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Evaluation of BMD Surface Mixtures with Conventional and High RAP Contents Under Laboratory-Scale and Full-Scale Accelerated Testing

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Abstract: Balanced Mix Design (BMD) is an asphalt mixture design method that replaces some aspects of traditional volumetric design with performance testing for the most common distresses, such as rutting and cracking. This approach provides an opportunity to properly design and produce engineered asphalt mixtures, including those with higher reclaimed asphalt pavement (RAP) contents, recycling agents (RAs), fibers, polymer modified binders, and so on. The results of laboratory performance tests play a crucial role in the BMD process because they ensure the production of high-performing materials. In addition to performance testing and evaluation in the laboratory, accelerated pavement testing serves as a valuable tool to bridge the important and significant gap between models developed using laboratory material characterization and actual long-term pavement performance monitoring.

The purpose of this study is to evaluate the application of the BMD concept to design durable and longer lasting surface mixtures with A and D designations in Virginia, with a focus on relatively higher RAP contents, or HRAP mixtures, (that is, greater than 30% RAP). A and D mixtures are designated for traffic loads of 0 to 3 million and 3 to 10 million equivalent single axle loads, respectively. The scope of work consisted of laboratory and accelerated pavement testing of six surface mixtures incorporating a range of RAP contents (conventional and high), two binder grades, one RA, and one warm mix additive.

The study revealed that designing a dense-graded, unmodified surface mixtures with higher RAP contents is possible, using the current the Virginia Department of Transportation (VDOT) BMD special provision. The plant can produce those mixtures with no significant differences in aggregate gradations and asphalt binder content from the design. Furthermore, the study revealed that using RAs or a softer binder, or both, may be necessary when designing conventional and HRAP surface mixtures to meet BMD requirements. In addition, researchers need to collect more data to evaluate the relationships between the test results for non-reheat and reheat specimens for all BMD performance tests. Finally, the current selected BMD tests characterized the laboratory performance of mixtures similarly to the performance observed under accelerated pavement testing.

This study recommends that VDOT should (1) consider allowing the use of other tools in addition to increasing binder content, such as RA or softer binder, or both, for the design and production of BMD surface mixtures with A and D designations, even at allowable RAP contents; (2) consider allowing mixtures with RAP contents of up to 45%, when properly controlled and where desired by the district, designed using current BMD specifications modified to allow additional tools like RA and softer binder; and (3) continue the efforts toward full implementation of BMD in Virginia for surface mixtures with A and D designations, using the currently selected performance tests.

FINAL REPORT

EVALUATION OF BMD SURFACE MIXTURES WITH CONVENTIONAL AND HIGH RAP CONTENTS UNDER LABORATORY-SCALE AND FULL-SCALE ACCELERATED TESTING

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and the University of Virginia since 1948)

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DISCLAIMER

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INTRODUCTION

Overview and Background

The Federal Highway Administration Expert Task Group on mixtures and construction defines Balanced Mix Design (BMD) as “asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress, taking into consideration mix aging, traffic, climate, and location within the pavement structure” (West et al., 2018; Yin and West, 2021). The BMD method replaces certain aspects of traditional volumetric design with performance testing criteria for the most common distresses such as rutting and cracking. Although BMD mixtures cannot compensate for an unsound underlying pavement structure or the selection of inappropriate maintenance treatments, BMD constitutes a significant step forward in the pursuit of better performing asphalt mixtures.

Numerous state highway agencies are looking into designing and accepting asphalt mixtures using the BMD concept (Diefenderfer et al., 2021a; West et al., 2018; Yin and West, 2021). The American Association of State Highway and Transportation Officials (AASHTO) PP 105, *Standard Practice for Balanced Design of Asphalt Mixtures*, proposes four primary approaches to BMD for mixture designs labeled A through D, with each successive approach having increased reliance on performance properties over volumetric requirements (AASHTO, 2020). The potential for innovation increases as compliance with the existing volumetric requirements decreases from Approach A (volumetric design with BMD verification) to Approach D (BMD design only) (AASHTO, 2020; Diefenderfer et al., 2021a; TRB, 2022; West et al., 2018; Yin and West, 2021).

In 2018, the Virginia Transportation Research Council (VTRC) undertook an initial effort to provide benchmark indications of performance for a number of accepted asphalt surface mixtures (SMs) that had been produced and sampled in 2015. VTRC researchers used three fast, simple, and practical performance-indicative tests addressing different modes of distress as part of the BMD method (Bowers et al., 2022; Diefenderfer et al., 2021a). The selected tests were the Cantabro test, the asphalt pavement analyzer (APA) rut test, and the indirect tensile cracking test (IDT-CT) at intermediate temperature for assessing the overall potential for durability, rutting, and cracking of asphalt mixtures, respectively. Then, the research team developed initial performance threshold criteria for the selected tests: a maximum mass loss of 7.5% for the Cantabro test, a maximum rut depth of 8.0 mm at 64°C for the APA rut test, and a minimum cracking tolerance (CT) index of 70 at 25°C for the IDT-CT. Test specimens compacted from reheated plant-produced mixtures produced the test results.

Reclaimed Asphalt Pavement in Asphalt Mixtures

The use of reclaimed asphalt pavement (RAP) greatly influences asphalt mixture production and development worldwide. Although RAP usage has increased throughout the years, its growth plateaued in the United States with a national average of approximately 20% in 2014 (Habbouche et al., 2023; West and Copeland, 2015; Williams et al., 2020). In the United States, the economic and associated environmental benefits gained by using RAP in asphalt mixtures have encouraged state agencies to introduce special provisions and specifications, allowing RAP use at higher contents in mixtures (Diefenderfer et al., 2021b; Diefenderfer et al., 2023; Epps Martin et al., 2020; Zaumanis et al., 2013). The primary concern when designing higher RAP content (HRAP) asphalt mixtures is that they can become overly stiff because of the increased amount of RAP used, making them more brittle and prone to premature cracking (Epps Martin et al., 2020; Habbouche et al., 2023). To effectively address the challenges arising from the use of HRAP asphalt mixtures, some state highway programs incorporate recycling agents (RAs) or softer binders, or both, within a performance-based framework such as the BMD approach (Habbouche et al., 2023). This approach provides a tool to properly design and produce engineered asphalt mixtures, including those with HRAP. It is important to note that the definition of HRAP mixtures is specific to each state. Currently, VDOT allows the incorporation of RAP contents up to 30% in dense-graded SMs having A and D binder designations. Mixtures having A and D binders are designated for traffic loads of 0 to 3 million and 3 to 10 million equivalent single axle loads (ESALs), respectively. In Virginia, the definition of HRAP mixtures are specifically those with RAP contents exceeding 30% (Habbouche et al., 2023).

Accelerated Pavement Testing and Evaluation

Laboratory performance tests play a crucial role in the BMD process because they ensure the production of high-performing materials. In addition to performance testing and evaluation in the laboratory, accelerated pavement testing (APT) serves as a valuable tool to bridge the important and significant gap between models developed using laboratory material characterization and the actual long-term pavement performance monitoring. APT involves applying wheel loading, sometimes surpassing the design load limit, to a pavement system to assess its response within a significantly condensed timeframe. Therefore, APT provides insights that complement long-term pavement performance monitoring and analysis (Harvey and Popescu, 2021). Researchers accomplish this accelerated evaluation through several means, including intensifying the number of load repetitions, adjusting loading conditions, introducing specific climatic conditions in terms of temperature and moisture, implementing thinner pavements with reduced structural capacity, or employing a combination of these factors (Steyn, 2012).

In the United States, Virginia is among the states that implemented the use of APT facilities for pavement evaluation purposes. In 2020, VTRC, VDOT, and Virginia Tech planned and executed a collaborative experiment at the Virginia APT facility at the Virginia Tech Transportation Institute (VTTI). Six experimental testing lanes were constructed for the study. These lanes featured the use of conventional and HRAP, RA, softer binder, and a warm mix asphalt (WMA) additive. This report documents the findings from this experiment.

PURPOSE AND SCOPE

The purpose of this experiment was to evaluate the application of the BMD concept to design durable and longer lasting SMs in Virginia, with a focus on HRAP mixtures. The experiment involved assessing and validating the developed performance-based specifications (BMD special provisions) in terms of design mechanism and selected tests. The scope of work consisted of laboratory and full-scale testing of six SMs, incorporating a range of RAP contents (conventional and high), two binder performance grades (PGs), one RA, and one WMA.

METHODS

The tasks of this effort included the experimental design, verification of mix design performance, testing and analysis of the volumetric and performance properties of mixtures in a laboratory setting, accelerated testing using a Heavy Vehicle Simulator (HVS) for rutting and cracking studies of full-scale pavement sections, analyses of collected pavement responses and generated data, coring of test lanes after APT testing, and documentation of observations and lessons learned.

Mixtures

In this study, the research team and sampled for evaluation one control and five BMD 9.5 mm nominal maximum aggregate size (NMAS) dense-graded SMs. The mixtures incorporated various combinations of RAP contents, two binder PGs, one RA, and one WMA additive. The mixtures' designs were in accordance with the two VDOT BMD special provisions, *Special Provision for Dense Graded Surface Mixtures Designed Using Performance Criteria* and *Special Provision for High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance Criteria*. The mixtures are defined as:

- 30_C—A non-BMD mixture serving as a control and including 30% RAP content and PG 64S-22 asphalt binder (with S denoting standard traffic). This mixture design follows the conventional Superpave mix design methodology through which the optimum binder content (OBC) was selected at 4% air voids.
- 30_O—A BMD optimized version of mixture 30_C (with O denoting optimized), featuring the use of 30% RAP content and a PG 64S-22 at a higher OBC than mixture 30_C.
- 45_HR—A BMD HRAP mixture containing 45% RAP and a PG 64S-22. The mixture design resulted in a much higher OBC than all other evaluated mixtures. The design and production of this mixture had no softer binder or RA.
- 45_HR_RA—A BMD HRAP mixture incorporating 45% RAP, a typical PG 64S-22, and a RA.
- 45_HR_L–A BMD HRAP mixture featuring the use of 45% RAP and a softer binder, PG 58-28.
- 60_HR_L_RA—A BMD HRAP mixture containing 60% RAP, a softer binder (PG 58-28), and a RA.

The design of the second through the sixth mixtures followed VDOT BMD specifications, using Approach D (performance only). Production of each mixture was for a single day. Researchers collected four samples (labeled A through D) per mixture to determine the variability during production in terms of volumetric properties and aggregate gradations and to assess any potential effects on the performance properties measured using BMD tests.

Laboratory Characterization

Evaluation of the mixtures produced at two different times occurred in this laboratory phase: those produced in the laboratory during design and those produced at the plant during construction of the APT sections. During design, production of each mixture occurred in the laboratory. The contractor evaluated volumetric properties, and VTRC evaluated performance properties. During construction, the contractor and either VTRC or VDOT Salem District evaluated volumetric and performance properties of each plant-produced mixture.

This study considered two types of plant-produced specimens:

- *Non-Reheat:* Specimens compacted in the laboratory without reheating the loose mixture sampled at the plant.
- *Reheat:* Specimens compacted and evaluated in the laboratory by reheating the loose mixture sampled at the plant. The process of preparing reheated specimens involved reheating the loose mixture in boxes until workable, splitting the material into

specimen quantities, and heating specimen quantities to the appropriate compaction temperature and compacting. Mixtures did not undergo any additional oven aging.

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, 2020). The asphalt binder content of each mixture was determined by the ignition method in accordance with Virginia Test Method (VTM) 102, *Determination of Asphalt Content from Asphalt Paving Mixtures by the Ignition Method* (Virginia Test Methods, 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, 2020), and AASHTO T 27, *Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates* (AASHTO, 2020). Loose mixtures were conditioned at the compaction temperature and then compacted to N_{design} gyrations using a Superpave gyratory compactor in accordance with AASHTO T 312, *Preparing and Determining the Density of Asphalt Mixtures Specimens by Means of the Superpave Gyratory Compactor* (AASHTO, 2019). 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.

Performance Grading

Researchers performed asphalt binder performance grading 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, 2019). They conducted performance grading on extracted and recovered asphalt binders from the mixtures collected at the plant. In addition, the researchers extracted the asphalt binder from collected mixtures in accordance with AASHTO T 164, *Quantitative Extraction of Asphalt Binder From Hot Mix Asphalt (HMA), Method A, Using N-Propyl Bromide as the Solvent* (AASHTO, 2018). To recover the asphalt binder from the solvent, researcher used the Rotavap recovery procedure specified in AASHTO T 319, *Quantitative Extraction and Recovery of Asphalt Binder From Asphalt Mixtures* (AASHTO, 2019).

BMD Performance Tests on Non-Reheated and Reheated Mixtures

Cantabro Test

The research team determined the Cantabro mass loss 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, 2021). A lower mass loss indicates increased durability.

Asphalt Pavement Analyzer Rut Test

The APA rut test was performed in accordance with AASHTO T 340, *Standard Method of Test for Determining the Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)* (AASHTO, 2019). All test specimens were compacted to 7.0 ± 0.5% air voids. After 8,000 cycles were applied at a temperature of 64°C, the deformation of the specimen noted lower APA as an indicator of greater resistance to rutting.

Indirect Tensile Cracking Test

The IDT-CT was conducted at 25°C in accordance with American Society for Testing and 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, 2019). All test specimens were compacted to 7.0 ± 0.5% air voids. The CT index was calculated from the test load-displacement curve collected during testing.

Performance Tests on Reheated Mixtures

Dynamic Modulus Test

The dynamic modulus (|E*|) test measures the stiffness of asphalt mixtures. Testing was conducted using the Asphalt Mixture Performance Tester in accordance with AASHTO T 378, *Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt (HMA)* (AASHTO, 2019). All tests used the uniaxial mode without confinement. All test specimens were compacted to 7.0 ± 0.5% air voids.

Statistical Analysis for Performance Test Results

The research team used the two-sample Students' *t*-test to investigate the difference in means between different variables (two at a time) as the following sections describe.

Accelerated Pavement Testing Experiment

Experimental Lanes and Test Cells

Six APT lanes were constructed with one mixture placed in each lane. Each lane was 300 ft long and 10 ft wide. Within each lane, five test cells (labeled A through E) were established. Test cells A, C, and E were specifically designated as the test cells for comprehensive data collection. These test cells were instrumented with strain gauges, pressure cells, moisture sensors, and thermocouples to collect pavement response data. Test cells B and D served as backup test cells to address unforeseen issues or unexpected damage during the experiment. Each test cell was 24 ft long, and the five test cells were positioned in the center 200 ft of each lane. Space between each test cell provided room for the HVS support structure. Figure 1 provides a visual representation of the site layout for APT. The pavement structure was consistent across all six constructed lanes. Each lane was built with a research mixture consisting of two 1.5-inch lifts, with a total thickness of 3 inches. Each research mixture was placed on top of a 12-inch

VDOT 21B base layer, followed by an additional 26-inch layer of VDOT 21B as a subgrade layer.

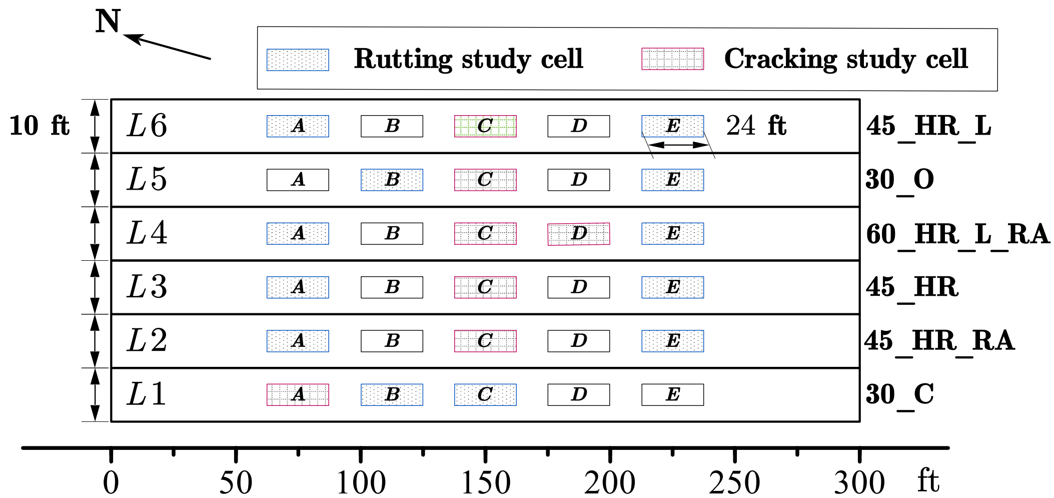


Figure 1. Site Layout for the Accelerated Pavement Testing Experiment. L1 Through L6 = Lane Numbering; N = North; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade.

Equipment and Instrumentation

The central component of the APT experiment was the Dynatest HVS Mark VI shown in Figure 2a. This system featured an environmental chamber designed to maintain a consistent temperature at the loaded area. The HVS automatically regulates the surface temperature to ensure continual maintenance of the desired temperature at a depth of 2 inches from the surface. A dual tire carriage was mounted inside the environmental chamber. Loading was applied using a dual tire assembly with 11.00R22.5 tires inflated to a pressure of 105 pounds per square inch. The system allowed for the completion of approximately 12,000 unidirectional passes or 24,000 bidirectional passes within a 24-hour period. The total load for the dual tire carriage ranged from approximately 9,000 to 15,000 pound-force (lbf).

(a) **(b)**

Figure 2. (a) Dynatest Mark VI Heavy Vehicle Simulator (HVS); (b) Laser Profiler Mounted on HVS Carriage

A laser profiler installed on the HVS carriage, shown in Figure 2b, scanned the pavement surface to quantify the rut depth present at the surface. A data acquisition system captured signals from various instruments. To facilitate this data acquisition process, input modules from National Instruments were installed in a chassis along with a controller. Researchers used LabVIEW software to develop an interactive interface for data management and analysis. A weather-proof chamber near the HVS housed the data acquisition system, along with its associated components. Figure 3 shows the typical instrumentation layout in plan and profile views.

