rut depths when other variables were comparable. Consequently, these findings validate the effectiveness of the current BMD tests and thresholds in indicating in-service asphalt mixture performance and support continued implementation by VDOT's Materials Division.

2. *The Virginia Transportation Research Council (VTRC) should continue monitoring the performance of pavements with BMD surface mixtures to further validate BMD criteria and to quantify the expected life of BMD mixtures*.

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding recommendation 1, VDOT's Materials Division agrees to continue the process of BMD implementation with efforts underway to increase design requirements for CT index in the 2026 specifications.

Regarding recommendation 2, VTRC submitted a research needs statement to the PaveRAC Subcommittee B on October 1, 2025 to support continued monitoring to assess lifetime performance for the sections evaluated in this study and BMD pavement sections paved from 2019 to 2021.

Benefits

VDOT's goal is to enhance the durability and long-term performance of its dense-graded asphalt surface mixtures through the implementation of the BMD concept. By integrating performance criteria into mixture design and acceptance, BMD optimizes mixtures to resist deterioration, contributing to a more sustainable, longer lasting, and economical roadway network, provided that these mixtures are placed on sound underlying pavement structures.

Using the data from the field sections at 8 years in service, a relationship between total cracking, defined as the area of all cracking divided by the lane area, and CCI can be determined using linear regression. Figure 24 indicates that 1% reduction of cracking results in 2.17 units of CCI improvement.

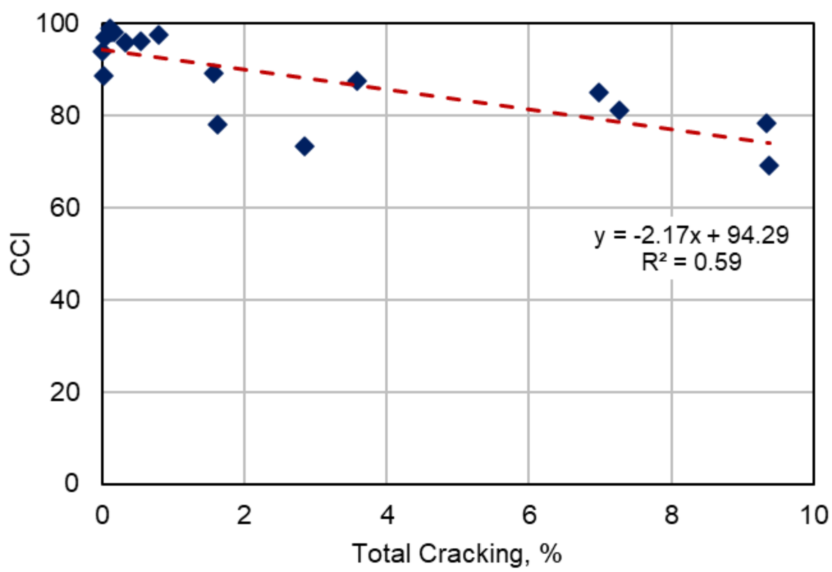

Figure 24. Total Cracking versus CCI at 8 Years in Service for Field Sections Evaluated in this Study. CCI = critical condition index.

Using the regression model developed from the field section data collected at 8 years in service (Equation 3), initial benefits to VDOT resulting from the implementation of BMD can be estimated. As previously shown, based on an increase in CT index during production from a value of 70 to a value of 100, a midrange AADT of 10,000, and as-constructed pavement voids of 7.5%, the model indicates that the increase in CT index during production from 70 to 100 results in 23.3% reduction in cracking for the surface mixture at 8 years of age. For initial cracking levels ranging from 1% to 20%, the increase in CT index corresponds to a reduction in total cracking between 0.8% to 15.3% (Table 11). By calculating the difference in cracking between a CT index of 70 and 100, the relationship previously described can be used to estimate the expected improvement in CCI.

Table 11. Improvement in CCI Resulting from an Increase in CT index from 70 to 100

Total Cracking at CT index = 70, %	Cracking Improvement by Increasing CT index to 100, %	Difference, %	Expected CCI Improvement
1.0	0.8	0.2	0.5
3.0	2.3	0.7	1.5
5.0	3.8	1.2	2.5
7.0	5.4	1.6	3.5
10.0	7.7	2.3	5.1
13.0	10.0	3.0	6.6
15.0	11.5	3.5	7.6
18.0	13.8	4.2	9.1
20.0	15.3	4.7	10.1
Average Expected Improvement in CCI	5.2		

CCI = critical condition index; CT = cracking tolerance.

Analyzing the PMS CCI data, 14.4% of segments were shown to be deficient, having CCI values less than or equal to 60 (Figure 25). This result is assumed to be representative of the current distribution of Pavement Maintenance contract route conditions. If CCI for each segment is improved by 5.2 units, only 9.88% of segments will have CCI values less than or equal to 60. This value means that approximately 4.16% of otherwise deficient segments should remain in sufficient condition if their CT index values are increased from 70 to 100 during production.

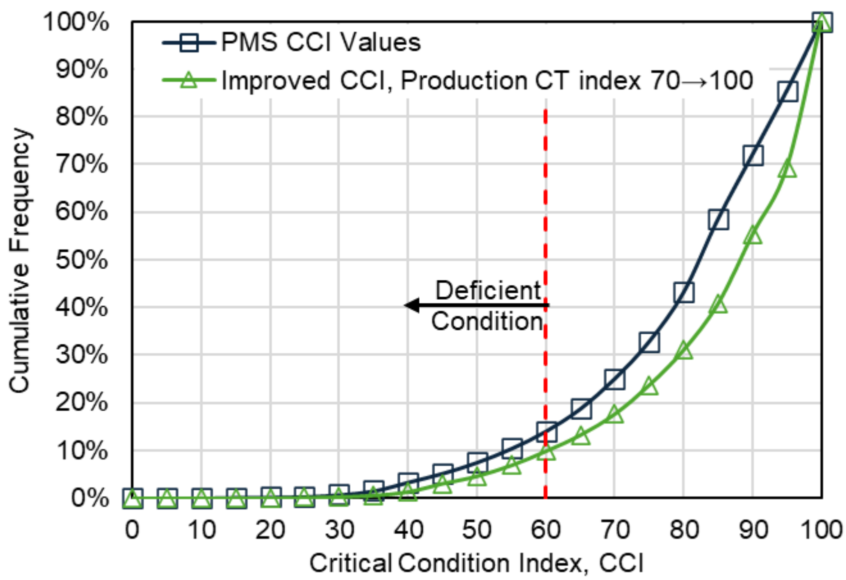

Figure 25. Shift in CCI Cumulative Frequency due to an Increase in CT Index Value from 70 to 100 during Production. Red dashed vertical line indicates CCI of 60, below which segments are considered deficient. CCI = critical condition index; CT = cracking tolerance; PMS = pavement management system.

If the 4.16% of now nondeficient segments is extrapolated to the statewide tonnage (1,516,067) let in the 2024 Pavement Maintenance contracts, it results in deferred maintenance for approximately 63,000 tons of surface mixtures. The average 2024 Pavement Maintenance contract statewide average cost per ton for surface mixtures was $108.52. Applying this amount to the deferred tonnage, the increase in production CT index value could result in approximately $6,836,592 in deferred costs for the year of analysis.

This estimate assumes that deficient segments are repaved and does not include application of any preventative maintenance treatments. Additional savings through maintenance deferral should accrue each year that the improved cracking performance allows CCI to remain above 60. However, additional evaluation of field performance is necessary to fully validate the estimates and assumptions of this analysis.

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