Modifying Existing Asphalt Mix Design Procedures for RAP/RAS Surface Mixtures

NCDOT Project 2021-06
FHWA/NC/2021-06
August 2023

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RESEARCH &
DEVELOPMENT

Technical Documentation Page

1. Report No.
FHWA/NC2021-06

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Modifying Existing Asphalt Mix Design Procedures for RAP/RAS Surface Mixtures

5. Report Date
August 2023

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.
None

9. Performing Organization Name and Address
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10. Work Unit No. (TRAIS)

11. Contract or Grant No.
NCDOT RP 2021-06

12. Sponsoring Agency Name and Address
North Carolina Department of Transportation
Research and Development Unit
1549 Mail Service Center
Raleigh, North Carolina 27699-1549

13. Type of Report and Period Covered
Final Report
January 1, 2021 – August 15, 2023

14. Sponsoring Agency Code
RP 2021-06

Supplementary Notes:

16. Abstract

The NCDOT mixture design procedure assumes 100 percent of the binder contained within reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) is available for blending with virgin asphalt. However, the literature shows that this assumption is flawed due to the presence of recycled asphalt material (RAM) agglomerations that prevent complete recycled binder availability (RBA). As a result, RAM mixtures designed using current practices may suffer from an inadequate amount of virgin asphalt, rendering them susceptible to cracking. Furthermore, past research highlights significant variability in the rheological properties of RAP and RAS stockpiles across North Carolina. Correspondingly, the objectives of this study were to: (1) modify the NCDOT's procedures for the design of surface mixtures containing RAP and RAS to improve performance, and (2) modify the NCDOT's current specifications to improve the consistency of RAP and RAS mixtures. To meet these objectives, a literature review was conducted that identified two approaches for addressing partial RBA in mixture design: the corrected optimum asphalt content (COAC) method specified by Georgia DOT and the availability adjusted mixture design method (AAMD) developed in NCDOT RP 2019-21. A review of plant operations was conducted to identify the range of RAP and RAS management and characterization processes in the state and select six plants to include in the experimental plan. 'Control' mixture designs were then identified from each of the selected plants for evaluation. The control mixtures correspond to approved Job Mix Formulas (JMFs) and thus, reflect mixture designs prepared according to current NCDOT practices. The control mixture designs were redesigned according to the COAC and AAMD approaches. The performance of the control and redesigned mixtures were evaluated through laboratory testing and pavement performance simulations. The COAC and AAMD methods produced mixtures with enhanced cracking performance compared to control mixtures. The COAC approach yielded negative consequences on asphalt mixture rutting susceptibility compared to the current practice. In contrast, the AAMD method, which addresses the role of RAM agglomerations on both RBA and aggregate structure, resulted in rut depths similar to the respective control mixtures for mixtures prepared with fixed RAP content. Consequently, the research team recommends that the NCDOT consider adopting the AAMD method for designing surface mixtures.

17. Key Words
Asphalt, recycling, reclaimed asphalt pavement, recycled asphalt shingles, mixture design

18. Distribution Statement

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
123

22. Price
... ...

Disclaimer

Acknowledgments

The research team would like to express their gratitude and appreciation to the North Carolina Department of Transportation (NCDOT) for the provided funding needed to conclude this research study. The research team also sincerely thanks the contractors who participated in the operational review and supplied the study materials. The research team is grateful to Ernie Song for help acquiring the study materials. The research team also appreciates the efforts of Jaime Preciado and Pablo Vestena for completing a portion of the Asphalt Mixture Performance Tester experiments.

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EXECUTIVE SUMMARY

The current mixture design procedure employed by the NCDOT is predominately based on research conducted during the 1990s under the Strategic Highway Research Program (SHRP), a time when the use of recycled asphalt material (RAM) was not widespread. Recycled asphalt binders are generally hardened and brittle due to oxidization. Furthermore, the asphalt binder in RAM is not fully available to blend with virgin materials. Consequently, high recycled content mixtures may be susceptible to cracking unless mixture design procedures incorporate appropriate measures to address these issues.

Several methods have been proposed in the literature to adjust mixture design procedures to account for partial recycled binder availability (RBA). Further research is necessary to assess the effectiveness of these design methods in mitigating the negative impact of RAM on asphalt mixture performance. Furthermore, past research highlights significant variability in the rheological properties of reclaimed asphalt pavement (RAP) and recycled asphalt shingle (RAS) stockpiles across North Carolina. Correspondingly, the objectives of this study were to: (1) modify the NCDOT's procedures for the design of surface mixtures containing RAP and RAS to improve performance, and (2) modify the NCDOT's current specifications to improve the consistency of RAP and RAS mixtures in North Carolina.

To meet these objectives, a literature review was conducted to identify existing methods to incorporate RBA into mixture design procedures and best practices for RAP and RAS management. Two mixture design methods were selected for evaluation based on the literature review: the corrected optimum asphalt content (COAC) method specified by Georgia DOT and the availability adjusted mixture design (AAMD) method developed in NCDOT RP 2019-21.

A review of plant operations was conducted to identify the range of RAP and RAS management and characterization processes in the state. The operational review identified the following factors that vary among asphalt plants in the North Carolina: (1) the number of unprocessed and processed RAP stockpiles, (2) the contractor and equipment for crushing RAM, (3) the time interval between processing of unprocessed RAP, and (4) practices for homogenizing RAM stockpiles.

Six plants were included in the experimental plan that encompasses the range in RAP and RAS stockpiling and processing practices identified through the plant operational review. 'Control' mixture designs were identified from each plant for evaluation. The control mixtures correspond to approved Job Mix Formulas (JMFs) and thus, reflect mixture designs prepared according to current NCDOT practices.

The component materials corresponding to the control mixtures were acquired and the corresponding RAP and RAS materials were characterized. The RAP stockpiles exhibited RBAs ranging from 40 to 61 percent with coarse RAP stockpiles generally having lower RBA than their fine RAP counterparts from the same plant. In contrast, RAS stockpile RBAs were notably lower than those of RAP, measuring at 12 and 31 percent. The RAP binder properties of the stockpiles evaluated displayed significant variability with high-temperature performance grades spanning 85.4°C to 105.4°C and low-temperature performance grades values ranging from -11.5°C to -19.9°C.

Subsequently, alternative mixture designs were prepared on the basis of the measured RBA using the same component materials as the respective control mixtures. Both the COAC and AAMD approaches were evaluated as alternative mixture design methods. The rutting and cracking resistance of the control and alternative mixture designs were evaluated through laboratory performance testing and pavement performance simulations.

The COAC and AAMD methods produced mixtures with enhanced cracking performance compared to control mixtures designed according to current NCDOT protocols. This effect is attributed to the elevated design asphalt content introduced by these methods. The COAC approach yielded negative consequences on asphalt mixture rutting susceptibility, attributed to the higher binder content imparted by the COAC method without adjustment to the aggregate structure. In contrast, the AAMD method, which addresses the role of RAM agglomerations on both RBA and aggregate structure, resulted in rut depths similar to the respective control mixtures for mixtures prepared with fixed RAP content. The changes imparted by the AAMD method were greater for RS9.5C than RS9.5B mixtures. This effect is attributed to the tighter gradation restrictions for RS9.5B mixtures, which limit adjustments to the Voids in Mineral Aggregate (VMA). AAMD-designed 50 percent RAP mixtures exhibited equal or better cracking performance to the control mixtures with lower RAP content and met NCDOT specifications for APA rut depth. Control virgin mixtures matching existing NCDOT JMFs displayed similar gradations to AAMD mixtures but exhibited notably higher available VMAs and binder contents. Consequently, control virgin mixtures demonstrated improved cracking resistance while displaying inferior rutting performance compared to RAM mixtures. In contrast, virgin mixtures and AAMD-designed RAP mixtures prepared with similar available volumetric and effective properties yielded similar cracking performance, suggesting that the AAMD counteracts RAP’s detrimental impact on cracking resistance.

Collectively, the performance measures support the conclusion that the AAMD framework is a rational approach to include RBA within mix design procedures to improve cracking resistance without compromising rutting resistance. On the basis of this conclusion, the research team recommends that the NCDOT consider adopting the AAMD framework for surface mixtures pending verification of the RBA results using asphalt mixtures produced under conditions that better simulate plant production. Furthermore, the research team proposes that the NCDOT allocate resources to assess the implications of specifying the effective recycled binder replacement (RBR) percentage, defined in the AAMD framework, for selecting virgin binders and establishing maximum RAM contents to improve the consistency of RAP and RAS mixtures in the state. To further promote consistency, the research team suggests that the NCDOT explore practical approaches for measuring RAP binder properties given the considerable variability observed in this project.

1. INTRODUCTION

1.1. Overview

1.1.1. Introduction

There is growing interest in utilizing high Recycled Asphalt Material (RAM) contents in surface asphalt mixtures due to the potential economic and environmental benefits. RAM encompasses both Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS). The current mixture design procedure employed by the NCDOT is predominately based on research conducted during the 1990s under the Strategic Highway Research Program (SHRP), a time when the use of RAM was not widespread. Recycled asphalt binders are generally hardened and brittle due to oxidization. Furthermore, the asphalt binder in RAM is not fully available to blend with virgin materials. Consequently, high recycled content mixtures may be susceptible to cracking unless mixture design procedures incorporate appropriate measures to address these issues.

1.1.2. Research Need Definition

The NCDOT mixture design procedure assumes 100 percent of the binder contained within RAP and RAS is available for blending with virgin asphalt. However, the literature shows that this assumption is flawed due to the presence of RAM agglomerations that prevent recycled binder from contacting and blending with virgin asphalt. As a result, RAM mixtures designed using current practices may suffer from an inadequate amount of virgin asphalt, rendering them susceptible to cracking. Several methods have been proposed in the literature to adjust mixture design procedures to account for partial recycled binder availability. Further research is necessary to assess the effectiveness of these design methods in mitigating the negative impact of RAM on asphalt mixture performance. This evaluation will provide valuable insights for refining the NCDOT's mixture design procedures. Furthermore, past research highlights significant variability in the rheological properties of RAP and RAS stockpiles across North Carolina (Khosla et al. 2015). Therefore, it is crucial for this study to encompass a diverse range of RAP and RAS sources, ensuring the generality of the findings. To best achieve reliable performance, the NCDOT specifications should also be revised to improve the consistency of recycled materials within the state.

1.1.3. Research Objectives

The objectives of the proposed research project are to:

(1) Modify the NCDOT’s procedures for the design of surface mixtures containing RAP and RAS to improve performance.
(2) Modify the NCDOT’s current specifications to improve the consistency of RAP and RAS mixtures within North Carolina.

1.2. Summary of the Literature

A comprehensive review of the literature pertaining to this project is presented in Appendix A. A summary of most relevant components of this review is presented below.

1.2.1. Terminology

The literature contains several terms to describe the distribution of recycled binder in RAM sources and asphalt mixtures. Herein, the term recycled binder availability (RBA) is considered an inherent property of a given RAM that reflects the proportion of the total recycled binder that is available to blend with virgin binder in a mixture (Castorena et al. 2022). In contrast, the term recycled binder contribution (RBC) is considered an asphalt mixture property that reflects the proportion of the total recycled binder contained within the virgin binder matrix due to the RBA as well as the interaction between RAM and virgin materials, any additives, and production conditions (Castorena et al. 2022).

1.2.2. Current State Agency Practices to Account for RBA in Mixture Design

Table 1 summarizes the practices of current agencies that assume partial RBA within their mixture design procedures (Epps Martin et al. 2020). Agencies that assume partial recycled binder availability adjust their mixture design procedures by either reducing the inferred RAM asphalt content (%AC), adjusting the RAS bulk specific gravity (G_{sb}), or increasing the virgin asphalt content determined from volumetric mixture design. The increase in virgin asphalt content is specified as a fixed amount or an amount equal to the amount of unavailable recycled binder in the mixture, termed the corrected optimum asphalt content (COAC) approach. Decreasing the credit given to the RAM %AC decreases the interpreted Voids in Mineral Aggregate (VMA) volume and recycled binder replacement (RBR) of a given asphalt mixture.

Table 1. Current State Agency Practices for Recycled Binder Availability

State	DE	IL	GA	TN	NY	OH	SC	KY	LA
RAP Availability (%)	90	100	60	100	100	100	75	100	92
RAS Availability (%)	80	85	--	75	60	60	75	75	--
Adjustment to Mix Design	↓RAM %AC	↓RAS G_{sb}	COAC	↓RAS %AC	↑%AC 0.2%	↓RAS %AC	COAC	COAC	↓RAP %AC

Among all the states that assume partial RBA, GDOT stands out as the only one with a documented basis for their assumed availability value. GDOT conducted initial experiments by blending RAP with virgin aggregate using a laboratory pugmill mixer (Stroup-Gardiner 2016). The pugmill mixer was utilized to preheat the virgin aggregate to an approximate temperature similar to that at an asphalt plant. Following this, room temperature RAP was introduced to the pugmill, and the materials were mixed for one minute. The outcome revealed minimal transfer of RAP binder to the virgin aggregate, suggesting that RAP particles act akin to primed aggregates.

Subsequent investigations involved evaluating the so-called ‘effective’ asphalt contents of RAP stockpiles from various locations across the state. This was achieved by removing RAP asphalt from a particular source using an ignition oven. Virgin binder was then incrementally added to the reclaimed aggregate. The asphalt content that resulted in a mixture visually resembling the original RAP, when heated to the temperature attained during dry mixing at an asphalt plant, was determined as the ‘effective’ RAP asphalt content. On average, the ratio of effective to total asphalt content in the characterized RAP stockpiles was 60 percent. Similar mixing trials between virgin aggregate and RAP were conducted at a drum plant, where limited transfer of RAP binder to virgin aggregate or disruption of RAP particles was observed, thereby corroborating the laboratory pugmill experiments.

GDOT shared their findings with contractors, leading to a mutual decision to initially adopt a RAP binder availability factor of 75 percent. Subsequently, this availability factor was adjusted to the empirically measured value of 60 percent (GDOT SOP 2 2019).

1.2.3. Recycled Binder Availability and Performance-graded Binder Property Measurements in North Carolina

NCDOT RP 2019-21 (Castorena et al. 2022) and other laboratory studies (e.g., Navaro et al. 2012, Bressi et al. 2015) provide compelling evidence that agglomerations of adhered RAP and RAS are the primary inhibitor of RBA in asphalt mixtures, aligning with GDOT findings that RAP particles act as primed rocks. Recycled binder contained within these agglomerations does not come into contact and blend with the virgin binder in asphalt mixtures. Furthermore, cracks in asphalt mixtures propagate around the agglomerations (Pape and Castorena 2022[b], Roberto et al. 2021). In NCDOT RP 2019-21, tracer-based microscopy was used to measure recycled binder contribution in laboratory-mixed, laboratory-compacted samples in a more direct and quantitative way than the methods used by GDOT. These experiments indicate that RAP binder contribution values in North Carolina vary from 50 to 90 percent with an average of around 60 percent, which aligns with the RBA factor adopted by GDOT. Measured RAS binder contribution values were notably lower than those measured for RAP, spanning from 0 to 30 percent. A method to estimate source-specific RAP binder availability using comparative sieve analysis of RAP and recovered RAP aggregate was established that yields good agreement with microscopy measurements of RBC in asphalt mixtures (Pape and Castorena 2022[a]). The ability to predict the RBC in asphalt mixtures using sieve analysis of the RAP indicates that the agglomerations are pre-existing and do not generally form or breakdown during typical laboratory mixing. Also noteworthy, NCDOT RP 2014-05 experimented on nine different RAP stockpiles from across the state and found a large variation in rheological properties with high temperature grades spanning PG 82 to PG 112 (Khosla and Ramoju 2017).

1.2.4. Availability Adjusted Mixture Design (AAMD)

NCDOT RP 2019-21 proposed several changes to mixture design procedures to more directly account for RAM agglomerations and RBA than the methods shown in Table 1, termed Availability Adjusted Mix Design (AAMD) (Castorena et al. 2022, Mocelin and Castorena 2022). AAMD differs from traditional mixture designs in two ways: (1) the RAM gradation (termed the ‘black curve’) rather than the recovered aggregate gradation (termed the ‘white curve’) is used to design the aggregate structure since RAM agglomerates act as black rocks, (2) the unavailable recycled binder bound within agglomerations is considered as part of the bulk aggregate volume when inferring the volumetric composition of the mixture. The changes align with the concept to adjust the inferred RAM binder content as implemented by several state agencies indicated in Table 1 but overcomes a limitation of the current practice by accounting for the effect of the unavailable recycled binder on the inferred bulk specific gravity and corresponding volume of the RAM aggregate.

Including the unavailable binder in the bulk aggregate volume lowers the calculated VMA volume compared to the current practice. The changes to both the interpretation of the RAM gradation and volumetric composition also impact the calculated dust-to-effective binder ratio of a mixture. Collectively, the changes suggest that mixtures designed assuming 100 percent availability may yield an actual VMA that is smaller than the calculated VMA so that the actual VMA may fall below the acceptable limits. NCDOT RP 2019-21 demonstrated that the AAMD method improves the cracking resistance of asphalt mixtures without having a detrimental effect on rutting resistance compared to the current practice for a given RAM content (Castorena et al. 2022). However, only three mixtures were evaluated and thus, the viability of the AAMD approach merits further investigation using a broader set of mixtures.

1.2.5. Summary of Knowledge Gaps and Applications

The literature substantiates the existence of partial RBA in RAP and RAS sources, owing to agglomerated recycled materials that function as 'black rocks.' The recent NCDOT RP 2019-21 introduces methodologies for quantifying RBA and adjusting mixture design procedures to account for RBA and the influence of RAM agglomerations on aggregate structure design. However, the evaluation of the AAMD method, developed in the context of NCDOT RP 2019-21, was restricted to just three mixtures. Previous research highlights considerable variability in the rheological properties of RAP binders and RBA of RAP stockpiles in North Carolina. Consequently, further research is imperative to comprehensively assess the efficacy of the AAMD method in enhancing performance in comparison to current practices. This research should also explore potential strategies to enhance the consistency of RAP and RAS materials within the state.

Moreover, NCDOT RP 2019-21 solely compared the AAMD method against the existing NCDOT practice at fixed RAM contents, without addressing whether the method can yield similar performance to virgin mixtures or facilitate an increase in RAM contents without compromising performance. Furthermore, the AAMD approach has not been contrasted with alternative methods to adjust mixture design for partial RBA. Hence, it is pertinent to evaluate the COAC approach specified by GDOT as a potential alternative to the AAMD method.

1.3. Organization of the Report

This report is composed of six primary sections and eight appendices. Section 1 presents the research needs, objectives, and summarizes the most relevant literature (see Appendix A for the full literature review). Section 2 describes the research methodology, including the study materials and experimental methods. Section 3 presents the research results and findings. Section 4 summarizes the conclusions and recommendations, and Section 5 provides a corresponding implementation and technology transfer plan. Section 6 includes a detailed bibliography for the references cited within the report. Appendix B presents the plant operational review questionnaire and corresponding results that was used to identify asphalt plant practices for stockpiling, processing, and managing RAP and RAS under the current NCDOT specifications. Appendix C presents the detailed sieve analysis procedure used to measure RAM black curves and calculate RAP RBA. Appendix D details how volumetric mixture design equations are amended in the AAMD method. Appendix E presents the black and white curves for all the RAM sources and tables that summarize the stockpile proportions used in each study mixture design. Appendix F contains the results of the statistical analysis of the experimental results. Appendix G presents comparisons between index test and Asphalt Mixture Performance Tester (AMPT) measures of rutting and cracking resistance. Appendix H shows the comparison of Asphalt Pavement Analyzer (APA) rut depths for specimens prepared at four and seven percent air voids for select study mixtures.

2. METHODOLOGY

2.1. Overview

Figure 1 provides an overview of the research approach. A review of plant operations was conducted to identify the range of RAP and RAS management and characterization processes in the state. Six plants were then selected that encompasses the range in RAP and RAS stockpiling and processing practices identified through the plant operational review. ‘Control’ mixture designs were identified from each of the selected plants for evaluation. The control mixtures correspond to approved Job Mix Formulas (JMFs) and thus, reflect mixture designs prepared according to current NCDOT practices. The component materials corresponding to the control mixtures were acquired and the corresponding RAP and RAS materials were characterized. Subsequently, alternative mixture designs were prepared on the basis of the measured RBA using the same component materials as the respective control mixtures. Both the COAC and AAMD approaches were evaluated as alternative mixture design methods. The rutting and cracking resistance of the control and alternative mixture designs were evaluated through laboratory performance testing and pavement performance simulations. The collective results were used to identify changes to NCDOT surface mixture design procedure that improve the performance and consistency of RAP and RAS surface mixtures. Further elaboration on the research methodology is provided in the subsequent sections.

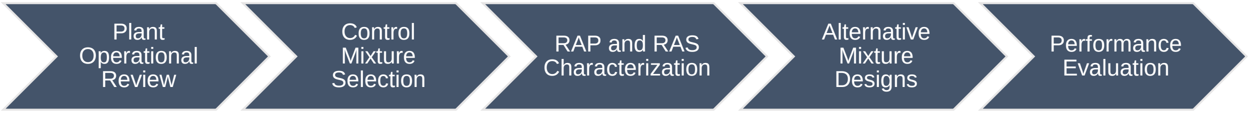


Figure 1. Overview of the research approach.

2.2. Plant Operational Review

Eight asphalt plants were interviewed to identify the range of current practices for RAP and RAS management in North Carolina. The eight plants varied in terms of geographic location, plant type, whether RAS is used or not, and average RAP content used. The operational review covered five topics: (1) general plant information, (2) RAM sources and stockpiling, (3) RAM processing, (4) RAM sampling and testing, and (5) mixture production and silo storage. The results of the plant operational review were used to: (1) identify potential sources of variability in RAP and RAS stockpiles within the state and (2) select the study materials to encompass the range of RAP and RAS management practices. The questionnaire used when interviewing plants and the detailed responses are provided in Appendix B. The eight plants included in the operational review are designated A through H to preserve their anonymity.

2.3. Control Mixture Designs

The control RAM surface mixtures used in this study were selected from existing JMFs approved by the NCDOT. Control virgin mixtures were also included in the experimental plan that use aggregates from the same sources of the respective control mixture, to serve as references without RAM. The control virgin mixtures also coincided with existing JMFs. All control mixtures were verified to meet the specified air void content and minimum VMA when prepared according to the respective JMF and adjusted, if necessary, to bring the mixture into acceptance. It is noted that the Plant A and H virgin mixture JMFs were older than 2018 at which time the

NCDOT specified different design gyration levels (N_{des}) than those currently used (and used in the respective control RAM mixtures). Therefore, the asphalt contents of these mixtures were adjusted to yield four percent air voids at the same N_{des} level as the respective control RAM mixture (i.e., using the more recent N_{des} levels). Table 2 and Table 3 sumamrize the control type B and C surface mixtures, respectively.

Table 2. Summary of the S9.5B and RS9.5B Control Mixtures

Source	**D**		**F**	
Mixture ID	D-0/0-C	D-30/0-C	F-0/0-C	F-40/0-C
Mixture Type	S9.5B	RS9.5B	S9.5B	RS9.5B
RAP (%)	0	30	0	40
RAS (%)	0	0	0	0
RBR (%)	0	23	0	30
Virgin Binder PG	64-22	64-22	64-22	58-28

Table 3. Summary of the S9.5C and RS9.5C Control Mixtures

Source	**A**			**C**		**G**		**H**	
Mixture ID	A-0/0-C	A-30/0-C	A-25/5-C	C-0/0-C	C-20/0-C	G-0/0-C	G-26/5-C	H-0/0-C	H-35/0-C
Mixture Type	S9.5C	RS9.5C	RS9.5C	S9.5C	RS9.5C	S9.5C	RS9.5C	S9.5C	RS9.5C
RAP (%)	0	30	25	0	20	0	26	0	35
RAS (%)	0	0	5	0	0	0	5	0	0
RBR (%)	0	26	43	0	17	0	36	0	28
Virgin Binder PG	64-22	64-22	58-28	64-22	64-22	64-22	58-28	64-22	64-22

2.4. Recycled Asphalt Material Characterization

The RAM stockpiles were characterized prior to preparing the alternative mixture designs. Small RAP and RAS samples were acquired at the time of the operational review and larger samples were obtained at a later date to execute the experimental plan. All characteristics were measured on the materials acquired during the second sampling whereas select properties were also measured on material acquired during the first sampling to provide an indication of stockpile variability.

The asphalt content of each RAM source was determined using the ignition oven, according to AASHTO T 308 (2020). Extraction and recovery of the RAP and RAS binders were performed following ASTM D2172 (2017) and ASTM D5404 (2021). The performance grades (PGs) of the recovered RAP binders were determined according to the guidance in AASHTO M 323 (2021) and the AASHTO M 320 (2021) performance-graded (PG) specification. Continuous grading temperatures were calculated according to ASTM D7643 (2022). Only high- and intermediate-temperature grades were determined for both the first and second samplings. For RAS binders, only high-temperature grades were determined. The RAS binder grades from the materials acquired from the first sampling were determined via direct testing of the RAS binder. However, because it is very difficult to work with RAS binder and grading requires testing at temperatures that exceed those of the typical Dynamic Shear Rheometer (DSR) calibration limits, the RAS binders from the second sampling were determined by testing of blends of virgin binder with recovered RAS binder. The virgin binder used has a continuous high-temperature grade of 62.1°C. An RBR of 0.15 was used for preparing the blends. To prepare the blend, the RAS binder was ground using a mortar and pestle and combined the virgin binder pre-heated to 160°C. Then, a drill was used to mix the system for one minute. The blend was aged in the Rolling Thin Film Oven (RTFO) according to AASHTO T 240 (2021) to ensure uniform dispersion of the RAS binder within the virgin binder and then tested in the DSR. The high-temperature grade of the RAS binders were back-calculated from the blended binder results using the virgin binder continuous grade and blended binder continuous grade, assuming a linear relationship between the continuous grade and RBR in accordance with AASHTO M 323 (2021).

Measurement of the RAM black curves and source-specific RAP RBA followed the methods employed in NCDOT RP 2019-21 (Castorena et al. 2022). The procedure is summarized herein for brevity and the detailed procedure is provided in Appendix C. To implement the method, pre-dried RAP samples were washed according to AASHTO T 11 (2020), dried, and then sieved according to AASHTO T 27 (2020) to find the black curve gradation. The RAP was collected from each sieve, combined and the asphalt was removed according to AASHTO T 308 (2020). The recovered aggregate was collected, and a subsequent washed sieve analysis was performed, incorporating the dust lost during the first washing to yield the white curve gradation. The black and white curve results combined with the RAP asphalt content and aggregate specific gravity are used to calculate the proportion of the mastic in the RAP that is contained within agglomerations and therefore, unavailable, on the basis of differences in the surface area of the RAP and recovered aggregate inferred from the gradation measurements.

Tracer-based microscopy of asphalt mixtures was used to verify that the RBA results from sieve analysis reflect RBC in asphalt mixtures. Tracer-based microscopy was also used to quantify RAS binder availability because a method to determine recycled binder availability directly from RAS does not presently exist. Tracer-based microscopy followed the specimen fabrication and analysis procedure proposed by Pape and Castorena (2021). Laboratory-mixed, laboratory-compacted samples were prepared using a titanium dioxide microparticle tracer with 0.2 micron diameter added to the virgin binder to distinguish it from the recycled binder. The laboratory-mixed samples were prepared using a conventional bucket mixer. Titanium is not naturally present in asphalt whereas sulfur is present in all binders. Measurements of titanium and sulfur are used to quantify the concentration of recycled binder within local regions of the virgin binder matrix of an asphalt mixture using Energy Dispersive X-ray Spectroscopy Scanning Electron Microscopy (EDS-SEM). The ratio of the measured recycled binder concentration to the expected value under the condition of complete availability reflects the recycled binder contribution. EDS-SEM measurements were made at a minimum of 10 locations within each mixture analyzed and averaged.

Tracer-based microscopy was applied to both the RAP and RAP/RAS control mixtures. Tracer-based microscopy of a RAP/RAS mixture yielded a measure of the combined contributions from RAP and RAS in the mixture. The overall mixture recycled binder contribution, expressed in terms of the individual contributions from the RAP and RAS availabilities, is shown in Equation (1). Herein, the RAP and RAS binder contents in a RAP/RAS mixture and the RAP binder availability determined from sieve analysis were input in Equation (1) and used to calculate the RAS binder availability value (i.e., $Availability_{RAS}$) that yields the recycled binder contribution value from tracer-based microscopy. This procedure aligns with the one used to determine RAS availability in NCDOT RP 2019-21 (Castorena et al. 2022). However, Equation (1) was not validated in that project. Therefore, additional RAP only and RAS only mixture designs were identified in the NCDOT's HiCAMS database and followed to prepare additional tracer-based microscopy samples so that the individual RAS and RAP contributions could be directly quantified and compared to the values from the sieve analysis procedure and Equation (1).

$$\text{Recycled Binder Contribution}(\%) = \frac{RAP_{AC} \times Availability_{RAP} + RAS_{AC} \times Availability_{RAS}}{RAP_{AC} + RAS_{AC}} \times 100\% \qquad (1)$$

where: RAP_{AC} = RAP binder content of the mix (i.e., mass of RAP binder/total mass of mix), RAS_{AC} = RAS binder content of the mix, $Availability_{RAP}$ = RAP binder availability, and $Availability_{RAS}$ = RAS binder availability.

All RAM materials were oven-dried at 60°C prior to use. When fabricating asphalt mixture samples, the dried RAM were added to virgin aggregates heated at 10°C above the mixing temperature, mixed, and conditioned in the aggregate oven for 45 minutes. Subsequently, the blend of virgin aggregates and recycled materials were mixed with the virgin binder.

2.5. Alternative Mixture Designs

2.5.1. Overview

Alternative mixture designs were prepared for each of the control RAM mixtures. AAMD designs were prepared for all control RAM mixtures, maintaining the control RAM content. In addition, 50 percent RAP AAMD mixture designs were prepared using the Plant A, C, and H component materials to assess the use of the AAMD method to increase RAP contents without compromising performance. Three control RAM mixtures, two RAP (Plants A and C) and one RAP/RAS (Plant G), were also adjusted using a COAC-based approach. Lastly, additional virgin mixture designs were prepared for select plants (Plants A and F). These so-called comparative virgin mixture designs were prepared using the same virgin aggregate stockpiles as the corresponding control mixture but the stockpile proportions were adjusted to achieve equivalent volumetric properties to the respective AAMD mixtures at control RAP content, when interpreted through the AAMD framework. These virgin mixture designs were prepared to enable a direct assessment of the performance of virgin and RAP containing mixtures that are volumetrically equivalent based on the AAMD method.

A naming convention was adopted to represent each of study mixture, with three sections:

- Section 1: a letter representing the material's source.
- Section 2: the percentages of RAP and RAS in the mix (%RAP/%RAS).
- Section 3: the experimental classification of the mix (C for the control mixtures designed according to current NCDOT procedures; COAC for the mixtures adjusted following the COAC-based approach; AAMD for mixtures redesigned following the AAMD method; or E for the comparative virgin mixtures designed with equivalent properties to the AAMD mixtures with control RAM content).

As an example, the control mixture from Plant A with 30% RAP is named A-30/0-C.

Collectively, the experimental plan yielded a total of 15 alternative mixture designs in addition to the 13 control mixture designs. Table 4 presents a summary of the alternative mixture designs prepared for each corresponding control RAM design. Details pertaining to the alternative mixture design procedures are provided in the subsequent sections.

Table 4. Summary of the Alternative Mixture Designs

Control Designs	Comparative Virgin	AAMD with Control RAM Content	50% RAP AAMD	COAC with Control RAM Content
A-30/0-C	✓	✓	✓	✓
A-25/5-C	-	✓	-	-
C-20/0-C	-	✓	✓	✓
D-30/0-C	-	✓	-	-
F-40/0-C	✓	✓	-	-
G-26/5-C	-	✓	-	✓
H-35/0-C	-	✓	✓	-

2.5.2. COAC Method

The COAC method was applied to adjust select control mixtures as specified by the GDOT SOP 2 (2019), with the exception that the source-specific RBA values were used instead of the fixed value of 60 percent adopted by GDOT. Correspondingly, the Not Credited Asphalt Content (NCAC) of each verified control mixture was calculated by multiplying the mixture's recycled binder content, expressed as a percentage of the total mixture mass, by the quantity of one minus the measured RBA. The virgin binder content of the mixture was then increased by the NCAC to yield a COAC equal to the original optimum asphalt content of the control mixture (OOAC) plus the NCAC.

The COAC method was used to adjust the Plant A and C control RAP mixtures and the control RAP/RAS mixture from Plant G. Notably, the NCAC was substantially higher for the RAP/RAS mixture than the RAP mixtures due to the comparatively low RBA of the RAS. It is important to note that the COAC method does not involve modifications to the gradation, and the adjusted volumetric properties are not evaluated at the altered asphalt content.

2.5.3. AAMD Method

The AAMD method was applied to redesign each control mixture at the same RAM content as the corresponding control mixture and to design three 50 percent RAP mixtures. The AAMD method can be used as a stand-alone mix design method for new mixtures without the need for a prior control mixture design. It can also be used to redesign existing NCDOT mixtures. Figure 2 presents a flowchart of the AAMD method for designing a new mixture.

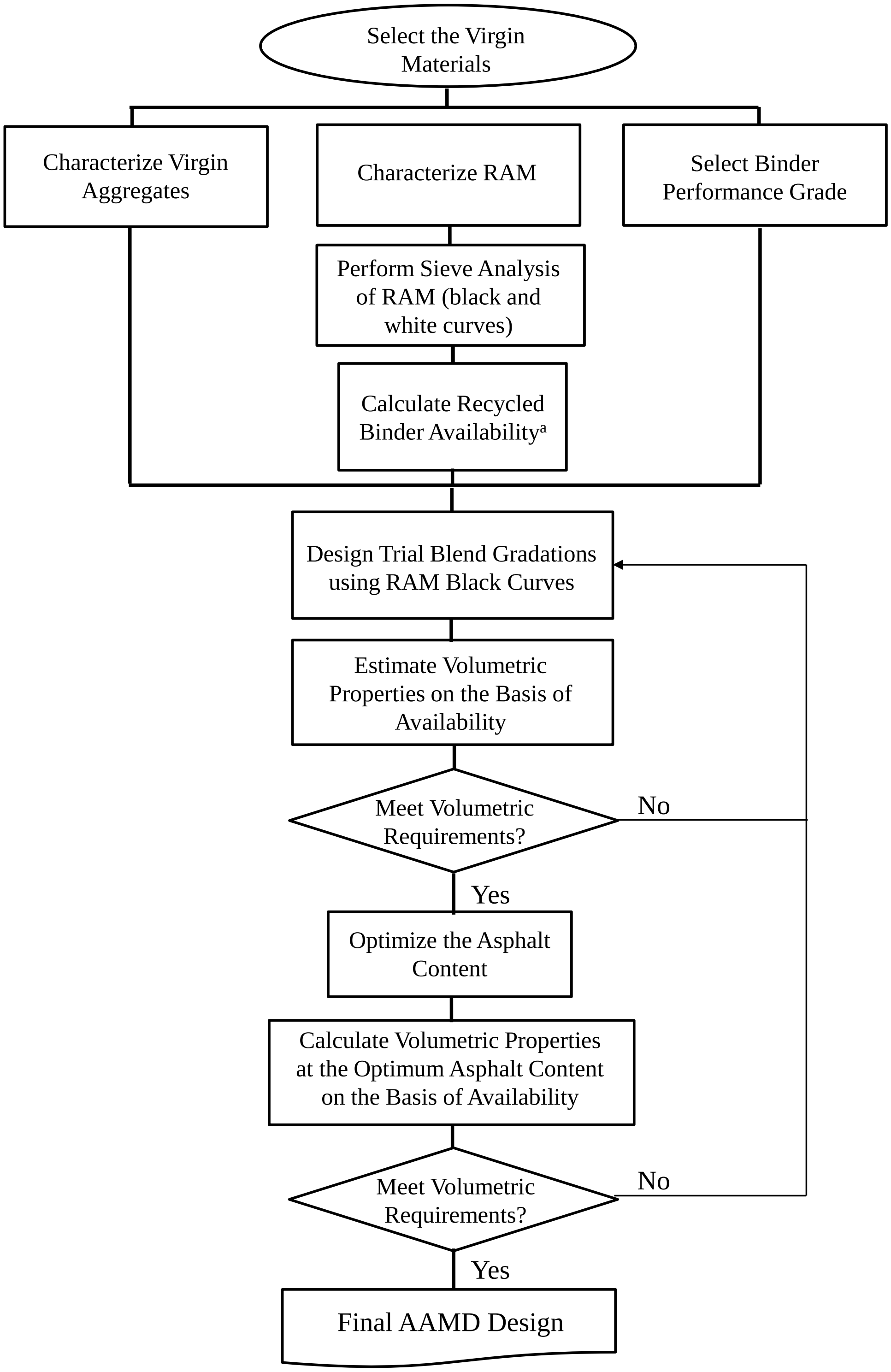
The first step to design a new mixture using the AAMD method is to select and characterize the component materials, similar to conventional volumetric mixture design. Washed sieve analysis is required for the RAM materials before and after ignition, to obtain the black and white gradation curves and the RAM binder content. The RAP and RAS black curves are used for designing the mixture aggregate structure. The white and black curves are also used to calculate the RAP binder availability, according to the sieve analysis method proposed by Pape and Castorena (2022^{a}). A practical method to determine RAS binder availability does not presently exist. Therefore, RAS binder availability can either be assumed or be determined by tracer-based microscopy. RAS binder availability values span from zero to approximately 30 percent based on the tracer-based microscopy study results herein and past studies (Castorena et al. 2022) with an average of approximately 20 percent.

Trial blend gradations are prepared using the RAM black curves and the virgin stockpile gradations that meet specified limits. The black curves are used instead of the white curves because they better represent the actual gradation of RAM materials in the mixture. Adjustment to the interpreted RAM particle size to account for the peripheral mastic coating on the design of aggregate gradations using black curves was evaluated and the adjustment was found to yield negligible differences. Thus, the RAM gradation is used as measured.

Gyratory-compacted samples are prepared at a single asphalt content for each trial gradation according to AASHTO T 312 (2019). The volumetric properties of the compacted specimens are evaluated and used to select a design gradation that is expected to meet volumetric requirements. If none of the trial gradations are deemed satisfactory, additional blends are established and tried. Once an aggregate structure is selected, additional compacted samples are prepared at several asphalt contents according to AASHTO T 312 (2019) and used to identify the optimum asphalt content that yields the desired air void content at the design compaction effort. Volumetric properties are evaluated at the optimum asphalt content, and if any fail, additional trial gradations are prepared and tried.

This general process is consistent with the current NCDOT mixture design procedure. However, the calculation of volumetric properties in AAMD method differs from the conventional method. Therefore, the equations specified in AASHTO R 35 (2017) for calculating the volumetric properties of asphalt mixtures were amended for partial RBA in accordance with the AAMD method and are presented in Appendix D.

Within this report, volumetric properties calculated according to the AAMD method are prefaced with the term ‘available’ or ‘effective’ whereas those calculated according to current NCDOT procedures are prefaced with ‘total’ or ‘specified’.



[a] For RAP the recycled binder availability can be obtained through the comparison of black and white curves (*9*), and for RAS an availability of 20% can be adopted in case tracer-based microscopy is not available.