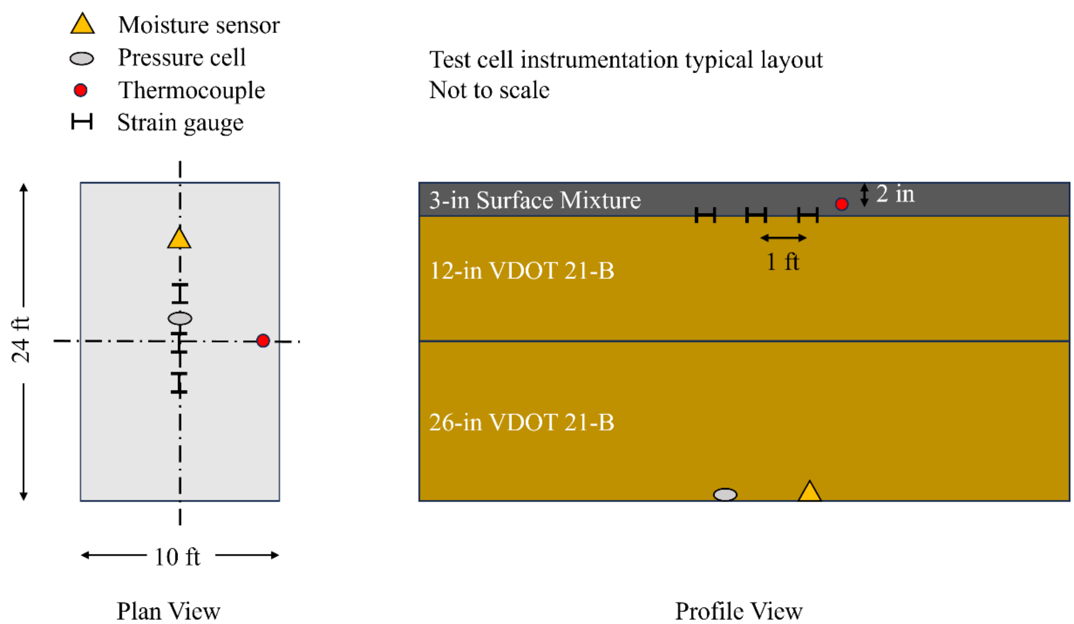


Figure 3. Instrumentation Layout in Plan and Profile Views

Loading Conditions

For the rutting tests, the loading protocol implemented within each rutting test cell was an initial wheel load of 9,000 lbf for the first 2 weeks, followed by 12,000 lbf for approximately 1 week, then finished with 15,000 lbf for approximately 1 week. This progressive loading protocol was designed to expedite pavement distresses development. The 9,000 lbf load level simulated one-half of an 18,000 lbf standard axle load. The internal pavement temperature was maintained at 40°C (104°F) and measured by a thermocouple embedded at a depth of 5.1 cm (2 inches) beneath the pavement surface.

For the cracking tests, the loading protocol implemented within each cracking test cell included a wheel load of 15,000 lbf until 3 million ESALs were applied (typically 6–8 weeks of testing). This loading protocol design was to expedite the development of pavement distresses. The only exception to this protocol occurred in the cracking test cell of the lane corresponding to mixture 30_C, for which a load of 9,000 lbf was initially applied for 1 week followed by subsequent loading at 15,000 lbf. The internal pavement temperature was a continuous 20°C (68°F), measured by a thermocouple embedded at a depth of 5.1 cm (2 inches) beneath the pavement surface.

In the APT facility, the loading carriage could move laterally. Specifically, lateral movement could occur in increments of 2 inches, with a maximum lateral displacement of ± 17 inches on either side of the centerline. The wandering pattern was established based on a normal distribution, with a mean value of 0 inches and a standard deviation of 10 inches. For the lanes with mixtures 30_C, 30_O, 45_HR, and 45_HR_RA, the wander pattern was slightly narrower. In addition, the wander pattern of 45_HR_RA exhibited a higher frequency of passes in the center compared with the other lanes. Researchers made no attempt to correct the collected data in this report because the influence of changes in wander pattern were unclear.

Initially, the dual tire assembly operated bidirectionally at a constant speed of 4 miles per hour (mph). Part way through the study, the loading speed increased to 6 mph to reduce the total testing time. As a result, most of the test cells experienced loading at 6 mph, with the exception of mixture 45_HR and a portion of the testing for the cracking section of mixture 45_HR_RA, which continued to be subjected to loading at 4 mph. Corrections to the results were not made because the change in loading speed was not expected to significantly influence the results.

Throughout the test period for both the rutting and cracking experiments, the HVS operated continuously, except for regular daily maintenance and occasional repairs. In addition, temporary staff shortages during the COVID-19 pandemic affected the testing schedule.

Field Cores

Field core samples were collected from each rutting and cracking test cell from in- and outside the wheel path after completing the experiments. The intention was to assess the thickness of the surface layer post rutting and to evaluate the presence and propagation of cracking in the cores collected from the cracking test cells.

Conversion of Applied Loading and Experiment Timeline

The APT loading was converted into ESALs, with the target of achieving approximately 0.5 and 3.0 million ESALs in each rutting and cracking test cell, respectively. Equation 1 calculates the number of ESALs (Kawa et al., 1998). The 18,000 lbf single-axle equivalency concept was introduced based on the American Association of State Highway Officials Road Test completed in 1961 (Kawa et al., 1998). One pass at the 9,000, 12,000, and 15,000 lbf load levels corresponded to 1.00, 3.35, and 8.55 ESALs, respectively.

$$\text{ESALs} = \left(\frac{\text{wheel load in lb}}{9{,}000}\right)^{4.2} \qquad \text{[Eq. 1]}$$

The APT experiment spanned approximately 3 years. The following sections detail information regarding the loading timeline and applied loading conditions for the pavement during the testing period.

Rutting Experiment Measurements

Rut Depth Measurement

The rut depth within the rutting cells was measured using the laser profiler positioned on the HVS carriage. The laser profiler captured surface elevation measurements of the test cell at

4-inch intervals in the longitudinal direction. Because the laser profiler was not directly under the loaded wheel, the assessment excluded a portion of the 24-ft-long test cell, resulting in a total scanned length of 5.4 m (17.7 ft). Seventy rut depth measurements (35 on each side of the center line) were conducted in the transverse direction, with a lateral spacing of 25.4 mm (1 inch). Figure 4a shows the result of a daily surface scan, presented as a three-dimensional image consisting of 53 transverse planes. Figure 4b shows the two-dimensional rut profile of one transverse plane.

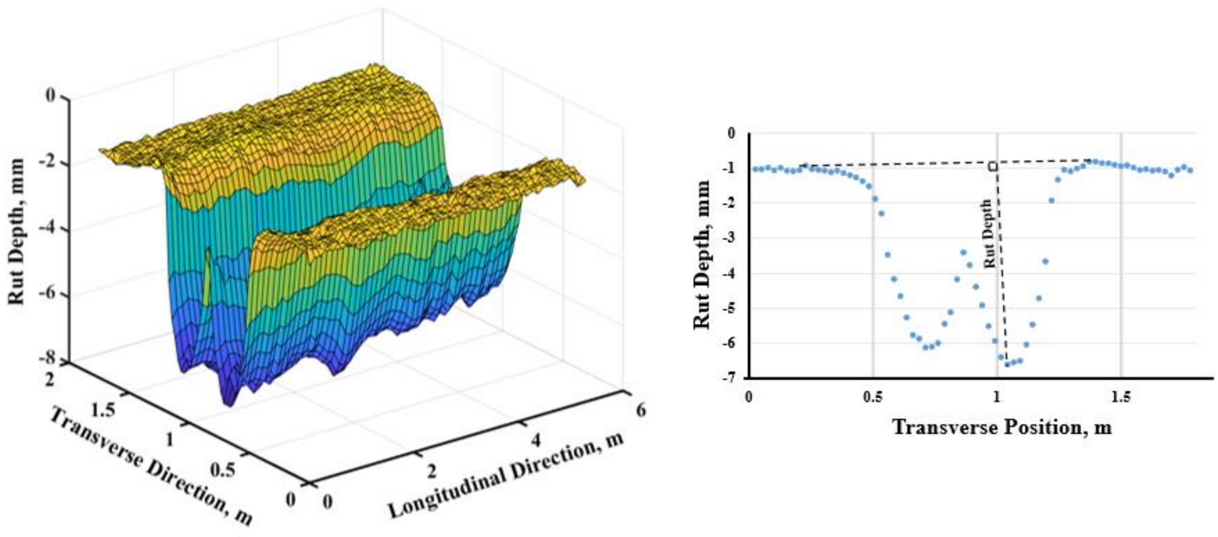


Figure 4. Example of Measurements Collected during the Rutting Experiment: (a) Three-Dimensional Laser Profile; (b) Rut Depth Illustration in a Specific Transverse Plane (blue dots = individual rut depth measurements in the transverse direction, dashed black line = projected surface elevation).

According to ASTM E 1703/E 1703M, *Standard Test Method for Measuring Rut-Depth of Pavement Surfaces Using a Straightedge*, rut depth is defined as "the maximum measured perpendicular distance between the bottom surface of the straightedge and the contact area of the gage with the pavement surface at a specific location" (ASTM, 2023). In this study, the median value of rut depth obtained from the 53 scanned transverse planes was a representative indicator used to quantify the progression of rutting magnitude.

Environmental Aging Effect

Upon placement and environmental exposure, asphalt mixtures undergo an aging process characterized by the oxidation of the asphalt binder, leading to changes in the viscous properties of the binder that affect the overall properties of the mixture (Cong et al., 2016). Because APT was conducted during 3 years, the aging process significantly affected the rutting performance of the respective mixtures. Prior to comparing the rutting performance across distinct mixtures and establishing a correlation with the results derived from laboratory testing, the results were normalized to the same set of initial conditions. Pavement age was investigated as a significant variable within the rutting model. Subsequently, an empirical model, expressed in Equation 2, was used to normalize the rut depth (Xue et al., 2017).

$$RD = \alpha * ESAL^{\beta_1} * Age^{\beta_2} \quad \text{[Eq. 2]}$$

where—

RD = rut depth, mm.
Age = number of days passed from pavement construction date to the rutting measurement.
α, β_1, and β_2 = regression coefficients.

Cracking Experiment Measurements

The research team considered three approaches for assessing the data and visual observations collected in the cracking experiment.

Observations of Initial Cracking

In an APT experiment, researchers can assess fatigue crack development by monitoring the degradation of the stiffness of the asphalt surface or base layers or by visually observing fine surface cracks (Long et al., 1996). As part of the daily machine maintenance, technicians conducted visual inspections, recorded the dates and times when surface cracks initially appeared, and took photographs. By documenting the dates when cracking occurred, calculating the corresponding cumulative loading passes at which the first cracking occurred was possible, thereby enabling the evaluation and ranking of the cracking performance of different mixtures.

Visual Distress Survey

A comprehensive condition survey conducted at the conclusion of the APT experiment for the six lanes included mapping of the entire loading area of each cracking cell and marking the final cracking length, along with its severity, determined by its width, for each cracking test cell.

Longitudinal Strain Responses

Three strain gauges were embedded in the longitudinal direction on the centerline of each cracking test cell at the bottom of the asphalt layers to monitor longitudinal strain during testing. They were spaced 12 inches apart. Data collection occurred at 4-minute intervals every 3 hours during each testing period. The three embedded strain gauges are expected to yield similar results, except for differences in timing (Figure 5a). The collected data were evaluated in terms of total strain per cycle and deviation from the reference table (defined as the strain level when no loading is applied).

The typical response of each strain gauge began with the detection of a compressive zone, followed by a tensile zone, and concluded with the detection of another smaller compressive zone (Figure 5b). The maximum magnitudes of compressive (ε_{c1}) and tensile strain (ε_t) were summed to compute a total strain (ε_{total}) adopted to describe the pavement response under loading.

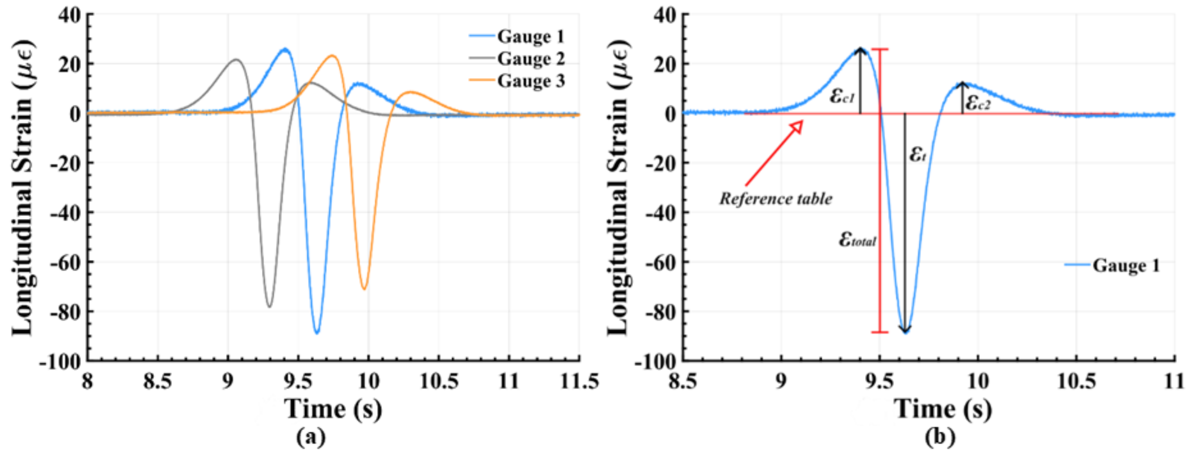


Figure 5. Collected Strain Data: (a) Example for Three Installed Strain Gauges; (b) Complete Single Measured Strain Response. ε_{c1} = Maximum Compressive Strain in the First Compressive Zone; ε_t = Maximum Tensile Strain; ε_{c2} = Maximum Compressive Strain in the Second Compressive Zone; ε_{total} = Total Strain = ε_{c1} + ε_t.

Considering the measurements taken throughout a given cycle and computing the deviation from the reference table was another way to analyze the data, as marked in Figure 5b. This deviation can capture the plastic deformation that is expected to increase with loading and the development of cracks. Figure 6 shows an example of data collected for a full cycle. The reference table represents the pavement response during the unloading period. Its values, marked by the green square symbols in Figure 6, were derived based on intermediate values from the time series of two peak tensile values.

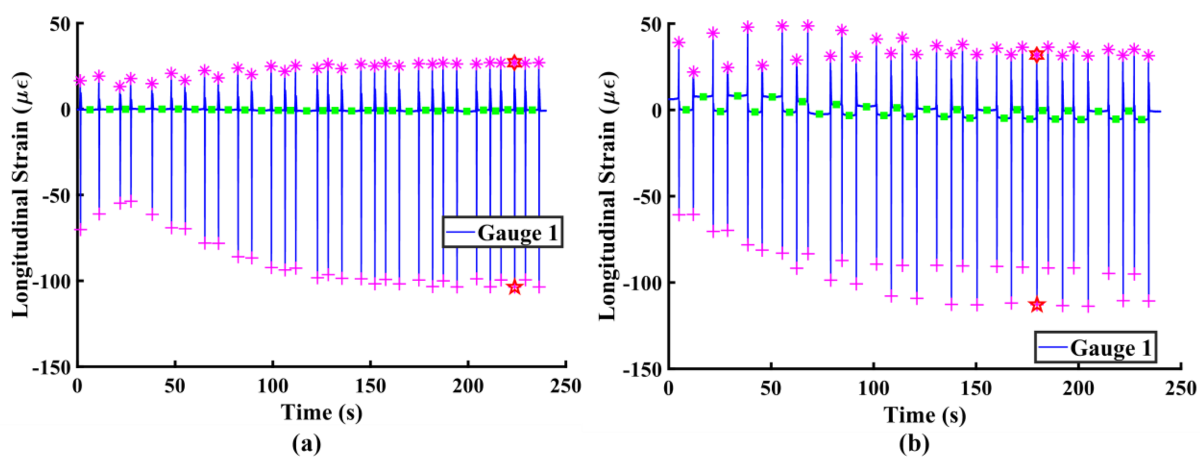


Figure 6. Example of Strains Collected during a Full Cycle Showing: (a) No Deviation from Reference Table; (b) Deviation from Reference Table. Blue Lines Represent the Measured Response. The Green Squares Indicate the Pavement Response during the Unloading Period. The Pink Stars Mark the Peak Tensile Strain, while the Pink Crosses Denote the Peak Compressive Strain. The Red Star Markers Correspond to the Locations of Peak Total Strain.

RESULTS AND DISCUSSION

Laboratory Evaluation of Asphalt Mixtures and Binders

Volumetric Properties and Aggregate Gradations of Mixtures

Table 1 shows the volumetric properties and gradations of all mixtures assessed and includes the BMD performance properties of the six mixtures determined at OBC during the design. According to Table 1, the major change noted among mixtures was that the selected OBCs for the five BMD mixtures 30_O(30_O, 45_HR, 45_HR_RA, and 60_HR_L_RA) were higher compared with the non-BMD control mixture (30_C), which could be attributed to the need for increased asphalt binder to meet the cracking performance criterion—a CT index of 70 for short-term aged mixtures. The use of a RA and/or a softer binder (mixtures 45_HR_RA, 45_HR_L, and 60_HR_L_RA) resulted in a lower OBC compared with mixture 45_HR, in which none of these alternatives were employed to address the use of HRAP. Finally, mixture 45_HR exhibited the highest sensitivity to asphalt binder content among all evaluated mixtures. During the development of the mixture design, it was observed that a slight change in the binder content (e.g., ± 0.2%) could result in passing or failing CT index values. The RAP materials used in the design had a binder content of 4.4% by the total weight of the material, whereas the extracted and recovered asphalt binder exhibited a PG of 89.5–12.2 (equivalent to PG 88–10).

Four samples (labeled A through D) were collected per day per mixture during production. Table 2 shows the Sample B volumetric properties and gradations of all mixtures collected during production. The volumetric properties and gradations for Samples A, C, and D are presented in Appendix A. The data associated with Sample B are shown in the body of this report because the |E*| performance evaluation was performed on plant-produced mixtures collected as part of Sample B. Furthermore, binders were extracted and recovered from Sample B mixtures and then subjected to PG evaluation.

Table 1. Volumetric Properties and Gradation for Accelerated Pavement Testing Mixtures during Design

Mixture ID	**30_C**	**30_O**	**45_HR**	**45_HR_RA**	**45_HR_L**	**60_HR_L_RA**
Description	Non-BMD	BMD	BMD HRAP	BMD HRAP	BMD HRAP	BMD HRAP
Composition						
RAP Content, %	30	30	45	45	45	60
Asphalt Binder	PG 64S-22	PG 64S-22	PG 64S-22	PG 64S-22	PG 58-28	PG 58-28
Additives	WMA	WMA	WMA	WMA + RA	WMA	WMA + RA
Property						
N_{design}, gyrations	50	50	50	50	50	50
NMAS, mm	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.60	6.00	6.80	6.20	6.00	6.00
RBR	0.24	0.22	0.29	0.32	0.33	0.44
Rice SG (G_{mm})	2.531	2.517	2.497	2.519	2.521	2.538
VTM, %	4.0	2.1	5.2	2.7	4.2	1.5
VMA, %	16.8	15.9	20.2	16.9	17.9	15.3
VFA, %	76.2	87.0	74.3	84.0	76.6	90.0
FA Ratio	1.0	1.1	1.2	1.2	1.3	1.5
Mixture Bulk SG (G_{mb})	2.429	2.465	2.367	2.452	2.415	2.500
Aggregate Bulk SG (G_{sb})	2.756	2.756	2.765	2.765	2.765	2.773
Field Correction Factor G_{sb} - G_{se}	0.014	0.016	0.021	0.020	0.012	0.026
Performance Properties at Optimum Asphalt Binder Content						
Cantabro Mass Loss, %	2.9	3.2	4.1	2.8	2.7	4.0
APA Rut Depth at 64°C, mm	5.4	4.2	5.6	7.2	4.9	3.7
CT index at 25°C	58	112	299	96	141	128
Gradation / Sieve Size	**% Passing**					
¾ in (19.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0
½ in (12.5 mm)	100.0	100.0	100.0	100.0	100.0	100.0
3/8 in (9.5 mm)	94.0	96.0	93.0	93.0	92.0	92.0
No. 4 (4.75 mm)	66.0	66.0	63.0	63.0	63.0	62.0
No. 8 (2.36 mm)	39.0	41.0	38.0	38.0	40.0	39.0
No. 16 (1.18 mm)	--	--	--	--	--	--
No. 30 (600 µm)	23.0	17.0	18.0	18.0	19.0	20.0
No. 50 (300 µm)	--	--	--	--	--	--
No. 100 (150 µm)	--	--	--	--	--	--
No. 200 (75 µm)	5.8	6.6	7.4	7.4	7.5	8.3

C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; BMD = Balanced Mix Design; S = Standard Traffic; WMA = Warm Mix Additives; NMAS = Nominal Maximum Aggregate Size; RBR = Recycled Binder Ratio; SG = Specific Gravity; VTM = Voids in Total Mixture; VMA = Voids in Mineral Aggregate; VFA = Voids Filled with Asphalt; FA = Fines to Aggregate; G_{se} = Aggregate Effective Specific Gravity; APA = Asphalt Pavement Analyzer; CT = Cracking Tolerance.

Table 2. Volumetric Properties and Gradation for Accelerated Pavement Testing Mixtures during Production—Sample B

Mixture ID	**30_C**	**30_O**	**45_HR**	**45_HR_RA**	**45_HR_L**	**60_HR_L_RA**
Description	Non-BMD	BMD	BMD HRAP	BMD HRAP	BMD HRAP	BMD HRAP
Composition						
RAP Content, %	30	30	45	45	45	60
Asphalt Binder	PG64S-22	PG64S-22	PG64S-22	PG64S-22	PG58-28	PG58-28
Additives	WMA	WMA	WMA	WMA + RA	WMA	WMA + RA
Property						
N_{design}, gyrations	50	50	50	50	50	50
NMAS, mm	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.44	6.14	7.22	6.15	6.00	6.14
Rice SG (G_{mm})	2.604	2.515	2.505	2.546	2.544	2.548
VTM, %	6.0	4.6	0.6	2.6	2.4	1.7
VMA, %	18.6	18.4	17.5	16.8	16.5	15.8
VFA, %	67.5	75.2	96.5	84.6	85.7	89.5
FA Ratio	1.12	1.07	1.21	1.39	1.21	1.35
Mixture Bulk SG (G_{mb})	2.448	2.400	2.490	2.480	2.482	2.506
Aggregate Effective SG (G_{se})	2.855	2.777	2.820	2.817	2.807	2.820
Aggregate Bulk SG (G_{sb})	2.841	2.761	2.799	2.797	2.795	2.794
Absorbed Asphalt Content (P_{ba}), %	0.18	0.21	0.27	0.26	0.16	0.34
Effective Asphalt Content (P_{be}), %	5.27	5.94	6.97	5.90	5.85	5.82
Effective Film Thickness (F_{be}), µm	9.2	10.9	10.8	9.1	9.7	8.7
E&R Asphalt Binder Grade	76.9-18.3	77.8-20.6	70.8-21.4	76.9-21.3	79.3-18.8	76.4-20.6
Gradation / Sieve Size	**% Passing**					
¾ in (19.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0
½ in (12.5 mm)	99.3	99.5	98.0	98.5	98.7	98.4
3/8 in (9.5 mm)	93.7	94.3	91.9	94.2	93.8	93.4
No. 4 (4.75 mm)	64.5	65.4	61.1	66.8	63.3	66.5
No. 8 (2.36 mm)	39.9	41.1	39.0	42.4	41.9	43.6
No. 16 (1.18 mm)	29.4	25.4	25.7	27.0	27.2	29.9
No. 30 (600 µm)	23.5	16.6	18.4	18.8	19.1	21.8
No. 50 (300 µm)	13.9	11.2	13.6	13.4	13.0	15.2
No. 100 (150 µm)	8.2	8.2	10.6	10.2	9.2	10.5
No. 200 (75 µm)	5.9	6.4	8.4	8.2	7.1	7.9

C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; BMD = Balanced Mix Design; S = Standard Traffic; WMA = Warm Mix Additives; NMAS = Nominal Maximum Aggregate Size; SG = Specific Gravity; VTM = Voids in Total Mixture; VMA = Voids in Mineral Aggregate; VFA = Voids Filled with Asphalt; FA = Fines to Aggregate; E&R = Extracted and Recovered.

During production, all mixtures except mixture 45_HR had binder contents that were similar to the design and within the allowable tolerance according to VDOT specifications. However, an increase of nearly 0.4% in binder content was observed for mixture 45_HR during production. No major changes in aggregate gradations between design and production were observed for any evaluated mixture regardless of the RAP content.

PG of Extracted and Recovered Binders

Table 2 provides the PG of extracted and recovered asphalt binders for Sample B of the plant-produced asphalt mixtures. The extracted and recovered asphalt binder from the produced mixtures exhibited similar low and high PG temperatures to each other, except for mixture 45_HR, which showed a much lower high temperature PG that could be attributed to the dominance of the relatively higher virgin binder content. No binder was extracted, recovered, and tested from Samples A, C, and D.

BMD Test Results on Non-Reheat and Reheat Specimens

Durability Assessment—Cantabro Mass Loss

The Cantabro test was performed on design, non-reheat, and reheat specimens. Figure 7 shows the mean mass loss (ML) values for all evaluated mixtures. Error bars indicate plus or minus one standard deviation. The mean ML values of the plant-produced mixtures (both non-reheat and reheat samples) were higher than the corresponding design ML, with the sole exception of mixture 45_HR, for which the higher asphalt content and lower voids in total mixture for the plant-produced mixture compared with the design resulted in the lower mean ML (Table 2). For all mixtures, the reheat mean ML values were higher than the non-reheat counterparts. All plant-produced HRAP BMD mixture samples complied with the 7.5% limit requirement.

Compared with HRAP mixtures, mixtures 30_C and 30_O exhibited a more noticeable discrepancy between plant-produced mixtures and laboratory-produced mixtures in terms of mean ML. This difference is particularly significant in the control mixture 30_C. Furthermore, the influence of plant production variability on the ML of control mixture 30_C was more apparent than that of the BMD mixtures. This result could potentially be attributed to the incorporation of higher binder contents, which may mitigate the effects of production variability on the ML for BMD mixtures.

By comparing the design and non-reheat mean ML values, the *t*-test results show that the difference in mean ML is statistically significant (p-value < 0.05) for mixtures 30_C, 45_HR, 45_HR_L and the mixtures combination. *t*-values were negative, indicating that the design specimens have a lower ML and suggesting better durability compared with the non-reheated specimens for these mixtures. However, the difference in ML between the design and non-reheat specimens is not statistically significant for mixtures 30_O, 45_HR_RA, and 60_HR_L_RA.

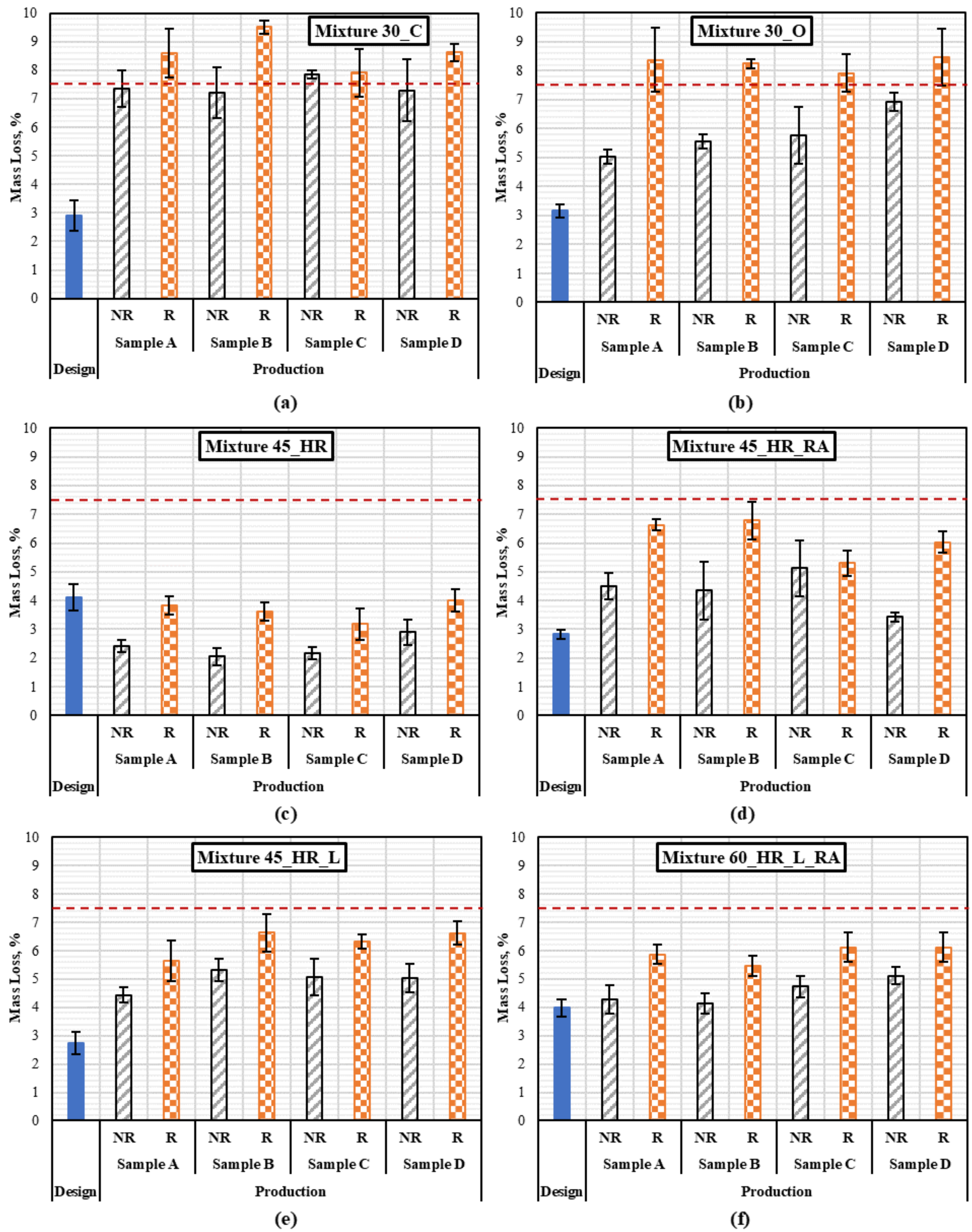


Figure 7. Performance Test Data for Mean Cantabro Mass Loss of Design, Non-Reheat, and Reheat Specimens for: (a) 30_C; (b) 30_O; (c) 45_HR; (d) 45_HR_RA; (e) 45_HR_L; (f) 60_HR_L_RA. Error bars Indicate Plus or Minus one Standard Deviation. NR = Non-Reheat; R = Reheat; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade. Dashed Red Line = VDOT's Balanced Mix Design Limit for Asphalt Surface Mixtures with A and D Designations.

Regarding the comparisons of the design versus reheat results for all six mixtures, the difference in the mean ML between the design and reheat results is statistically significant (p-value < 0.05), except for mixture 45_HR. t-values were negative, indicating that the design process results in a lower ML compared with the reheat results. This finding is consistent across all six mixtures except for mixture 45_HR, suggesting that the reheating process may generally result in lower durability.

Figure 8 shows the relationship between the mean ML values of the non-reheat and reheat specimens for the six evaluated mixtures. Comparing non-reheat and reheat mixtures results in a statistically significant difference in mean ML (p-value < 0.05). t-values were negative, showing that the reheating process resulted in a higher ML, indicating a potential degradation of durability for asphalt mixtures.

VDOT's current ML requirement is based on reheated test specimens. Researchers found that a mean ML of 7.5% for reheat specimens was equivalent to a mean ML of 5.8% for non-reheat specimens based on the regression equation in Figure 8. Nineteen of 24 (79.16%) mean ML values for non-reheat specimens were less than 5.8%.

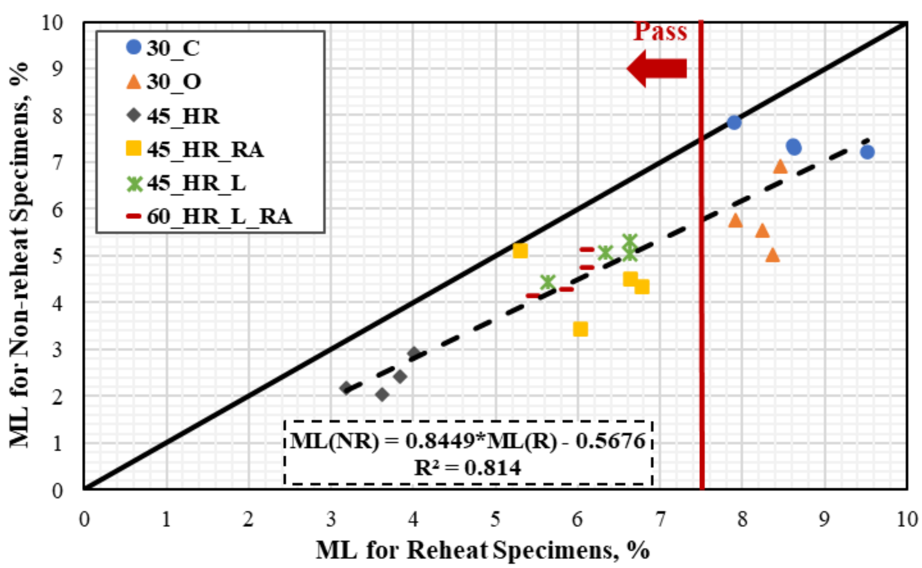


Figure 8. Relationship between Mean ML Values of Non-Reheat and Reheat Specimens for all Evaluated Mixtures of all Samples. ML = Mass Loss; NR = Non-Reheat; R = Reheat; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade. Solid Black Line = Equality Line. Solid Red Line = VDOT's Balanced Mix Design Limit for Reheated Asphalt Surface Mixtures with A and D Designations.

Rutting Assessment—Asphalt Pavement Analyzer Rut Depth

The APA rut test was conducted on design, non-reheat, and reheat specimens. Figure 9 shows the mean APA test results. Error bars indicate plus or minus 1 standard deviation. Both the non-reheat and reheat specimens included four sets of specimens for each mixture, whereas the design sample included only one set. The red dashed line represents the maximum limit of 8 mm as specified by the VDOT BMD special provision. All mean APA rut depth values except the non-reheat specimens of mixture 45_HR, regardless of their category, met the VDOT BMD recommended threshold.

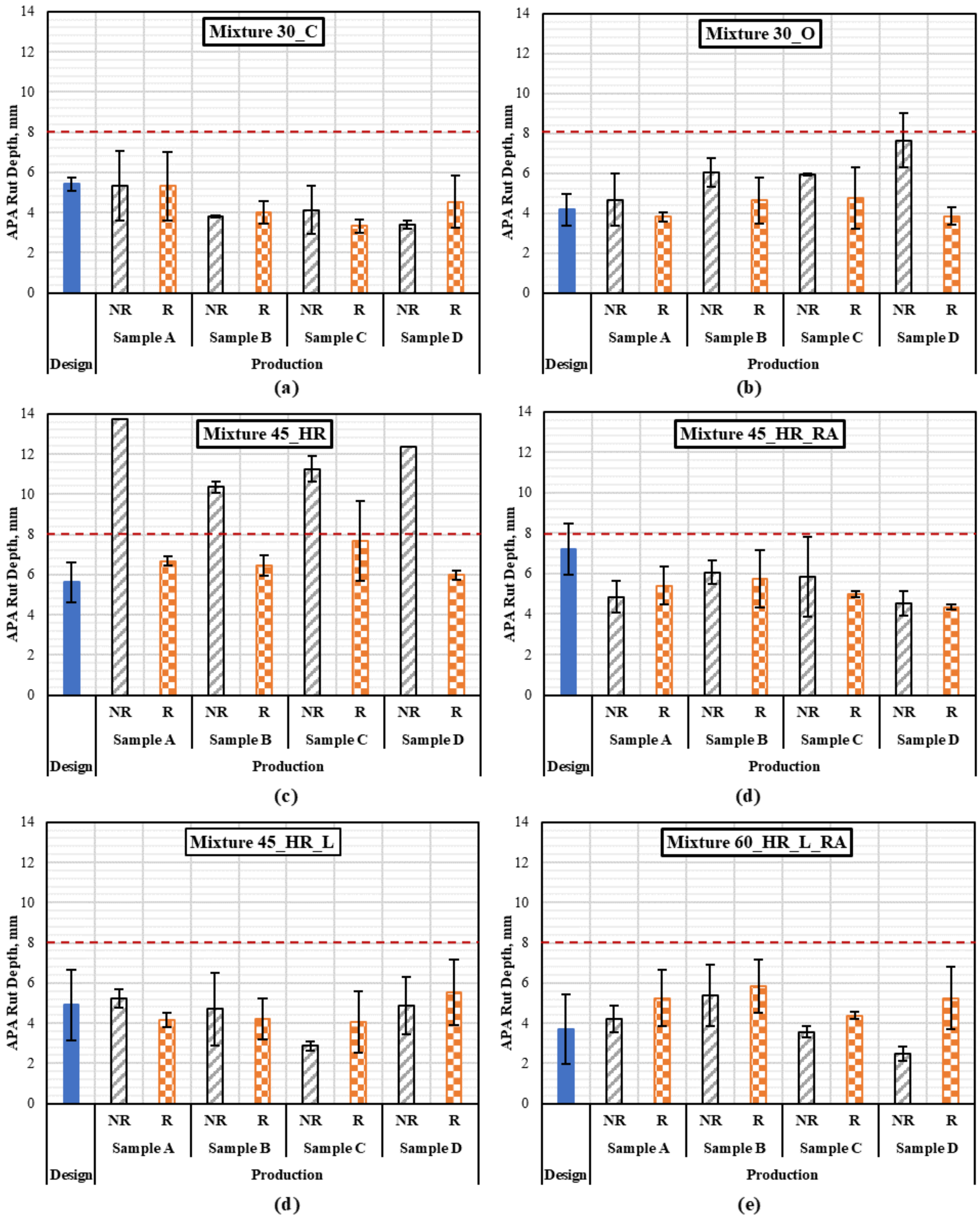


Figure 9. Performance Test Data for Mean APA Rut Test for Design, Non-Reheat, and Reheat Specimens of: (a) 30_C; (b) 30_O; (c) 45_HR; (d) 45_HR_RA; (e) 45_HR_L; (f) 60_HR_L_RA. Error Bars Indicate Plus or

Minus one Standard Deviation. APA = Asphalt Pavement Analyzer; NR = Non-Reheat; R = Reheat; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade. Dashed Red Line = VDOT's Balanced Mix Design Limit for Asphalt Surface Mixtures with A and D Designations.

Statistical analysis using the *t*-test shows that the difference in mean APA rut depths when comparing design and non-reheat specimens was statistically significant only for mixture 45_HR. The difference in mean APA rut depths were not statistically significant when comparing design and reheat specimens. Figure 10 shows the relationship between the mean APA rut depths of the non-reheat and reheat specimens for the six evaluated mixtures. For most mixtures, the difference in performance between non-reheat and reheat specimens was not statistically significant, except for mixtures 30_O and 45_HR. Twenty of 24 (83.33%) mean rut depth values for non-reheat specimens were less than 8.0 mm.