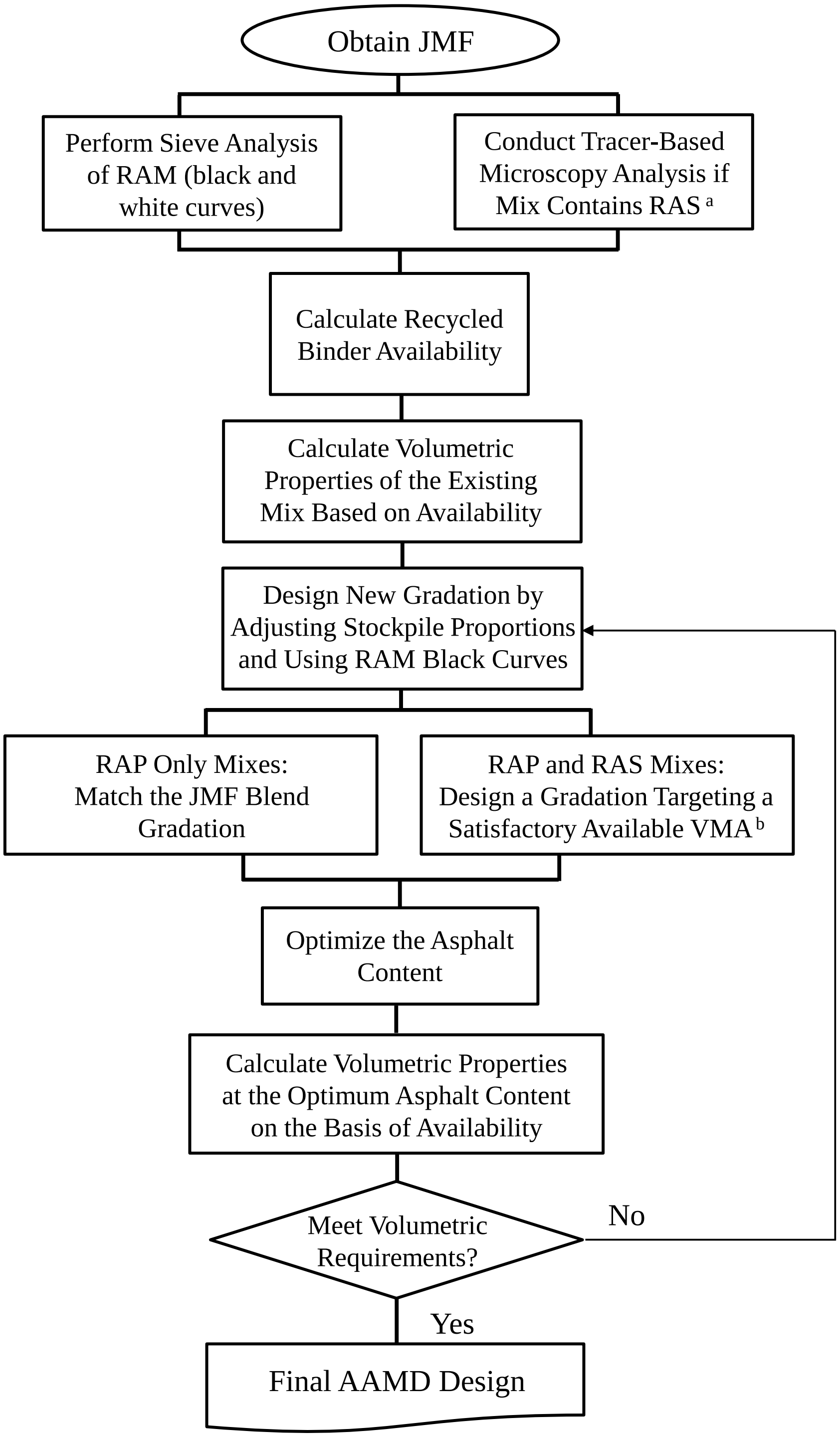
Figure 2. AAMD method flowchart for designing new mixtures.

To redesign an existing JMF using the AAMD method, as done in this project, some simplifications can be made to the framework as shown in the flowchart presented in Figure 3. These simplifications are possible since the original mixture serves as a basis for the redesign. The first step when redesigning a mixture is to characterize the RAM black curve and availability as described above. The white curves, corresponding to the recovered aggregate, are substantially finer than the black curves, corresponding to the RAM itself, due to the presence of agglomerations. The evaluation of this difference results in the determination of the RAP RBA. Once availability and black curve results are obtained, the existing mixture gradation can be evaluated using the RAM black curves and the available VMA of the existing mixture can be calculated according to the changes in volumetric properties interpretation of the AAMD method. This evaluation can guide adjustment to the existing stockpile proportions to yield an aggregate structure that meets gradation requirements and has sufficient available VMA.

Once an aggregate structure has been established, compacted asphalt mixture samples are prepared at four asphalt contents according to AASHTO T 312 (2019) to select the optimum asphalt content that yields the target air void level at the design compaction effort. Volumetric properties are evaluated, including the described adjustments to account for availability. If the volumetric properties meet specifications, the mixture is accepted and if not, alternative gradations must be established and tried until a satisfactory mixture is achieved.

When redesigning RAP-only mixtures herein, the virgin stockpile proportions were adjusted to yield a blend gradation when using the RAP black curve that is close to the existing mixture gradation prepared using the RAP white curve. These adjustments are achieved by decreasing coarse aggregate stockpile proportions and increasing fine stockpile proportions. This approach generally yielded a satisfactory available VMA based on the majority of cases evaluated, often similar to the specified VMA for the control mixture. According to the literature (Vivanco Sala et al. 2022) and verified by analyzing multiple JMFs from different plants in North Carolina, a given asphalt mixture producer often uses similar aggregate structures across mixtures of a given designation. Therefore, the approach followed is thought to reflect how a mixture designer might approach adjusting their current practice if implementing AAMD. For mixtures containing RAS, matching the white curve gradation of the existing mixtures but using the black curves resulted in mixtures with available VMAs below the NCDOT's specified limit. Therefore, further adjustments were made to design a gradation with sufficient available VMA. A summary of the control and AAMD mixture stockpile proportions are given in Appendix E, as well as the black and white curves for all the RAM sources.

The virgin binder used for the AAMD mixtures at the control RAM content was maintained the same as the respective control mixtures to allow more direct performance comparisons, despite the fact that the change in RBR calculations from the AAMD method could lead to a change in the recommended virgin binder according to the NCDOT specifications. The establishment of thresholds for virgin binder selection based the effective RBR merits further research. For the 50 percent RAP content mixtures, the virgin binder selection followed the NCDOT specifications (i.e., based in the total RBR).



[a] An availability of 20% can be adopted for RAS in case the direct measurement is not possible.

[b] The target VMA can be obtained either through methods such as Bailey, or through the designer experience.

Figure 3. AAMD method flowchart for redesigning existing mixtures.

2.5.4. Comparative Virgin Mixtures

The control virgin mixtures were found to have substantially higher VMA and therefore, asphalt content than the respective RAM mixtures. Therefore, virgin mixture designs with equivalent available volumetric properties to the respective AAMD mixtures with the control RAP content were prepared for Plants A and F. These virgin mixture designs were prepared to enable a direct assessment of the performance of virgin and RAP containing mixtures that are volumetrically equivalent according to the AAMD method. This was achieved by adjusting the virgin aggregate stockpile proportions to yield gradations that provided similar available binder content and VMA to the respective AAMD mixture from the same source.

In addition, the virgin binder for the comparative virgin mixtures were selected with AASHTO M 320 high-temperature grades (HPGs) that were very similar to the estimated HPGs of the effective binder matrix in the respective AAMD mixture. The HPGs of the effective binder matrix in the AAMD mixtures were estimated using blending charts under the assumption of complete blending between the available recycled binder and the virgin binder, according to AASHTO M 323 (2021). Equation (2) shows the calculation of the critical temperature of the total binder blend according to AASHTO M 323 (2021) and Equation (3) shows how the equation was amended to align with the AAMD method.

$$\mathrm{T_{blend}} = \mathrm{T_{virgin}} \times (1 - \mathrm{RBR}) + \mathrm{T_{RAP}} \times \mathrm{RBR} \tag{2}$$

$$\text{Available } \mathrm{T_{blend}} = \mathrm{T_{virgin}} \times (1 - \text{Effective RBR}) + \mathrm{T_{RAP}} \times \text{Effective RBR} \tag{3}$$

where: T_{blend} = critical temperature of the total binder blend, T_{virgin} = critical temperature of the virgin asphalt binder, RBR = recycled binder replacement ratio, T_{RAP} = critical temperature of the RAP binder, Available T_{blend} = critical temperature of the available binder blend, and Effective RBR = effective recycled binder replacement ratio, defined in Appendix D.

2.6. Performance Evaluation

Index performance tests, including the Indirect Tension Asphalt Cracking Tests (IDEAL CT) and the APA, were used to evaluate the cracking and rutting performance of all study mixture designs. In addition, AMPT dynamic modulus, cyclic fatigue, and Stress Sweep Rutting (SSR) tests were conducted on select mixture designs to verify the findings from the index tests using more fundamental mechanical tests. The AMPT test results were used within pavement performance simulations to evaluate the effects of the observed material-level differences on simulated pavement structural performance. Table 5 presents a summary of the tests conducted for each of the study mixture design. Additional details on the performance tests and pavement performance simulations are provided in the subsequent sections.

Table 5. Summary of Performance Tests

Control Designs	Control Virgin	Comparative Virgin	Control RAM	AAMD with Control RAM Content	50% RAP AAMD	COAC with Control RAM Content
A-30/0-C	Index & AMPT	Index	Index & AMPT	Index & AMPT	Index & AMPT	Index & AMPT
A-25/5-C	*	-	Index & AMPT	Index	-	-
C-20/0-C	Index	-	Index	Index	Index	Index
D-30/0-C	Index	-	Index	Index	-	-
F-40/0-C	Index	Index	Index	Index	-	-
G-26/5-C	Index & AMPT	-	Index & AMPT	Index & AMPT	-	Index & AMPT
H-35/0-C	Index & AMPT	-	Index & AMPT	Index & AMPT	Index & AMPT	-

*Control virgin mixture for A-25/5-C is the same as for A-30/0-C.

2.6.1. Index Testing

IDEAL CT tests were used to measure the cracking tolerance index (CT_{index}) of all study mixture designs according to ASTM D8225 (2019). A minimum of three test specimens with 150-mm diameter and 62-mm height were fabricated and tested with 7 ± 0.5 percent air voids.

APA tests were used to assess the rutting resistance of all study mixture designs, according to AASHTO T 340 (2019) and NCDOT requirements. The tests were conducted at 64°C on two sets of two specimens for each mixture. The test results are reported as the average rut depth after 8,000 load repetitions. The APA specimens were fabricated with 4 ± 0.5 percent air voids and with 150-mm diameter and 75-mm height, in accordance with the NCDOT requirements (NCDOT 2022). APA testing was also conducted on specimens fabricated with 7 ± 0.5 percent air voids for select mixtures designs from Plants C, D, and H to understand the generality of the findings at 4 percent air voids to other air void levels. The comparison between APA test results obtained at four and seven percent air voids is presented in Appendix H.

One-way analysis of variance (ANOVA) tests were used to support the observations and conclusions of the index test results for all the relevant pairwise comparisons of each mixture source, and are presented in Appendix F.

2.6.2. Asphalt Mixture Performance Tester (AMPT) Testing

AMPT tests were conducted for select mixture designs to evaluate and verify the findings obtained through the index testing using more fundamental tests and accompanying pavement performance simulations. All AMPT test specimens were prepared at 4 ± 0.5 percent air voids. Specimens were fabricated according to AASHTO PP 99 (2019) for dynamic modulus and cyclic fatigue tests and according to AASHO R 83 (2017) for SSR test specimens. Dynamic modulus tests were conducted according to AASHTO TP 132 (2019) and cyclic fatigue tests were conducted according to AASHTO TP 133 (2019). SSR tests were conducted according to AASHTO TP 134 (2019). The SSR test temperatures were selected based on weather stations near the plant from which the materials were sourced.

The apparent damage capacity, S_{app}, and the rutting susceptibility index (RSI) were obtained from the performance testing results analyzed using FlexMAT$^{\text{TM}}$ (v2.1.2) analysis tool. The S_{app} parameter indicates the fatigue damage capacity of asphalt mixtures and is obtained from collective dynamic modulus and cyclic fatigue tests and the simplified viscoelastic continuum damage model (S-VECD) (Wang et al. 2020). The S_{app} was calculated at 18°C, aligning with requirements for PG 64-22 climates and the RSI was calculated according to the climate records at the nearest weather station to the respective plant. The RSI parameter indicates the rutting resistance of asphalt mixtures based on the permanent deformation shift model and is obtained from SSR tests (Ghanbari et al. 2022). The AMPT performance index results and their comparisons to the index test results are presented in Appendix G.

2.6.3. Pavement Performance Simulations

The AMPT performance test results allow the simulation of the mixture’s performance within a pavement structure under simulated traffic and climate conditions. Correspondingly, pavement performance predictions were carried out using AASHTO Pavement ME Design v2.6.2.2 and FlexPAVE™ v2.1.6. The Pavement ME software was selected for bottom-up fatigue cracking simulations since it was locally calibrated in North Carolina through the research efforts carried out under the FHWA\NC\2007-07 project (Kim et al. 2011). Furthermore, material-level inputs for Pavement ME can be obtained from dynamic modulus and cyclic fatigue test results. Rutting simulations were carried out using FlexPAVE™ because the SSR test generates the material level inputs for rutting performance predictions in FlexPAVE™ but cannot be used to simulate rutting performance in Pavement ME.

The S-VECD model parameters were used to generate the fatigue cracking material-specific parameters (K_1, K_2, K_3) shown in Equation (4) following the approach used in the FHWA\NC\2007-07 project (Kim et al. 2011) but adjusting for the more recent fatigue failure definition specified in AASHTO TP 133 (2021). It is worth mentioning that the total volumetric properties were used in Equation (5) since this equation was built and calibrated utilizing total volumetric properties and trying the available volumetric properties did not yield a big difference.

$$N_f = 0.00432 \times C \times \beta_{f1} K_1 \left(\frac{1}{\varepsilon_t} \right)^{K_2 \beta_{f2}} \left(\frac{1}{|E^*|} \right)^{K_3 \beta_{f3}} \tag{4}$$

$$C = 10^{4.84\left(\frac{Vbe}{Va+Vbe} - 0.69 \right)} \tag{5}$$

where: N_f = the allowable number of axle load applications, ε_t = tensile strain at critical locations and calculated by the structural response model (in/in), $|E^*|$= dynamic modulus of the AC layer (psi), K_1, K_2, K_3= mix laboratory-derived model coefficients, β_{f1}, β_{f2}, β_{f3}= local mixture calibration factors, V_{be} = effective asphalt content by volume (percent), and V_a= air voids in the AC mixture (percent). The specific material factors used to characterize each evaluated mixture's Pavement ME fatigue model were derived from the respective mixture cyclic fatigue test results and are shown in Table 6.

Table 6. Fatigue Model Coefficients Utilized for Pavement ME Simulations

Mix	Pavement ME AC Fatigue Calculated Model Coefficients		
	K_1	K_2	K_3
A-0/0-C	1.35E+15	6.59E+00	5.60E+00
A-30/0-C	1.67E+06	6.85E+00	4.30E+00
A-30/0-COAC	2.23E+08	6.94E+00	4.72E+00
A-30/0-AAMD	5.04E+07	6.97E+00	4.56E+00
A-50/0-AAMD	3.50E+08	7.13E+00	4.80E+00
G-0/0-C	3.04E+15	6.83E+00	5.81E+00
G-26/5-C	5.32E-02	7.16E+00	3.32E+00
G-26/5-COAC	2.34E+14	7.16E+00	5.83E+00
G-26/5-AAMD	1.48E+09	7.40E+00	5.13E+00
H-0/0-C	7.45E+16	7.25E+00	6.29E+00
H-35/0-C	2.41E+06	7.25E+00	4.60E+00
H-35/0-AAMD	6.10E+08	7.35E+00	4.97E+00
H-50/0-AAMD	1.91E+16	7.36E+00	6.33E+00

Figure 4 depicts the two types of pavement structures used for the pavement performance predictions, designated as ‘thick’ and ‘thin’. Each type of pavement structure was comprised of an asphalt layer, an unbound aggregate base course layer, and a subgrade. The simulations were performed using the mechanical properties of each asphalt mixture evaluated.

Climate data from MERRA climate station 139553, located within the Piedmont region of NC, was used in the simulations had a mean annual air temperature of 16.65ºC and a mean annual precipitation of 119.61 cm. The traffic level for the performance simulations in both Pavement ME and FlexPAVE™ was 30 million ESALs over 20 years since all the evaluated study mixtures were RS9.5C mixtures which are specified for roads with 3 to 30 million design ESALs.

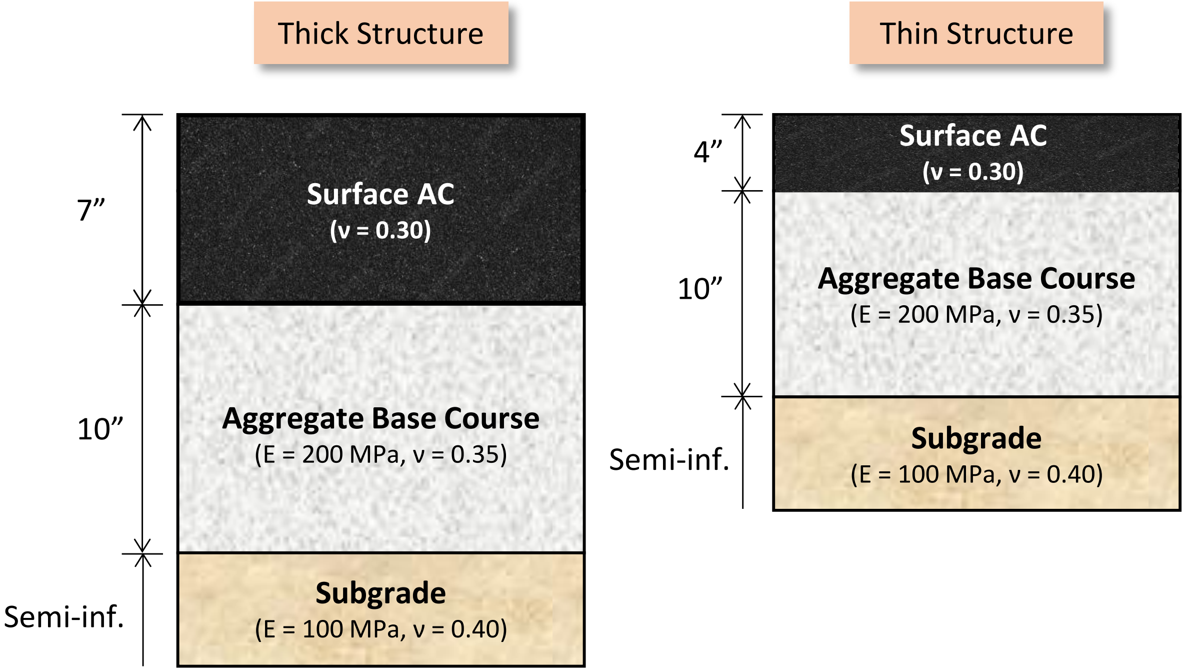


Figure 4. Pavement structures used for Pavement ME and FlexPAVE^{TM} simulations.

3. RESULTS

3.1. Key Insights from the Plant Operational Review

The plant operational review revealed important stockpiling and processing practice differences across plants that may affect the consistency of RAP and RAS materials in North Carolina. Eight plants from different areas in the state were interviewed to account for any potential differences within divisions and regions in the state. Three of the plants use both RAP and RAS whereas the others only use RAP. Detailed operational review results are presented in Appendix B. In summary, the operational review identified the following factors that may affect recycled material consistency in North Carolina:

1. *Number of unprocessed RAP stockpiles*: Some plants only maintained a single unprocessed stockpile whereas others maintained separate unprocessed stockpiles for different sources of RAP, which are combined in prescribed proportions upon processing. For example, one plant maintained separate stockpiles of surface millings and other sources and then combined them at a prescribed ratio of 3:1 upon processing to produce a single processed RAP stockpile.
2. *Number of processed RAP stockpiles*: The plants interviewed maintained one to three processed RAP stockpiles. Plants maintaining two stockpiles separated the RAP into coarse and fine fractions. Plants maintaining three stockpiles separated the RAP into coarse, fine, and a combination of coarse and fine material.
3. *Processing of the recycled material*: The plants interviewed receive services for crushing of RAP from one of two different contractors. The crushing equipment used by the contractors varies and may lead to differences in the extent of agglomeration with the processed RAP material. Two of the three plants that were interviewed that use RAS obtained pre-processed RAS whereas the third processes their RAS on-site.
4. *Time period between processing of unprocessed material*: The frequency of processing and replenishing the processed recycled material stockpiles varied considerably among the interviewed plants, ranging from near continuous replenishment to only one to two times per year.
5. *Stockpile homogenization practices*: Several plants indicated that a loader works the processed recycled material stockpiles daily to homogenize. Another plant indicated that an onsite crusher is occasionally used for homogenization. Others indicated the stockpiles were worked "as needed". Stockpile heights at the plants varied between roughly 20 and 100 feet. Stockpiles were also visually contaminated in two plants. The processed RAP stockpiles from two of the eight plants contained teeth marks, indicating the material was highly consolidated.

Additional variables that may impact the consistency of plant-produced mixtures include the RAP screen size opening in the plant, how the RAP/RAS is taken from the stockpile to the plant, and silo storage time.

Six of the eight plants that were interviewed were selected for inclusion in the experimental plan. These plants were selected to encompass the range of operating conditions identified. Brief justifications are given below for the selected plants:

Plant A is in the Piedmont region and receives RAP crushing services from a different contractor than all other plants, which may influence the extent of RAP particle agglomeration, and in turn, recycled binder availability. Plant A also includes RAS that is pre-processed. Plant A uses a typical average RAP content in their mixtures based on the collective input from the surveyed plants.

Plant C is a RAP only plant in the Coastal region and uses the lowest average RAP content of all of the surveyed plants. Plant C also uses a unique means to combine material from two unprocessed RAP stockpiles (millings and scrap) into a single processed RAP stockpile. In so doing they maintain a crushed millings to scrap pile ratio of 3:1. No other plants indicated such measures to promote homogeneity when combining material from two unprocessed stockpiles. Plant C's processed RAP stockpile had visual teeth marks, indicating it was highly consolidated. Stockpiles were also visually contaminated, which was only observed in two of the eight plants.

Plant D is the only plant interviewed in the Mountain regions and houses a modified batch plant whereas the other selected plants are drum plants. Plant D uses the typical average RAP content (20 to 30 percent) based on the plants interview and does not use RAS.

Plant F is in the Coastal region. It uses the highest average RAP content of all of the surveyed plants and contains a relatively high number of processed RAP stockpiles (3), which may help promote consistency. Plant F does not use RAS.

Plant G is in the Coastal region and uses both RAP and RAS. Plant G was primarily selected due to the fact that it procures and processes RAS differently than Plant A. Plant G stores both unprocessed RAS and receives RAS processing onsite whereas Plant A obtains processed RAS directly from a subcontractor. In addition, the RAS is processed at different time intervals (one to two times per year at Plant G whereas continuously by the subcontractor at Plant A). Processed RAS is also stockpiled for different periods of time (2 months at Plant A versus 6 months at Plant G). Plant G also has RAP stockpiles that were clearly contaminated with sand, which was distinct from the other plants.

Plant H is in the Piedmont region and includes distinct unprocessed RAP stockpiles for everything versus surface millings from only their projects. Plant H maintains a relatively high number of processed RAP stockpiles, including fine, coarse, and a combination. A unique feature at Plant H is that RAP is used almost immediately and therefore, not stockpiled for long whereas the other plants generally stockpile RAP for three to six months.

3.2. Recycled Materials Characterization

Table 7 and Table 8 show the study RAP and RAS properties, respectively. The continuous high-temperature performance grade (HPG), critical intermediate temperature (IT), and asphalt content (AC) were determined from samples acquired during the first and second samplings whereas low-temperature performance grades (LPGs), corresponding delta T critical (ΔT_c) values, and RBA were only quantified using samples from the second sampling. Table 7 shows that the acquired RAP materials used for execution of the experimental plant (i.e., from the second sampling) encompass a broad range in rheological properties (HPGs spanning 85.4°C to 105.4°C and LPGs spanning -11.5°C to -19.9°C) and total asphalt contents (AC) (4.0 to 5.7 percent). The RBA values vary between 43 percent and 61 percent, with fractionated RAP sources showing a notably lower RBA for the coarse stockpile compared to the fine stockpile. Most fine RAP stockpiles exhibit RBA values very close to the 60 percent adopted by GDOT. Also noteworthy, the AC and rheological properties varied substantially between the first and second sampling for a given RAP source. For example, the Plant F coarse RAP stockpile exhibits a 0.8 percent change in the AC content and a 9°C difference in the HPG between the two samples. Table 8 shows that the two binder RAS sources had similar AC contents and HPG values falling between 130°C and 140°C for RAS acquired during the second sampling. The HPG values from the first sampling are notably higher. However, as discussed in Section 2.4, the HPG values for the first sampling were determined from direct testing of the RAS, which is considered less reliable than inferring the HPG from testing of a blend of RAS and virgin binder as was done in the second sampling. The RBA values of RAS are notably lower than RAP. The RBA for the Plant A RAS is notably lower than the Plant G RAS despite similar AC and rheological properties. The RAP and RAS black and white curve gradations are presented in Appendix D.

Table 7. RAP Properties

Plant	Sampling	HPG (°C)	IT (°C)	LPG (°C)	ΔT_c	AC (%)	RBA (%)
A	1	102.1	33.7	--	--	5.2	--
	2	98.6	35.0	-14.9	-3.3	4.7	59
C	1	101.9	34.0	--	--	5.1	--
	2	95.4	33.7	-15.7	-3.8	4.8	56
D	1	96.6	28.8	--	--	5.7	--
	2	85.4	28.9	-19.9	-2.7	4.8	61
F (Coarse)	1	106.7	37.6	--	--	4.1	--
	2	97.7	37.2	-14.0	-1.5	4.9	48
F (Fine)	1	108.3	38.7	--	--	5.3	--
	2	99.1	36.4	-13.1	-0.8	5.6	61
G	1	100.7	35.2	--	--	5.7	--
	2	105.4	38.7	-11.5	-3.5	5.7	47
H (Coarse)	1	95.2	30.8	--	--	4.0	--
	2	98.7	36.7	-14.5	-1.7	4.0	43
H (Fine)	1	94.5	30.3	--	--	5.4	--
	2	96.8	36.9	--	--	5.2	57

Table 8. RAS Properties

Plant	Sampling	HPG	AC (%)	RBA (%)
A	1	173.4	19.7	--
	2	130.1	20.0	12
G	1	154.5	18.7	--
	2	138.8	18.7	31

Figure 5 shows the RBA results from sieve analysis and RBC results from tracer-based microscopy for the RAP materials and RAP mixtures. Results from the current project and past NCDOT RP 2019-21 are shown together. The sieve analysis and tracer-based microscopy results are generally in good agreement and corroborate that complete RBC is unlikely. Figure 6 shows the comparison of the tracer-based microscopy measurements of RBC in RAP, RAP/RAS, and RAS mixtures for Plants A and G. The estimates of RAS RBC calculated using Equation (1) from the collective RAP and RAP/RAS mixture results are also shown. The estimates from Equation (1) are in good agreement with the RBC measurements for the respective RAS-only mixtures. Therefore, the RAS RBC values calculated from Equation (1) are reported as the RAS RBAs in Table 8 and were used when preparing AAMD and COAC mixture designs.

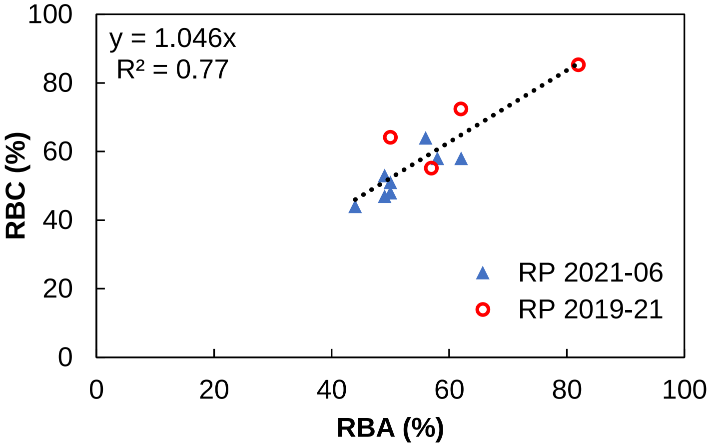


Figure 5. Comparison between RAP RBA and RBC results.

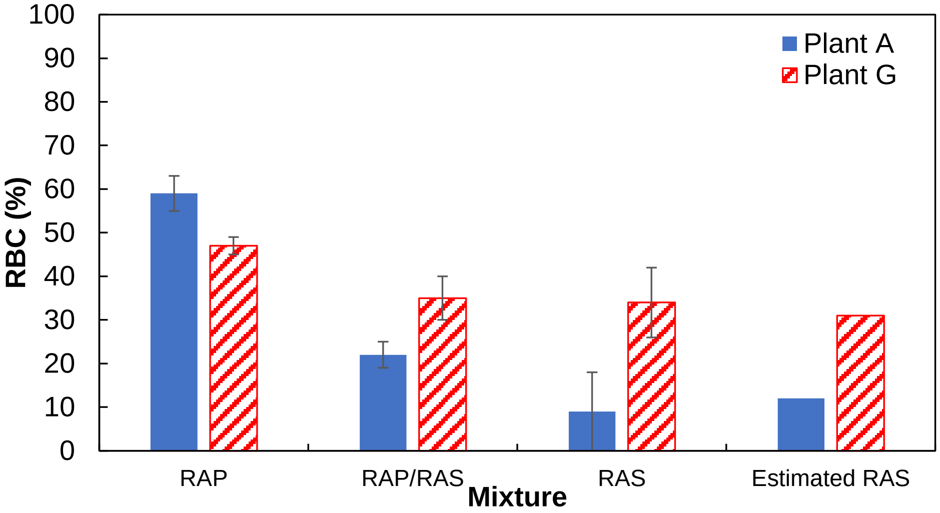


Figure 6. Comparison between RBC measurements and RBC estimates of RAS RBC from Equation (1).

3.3. Evaluation of Alternative Design Methods to Consider Recycled Binder Availability

3.3.1. Comparison of Control, COAC and AAMD Mixture Designs at Fixed RAM Content

Two RAP control mixtures (A-30/0-C and C-20/0-C) and one RAP/RAS control mixture (G-26/5-C) were redesigned using both the COAC and AAMD approaches while maintaining the control mixture RAM content. All of these control mixtures are RS9.5C mixtures. The source-specific RBA values were used within the COAC-based method to adjust the control mixtures' virgin binder content by an amount equal to the unavailable recycled binder content of the respective mixture. In the AAMD method, the virgin stockpile proportions of the control mixture were adjusted to achieve an available VMA close to the specified (i.e., intended) VMA for the respective control mixture.

Figure 7, Figure 8, and Figure 9 present the comparisons between the control and AAMD mixture blend gradations for Plants A, C and G, respectively. Within these and subsequent graphs, the 'black curve' shows the blend gradation that is calculated when using the RAM black curve to reflect its gradation whereas the 'white curve' shows the blend gradation calculated when using the RAM white curve to reflect its gradation. The graphs show that the gradation interpreted using the RAM white curve is finer than the gradation interpreted using the RAM black curve for a given mixture due to the presence of agglomerations of adhered RAM particles.

Figure 7 and Figure 8 show that the control mixture white curves are similar to the corresponding AAMD mixture black curves for Plants A and C, which was intentional to reflect what a mixture designer might do. According to the analysis of different JMFs in North Carolina, a given asphalt mixture producer often uses similar aggregate structures across mixtures of a given designation. Through the research project, this approach was found to generally yield an available VMA in the AAMD mixture that was close to the specified (i.e., intended) VMA of the corresponding control mixture.

Figure 9 shows that the Plant G AAMD black curve is more distinct from the control mixture white curve than those for Plants A and C. For the Plant G case (i.e., RAP/RAS mixture), adjusting the virgin aggregate stockpile proportions to match the specified control mixture gradation when using the RAM black curves yielded an available VMA that fell below the NCDOT's specified limit. Therefore, further adjustment of the virgin stockpile proportions to yield a finer gradation and increase the available VMA was necessary.

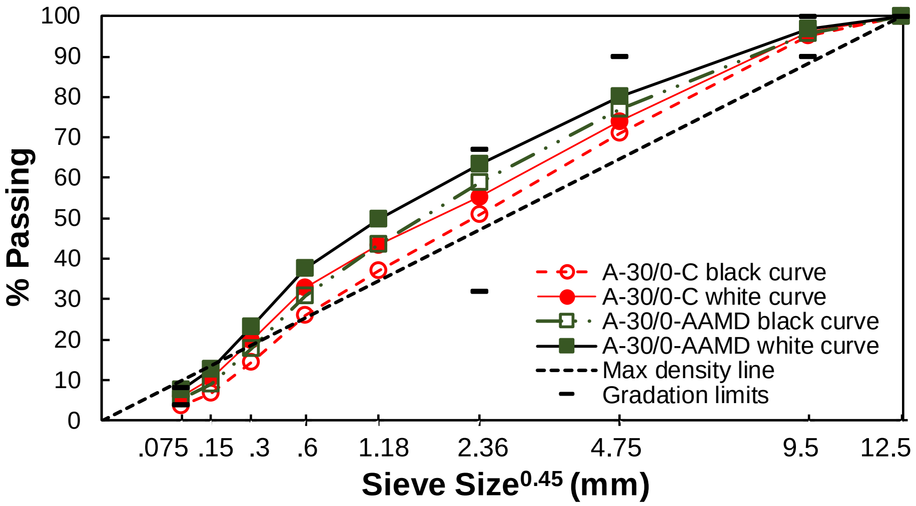


Figure 7. Black and white blend gradations for the Plant A control and AAMD RAP mixtures.

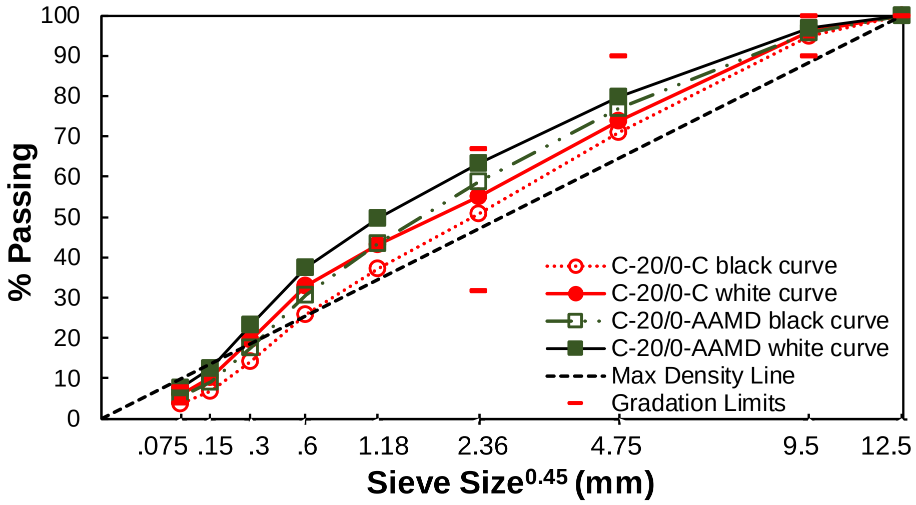


Figure 8. Black and white blend gradations for the Plant C control and AAMD RAP mixtures.

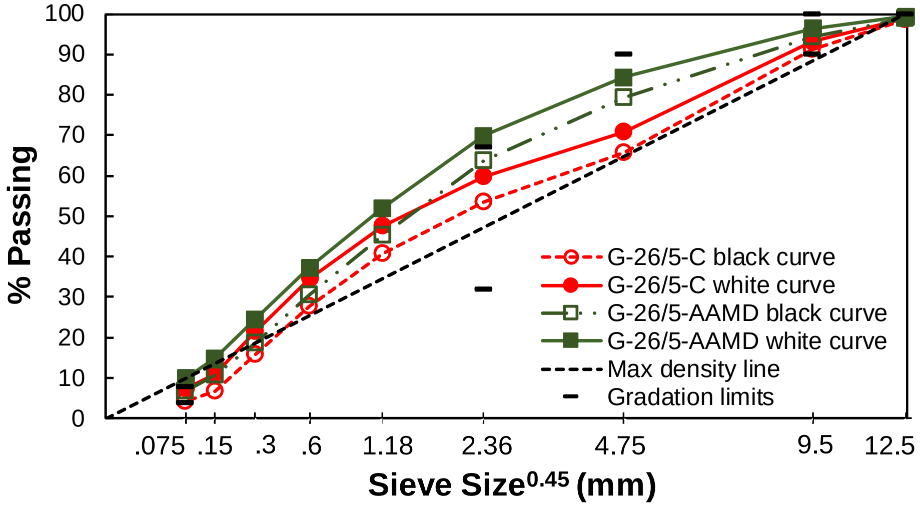


Figure 9. Black and white blend gradations for the Plant G control and AAMD RAP/RAS mixtures.

Table 9 provides a comprehensive breakdown of the composition of the control, AAMD, and COAC mixture designs for the Plant A, C, and G mixtures. The quantities designated as ‘total’ and ‘specified’ correspond to calculations made under the assumption of complete RBA, aligning with the current NCDOT practice. In contrast, the ‘available’ and ‘effective’ quantities align with calculations according to the AAMD method (detailed in Appendix D). The volumetric properties of the COAC mixtures are unknown because design specimens were not fabricated and evaluated at the corrected asphalt content.

Table 9 demonstrates that both the AAMD and COAC methods yield higher asphalt contents for a given control mixture. In the cases of Plant A and C mixtures, both the COAC and AAMD approaches result in similar increases to the virgin asphalt content. In contrast, G-26/5-COAC mixture exhibits a notably higher total binder content compared to the G-26/5-AAMD mixture.

Furthermore, Table 9 underscores the significant impact of discrediting unavailable binder on the interpretation of mixture volumetric properties. The AAMD method results in lower calculated values for RBR, VMA, VFA and DP than those calculated when assuming complete RBA. Notably, the available VMA values for the C-20/0-C and G-26/5-C mixtures fall short of meeting the NCDOT's minimum limit, indicating that these mixtures would be rejected under the AAMD framework. Although the available VMA for A-30/0-C does meet the minimum limit, it approaches the specified limit, which differs from the typical practice of North Carolina contractors who often aim for a higher VMA than the minimum to ensure compliance during plant production.