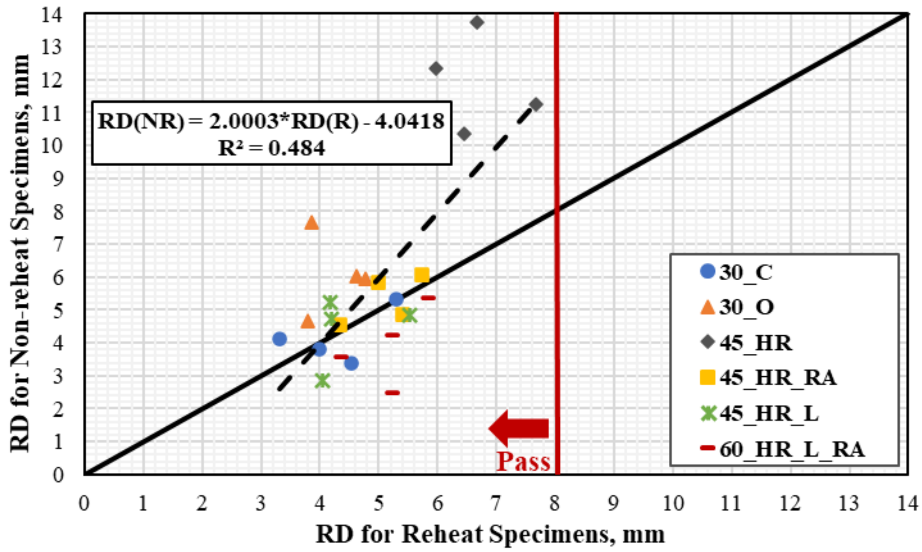


Figure 10. Relationship Between APA Rut Depth Values of Non-Reheat and Reheat Specimens for all Evaluated Mixtures of all Samples. RD = Rut Depth; NR = Non-Reheat; R = Reheat; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade. Solid Black Line = Equality Line. Solid Red Line = VDOT's Balanced Mix Design Limit for Reheated Asphalt Surface Mixtures with A and D Designations.

Cracking Assessment—Cracking Tolerance Index

IDT-CT was conducted on design, non-reheat, and reheat specimens. Figure 11 presents the mean IDT-CT test results of all samples for the six mixtures. Error bars represent plus or minus one standard deviation. Non-reheat samples generally demonstrated greater mean CT index values than the design and reheat specimens demonstrated. However, the sensitivity to reheating varied among different mixtures. When comparing specimen fabrication methods, the two-sample *t*-test revealed statistically significant differences when comparing the mean IDT-CT results for design versus non-reheat specimens for mixtures 30_C, 45_HR, and 45_HR_RA.

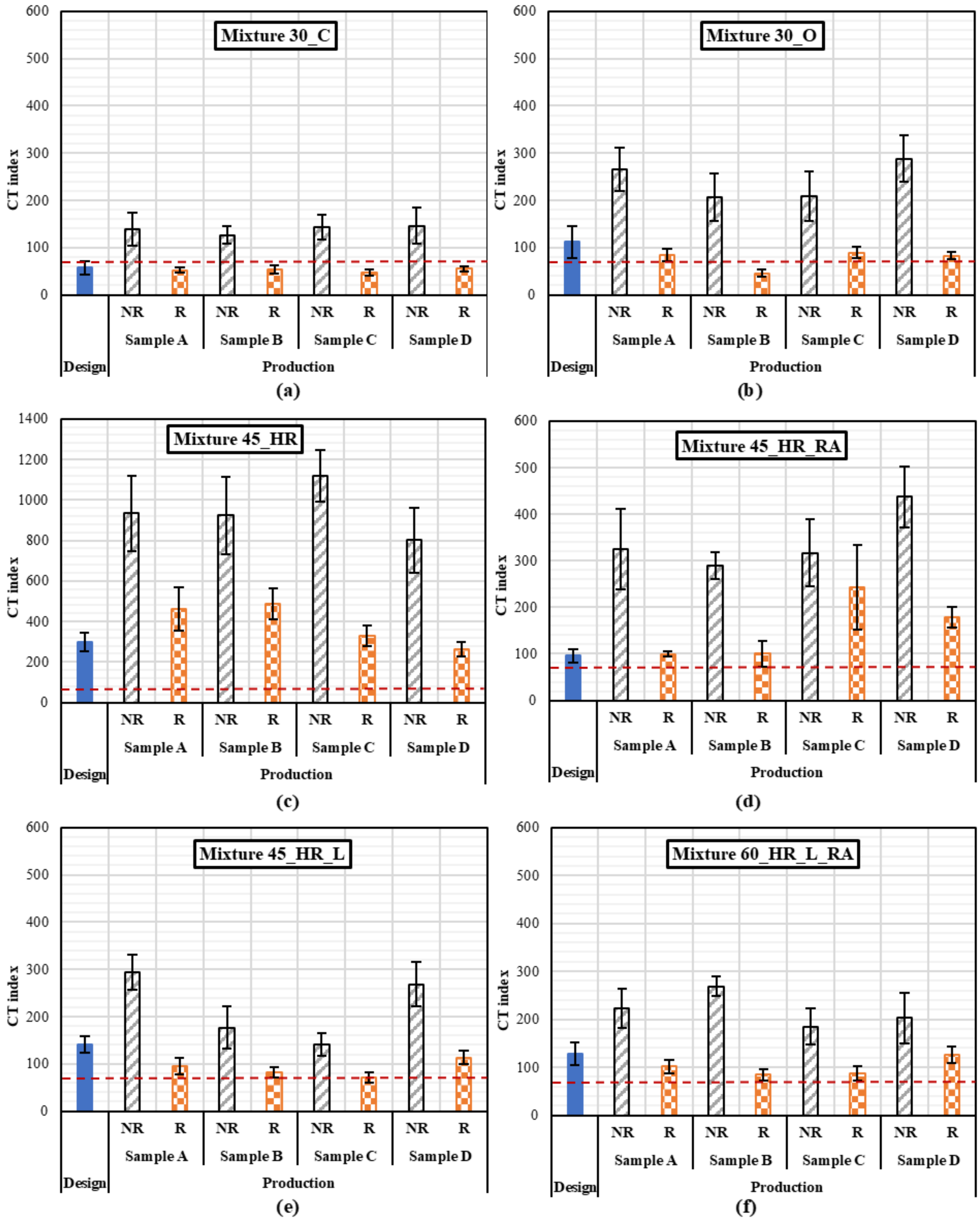


Figure 11. Performance Test Data for IDT-CT of Design, Non-Reheat, and Reheat Specimens for: (a) 30_C; (b) 30_O; (c) 45_HR; (d) 45_HR_RA; (e) 45_HR_L; (f) 60_HR_L_RA. Error Bars Indicate Plus or Minus one Standard Deviation. IDT-CT = Indirect Tensile Cracking Test; CT = Cracking Tolerance; NR = Non-Reheat; R = Reheat; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade. Solid Black Line = Equality Line. Dashed Red Line = VDOT's Balanced Mix Design Limit for Asphalt Surface Mixtures with A and D Designations.

No statistically significant differences were found for the mean CT index values when comparing design and reheat mixtures. However, a comparison of mean CT index values from non-reheat and reheat mixtures indicated statistically significant differences (Figure 12). An analysis of an independent dataset conducted by VTRC evaluated the potential correlation between CT index values for reheat and non-reheat specimens, using data from 2019, 2020, and 2021 field trials (Boz et al., 2023), all of which included control and BMD mixtures. The study recommended a CT value of 95 for non-reheated specimens. Using 95 as a criterion, all non-reheated specimens (100%) evaluated in this study exhibited mean CT index values greater than 95.

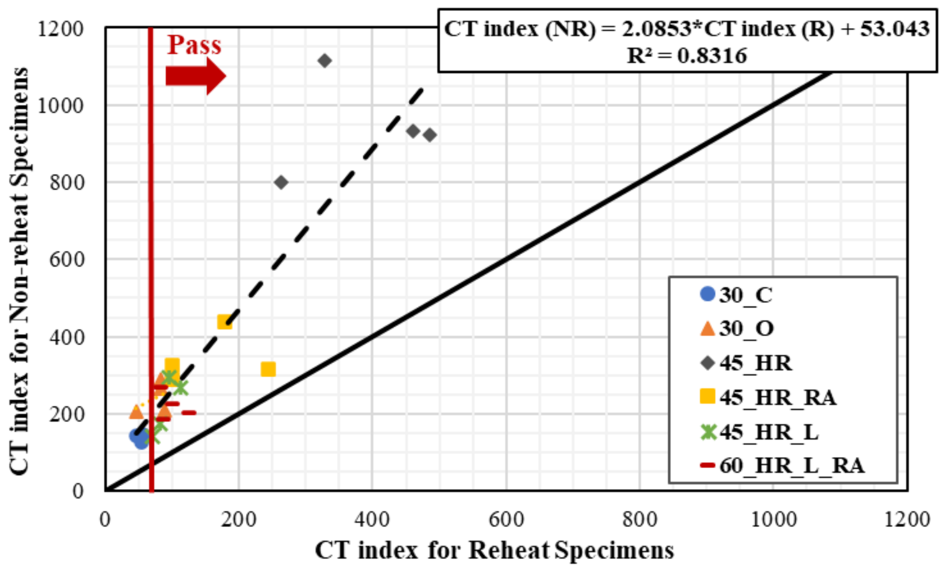


Figure 12. Relationship Between CT Index Values of Non-Reheat and Reheat Specimens for all Evaluated Mixtures of all Samples. CT = Cracking Tolerance; NR = Non-Reheat; R = Reheat; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade. Solid Red Line = VDOT's Balanced Mix Design Limit for Reheated Asphalt Surface Mixtures with A and D Designations.

Performance Test Results on Reheated Specimens

Stiffness Properties—Dynamic Modulus

Figures 13a and 13b show the |E*| and phase angle (δ) of the six mixtures, respectively. The data in these figures were constructed at a reference temperature of 21.1°C, using the 2S2P1D model[1] for both |E*| and δ data (FHWA, 2019). A higher |E*| value at higher temperatures, which correspond to the lower reduced frequencies shown in Figure 13) is often attributed to a potential higher rutting resistance of asphalt mixtures. The data in Figure 13a show that mixture 45_HR had significantly lower |E*| values compared with the remaining mixtures at low and intermediate test frequencies. The low |E*| values are attributed to the higher binder content of the mixture and could indicate a potential greater rutting susceptibility of the mixture. All remaining mixtures had similar |E*| values at low and intermediate frequencies. Excluding mixture 45_HR, mixture 60_HR_L_RA exhibited the lowest stiffness at lower

[1] S, P, and D stands for spring, parabola, and dashpot elements, respectively.

frequencies, which can be attributed to the incorporation of a softer binder and RA. Figure 13b shows significantly higher δ values for mixture 45_HR at relatively lower and intermediate reduced frequencies, indicating a potential greater cracking resistance among the six mixtures. For the remaining mixtures, Figure 13b shows that mixture 60_HR_L_RA and mixture 30_O have the highest and lowest δ values at relatively lower frequencies, respectively. A higher |E*| value and lower δ at lower temperatures (and higher frequencies) are often associated with the potential for greater cracking susceptibility.

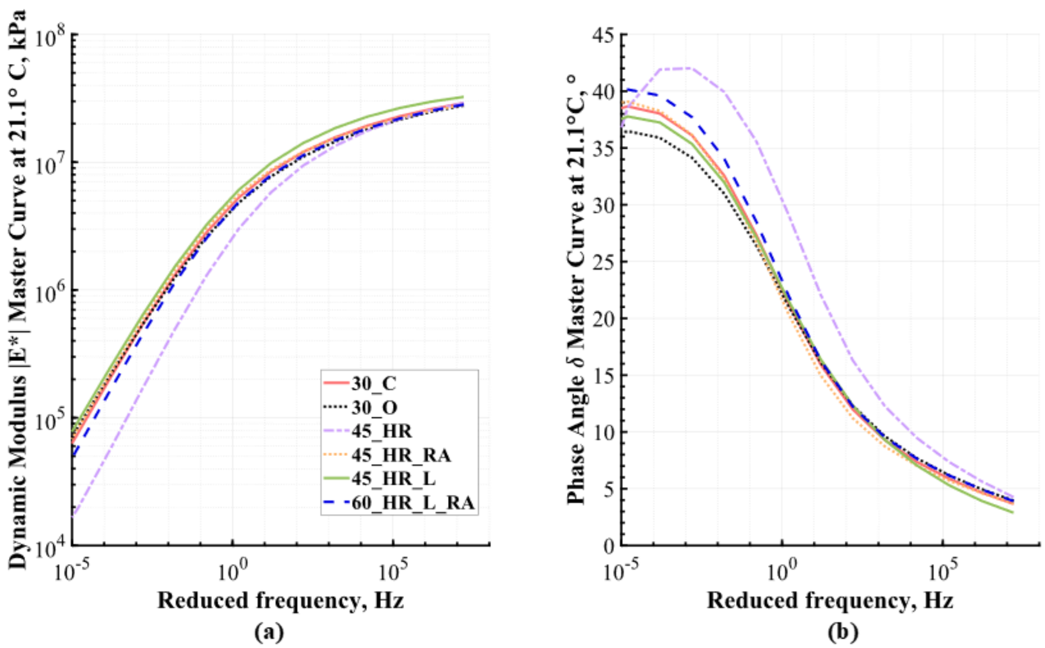


Figure 13. Dynamic Modulus Test Results: (a) |E*| Master Curves; (b) δ Master Curves. |E*| = Dynamic Modulus; δ = Phase Angle; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; ESALs = Equivalent Single Axle Loads.

Accelerated Pavement Testing Rutting Experiment

Applied Loading

The APT experiment was conducted during approximately 3 years. Detailed information regarding the loading timeline and applied loading conditions for the pavement during the testing period are in Appendix B. The notation R1 is used to indicate rutting cell 1, which underwent testing prior to rutting cell 2 denoted by R2. This differentiation is made to facilitate the subsequent explanation of potential environmental aging effects. Figure 14 shows the loading scheme employed for the test cells. The slope of the curves depicted in the figure indicated the loading rate, which was primarily driven by the magnitude of the applied load and to a lesser extent by daily management practices. Specifically, as the loading magnitude increased, the slope of the curves became steeper. Figure 14 shows that the accumulated ESALs for cell 45_HR_R1 and 45_HR_R2 were relatively lower than other test cells, which occurred because these cells experienced rutting failure at an earlier stage compared with the remaining cells.

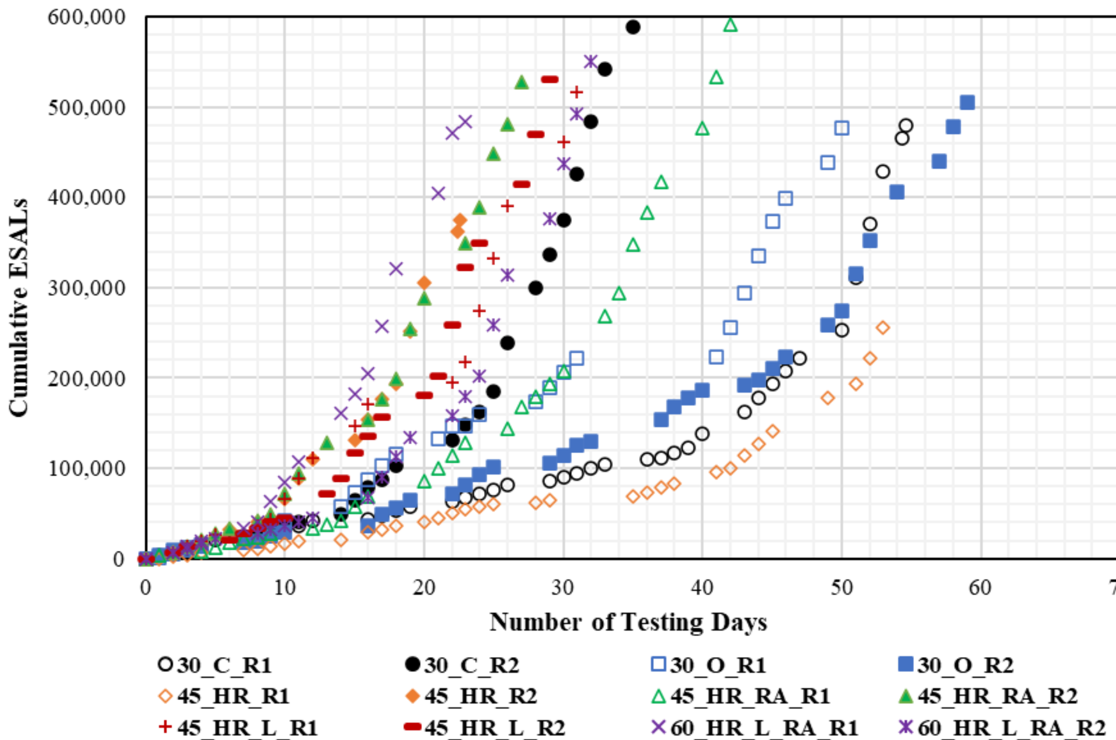


Figure 14. Test Cell Loading. ESALs = Equivalent Single Axle Loads; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; R1 and R2 = Rutting Test Cells.

Collected Rut Depth Measurements

Figure 15 shows the rut depth measurements collected within the 12 rutting test cells, with two rutting cells (R1 and R2) for each lane. Mixture 45_HR showed the poorest rutting resistance compared with the other five mixtures, as indicated by its rapid accumulation of rut depth (Figure 15). This performance can be attributed to the significantly higher flexibility resulting from the high OBC used in the design and production of mixture 45_HR. The rutting performance of the remaining five mixtures appeared comparable, except for 60_HR_L_RA_R2, which exhibited a significant difference from 60_HR_L_RA_R1 after increasing the load magnitude from 9,000 to 12,000 lbf, with its rut depth approaching 12.5 mm at the end of loading cycles.

Determining the rutting performance ranking proved to be difficult given the variance in test results observed between the corresponding test cells, R1 and R2, which can confound a simple ranking approach. Consequently, further investigation highlighting the effect of environmental aging was conducted to explain the observed differences in performance between test cells R1 and R2.

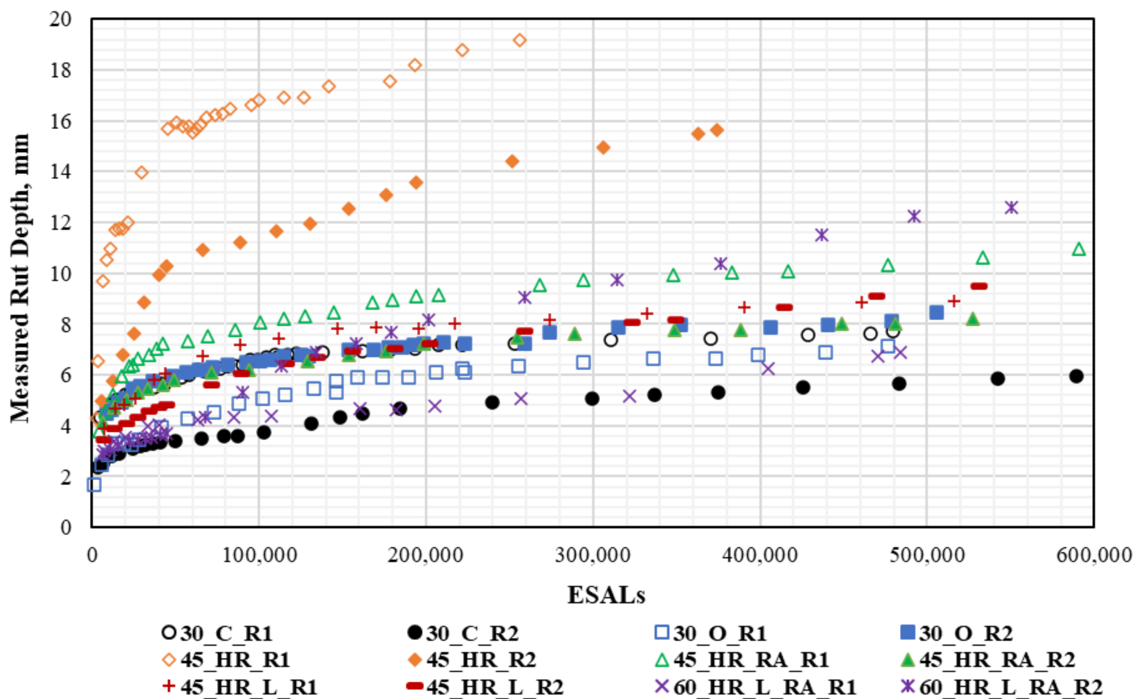


Figure 15. Rutting Depth for 12 Rutting Test Cells. ESALs = Equivalent Single Axle Loads; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; R1 and R2 = Rutting Test Cells.

Environmental Aging and Speed Effects

Appendix B shows a summary of the regression coefficients using the rutting model. Notably, loading speed was extended into Equation 2 to account for its potential influence on rutting performance, particularly for mixtures 30_O and 45_HR. However, the results of the regression and statistical analyses revealed that loading speed was not a significant predictor in these cases. The rut depth measurements were also found to be less sensitive to loading speed compared with the effects of ESALs and pavement age. Therefore, Equation 2 was deemed sufficient for regression analysis across all test lanes. Figure 16 shows the progression of rut depth for each mixture, normalized with respect to aging and averaged with respect to cell R1 and R2.

Figure 16 shows that mixture 45_HR exhibited the highest rut depths, followed by mixtures 60_HR_L_RA and 45_HR_RA, and then mixtures 45_HR_L, 30_C, and 30_O. It was observed that all BMD HRAP mixtures showed higher rut depths compared with the control mixture 30_C. This fact can be attributed to the inclusion of an increased binder content, along with the use of a RA and softer binder grade in BMD HRAP mixtures to balance the mixture and enhance the cracking resistance. Despite the similarity in rutting performance between mixtures 30_O and 30_C as Figure 15 shows, testing for cells containing mixture 30_O was conducted 203 days earlier than that for mixture 30_C. Also, mixture 30_O exhibited better rutting performance compared with mixture 30_C.

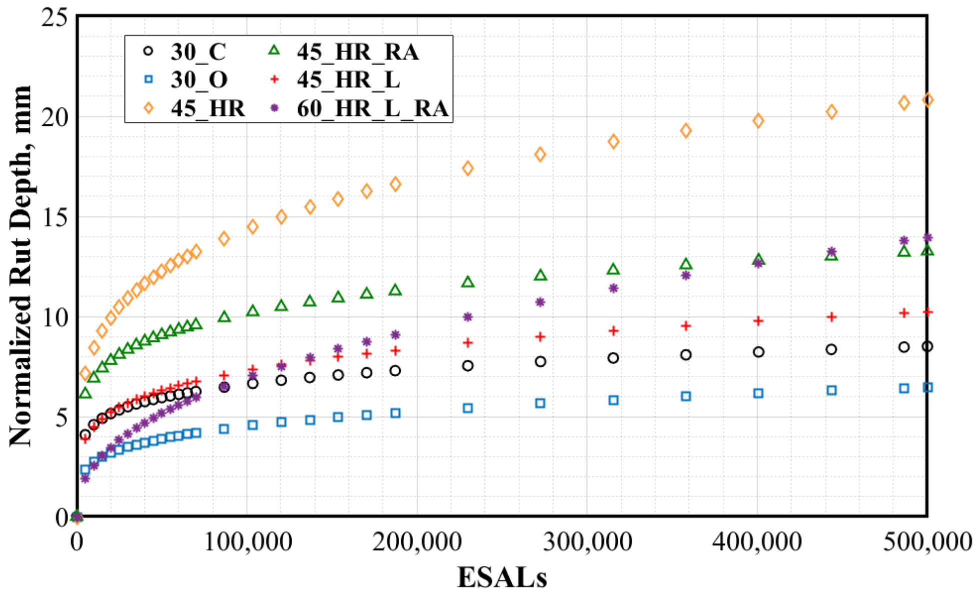


Figure 16. Normalized Average Rut Depth Values and Curves. ESALs = Equivalent Single Axle Loads; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade.

Accelerated Pavement Testing Cracking Experiment

Applied Loading

The APT experiment was conducted during approximately 3 years. Appendix B contains detailed information regarding the loading timeline. Figure 17 shows loading applied to the cracking test cells. One test cell was evaluated per lane and mixture, except for mixture 60_HR_L_RA, for which two cracking cells (C1 and C2) were considered. The slope of the curves depicted in the figure indicates the loading rate, which was primarily driven by the magnitude of the applied load and influenced to a lesser extent by daily management practices. Loading of test cell 60_HR_L_RA_C2 was stopped at approximately 2.0 million ESALs because of limitations in the testing schedule and reaching a relatively high rutting level (8.0 mm).

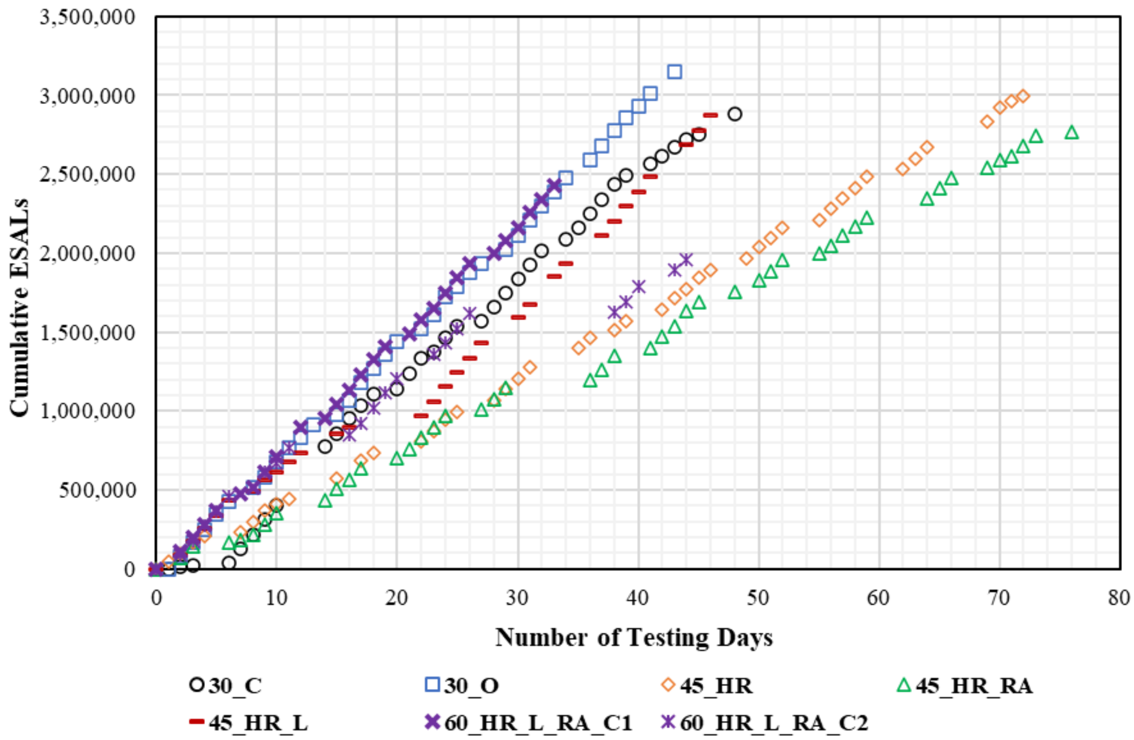


Figure 17. Test Cell Loading. ESALs = Equivalent Single Axle Loads; C = Control; O = Optimized, HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; C1 and C2 = Cracking Test Cells.

Passes to Initial Cracking

Table 3 shows the number of loading passes during which the first cracks occurred for each of the tested mixtures. Overall, HRAP mixtures (45% RAP) featuring the use of either a RA or softer binder grade withstood the highest number of passes before developing the first visible surface crack, which was followed by mixtures 45_HR, 60_HR_RA_L (based on average values from cells C1 and C2), 30_C, and finally 30_O.

Table 3. Number of Passes to Observation of Initial Surface Cracking per Cracking Test Cell

	Mixture						
	30_C	**30_O**	**45_HR**	**45_HR_RA**	**45_HR_L**	**60_HR_RA_L_C1**	**60_HR_RA_L_C2**
Number of Passes until Observed Cracking	176,205	60,654	229,919	323,876	335,882	132,911	228,753[a]

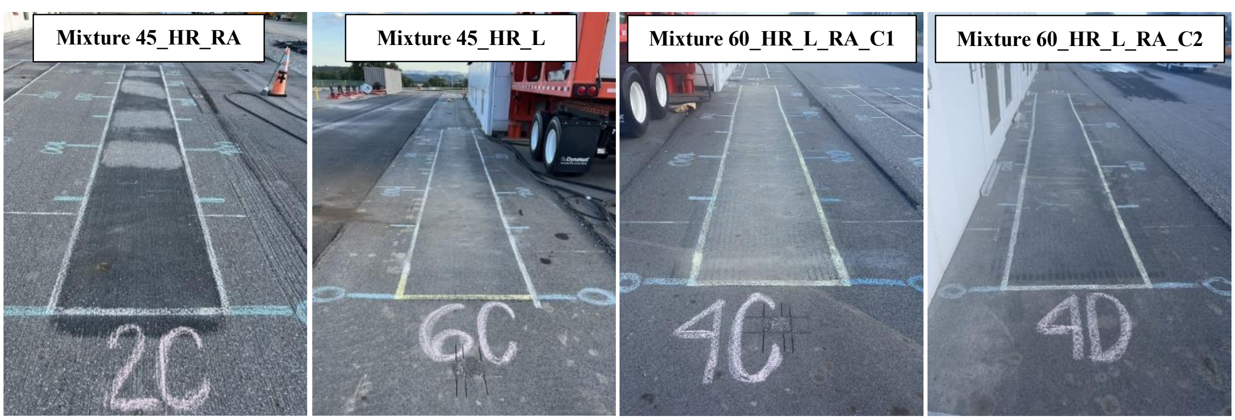
C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade. [a] One Transverse Crack Along the Entire Width of this Cell was Observed 2 days Before Stopping Testing.

Cracking Quantification

Figures 18 and 19 show the cracking cells of the six experimental lanes after full-scale testing at the end of the experiment. The final cracking length was marked for each test section. The severity of each crack was quantified by its width as shown in Table 4. Since there is no standard definition of crack severity for APT testing, crack severity was defined as low, medium, and high based on crack widths of 0.1 mm, 0.1 to 0.4 mm and greater than 0.4 mm, respectively. These classifications are intended solely for relative comparison among the six evaluated mixtures, serving specifically to establish a performance ranking. In accordance with ASTM D6433-18, cracking having a width of less than 10 mm is defined as low severity. Overall at the conclusion of the experiment, HRAP mixtures (45% RAP) that used either a RA or softer binder grade exhibited the fewest number of cracks.

(a) (b) (c)

Figure 18. Cracking Cells after Testing with Cracks Marked: (a) 30_C; (b) 30_O; (c) 45_HR. C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement.



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

Figure 19. Cracking Cells after Testing with Cracks Marked: (a) 45_HR_RA; (b) 45_HR_L; (c) 60_HR_L_RA_C1; (d) 60_HR_L_RA_C2. HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; C1 and C2 = Cracking Test Cells.

Table 4. Summary of Surface Cracking per Cracking Cell

Severity	Total Crack Length (mm)						
	30_C	**30_O**	**45_HR**	**45_HR_RA**	**45_HR_L**	**60_HR_RA_L_C1**	**60_HR_RA_L_C2**
Low	20,152	14,831	10,105	3,790	6,974	2,765	12,102
Medium	0	360	1,800	0	1,800	8,295	1,500
High	0	180	300	0	0	44,243	0
Total	**20,152**	**15,371**	**12,205**	**3,790**	**8,774**	**55,303**	**13,602**

C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; C1 and C2 = Cracking Test Cells.

Strain Measurements

In most cases, the response recorded by the three strain gauges varied when subjected to the same traffic loading conditions. Figures 20 and 21 display the recorded total and tensile strain, respectively, under the centerline of one of the dual tires for the mixtures throughout the testing period. Every strain gauge remained functional after construction, except for one in the test cell for mixture 45_HR. In addition, one strain gauge in both mixtures 30_C and 45_HR_L experienced a malfunction early in the testing phase. This malfunction could have been due to issues with the strain gauge or to the fixtures loosening during construction, potentially causing the embedded strain gauges to slide and resulting in inaccurate measurements.

Based on the data in Figures 20 and 21, all measured total strain values exhibited a rapid increase during the early stages of testing, followed by a trend of either remaining relatively constant or increasing slowly. Some cases even displayed a decreasing trend (second stage). The initial rapid increase is believed to result from pavement deterioration, indicating a decrease in stiffness. After this initial phase, during which the total strain remained constant or increased slowly, the research team inferred that microcracking occurred. The appearance of a drop in total strain values is believed to mark the initiation of macrocracking.

Under the same stress loading conditions, from an energy perspective, some of the loaded energy dissipated within the microcrack zones. During this period, the reference table began to fluctuate, and recorded responses during the unloading phase were no longer at zero (Figures 22 and 23). This change may be indicative of the occurrence of microcracking, leaving a residual strain on the strain gauges. In this phase, the pavement was considered to still possess adequate resistance to cracking under the current loading conditions.

Furthermore, based on the initial recordings of total strain, all collected strains began from a value of 100 microstrains. This observation can be attributed to comparable stiffness values of the pavements of the various lanes in its intact state, which is also reflected in the |E*| testing results.

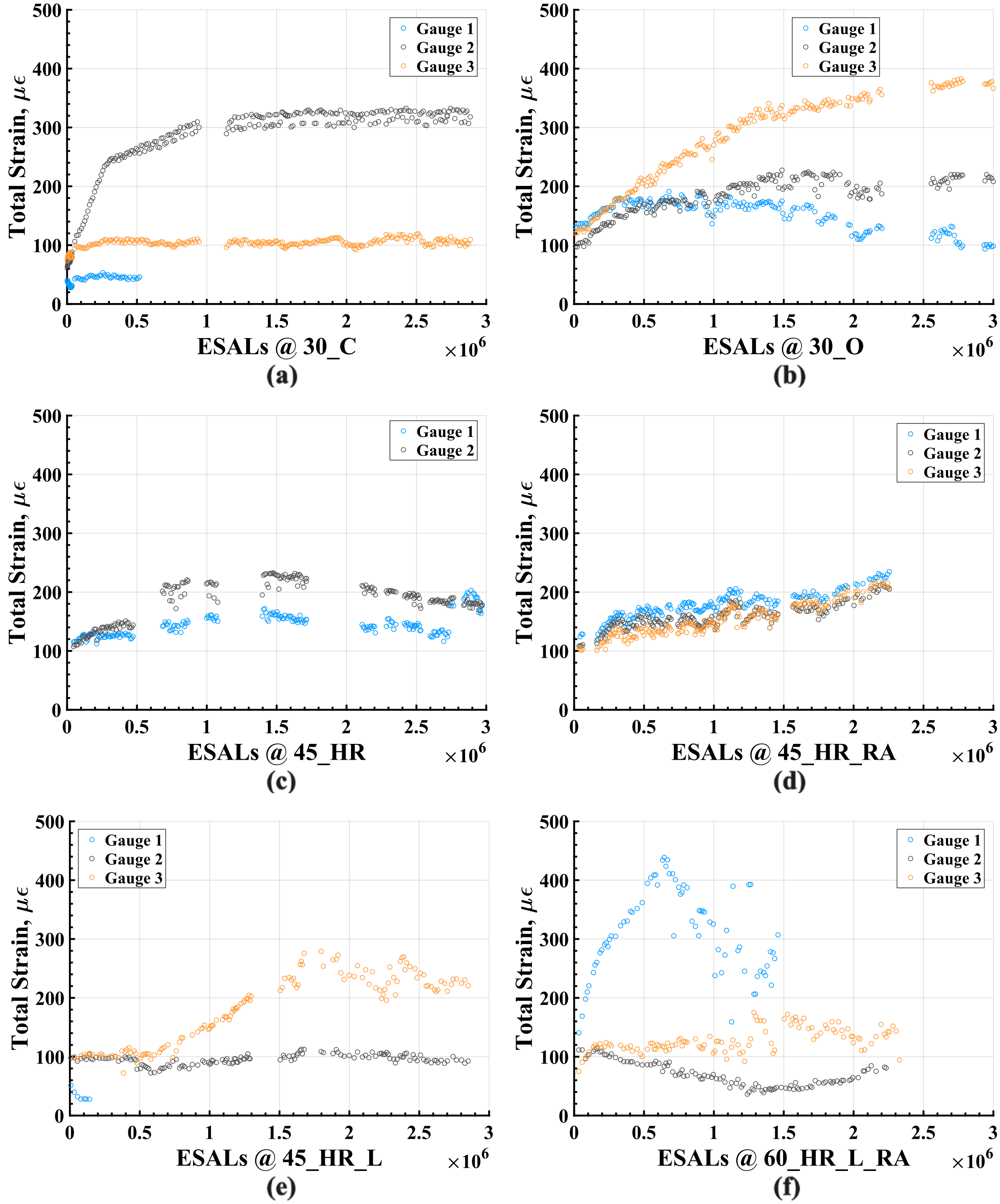


Figure 20. Total Strain Calculated from Collected Data throughout Testing for all Mixtures: (a) 30_C; (b) 30_O; (c) 45_HR; (d) 45_HR_RA; (e) 45_HR_L; (f) 60_HR_RA_L. C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; ESALs = Equivalent Single Axle Loads.