Table 9. Specified and Available Volumetric Properties for the Plant A, C, and G Mixture Designs at Fixed RAM Content

Mix properties	Plant A			Plant C			Plant G			Spec. limits
	A-30/0-C	A-30/0-AAMD	A-30/0-COAC	C-20/0-C	C-20/0-AAMD	C-20/0-COAC	G-26/5-C	G-26/5-AAMD	G-26/5-COAC	
Total binder content (%)	6.0	6.7	6.6	5.7	6.4	6.5	6.2	6.9	7.6	--
Available binder content (%)	5.4	6.1	6.0	5.3	6.0	5.4	4.7	5.4	6.2	--
Virgin binder content (%)	4.4	5.2	5.1	4.7	5.4	4.1	3.7	4.4	5.1	--
Total RBR (%)	25.9	22.8	23.2	17.3	15.4	37.9	41.0	36.0	40.4	--
Effective RBR (%)	17.1	14.8	15.1	10.5	9.2	25.4	22.0	19.0	15.2	--
Total Binder Blend HPG	75.6	74.7	74.8	72.5	72.0	73.4	84.3	81.6	79.4	--
Available Binder Blend HPG	72.9	72.2	72.3	70.6	70.3	69.0	71.1	69.6	68.5	--
Specified VMA (%)	16.8	17.7	-	15.8	16.9	16.3	17.9	18.2	-	Min. 15.5
Available VMA (%)	15.9	16.9	-	15.3	16.3	15.9	15.4	15.7	-	
Specified VFA (%)	76.1	77.3	-	74.7	76.3	75.4	77.7	78.0	-	65-78
Available VFA (%)	74.9	76.3	-	73.8	75.5	74.9	74.1	74.6	-	
Specified DP	1.08	1.30	-	1.09	1.12	1.54	1.18	1.45	-	0.6-1.4
Available DP	0.71	0.97	-	0.80	0.86	0.78	0.87	1.30	-	

Table 9 also shows that the effective RBR values for RAM mixtures are consistently lower than their corresponding total RBR values. Both total and available HPG values were determined using a linear blending chart based on total and effective RBRs, respectively. It is important to acknowledge that these values are approximations. In the Plant A and C mixtures, that do not contain RAS, the disparity between using total versus effective RBR for blend PG calculations is marginal. In contrast, the effect is more pronounced for Plant G mixtures, which include both RAP and RAS. Despite these variations, all mixtures satisfied the minimum intended high-temperature grade of 64°C based on both total and effective RBR considerations.

Figure 10 presents the IDEAL CT and APA results for the control, AAMD and COAC designs prepared at fixed RAM content for Plants A, C, and G. The error bars in Figure 10 and subsequent graphs represent the standard error of the test results. The outcomes of statistical tests used to evaluate the significance of the observed performance differences among the mixture design alternatives from a given plant are provided in Appendix F. The control mixtures exhibit CT_{index} values that are significantly lower than the respective COAC and AAMD mixtures. In the case of Plant G, the COAC approach yielded a higher CT_{index} than the AAMD method because this approach yielded a much higher asphalt content due to the very low availability of the RAS. In the case of Plants A and C, the COAC and AAMD CT_{index} results are statistically equivalent, likely due to their similar asphalt contents.

All of the mixtures meet the APA rutting depth requirements specified by the NCDOT for RS9.5C mixtures. For Plant C, the control, COAC, and AAMD mixtures all present similar APA rut depths. This result is attributed to the Plant C mixtures’ lower RAP content of 20 percent compared to the Plant A and G mixtures. However, noteworthy differences in the APA test results exist among the Plant A and G mixture design alternatives. Rutting performance test results often show the opposite trend of cracking test results when evaluated with respect to mixture design alternatives. This trend is generally observed when comparing the control and COAC approaches. The A-30/0-COAC mixture has a significantly higher rut depth than the A-30/0-C mixture. Similarly, the G-26/5-COAC mixture has a significantly higher rut depth than the G-26/5-C mixture. In addition, the G-26/5-COAC mixture appeared flushed due to its excessive binder content and thus, may also pose constructability and safety concerns. However, the results demonstrate that while the AAMD method yield improved cracking resistance compared to the respective control RAM mixture, the APA results do not differ significantly among the AAMD and corresponding control mixture designs. While the AAMD mixtures do have notably higher available binder content than the respective control mixtures, the gradation design changes on the basis of the RAM black curves implemented within the AAMD method appear to mitigate negative consequences of this additional binder on mixture rutting resistance.

Collectively, the results suggest that the AAMD method improves cracking resistance without having a detrimental effect on rutting resistance compared to the current practice. While the COAC method also improves cracking resistance, it detrimentally affect the rutting resistance of high RAM content mixtures Moreover, the integration of the COAC method into the NCDOT's existing quality assurance and control procedures poses challenges, particularly regarding VMA controls during production. This is due to the absence of volumetric property measurement at the COAC. Consequently, additional specimen fabrication and evaluation would be necessary to ascertain appropriate VMA requirements, making the COAC approach impractical. Alternatively, VMA requirements during production would need to be omitted. As a result, the COAC approach was not subject to further evaluation, and efforts continued to focus on a more in-depth assessment of the AAMD approach.

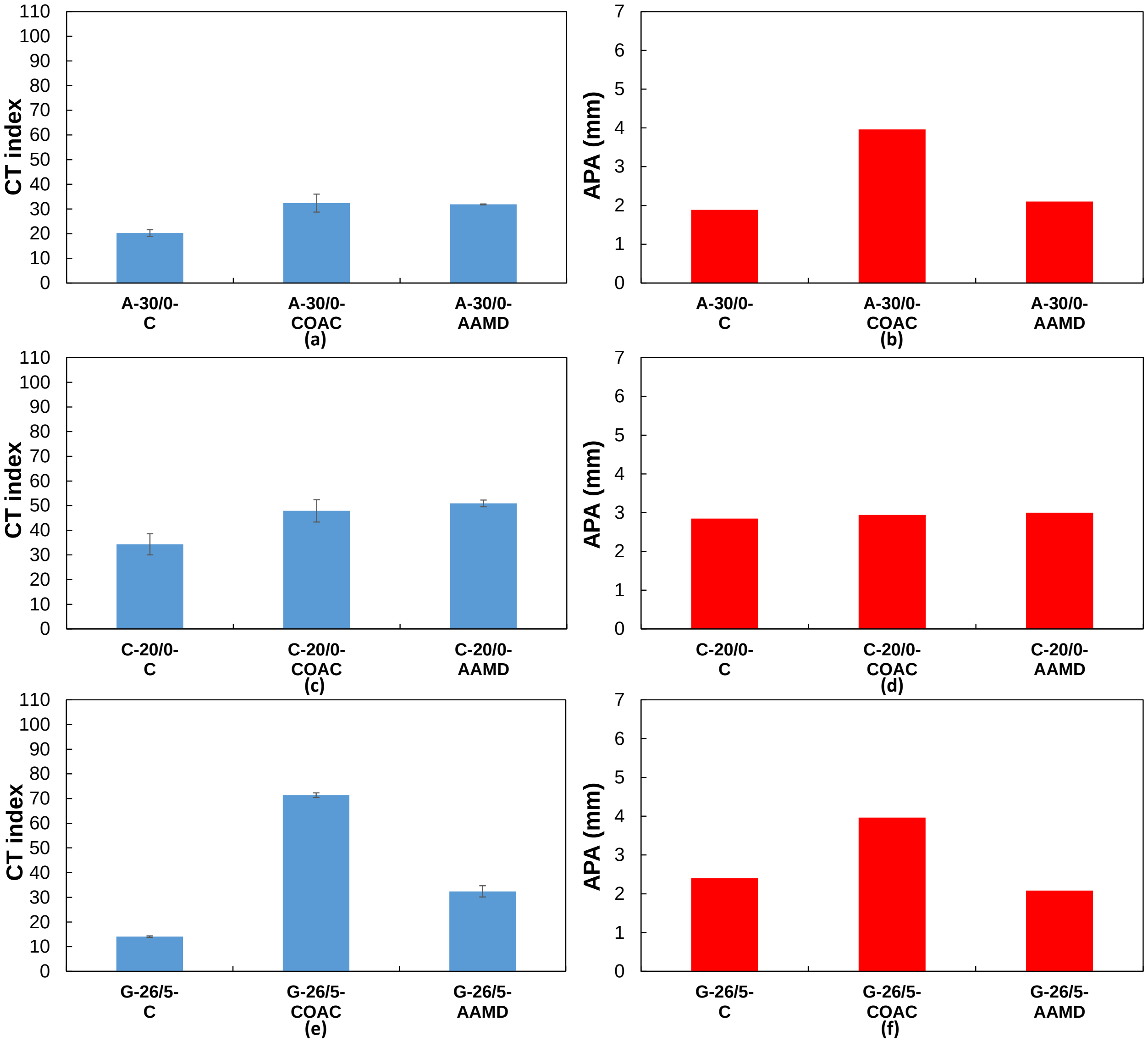
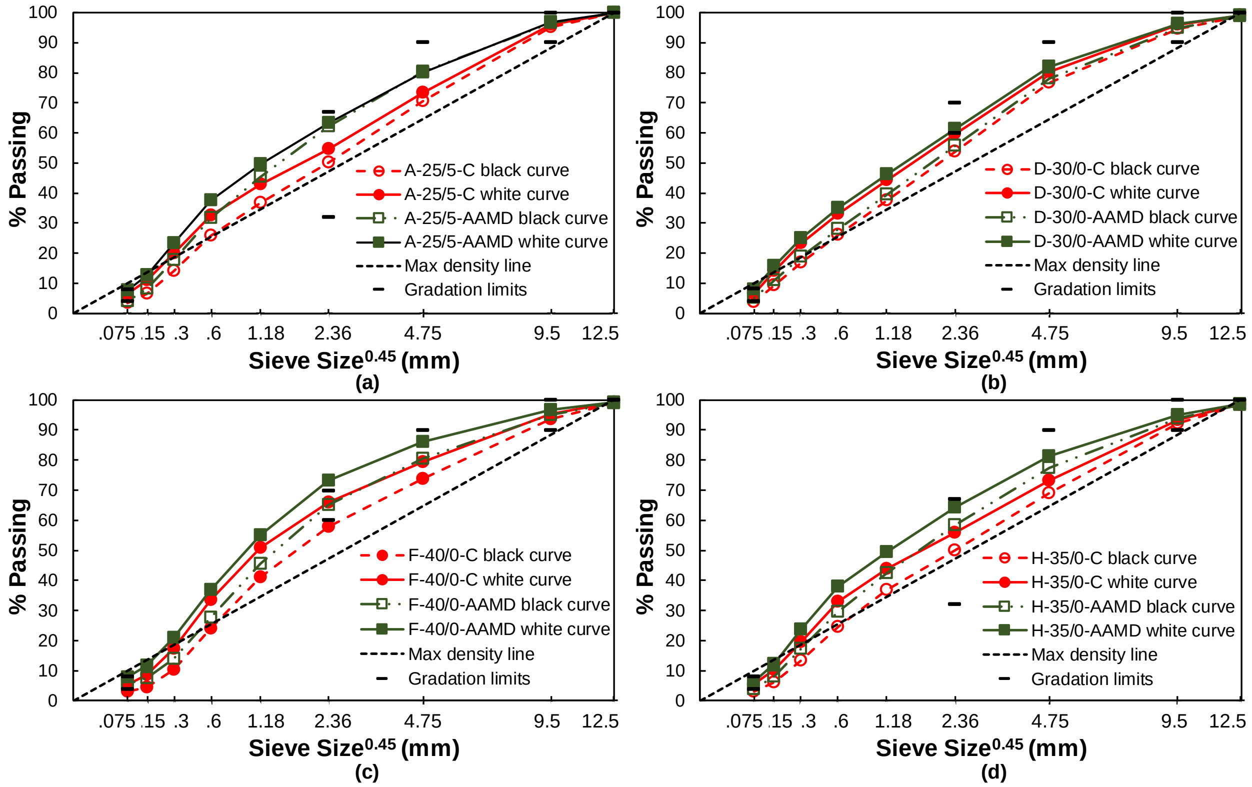


Figure 10. Cracking and rutting index test results for the mixtures at fixed RAM content corresponding to: Plant A ((a) and (b)), Plant C ((c) and (d)), and Plant G ((e) and (f)).

3.3.2. Comparison of Additional Control and AAMD Mixture Designs at Fixed RAM Content

Additional NCDOT-approved control mixture designs were identified from Plants A, D, F, and H. In the case of Plant A, this mixture is also referred to as a control mixture, but represents a different mixture design, from the one described in the preceding section. For each of these control mixtures, an alternative mixture design, using the same RAM content but based on the AAMD design method was also developed. The Plant A and the Plant H mixtures are classified as RS9.5C mixtures like the previously presented mixtures whereas the Plant D and Plant F mixtures are classified as RS9.5B mixtures. Figure 11 shows the blend gradations for the additional Plant A, D, F and H mixtures. Similar to the previously presented results, the AAMD gradations for RAP-only mixtures were prepared by adjusting the virgin stockpile proportions to yield a similar gradation black curve to the respective control mixture white curve gradation. For the Plant A RAP/RAS mixture, a finer AAMD gradation than specified for the control was required to achieve an available VMA that met NCDOT requirements.



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

Figure 11. Black and white blend gradations for: (a) Plant A, (b) Plant D, (c) Plant F, and (d) Plant H control and AAMD mixtures.

Table 10 provides an overview of the specified and available volumetric properties for the supplementary control and AAMD mixture designs obtained from Plants A, D, F, and H. The application of AAMD methodology resulted in enhanced VMA, VFA, and binder contents in the RS9.5C mixtures from Plants A and H. Notably, the volumetric composition displayed only minor variations when comparing RS9.5B control and corresponding AAMD mixture designs from Plants D and F, despite evident gradation differences. This marginal impact on volumetric composition in the RS9.5B mixtures from Plants D and F may be attributed to the stringent constraints set by the NCDOT on the #8 sieve. The #8 sieve is the primary control sieve for the 9.5-mm NMAS mixtures. The influence of the percentage passing the primary control sieve on VMA is well-documented in the literature (Vavrik et al. 2002). Consequently, the relatively minor discrepancies in the percentage passing the #8 sieve between control and AAMD mixtures from Plant D and F, due to NCDOT's gradation specifications, may account for the limited extent of changes observed in the volumetric properties of these mixtures.

Table 10. Specified and Available Volumetric Properties for the Plant A, D, F, and H Control and AAMD Designs Prepared at Fixed RAM Content

Mix properties	Plant A		Plant D		Plant F		Plant H		Spec. limits
	A-25/5-C	A-25/5-AAMD	D-30/0-C	D-30/0-AAMD	F-40/0-C	F-40/0-AAMD	H-35/0-C	H-35/0-AAMD	
Total binder content (%)	5.7	7.3	6.4	6.7	6.6	6.6	6.0	6.7	--
Available binder content (%)	4.2	5.8	5.7	5.9	5.8	5.8	5.2	5.9	--
Virgin binder content (%)	3.2	5.1	4.9	5.2	4.6	4.7	4.3	5.0	--
Total RBR (%)	43.1	30.5	23.0	21.9	29.8	29.7	27.8	24.4	--
Effective RBR (%)	21.8	12.4	13.0	12.1	20.2	19.8	17.3	14.9	--
Total Binder Blend HPG	84.5	78.7	73.9	73.6	72.3	72.3	74.5	73.3	--
Available Binder Blend HPG	68.5	66.1	71.6	71.4	68.8	68.8	71.6	71.0	--
Specified VMA (%)	16.8	19.7	18.0	18.8	17.9	18.2	16.8	18.3	Min. 15.5 (C), 16.0 (B)
Available VMA (%)	13.0	17.1	16.3	17.1	17.0	17.3	15.2	16.7	
Specified VFA (%)	76.2	79.7	77.8	78.7	77.7	78.1	76.2	78.1	65-78 (C), 70-80 (B)
Available VFA (%)	69.3	76.7	75.5	76.6	76.4	76.9	73.6	76.0	
Specified DP	1.19	1.04	1.14	1.09	0.88	1.57	1.02	1.08	0.6-1.4
Available DP	0.86	0.69	0.64	0.87	0.56	1.30	0.66	0.76	

Figure 12 presents the IDEAL CT and APA results for the supplementary control and AAMD mixture designs that have the same RAM contents. Generally, the trends observed align with the earlier findings presented for the Plant A (RAP-only), C, and G scenarios. The AAMD mixtures notably exhibit higher CT_{index} results, while simultaneously achieving APA rut depths that are statistically the same as the corresponding control mixtures. However, an exception is evident for Plant D where the rut depth is significantly higher for the D-30/0-AAMD mixture compared to the D-30/0-C mixture. It is noteworthy, that all mixtures meet the NCDOT specifications for APA rut depth.

The increase in CT_{index} imparted by the AAMD method in the Plant A and H mixtures is attributed to their higher binder contents. Conversely, in Plant D and F instances, both the AAMD and control mixtures have comparable binder contents. However, the Plant D and F control and AAMD mixtures have notably different gradations than the respective control mixtures, which may explain the CT_{index} differences and the increase in rut depth in the case of Plant D. Furthermore, variations in aggregate shape, angularity, and texture, stemming from modifications in virgin stockpile proportions, may have also contributed to the observed performance differences.

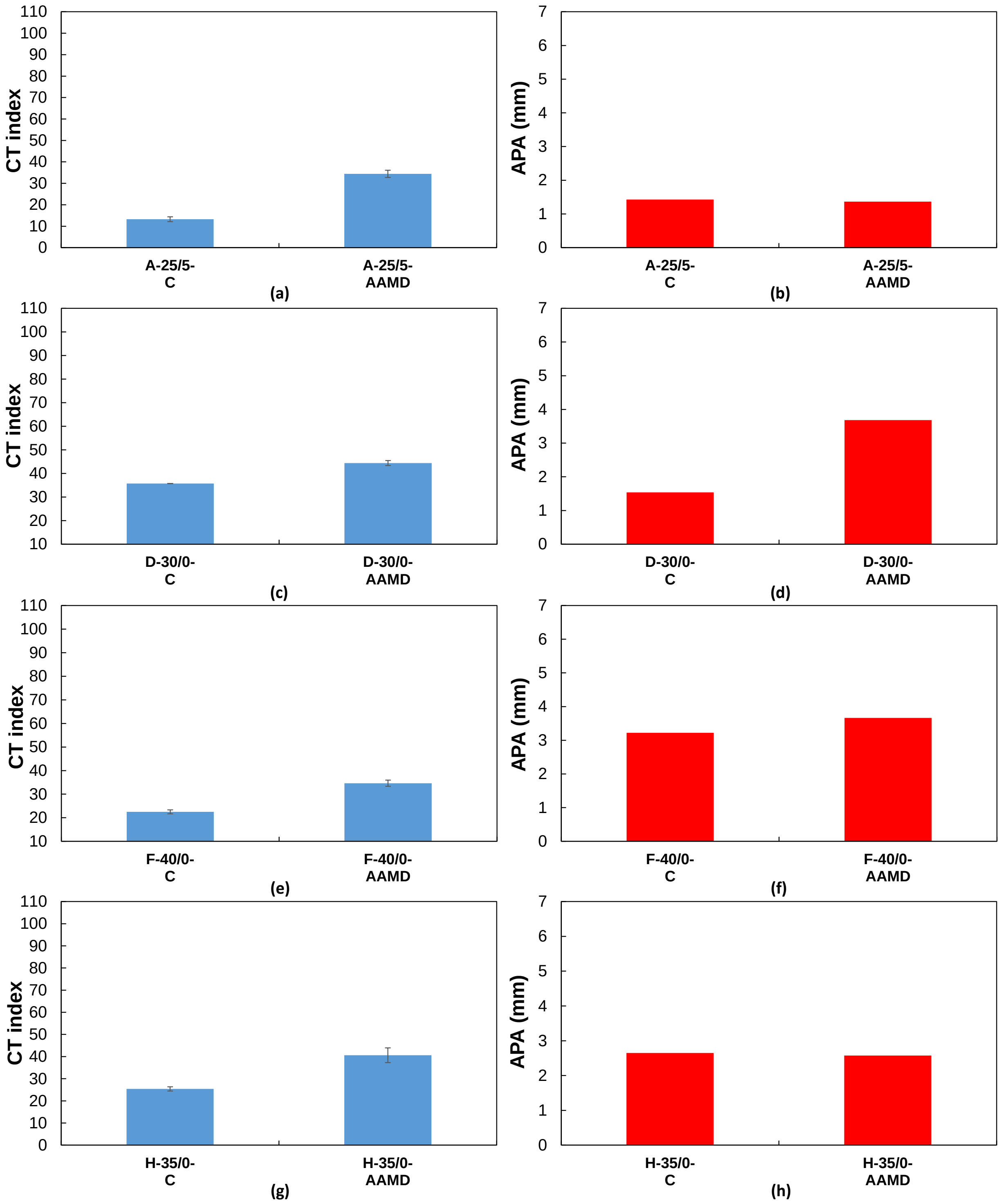


Figure 12. Cracking and rutting index test results for the additional control and AAMD mixtures prepared at fixed RAM content for: Plant A ((a) and (b)), Plant D ((c) and (d)), Plant F ((e) and (f)) and Plant H ((g) and (h)).

Collectively, the results of the additional AAMD designs prepared at fixed RAM content support the findings from the previously presented mixture for RS9.5C mixtures but highlight important limitations for adjusting the aggregate structure and corresponding volumetric properties of RS9.5B mixtures due to the tight band specifications imposed on the #8 sieve.

3.4. Evaluation of the Ability of the AAMD Method to Mitigate the Adverse Effects of RAM

The previous sections evaluated the ability of the AAMD and COAC approaches to improve the performance of asphalt mixtures when applied to adjust existing NCDOT mixtures while maintaining fixed RAM content. In this section, the AAMD method is further evaluated by comparing the performance of virgin mixtures and the previously presented AAMD mixtures containing RAM. In addition, AAMD mixture designs prepared with 50 percent RAP are compared to the previously presented mixtures with lower RAP content to evaluate the use the AAMD method to increase RAP contents without negatively impacting performance.

3.4.1. Comparison of the Control Virgin and AAMD Mixture Designs

Control virgin mixtures were compared to the AAMD mixture designs presented in the Section 3.3. The control virgin mixtures correspond to virgin JMFs from the same plants the RAM control mixtures were sourced from. Figure 13 and Figure 14 present the comparisons between the blend gradations for the control virgin and AAMD mixture designs for RS9.5C and RS9.5B mixtures, respectively. With one exception (H-35/0-AAMD), the virgin mixture gradations are generally similar to the corresponding AAMD RAP mixture gradations when interpreted using the RAP black curve. Recall that the AAMD RAP mixtures were designed to yield similar blend black curves to the specified white curves for the corresponding RAP control mixtures. Thus, these results confirm that a given plant in North Carolina generally targets very similar gradations for a given mixture class. The AAMD RAP/RAS mixture black curves are somewhat finer than the respective control virgin mixtures. The AAMD RAP/RAS mixtures were prepared to have finer gradations relative to the specified control RAM mixture to achieve an acceptable available VMA.

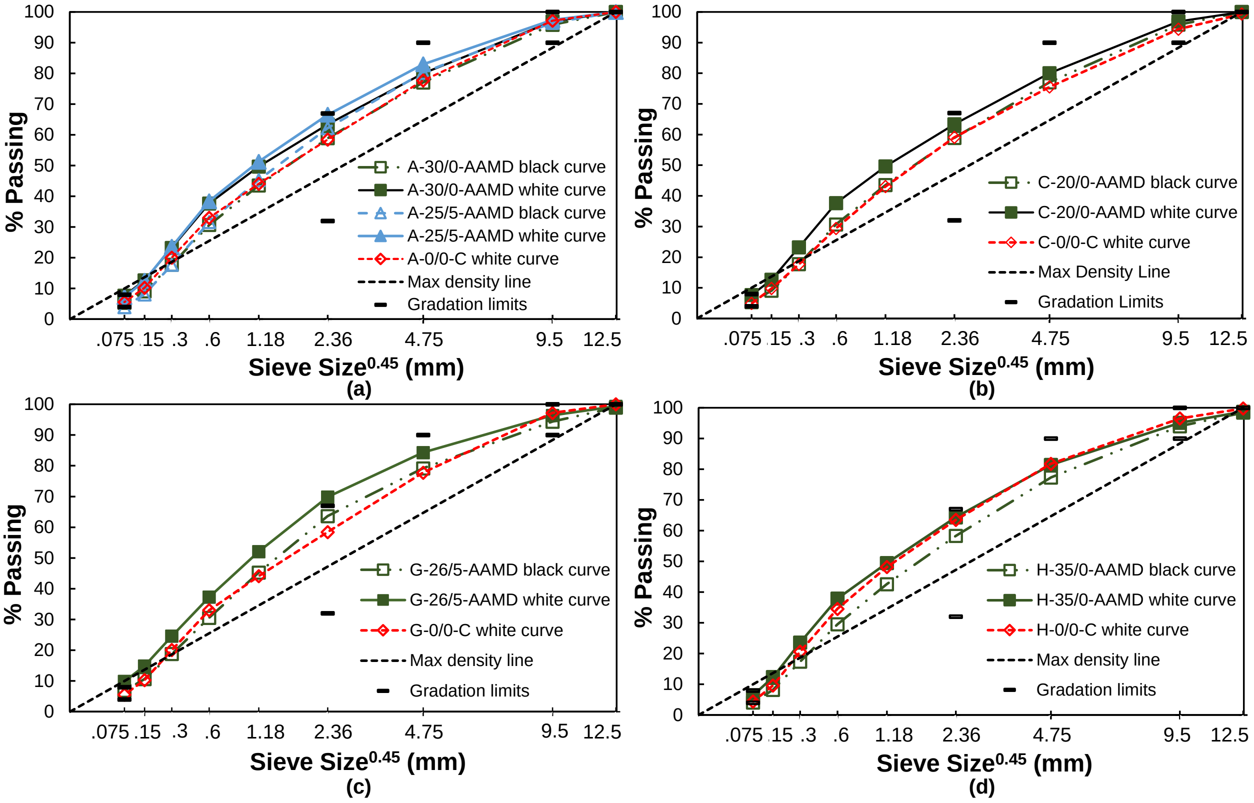


Figure 13. Blend gradations for the RS9.5C control virgin and AAMD mixtures for: (a) Plant A, (b) Plant C, (c) Plant G, and (d) Plant H.

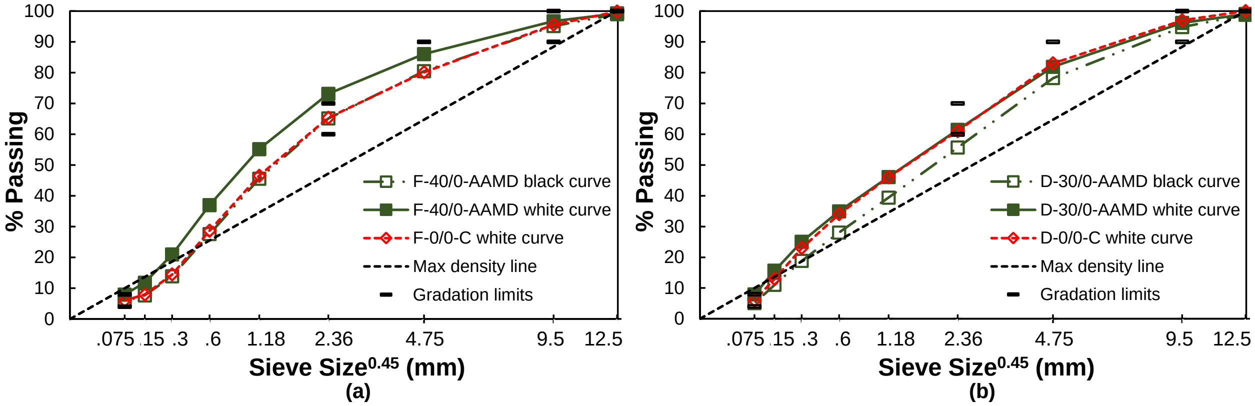


Figure 14. Blend gradations for the RS9.5B control virgin and AAMD mixtures for: (a) Plant F and (b) Plant D.

Table 11 and Table 12 present the comparison of the volumetric properties of the control virgin and AAMD mixture designs for the RS9.5C and RS9.5B mixtures, respectively. Note that the specified and available volumetric properties of the virgin mixtures are the same because there is no recycled, and therefore, unavailable binder. Table 11 and Table 12 show that the virgin control mixtures have higher available binder contents, VMAs, and blended binder properties compared to the corresponding AAMD RAP mixtures despite their similar gradations when interpreted using the RAM black curves. This suggests that the control virgin mixture aggregate blends had different shape, angularity, and/or texture than the respective AAMD mixtures. These differences would have affected the packing and consequently void content of the compacted aggregate blend within the mixture. The control virgin mixtures all have VMAs two to three percent above the specified limit, leading to very high binder contents that may render the mixtures costly.

Table 11. Specified and Available Volumetric Properties for the RS9.5C Control Virgin and AAMD Mixture Designs

Mix properties	Plant A			Plant C		Plant G		Plant H		Spec. limits
	A-0/0-C	A-30/0-AAMD	A-25/5-AAMD	C-0/0-C	C-20/0-AAMD	G-0/0-C	G-26/5-AAMD	H-0/0-C	H-35/0-AAMD	
Total binder content (%)	6.7	6.7	7.3	6.5	6.4	7.0	6.9	7.2	6.7	--
Available binder content (%)	6.7	6.1	5.8	6.5	6.0	7.0	5.4	7.2	5.9	--
Virgin binder content (%)	6.7	5.2	5.1	6.5	5.4	7.0	4.4	7.2	5.0	--
Total RBR (%)	0.0	22.8	30.5	0.0	15.4	0.0	36.0	0.0	24.4	--
Effective RBR (%)	0.0	14.8	12.4	0.0	9.2	0.0	19.0	0.0	14.9	
Total Binder Blend HPG	67.6	74.7	78.7	67.6	72.0	67.6	81.6	66.7	73.7	--
Available Binder Blend HPG	67.6	72.2	66.1	67.6	70.3	67.6	69.6	66.7	71.0	--
Specified VMA (%)	18.0	17.7	19.7	17.7	16.9	19.0	18.2	20.8	18.3	Min. 15.5
Available VMA (%)	18.0	16.9	17.1	17.7	16.3	19.0	15.7	20.8	16.7	
Specified VFA (%)	77.7	77.3	79.7	77.5	76.3	78.9	78.0	81.0	78.1	65-78
Available VFA (%)	77.7	76.3	76.7	77.5	75.5	78.9	74.6	81.0	76.0	
Specified DP	0.90	1.30	1.04	0.81	1.12	0.95	1.45	0.80	1.08	0.6-1.4
Available DP	0.90	0.97	0.69	0.81	0.86	0.95	1.30	0.80	0.76	

Table 12. Specified and Available Volumetric Properties for the RS9.5B Control Virgin and AAMD Mixture Designs

Mix properties	Plant D		Plant F		Spec. limits
	D-0/0-C	D-30/0-AAMD	F-0/0-C	F-40/0-AAMD	
Total binder content (%)	6.8	6.7	6.9	6.6	--
Available binder content (%)	6.8	5.9	6.9	5.8	--
Virgin binder content (%)	6.8	5.2	6.9	4.7	--
Total RBR (%)	0.0	21.9	0.0	29.7	--
Effective RBR (%)	0.0	12.1	0.0	19.8	--
Total Binder Blend HPG	66.7	73.6	67.6	72.3	--
Available Binder Blend HPG	66.7	71.4	67.6	68.8	--
Specified VMA (%)	19.2	18.8	18.6	18.2	Min. 16.0
Available VMA (%)	19.2	17.1	18.6	17.3	
Specified VFA (%)	79.1	78.7	78.0	78.1	70 – 80
Available VFA (%)	79.1	76.6	78.0	76.9	
Specified DP	0.64	1.09	0.92	1.57	0.6 – 1.4
Available DP	0.64	0.87	0.92	1.30	

Figure 15 and Figure 16 show comparisons between the IDEAL CT and APA test results of the control virgin and AAMD mixtures for RS9.5C and RS9.5B mixtures, respectively. In all cases, the virgin mixtures have significantly higher CT_{index} values than the comparative AAMD mixtures. With the exception of Plant D, all control virgin mixtures have significantly higher APA rut depths than the respective AAMD mixtures. However, all control virgin mixtures meet the NCDOT-specified limits for APA test results. The higher CT_{index} values and APA rut depths of the virgin control mixtures are attributed to their higher available binder contents and softer effective binder matrices.

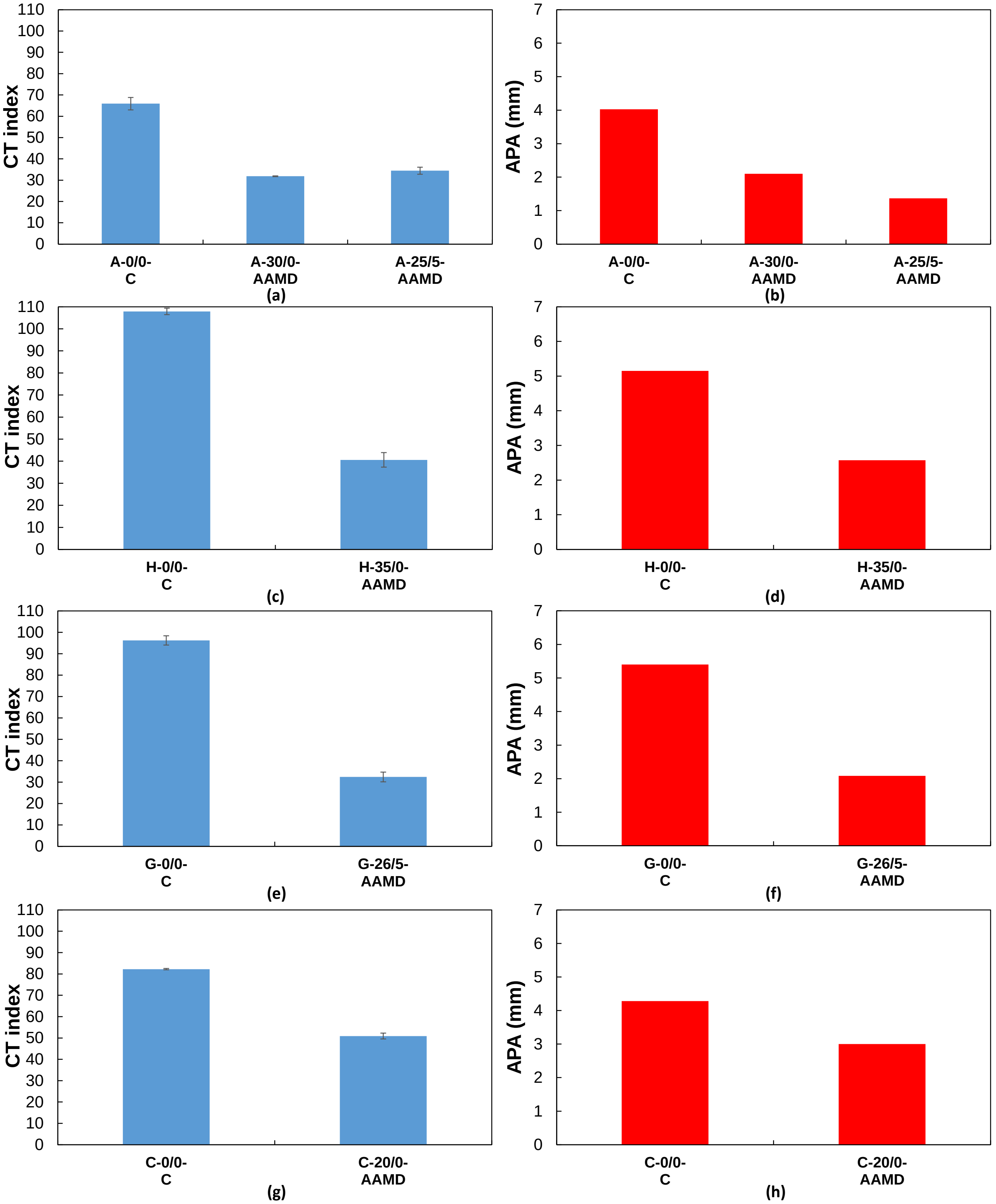


Figure 15. Cracking and rutting index results for the RS9.5C control virgin and AAMD mixture designs for: Plant A ((a) and (b)), Plant H ((c) and (d)), Plant G ((e) and (f)) and Plant C ((g) and (h)).

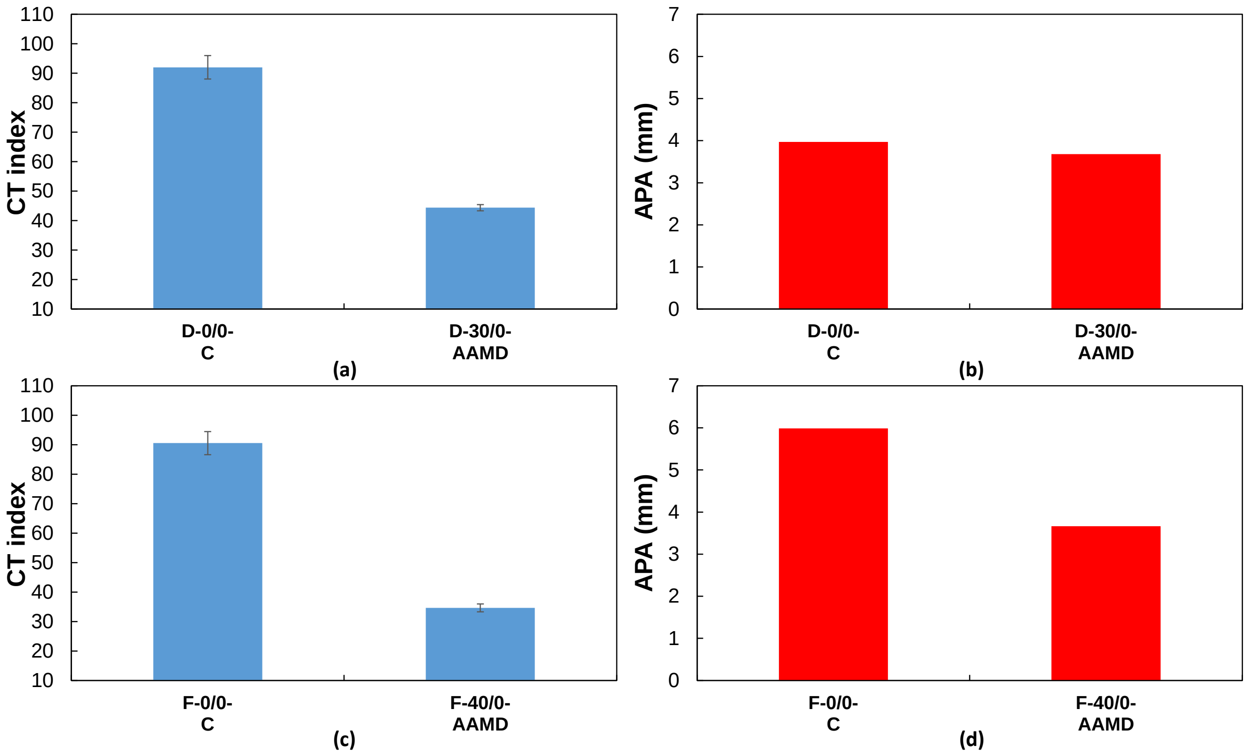


Figure 16. Cracking and rutting index results for the RS9.5B control virgin and AAMD mixtures designs for: Plant D ((a) and (b)) and Plant F ((c) and (d)).

3.4.2. Comparison of the Comparative Virgin and AAMD Mixture Designs

The differences in the available VMAs and associated asphalt contents of the control virgin and AAMD RAP mixtures precluded a direct assessment of the AAMD method's ability to mitigate the adverse effects of RAM on performance. Therefore, additional virgin mixtures were designed using Plant A and F virgin aggregate stockpiles to achieve similar available VMA and binder contents to the respective AAMD RAP mixtures (i.e., A-0/0-E was prepared to be similar to A-30/0-AAMD and F-0/0-E was prepared to achieve similar available properties to F-40/0-AAMD). These virgin mixtures are termed 'comparative' virgin mixtures herein and are identified as A-0/0-E and F-0/0-E. The A-0/0-E and F-0/0-E mixtures adhered to NCDOT specifications for RS9.5C and RS9.5B mixtures, respectively.

Figure 17 presents the blend gradations for the comparative virgin, control RAP, and AAMD RAP mixtures for Plants A and F. In these graphs, the RAP black curves are used to reflect the RAP gradation in the control and AAMD mixtures. The comparative virgin mixtures coarser gradations compared to the respective AAMD mixtures, which was required to achieve similar available volumetric properties.