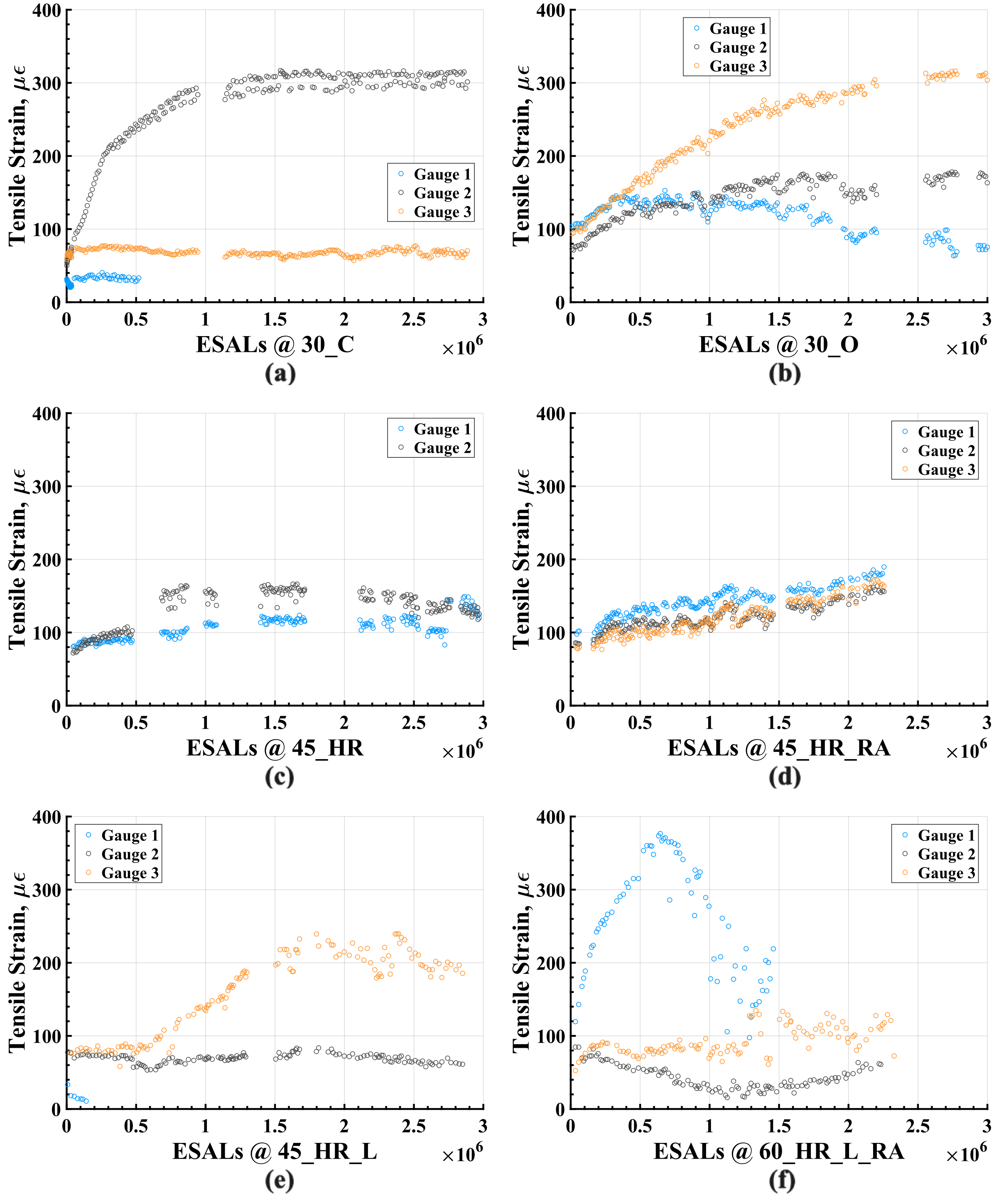


Figure 21. Tensile Strain Calculated from Collected Data throughout Testing for all Mixtures: (a) 30_C; (b) 30_O; (c) 45_HR; (d) 45_HR_RA; (e) 45_HR_L; (f) 60_HR_RA_L. C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; ESALs = Equivalent Single Axle Loads.

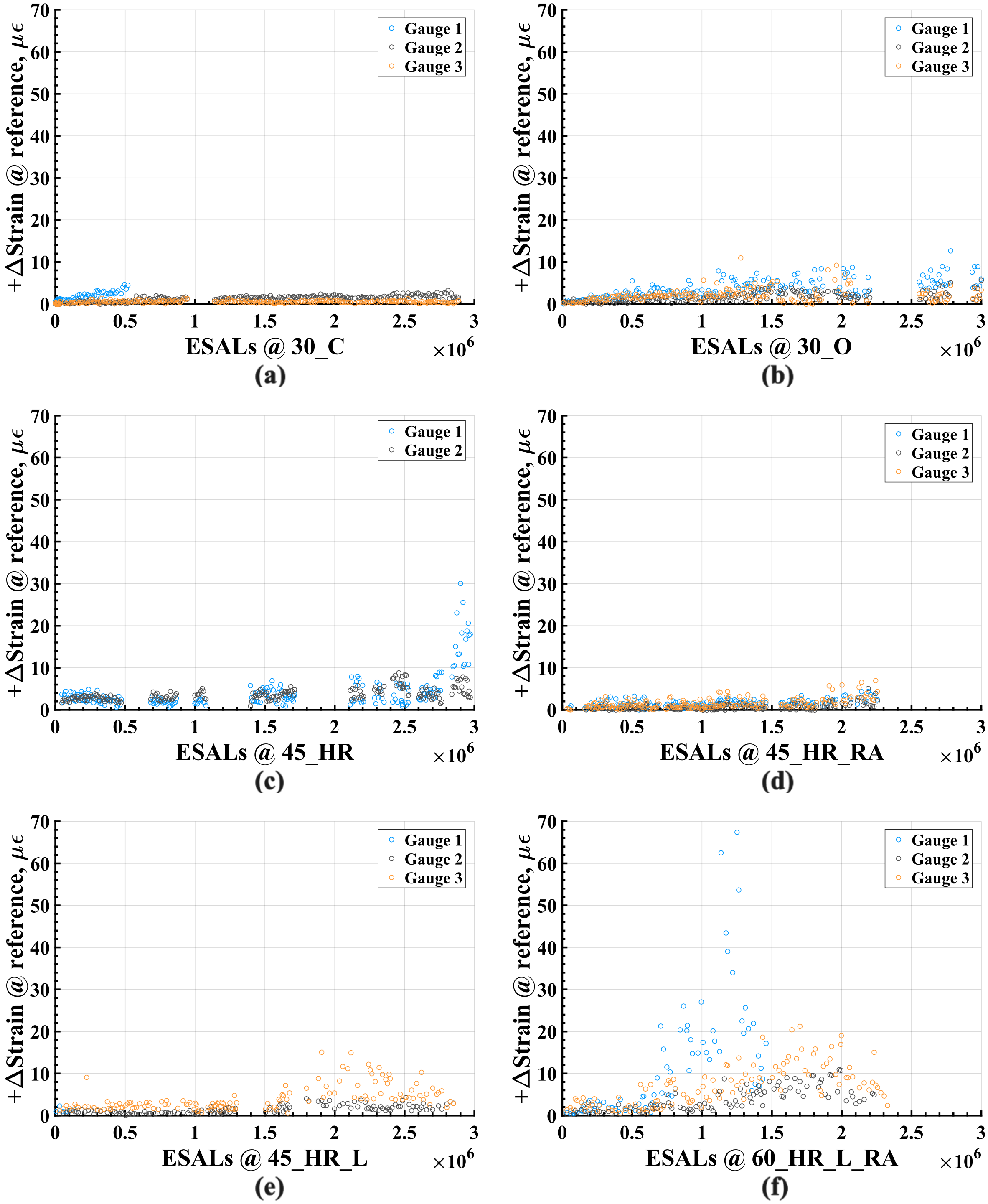


Figure 22. Maximum Remaining Strain (+ΔStrain) at Reference Table from Collected Data throughout Testing for all Mixtures: (a) 30_C; (b) 30_O; (c) 45_HR; (d) 45_HR_RA; (e) 45_HR_L; (f) 60_HR_L_RA. C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; ESALs = Equivalent Single Axle Loads.

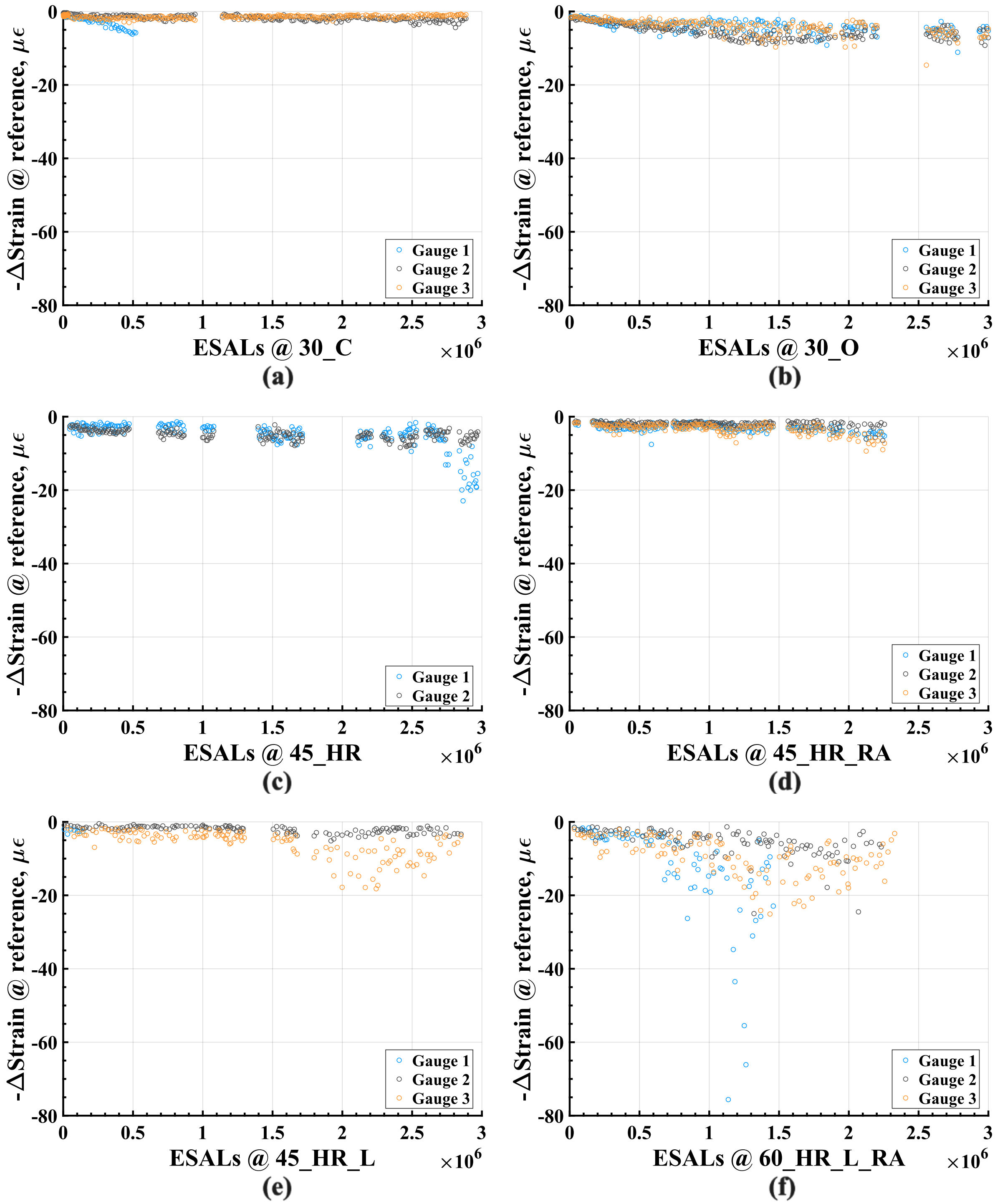


Figure 23. Minimum Remaining Strain (-ΔStrain) at Reference Table from Collected Data throughout Testing for all Mixtures: (a) 30_C; (b) 30_O; (c) 45_HR; (d) 45_HR_RA; (e) 45_HR_L; (f) 60_HR_L_RA. C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; ESALs = Equivalent Single Axle Loads.

Field Cores

After completing full-scale testing, researchers collected 83 cores from the rutting and cracking cells from within and outside the wheel path (the area that was not loaded). These cores were inspected for potential bottom-up cracks. The observations could be subjective and might have been influenced by minor cracks initiated during the coring process. However, overall, two cores showed some major cracks for mixture 60_HR_L_RA. The notable difference in thickness for the surface asphalt layer of various test cells and lanes was another major observation. Figure 24 shows photographs taken of cores collected in cracking cells within the wheel path and loaded area.

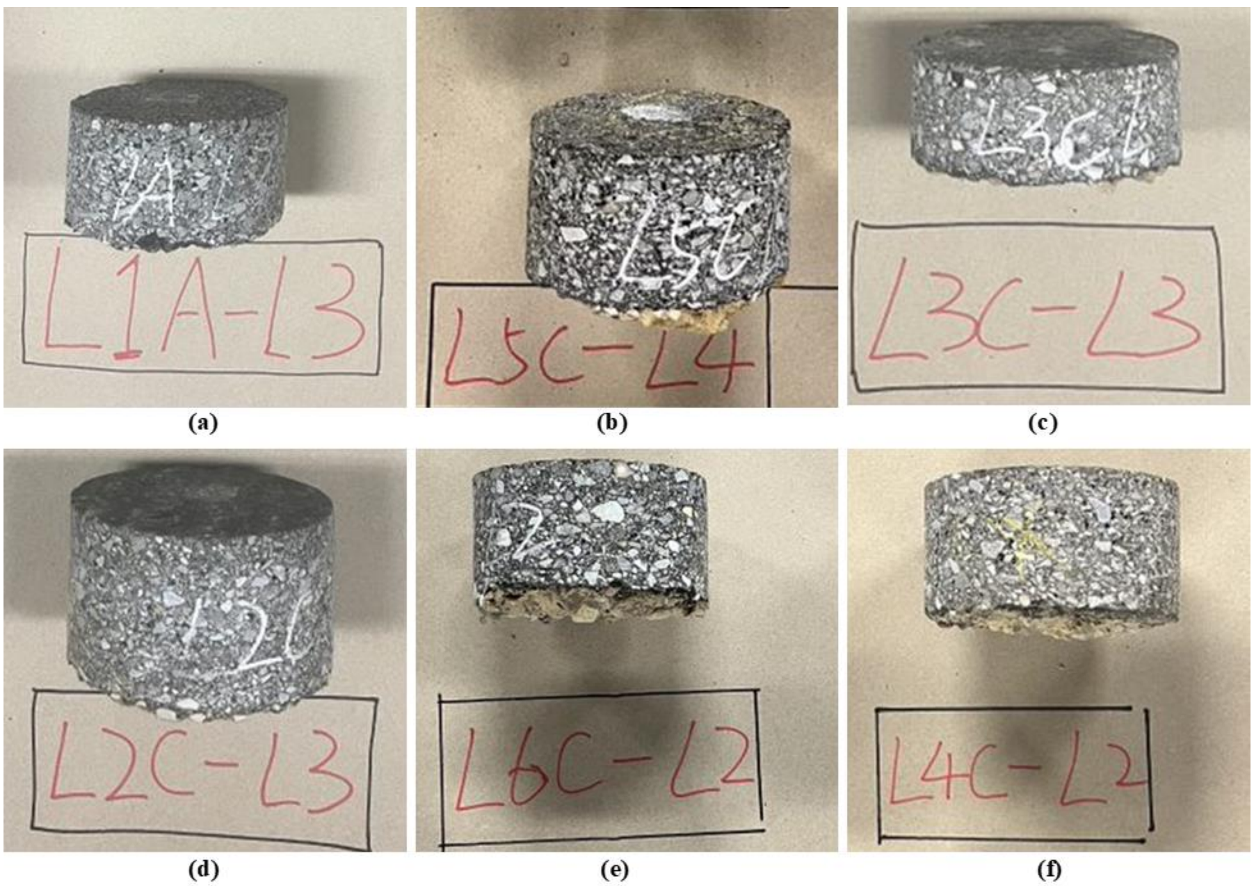


Figure 24. Photographs Taken of Cores Collected from all Experimental Lanes after Full-Scale Testing: (a) 30_C; (b) 30_O; (c) 45_HR; (d) 45_HR_RA; (e) 45_HR_L; (f) 60_HR_L_RA. C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade.

Correlation Analysis, Relationships, and Ranking

Laboratory and Full-Scale Results for Rutting

Table 5 summarizes the laboratory and full-scale rutting results. Among these, the APT results were selected based on the normalized rut depth for each lane at the culmination of 500,000 ESALs. For mixture 30_O, the average value of 6.46 mm was obtained by considering the mean rut depth measurements derived from test cell 30_O_R1 (6.25 mm) and test cell

30_O_R2 (6.67 mm). Conversely, for mixture 60_HR_L_RA, the rut depth of 13.93 mm at the termination of 500,000 ESALs was recorded from test cell 60_HR_L_RA_R2 and used for subsequent analysis. The average APA results were computed from four sets each of non-reheat and reheat specimens along with their standard deviations and included in Table 6 for comprehensive comparison.

Table 5. Laboratory and Full-Scale Rutting Results

Rutting Performance	**Mixture**					
	30_C	**30_O**	**45_HR**	**45_HR_RA**	**45_HR_L**	**60_HR_L_RA**
APT Normalized Rut Depth, mm	8.5	6.5	20.8	13.3	10.2	13.9
Avg APA Rut Depth for Non-Reheat, mm	4.2	6.1	11.9	5.3	4.4	3.9
Stdv APA Rut Depth for Non-Reheat, mm	0.8	1.2	1.5	0.7	1.1	1.2
Avg APA Rut Depth for Reheat, mm	4.3	4.3	6.7	5.1	4.5	5.2
Stdv APA Rut Depth for Reheat, mm	0.8	0.5	0.7	0.6	0.7	0.6

APT = Accelerated Pavement Testing; APA = Asphalt Pavement Analyzer; Stdv = Standard Deviation; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade.

Table 6. Laboratory and Full-Scale Mass Loss and Cracking Results

Durability and Cracking Performance	**Mixture**						
	30_C	**30_O**	**45_HR**	**45_HR_RA**	**45_HR_L**	**60_HR_L_RA**	
APT Total Crack Length, mm	20,152	15,371	12,205	3,790	8,774	55,303 (C1)	13,602 (C2)
APT Number of Passes Until 1st Crack	176,205	60,654	229,919	323,876	335,882	132,911 (C1)	228,753 (C2)
Avg ML index for Non-Reheat, %	7.4	5.8	2.4	4.3	5.0	4.6	
Stdv ML index for Non-Reheat, %	0.3	0.8	0.4	0.7	0.4	0.4	
Avg ML index for Reheat, %	8.7	8.2	3.7	6.2	6.3	5.9	
Stdv ML index for Reheat, %	0.7	0.2	0.4	0.7	0.5	0.3	
Avg CT index for Non-Reheat	139	242	944	342	220	220	
Stdv CT index for Non-Reheat	9	41	130	65	73	36	
Avg CT index for Reheat	52	75	385	155	90	100	
Stdv CT index for Reheat	4	20	106	69	18	19	

APT = Accelerated Pavement Testing; Avg = Average; CT = Cracking Tolerance; Stdv = Standard Deviation; ML = Mass Loss; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade.