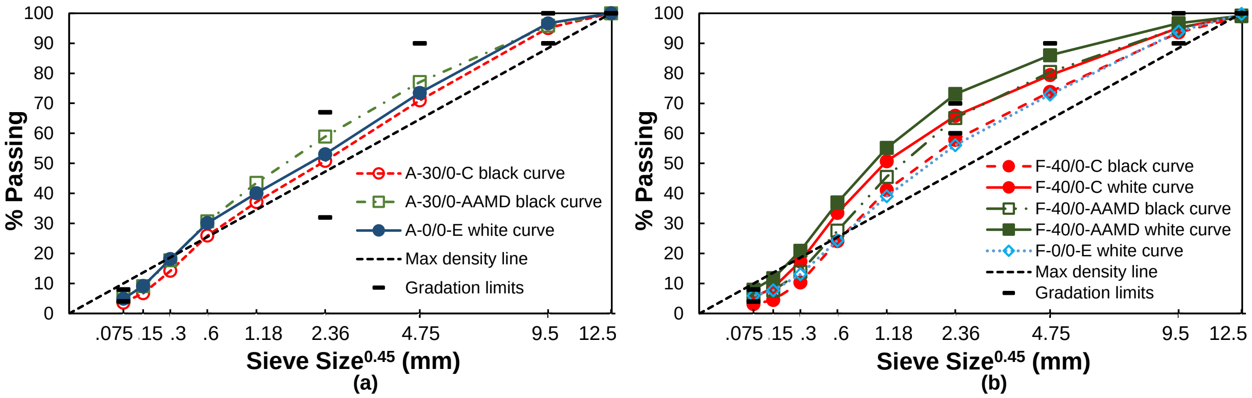


Figure 17. Blend gradations for the comparative virgin mixtures and AAMD RAP mixtures for: (a) Plant A and (b) Plant F.

Table 13 presents the volumetric properties of the comparative virgin and AAMD RAP mixtures for Plants A and F. The control RAP mixtures are also shown for comparison. The A-0/0-E has similar available VMA, VFA, and binder content values to the A-30/0-AAMD mixture. Moreover, the A-0/0-E mixture has similar total VMA, VFA, and binder content to the A-30/0-C mixture. The F-0/0-E has similar available VMA and VFA values and 0.4 percent higher available binder content compared to both the F-30/0-AAMD and F-30/0-C mixtures. Recall that the VMA of the F-30/0-C could not be increased substantially when preparing the F-30/0-AAMD mixture due to the tight gradation restrictions on the #8 sieve for RS9.5B mixtures. This restriction on the #8 sieve also made it difficult to achieve the same available VMA in the comparative virgin and RAP mixtures. Table 13 shows that the estimated available HPG values of the virgin and respective AAMD RAP mixtures are within 1.1°C in both cases, which was intentional. The virgin binder used for the virgin mixtures were also selected so that the HPG is close to the available blend HPG of the RAP mixtures. Correspondingly, a PG 70-22 virgin binder was used in the A-0/0-E mixture and a PG 64-22 was used in the F-0/0-E mixture. However, simultaneously matching all volumetric properties in a given virgin and RAP mixture is not possible given the limited virgin stockpiles available in each control JMF. Consequently, the available DP of the comparative virgin mixtures are higher than that of the corresponding control mixtures and lower than that of the corresponding AAMD mixtures.

Table 13. Specified and Available Volumetric Properties of the Control, AAMD, and Comparative Virgin Mixtures

Mix properties	Plant A			Plant F			Spec. limits
	A-0/0-E	A-30/0-C	A-30/0-AAMD	F-0/0-E	F-40/0-C	F-40/0-AAMD	
Total binder content (%)	6.1	6.0	6.7	6.2	6.6	6.6	--
Available binder content (%)	6.1	5.4	6.1	6.2	5.8	5.8	--
Virgin binder content (%)	6.1	4.4	5.2	6.2	4.6	4.7	--
Total RBR (%)	0.0	25.9	22.8	0.0	29.8	29.7	--
Effective RBR (%)	0.0	17.1	14.8	0.0	20.2	19.8	--
Total Binder Blend HPG	72.0	75.6	74.7	67.6	72.3	72.3	--
Available Binder Blend HPG	72.0	72.9	72.2	67.6	68.8	68.8	--
Specified VMA (%)	17.1	16.8	17.7	17.2	17.9	18.2	Min. 15.5 (C), 16.0 (B)
Available VMA (%)	17.1	15.9	16.9	17.2	17.0	17.3	
Specified VFA (%)	76.6	76.1	77.3	76.8	77.7	78.1	65-78 (C), 70-80 (B)
Available VFA (%)	76.6	74.9	76.3	76.8	76.4	76.9	
Specified DP	0.86	1.08	1.30	1.03	0.88	1.57	0.6-1.4
Available DP	0.86	0.71	0.97	1.03	0.56	1.30	

Figure 18 shows the comparison of the IDEAL CT and APA test results of the comparative virgin and respective RAP mixtures. The average CT_{index} results of the A-0/0-E and A-30/0-AAMD are statistically the same whereas the A-30/0-C mixture exhibits a significantly lower result. The F-0/0-E mixture has a marginally higher CT_{index} than the F-40/0-AAMD mixture, which is attributed to its 0.4 percent higher available binder content. The comparative virgin mixtures both have higher APA rut depths than the respective RAP mixtures, indicating that the RAP mixtures may have superior aggregate structures. However, all mixtures met NCDOT specifications for the APA rut depth. Collectively, the similar cracking performance achieved in the comparative virgin and AAMD mixture results demonstrate that the AAMD approach can mitigate the adverse effects of RAP through the control of available volumetric and effective binder properties.

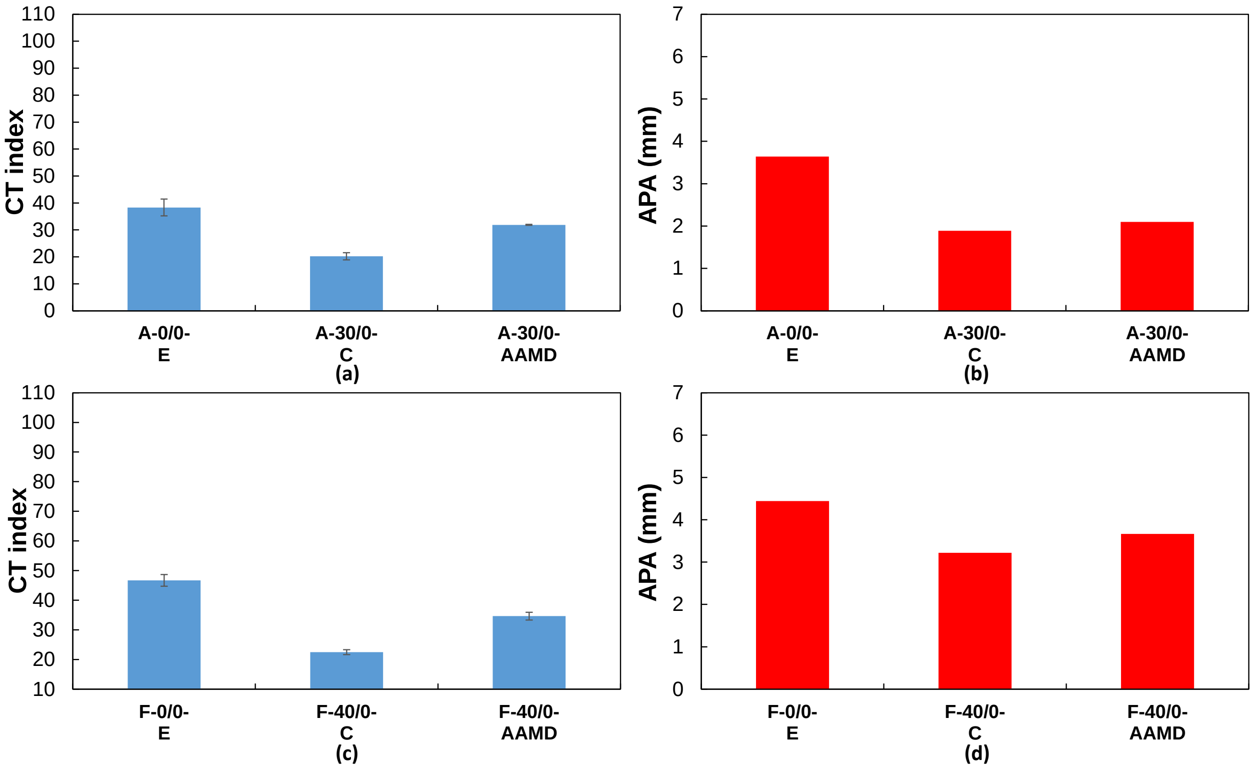


Figure 18. Cracking and rutting index results for the comparative virgin mixture and the RAP mixtures for: Plant A ((a) and (b)) and Plant F ((c) and (d)).

3.4.3. Comparison of Control and AAMD Mixture Designs with Higher RAP Content

The capability of the AAMD method to increase the RAP content without compromising performance was assessed for three of the RS9.5C control mixtures. The RAP content of these three control mixtures (A-30/0-C, C-20/0-C, and H-35/0-C) were increased to 50 percent. To align with the NCDOT RBR specifications, a PG 58-28 virgin binder was used in all 50 percent RAP AAMD designs. To increase the RAP content of a mixtures to 50 percent, the RAP black curves were used to reflect its gradation and the virgin aggregate stockpiles proportions were adjusted to accommodate the additional RAP content and achieve a similar blend gradation to that specified (i.e., the white curve) for the respective control mixture. For Plants A and C, all the virgin stockpiles used in the control mixtures were retained for the 50 percent RAP AAMD mixtures. However, for the H-50/0-AAMD mixture, the coarse virgin stockpile (78M) had to be excluded to meet NCDOT requirements for the minimum amount of aggregate passing the #200 sieve. Plant H used fractionated RAP and so to create the H-50/0-AAMD mixture, the coarse and fine RAP stockpile contents were increased while maintaining the proportions of 60 percent fine RAP and 40 percent coarse RAP that were used in the control mixture.

Figure 19 presents the resultant blend gradations. The control mixture gradations are also shown for comparison. In general, the 50 percent RAP mixture black curves are similar to the corresponding control mixture white curve. However, some differences are observed. The high RAP content made it more difficult to manipulate the blend gradation through adjustment of the virgin stockpile proportions than the lower RAP content mixtures.

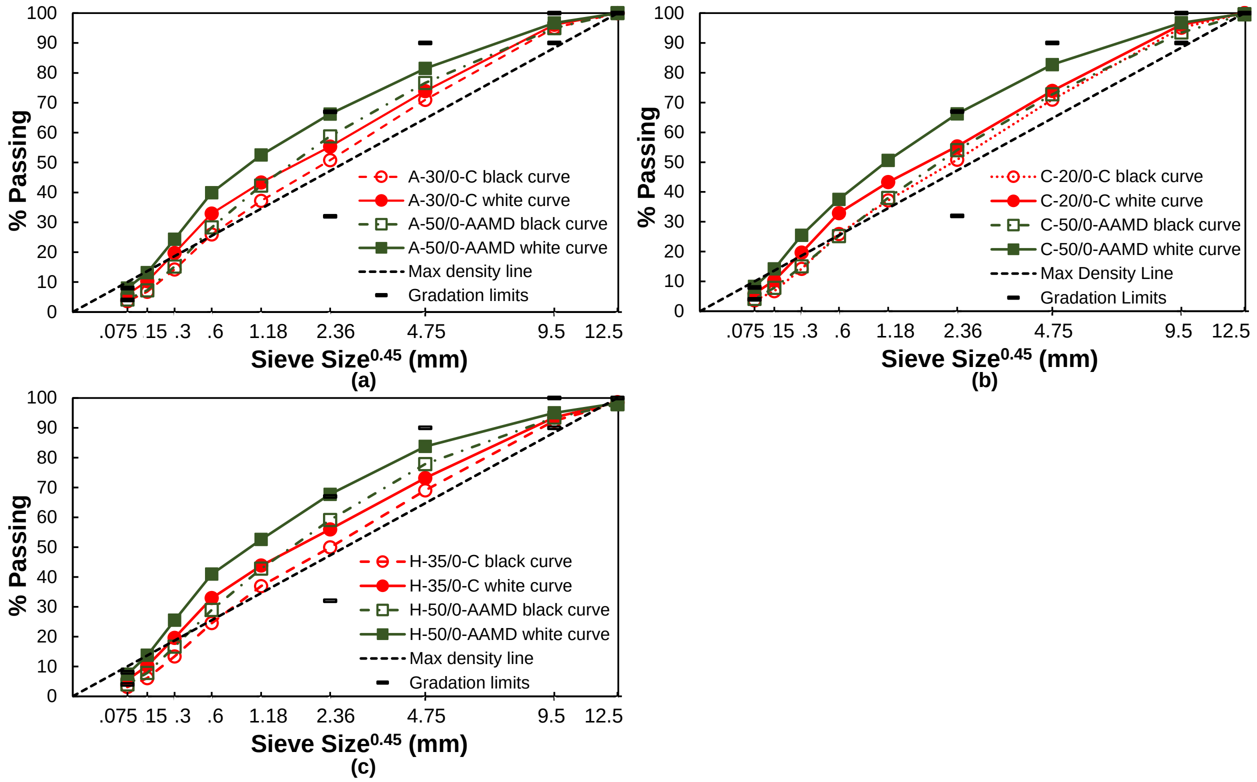


Figure 19. Blend gradations for the control and 50 percent RAP AAMD mixtures for (a) Plant A, (b) Plant C and (c) Plant H.

Table 14 presents the comparison of the volumetric properties of the control and 50 percent RAP AAMD mixture designs. The available binder contents of the control and 50 percent RAP mixtures are similar for Plants A and C. Also, the available VMAs of the control and corresponding 50 percent RAP AAMD mixtures are all within 0.6 percent of each other. The Plant A and C control mixtures exhibit lower virgin binder content than the respective 50 percent RAP mixtures, indicating the high RAP content may be economically advantageous if performance is satisfactory. In contrast, the H-50/0-AAMD mixture exhibits 0.7 percent more available binder than the H-35/0-C mixture and thus, was less similar, but still relatively close to the control. The H-50/0-AAMD mixture also had a higher virgin binder content than the control mixture, indicating that the higher RAP content may be less economical. The available DPs of the control and respective 50 percent RAP AAMD mixtures are all similar.

The virgin binder used for all the mixtures with 50 percent RAP was PG 58-28, selected based on the total RBR according to NCDOT guidelines. The control mixtures all contained PG 64-22 virgin binder. Note that even at 50 percent RAP content, the effective RBRs of all the mixtures are still lower than the 30 percent RBR threshold specified by the NCDOT for switching to a softer virgin binder. With the use of a softer virgin binder, the estimated available binder blend HPG of the 50 percent RAP mixtures are 1°C to 4°C lower than the respective control mixtures.

Table 14. Specified and Available Volumetric Properties of the Control and 50 percent RAP AAMD Mixture Designs

Mix properties	Plant A		Plant C		Plant H		Spec. limits
	A-30/0-C	A-50/0-AAMD	C-20/0-C	C-50/0-AAMD	H-35/0-C	H-50/0-AAMD	
Total binder content (%)	6.0	6.7	5.7	6.5	6.0	7.0	--
Available binder content (%)	5.4	5.7	5.3	5.4	5.2	5.9	--
Virgin binder content (%)	4.4	4.2	4.7	4.1	4.3	4.6	--
Total RBR (%)	25.9	37.7	17.3	37.9	27.8	33.4	--
Effective RBR (%)	17.1	26.3	10.5	25.4	17.3	21.4	--
Total Binder Blend HPG	75.6	74.3	72.5	73.4	74.5	71.5	--
Available Binder Blend HPG	72.9	69.9	70.6	69.0	71.6	67.4	--
Specified VMA (%)	16.8	17.2	15.8	16.3	16.8	18.1	Min. 15.5
Available VMA (%)	15.9	15.9	15.3	15.9	15.2	15.8	
Specified VFA (%)	76.1	76.8	74.7	75.4	76.2	78.0	65-78
Available VFA (%)	74.9	74.9	73.8	74.9	73.6	74.8	
Specified DP	1.08	1.39	1.09	1.54	1.02	1.20	0.6-1.4
Available DP	0.71	0.81	0.80	0.78	0.66	0.77	

Figure 20 shows the comparison of the IDEAL CT and APA results of the control and AAMD RAP mixtures from Plants A, C, and H. The A-50/0-AAMD mixture exhibits a significantly higher CT_{index} and statistically equal APA rut depth to the A-30/0-C control mixture. The CT_{index} and APA rut depths of the A-50/0-AAMD and A-35/0-AAMD mixtures are statistically the same. The improved cracking performance of A-50/0-AAMD compared to the A-30/0-C control mixture with similar available volumetric properties is speculated to be due the use of a softer virgin binder used in the A-50/0-AAMD, resulting in a softer effective binder matrix in the mixture. The cracking and rutting performances of the C-50/0-AAMD mixture is statistically similar to the C-20/0-C control mixture with 20 percent RAP, attributed to their similar available binder contents and available binder blend HPG.

The H-50/0-AAMD exhibits a significantly higher CT_{index} compared to the H-35/0-C and H-35/0-AAMD mixtures designed with lower RAP content. The H-50/0-AAMD mixture also exhibits a significantly higher APA rut depth than the lower RAP content mixtures but still meets the NCDOT’s specified rut depth limit for RS9.5C mixtures. It is speculated that the inferior rutting performance of the H-50/0-AAMD is due to the use of the PG 58-28 virgin binder, compared to the PG 64-22 used in the Plant H mixtures with 35 percent RAP, a relatively high available binder content, and the elimination of the 78M coarse virgin aggregates. The 78M coarse virgin aggregate may have superior shape, angularity, and texture compared to the coarse RAP particles, which consist of agglomerated finer particles. Table 14 shows the available HPG for the H-50/0-AAMD mixture was 4°C lower than the H-35/0-C mixture, representing the largest difference among the sources evaluated and possibly suggesting that a PG 64-22 virgin binder would have been more suitable.

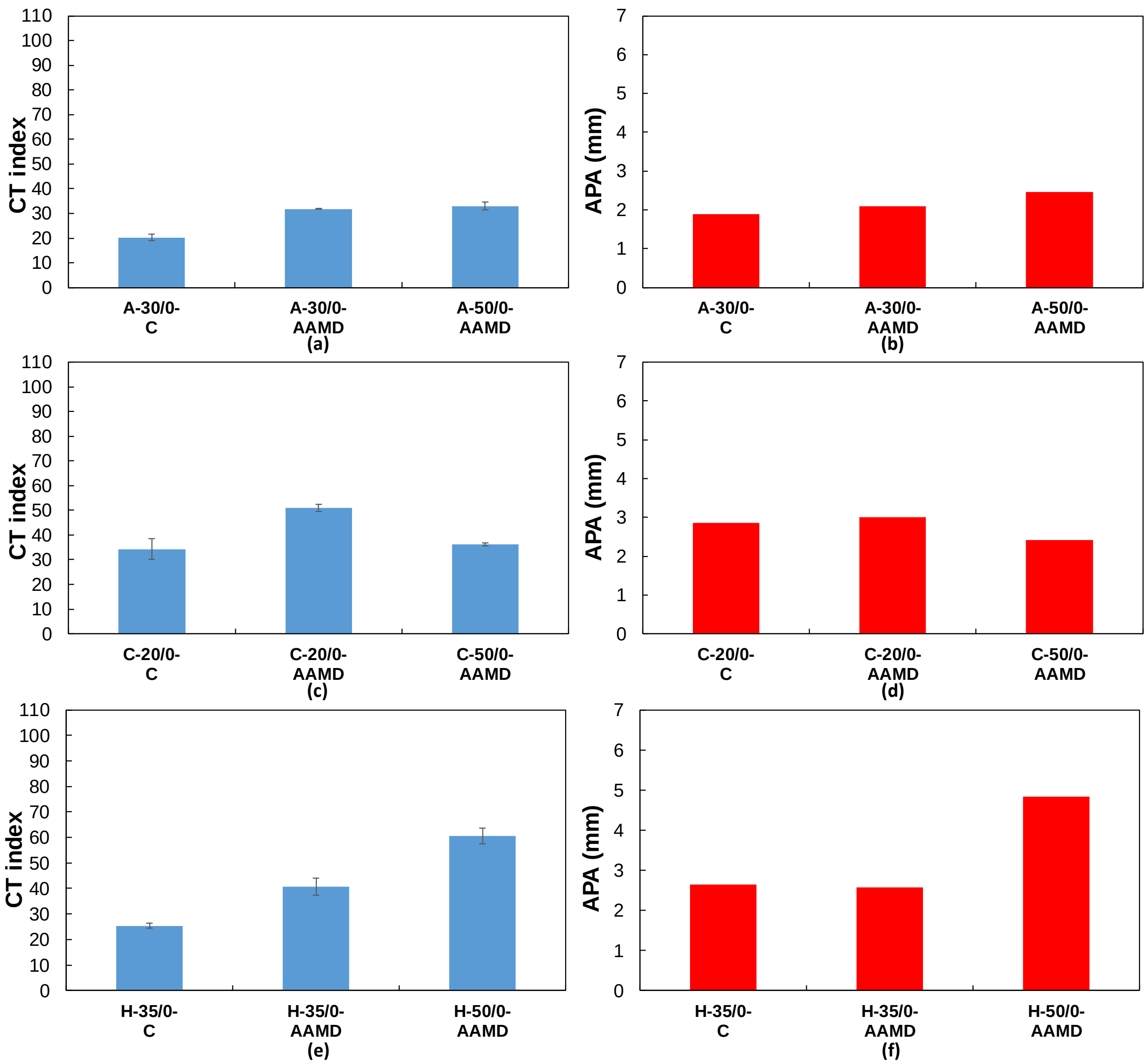


Figure 20. Cracking and rutting index results for the control and AAMD mixtures for Plant A ((a) and (b)), Plant C ((c) and (d)), and Plant H ((e) and (f)).

The collective results suggest promise that the AAMD method is able to mitigate negative performance consequences of RAP on cracking resistance through the control of available binder and volumetric properties. The results suggest the potential for increasing RAP contents without detrimentally impacting cracking resistance. Satisfactory rutting resistance, according to NCDOT requirements for APA test results, was also achieved in all AAMD mixture designs. However, the morphology of RAP versus virgin aggregate particles and its impact on rutting resistance merits future research.

3.5. Verification of the Index Test Findings through Pavement Performance Simulations

AMPT tests were conducted for select mixture designs from Plants A, G, and H to evaluate the generality of the findings obtained through the index testing using more fundamental tests and accompanying pavement performance simulations. Bottom-up fatigue cracking simulations were carried out using Pavement ME and the local calibration coefficients and material-level inputs obtained from dynamic modulus and cyclic fatigue test results. Rutting simulations were carried out using FlexPAVE™ and incorporating the SSR test results. Note that SSR test results are not compatible with Pavement ME. Two pavement structures that are detailed in Section 2.6.3 were evaluated in the structural pavement performance predictions. Note that material-level performance indices obtained from the AMPT tests were also evaluated. The AMPT performance indices and their comparisons to the index test results and pavement performance simulations are presented in Appendix G.

3.5.1. Comparison of IDEAL CT Results and Pavement ME Predictions of Bottom up Cracking

Figures 21, 22, and 23 present the comparisons between IDEAL CT results and Pavement ME predictions of bottom up cracking for the Plant A, G, and H mixtures, respectively. As anticipated, the predicted bottom up cracking in the thin pavement structures is consistently higher than the comparative thick pavement structures. However, the trends in the extent of bottom up cracking predicted among the mixture design alternatives from a given plant are consistent for the thin and thick section scenarios. Furthermore, in all cases, the trends in CT_{index} and bottom up cracking results among the mixture designs from a given plant align. That is, higher CT_{index} results correspond to lower bottom up cracking. Both bottom up cracking predictions and CT_{index} results indicate that the control virgin mixtures exhibit better cracking resistance than the RAM mixtures. Additionally, both bottom up cracking predictions and CT_{index} results indicate that the control RAM mixtures exhibit inferior cracking resistance than the COAC and AAMD mixtures. Differences in the predicted bottom up cracking among the control and AAMD mixtures are substantial in many cases, suggesting that the performance benefits imparted by the AAMD may be significant.

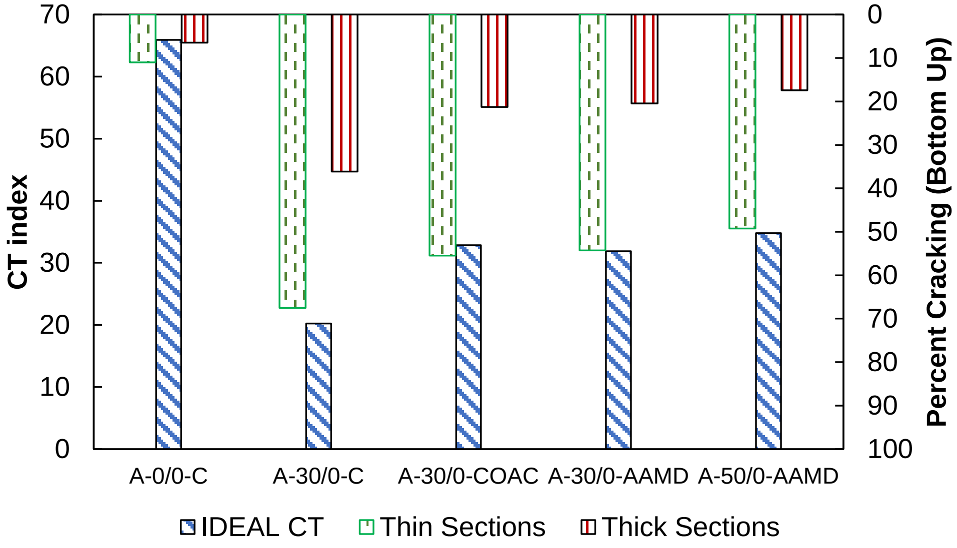


Figure 21. Comparison of IDEAL CT results and predictions of cracking for Plant A.

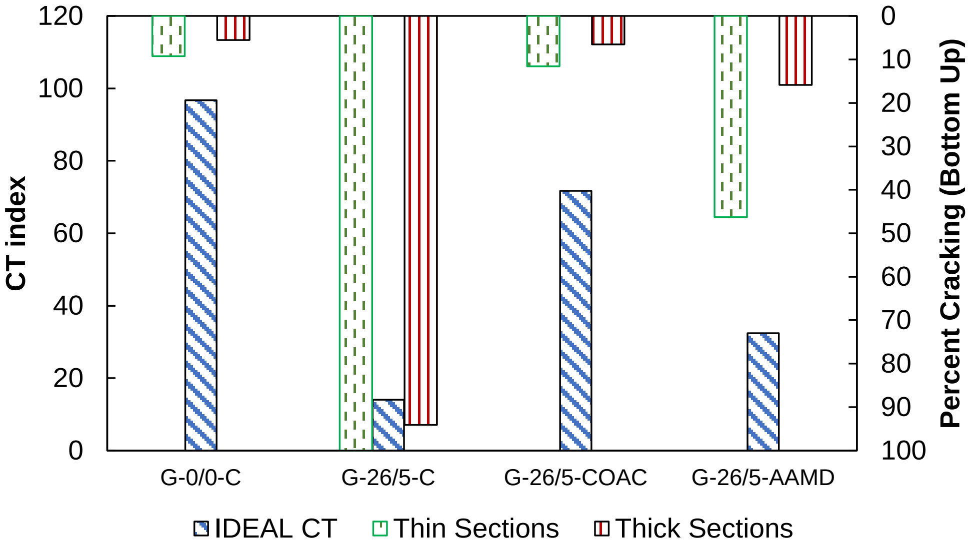


Figure 22. Comparison of IDEAL CT results and cracking predictions for Plant G.

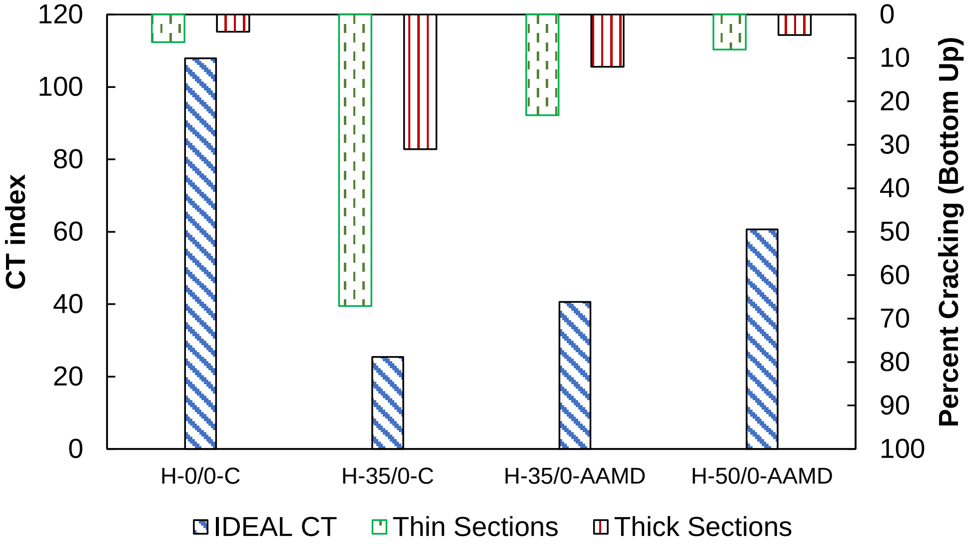


Figure 23. Comparison of IDEAL CT results and cracking predictions for Plant H.

Figure 24 presents the comparison of IDEAL CT results and bottom up cracking predictions for the collective Plant A, G, and H mixtures. The results demonstrate the IDEAL CT results and Pavement ME predictions of bottom up cracking are highly correlated for each pavement structure evaluated, suggesting that the good agreement between trends in IDEAL CT results and Pavement ME predictions extends beyond mixture design alternatives from the same plant.

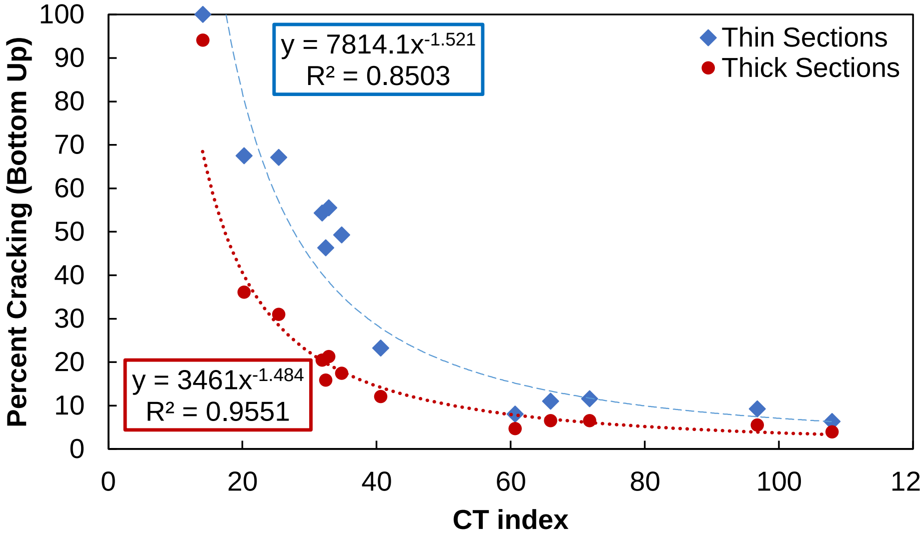


Figure 24. Comparison of the collective bottom up cracking predictions and IDEAL CT results.

3.5.2. Comparison of APA Results and FlexPAVE™ Predictions of Rut Depth

Figures 25, 26, and 27 present the comparisons between APA results and FlexPAVE™ predictions of rut depth in the asphalt layer for the Plant A, G, and H mixtures, respectively. The rut depths predicted in the thick pavement structures are consistently higher than the comparative thin pavement structures. However, the trends in the predicted rut depths among the various mixture design alternatives within a specific plant remain uniform across both the thin and thick section scenarios. Both the material-level and structural-level measures of rutting resistance indicate that the control virgin mixtures have the poorest rutting resistance and that the AAMD and control mixtures with the same RAM content have similar rutting performance. The 50 percent RAP AAMD mixtures (A-50/0-AAMD and H-50/0-AAMD) exhibit higher rut depths than the respective control mixtures, which as previously discussed, is attributed to their softer effective binder matrices and potentially inferior coarse aggregate morphology.

The FlexPAVE™ predictions and APA results provide notably distinct inferences of the rutting resistance of the COAC mixtures relative to the alternative mixture designs. While the APA test results suggest the A-30/0-COAC mixture has inferior rutting resistance compared to the other Plant A RAP mixtures, the predictions of pavement rut depth suggest that the A-30/0-COAC mixture has comparable rutting resistance to the A-30/0-C mixture. This result indicates that the COAC approach may have only marginal effects on the rutting resistance of RAP mixtures with low to moderate RBRs. However, while the APA test results indicate that the G-26/5-COAC mixture has better rutting resistance than the G-0/0-C mixture, the predictions of pavement rut depth are very high for the G-26/5-COAC mixture and surpass those of the G-0/0-C mixture. Overall, these findings from the pavement performance simulations corroborate the findings from the APA test results that suggest the AAMD approach is advantageous over the COAC approach given that the COAC approach can detrimentally affect rutting resistance whereas the AAMD method does not in cases where the target volumetric and effective binder properties are achieved.

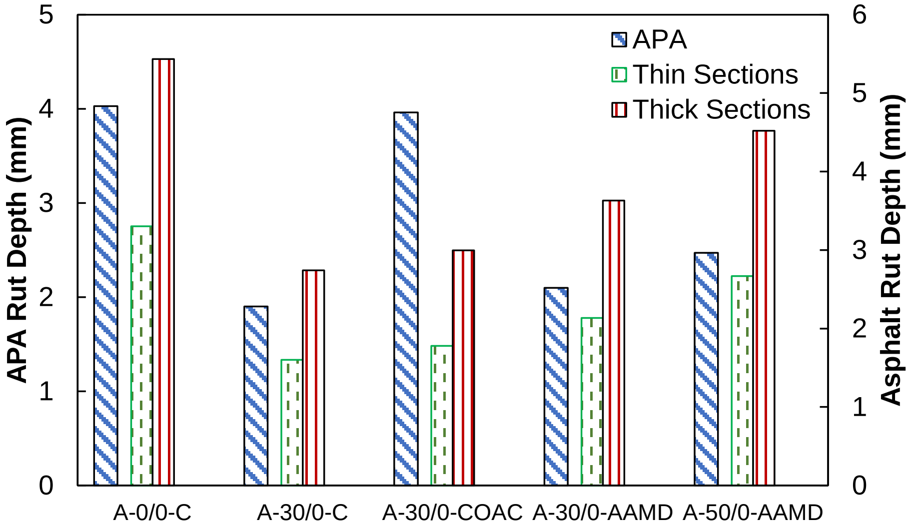


Figure 25. Comparison of APA results and rutting predictions for Plant A.

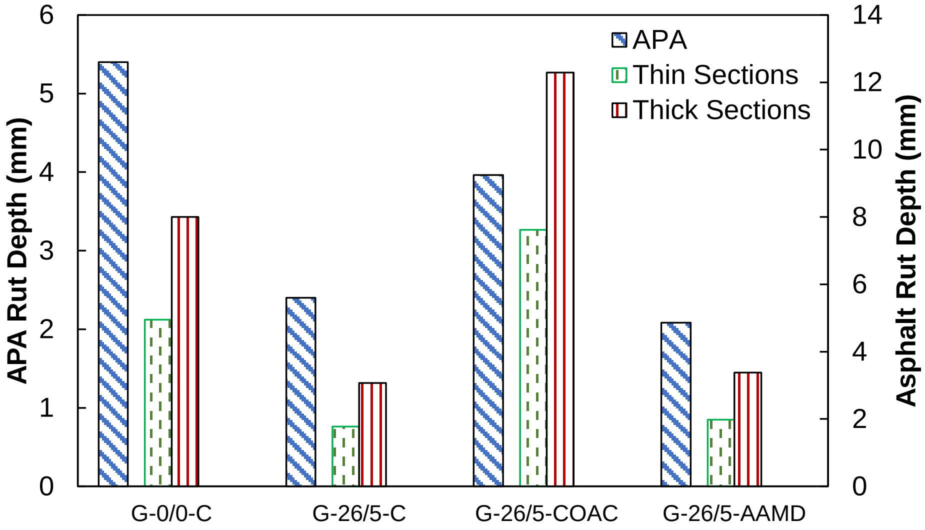


Figure 26. Comparison of APA results and rutting predictions for Plant G.

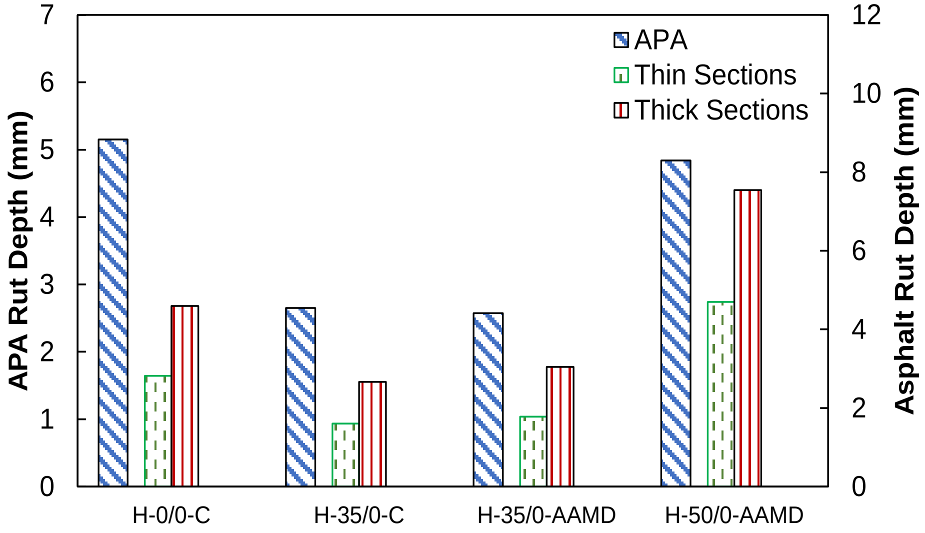


Figure 27. Comparison of APA results and rutting predictions for Plant H.

Figure 28 presents the comparison of APA results and asphalt rut depth predictions for the collective Plant A, G, and H mixtures. Weak correlations between the two measures of rut depth are observed for thick and thin sections when all results are included. However, when the COAC mixtures are excluded, the correlations between the APA results and FlexPAVE™ predictions of asphalt rut depths improve substantially as shown in Figure 29. All study mixtures were designed to achieve four percent air voids at N_{des} with the exception of the COAC mixtures, which may explain their outlier behavior.

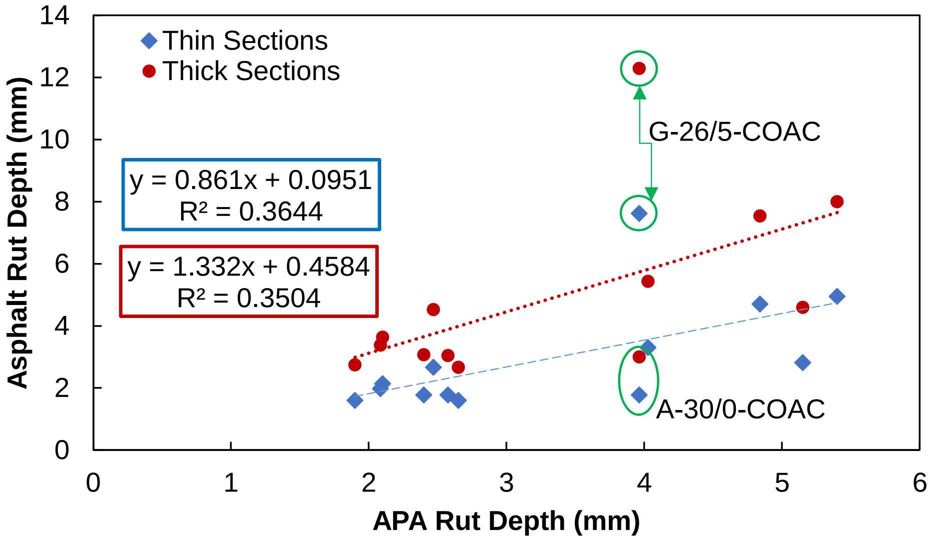


Figure 28. Comparison of the collective rut depth predictions and APA results.

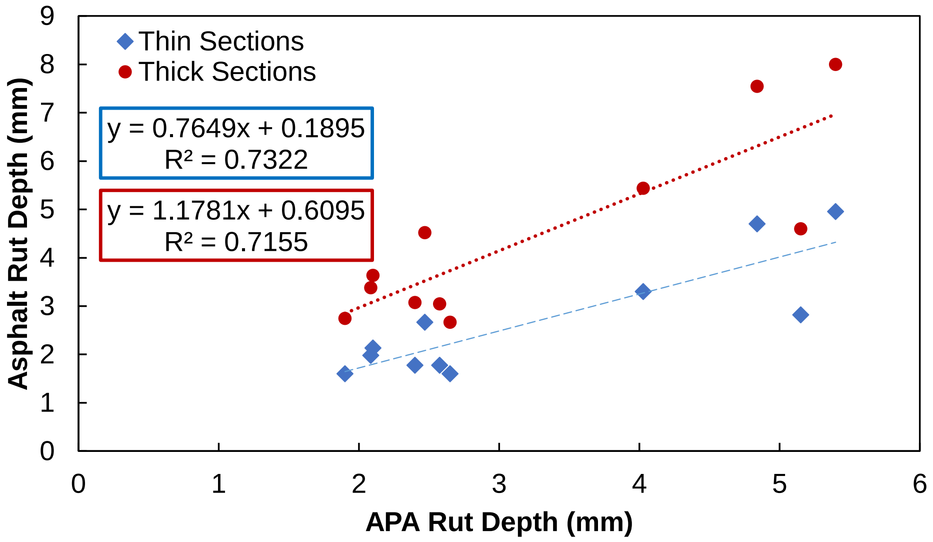


Figure 29. Comparison of the rut depth predictions and APA results, excluding the COAC mixtures.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

The following conclusions are drawn from the results of this project:

- The operational review identified the following factors that vary among asphalt plants in the North Carolina: (1) the number of unprocessed and processed RAP stockpiles, (2) the contractor and equipment for crushing RAM, (3) the time interval between processing of unprocessed RAP, and (4) practices for homogenizing RAM stockpiles.
- RAP stockpiles exhibited RBAs ranging from 40 to 61 percent with coarse RAP stockpiles generally having lower RBA than their fine RAP counterparts from the same plant. In contrast, RAS stockpile RBAs were notably lower than those of RAP, measuring at 12 and 31 percent.
- RAP binder properties in North Carolina displayed significant variability. Samples from six plants included HPG values spanning 85.4°C to 105.4°C and LPG values ranging from -11.5°C to -19.9°C.
- The COAC and AAMD methods produced mixtures with enhanced cracking performance compared to control mixtures designed according to current NCDOT protocols. This effect is attributed to the elevated design asphalt content introduced by these methods.
- The COAC approach can increase the APA rutting in comparison to the current practice. This increase in rutting susceptibility is attributed to the higher binder content imparted by the COAC method coupled with the fact that the aggregate structure is not adjusted. In contrast, the AAMD method resulted in rut depths similar to the respective control mixtures for mixtures prepared with fixed RAP content. The AAMD method also results in increased binder content, but the aggregate structure is also adjusted to account for the presence of RAM agglomerations.
- The changes imparted by the AAMD method were greater for RS9.5C than RS9.5B mixtures, attributed to the tighter gradation restrictions for RS9.5B mixtures.
- AAMD-designed 50 percent RAP mixtures exhibited equal or better cracking performance to the control mixtures with lower RAP content. In some instances, the 50 percent RAP mixtures displayed greater rutting susceptibility than the control mixtures but still met NCDOT limits for APA test results. This inferior rutting resistance is attributed to the virgin binder selection using total rather than effective RBR and potentially inferior morphology of coarse RAP particles compared to coarse virgin aggregate particles.
- Control virgin mixtures matching existing NCDOT JMFs displayed similar gradations to AAMD mixtures but exhibited notably higher available VMAs and binder contents. Consequently, control virgin mixtures demonstrated improved cracking resistance while displaying inferior rutting performance compared to RAM mixtures.
- Virgin mixtures and AAMD RAP mixtures prepared with similar available volumetric and effective properties yielded similar cracking performance, suggesting that the AAMD counteracts RAP's detrimental impact on cracking resistance. The comparative virgin mixtures displayed inferior rutting resistance compared to the AAMD RAP mixtures.
- IDEAL CT test results and Pavement ME predictions of bottom up cracking provided consistent trends in the relative cracking resistance of the study mixtures. Both measures indicate that the AAMD mixtures exhibit better cracking resistance than the respective control mixtures designed according to current NCDOT procedures.

- APA test results and FlexPAVE™ predictions of asphalt rut depth provided consistent trends in the relative rutting resistance of the study mixtures with the exception of those designed using the COAC approach. The COAC mixtures were the only mixtures where the asphalt content was not selected to achieve four percent air voids at the design compaction level, which may explain their outlier behavior.
- Collectively, the performance measures support that the AAMD framework is a rational approach to include RBA within mix design procedures to improve cracking resistance without compromising rutting resistance. It is important to note, however, that this research project was limited to the evaluation of laboratory-mixed, laboratory-compacted asphalt mixtures.

4.2. Recommendations

Based on these conclusions, the research team has made the following recommendations:

- The AAMD method warrants consideration for designing surface mixtures, pending verification of RBA results using asphalt mixtures produced under conditions that better simulate those in a plant. If applied to RS9.5B mixtures, it is advised that less restrictive gradation limits are imposed for the #8 sieve to enable greater variation in the available VMA.
- The implications of specifying the effective RBR, defined in the AAMD framework, for selecting virgin binders and establishing maximum RAM content should be assessed. Findings from this project suggest that the available binder characteristic within the mixture, as reflected by the effective RBR, better indicates mixture performance compared to binder characteristics inferred from the current NCDOT-specified total RBR.
- Practical approaches to measure RAP binder properties should also be explored. The results of this study demonstrate considerable variability in the rheological properties of RAP binders in North Carolina, which are not captured through current NCDOT specifications or the AAMD method.
- The impact of variables identified in the plant operational review on RAM consistency and, consequently, asphalt mixture performance, should be thoroughly examined to inform improved quality assurance and control protocols.

5. IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

The Materials and Tests Unit of the NCDOT are the primary users of the outcomes of this research. The proposed changes to volumetric mixture design procedures can be integrated into NCDOT specifications without the need for new equipment. To support technology transfer, Appendix C provides detailed guidance for measuring RAP and RAS black curves and quantifying RAP binder RBA from sieve analysis results. Appendix D details how conventional volumetric mixture design equations are amended in the AAMD method to incorporate RBA. The research team has also prepared Excel templates for calculating RAP RBA from sieve analysis results and calculating the volumetric properties of compacted asphalt mixtures according to the AAMD method.

The research team suggests that the NCDOT considers allocating resources to support the following activities:

- Consider adopting less restrictive gradation specifications for the #8 sieve in RS9.5B mixtures.
- Verify the RBA results of this study using asphalt mixtures produced under conditions that better simulate asphalt plant production.
- Assess the performance impacts of specifying the effective rather than total RBR for virgin binder selection and limiting RAM contents.
- Assess the impacts of the identified plant variables on RAM stockpile consistency and performance to identify improved quality control and assurance procedures.
- Explore practical approaches for quantifying RAP binder properties to enable improved virgin binder selection.

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APPENDIX A: DETAILED LITERATURE REVIEW

The literature review for this project and summarizes and synthesizes relevant research and documentation on recycled materials specifications and research in the state of North Carolina, laboratory procedures for recycled materials (including but not limited to mixture design procedures), measurements of recycled binder availability and contribution, reported effects of RAP and RAS materials on performance, and processes that reduce the variability of recycled asphalt materials.

Past Recycled Material Research in North Carolina

Recycled materials in North Carolina are restricted based on the type of recycled material and the layer in which the material is applied. The use of recycled asphalt shingles (RAS) is restricted to a maximum recycled binder replacement (RBR) of 20 percent for surface mixtures and 23 percent for intermediate and base mixes. The use of reclaimed asphalt pavement (RAP) or a combination of RAP and RAS is restricted to a maximum RBR of 40 percent for surface mixes and 45 percent for intermediate and base mixes except for class D that imposes a more restrictive limit. Moreover, when the RBR exceeds 30 percent a PG 58-28 virgin binder grade is required (NCDOT 2020).

Several NCDOT research projects in the past have studied the properties of recycled binders in the state. NCDOT RP 2012-04 (Khosla et al. 2015) and RP 2013-06 (Khosla and Musty 2016) proposed maximum limits for allowable RBR% in RAP and RAS in asphalt mixtures as a function of virgin binder grade. Their proposed limits were based on the intermediate temperature PG characteristics of three recycled binders, including manufactured-waste RAS (MRAS), post-consumer RAS (PRAS), and RAP. Each study considered a single source of each recycled material type. The proposed RBR limits from the two projects were very different, indicating that the rheological properties of RAP and RAS binders from within the state vary. To further evaluate the variability of recycled material sources in the state of North Carolina, NCDOT RP 2014-05 experimented on nine different RAP stockpiles from across the state and determined the high temperature and intermediate temperature performance-graded (PG) property differences between and within stockpiles (Khosla and Ramoju 2017). The research found a large variation in rheological properties (high temperature grades varied from PG 82 to PG 112), and subsequently a large variation in maximum allowable RBR values with prescribed limits on the rheological properties of the blended asphalt (from 10 percent to 24 percent when the virgin binder grade was PG 64-22 and 34 percent to 59 percent when the virgin binder grade was changed to PG 58-28). The most important finding from RP 2014-05 was that RAP stockpiles across North Carolina could vary greatly with respect to rheological properties despite the NCDOT's current requirements for processing and quality control of recycled materials. The past research projects did not attempt to identify sources of variability within and among recycled material stockpiles.

In North Carolina, reports of the effect of recycled asphalt materials on asphalt mixture performance are variable. NCDOT RP 2007-07 (Kim et al. 2009) found systematically lower cracking performance and systematically greater rutting performance from RAP mixtures when compared to virgin mixtures from comparative sources and designations. Other past NCDOT research projects (i.e., RP 2008-03 (Khosla and Visintine 2011), RP 2012-04 (Khosla et al. 2015), and RP 2013-06 (Khosla and Musty 2016)) have evaluated the impact of recycled material content on performance under the NCDOT's current mixture design procedure. These studies generally suggested that increasing the recycled material content improves both rutting and cracking performance. However, these studies relied on dynamic modulus measurements to infer cracking performance. Dynamic modulus test results provide a measure of the expected strains that a pavement under traffic loading will experience but fail to quantify damage resistance. Recycled materials generally contain binder that is oxidized and embrittled and thus, degrade damage resistance, suggesting potential limitations of some the past studies that did not directly measured cracking resistance.

In NCDOT RP 2007-07, Kim et al. (2009) studied the fatigue damage resistance and rutting performance of 12 different North Carolina surface, intermediate and base layer mixtures, from which 6 contained RAP (RS9.5B, RS9.5C, RS12.5C, RI19B, RI19C, and RB25B). Fatigue was assessed using uniaxial cyclic fatigue tests coupled with the Simplified Viscoelastic Continuum Damage (S-VECD) model. Rutting was assessed using triaxial repeated load tests. The authors reported a systematically lower cracking performance and systematically greater rutting resistance from RAP mixtures when compared to virgin mixtures from comparative sources and designations.

The effect of RAP content on North Carolina asphalt mixtures cracking performance was more recently evaluated by Mocelin et al. (2019). The authors used an RS9.5B mixture, originally designed with 30% RAP, and redesigned it for 0% and 50% RAP, maintaining the same aggregate gradation and selecting the virgin binder grade according to the NCDOT’s binder grade requirements. Therefore, a PG 64-22 binder was used for the 0% RAP mixture, and a PG 58-28 binder was used for the 30% and 50% RAP mixtures. The cracking performance was evaluated by means of Asphalt Mixture Performance Tester (AMPT) cyclic fatigue tests and the associated S-VECD model in accordance with AASHTO TP 133. The results indicated no significant changes in performance when the RAP amount was increased from 0 percent to 30 percent following the NCDOT binder selection guideline. However, significantly increased cracking susceptibility was observed when the RAP content was increased to 50 percent compared to the lower RAP content mixtures.

NCDOT RP 2019-21 (Castorena et al. 2022) found that agglomerations of adhered RAP and RAS are the primary inhibitor of recycled binder availability in asphalt mixtures. Recycled binder contained within these agglomerations does not come into contact and blend with the virgin binder in asphalt mixtures. Furthermore, cracks in asphalt mixtures propagate around the agglomerations, suggesting they can be considered ‘black rocks’. In NCDOT RP 2019-21, tracer-based microscopy was used to measure recycled binder contribution in laboratory-mixed, laboratory-compacted samples. These experiments indicate that RAP binder contribution values in North Carolina vary from 50 to 90 percent with an average around 60 percent. Measured RAS binder contribution values were notably lower than those measured for RAP, spanning from 0 to 30 percent. A method to estimate source-specific RAP binder availability using comparative sieve analysis of RAP and recovered RAP aggregate was established that yields good agreement with microscopy measurements in asphalt mixtures. Recycled binder availability was considered the proportion of total recycled binder in a given RAM source that is available to blend with virgin binder. The ability to predict the recycled binder contribution in asphalt mixtures using sieve analysis of the RAP indicates that the agglomerations are pre-existing and do not generally form or breakdown during typical lab mixing.

NCDOT RP 2019-21 proposed several changes to mixture design procedures to more directly account for RAM agglomerations and recycled binder availability, termed Availability Adjusted

Mix Design (AAMD) (Castorena et al. 2022, Mocelin and Castorena 2022). AAMD differs from traditional mixture designs in two ways: (1) the recycled asphalt material (RAM) gradation rather than the recovered aggregate gradation is used to design the aggregate structure since RAM agglomerates act as black rocks, (2) the unavailable recycled binder bound within agglomerations is considered as part of the bulk aggregate volume when inferring the volumetric composition of the mixture

Including the unavailable binder in the bulk aggregate volume lowers the calculated Voids in Mineral Aggregate (VMA) percentage compared to the current practice. The changes to both the interpretation of the RAM gradation and volumetric composition also impact the calculated dust to effective binder ratio of a mixture. Collectively, the changes suggest that mixtures designed assuming 100 percent availability may yield an actual VMA that is smaller than the calculated VMA so that the actual VMA may fall below the acceptable limits. NCDOT RP 2019-21 demonstrated that the AAMD method improves the cracking resistance of asphalt mixtures without having a detrimental effect on rutting resistance compared to the current practice for a given RAM content (Castorena et al. 2022). However, only three mixtures were evaluated and thus, the viability of the AAMD approach merits further investigation using a broader set of mixtures.

Laboratory Procedures with Recycled Materials

RAP and RAS in Volumetric Mix Design Procedures

The Superpave mix design method (AASHTO R 35-17, AASHTO M 323-17) is currently the most widely used volumetric mixture design method in United States. This method was implemented in the 1990s and was originally developed for virgin mixtures with no initial guidance for the use of recycled materials. In 1997, the Federal Highway Administration (FHWA) Superpave Mixtures Expert Task Group developed provisional guidelines for the inclusion of RAP (FHWA 1997). However, pushed by the economic and environmental concerns, many State Departments of Transportation (DOT) had already successfully implemented the use of RAP long before the formal national guidance was incorporated into the AASHTO standards for mix design (Sondag et al. 2002; Copeland 2011).

In the most recent version of the Superpave mix design standards (AASHTO M 323-17 and AASHTO R 35-17), guidelines are provided for the use of recycled materials. The present standards recommend changes to the virgin binder PG based on the RAP content or RBR and assumes that the recycled binder is fully contributing in volumetric calculations. AASHTO M 323 suggests that mixtures with 15 to 25 percent RAP should include a virgin binder that is one grade softer than normal, and that mixtures with greater than 25 percent RAP require the use of a blending chart to determine an appropriate virgin binder PG grade (McDaniel and Anderson 2001). AASHTO M 323 suggests that no change in the binder grade selection is required if the mixture RBR is below 0.25 and that blending charts should be used for virgin binder selection at higher RBR values. Blending charts are developed to determine the required virgin binder grade as a function of the asphalt binder replacement ratio based on the high and low temperature PG temperatures of the recycled binder using Equation (A.1).

$$T_{virgin} = \frac{T_{blend} - RBR \cdot T_{RAP/RAS}}{1 - RBR} \tag{A.1}$$

Where: T_{virgin} = critical temperature of the virgin asphalt binder; T_{blend} = critical temperature of the blended asphalt binder (i.e., final desired); $T_{RAP/RAS}$ = critical temperature for the recovered recycled binder; and RBR = recycled asphalt binder replacement ratio.

AASHTO M 323 (2017) also describes a procedure in which the RAP properties can be characterized for a given geographic area, and then used to develop appropriate virgin binder grade selection criteria for that area to mitigate characterization of project-specific RAP binders. When following this approach, the geographical area should be chosen considering climate and material sources, and should encompass numerous RAP stockpiles to ensure the results are generally applicable to RAP materials in the area.

The current guidelines for inclusion of recycled materials in the Superpave mix design were largely developed based on National Cooperative Highway Research Program (NCHRP) Project 9-12 (McDaniel et al. 2000) and NCHRP Project 9-43 (West et al. 2013).

NCHRP Project 9-12 systematically studied the effects of RAP in asphalt mixtures (McDaniel et al. 2000). In this research, three studies were conducted: (i): “black rock study”, which aimed to evaluate whether the RAP acts like a black rock (i.e., the RAP binder is not mobilized) or it blends considerably with the virgin binder; (ii): “binder effects study”, where the RAP and virgin binders were mixed at different proportions and the properties of the blends were evaluated; (iii): “mixture effects study”, in which the mixtures designed with different RAP contents were tested for performance evaluation. The results of NCHRP Project 9-12 led to the current guidance for virgin binder grade selection as a function of RAP content and the assumption of complete blending in volumetric calculations currently included in AASHTO M 323-17.

For the “black rock study”, mixtures were fabricated with different RAP sources, contents, and virgin binders following three methodologies: (1) by extracting the RAP binder and using just the RAP aggregates with the virgin aggregates and binder to simulate the scenario that the RAP binder does not contribute at all, (2) by extracting the binder from RAP and blending it with the virgin binder in the appropriate proportions followed by subsequent mixing with virgin and recovered RAP aggregate, thereby ensuring 100 percent blending of the RAP and the virgin binder; and (3) combining virgin aggregate, RAP aggregate, and virgin binder following typical laboratory fabrication protocols. The specimens fabricated were subjected to Superpave shear tests at high temperatures and indirect tensile creep and strength tests at low temperatures. The results demonstrate that the assumption of black rock is significantly different from the other two conditions, suggesting that RAP does not act fully as a “black rock”. Furthermore, the results from the 100 percent blending scenario where the extracted and recovered RAP was blended with the virgin binder prior to mix fabrication were generally close to the specimens fabricated following typical practice (McDaniel et al. 2000). Therefore, the authors concluded that significant blending occurs between the virgin and aged binders, leading to the current guidance in AASHTO M 323 and R 35.

The “binder effects study” was conducted to investigate the effects of the aged binder on the blend with virgin binders at different proportions. The results demonstrate that the same tests performed for virgin binders can be applied to blended binders and that using linear blending equations is appropriate, which is the basis for blending charts. Some nonlinearity begins to appear at recycled binder concentrations higher than 40 percent. The blended binder properties was classified as having three tiers, at low concentration the effects of RAP are negligible, at intermediate percentage the effects of RAP are significant but can be compensated by a softer virgin binder, and at high RAP levels a blending chart should be used (McDaniel et al. 2000).

For the “mixture effects study”, mixtures with different RAP contents (0%, 10%, 20% and 40%) were subjected to indirect tensile and shear tests at high, intermediate and low temperatures, and beam fatigue test at intermediate temperatures. For low RAP concentrations the results were close to the virgin mixture. At intermediate and high RAP levels, the high temperature performance was improved, but the intermediate and low temperatures performance was deteriorated when no change in the virgin binder grade was made (McDaniel et al. 2000). The results again supported the need of a softer binder to compensate for the increased stiffness in recycled materials at high recycled binder replacement ratios.

NCHRP Project 9-46 conducted a systematic study of the effects of RAP content and virgin binder grade on asphalt mixture performance to inform improvement of mix design procedures (West et al. 2013). A total of 30 minutes were evaluated. The mixtures were designed following the Superpave volumetric criteria, and additional performance tests were conducted to assess the dynamic modulus, resistance to moisture damage, permanent deformation, fatigue cracking and low-temperature cracking. The inclusion of RAP was found to increase the dynamic modulus of asphalt mixtures but could be mitigated with the use of a softer virgin binder. Some high RAP content mixtures did not have acceptable moisture susceptibility without the use of an antistrip additive. Rutting performance of mixtures with higher RAP contents was generally found to be better than virgin mixtures. Fatigue cracking evaluation was done by means of fracture energy tests; it was found that virgin mixtures have significantly better fracture energy than mixtures with RAP if a softer virgin binder is not used in the RAP mix. A soft virgin binder was found to be effective for mitigating the adverse effect of RAP on fracture energy. Trends in the thermal cracking results did not reveal consistent trends with respect to the material variables evaluated.

Based on the aforementioned findings of NCHRP Project 9-46, West et al. (2013) suggested a series of changes to AASHTO M 323 and R 35 as well as improved measures for recycled material quality control. The recommendations included: the use of RBR, instead of percent of RAP and RAS by mix weight as the basis for virgin binder selection; selection of the virgin binder grade should be based on the measured performance grade of the recovered recycled binder, the climate performance grade, and the desired %RAP or the performance grade of the virgin binder; inclusion of performance tests for design of mixtures with high recycled binder replacement, such as moisture damage susceptibility and low-temperature cracking test for regions prone to thermal cracking; and a more strict protocol for recycled materials sampling and characterization. The guidance for virgin binder selection as a function of RBR is included in the present AASHTO M 323. West et al. (2013) also acknowledged that consideration of fatigue cracking performance is important but no specific test was recommended.

Many state agencies follow the Superpave guidelines. However, many state DOTs still have expressed concerns about the lack of formal guidance to include recycled materials in asphalt mixtures, lack of documented information about its long-term performance, and the questionable assumption of complete blending in recycled mixtures that forms the basis of current specifications according to Copeland (2011). Therefore, some state DOTs have developed their own specifications for the inclusion of reclaimed asphalt materials on the mix design process, based on studies conducted with regional materials.

The inaccurate assumption of complete recycled binder availability has consequences, notably leading to a lower effective binder content, and therefore, lower VMA than what may be calculated. Consequently, the mixtures designed under current procedures may have insufficient virgin asphalt and lack durability.

A survey of state agencies conducted in 2019 indicates that 9 out of 38 respondents assume partial availability (4 for RAP and 7 for RAS) in their mixture design procedures (Epps Martin et al. 2020[a], Abdelaziz et al. 2021). Given the lack of an accepted method to quantify recycled binder availability from RAP or RAS, these nine agencies currently use a single RAP recycled binder availability value and a single (often distinct) RAS recycled binder availability value, irrespective of the source. Figure 30 presents the recycled binder availabilities considered for the 9 state agencies.

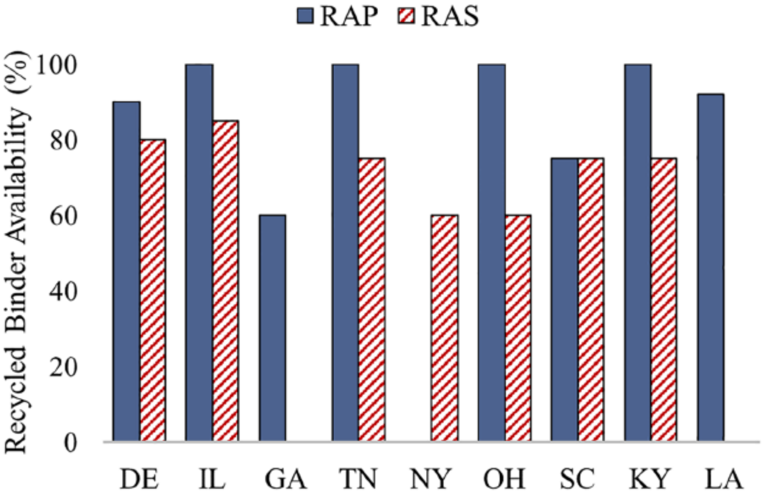

Figure 30. Recycled binder availability adopted by state agencies (Abdelaziz et al. 2020[a]).

Two methods of considering partial availability have been used by the state agencies. One method is by discounting the unavailable binder and considering a reduced binder content for RAP and RAS during the design of the mix. An example of the use of this approach is the Kentucky method (Kentucky 2019), in which the RAS binder content is discounted by 25% and the RAP binder is considered 100% available. The use of this method has implications on the mix' total binder content and also on the virgin binder selection, which is affected by the reduction in recycled binder replacement. The total recycled binder in the mix is calculated according to Equation (A.A.2).

$$\text{Total recycled binder content} = (A \times B) + (0.75 \times C \times D) \quad \text{(A.2)}$$

where: A = asphalt binder content of the RAP (%); B = % RAP in the mix; C = asphalt binder content of the RAS (%); D = % RAS in the mix.

Another method to consider recycled binder availability is by making an adjustment to the virgin binder content after the volumetric mix design, and adding virgin binder content to compensate the discounted recycled binder. Many agencies have used this method for its practicality, since it does not require modifications on the mix design process, and the existing designed mixes can be easily adapted to consider partial availability. An example of use of this method, which have been followed by other agencies, is the so-called Corrected Optimum Asphalt Content (COAC) method, implemented by the Georgia Department of Transportation (GDOT SOP2 2019). In this approach, the mixture with recycled materials is first designed according to Superpave volumetric mix design and assuming 100% availability, and the original optimum asphalt content (OOAC) is determined, then part of the RAP/RAS binder is accounted as Not Credited Asphalt Content (NCAC) (i. e. not mobilized) and virgin binder is added to compensate. The volumetric properties are not recalculated to account for the additional virgin binder and the NCAC, which may impact the Superpave volumetric requirements of the final mixture.

The Georgia approach is based on an experimental study that suggested incomplete blending in RAP mixtures (NCAT 2013). In this study, they heated RAP and observed the consistency and coating of binder on the RAP particles. Visual observation indicated that very little binder transfer occurs during dry mixing. After observing the RAP, the binder content was measured by ignition oven, and the clean RAP aggregates were collected. They then added virgin binder back to the clean RAP aggregates, in increments of 0.25 percent until they estimated that original RAP consistency was reached. The difference between the virgin binder content and the RAP binder content at the same consistency was evaluated as the effective asphalt content, and eventually an average effective asphalt content of 75 percent was selected although the average measured result was 60 percent (NCAT 2013). More recently, the value was reduced to 60 percent (GDOT SOP2 2019).

Many states also do not follow the guidance from NCHRP 9-12 and AASHTO M 323 directly for virgin binder selection. For example, Maryland DOT requires no virgin binder grade change for RAP or RAP/RAS mixtures with RBRs of 30 percent or lower and RAS with RBRs of 20 percent or lower. They require that blending charts be used to select the appropriate virgin binder grade when the RBR exceeds these thresholds (Maryland 2014). New York DOT limits RAP contents to 20 percent by weight of mixture and makes no mention of a virgin binder grade selection procedure (New York 2012). Texas DOT specifies allowable RBR values based on the specified and substitute virgin binder grades, the type of recycled materials, mixture type, and the pavement layer (Texas 2014). For HMA with a maximum RBR of 20 percent, a substitute binder with a high temperature PG that is one high temperature PG grade softer than specified and no adjustment to the low temperature grade is required (i.e., substituting PG 58-28 for PG 64-28). However, if the substitute binder is one PG grade softer in both high and low temperatures (i.e., substituting 58-28 for 64-22), the specification allows up to 30 percent RBR in the surface, 35 percent RBR in the intermediate layer, and 40 percent RBR in the base. In the NCDOT Quality Management System (QMS) manual (NCDOT 2020), tables are provided to specify virgin binder grades for RAP and RAS mixtures, without requiring blending charts. NCDOT allows up to 45 percent RBR in intermediate and base mixes, and up to 40 percent RBR in most surface mixes, with lower limits for RAS-only mixes and mixes with polymer-modified binders. A substitute binder grade is only used when the RBR is greater than 30 percent, or if RAS is used, allowing for higher recycled mixes to be used more easily than other agencies. In the case a contractor wishes to use a mixture with recycled material amounts exceeding the maximum limits, additional tests will be required to verify the PG of the recycled binder, and the contractor has the option of performing additional tests for the resultant mixtures, which should be submitted for the agency approval.

BMD+ and BMD Mix Design Approaches

Balanced Mix Design Plus (BMD+) and Balanced Mix Design (BMD) consist of asphalt mix design methods in which the mixtures are tested for performance as criteria to material selection and dosage. The BMD+ approach uses mechanistic tests in which the material's properties are measured, whereas BMD approach uses index tests that relate to the true material performance. The use of performance tests to complement the volumetric criteria in the mix design stage is understood as a necessity to ensure satisfactory material performance especially for the case of RAP and RAS mixtures where the recycled binder availability is generally unknown (Hajj et al. 2019). The performance optimization might allow the inclusion of higher RAP or RAS amounts in asphalt mixtures by compensating any possible adverse effect with changes in the constituent materials and their proportions.

A balanced mix design method for mixtures with recycled materials was proposed by Zhou et al. (2011) for the Texas DOT. In this method, the optimum asphalt content is determined by optimizing the volumetric properties, and by achieving thresholds for rutting and cracking performance, and moisture damage susceptibility. The moisture and rutting performance are evaluated by using Hamburg Wheel Tracking Test (HWTT), and cracking is evaluated using the Overlay Test (OT). The volumetric properties in this method refer to density, and the VMA is not considered, due to the uncertainties with the RAP bulk aggregate specific gravity calculation and the amount of blending of virgin and aged binders.

AASHTO PP 105-20 specifies four approaches for BMD. In approach 1, performance tests are conducted after completing volumetric mixture design to ensure satisfactory performance is achieved. Approach 2 still requires compliance with volumetric requirements but the binder content can be optimized through performance measures. Approach 3 relaxes volumetric property requirements as long as performance criteria are satisfied. Approach 4 relies solely on performance properties for the optimization of mixtures without imposing volumetric property requirements. Some states have implemented or are working towards implementing BMD procedures. Select examples follow.

Currently, BMD approach 1 is implemented byTexas DOT for premium asphalt mixtures such as porous friction courses, stone matrix asphalt, and thin overlay mixtures. The BMD is conducted through volumetric mix design along with two performance tests, namely, HWTT and OT, to evaluate mixtures' resistance to rutting, moisture damage, reflective cracking, and bottom-up cracking. For HWTT, 10,000 cycles, 15,000 cycles, and 20,000 cycles are the required minimum number of cycles to rut depth of 12.5 mm at a test temperature of 50°C for mixtures produced with high-temperature binder PG of 64°C and lower, 70°C, and 76°C and higher, respectively. Minimum critical fracture energy of 1 in-lb/in2 and a maximum crack propagation rate of 0.45 are the required limits for the OT test (Texas DOT, 2019). In addition, the Indirect tension (IDT) test at intermediate and high temperatures was recommended by Zhou et al. (2020) as a quality control/quality assurance (QA/AC) test. A 105 minimum CT index at 25°C and a minimum of 1.02 MPa IDT shear strength at 50°C were recommended as QC production acceptance criteria.

New Jersey DOT also implements BMD approach 1 but currently uses APA testing at 64°C, tensile strength ratio, OT testing at 25°C, and BBF testing at 15°C to evaluate different types of asphalt mixtures. BMD is implemented for high-performance thin overlay, bottom rich base course, high reclaimed asphalt pavement (RAP), and several other mixture types. The performance testing is required for mix design as well as plant production. Rut depth of 4.0 mm and 7.0 mm are the maximum required APA limits after 8,000 cycles of loading at 64°C for high RAP mixtures and modified or unmodified binders, respectively. For the OT test, 275 cycles and 200 cycles are the minimum number of cycles to failure for high RAP and unmodified mixtures, respectively. For intermediate and base mixtures, the minimum OT cycles to failure are 150 and 100 for high RAP mixtures with modified and unmodified binders, respectively. New Jersey DOT is considering shifting to the simpler and quicker IDT strength test at intermediate (IDEAL CT) and high temperature (IDEAL RT). Tentative thresholds have been determined and are being evaluated for possible future implementation (Bennert et al. 2020).

The Illinois DOT utilizes HWTT, Illinois Flexibility Index (I-FIT), and a modified version of the tensile strength ratio test as evaluation tools for rutting, fatigue, and moisture susceptibility, respectively. The DOT is currently in the process of implementing BMD approach 1, under which, mixtures are designed volumetrically and required to pass a specific performance criterion. The minimum limits for the mean flexibility index (FI) of plant-produced, laboratory-compacted specimens are eight and five for unaged and oven-aged specimens, respectively. For the plant-produced laboratory-compacted specimens, the limit for oven-aged specimens decreased to four. The unaged FI was kept the same as for the plant-produced mixtures. (Al-Qadi et al., 2019).

California established a framework for BMD mixtures based on performance-related specification and CalME, which is a mechanistic-empirical pavement design program. In general, BMD mixture design is applied for mixtures that are designed to be placed on very high traffic volume roads. The repeated simple shear test (RSS), BBF, and HWTT are utilized as the performance test methods. The specification criteria limits are based on the number of repetitions to 5 percent permanent strain for the RSS test and to the loss of 50 percent of the flexural stiffness at 20°C and 10 Hz from the BBF test (Harvey et al. 2014).

Despite designing most of the asphalt mixtures within the state following the Superpave volumetric mix design, Iowa DOT requires the evaluation of mixtures designed to be placed on very high traffic volume roads by HWTT for rutting resistance in line with BMD approach 1. The HWTT may be conducted by the contractor or a third-party approved laboratory at a temperature that is a function of the high-temperature performance grade of the asphalt binder. A minimum stripping inflection point of 10,000 cycles is required for plant-produced mixtures with traffic classification of Standard (S) and High (H). For a Very High (V) traffic classification mixture, the minimum stripping inflection point is 14,000 cycles. In addition to HWTT, the Iowa DOT is considering the addition of the disc-shaped compact tension test as an evaluation tool for thermal cracking under their BMD implementation efforts (West et al. 2018).

Loaded Wheel Tracking (LWT) and Semi-Circular Bend Test (SCB) along with volumetric criteria are being used the Louisiana DOT in their implementation of BMD approach (Mohammad et al., 2016). A maximum rut depth that is less than 6 mm from the LWT test conducted at 50°C and 20,000 cycles is required under the current specifications for polymer and crumb rubber modified mixtures. For unmodified mixtures, the limited increases to 10 mm under the same testing conditions as the modified mixtures. For unmodified and modified mixtures, minimum fracture energy (SCB-Jc) requirements are 0.5 kJ/m^2 and 0.6 kJ/m^2 at 25°Cfor unmodified and modified mixtures, respectively (Cooper et al., 2016).

Sabouri (2020) proposed a BMD+ framework for mixtures containing RAP. The fatigue and rutting performance of asphalt mixtures with different RAP contents (0%, 20%, and 40%) and different binder contents (optimum, -0.5%, and +0.5%) were studied utilizing the S-VECD model and Triaxial Stress Sweep (TSS) tests, as well as through FlexPAVE^{TM} pavement simulations. Based on the fatigue and rutting performance results as a function of asphalt content, the author selected the mixture binder content to allow for both satisfactory fatigue and rutting performance.

RAP and RAS Handling in the Laboratory

A uniform laboratory procedure for handling recycled materials when preparing asphalt mixture samples does not exist today. Thus, local RAP handling procedures in the laboratory vary considerably. The incorporation of RAP and RAS in the laboratory can be quite different than in plants. In the laboratory, the recycled materials are typically dried beforehand and may or may not be combined with superheated aggregate. Material preheating, mixing, and conditioning procedures can impact blending and aging of the constituent binders and thus are an important consideration.

AASHTO R 35-17 also recommends limiting the heating of recycled materials in the oven for laboratory specimen fabrication to avoid further aging, which is not terribly specific and studies suggest that longer times in the oven may improve the blending with virgin binder (Lo Presti et al. 2019). Preheating temperatures for RAP from state agencies vary considerably. New York DOT (2012) attempts to limit RAP heating by specifying that RAP is dried immediately before use, batched hot, and prohibiting RAP from being conditioned at mixing temperature for more than one hour. Maryland DOT (2014) heats RAP at 60°C for a maximum of 4 hours, and then superheats the virgin aggregates to achieve a temperature within the mixing range when the two are mixed. Texas DOT (2016) heats RAP at the mixing temperature for a minimum amount of time; however, they do not directly specify any amount of time or target temperature.

Superpave specifies mixing and compaction temperatures based on the virgin binder viscosity measured in the rotational viscometer (AASHTO M 323). However, aged recycled binder is expected to require higher mixing and compaction temperatures to achieve the same target viscosity ranges. Texas DOT specifies mixing and compaction temperatures for mixtures based on the specified binder grade and requires recycled mixes with softer binders to use the mixing and compaction temperatures of the originally specified binder (Texas 2004).

NCHRP Project 9-12 suggested heating the aggregates at mixing temperature + 10°C and conditioning the RAP at 110°C for no more than 2 hours, as higher temperatures and longer times can change the properties of some RAP materials (McDaniel et al. 2001). However, this method does not consider what occurs in an asphalt plant, and purely focuses on limiting aging of the RAP binder. Most asphalt plants do not preheat RAP. Instead, ambient temperature RAP is mixed to superheated aggregates (West 2015). Furthermore, the guidelines are only for RAP and do not include RAS.

Past research with recycled materials has incorporated a wide range of handling procedures and preheating temperatures. In the recent NCHRP Project 9-58 (Epps et al. 2020), aggregates were heated overnight at mixing temperature, and then mixed with the recycled material (RAP and/or RAS) at ambient temperature. The blend was conditioned at mixing temperature for 2 hours. The virgin binder was also conditioned at mixing temperature for 2 hours, and following the conditioning, mixed with the RAP/RAS/aggregate blend. This procedure promotes higher interaction between the recycled materials with the virgin aggregate; however, it is not representative of what happens in an asphalt plant and heating the RAP/RAS at mixing temperature for 2 hours can potentially promote further aging. Another method also used is to heat the RAP until it reaches the mixing temperature, and then start the mixing with the aggregates at the same temperature, with no further conditioning (Barton 2011).