Figures 25a and 25b compare the APT normalized rut depth measurements with the APA average rut depth from non-reheat and reheat specimens, respectively. Error bars indicate plus or minus one standard deviation. The use of linear regression provided a characterization of the relationships between the two testing methods. Moderate and strong positive relationships were observed between the APT normalized rut depth measurements and the APA average rut depth collected on non-reheat and reheat specimens, respectively.

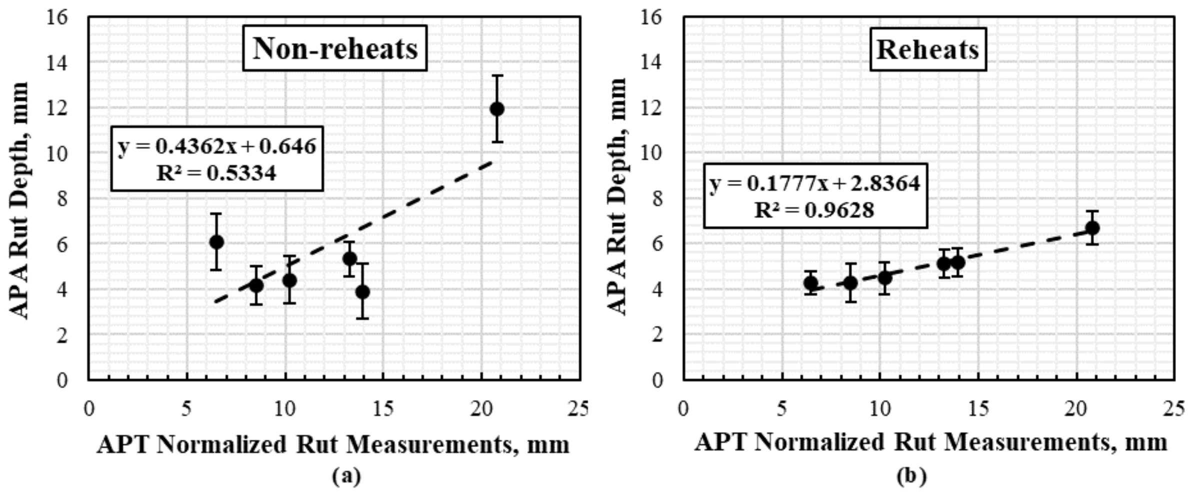
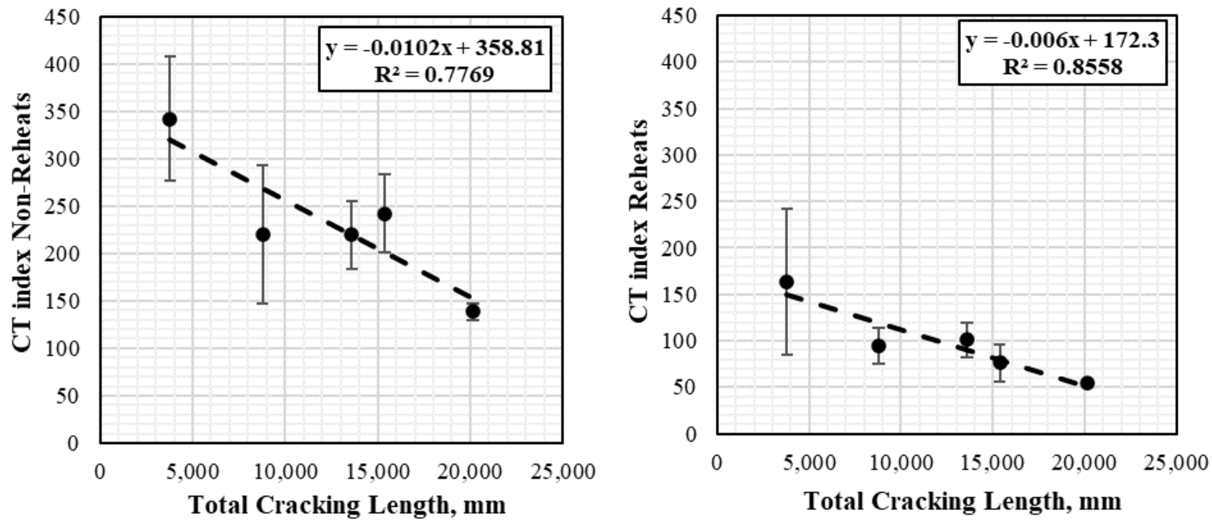


Figure 25. Correlation Analysis APT Normalized Rut Depth and APA Rut Depth of: (a) Non-Reheat Specimens; (b) Reheat Specimens. APT = Acceelrated Pavement Testing; APA = Asphalt Pavement Analyzer. Error Bars Indicate Plus or Minus one Standard Deviation.

Laboratory and Full-Scale Results for Cracking and Durability

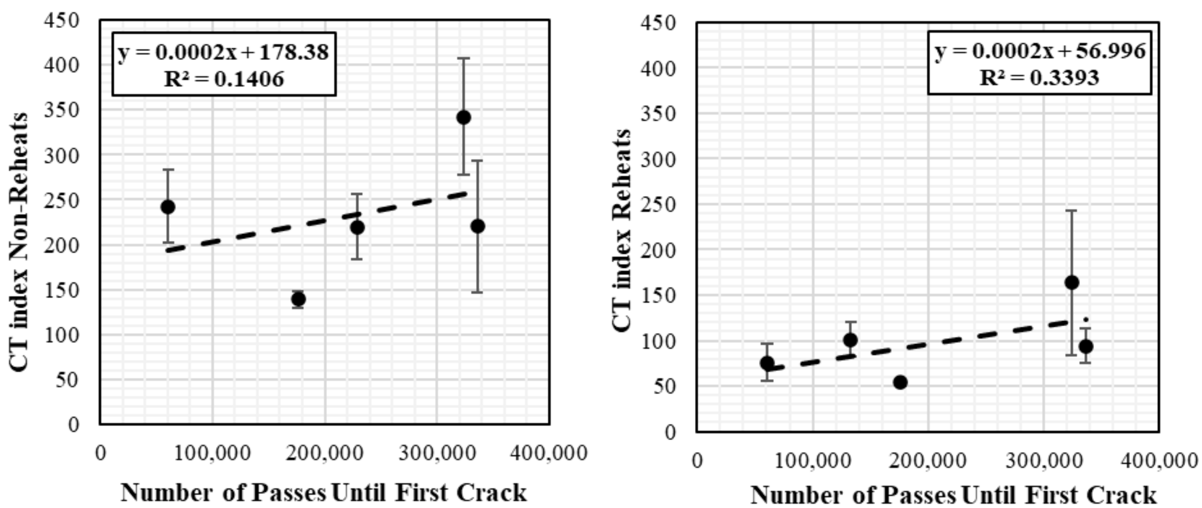
This section compares laboratory test results in terms of CT index and ML for non-reheat and reheat specimens with APT cracking measurements, considering the number of loading cycles until the first crack was observed and the total crack length at the end of the experiment (Table 6 and Figures 26 through 29). In the case of CT index, the data for mixture 45_HR were excluded from the comparison because of their significantly higher values compared with other mixtures evaluated in this study and with typical CT index values of A and D SMs, commonly produced in Virginia. Moreover, Figures 26 through 29 show the data collected for 60_HR_L_RA_C2.

Figure 26 shows a good-to-strong correlation between the CT index values for reheat and non-reheat specimens and the total cracking length of each crack test cell. Figure 27 shows a poor correlation between the number of passes made until the first crack was observed and the total cracking length of each crack test cell, which was expected because this approach is more subjective. These correlations were not used to validate the current BMD CT threshold because the cracking was expressed in terms of crack length and not in terms of an area of cracking, as typically reported in the pavement management system database. The calculation of the percentage of cracked area was not pursued because most of the identified cracks were hairline sized and did not constitute localized fatigue cracking area. Although the width of the cracks was measured, the percentage of the cracking area (length * width) was minimal compared with the total area of the test cell.



(a) (b)

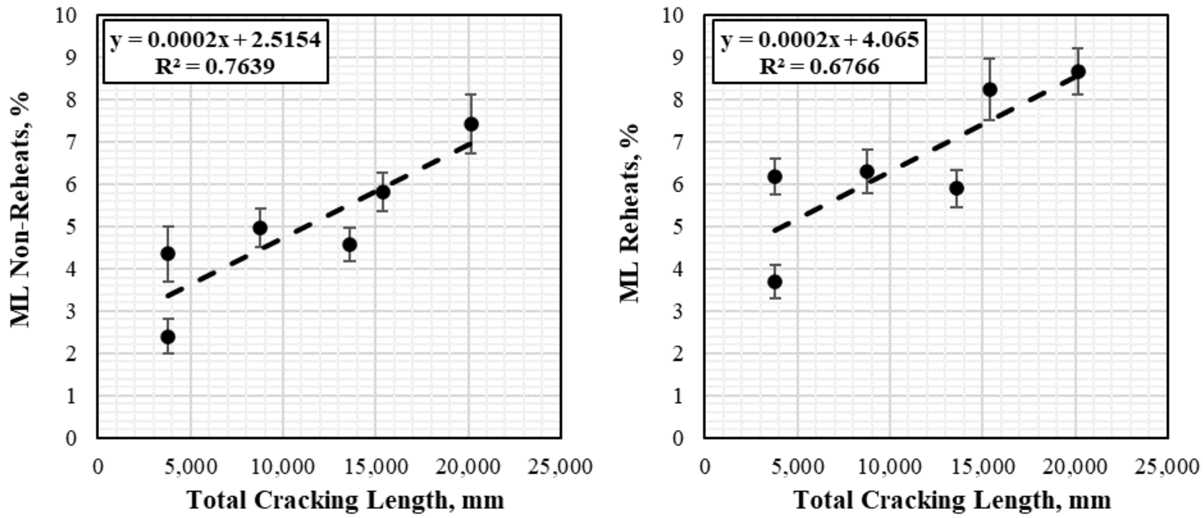
Figure 26. CT Index versus Total Cracking Length: (a) Non-Reheat Specimens; (b) Reheat Specimens. CT = Cracking Tolerance. Error Bars Indicate Plus or Minus one Standard Deviation.



(a) (b)

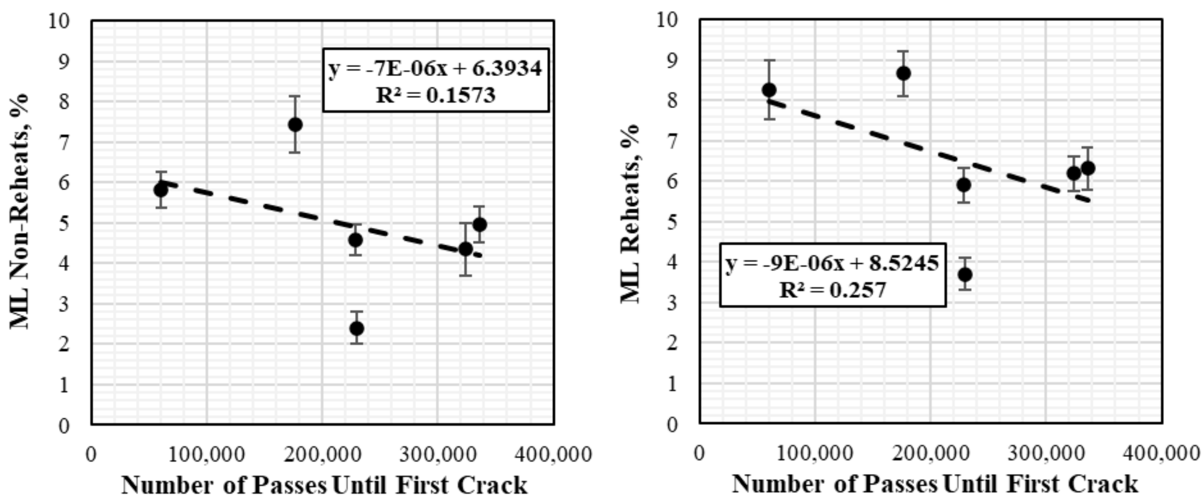
Figure 27. CT Index versus Number of Passes until First Crack: (a) Non-Reheat Specimens; (b) Reheat Specimens. CT = Cracking Tolerance. Error Bars Indicate Plus or Minus one Standard Deviation.

Figure 28 shows a fair-to-good correlation between the ML for reheat and non-reheat specimens and the total cracking length of each crack test cell. Figure 29 shows a poor-to-fair correlation between ML and the total cracking length of each crack test cell. These observations were not unexpected, given the different distress modes described by durability and cracking tests.



(a) (b)

Figure 28. ML versus Total Cracking Length: (a) Non-Reheat Specimens; (b) Reheat Specimens. ML = Mass Loss. Error Bars Indicate Plus or Minus one Standard Deviation.



(a) (b)

Figure 29. ML versus Number of Passes until First Crack: (a) Non-Reheat Specimens; (b) Reheat Specimens. ML = Mass Loss. Error Bars Indicate Plus or Minus one Standard Deviation.

Performance Ranking

The results were compared in terms of their potential to rank the performance of the mixtures toward various distresses, including durability, cracking, and rutting, using data collected both in the laboratory and under APT. This comparison involved sorting the average value of each test result from the highest to the lowest values. Table 7 illustrates the ranking order of the mixtures from the best performing (A) to the least performing (F/G) for each index or parameter.

Table 7. Ranking of Mixtures Based on Average Performance Index Values. A is Best Performing; F/G is Worst Performing.

Parameters / Mixture	30_C	30_O	45_HR	45_HR_RA	45_HR_L	60_HR_L_RA
Rutting						
APA Rut Depth (design)	D	B	E	F	C	A
APA Rut Depth (non-reheat)	B	E	F	D	C	A
APA Rut Depth (reheat)	B	A	F	D	C	E
APT Normalized Rut Depth	B	A	F	D	C	E
Durability and Cracking						
ML (design)	C	D	F	B	A	E
ML (non-reheat)	F	E	A	B	D	C
ML (reheat)	F	E	A	C	D	B
CT (design)	F	D	A	E	B	C
CT (non-reheat)	F	C	A	B	D	E
CT (reheat)	F	E	A	B	D	C
APT Total Crack Length	F	E	C	A	B	G (Cell 1) / D (Cell 2)
APT Number of Passes until First Crack	E	G	C	B	A	F (Cell 1) / D (Cell 2)

C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; APA = Asphalt Pavement Analyzer; APT = Accelerated Pavement Testing; ML = Mass Loss; CT = Cracking Tolerance.

The rankings for rutting performance show excellent agreement between the APT normalized rut depth and APA reheat rut depth for all mixtures. APA non-reheat result rankings agree with both APA reheat and APT rankings, except for mixtures 30_O and 60_HR_L_RA. The APA design rankings showed agreement only with other APA or APT rankings for two mixtures, likely due to the differences between laboratory production and plant production of design mixtures. Overall, the similarities between the APA non-reheat, APA reheat, and APT rankings are most likely related to these mixtures being plant produced. Differences are related to the mixtures' response to aging experienced during reheating or paving.

The comparisons of rankings for durability, as indicated by ML and the APT total crack length or APT passes until the first crack, showed mixed trends. The non-reheat and reheat rankings for ML showed better agreement with the APT total crack length ranking than with the APT passes until first crack ranking, although all ranked the 45% RAP mixes and mixture 60_HR_L_RA (cell 2) as the four highest performers. The design ML ranking agreed only with either of the APT cracking rankings for mixtures 45_HR_RA and 45_HR_L. Ranking results for all other mixtures varied. The disparities between the rankings are likely due to the different distress modes assessed by the Cantabro test and APT cracking experiment.

The reheat CT index showed somewhat positive agreement with the APT total crack length and APT passes until first crack in indicating that the 45% and 60% (cell 2) mixtures should show better performance than the 30% or 60% (cell 1) mixtures. However, the non-reheat CT index results indicate that mixture 30_O and the 45% RAP mixtures should perform best. The design CT index results differ from both, except for ranking mixtures 45_HR and 45_HR_L as the best performers and mixture 30_C as the worst performer. Overall, the ranking indicates that all BMD mixtures, except for mixture 60_HR_L_RA (cell 1), should perform better than the non-BMD control mixture 30_C and better than the BMD optimized mixture 30_O in most cases. The performance of the 60% RAP mixture varied, based on the results of either cells 1 or

2.

Rankings for plant-produced mixtures (non-reheat, reheat, and APT results) tended to agree more among themselves than with rankings from laboratory-produced design mixtures. These differences in rankings are due to the differences between laboratory and plant production. Although laboratory production is intended to simulate plant production, the mixture responses are not always comparable.

Mixture 30_C was ranked as nearly the best in rutting resistance and worst in cracking resistance, illustrating the bias toward rutting resistance in VDOT's Superpave design procedures. For mixture 30_O, using only gradation and binder content adjustments to optimize the mixture limited the amount of improvement in cracking performance achieved using BMD mixtures. Mixture 45_HR performed worst in rutting but well in cracking because of the mixture's higher binder content. In general, the mixtures that did not include a softer binder or RA and that ranked better in the rutting evaluation ranked worse in cracking and durability evaluation. This result demonstrates the importance of balancing performance during design. Mixture 45_HR_L was most balanced based on rankings of laboratory testing. Overall, 45% RAP mixtures containing the softer binder and RA were more balanced than either the 30% or 60% RAP mixtures.

SUMMARY OF FINDINGS

Volumetric Properties and Gradations

- The OBC of all BMD mixtures was higher than the control mixture, suggesting that the BMD process may result in additional binder being used for some mixtures.
- The mixtures that included a RA or softer binder, or both, (45_HR_RA, 45_HR_L, and 60_HR_RA_L) had a lower OBC compared with the mixture that did not include a RA or softer binder (45_HR).
- The binder content of the 45_HR mixture was 6.8%, which was much higher than expected or typical.
- The voids filled with asphalt for mixtures 30_O, 45_HR_RA, and 60_HR_L_RA were 87.0, 84.0, and 90.0%, respectively, which is much higher compared with the control mixture (30_C).
- The ML values for mixtures 30_O, 45_HR, and 60_HR_L_RA were higher than the control (30_C). However, all values passed VDOT's design criteria of 7.5%.
- The design APA rut depth result for mixtures 30_O, 45_HR_L, and 60_HR_L_RA was lower than the control (30_C). However, all values passed VDOT's design criteria of 8.0 mm.
- The CT index for all mixtures was greater than the control, resulting in all mixtures, other than the control, passing VDOT's design criteria of 70.

Laboratory Evaluation

- ML of production reheat specimens from all mixtures was similar to or lower than the control mixture.
- ML of production reheat and non-reheat specimens from all mixtures was well correlated.
- The APA rut depth of production reheat specimens from all mixtures was similar to or lower than the control, except for mixture 45_HR.
- The APA rut depth of production reheat and non-reheat specimens from all mixtures was not well correlated.
- The CT index of production reheat specimens from all mixtures was similar to or greater than the control (30_C).
- The CT index of production reheat and non-reheat specimens from all mixtures was well correlated.
- The dynamic modulus of mixture 45_HR was lower than the other mixtures at low and intermediate test frequencies, indicating lower stiffness at higher temperatures.
- The phase angle modulus of mixture 45_HR was higher than the other mixtures at low and intermediate test frequencies, suggesting better cracking resistance than the other mixtures.
- The phase angle of mixture 30_O was lower than the other mixtures at lower test frequencies, suggesting poorer crack resistance than the other mixtures.
- Based on the results for the mixtures tested in this study, mixture 30_O did not perform well compared with other BMD mixtures.

Accelerated Pavement Testing Experiment

- The APT rutting experiment found that BMD mixtures (30_O, 45_HR, 45_HR_RA, 45_HR_L, and 60_HR_RA_L) showed higher rut depths compared with the control mixture (30_C).
- The APT cracking experiment found that BMD mixtures (30_O, 45_HR, 45_HR_RA, and 45_HR_L) exhibited less total cracking compared with the control mixture (30_C).
- Low severity (based on the definition used in this study) cracks were observed for all evaluated mixtures.
- Medium severity (based on the definition used in this study) cracks were observed for mixtures 30_O, 45_HR, 45_HR_L, and 60_HR_RA_L, but none were observed for the control mixture (30_C) or mixture 45_HR_RA.
- High severity (based on the definition used in this study) cracks were observed for mixtures 30_O, 45_HR, and 60_HR_L_RA, but none were observed for the control mixture (30_C) or mixtures 45_HR_RA and 45_HR_L.
- A high positive correlation was found between APA rut test results and APT rut measurements.

- A high positive correlation was found between CT index results and APT total cracking length.
- A poor low positive correlation was found between CT index results and APT number of passes to first crack.
- A high positive correlation was found between ML and APT total cracking length.
- A low negative correlation was found between ML and APT number of passes to first crack.
- Rankings for plant-produced mixtures (non-reheat, reheat, and APT) tended to agree more among themselves than with rankings from laboratory-produced design mixtures because of the differences between laboratory and plant-produced mixtures.
- In general, mixes that ranked better in the rutting evaluation ranked worse in cracking and durability evaluation, demonstrating the importance of balancing performance during design.

CONCLUSIONS

- *Effective use of BMD should include the ability to optimize mixtures, using a variety of tools instead of solely relying on increasing the asphalt binder content.* Mixture 30_O underperformed compared with the other BMD mixtures evaluated in this study because of the limited optimization process, which solely involved gradation adjustments and an increase in binder content.
- *Dense-graded unmodified surface mixtures with high RAP contents exceeding 30%, as set forth by the current VDOT specifications, can be designed using the current VDOT BMD special provision.*
- *Higher RAP content surface mixtures can be produced through the plant with no significant design differences in aggregate gradations and asphalt binder content.*
- *Recycling agents or a softer binder, or both, may be necessary when designing conventional and higher RAP content surface mixtures to meet VDOT BMD requirements.* The design of mixture 45_HR using a conventional binder grade and no RA resulted in a significantly higher OBC compared with HRAP with RA a or softer binder, leading to low rutting resistance in the laboratory and under APT.
- *More data need to be collected to evaluate the relationships among the test results for non-reheat and reheat specimens for all BMD performance tests.*
- *The currently selected BMD tests characterized the laboratory performance of mixtures similar to the performance observed under APT.*

RECOMMENDATIONS

1. *VDOT's Materials Division should consider allowing the use of other tools in addition to increasing binder content, such as a RA or softer binder, or both, for the design and production of BMD SMs with A and D designations even at allowable RAP contents.*

2. *VDOT's Materials Division should consider allowing mixtures with RAP contents of up to 45%, when properly controlled, desired by the district, and designed using current BMD specifications modified to allow additional tools such as a RA or softer binder, or both.* The use of HRAP mixtures is not appropriate in all locations or situations. It should be considered in locations or situations that have sufficient quantities of RAP available to use and producers with expertise, approved RAP management practices, and plants with the capability to produce such mixtures.
3. *VDOT's Materials Division should continue its efforts toward full implementation of BMD in Virginia for SMs, with A and D designations using the currently selected performance tests.*

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments section) for the project collaborated to craft a plan to implement the study recommendations and to determine the benefits of doing so. This action 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, as part of Project 117566, *Engineered Frameworks for Evaluating the Use of Recycling Agents in Surface Asphalt Mixtures for Virginia*, VTRC recommended two performance-based engineered frameworks. These frameworks aim to streamline the evaluation process and determine the acceptability of RA products for inclusion on VDOT's Approved Product List. VTRC is currently working with VDOT's Materials Division to validate these frameworks. This validation involves using data collected from additional field trials featuring the use of RAs and developing a corresponding Virginia Test Method. This process is part of the ongoing Project 124560, *Characterizing and Improving Binder Availability and Activity in Asphalt Mixtures with Reclaimed Asphalt Pavement (RAP)*. Based on the findings of this ongoing study, VDOT's Materials Division intends to decide whether to allow the use of RAs and softer binders in the design and production of BMD SMs with A and D designations, irrespective of the RAP content. This effort is expected to be completed by no later than the spring of 2025.

Regarding Recommendation 2, VDOT's Materials Division will collaborate with VTRC to continue ongoing research regarding BMD critical aging, RAP quality control tests, binder availability, and activity in RAP. In addition, a Research Needs Statement addressing the evaluation of the field performance of HRAP sections constructed in 2013 and 2014 (pre-BMD) has been drafted and will be submitted to the appropriate Pavement Research Advisory Subcommittee for funding consideration. If selected, VTRC will undertake a project to collect and assess field performance from high RAP trials constructed in 2013 and 2014. On completing these efforts, VDOT's Materials Division and VTRC will develop a comprehensive plan and roadmap outlining the necessary strategies for the responsible and successful implementation of HRAP mixtures. This work started in the spring of 2024 and be completed by the fall of 2027.

Regarding Recommendation 3, VDOT's Materials Division began fully implementing BMD, using the currently selected performance tests for all SM-9.5 and SM-12.5 mixtures with A and D designations produced during the 2024 paving season.

Benefits

This project assessed the application of the BMD concept to design durable and longer lasting SMs in Virginia with a focus on HRAP mixtures through full-scale accelerated testing. Furthermore, this project validated the selection of the three performance tests for inclusion in the BMD framework.

Ensuring sustained progress by implementing BMD will contribute to the production of longer lasting, cost-effective, and environmentally sustainable asphalt mixtures. Moreover, the BMD framework will enable the incorporation of innovative practices and technologies with promising performance prospects.

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APPENDIX A

VOLUMETRIC PROPERTIES AND GRADATIONS

Table A1. Volumetric Properties and Gradation for APT Mixtures During Production—Sample A

Mixture ID	**30_C**	**30_O**	**45_HR**	**45_HR_RA**	**45_HR_L**	**60_HR_L_RA**
Description	Non-BMD	BMD	BMD HRAP	BMD HRAP	BMD HRAP	BMD HRAP
Composition						
RAP Content, %	30	30	45	45	45	60
Asphalt Binder	PG64S-22	PG64S-22	PG64S-22	PG64S-22	PG58-28	PG58-28
Additives	WMA	WMA	WMA	WMA + RA	WMA	WMA + RA
Property						
N_{design}, gyrations	50	50	50	50	50	50
NMAS, mm	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.47	6.12	6.72	6.19	5.97	5.89
Rice SG (G_{mm})	2.545	2.524	2.506	2.541	2.536	2.550
VTM, %	4.6	5.4	0.8	2.1	2.0	1.4
VMA, %	17.1	19.1	16.4	16.4	16.0	15.0
VFA, %	72.9	71.7	95.3	87.5	87.7	90.4
FA Ratio	1.07	1.05	1.12	1.47	1.24	1.39
Mixture Bulk SG (G_{mb})	2.427	2.387	2.487	2.489	2.486	2.514
Aggregate Effective SG (G_{se})	2.781	2.788	2.795	2.814	2.795	2.810
Aggregate Bulk SG (G_{sb})	2.767	2.772	2.774	2.794	2.783	2.784
Absorbed Asphalt Content (P_{ba}), %	0.19	0.21	0.28	0.26	0.16	0.34
Effective Asphalt Content (P_{be}), %	5.29	5.92	6.45	5.94	5.82	5.56
Effective Film Thickness (F_{be}), µm	9.4	10.9	10.9	8.6	9.5	8.4
Gradation / Sieve Size	**% Passing**					
¾ in (19.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0
½ in (12.5 mm)	99.4	100.0	97.2	99.3	98.8	99.6
3/8 in (9.5 mm)	94.5	95.9	90.8	95.4	93.2	94.3
No. 4 (4.75 mm)	64.7	66.8	59.2	68.6	61.3	65.0
No. 8 (2.36 mm)	39.9	41.5	37.7	43.8	40.6	42.7
No. 16 (1.18 mm)	29.1	25.5	24.7	28.6	27.5	29.7
No. 30 (600 µm)	22.9	16.7	17.7	20.5	20.1	21.9
No. 50 (300 µm)	13.5	11.1	12.7	14.4	13.7	15.4
No. 100 (150 µm)	8.0	8.1	9.5	10.9	9.5	10.6
No. 200 (75 µm)	5.7	6.2	7.2	8.7	7.2	7.7

APT = Accelerated Pavement Testing; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; BMD = Balanced Mix Design; HRAP = High Reclaimed Asphalt Pavement; S = Standard Traffic; WMA = Warm Mix Additives; NMAS = Nominal Maximum Aggregate Size; SG = Specific Gravity; VTM = Voids in Total Mixture; VMA = Voids in Mineral Aggregate; VFA = Voids Filled with Asphalt; FA = Fines to Aggregate.

Table A2. Volumetric Properties and Gradation for APT Mixtures During Production—Sample C

Mixture ID	30_C	30_O	45_HR	45_HR_RA	45_HR_L	60_HR_L_RA
Description	Non-BMD	BMD	BMD HRAP	BMD HRAP	BMD HRAP	BMD HRAP
Composition						
RAP Content, %	30	30	45	45	45	60
Asphalt Binder	PG64S-22	PG64S-22	PG64S-22	PG64S-22	PG58-28	PG58-28
Additives	WMA	WMA	WMA	WMA + RA	WMA	WMA + RA
Property						
N_{design}, gyrations	50	50	50	50	50	50
NMAS, mm	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.76	6.09	7.11	6.34	6.16	5.88
Rice SG (G_{mm})	2.538	2.529	2.508	2.541	2.533	2.546
VTM, %	4.0	5.9	0.6	2.6	2.6	2.4
VMA, %	17.2	19.5	17.2	17.3	17.0	15.8
VFA, %	77.0	69.8	96.4	84.7	84.8	84.6
FA Ratio	1.03	1.01	1.19	1.23	1.20	1.33
Mixture Bulk SG (G_{mb})	2.437	2.380	2.492	2.474	2.467	2.483
Aggregate Effective SG (G_{se})	2.787	2.792	2.817	2.821	2.801	2.803
Aggregate Bulk SG (G_{sb})	2.773	2.776	2.796	2.801	2.789	2.777
Absorbed Asphalt Content (P_{ba}), %	0.19	0.21	0.27	0.26	0.16	0.34
Effective Asphalt Content (P_{be}), %	5.58	5.89	6.85	6.10	6.01	5.56
Effective Film Thickness (F_{be}), µm	9.7	11.4	10.6	9.9	9.9	8.7
Gradation / Sieve Size	**% Passing**					
¾ in (19.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0
½ in (12.5 mm)	100.0	99.5	98.7	99.0	99.3	98.5
3/8 in (9.5 mm)	96.3	94.2	93.2	95.0	93.0	93.2
No. 4 (4.75 mm)	67.3	65.1	63.3	68.0	62.2	65.4
No. 8 (2.36 mm)	41.5	40.1	40.5	43.3	41.5	43.0
No. 16 (1.18 mm)	30.3	24.1	26.7	27.3	27.5	29.0
No. 30 (600 µm)	24.1	15.8	19.0	18.6	19.2	20.8
No. 50 (300 µm)	14.1	10.5	13.7	12.9	12.9	14.3
No. 100 (150 µm)	8.1	7.6	10.3	9.5	9.3	9.9
No. 200 (75 µm)	5.7	5.9	8.2	7.5	7.2	7.4

APT = Accelerated Pavement Testing; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; BMD = Balanced Mix Design; HRAP = High Reclaimed Asphalt Pavement; S = Standard Traffic; WMA = Warm Mix Additives; NMAS = Nominal Maximum Aggregate Size; SG = Specific Gravity; VTM = Voids in Total Mixture; VMA = Voids in Mineral Aggregate; VFA = Voids Filled with Asphalt; FA = Fines to Aggregate.

Table A3. Volumetric Properties and Gradation for APT Mixtures During Production—Sample D

Mixture ID	**30_C**	**30_O**	**45_HR**	**45_HR_RA**	**45_HR_L**	**60_HR_L_RA**
Description	Non-BMD	BMD	BMD HRAP	BMD HRAP	BMD HRAP	BMD HRAP
Composition						
RAP Content, %	30	30	45	45	45	60
Asphalt Binder	PG64S-22	PG64S-22	PG64S-22	PG64S-22	PG58-28	PG58-28
Additives	WMA	WMA	WMA	WMA + RA	WMA	WMA + RA
Property						
N_{design}, gyrations	50	50	50	50	50	50
NMAS, mm	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.39	5.97	6.97	6.21	6.02	5.90
Rice SG (G_{mm})	2.546	2.523	2.510	2.535	2.537	2.542
VTM, %	4.4	5.4	0.6	2.3	3.0	2.2
VMA, %	16.7	18.8	16.9	16.7	17.0	15.7
VFA, %	73.6	71.1	96.4	86.0	82.3	85.9
FA Ratio	1.08	1.12	1.21	1.27	1.20	1.39
Mixture Bulk SG (G_{mb})	2.433	2.386	2.495	2.476	2.460	2.485
Aggregate Effective SG (G_{se})	2.779	2.778	2.813	2.806	2.799	2.799
Aggregate Bulk SG (G_{sb})	2.765	2.762	2.792	2.786	2.787	2.773
Absorbed Asphalt Content (P_{ba}), %	0.19	0.21	0.28	0.26	0.16	0.34
Effective Asphalt Content (P_{be}), %	5.21	5.77	6.71	5.96	5.87	5.58
Effective Film Thickness (F_{be}), µm	9.3	10.7	10.1	9.6	10.0	8.6
Gradation / Sieve Size	**% Passing**					
¾ in (19.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0
½ in (12.5 mm)	99.5	99.6	99.4	98.9	98.4	98.6
3/8 in (9.5 mm)	93.8	94.8	95.0	95.0	92.7	93.5
No. 4 (4.75 mm)	62.4	64.4	66.1	66.9	61.6	65.9
No. 8 (2.36 mm)	38.8	40.6	43.4	42.8	39.6	43.8
No. 16 (1.18 mm)	28.8	24.6	29.2	27.3	25.8	29.0
No. 30 (600 µm)	23.2	16.1	20.8	18.7	18.2	20.4
No. 50 (300 µm)	13.7	10.8	14.6	12.8	12.5	14.0
No. 100 (150 µm)	7.9	8.0	10.7	9.5	9.0	10.0
No. 200 (75 µm)	5.6	6.4	8.1	7.6	7.0	7.7

APT = Accelerated Pavement Testing; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; BMD = Balanced Mix Design; HRAP = High Reclaimed Asphalt Pavement; S = Standard Traffic; WMA = Warm Mix Additives; NMAS = Nominal Maximum Aggregate Size; SG = Specific Gravity; VTM = Voids in Total Mixture; VMA = Voids in Mineral Aggregate; VFA = Voids Filled with Asphalt; FA = Fines to Aggregate.

APPENDIX B

ACCELERATED PAVEMENT TESTING RUTTING AND CRACKING EXPERIMENTS

Table B1. Summary of Paving Dates and Testing Timeline for Rutting Experiment

Test ID	Paving Date	Test Period		Loading		
		Start	End	Speed	# of passes	# of ESALs
30_C_R1	10/20/2020	06/22/2021	08/13/2021	6 mph	182,605	479,170
30_C_R2	10/20/2020	09/13/2022	10/17/2022	6 mph	136,422	589,261
30_O_R1	04/29/2020	06/10/2020	07/30/2020	4 mph	116,199	476,737
30_O_R2	04/29/2020	08/03/2020	10/02/2020	4 mph	134,378	505,751
45_HR_R1	07/15/2020	10/29/2020	12/19/2020	4 mph	135,411	256,075
45_HR_R2	07/15/2020	04/18/2022	05/09/2022	6 mph	110,664	374,457
45_HR_RA_R1	07/17/2020	08/20/2021	09/30/2021	6 mph	136,912	590,851
45_HR_RA_R2	07/17/2020	05/16/2022	06/11/2022	6 mph	132,439	527,431
45_HR_L_R1	10/22/2020	11/08/2021	12/08/2021	6 mph	130,645	516,337
45_HR_L_R2	10/22/2020	07/28/2022	08/25/2022	6 mph	130,358	530,659
60_HR_L_RA_R1	10/23/2020	10/13/2021	11/03/2021	6 mph	122,395	483,630
60_HR_L_RA_R2	10/23/2020	06/21/2022	07/22/2022	6 mph	132,661	550,435

R1 = Rutting Cell_1; R2 = Rutting Cell_2; # = Number; ESALs = Equivalent Single Axle Loads; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade.

Table B2. Regression Coefficients and Statistical Analysis of Empirical Rutting Model

Mixture / Cell ID	α	β_1	β_2	R^2	$R^2_{adjusted}$
30_C	13.171	0.170	-0.475	0.9791	0.9784
30_O_R1	0.410	0.269	-0.143	0.9900	0.9892
30_O_R2	4.256	0.194	-0.375	0.9934	0.9930
45_HR	3.810	0.237	-0.253	0.9500	0.9478
45_HR_RA	20.229	0.179	-0.495	0.9851	0.9845
45_HR_L	1.578	0.215	-0.169	0.9661	0.9641
60_HR_L_RA_R1	2.203	0.130	-0.137	0.9810	0.9772
60_HR_L_RA_R2	0.120	0.437	-0.175	0.9851	0.9835

C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade; R1 and R2 = Rutting Test Cells.

Table B3. Summary of Paving Dates and Testing Timeline for Cracking Experiment

Test ID	Paving Date	Cracking Experiment		Loading		
		Start Date	End Date	Speed	# of passes	# of ESALs
30_C	10/20/2020	01/05/2022	02/21/2022	6 mph	333,394	2,885,258
30_O	04/29/2020	02/28/2022	04/11/2022	6 mph	368,198	3,146,634
45_HR	07/15/2020	01/13/2021	03/25/2021	4 mph	350,434	2,994,822
45_HR_RA	07/17/2020	03/29/2021	06/14/2021	4 then 6 mph	323,876	2,767,856
45_HR_L	10/22/2020	11/07/2022	12/22/2022	6 mph	335,882	2,870,460
60_HR_L_RA_C1	10/23/2020	01/17/2023	02/18/2023	6 mph	284,488	2,431,245
60_HR_L_RA_C2	10/23/2020	02/28/2023	04/10/2023	6 mph	228,753	1,954,932

C1 = Cracking Cell_1; C2 = Cracking Cell_2; # = Number; ESALs = Equivalent Single Axle Loads; C = Control; O = Optimized; HR = High Reclaimed Asphalt Pavement; RA = Recycling Agent; L = Softer Virgin Binder Grade.