Kvasnak (2010) evaluated four different laboratory RAP preheating scenarios. The first three scenarios included conditioning of the RAP at the mixing temperature for 30 minutes, 3 hours, and 16 hours at the mixing temperature after which the RAP was mixed with virgin aggregate conditioned to the mixing temperature. The fourth scenario included mixing room-temperature RAP with superheated virgin aggregate to mimic typical plant operations. Dry mixing was conducted without the addition of virgin binder. After mixing, the RAP binder was recovered, with the exception of the 16-hour preheated RAP scenario where the binder could not be recovered, presumably due to the changes in binder properties from such an aggressive preheating time. Significant recovered binder property changes were observed in the superheated virgin aggregate scenario so the authors proposed that RAP should be preheated to the mixing temperature for 30 minutes to 3 hours. Zhou et al. (2011) used Kvasnak's guidance to propose a two-step procedure for pre-heating RAP materials prior to introducing to virgin materials. Their procedure includes drying the RAP at 60°C overnight (12 to 15 hours) and then preheating the RAP for two hours at mixing temperature. Lab-produced samples following this procedure were compared with quality control samples from contractors, and the results were satisfactorily consistent, although the specific measure of "consistent" was not reported.

Rinaldini et al. (2014) followed the standard procedure from the Swiss Federal Laboratories for Materials Science and Technology (EMPA) to prepare samples for their blending analyses. They preheated aggregate at 185°C for 24 hours, RAP in a 1 cm layer in the pan at 130°C for 3 hours, and virgin binder at 130°C for 1 hour. The aggregate and RAP were added to the mixing bucket and mixed for two minutes before adding the virgin binder and mixing for another two minutes. Cavalli et al. (2016) explored the impacts of the mixing and short-term aging temperature, modifying the Swiss standard 640431–8a-NA, to preheat the RAP at 135°C for 1 hour, the virgin aggregates at 180°C for 3 hours, and the binder at 130°C for 1 hour. Navaro et al. (2012) compared RAP mixtures with three different intended production temperatures: 110°C, 130°C, and 160°C. To achieve those production temperatures when mixed with RAP at a consistent temperature, the virgin aggregates were preheated at 105°C, 200°C and 296°C. Their results suggested that the size of unblended agglomerations of RAP is a combined effect of production temperature and mixing time. Their work indicates that temperature has a more significant effect than mixing time. Specifically, for a 30°C reduction in production temperature the mixing time would have to be 2 to 3 times longer to produce the same level of blending.

RAP and RAS material incorporation in the laboratory often differ because RAS has a much higher binder content and stiffness than RAP. AASHTO PP 53 advised adding the RAS at ambient temperature to the hot aggregates during laboratory mixing with no adjustment to the temperature of the virgin aggregates. In contrast, Texas DOT (2016) heats RAS in the same manner as RAP, at mixing temperature for a minimum amount of time.

RAP and RAS Gradation Measurements

Characterization of the RAP and RAS gradation is important for the design of asphalt mixture aggregate structures. Conventionally, the recovered aggregate gradation, termed the white curve, is used. However, as previously noted, NCDOT RP 2019-21 recommended using the RAM gradation, termed the black curve (Castorena et al. 2022). Several other studies have evaluated and compared these two measures of RAM gradation. According to several complementary studies, the black curve contains higher amounts of large particles and fewer fines compared to the white curve (Al-Qadi et al. 2009, Yan et al. 2017, Park et al. 2020). The difference is caused by the agglomerations of adhered RAM particles. Other studies also state that agglomerations of particles reduce the surface area of recycled binder and prevents the physical interaction and the diffusion of virgin binders with the aged binder within the cluster, therefore preventing its mobilization (Stimilli et al. 2015, Bressi et al. 2015). These accounts in the literature align with the findings of NCDOT RP 2019-21 (Castorena et al. 2022).

One study suggested that the black curve does not represent the RAP as it exists in the mixture based on comparisons between the rutting resistance of a virgin and RAP mixture (Saliani et al. 2019). However, binder properties and differences in volumetric properties could have also influenced the observed performance trends. Another study reported that the RAP black curve can be influenced by the sieve analysis procedure itself (i.e., sieve size for washing, sieves used, agitation time, etc.) (Tebaldi et al. 2018). Thus, if the black curve is adopted, it is important to provide specifications for these parameters to ensure the results are reproducible.

Several researchers have examined the differences between the black and white curves of RAP sources. Guduru et al. (2020) evaluated the relationship between the difference in the percentage of fines in the black and white curve of the RAP material with the results of the fragmentation test at 5°C, which they believed to be an indicator of the number of agglomerations in milled RAP. Zaumanis et al. (2021) presented the *Chunk Index* which is based on the difference between the area below the milled RAP white curve and the milled RAP black curve. The procedure consisted of obtaining the white curve by sieving extracted RAP aggregates for 10 min dry, followed by 10 min water sieving of the entire tower. For the black curve, the RAP was dried at 40°C for at least 16 hour, and then sieved.

Recycled Binder Availability and Contribution Measurements

As discussed, most of the current methods to design asphalt mixtures with RAP and RAS assume mobilization and blending of the recycled binder with the virgin binder, presumably largely due to the lack of an accepted method to quantify the percentage of the recycled binder in a given RAP or RAS source that contributes to the mixture (Zhou et al. 2011). Numerous studies have sought to investigate this issue and a number of terms have been used to describe the state of recycled binder (e.g., degree of blending, recycled binder contribution, degree of activity, recycled binder availability). A summary of some of the more widely applied methods that have been used is presented herein. Additional methods are discussed within the literature review of the final report for NCDOT RP 2019-21 (Castorena et al. 2022). All of the studies discussed below suggest that complete blending of recycled and virgin binders in asphalt mixtures is unlikely.

Navaro et al. (2012) proposed a methodology to evaluate what was termed the degree of blending of RAP and virgin binders using image analysis. To make it possible, a virgin binder that is clear under white light and fluoresces under ultraviolet light was used in a mixture containing 70 percent RAP. Through this technique, the authors observed RAP clusters and thus, findings generally aligned with NCDOT RP 2019-21, suggesting agglomerations are the primary inhibitor of recycled binder availability.

Castorena et al. (2016), introduced a method using energy dispersive X-ray spectroscopy (EDS) scanning electron microscopy to analyze the blending of RAP and virgin materials. In this study, a tracer (titanium dioxide) was added to the virgin binder prior the production of the asphalt mixtures. Microscopy specimens were cut from asphalt specimens and the tracer made the virgin binder distinguishable from the RAP binder when analyzed by EDS. The results indicated that the method was effective to evaluate the degree of blending. The results also revealed that the blending was significantly improved by preprocessing the RAP, as well as by the mixture conditioning. This is the method that was used in NCDOT RP 2019-21 (Castorena et al. 2022).

An indirect methodology to evaluate the so-called degree of blending was proposed by Bonaquist (2007). The method consists in measuring the dynamic modulus of mixtures containing RAP, and conduct extraction and recovery of its binder to measure the dynamic shear modulus of the extracted binder. The extraction and recovery process makes the binders to be fully blended. The binder dynamic modulus is then used as an input for the Hirsch model, which allows the estimation of mixture dynamic modulus. By comparing the measured dynamic modulus (in which the degree of blending is unknown) with the estimated (in which complete blend is ensured) it is possible to infer about the degree of blending on the mixture. If the measured and estimated modulus matches, complete blending is assumed. However, the method assumes the Hirsch model accurately predicts the mixture modulus, which is questionable.

NCHRP 09-58 recently developed a size exclusion method to determine recycled binder availability (Kaseer et al. 2019, Epps Martin et al. 2020[b]). The NCHRP 09-58 method quantifies recycled binder availability based on an aggregate size exclusion method using comparative virgin and RAP mixtures. The virgin mixture is prepared using four aggregate sizes and virgin binder. The recycled mixture is prepared in the same way but with No. 4 size RAP aggregates in place of the virgin aggregates of the same size. Fabricated loose mixtures are sieved and the binder content of the No. 4 sieve-size materials are measured via ignition oven. The results are used to calculate a RAP binder availability factor (BAF). However, the use of a single size of RAP particles does not allow for assessing the impacts of RAP agglomerations that occurs over a range of particle sizes. Selecting an appropriate total binder content to avoid drain down while providing adequate aggregate coating in both the RAP and virgin mixtures is challenging for certain materials (Pape and Castorena 2021). The method also requires extensive ignition oven testing (No. 4 size RAP, No. 4 size particles sieved from the virgin mix, and No. 4 size particles from the RAP mix).

RILEM TC 264 TG 5 proposed an alternative procedure to quantify recycled binder availability that utilizes 100 percent RAP mixtures (without the addition of virgin binder) (Menegusso Pires et al. 2021). RAP is conditioned for four hours at various temperatures spanning from 70°C to 190°C, compacted, and subjected to indirect tensile strength (ITS) testing. RAP specimens with higher ITS are assumed to have higher recycled binder availability. Correspondingly, the ratio between the measured ITS at the temperature of interest and a maximum ITS assumed to coincide with 100 percent availability is reported as the degree of activity (DoA). The RILEM procedure was recently evaluated using a wide range of RAP materials from the U.S. (Abdelaziz et al. 2021, Sobieski et al. 2021). Both studies suggested the method could be used to identify the production temperature to yield maximum availability in a given RAP source. However, the studies recognized there is considerable uncertainty in defining the maximum ITS for a given RAP source given that complete availability is unlikely at any production temperature. Also, differences in ITS of a given RAP as a function of conditioning temperature can arise from sources other than availability, potentially compromising the use of ITS ratios as a measure of availability.

According to a comprehensive literature review presented by Lo Presti et al. (2019), the following factors may affect the extent of interaction and blending between virgin and recycled binders in a mixture:

- Mixing temperature: higher temperatures makes the recycled binder softer and available for blending.
- Mixing and conditioning time: longer times leads to more interaction between the binders and promotes more diffusion.
- Proportion of each binder: high percentages of RAP needs more energy to blend well.
- Aggregates shape: virgin aggregates with more angular shape helps to activate the recycled binder from the recycled material.
- Virgin binder viscosity: virgin binders with lower viscosity improve the degree of blending.
- RAP/RAS binder properties: stiffer recycled binders have more difficulties to blend well.
- RAP/RAS binder film thickness: thicker films favor the blend with virgin binders.

The above factors may affect the proportion of peripheral binder in RAP and RAS agglomerations that blend with virgin binder. However, they are not expected to be direct indicators of the extent of agglomeration in a RAP or RAS source, which as previously discussed are the primary culprit of partial recycled binder available. NCDOT RP 2019-21 (Castorena et al. 2022) and complementary studies that only peripheral mastic in RAP and RAS agglomerations is available to blend with virgin asphalt. Therefore, the above factors may affect the proportion of available binder that blends with virgin binder. However, in NCDOT RP 2019-21, tracer-based microscopy did not provide evidence of available recycled binder that did not blend with virgin binder. Therefore, it is speculated that RAP and RAS processing have greater effects on the proportion of recycled binder that blends with virgin asphalt compared to the above factors.

Influence of Recycled Materials on Asphalt Mixtures Performance

Due to the aged and embrittled asphalt binder contained in RAP and RAS, the primary performance concerns generally associated with their use are fatigue and low temperature cracking (Bennert et al. 2014, Epps et al. 2020). Compromised cracking performance in high RAP or RAS content may also be associated with a lower effective asphalt content than intended due to the unavailable binder that may act as a ‘black rock’ that generally is not accounted for. Rutting resistance is generally assumed to improve with the addition of RAP and RAS to asphalt mixtures. Numerous studies have evaluated the effects of RAP and RAS on performance. Select studies are summarized herein.

Ozer et al. (2013) studied the performance of asphalt mixtures designed for low traffic volumes with high RBRs (ranging from 43% to 64%) from combined use of RAP and RAS. The mixtures were tested for dynamic modulus, reflective cracking resistance (OT), fatigue (cyclic fatigue), low temperature cracking (SCB and DCT) and permanent deformation (HWTT). The high RBRs increased the dynamic modulus of mixtures, and as a consequence improved the rutting performance, even when a softer virgin binder was used. The results from SCB and DCT tests, both monotonic, were inconclusive and the authors concluded that the tests may not be able to differentiate the effects of the RAP and RAS. In terms of reflective cracking and fatigue resistance, increases in the RAS content dramatically deteriorated the performance, and when a softer binder was used, the performance was improved to a certain extent, but not enough to compensate to the condition of the no RAS case.

Zhou et al. (2014) conducted a review of RAP and RAS mixture field performance in Texas. The mixtures were designed following the balanced mix design method from Texas, described earlier (Zhou et al. 2011). Results were variable. The observed field cracking performance reported did not match the laboratory test's predictions and some sections with good laboratory performance performed poorly in the field, whereas some sections with poor OT results performed well in field.

Norouzi et al. (2014) evaluated two plant-produced mixtures from two sources in Vermont and Manitoba. Mixtures were produced with varying RAP content (up to 50 percent). Dynamic modulus and cyclic fatigue tests were performed. For the Manitoba case, the increase in RAP content resulted in a stiffer mixture with diminished fatigue performance. When a softer virgin binder grade was used for Manitoba high RAP mixture, the negative effect of RAP on the fatigue performance was reversed, even for 50 percent RAP content case. However, the Vermont mixtures showed no significant difference in terms of stiffness and fatigue performance for the different RAP contents evaluated. The authors speculated that this could have been due to differences in the binder characteristics of the RAP sources evaluated.

Sabouri et al. (2015) evaluated the fatigue performance of twelve asphalt mixtures, from two different sources, Vermont and New Hampshire. RAP contents of 0, 20, 30 and 40 percent were evaluated. The tests performed include BFF, OT, cyclic fatigue, and dynamic modulus. The dynamic modulus and cyclic fatigue results were used for FlexPAVE^{TM} structural pavement performance simulations. The results show that the effect of RAP on fatigue performance varied from mixture to mixture. For the Vermont mixtures, when a virgin binder PG 64-28 was used, the increase in RAP content did not affect the modulus and fatigue resistance, whereas when a softer virgin was used, the increase in RAP increased the modulus and decreased the fatigue life. This result is explained by the bigger difference between the virgin and RAP binder's PG for the softer binder case. By comparing the fatigue performance of these two mixtures it can also be said that using a softer virgin binder compensate for the RAP's stiffer binder. For the New Hampshire mixtures, the results were somewhat affected by the silo storage times. These effects were highest for mixtures with low RAP content, which the authors speculated indicated the storage caused more aging in the lower RAP content mixtures. The simulations in FlexPAVE^{TM} showed that using a thicker asphalt layer reduces the adverse effects of RAP.

Sabouri (2020) studied the performance of asphalt mixtures with three different RAP contents, 0%, 20% and 40%, and three different total binder contents, 5.3% (optimum), 6.3% and 4.8%. The mixtures gradation were kept the same for all the conditions. Cyclic fatigue tests and triaxial repeated load stress sweep rutting tests were performed for all mixtures, and FlexPAVE^{TM} to simulate the performance in a pavement structure. The results show that increasing the RAP content deteriorates the fatigue performance and improve the rutting performance, since the binder in RAP is aged and stiffer whereas the fatigue life improves whereas the rutting deteriorates as the virgin binder content is increased at a fixed RAP content. All the RAP binder was considered to be contributing in the total binder content.

Mensching et al. (2014) evaluated the low-temperature performance of mixtures with different RAP contents and different virgin binder grades through Thermal Stress Restrained Specimen Test (TSRST). Results showed that the use of softer virgin binders lowers the failure temperature, even for mixtures with 40 percent RAP.

Stimilli et al. (2015) evaluated the thermal cracking performance of mixtures containing RAP using an Asphalt Thermal Cracking Analyzer (ATCA). The RAP mixtures were fabricated with different polymer-modified virgin binders, different binder contents and RAP contents. The authors found that the use of polymer-modified binders can overcome the negative effects of increasing RAP content on thermal cracking performance. Moreover, increasing the binder content was found to lower the critical failure temperature, but also decrease the critical failure strength, because the mixture become softer.

The aging of asphalt binders is also affected by the amount of recycled asphalt in the mixtures. Because the recycled materials are already aged, the aging susceptibility of mixtures with RAP or RAS is generally lower compared to mixtures without RAP (Elwardany 2017, Mocelin et al. 2019, Saleh et al. 2020).

All of the aforementioned studies focused on the effect of RAM content, virgin binder content at a fixed RAP content, and the use of soft binders to negate the effects of RAM on mixtures volumetrically designed using the conventional Superpave approach. The aforementioned studies did not modify the design of the aggregate structure as a means to try to counteract the negative effects of RAM and/or measures used to improve cracking resistance. However, the aggregates play a major role on the asphalt mixture performance, especially rutting resistance (Vavrik 2000). It becomes especially important when solutions such as increased binder content and/or selection of a softer virgin binder, are used to compensate for the higher stiffness or RAM materials.

A few studies attempted to assess the effects of recycled binder contribution on performance. Xu et al. (2019) studied the effect of blending on the performance of mixtures with high RAP content. The authors promoted different degrees of blending for mixtures with varying RAP contents by changing the mixing temperature and estimated the degree of blending by using the indirect method proposed by Bonaquist (2007). The authors reported that the extent of blending varied from 75 percent to 95 percent for the RAP contents and temperatures selected. The authors reported that higher binder blending may improve the cracking performance and decrease the rutting susceptibility. Wen and Zhang (2016) produced RAP mixtures that were expected to have different levels of blending by utilizing different laboratory mixing, conditioning, and compaction procedures. They found that diffusion of the virgin and RAP binders within the asphalt mixture changes the dynamic modulus and improves the fracture resistance of RAP mixture. However, aging level differences imposed by the different mixture production procedures could have confounded the inferences of true differences in blending levels using the mechanical properties measured in both the Wen and Zhang (2016) and Xu et al. (2019) studies.

Jacques et al. (2016) evaluated the effects of silo storage time on the performance of RAP and virgin mixtures. Performance testing results indicated that both virgin and RAP mixtures aged with an increase in silo storage time. However, the RAP mixtures experienced greater changes in dynamic modulus and cyclic fatigue performance with silo storage time than the virgin mixtures, which could not be explained by oxidation levels. Therefore, the authors attributed the changes in performance in the RAP mixtures with silo storage time largely to diffusion of the virgin and RAP binders while in the silo.

Measures to Reduce Variability and Improve the Quality of RAP and RAS

Stockpiling, Processing, and Fractionation Practices

Variability in RAP and RAS stockpiles can be caused by different sources including the presence of deleterious materials, RAP/RAS obtained from multiple sources and mixed in a single stockpile, RAP from different asphalt layers (i.e., base, intermediate, and surface courses), and RAP from the original asphalt layer which had been treated with patches, chip seals, and other maintenance treatments (West 2015). Poor stockpiles management has also been raised as one of the reasons that agencies hesitate to allow higher amounts of recycled materials in asphalt mixtures (West et al. 2013). Understanding best practices for recycled material stockpiling, processing, and quality control may help to improve measures to limit variability within the state.

Contamination of RAP and RAS should be inspected prior to its acquisition and stockpiling. When collected from the field, RAP materials should be inspected to check the presence of deleterious materials, such as excessive dirt, rubbish, or vegetation. For manufactured waste RAS, little or no inspection or separation of contaminants is necessary, whereas for post-consumer RAS more caution should be taken since this material can contain asbestos and other deleterious materials from construction such as wood, metal, and plastic (Zhou et al. 2012).

Best practices suggest that RAP and RAS should be stockpiled separately, and different RAP and RAS sources should be isolated if possible, considering the space limitations of the plant (West 2015). Also, it is recommended to use arc-shaped, uniformly layered stockpiles when storing milled or unprocessed material, and conical or low-sloped stockpiles when storing processed material. The National Asphalt Pavement Association (NAPA) best practices for RAP and RAS Management (2015) further suggests paving stockpiles resting area to minimize contamination, covering the stockpile to minimize accumulation of moisture and preventing the formation of clumps, and not driving heavy equipment on the stockpile to avoid compaction. If the source of RAP/RAS changes from the one used to design the mix, testing should be performed to verify its compatibility with the current mix design.

The RAP and RAS stockpiles can be either captive or continuously replenished, depending on the agency requirements. Some agencies require that recycled materials from different sources is stockpiled separately, termed captive. No additional material can be added to a captive stockpile once it is built and characterized. In continuously replenished stockpiles, the addition of new RAP/RAS is allowed. Although the captive approach is more conservative, the continuously replenished stockpiles are also considered appropriate as long as the consistency can be verified through a quality control plan (West 2015). The NCDOT allows the addition of recycled materials from different sources as long as the materials are processed and uniformly blended for stockpiling, prior to sampling and testing, and the differences in the characteristics when compared to the material used for the mix design are within certain limits, which depends on the amount of material in the asphalt mixtures (NCDOT 2020).

The NCDOT QMS manual (NCDOT 2020) requires the processing of the RAP to eliminate clusters of material bigger than 25 mm, whereas for the RAS, processing should ensure that the particles are finer than 9.5 mm. Screening before crushing is a good practice for processing RAP, which consists of RAP separation based on size, this is important since it increases control and reduces variability. Also, crushing to improve the consistency, in most cases either 1/2 in or 3/8 in, to produce material with a suitable top size to use in new asphalt mixes. Another important consideration is choosing the maximum particle size for the crushing operation given that crushing to smaller top sizes will increase the dust content and limit the amount of RAP that can be used in the new mix design (West 2015). Finally, before processing stockpiles, blending and homogenization should be conducted for the case of a multiple-source stockpile, which contributes to uniformity.

Fractionation to minimize segregation of RAP particles is a practice where processed RAP is divided into different size fractures, which yields better consistency and more flexibility to achieve mix design requirements. Vavrik et al. (2008) compared the consistency between the dynamic modulus of plant-produced asphalt mixtures containing RAP and virgin mixtures and showed that, especially for high RAP contents, fractionation of RAP in fine and coarse fractions is fundamental to achieve consistency. The NCDOT previously required that if the RAP content exceeds 30 percent in a mixture, this material should be fractionated in a minimum of two components, fine and coarse (NCDOT 2020). However, that requirement was omitted in 2023.

Good RAP processing practices involve a) collection, in which dirt, vegetation, and other possible construction debris should be avoided; b) sorting of materials and homogenization, to ensure a uniform stockpile; c) separation or break of large agglomerations of material to a proper size to use in asphalt mixtures; d) reduction of the particles size to attend the mixture in which it will be used, and e) stockpiling (West et al. 2013).

Proper RAS processing practices involve: a) collection in a way that avoids contamination; b) sorting, to remove unwanted debris; b) grinding, usually in pieces smaller than 0.5 inches, to promote better mixing and mobilization of the binder; c) screening, to remove large pieces that may not be ground; and d) storing in stockpiles (Zhou et al. 2012). RAS is usually less variable compared to RAP. Drying of RAS should be conducted with extra caution since this material can absorb a significant amount of water. Ideally, the stockpiles should be covered to avoid excessive water (Zhou et al. 2012).

Quality Control Practices for RAP and RAS

As discussed, RAP and RAS materials can be obtained from multiple sources, which may vary significantly. Therefore, it need to be processed to become a homogeneous material. The homogeneity and consistency of these materials should be constantly monitored by quality control process to achieve the greatest benefits.

The NCDOT’s QMS manual requires the RAP and RAS materials to be sampled and tested for binder content and recovered washed aggregate gradation at the beginning of production, and weekly thereafter. This sampling and testing must be done by certified quality control and quality assurance personnel. The minimum amount of material required is 25 lbs, which should be quartered to the appropriate test sample size. The moisture content on the recycled materials must also be measured at the beginning of production and daily during production for quality control and to ensure the right proportions of each material in the resultant asphalt mixture (NCDOT 2020).

To control the quality and consistency of RAP materials, West (2015) stated the best practice is to sample and perform at least one set of tests per 1000 tons of RAP used, which is higher than what is required for virgin aggregates, and that a minimum of 10 tests per stockpile should be performed for consistency evaluation in terms of binder content and gradation (West 2015). The NCDOT QMS requires a minimum of one set of tests per 1000 tons of RAP with at least 5 tests per stockpile (NCDOT 2020). The recommended maximum standard deviation for quality control are 0.5 percent for asphalt content and, in terms of gradation, 5 percent for the material passing the median sieve and 1.5 percent for the material passing 0.075 mm sieve (West 2015).

Some of the processes for quality control of RAP materials also applies for RAS, with the consideration that RAS has some particularities, such as the higher presence of deleterious materials. The characterization required in terms of mix design are binder content, gradation, aggregate specific gravity, the determination of deleterious materials content, and in some cases the recovered binder properties. A minimum of three tests are recommended for each property, since RAS is usually not as heterogeneous as RAP (West 2015).

The samples of recycled materials for quality control testing can be taken either from the stockpile or from the cold feed conveyor belt. It is easier to obtain a representative sample from the conveyor belt, so this approach is preferable. In case the sample is to be obtained from the stockpile, it should be taken from different locations around the stockpile and to study variability. Ideally, the characterization should be performed when the stockpile is built, before a crust forms on the stockpile (NCDOT 2020, West 2015). The ASTM D75/D75M (2019) standard describes a method to take samples from a stockpile, in which a loader is required to take a full load of material from the stockpile portion that is being fed into the asphalt plant, and then with that material create a smaller sampling pile, that should have the top flattened and the samples should be obtained from equal amounts across each quadrant of the sampling pad. A common practice for RAS stockpiles is to mix the material with some sort of fine aggregate, to minimize agglomerations, but the initial characterization of the RAS material is recommended to be performed prior the blending (West 2015).

RAP and RAS Handling in the Asphalt Plant

There are many ways that recycled materials are incorporated into plant operations (Kandhal and Mallick 1997, Williams et al. 2019). Recycled materials cannot be treated as aggregates because the heat from the burner flame will result in smoking of the residual binder, which can damage equipment and stop operations. To combat smoking, ambient temperature RAP/RAS is typically added to superheated virgin aggregate. To add the RAP into the plant, a wide variety of plant modifications and configurations have been developed, each with their own strengths and weaknesses. Different plant configurations will result in different lengths of contact and mixing between RAP, virgin binder, and aggregates (Kandhal and Mallick 1997, Williams et al. 2019).

Asphalt plants can be divided into two broad categories: batch plants and drum plants. Batch plants add measured amounts of components to a pugmill and then mix and discharge before repeating the cycle in batches. Batch plants contain a separate aggregate dryer for the virgin aggregates. Drum plants operate a continuous feed of material into and out of the mixer, dispensing wet aggregate into the mixer and drying it before adding asphalt. Drum plants are prevalent in most parts of the US, and in North Carolina specifically, with drum plants comprising more than 80 percent of the 161 asphalt plants approved by NCDOT (Whittington 2018). Drum plants are considered to be more suited when using recycled materials, and can handle mixtures with higher recycled material contents than batch plants (NCDOT 2020, Kandhal and Mallick 1997). The Massachusetts Department of Transportation (2015) goes as far as to specify a limit of 20 percent recycled materials (including RAP, manufactured waste RAS, and processed glass aggregate) by total weight of mixture in a batch plant, but they allow up to 40 percent in a drum plant. A survey from 2009 indicates that at least four other states also have lower limits for RAP usage in batch plants than drum plants (Copeland 2011).

In a batch plant, recycled materials can be introduced in at least five different ways, as outlined by Kandhal and Mallick (1997). RAP and/or RAS can be mixed with virgin aggregates in the hot elevator, in a mixed hot bin, a separate hot bin, in the hopper, or in the pugmill. Each of these methods exposes the recycled materials to the virgin aggregate and heat for a different amount of time. The method in which the recycled materials are added directly to the pugmill from its own hopper would result in very little time of contact with the virgin aggregates, while mixing the recycled materials with virgin aggregate in a hot bin results in a much longer time of contact. It is also suggested that silo storage may be helpful to increase the time the recycled binders are conditioned at elevated temperature to promote blending.

Drum plants include many different configurations, including parallel flow and counter flow options, which describes how the material travels with respect to the burner flame. Some configurations have isolated mixing areas to help keep the recycled material and virgin asphalt further from the burner flame. The aggregate dryer can be separate from the mixer, or it can be an all-in-one apparatus. Some drums even have extra barrels; double barrel drums are relatively common and triple barrel drums exist as well (Kandhal and Mallick 1997). Each of these plant configurations introduce differences in the heating times and temperatures of the RAP, as well as mixing times, and temperatures of the virgin aggregates, which all affects the extent of blending, allowing different lengths of interaction between the recycled material, virgin binder and aggregates (Williams et al. 2019).

Although the introduction of RAS and RAP in some asphalt plants is similar, some plant modifications have been found to be helpful to incorporate RAS in mixture production, such as to use feed bins with steeper walls to prevent material from agglomerating and forming bridges; use load cells to control the feed rate by weight, since usually a small amounts of RAS are added to the mixes; and cover the RAS conveyors or configure it in a way that the RAS is covered by RAP in the feeding process, to avoid RAS to blow out of the conveyor, since RAS materials are relatively light (Williams et al. 2019).

Summary

The literature demonstrates that the majority of state agencies assume complete recycled binder availability in their mixture design procedures. The states that do consider partial recycled binder availability adopt fixed values, irrespective of the source and do not account for the unavailable recycled binder rigorously when interpreting the volumetric composition of asphalt mixtures. BMD and BMD+ approaches offer a means to ensure adequate performance is achieved in RAM mixtures even when recycled binder availability is unknown. However, the majority of implemented BMD procedures still rely to volumetric proportioning and property requirements to some extent, rendering the issue of recycled binder availability still relevant. A wide arrange of methods have been employed to investigate and quantify recycled binder availability and blending. Despite their differences, all generally suggest complete blending is unlikely. Much of the recent literature, including the recent NCDOT RP 2019-21, suggest that partial RBA is a consequence of agglomerations of adhered RAP and RAS particles. The extent of this agglomeration and, in turn, recycled binder availability can be inferred from comparative sieve analysis of RAP and recovered RAP aggregate.

Numerous studies have evaluated the role of RAP and RAS on mixture performance. However, the majority of these studies focus on the effect of RAM content, virgin binder grade, and/or virgin binder content effects on mixtures designed using the conventional Superpave approach.

These studies generally suggest increasing RAP and RAS contents increase the modulus and rutting resistance of asphalt mixtures but decrease the cracking resistance. The use of a softer virgin binder and/or increased virgin binder content alleviate the negative effects of RAM on cracking resistance but also can have detrimental effects on rutting resistance.

The recent NCDOT RP 2019-21 introduced the AAMD method to adjust mixture design procedures for recycled binder availability and the role of RAM agglomerations on the design of the aggregate structure. The method was found to improve the cracking resistance of asphalt mixtures containing RAP and RAS without having a detrimental effect on rutting performance compared to the conventional volumetric mixture design. However, the AAMD method developed in NCDOT RP 2019-21 was only evaluated using three mixtures and thus, merits further evaluation using a broader set of materials and performance measures.

Also noteworthy, past research demonstrates considerable variability in the rheological properties of RAP binders and recycled binder availability of RAP stockpiles in North Carolina. The literature suggests a wide array of measures that promote the consistency of RAP and RAS materials. An understanding of if and how these methods are used by asphalt plants in North Carolina under the current specifications is needed to guide potential specification changes that could promote improved consistency.

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APPENDIX B: PLANT OPERATIONAL REVIEW RESULTS

The operational review questionnaire and corresponding detailed results of the eight plants that were interviewed are provided in this appendix. The plants have been designated A through H to preserve the anonymity of the participants.

Plant Operational Review Questionnaire and Responses

Topic 1: General Asphalt Plant Information

1. What type of asphalt plant mixing configuration does your facility use (e.g., double-barrel counter-flow drum)?*
2. How do you introduce RAP into the mixing process, please be as specific as possible (e.g., we have a RAP collar approximately 1/3rd of the distance down the mixing drum)? This will most likely be the same for all plants, unless there is a batch plant.
3. How many asphalt tanks do you have?* If multiple, what binder grades do you typically use?
4. What is the typical range of RAP contents that you use in your mixtures? Why?
5. How many cold feed bins do you have for RAP and/or RAS?
6. Do you currently use or have you recently (last 12 months) used RAS? Why or why not?

Topic 2: Recycled Material Sources and Stockpiling

1. What sources of recycled materials do you accept? Only state-owned roads? Private roads? Parking lots? Plant waste? Post-consumer RAS? Manufactured waste RAS?
2. How many stockpiles of unprocessed RAP do you maintain? If multiple, what is the difference among the stockpiles (e.g., project, or source specific)?
3. How many stockpiles of processed RAP do you maintain? If multiple, what is the difference among the stockpiles (e.g., coarse vs. fine, size, source, etc.)
4. Are any of the recycled material stockpiles visually contaminated. If so, with what?* (Trimat should infer this without asking the plant)
5. Are your RAP stockpiles captive, meaning that no additional material is added once built and tested, or continuously replenished? If it depends, please elaborate.
6. What efforts are made to homogenize and/or avoid segregation of unprocessed and processed recycled material stockpiles?
7. What is the maximum recycled material stockpile height that you see (approximate)? If it varies according to the stockpile material (e.g., unprocessed, processed, RAP vs. RAS), please describe for each stockpile type.
8. *If the plant uses RAS*, do you accept post-consumer and/or manufactured waste shingles?
9. *If the plant uses RAS*, how many processed and unprocessed RAS stockpiles are maintained?
10. *If the plant uses RAS*, are the stockpiles captive or continuously fed?
11. *If the plant uses RAS*, is the RAS mixed with other material (fine aggregate, RAP) when stockpiled?

Topic 3: Recycled Material Processing

1. Who performs crushing of your RAP? If known, what type of crusher is used (e.g., roller or mill-type breakers, compression-type crusher, milling machines)
2. How often do you crush RAP?

3. Do you fractionate your RAP?
4. Do you avoid processing operations in certain weather conditions? If so, what conditions?
5. Do you have any measures in place to minimize recycled material stockpile moisture content?
6. How long are RAP materials stockpiled for after crushing and before use?
7. *If the plant uses RAS*, who performs grinding of your RAS?
8. *If the plant uses RAS*, how often is grinding performed?
9. *If the plant uses RAS*, how and when is the RAS cleaned (i.e., deleterious materials removed)? At the source? During processing?
10. *If the plant uses RAS*, what grind size is used when processing?
11. *If the plant uses RAS*, how long are RAS materials stockpiled for after grinding and before use?

Topic 4: Sampling and Testing

1. How and where do you sample from the recycled material stockpile for QC testing (e.g., random, combine material from multiple locations, from the location the material will be batched from for production; using front-end loader, shovel, etc.)?
2. Do you measure the asphalt content, recovered aggregate gradation, and/or recycled material moisture content more frequently than required by the NCDOT? If so, how frequently and why?
3. Do you ever characterize the extracted and recovered binder properties from your recycled material stockpiles? If so, when/how often?
4. Would you be willing to share QC records for the research team to evaluate inherent variability in recycled material stockpiles with time?

Topic 5: Asphalt Mix Production and Silo Storage

1. How do you transfer recycled material from stockpiles to cold feed bins? (e.g., from a single side, combine from multiple locations, etc.)
2. Is any inline plant screening and/or crushing of recycled materials performed during mix production? If so, please describe.
3. How do you ensure the recycled material is dried during mix production? Do you vary production conditions as a function of the recycled material moisture content?
4. How long do you store produced mixture in the silo? Please indicate typical and maximum allowable storage times.
5. *If the plant uses RAS*, are processed RAS and RAP or RAS and fine aggregate combined prior to feeding into the asphalt plant? If so, please describe.
6. *If the plant uses RAS*, are there any measures in place to remove residual nails, fibers, or deleterious materials during production?

Table 15. Topic 1 Responses

Plant	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Location	Piedmont	Piedmont	Coastal	Mountains	Coastal	Coastal	Coastal	Piedmont
TOPIC 1								
Plant Type	Counter flow single	Double Barrell	Counter flow single	Modified batch	Modified batch to work as a hybrid	Double Barrell	Double Barrell	Counter flow single
Manufacturer	Gencor	Astec	Gencor	Warren brothers. Herman grant. Estee mixer	Cedar Rapids	Astec	Astec	Astec
How is RAP introduced?	Rap collar, approx 15' from flame	Rap collar in outer drum above flame	Rap collar approx 1/3 up drum	Rap collar at end of drum before exiting into pug mixer	Rap collar about 5 feet from end of drum near flame	Rap collar in outer drum above flame	Rap collar in outer drum above flame	Rap collar approx 10 feet from flame
Number of liquid tanks	3	2	2	2	1	2	2	3
Grades of binder	58 and 64	58 and 64	All 64	64 and 76	58	58 and 64	58 and 64	64 and 76
Typical RAP contents	20-30%	20-30%	10-20%	20-30%	20-30%	30-40%	20-30%	20-30%
# RAP/RAS Cold Feed Bins	2	2	1	2	2	2	2	3
RAS Used?	yes	no	no	no	yes	no	yes	no

Table 16. Topic 2 Responses

Plant	A	B	C	D	E	F	G	H
Location	Piedmont	Piedmont	Coastal	Mountains	Coastal	Coastal	Coastal	Piedmont
TOPIC 2								
Stockpile Sources	State roads,Private,Parking lots,Plant waste	Private,Parking lots,Plant waste, State roads	Plant waste,Parking lots,Private, State roads	Plant waste,Parking lots,Private, State roads	Plant waste,PRAS	Private,Parking lots, State roads,Plant waste	PRAS,MRAS, State roads,Private,Parking lots,Plant	Only State roads,Private,Plant waste,Parking lots
Number of Unprocessed Stockpiles	1	1	2	1	4	1	2	2
Explanation		Unprocessed rap. About 100 ft tall	One pile is everything (scrap) and one is millings	Unprocessed	Millings, waste pile, lower ac coarse rap for base and binder, Rainy day pile	Unprocessed rap. About 75 - 100 feet tall, collects everything	Unprocessed RAP and PRas	One with everything and one with surface millings only from their projects
Number of Processed RAP Stockpiles	1	2	1	1	4	3	1	3
Explanation		Fine - 3/8" minus; Coarse 5/8" minus	Crushed milling pile using 3:1 ration (millings to scrap)		2 - coarse piles, 2 - fine piles	Fine - -3/8"; Coarse 3/8 - 9/16; combined pile	RAP, minus 1/2"	Fine Rap -1/4"; Coarse 1/2 - 5/8; Combo - -5/8"
Are stockpiles contaminated?	no		yes.	no	no	no	yes	no
Explanation			some raw aggregates present				soil present	
Are RAP stockpiles captive?	always being replenished	no	no	no	no	replenished daily	replenished daily	replenished daily
Explanation		Constantly replenished	constantly replenished	constantly replenished	constanly replenished			
What efforts are made to avoid segregation of stockpiles	Loader works the pile each night		Pile is fairly tight, they use a track hoe to break it up	Dozer or track hoe is brought in when needed	Occasionally they will run RAP piles through an onsite crusher to make it more consistent.	Pile will be worked with a loader daily then a dozer will come in occasionally	Dozer onsite at al times. Piles are worked as needed	Crushing sub works the pile and combines material during crushing. Loader works pile daily
Max stockpile height	RAP-30'; Unprocessed RAP - 75'; RAS - 20'	35' fine; 20' coarse	30 ft processed, 100 ft unprocessed	50 feet - both	50 feet	Fine - 30'; Coarse - 25'; Combo - 30'	40 feet	50 feet

Table 17. Topic 3 Responses

Plant	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Location	Piedmont	Piedmont	Coastal	Mountains	Coastal	Coastal	Coastal	Piedmont
TOPIC 2								
RAS PLANTS ONLY								
Are RAS stockpiles captive?	Continuously fed by supplier				no, continuously fed		Processed - yes, unprocessed piles are fed consistently from contractors, etc. PRAS and MRAS	
How many RAS piles are present?	1				1		2 - one unprocessed and one processed.	
Is RAS mixed with other materials when stockpiled or when introduced into plant?	no				no		no	

Table 18. Topic 3 Responses

Plant	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Location	Piedmont	Piedmont	Coastal	Mountains	Coastal	Coastal	Coastal	Piedmont
TOPIC 3								
Who performs crushing?	Smith Rowe	Empire, Blackrock	Blackrock	Blackrock	Blackrock	Blackrock	Blackrock	Blackrock
Crusher Type	Impact	Impact	Rotary	unknown	unknown	Portable impact (McClosky 144v3)	not sure	Rotary style
How often is RAP crushed?	once a year	3 times a year	once a year	2-3 times a year	1-2 times a year	1-3 times a year	1-2 times a year	2-3 times a year
Is RAP fractionated?	no	yes	no	sometimes	no	yes	no	yes
Is crushing avoided in certain weather?	yes	yes	yes.	yes	yes	no	not in heavy rain	yes
Explanation	rain	not in freezing or heavy rain	rain	heavy rain	heavy rain	any weather		not in heavy rain
Any measures in place to minimize moisture in RAP?	sloped site	sloped stockpile	stockpile is tight and drains well	site is sloped and paved	no	sloped site	sloped site. Not paved	sloped site, not paved
How long is RAP stockpiled?	6 month to a year	3-4 months	3-6 months	6 months	6 months	3-4 months	6 months	used pretty immediately
RAS PLANTS ONLY								
Who performs grinding?	A1 Sand Rock				pre-crushed from Premier		Sandrock	
How often?	continuously by sub				not sure		1-2 times a year	
How is RAS cleaned?	Precleaned by sub. Pile is clean except for some				at source		cleaned prior to arrival	
What size is RAS grind?	minus 3/8"				minus 3/8"		Minus 3/8"	
How long is RAS stockpiled?	2 months. Small pile				depends. Always have about 100 tons onsite		6 months	

Table 19. Topic 4 Responses

Plant	A	B	C	D	E	F	G	H
Location	Piedmont	Piedmont	Coastal	Mountains	Coastal	Coastal	Coastal	Piedmont
TOPIC 4								
How and where do you sample from the recycled material stockpile for QC testing (e.g., random, combine material from multiple locations, from the location the material will be batched from for production; using front-end loader, shovel, etc.)?	load face only using front end loader and NCDOT method	load face only using front end loader and NCDOT method	load face only using front end loader and NCDOT method	load face only	load face only, using NCDOT method	load face only	Load face only with front end loader and NCDOT method	cold feed belt with shovel
How often is RAP sampled?	Weekly; daily when crushing	Weekly; daily when crushing	weekly	weekly, daily when crushing	weekly	weekly, more when crushing	weekly during NCDOT work	weekly
Do you measure the asphalt content, recovered aggregate gradation, and/or recycled material moisture content more frequently than required by the NCDOT? If so, how frequently and why?	Daily when crushing	Daily when crushing	Daily when crushing	Daily when crushing	Daily when crushing	when crushing	no	Daily when crushing
Do you ever characterize the extracted and recovered binder properties from your recycled material stockpiles? If so, when/how often?	no	not recently	no	One time, via NCAT over 5 years ago	no	no	no	6-8 times. Haven't done recently

Table 20. Topic 5 Responses

Plant	A	B	C	D	E	F	G	H
Location	Piedmont	Piedmont	Coastal	Mountains	Coastal	Coastal	Coastal	Piedmont
TOPIC 5								
Is RAS/RAP loaded from multiple locations in the stockpile or one face?	changes faces from day to day	Uses one load face	multiple locations	uses multiple locations along load face	one face	works along one face	Load face only with front end loader and NCDOT method	works along face of pile continuously
Does RAP get screened during production?	yes	yes	yes.	yes	yes. Scalping screen on shaker bin	yes	yes	yes
Explanation	3/8" screen	shaker screen	3/4" screen	3/4" screen deck		screen deck at the end of the belt	2" screen on the deck	5/8" screen deck
How do you ensure the recycled material is dried during mix production? Do you vary production conditions as a function of the recycled material moisture content?	All plants use a similar process to determine when the RAP and RAS are dry and it is usually based on temperature at the end of the drum or in drag slat. At start up, they watch the temp and when they get to the point where they are consistent, they start full production.							
How long do you store produced mixture in the silo? Please indicate typical and maximum allowable storage times	overnight - 50% of the time	5-10 percent of the time	rarely	overnight pretty often. Once a week	no silos	12-16 hours fairly often	12-16 hours a few times a year	overnight, 70% of the time
RAS Plants - how are deleterious materials removed?	removed by crushing sub prior to delivery				removed at source		magnet is used to remove nails, but most of the shingle materials are prescreened before being dropped off	

APPENDIX C: SIEVE ANALYSIS PROCEDURE TO QUANTIFY RECYCLED BINDER AVAILABILITY

Note that Steps A through C can also be used be applied to RAS to obtain its black curve.

A. RAP Drying

1. Place damp RAP in large aggregate pans such that the thickness does not exceed 2 in.
    - A 5-gallon bucket of RAP must be dried in 4 large aggregate pans or 2 at minimum.
2. Put pans in an oven at **60°C** until the RAP reaches a constant mass.
    - Most samples are dry 12-15 hours, however, some have required as long as 18 hours or more, depending on the moisture content of the stockpile.
3. Remove pans from the oven and stir.
    - While the RAP is still warm (around **5 minutes** after drying), manually sieve the RAP pans over a sieve one size larger than the RAP maximum aggregate size.
    - Spread the RAP in the metal pans and allow it to cool before returning it to a labeled **dry** plastic bucket.

B. RAP Batching

1. Use an aggregate splitter to separate a bucket of RAP into weights as close to the batch weight as possible.
    - Follow Method A in AASHTO R 76.
2. Use a scoop for small adjustments in the sample weight to achieve the target RAP weight and place it in a pan or bowl. The required sample size should be in accordance with AASHTO T 308 plus 100 to 150 grams (to account for any losses during washing, sieving, or material transfer).
    - Record the dry weight for the batched dry RAP at room temperature

C. RAP Washed Sieve Analysis (Black Curve Gradation)

1. Wash the RAP sample.
    - Two sieves will be used for the washing process, the top sieve should be the No. 16 (1.18 mm) mesh sieve and the bottom sieve must be the No. 200 (75 µm) mesh sieve.
    - Record the dry weight of the dry RAP sample. Place the sample in a bowl and add enough water to cover the material completely, and then stir it gently.
    - The water color will get dark because of the fine particles floating. Start by pouring the water from the bowl through the sieves and washing the fine particles over the sieves until the water coming out under the sieves is clear. Be careful to not lose any material.
    - Change the water in the bowl and repeat this process until the water in the bowl gets clearer.
    - Once the water is clearer, wash the material from the sieves into a clean pan. **Decant the excess water from the pan back to the sieves if necessary. This step is important to limit the amount of water in the pan later for drying.**
    - Start washing small portions of the coarser particles over the nest of two sieves. Wash it thoroughly while being careful not to lose any of the material. When the water coming out under the sieves is clear the material retained in both sieves can be dumped into the pan.
    - Wash all of the RAP material by repeating this process with small portions.

- Spread the sample in a pan or pans to avoid the formation of agglomerations during the drying process as shown in Figure 31 (a). Do not put the pan in the oven without spreading the sample as illustrated in Figure 31 (b).
- Dry the sample to a constant weight in an oven at a temperature of 100°C. While the samples are still hot, any weak agglomerations that may have formed during the drying process, as well as pre-existing weak agglomerations, shall be broken apart by hand similarly to the preparation of G_{mm} samples.

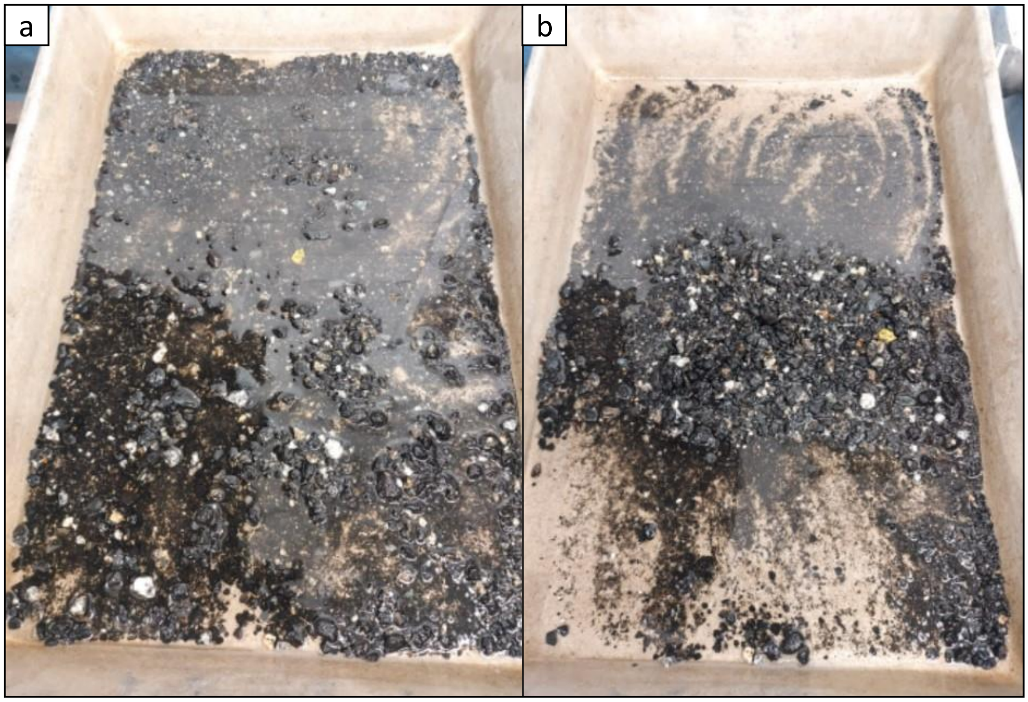

Figure 31. Washed RAP sample (a) after spreading and (b) without spreading.

2. Sieve and record the gradation of the entire RAP test sample after drying according to AASHTO T 30. Calculate the total weight and ensure it passes verification requirements in AASHTO T 30.
    - Spread the sample in the pans in the same way as in Step C 1.
    - Make sure to remove all of the materials from the pan after drying; these materials will be used in Step D below.

D. Recovered Aggregate Washed Sieve Analysis (White Curve Gradation)

1. Use the ignition oven to obtain the extracted aggregates from the RAP used in Step C according to AASHTO T 308.
2. Wash the material following the procedures described in Step C1.
3. Dry the sample to a constant weight in an oven at a temperature of 110°C, then accurately weigh and record.
4. Sieve and record the gradation of the entire test sample after drying according to AASHTO T 30. When interpreting the gradation, incorporate the dust lost during the first washing of the RAP from Step C.

E. Calculations

1. Calculate the total volume of mastic in a sample of RAP containing 100 g of aggregate using Equation (C.1).

$$V_{mastic} = V_{be} + V_{filler} = \frac{P_{be}\left(1+\frac{P_{be}}{(100-P_{be})}\right)}{G_b} + \frac{P_{200}}{G_{sb}} \qquad \text{(C.1)}$$

Where: V_{mastic} = volume of mastic in a mix with 100 g of aggregate (cm^3); V_b = binder volume (cm^3); V_{filler} = volume of filler (cm^3); P_{be} = effective binder content; G_b = binder specific gravity; G_{sb} = bulk aggregate specific gravity; and P_{200} = percent passing the No. 200 (0.075 mm) sieve for the recovered aggregate.

2. Using the white curve, calculate the average mastic film thickness in the RAP, *t*, via optimization to minimize the absolute difference between the volume of mastic calculated using Equation (C.2) and the total known volume of mastic calculated using Equation (C.1). Equation (C.2) computes the volume of mastic in the RAP by assuming spherical aggregate particles are coated in a concentric shell of mastic with a uniform thickness equal to *t*.

$$V_{mastic} = \sum N_i \times V_i = \sum \frac{P_{i+1}-P_i}{G_{sb}\times\rho_{water}\times{}^{\pi}\!/_{6}\times\left(\left(d_{i+1}+d_i\right)/2\right)^3} \times \frac{\pi}{6}\left[\left(\frac{d_{i+1}+d_i}{2}+2t\right)^3 - \left(\frac{d_{i+1}+d_i}{2}\right)^3\right] \qquad \text{(C.2)}$$

where: V_{mastic} = volume of mastic in a mix with 100 g of aggregate (cm^3); N_i = number of particles of size i; V_i = volume of mastic coating aggregate of size i (cm^3); P_i = recovered aggregate percent passing sieve size i; and d_i = sieve size (mm).

3. Calculate the volume of peripheral (i.e., available) mastic coating the RAP particles using Equation (C.3) by inputting the black curve and calculated *t* from Step E2. Equation (C.3) resembles Equation (C.2) but utilizes the black curve instead of the white curve. Also, an adjustment to the particle diameter corresponding to each sieve size is made to account for the peripheral mastic film present on the RAP particles (i.e., particle size = $d_i - 2t$).

$$V_{available\ mastic} = \sum N_i \times V_i = \sum \frac{RP_{i+1}-RP_i}{G_{sb}\times\rho_{water}\times{}^{\pi}\!/_{6}\times\left(\left(d_{i+1}+d_i\right)/2-2t\right)^3} \times \frac{\pi}{6}\left[\left(\frac{d_{i+1}+d_i}{2}\right)^3 - \left(\frac{d_{i+1}+d_i}{2}-2t\right)^3\right] \qquad \text{(C.3)}$$

where: $V_{available\ mastic}$ = volume of available mastic in a mix with 100 g of aggregate (cm^3); and RP_i = RAP percent passing sieve size i.

4. Calculate the RBA using Equation (C.4). The filler content of the mastic is assumed to be consistent within the available and unavailable mastic. Thus, the ratio of available to total mastic volume provides the RBA.

$$Availability = \frac{V_{available\ mastic}}{V_{mastic}} \times 100\% = \frac{V_{available\ binder}}{V_{binder}} \times 100\% \qquad \text{(C.4)}$$

where: $V_{available\ binder}$ = volume of available binder in the mastic; and V_{binder} = volume of binder in the mastic.

APPENDIX D: VOLUMETRIC MIXTURE DESIGN CALCULATIONS ACCORDING TO THE AVAILABILITY ADJUSTED MIXTURE DESIGN METHOD

This appendix presents the amended equations to calculate asphalt mixture volumetric properties according to the AAMD method.

The recycled binder that is unavailable in an asphalt mixture is considered a 'black rock' (Lo Presti et al. 2020, Mocelin and Castorena 2022), therefore, under the AAMD method, this unavailable recycled binder is included in the bulk aggregate volume rather than binder volume (Mocelin and Castorena 2022) in contrast to conventional mixture design methods. Accordingly, the revised aggregate content of the asphalt mixture, expressed as a percentage of mixture mass ($P_{\text{s revised}}$), is calculated using Equation (D.1).

$$P_{\text{s revised}} = 100 - P_{\text{b available}} \tag{D.1}$$

where: $P_{\text{b available}}$ = available recycled binder content, expressed as a percentage of total mixture mass and calculated using Equation (D.2)

$$P_{\text{b available}} = P_{\text{b total}} - P_{\text{b RAM1}} \times (1 - RBA_{\text{RAM1}}) - P_{\text{b RAM2}} \times (1 - RBA_{\text{RAM2}}) - \ldots - P_{\text{b RAMn}} \times (1 - RBA_{\text{RAMn}}) \tag{D.2}$$

where: $P_{\text{b total}}$ = total asphalt percentage in the mix, $P_{\text{b RAM1}}$, $P_{\text{b RAM2}}$, …, $P_{\text{b RAMn}}$ = total recycled asphalt binder percentage, expressed as a percentage of total asphalt mixture mass from RAM stockpiles 1, 2, …, n and RBA_{RAM1}, RBA_{RAM2}, …, RBA_{RAMn} = recycled binder availabilities of RAM stockpiles 1, 2, …, n.

In addition, the blended aggregate bulk specific gravity must be revised to include the unavailable binder within the bulk aggregate volume, as conveyed by Equation (D.3) Note that the RAM effective specific gravity (G_{se}) is used instead of the RAM G_{sb}, because the absorbed recycled asphalt is considered as part of the unavailable binder (Mocelin and Castorena 2022).

$$G_{\text{sb revised}} = \frac{P_1 + \ldots + P_n + P_{\text{RAM1}} + \ldots + P_{\text{RAMn}} + P_{\text{b unavailableRAM1}} + \ldots + P_{\text{b unavailableRAMn}}}{\frac{P_1}{G_{\text{sb1}}} + \ldots + \frac{P_n}{G_{\text{sbn}}} + \frac{P_{\text{RAM1}}}{G_{\text{se RAM1}}} + \ldots + \frac{P_{\text{RAMn}}}{G_{\text{se RAMn}}} + \frac{P_{\text{b unavailable RAM1}}}{G_{\text{b RAM1}}} + \ldots + \frac{P_{\text{b unavailableRAMn}}}{G_{\text{b RAMn}}}} \tag{D.3}$$

where: $G_{\text{sb revised}}$ = bulk specific gravity of the aggregate blend in the mixture calculated on the basis of availability; P_1, P_2, …, P_n = aggregate stockpile contents, expressed as a percentage of the total aggregate blend mass, of virgin aggregate stockpiles 1, 2, …, n; P_{RAM1}, P_{RAM2}, …, P_{RAMn} = RAM stockpile contents, expressed as a percentage of the total aggregate blend, of RAM stockpiles 1, 2, …, n; $P_{\text{b unavailableRAM1}}$, $P_{\text{b unavailableRAM2}}$, …, $P_{\text{b unavailableRAMn}}$ = unavailable recycled binder content of RAM stockpiles 1, 2, …, n, calculated according to Equation (D.4); G_{sb1}, G_{sb2}, …, G_{sbn} = aggregate bulk specific gravities of virgin aggregate stockpiles 1, 2, …, n; G_{seRAM1}, G_{seRAM2}, …, G_{seRAMn} = effective specific gravities of the RAM aggregate stockpiles 1, 2, …, n; and $G_{\text{b RAM1}}$, $G_{\text{b RAM2}}$, …, $G_{\text{b RAMn}}$ = specific gravities of the recycled binder in RAM stockpiles 1, 2, …, n.

$$P_{\text{b unavailableRAMn}} = P_{\text{b RAMn}} \times (1 - RBA_{\text{RAMn}}) \tag{D.4}$$

The above revised calculations have notable consequences on the interpreted voids in mineral aggregates (VMA), voids filled with asphalt (VFA), dust-to-binder proportion (DP), and RBR of a given mixture.

In conventional volumetric mixture design, the unavailable recycled binder is included in the VMA (AASHTO R 35 2021). Accordingly, the VMA is calculated by Equation (D.5).

$$\mathrm{VMA} = 100 - \frac{\mathrm{G_{mb}P_s}}{\mathrm{G_{sb}}} \tag{D.5}$$

where: G_{mb} = asphalt mixture bulk specific gravity of the mix, P_s = aggregate content, percent by total mass of mixture, and G_{sb} = aggregate bulk specific gravity.

The revised VMA calculation ($VMA_{available}$) according to the AAMD approach is given in Equation (D.6). The VMA calculated according to Equation (D.6) is less than that calculated using Equation (D.5) since the unavailable binder is not considered as part of the VMA in the revised calculation. Thus, the inaccurate RBA assumption leads to mixtures with lower effective binder content and lower VMA than expected, potentially resulting in mixtures with insufficient virgin binder and inadequate durability.

$$\mathrm{VMA_{available}} = 100 - \frac{\mathrm{G_{mb}P_{s\ revised}}}{\mathrm{G_{sb\ revised}}} \tag{D.6}$$

The VFA is calculated according to Equation (D.7) in conventional volumetric mixture design.

$$\mathrm{VFA} = \frac{\mathrm{VMA - V}_a}{\mathrm{VMA}} \times 100\% \tag{D.7}$$

The air void content (V_a) in a mix is not affected by RBA. Consequently, the VFA calculated according to AAMD ($VFA_{available}$) is directly affected by the reduction in VMA described above and is calculated using Equation (D.8).

$$\mathrm{VFA_{available}} = \frac{\mathrm{VMA_{available} - V_a}}{\mathrm{VMA_{available}}} \times 100\% \tag{D.8}$$

The DP is directly impacted by the gradation of the RAM. Thus, since the AAMD method uses the RAM black curve whereas conventional mixture design uses the RAM white curve, the DP calculated according to the AAMD approach differs from that calculated using the conventional approach. The RAM black gradation has significant lower P_{200} ($P_{200\ black}$) content than the white curve, as they are predominantly trapped in agglomerations of larger sized particles (Roque et al. 2015, Mocelin and Castorena 2022, Abdelaziz et al. 2021). The P_{be} of the mixes is also affected by RBA as only the available binder content ($P_{b\ available}$) defined in Equation (D.2) should be considered in its calculation. The revised P_{be} ($P_{be\ available}$) is shown in Equation (D.9), and the revised DP ($DP_{available}$) is calculated per Equation (D.13). The decrease in the P_{200} content is greater than the reduction in P_{be} when accounting for RBA, yielding a net decrease in DP under the AAMD compared to the conventional approach based on past studies (Mocelin and Castorena 2022, Mocelin et al. 2023).

$$\mathrm{DP} = \frac{\mathrm{P_{200}}}{\mathrm{P_{be}}} \tag{D.9}$$

$$P_{\text{be available}} = P_{\text{b available}} - \left(\frac{P_{\text{ba virgin}}}{100} \times P_{\text{s revised virgin}} \right) \tag{D.10}$$

where: $P_{\text{b available}}$ = available recycled binder content, $P_{\text{ba virgin}}$ = percent binder absorption of the virgin aggregates, and $P_{\text{s revised virgin}}$ = revised virgin aggregate content of the asphalt mixture, according to Equation (D.11), and $P_{\text{s revised virgin}}$ = revised virgin aggregate content of the asphalt mixture, according to Equation (D.12).

$$P_{\text{ba virgin}} = 100 \frac{(G_{\text{se virgin}} - G_{\text{sb virgin}})}{(G_{\text{se virgin}} \times G_{\text{sb virgin}})} G_{\text{b virgin}} \tag{D.11}$$

where: $G_{\text{se virgin}}$ = effective specific gravity of the virgin aggregates, $G_{\text{sb virgin}}$ = bulk specific gravity of the virgin aggregates, $G_{\text{b virgin}}$ = specific gravity of the virgin binder.

$$P_{\text{s revised virgin}} = 100 - P_{\text{b virgin}} - (P_{\text{RAM1}} + P_{\text{RAM2}} + ... + P_{\text{RAMn}}) \tag{D.12}$$

where: $P_{\text{b virgin}}$ = virgin binder content in the mix, P_{RAM1}, P_{RAM2}, …, P_{RAMn} = RAM stockpile contents, expressed as a percentage of the total aggregate blend, of RAM stockpiles 1, 2, …, n.

$$DP_{\text{available}} = \frac{P_{\text{200 black}}}{P_{\text{be available}}} \tag{D.13}$$

where: $P_{\text{200 black}}$ = percent passing #200 sieve on the black curve gradation.

The conventional RBR definition is given in Equation (D.14) AASHTO M 323 (2021) recommends the use of either the percent of RAP/RAS by mass of mixture or the RBR to guide the virgin binder performance grade (PG) selection for a mixture. Also, many state agencies specify virgin PG selection and/or define maximum RAM content limits on the basis of the RBR, including North Carolina from which the study materials were sourced.

$$RBR = \frac{P_{\text{RAM1}} \times P_{\text{b RAM1}} + P_{\text{RAM2}} \times P_{\text{b RAM2}} + ... + P_{\text{RAMn}} \times P_{\text{b RAMn}}}{P_{\text{b total}}} \tag{D.14}$$

where: P_{RAM1}, P_{RAM2}, …, P_{RAMn} = RAM stockpile contents, expressed as a percentage of the total aggregate blend, of RAM stockpiles 1, 2, …, n; $P_{\text{b RAM1}}$, $P_{\text{b RAM2}}$, …, $P_{\text{b RAMn}}$ = total recycled asphalt binder percentage, expressed as a percentage of total asphalt mixture mass from RAM stockpiles 1, 2, …, n; and $P_{\text{b total}}$ = total asphalt percentage in the mix.

On the basis of RBA, the AAMD approach suggests the calculation of the Effective RBR in place of the total RBR. The Effective RBR is defined in Equation (D.15) and is lower than the total RBR for a given mixture. The performance consequences of specifying the Effective RBR merits further research.

$$\text{Effective RBR} = \frac{P_{\text{RAM1}}(P_{\text{b RAM1}} \times RBA_{\text{RAM1}}) + P_{\text{RAM2}}(P_{\text{b RAM2}} \times RBA_{\text{RAM2}}) ... + P_{\text{RAMn}}(P_{\text{b RAMn}} \times RBA_{\text{RAMn}})}{P_{\text{b available}}} \tag{D.15}$$

APPENDIX E: RAM BLACK AND WHITE CURVES AND STOCKPILE PROPORTIONS FOR THE MIXTURE DESIGNS

The RAM black curves, used to design the mixtures according to Superpave method, and the RAM white curves, used to design the mixtures according to the AAMD method, are presented in Figure 32.

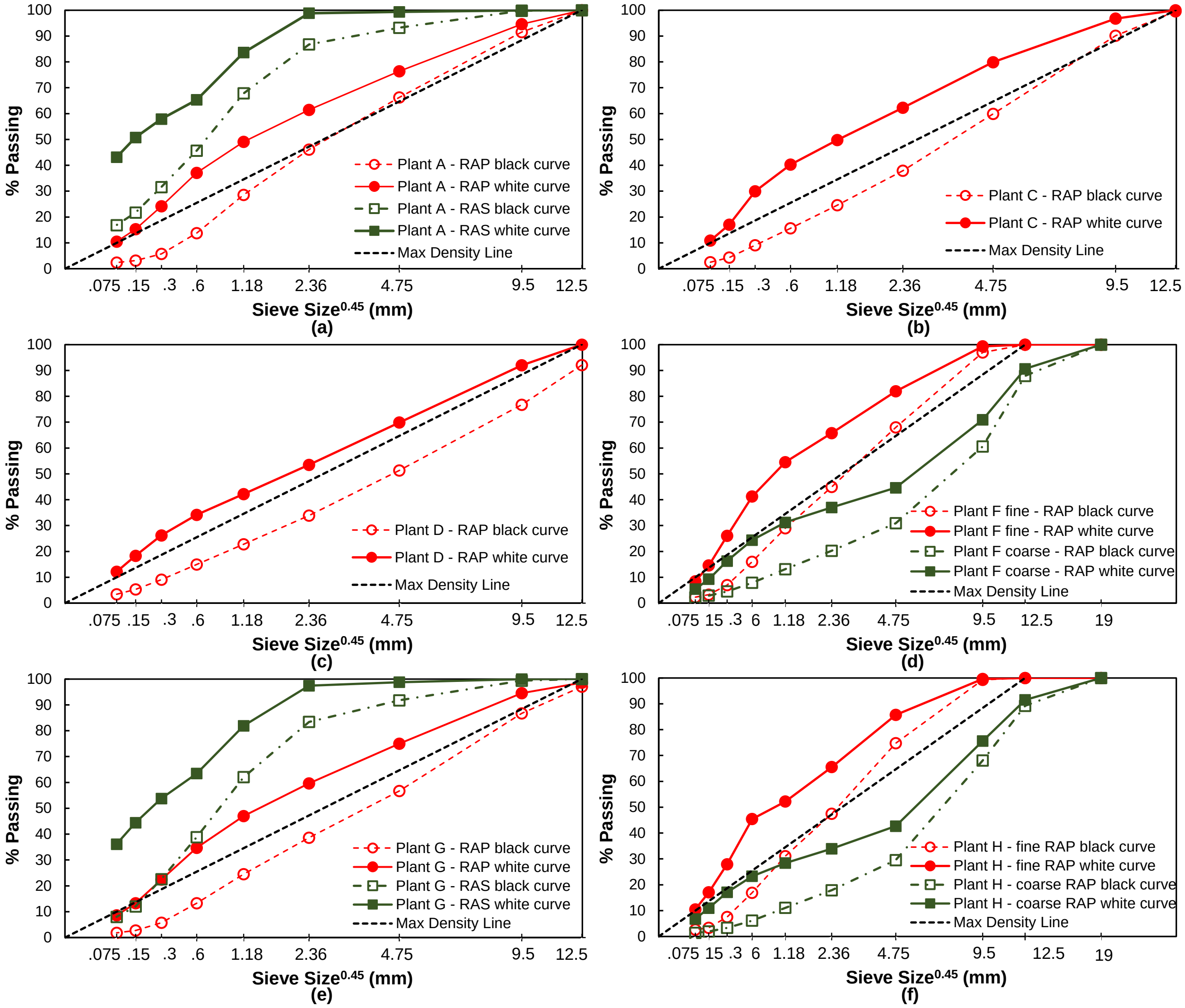

Figure 32. Black and white curve gradations of the (a) Plant A RAP and RAS, (b) Plant C RAP, (c) Plant D RAP, (d) Plant F fine and coarse RAP, (e) Plant G RAP and RAS, and (f) Plant H fine and coarse RAP.

The stockpile proportions used to design the gradation of all the mixture designs are shown in this appendix. Tables 21 to 26 show the stockpile proportions for the Plants A, C, D, F, G and H, respectively. Note that in the AAMD mixture designs the RAM white curves are used as representative of the RAP and RAS, whereas in the control mixtures the RAM black curves are used. In COAC method the gradations are not changed as a function of the availability, therefore, the gradation used for the COAC designs are the same as its respective control mixtures.

Table 21. Stockpile Proportions for the Plant A Mixtures

Stockpile	A-0/0-C	A-0/0-E	A-30/0-C	A-30/0-AAMD	A-50/0-AAMD	A-25/5-C	A-25/5-AAMD
	Proportions (%)						
Dry screenings	25	21	10	25	13	0	0
Washed screenings	30	27	20	15	17	27	43
Sand	10	10	10	10	10	10	10
78M	35	42	30	20	10	33	17
RAP fine	0	0	30	30	50	25	25
RAS	0	0	0	0	0	5	5

Table 22. Stockpile Proportions for the Plant C Mixtures

Stockpile	C-0/0-C	C-20/0-C	C-20/0-AAMD	C-50/0-AAMD
	Proportions (%)			
Dry screenings	35	20	27	20
Washed screenings	30	27	32	20
78M	35	33	21	10
RAP fine	0	20	20	50

Table 23. Stockpile Proportions for the Plant D Mixtures

Stockpile	D-0/0-C	D-30/0-C	D-30/0-AAMD
	Proportions (%)		
Washed screenings	80	58	63
78M	20	12	5
Bag House fines	0	0	2
RAP fine	0	30	30

Table 24. Stockpile Proportions for the Plant F Mixtures

Stockpile	F-0/0-C	F-0/0-E	F-40/0-C	F-40/0-AAMD
	Proportions (%)			
Dry screenings	35	35	11	30
Sand	36	25	34	25
78M	29	40	15	5
RAP fine	0	0	32	32
RAP coarse	0	0	8	8

Table 25. Stockpile Proportions for the Plant G Mixtures

Stockpile	G-0/0-C	G-26/5-C	G-26/5-AAMD
	Proportions (%)		
Dry screenings	44	17	49
Sand	27	27	10
78M	29	25	10
RAP fine	0	26	26
RAS	0	5	5

Table 26. Stockpile Proportions for the Plant H Mixtures

Stockpile	H-0/0-C	H-35/0-C	H-35/0-AAMD	H-50/0-AAMD
	Proportions (%)			
Washed screenings	47	33	50	45
Sand	15	10	5	5
78M	38	22	10	0
RAP fine	0	14	14	20
RAP coarse	0	21	21	30

APPENDIX F: STATISTICAL TESTS FOR THE PERFORMANCE COMPARISONS

One-way analysis of variance (ANOVA) for all the relevant pairwise comparisons of cracking (CT_{index}) and rutting (APA rut depth) performance for the sources A, C, D, F, G and H are presented in Tables 27 to 32, respectively. The ANOVA tests were used to compare the results and support the analysis and conclusions.

It should be noted that the CT_{index} results are reported as the average of at least three tests and the APA rut depth as the average of two sets of specimens. For two cases of APA results, the research team was only provided the average result, and therefore the statistical analysis could not be performed (G-0/0-C and G-26/5-C).

Table 27. ANOVA Results for Plant A Mixtures

Source	Comparison		CT_{index}		APA rut depth	
			p-value	Difference	p-value	Difference
Plant A	A-0/0-C	A-30/0-C	0.00031	Significant	0.00007	Significant
	A-0/0-C	A-30/0-AAMD	0.00068	Significant	0.01535	Significant
	A-0/0-C	A-0/0-E	0.00612	Significant	0.34175	Not Significant
	A-0/0-E	A-30/0C	0.01213	Significant	0.0009	Significant
	A-0/0-E	A-30/0-AAMD	0.16762	Not Significant	0.04779	Significant
	A-30/0C	A-30/0-AAMD	0.00212	Significant	0.24136	Not Significant
	A-30/0C	A-30/0-COAC	0.06239	Not Significant	0.00051	Significant
	A-30/0-COAC	A-30/0-AAMD	0.91061	Not Significant	0.03463	Significant
	A-30/0C	A-50/0-AAMD	0.00394	Significant	0.09573	Not Significant
	A-30/0-AAMD	A-50/0-AAMD	0.61191	Not Significant	0.50247	Not Significant
	A-25/5-C	A-25/5-AAMD	0.0001	Significant	0.92256	Not Significant

Table 28. ANOVA Results for Plant C Mixtures

Source	Comparison		CT_{index}		APA rut depth	
			p-value	Difference	p-value	Difference
Plant C	C-0/0-C	C-20/0-C	0.00403	Significant	0.05505	Not Significant
	C-20/0-C	C-20/0-AAMD	0.01679	Significant	0.82878	Not Significant
	C-20/0-C	C-20/0-COAC	0.00088	Significant	0.84978	Not Significant
	C-20/0-AAMD	C-20/0-COAC	0.48091	Not Significant	0.92314	Not Significant
	C-20/0-AAMD	C-50/0-AAMD	0.02516	Significant	0.41474	Not Significant
	C-20/0-C	C-50/0-AAMD	0.06414	Not Significant	0.43516	Not Significant
	C-0/0-C	C-20/0-AAMD	0.02456	Significant	0.12472	Not Significant

Table 29. ANOVA Results for Plant D Mixtures

Source	Comparison		CT_{index}		APA rut depth	
			p-value	Difference	p-value	Difference
Plant D	D-0/0-C	D-30/0-C	0.00089	Significant	0.06662	Not Significant
	D-0/0-C	D-30/0-AAMD	0.00953	Significant	0.7033	Not Significant
	D-30/0-C	D-30/0-AAMD	0.0136	Significant	0.0002	Significant

Table 30. ANOVA Results for Plant F Mixtures

Source	Comparison		CT_{index}		APA rut depth	
			p-value	Difference	p-value	Difference
Plant F	F-0/0-C	F-40/0-C	0.00016	Significant	0.05783	Not Significant
	F-0/0-C	F-40/0-AAMD	0.00038	Significant	0.06104	Not Significant
	F-0/0-C	F-0/0-E	0.00121	Significant	0.20702	Not Significant
	F-0/0-E	F-40/0-C	0.00079	Significant	0.08439	Not Significant
	F-0/0-E	F-40/0-AAMD	0.01393	Significant	0.07768	Not Significant
	F-40/0-C	F-40/0-AAMD	0.00338	Significant	0.35204	Not Significant

Table 31. ANOVA Results for Plant G Mixtures

Source	Comparison		CT_{index}		APA rut depth	
			p-value	Difference	p-value	Difference
Plant G	G-0/0-C	G-26/5-C	0.02759	Significant	NA	NA
	G-0/0-C	G-26/5-AAMD	0.08452	Not Significant	NA	NA
	G-0/0-C	G-26/5-COAC	0.69456	Not Significant	NA	NA
	G-26/5-C	G-26/5-AAMD	0.00011	Significant	NA	NA
	G-26/5-C	G-26/5-COAC	0.00000	Significant	NA	NA
	G-26/5-AAMD	G-26/5-COAC	0.00002	Significant	0.04735	Significant

Table 32. ANOVA Results for Plant H Mixtures

Source	Comparison		CT_{index}		APA rut depth	
			p-value	Difference	p-value	Difference
Plant H	H-0/0-C	H-35/0-C	0.00001	Significant	0.00029	Significant
	H-0/0-C	H-35/0-AAMD	0.00013	Significant	0.00329	Significant
	H-0/0-C	H-50/0-AAMD	0.0004	Significant	0.52047	Not Significant
	H-35/0-C	H-35/0-AAMD	0.02674	Significant	0.66286	Not Significant
	H-35/0-C	H-50/0-AAMD	0.00109	Significant	0.03195	Significant
	H-35/0-AAMD	H-50/0-AAMD	0.02236	Significant	0.03352	Significant

APPENDIX G: COMPARISONS BETWEEN DIFFERENT PERFORMANCE MEASURES

Overview

This appendix provides comparisons between the results from index testing, AMPT testing, and pavement performance simulations for the Plant A, G, and H mixtures. Note that some information from the main body of the report is repeated within the appendix to provide context to the collective results of the performance measures. To complement visual comparisons, statistical tests were conducted to compare the index test and AMPT performance measures. One-way analysis of variance (ANOVA) and Tukey's Honest Significant Difference (HSD) tests at a 5 percent significance level (α) were conducted to compare the group means and determine if there were any pairwise significant differences among the different mixtures within the same source in terms of cracking (CT_{index} and S_{app}) and rutting (APA rut depth) performance. Note that statistical analysis of RSI was not conducted because RSI cannot be calculated from a single test result. Rather, the results of distinct specimens tested at different temperatures are required.

It should be noted that the CT_{index} and S_{app} means are compared as the average of at least three tests and the APA rut depth as the average of two sets of specimens. For Plant G, only the average test results were reported to the authors, and therefore the statistical analysis could not be performed.

Results

Plant A

Figure 33 and Figure 34 show the Plant A mixture performance index and pavement performance prediction results. Throughout the results, error bars represent the standard deviation in the test results. Figure 33(a) shows that the A-0/0-C mixture exhibits a higher CT_{index} value when compared to the mixtures that included RAM, which is attributed to the virgin mixture's higher available binder content and softer effective binder matrix than the corresponding RAM mixtures. It is also evident that the COAC (A-30/0-COAC) and AAMD (A-30/0-AAMD, A-50/0-AAMD) mixtures exhibit similar CT_{index} values that are higher than the A-30/0-C mixture based on visual inferences and the Tukey test results from Figure 35. The higher CT_{index} values can be explained by the higher available binder contents in the COAC and AAMD mixtures compared to the control as well as the softer effective binder matrix in the case of the A-50/0-AAMD case. Furthermore, Figure 33(a) shows that the CT_{index} and S_{app} parameters result in similar rankings among the Plant A mixtures, with the CT_{index} appearing more sensitive to the effective binder content differences among the mixtures. While the trends in mean S_{app} and CT_{index} align, the S_{app} differences among the Plant A mixtures are statistically insignificant. Figure 34(a) shows that the trends in the bottom-up cracking pavement performance predictions align with those for the CT_{index} for the Plant A mixtures in the cases of both the thin and thick pavement sections considered wherein A-0/0-C mixture exhibits the least and A-30/0-C exhibits the most bottom-up cracking.

Figure 33(b) shows that the A-0/0-C and A-30/0-COAC mixtures exhibit similar APA rut depths that are higher than those for the A-30/0-C, A-30/0-AAMD, and A-50/0-AAMD mixtures. The control and AAMD mixtures exhibit statistically equal mean APA rut depths. The similar rut depths in the AAMD and control RAP mixtures are attributed to the superior aggregate structure in the AAMD mixtures. However, the RSI results indicate that the A-30/0-C and A-30/0-COAC mixtures have very similar rutting resistance with the A-50/0-AAMD mixture exhibiting the poorest result among the RAP mixtures. Figure 34(b) shows that the pavement simulation results follow the trends seen in RSI for the Plant A mixtures, which was expected given that FlexPAVE^{TM} uses the same test results and associated models that are used to calculate RSI, with the thick sections exhibiting higher rut depths than the thin pavement cases but the same rankings among the mixtures.

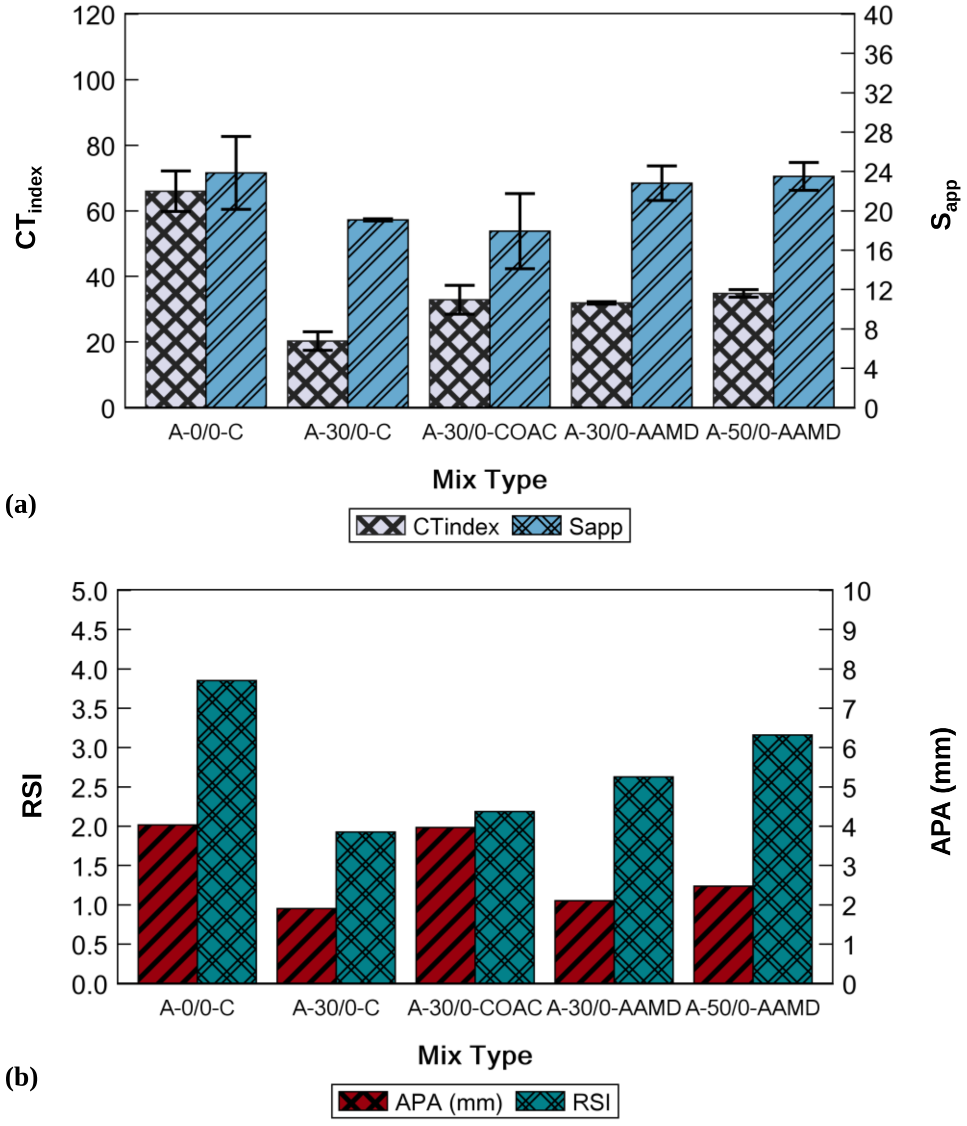

Figure 33. Mixtures performance indices for the evaluated mixtures from Plant A: (a) cracking indices and (b) rutting indices.

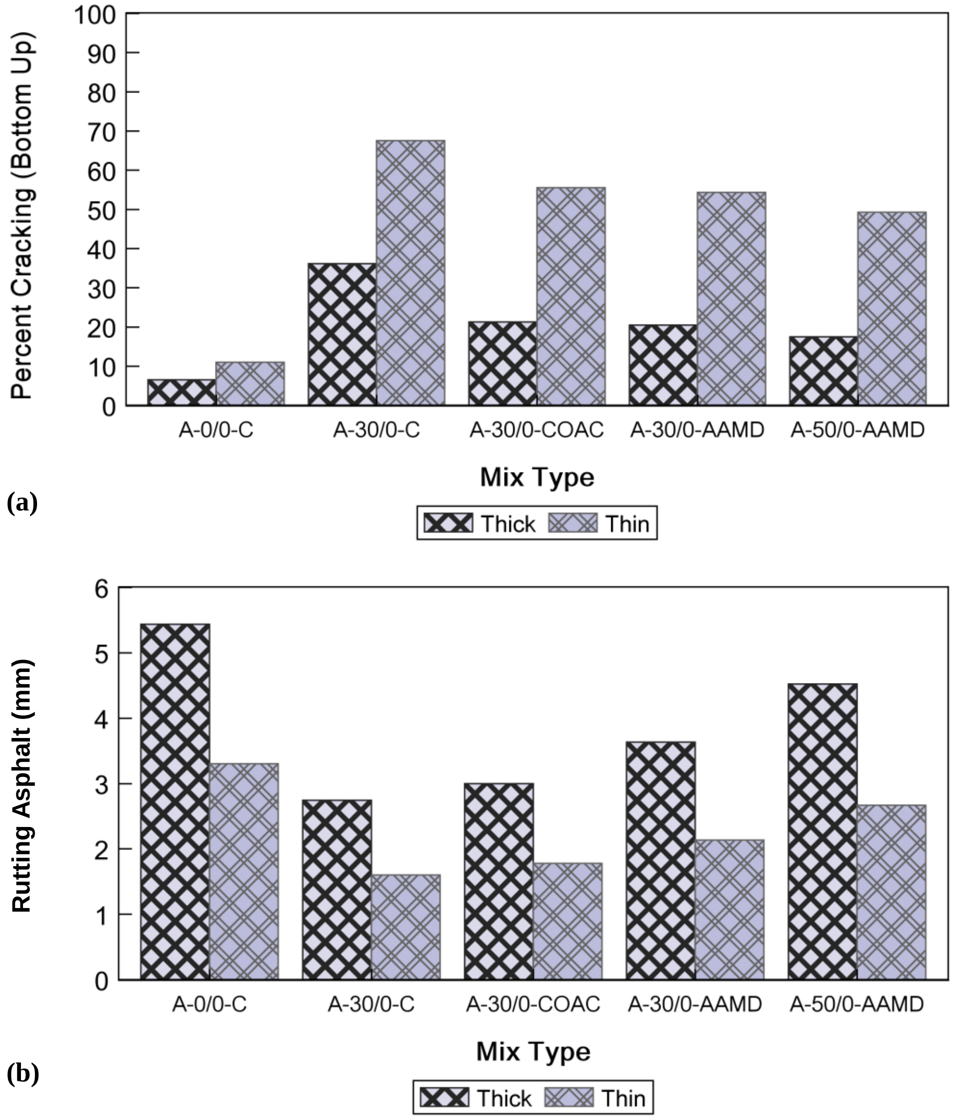

Figure 34. Pavement performance of the simulated pavement sections from Plant A: (a) bottom-up fatigue cracking and (b) asphalt rutting.

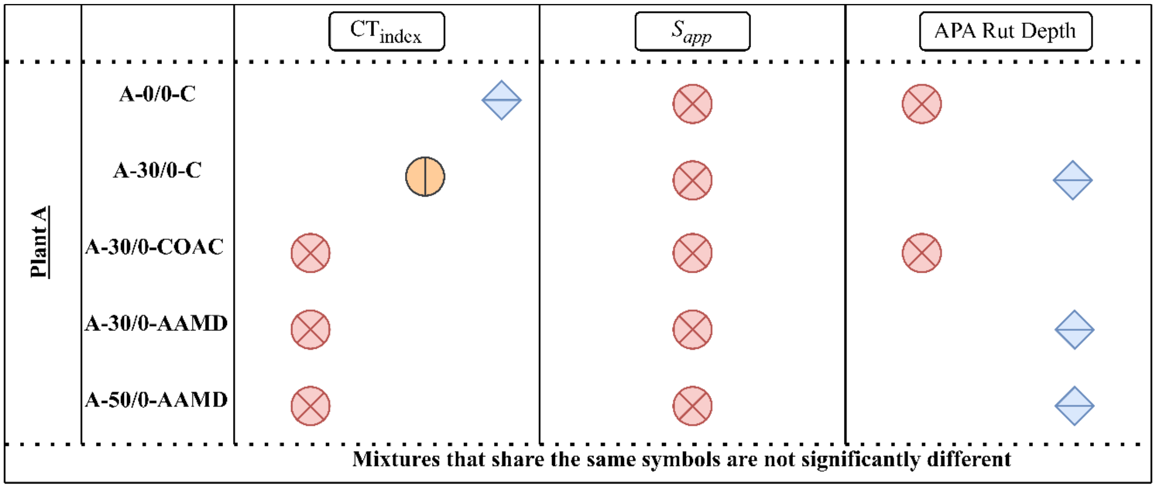

Figure 35. Plant A Tukey grouping results summary for CT_{index}, S_{app}, and APA values.

Plant G

Figure 36 and Figure 37 show the Plant G mixture performance index and pavement performance prediction results, respectively. The Plant G results shown in Figure 36(a) indicate that all mixture design alternatives have distinct CT_{index} results, with the G-0/0-C mixture displaying the highest CT_{index} and the G-26/5-C mixture exhibiting the lowest CT_{index}, which aligns with rankings of the Plant G mixtures in terms of available binder content. The G-26/5-COAC mixture exhibits a higher CT_{index} than the G-26/5-AAMD mixture, likely the result of its higher binder content. In contrast, the G-26/5-COAC had the highest S_{app}. However, the Tukey test results (Figure 38) show that the G-26/5-COAC S_{app} value does not differ significantly from that of the G-0/0-C or G-26/5-AAMD mixtures. Furthermore, the G-0/0-C, G-26/5-C, and G-26/5-AAMD mixtures S_{app} values do not differ significantly, indicating all of the observed differences in S_{app} are marginal and aligning with the Plant A findings that CT_{index} results are more sensitive to mixture design variations than S_{app} results. Also matching findings from Plant A, the Plant G bottom-up cracking performance simulation results shown in Figure 37(a) provide the same ranking among the mixture design alternatives as the CT_{index} results for both the thick and thin structures evaluated. Also notable, Figure 37(a) indicates very poor cracking resistance (i.e., complete failure) of the G-26/5-C mixture indicating the current mixture design practice may result in very poor performance of RAP/RAS mixtures.

Collectively, the results show that redesigning G-26/5-C mixture using the AAMD and COAC approaches led to improved cracking performance based on the CT_{index} and bottom-up cracking prediction results. However, both APA rut depth and the RSI values results in Figure 36(b) show that the G-26/5-COAC mixture has inferior rutting resistance compared to the G-26/5-C mixture whereas the rutting performance for the G-26/5-AAMD mixture remained at the same level as the G-26/5-C mixture. The G-26/5-COAC mixture exhibits an RSI value substantially higher than the G-0/0-C mixture. In contrast, the G-0/0-C mixture exhibits a higher APA rut depth than the G-26/5-COAC mixture. As explained in the methodology section, there were not enough data to conduct the test on the APA results from this plant. Figure 37(b) shows that the pavement rutting predictions for the Plant G mixtures follow the same trends as RSI, with the thick sections exhibiting higher rut depths than the corresponding thin sections. The G-26/5-COAC mixture appeared flushed due to the excessive amount of added virgin binder without introducing any changes to the design aggregate structure, which may explain its poor rutting performance. In contrast, the altered aggregate structure in the G-26/5-AAMD mixture may explain how it was able to maintain the same rutting resistance as the control case despite having a higher asphalt content.

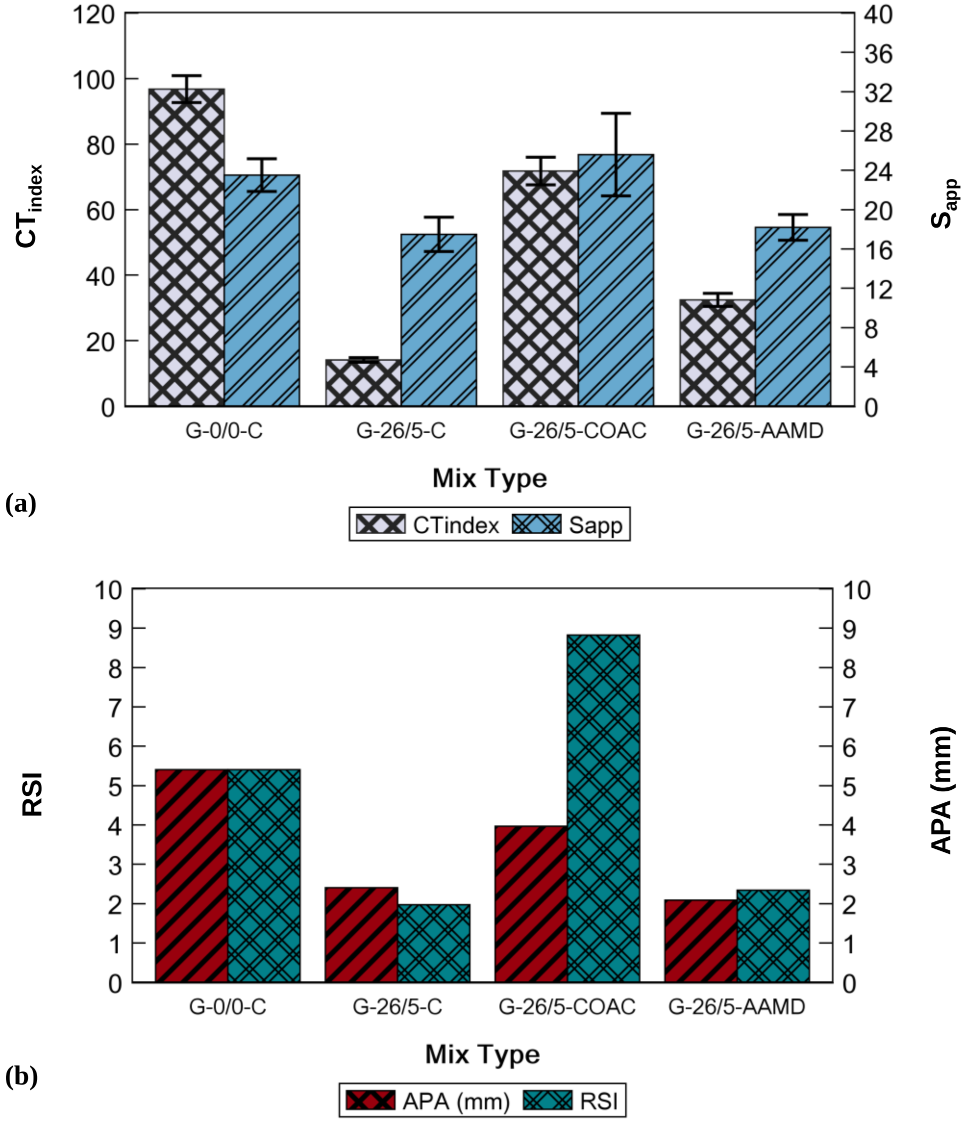

Figure 36. Mixtures performance indices for the evaluated mixtures from Plant G: (a) cracking indices and (b) rutting indices.

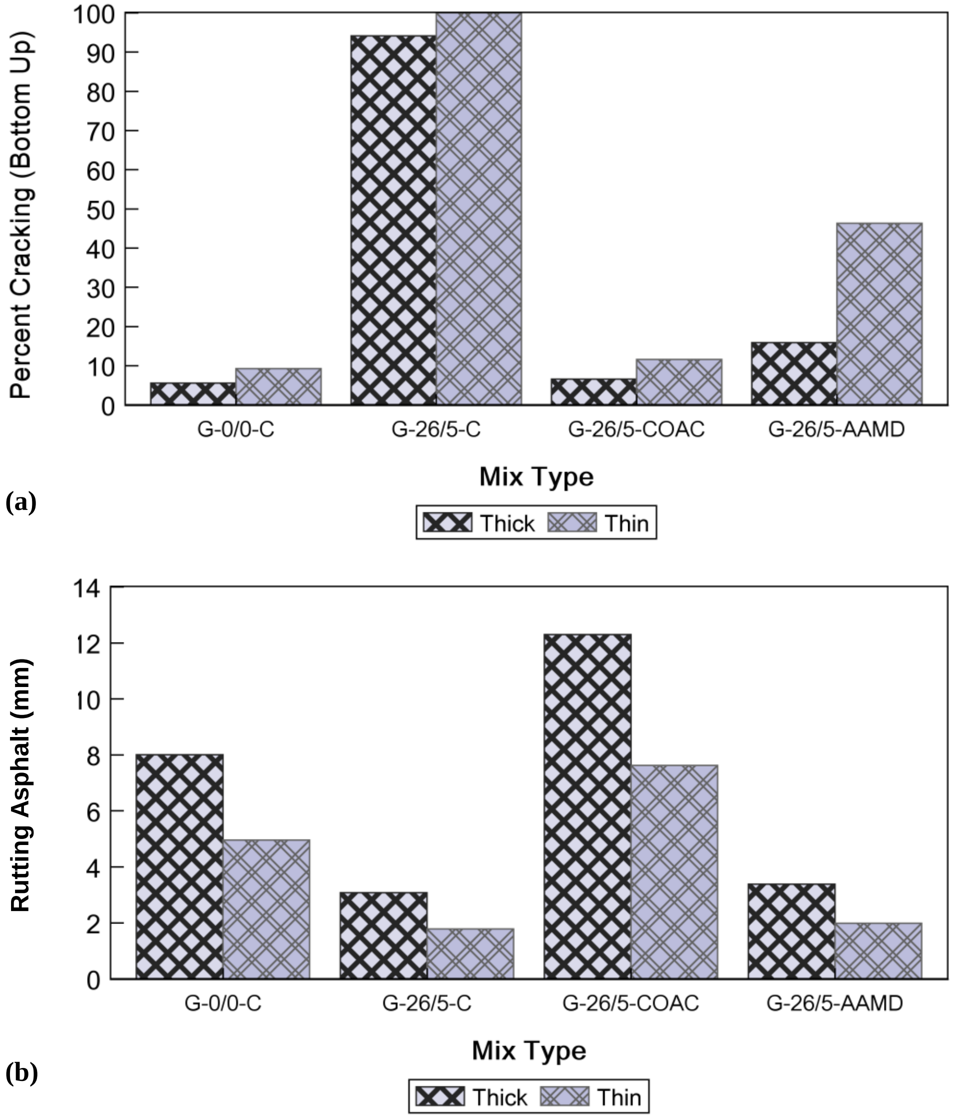

Figure 37. Pavement performance of the simulated pavement sections from Plant G: (a) bottom-up fatigue cracking and (b) asphalt rutting.

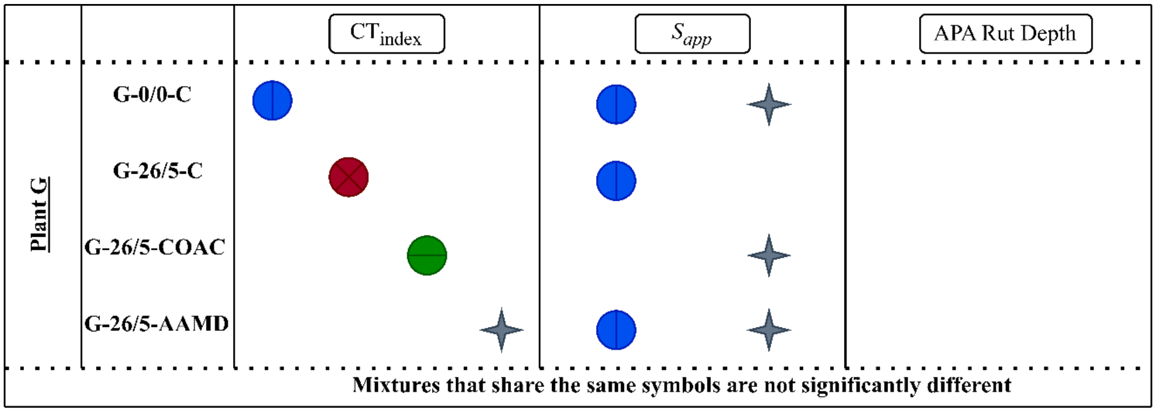

Figure 38. Plant G Tukey grouping results summary for CT_{index}, S_{app}, and APA values.

Plant H

Figure 39 and Figure 40 show the Plant H mixture performance index and pavement performance prediction results, respectively. Figure 39(a) shows that the H-0/0-C mixture exhibits the highest CT_{index} and S_{app} of the Plant H mixture designs evaluated, matching expectations based on available binder contents. However, the Tukey test results presented in Figure 41 suggest that S_{app} values of the H-35/0-AAMD and the H-0/0-C mixtures do not differ significantly. Furthermore, the S_{app} values of the H-35/0-AAMD, H-35/0-C, and H-50/0-AAMD resulted in the same Tukey grouping, suggesting differences in S_{app} results among the Plant H mixtures are marginal. In contrast, the CT_{index} values of the Plant H mixtures all differ significantly, aligning with the findings from the previously presented plants that indicate the CT_{index} is more sensitive to mixture design variations than S_{app}. Both AAMD mixtures exhibit higher CT_{index} values than the H-35/0-C mixture with the H-50/0-AAMD mixture showing a higher value than the H-35/0-AAMD mixture. Similar to the Plant A case, the higher CT_{index} results of the AAMD mixtures compared to the associated with their higher available content and softer effective binder matrices. Figure 40(a) shows that the trends in the bottom-up cracking among the Plant H mixtures, obtained from the pavement performance simulations, match those from the CT_{index} results. Pavement simulations indicate that H-0/0-C and H-50/0-AAMD are the best-performing mixtures in terms of bottom-up cracking, followed by H-35/0-AAMD mixture. Also notable, the performance of the H-35/0-C mixture in the thin pavement scenario resulted in very extensive bottom-up cracking in the performance prediction, indicating the current practice may yield poor cracking resistance in certain scenarios.

Figure 39(b) shows that the H-35/0-C and H-35/0-AAMD mixtures have very similar APA rut depths and RSI values, suggesting the superior aggregate structure imparted by the AAMD method mitigated any negative effects of the additional binder content on the rutting resistance. However, the H-50/0-AAMD mixture exhibits inferior rutting resistance compared to the H-35/0-C and H-35/0-AAMD mixtures designed with lower RAP content on the basis of both APA rut depth and RSI results. The APA rut depth of the H-50/0-AAMD and H-0/0-C mixtures do not differ significantly and both meet the NCDOT’s specified limit for APA rut depth of 6.5 mm. However, the RSI of the H-50/0-AAMD mixture is notably higher than that of the H-0/0-C mixture. Matching trends for the mixture indices, Figure 40(b) shows that rut depth predictions from the pavement performance simulations for both the thin and thick sections indicate the H-35/0-C and the H-35/0-AAMD yield equivalent rutting resistance that is better than the other Plant H mixtures. Matching RSI trends, the predicted rut depths suggest that the H-0/0-C mixture has better rutting resistance than the H-50/0-AAMD mixture. It is speculated that the inferior rutting performance of the H-50/0-AAMD mixture is due to the use of the PG 58-28 virgin binder, compared to the PG 64-22 used in the mixtures with 35 percent RAP and the elimination of the coarse virgin aggregate stockpile. The available HPG for the H-50/0-AAMD mixture was 4°C lower than the H-35/0-C mixture. Furthermore, the coarse virgin aggregate likely has superior shape, angularity, and texture compared to the coarse RAP particles, which include agglomerated fine particles.

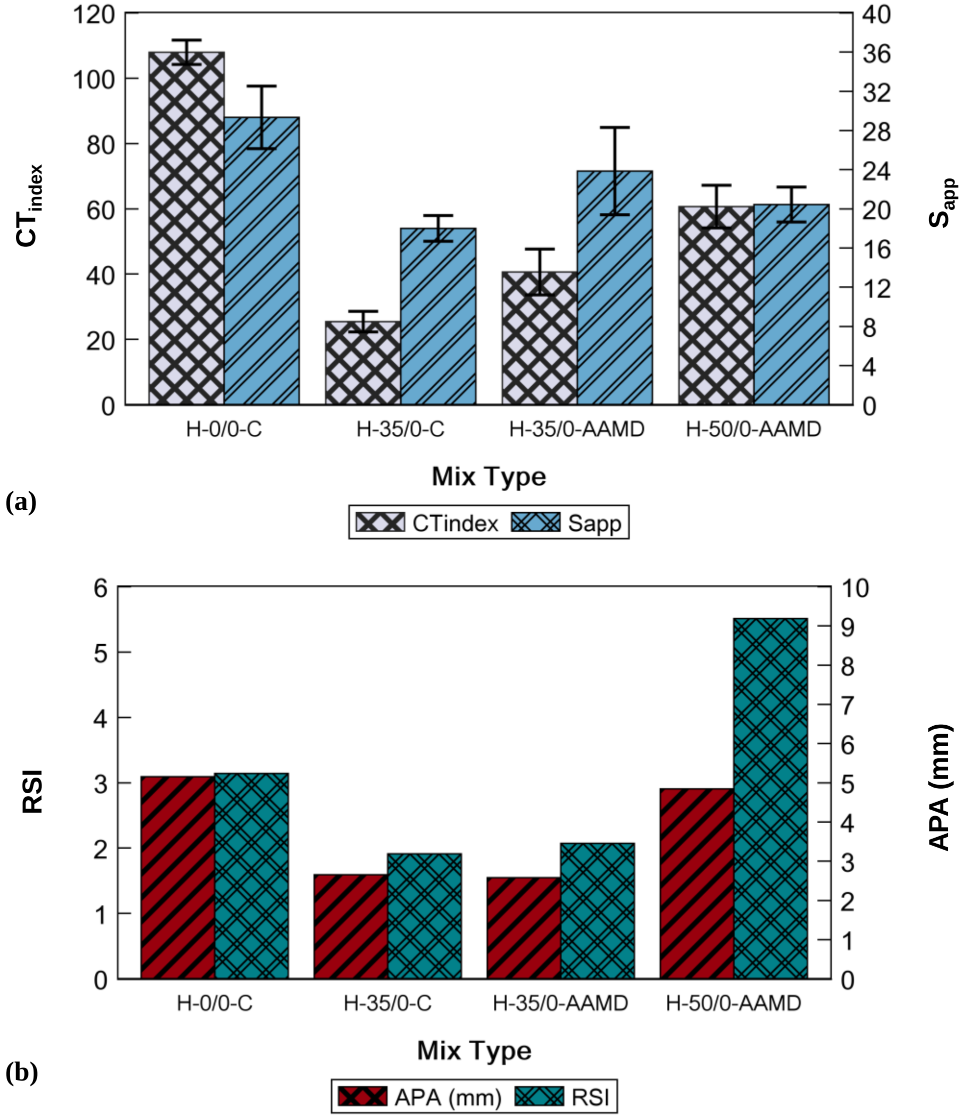

Figure 39. Mixtures performance indices for the evaluated mixtures from Plant H: (a) cracking indices and (b) rutting indices.

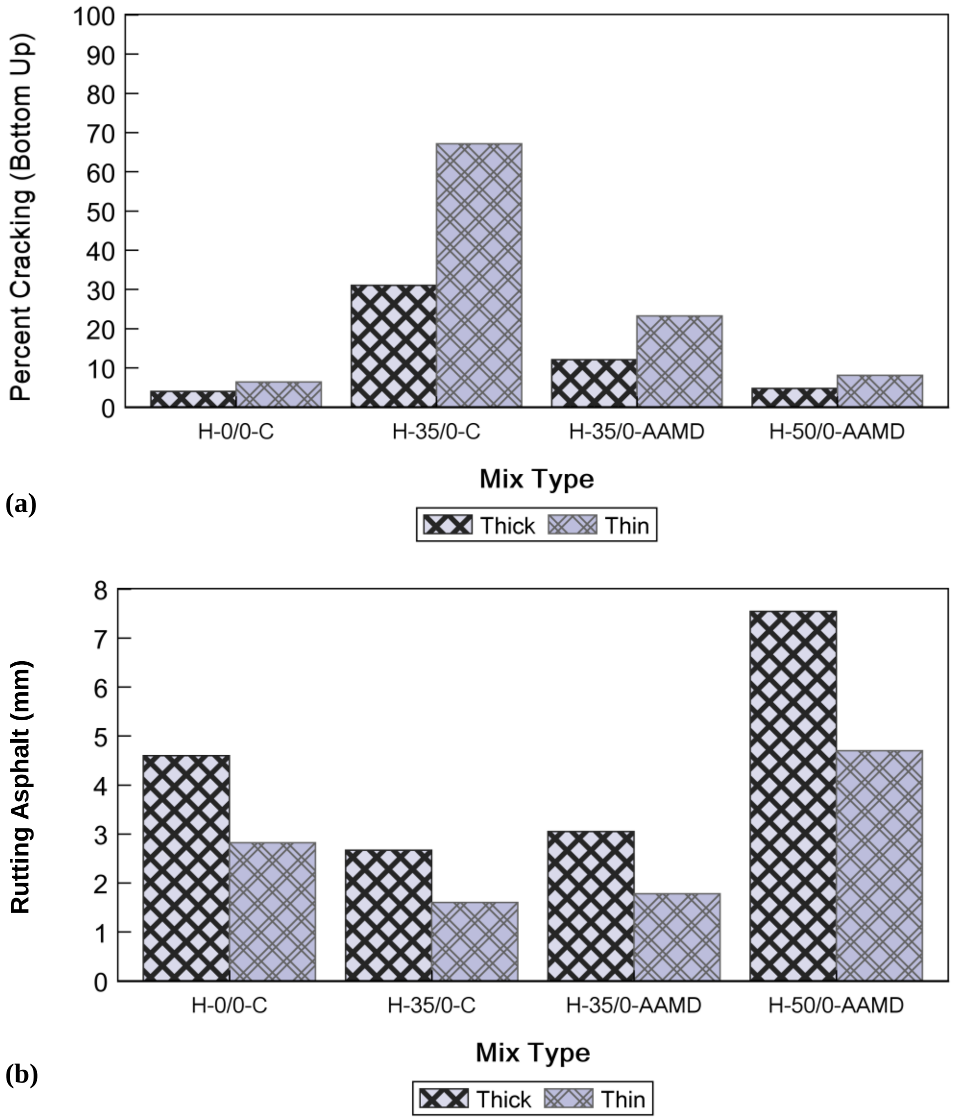

Figure 40. Pavement performance of the simulated pavement sections from Plant H: (a) bottom-up fatigue cracking and (b) asphalt rutting.

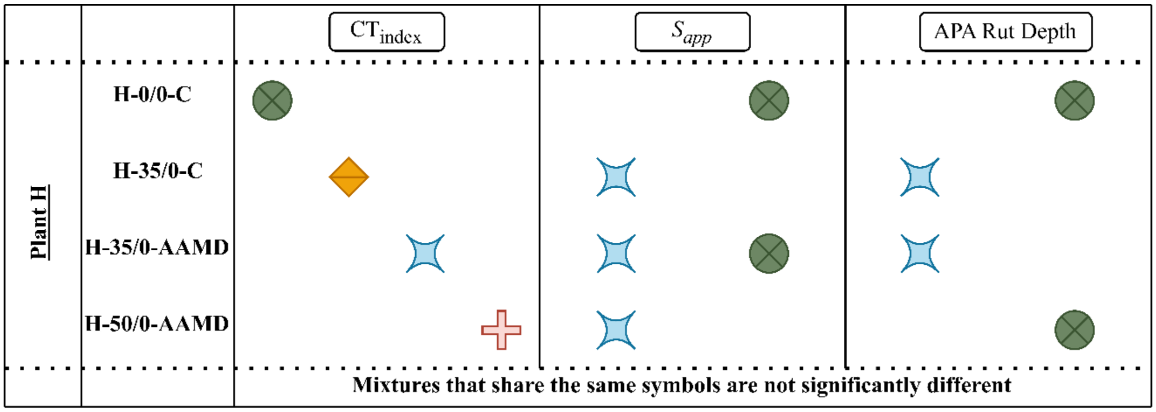

Figure 41. Plant H Tukey grouping results summary for CT_{index}, S_{app}, and APA values.

Summary

The relative ranking of mixture design alternatives prepared using the component materials from a given plant using the CT_{index} and Pavement ME predictions of bottom-up cracking aligned in all cases evaluated. In contrast, the S_{app} parameter was generally insensitive to the mixture design alternatives evaluated (i.e., asphalt content and gradation differences) for a given plant. The Pavement ME bottom-up cracking predictions were implemented using material-specific dynamic modulus and cyclic fatigue model inputs. The same dynamic modulus and cyclic fatigue test results were used to calculate S_{app} and thus, the contradictory findings of S_{app} and the Pavement ME predictions are a noteworthy finding that merits further exploration to potentially refine S_{app} to better reflect cracking performance in pavements. In the majority but not all cases evaluated, APA rut depths and RSI values provided similar insights regarding the relative rutting resistance of the mixture design alternatives from a given plant. FlexPAVE^{TM} predictions of rut depth consistently aligned with trends in RSI results, which was expected given that FlexPAVE^{TM} uses the same test results and associated models that are used to calculate RSI.

APPENDIX H: COMPARISON BETWEEN APA TEST RESULTS AT FOUR AND SEVEN PERCENT AIR VOIDS

The comparison of APA test results at 4 percent and 7 percent air void contents are shown in Figures 42, 43, and 44 for the Plants C, D, and H, respectively. Mixtures with higher air voids percentage are expected to be more susceptible to permanent deformation. However, the APA rut depths show mixed trends with respect to air void content for the Plant D mixtures. Interestingly, the APA rut depth of the D-30/0-C mixture is substantially lower than the D-0/0-C and D-30/0-AAMD mixtures at the 4 percent air level. However, all mixtures show similar rut depths near 4 mm at the 7 percent air level with the exception of the C-20/0-AAMD mixture, which appears to be an outlier. For the D-0/0-C and D-30/0-AAMD mixtures, this amounted to a marginal decrease in rut depth at the 7 percent air void content compared to the 4 percent air void content. In contrast, the D-30/0-C mixture shows a drastic increase in rut depth as the air void content increased from 4 percent to 7 percent. For the Plant H and C mixtures, the APA trends follow the expectation with respect to air void content. Both the control and AAMD mixtures with 7 percent air voids have a higher rut depth than their respective mixtures with 4 percent air voids. The Plant H mixtures show similar rut depths at 4 percent air voids and also show similar rut depths at 7 percent air voids. The rut depths of the Plant H mixtures at the 7 percent air void level are very similar to those of the Plant D mixtures at the same air level. Thus, the limited results may suggest more limited sensitivity of APA test results to the mixture source and design at the 7 percent air void level compared to the 4 percent air void level currently specified by the NCDOT.

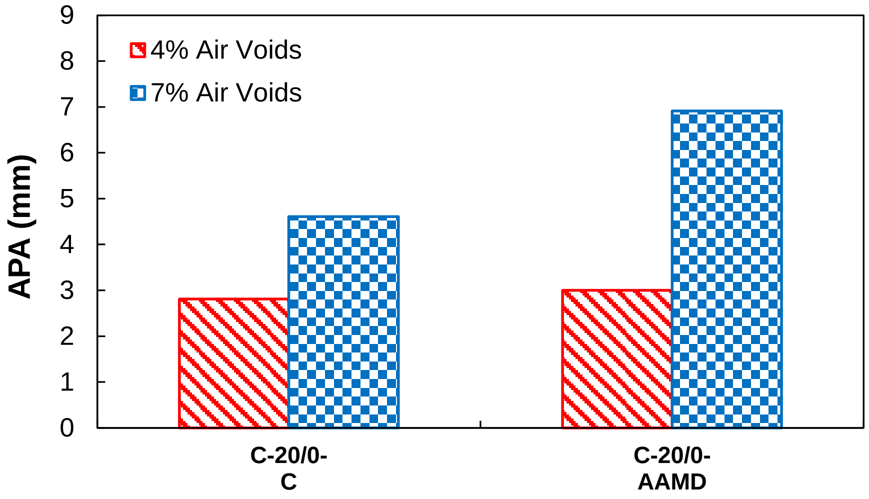

Figure 42. APA rut depths for the Plant C mixtures with 4% and 7% air voids.

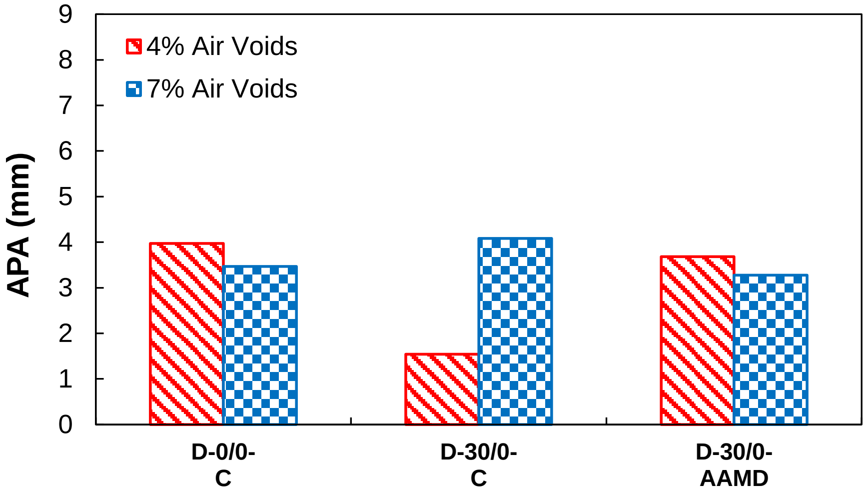

Figure 43. APA rut depths for the Plant D mixtures with 4% and 7% air voids.

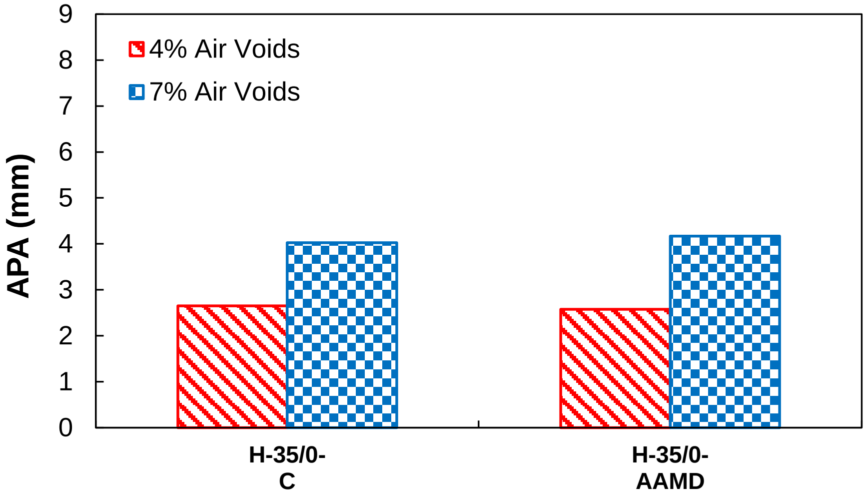

Figure 44. APA rut depths for the Plant H mixtures with 4% and 7% air voids.