Evaluation of RAP/RAS Stockpiles in North Carolina and Changes in these Stockpiles Over Time

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16. Abstract

This report summarizes the findings of a study evaluating the variability of Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) stockpiles across North Carolina and the corresponding performance of plant-produced asphalt mixtures. The goal of this study was to inform improved specifications for recycled materials in asphalt mixtures by assessing how processing and stockpiling practices influence material consistency and mixture performance. Seven asphalt plants operated by five contractors were selected across the coastal and piedmont regions of the state. Over approximately 1.5 years, researchers conducted operational reviews and repeatedly collected samples of plant-produced mixtures, RAP, RAS, and virgin binder. These materials underwent laboratory testing to evaluate binder content, aggregate gradation, specific gravity, recycled binder availability (RBA), and recovered binder performance grade (PG). Asphalt mixture performance was assessed using indirect tensile cracking test (IDT-CT) and asphalt pavement analyzer rutting (APA) test. RAP binder contents ranged from 4.3% to 5.4%. While some plants maintained consistent RAP properties, one plant which performed monthly in-house jaw crushing, exhibited greater variability in asphalt content. Plants relying on outsourced impact crushing with less frequent replenishment showed more stable asphalt content results. A probabilistic analysis of NCDOT's recycled binder replacement percentage (RBR%) limits showed that lowering the limit for PG 64-22 mixtures from 30% to 20% increased the probability of meeting AASHTO M 320 intermediate- and low-temperature PG requirements from 75% to 95%. This compliance could be maintained at higher RBR% levels using PG 58-28 binder. IDT-CT results were generally consistent within a given plant over time but varied across plants. Rutting performance also varied but all mixtures fell well below NCDOT's APA limits. IDT-CT results were most strongly correlated with VMA, asphalt content, and binder properties, while APA results were linked to aggregate gradation. The findings support tighter controls on mixture volumetrics and gradation, and highlight the need to incorporate cracking performance tests into mixture design and potentially quality assurance to ensure consistent performance when using recycled materials.

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EXECUTIVE SUMMARY

This report presents the findings of a comprehensive study evaluating the variability of Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) stockpiles across North Carolina and corresponding plant-produced asphalt mixtures, to inform improved specifications for the use of recycled materials in asphalt mixtures. While RAP and RAS are used in nearly all asphalt mixtures produced in the state, previous studies and agency experience have highlighted substantial variability in these materials and their effects on pavement performance. This research aimed to assess how plant processing and stockpiling practices influence material consistency, evaluate how variability affects asphalt mixture performance, and recommend specification improvements.

Seven asphalt plants, operated by five contractors across North Carolina's coastal and piedmont regions, were selected based on criteria including recycled content levels, ongoing mixture production, and regional diversity. An operational review of each plant was conducted, and samples of plant-produced surface mixtures, RAP, RAS, and virgin binder were collected from the study plants over a timespan of approximately 1.5 years. Each material was subjected to comprehensive laboratory characterization, including binder content, gradation, specific gravity, recycled binder availability (RBA), and recovered binder performance grade (PG). Asphalt mixture performance was evaluated using the indirect tensile cracking test (IDT-CT) and the asphalt pavement analyzer rutting (APA) test.

Binder content of RAP ranged from 4.3% to 5.4%. RBA ranged from 43% to 67%, with within-plant variation up to 12%. Although many plants maintained consistent material properties over time, discrepancies between measured properties and JMF values were observed, exceeding allowable limits in some cases. Plant K, which crushed RAP in-house using a jaw crusher every month, exhibited the greatest variability in RAP binder content over time. In contrast, plants that outsourced crushing to contractors using impact crushers and performed it less frequently showed more stable results. The RAS stockpile evaluated demonstrated comparatively higher variability over time than RAP, with a nearly 20°C change in continuous high-temperature grade of the recovered binder and a 2.6 percent change in asphalt content. This variability affected the blended binder properties of asphalt mixtures, contributing to differences in IDT-CT results.

A probabilistic evaluation showed that lowering the maximum recycled binder replacement percentage (RBR%) limit for PG 64-22 mixtures from 30% to 20% increased the likelihood of meeting intended performance-graded requirements. Using PG 58-28 at an RBR% level of 20% maintained compliance with high-temperature requirements. Current maximum RBR% limits for PG 58-28 provide a high probability of meeting intermediate-temperature performance-graded requirements.

Plant-produced, laboratory-compacted asphalt mixture cracking and rutting performance measures varied significantly among plants but were more consistent within a given plant over time. The CT_{Index} from the IDT-CT test was most strongly correlated with VMA, asphalt content, and blended binder properties. APA rut depth was primarily influenced by the percent passing the 2.36 mm and 1.18 mm sieves. Mixtures with softer binders and higher VMA generally were associated with higher CT_{Index} values, while finer gradations led to increased APA rut depths. On average, the CT_{Index} values and APA rut depths of RS9.5B mixtures were higher than those for RS9.5C mixtures. All APA rut depths of the plant-produced mixtures fell well below established limits for mixture design for RS9.5B and C designations. Mixtures produced with PG 58-28 binder exhibited higher average CT_{Index} values and greater variation across plants than those with PG 64-22. In contrast, binder grade did not significantly affect APA rut depth.

Based on the findings of this study, the following recommendations are made:

- Lower the RBR% Limit for PG 64-22 mixtures from 30% to 20% and specify PG 58-28 for higher RBR% levels.
- Incorporate a cracking test into mixture design to better account for variability in recycled binder properties and availability across plants. Also, reduce the minimum percent passing limit for the 2.36 mm sieve in RS9.5B mixtures to allow greater flexibility in adjusting VMA. This change can help optimize both cracking and rutting performance.
- Tighten asphalt content tolerance limits during production or implement thresholds that trigger performance testing when significant deviations occur. Additionally, reduce production tolerance limits for the 2.36 mm and 1.18 mm sieves to minimize variability in rutting performance.
- Require that the asphalt content in processed RAP and RAS stockpiles remains within tolerance limits of the Job Mix Formula (JMF) whenever stockpiles are replenished. Investigate how crusher type influences RAP consistency.
- Given the importance of recycled binder properties in cracking performance, develop practical methods for routine binder characterization without requiring solvent extraction and recovery.

The study provides a comprehensive evaluation of recycled material variability and its implications for asphalt mixture performance. Findings support updates to mixture design and specification practices to improve consistency and long-term pavement performance, particularly as the use of high-RAP and RAS content mixtures continues to grow.

1. INTRODUCTION

1.1. Overview

1.1.1. Introduction

The vast majority of asphalt mixtures produced in North Carolina contain recycled materials, including Reclaimed Asphalt Pavement (RAP) and/or Recycled Asphalt Shingles (RAS). To support the effective use of these materials, NCDOT has funded several research projects evaluating their impacts on asphalt binder and mixture performance and informing specification strategies to mitigate potential performance issues. These studies consistently highlight substantial variability in the properties and processing of RAP and RAS. For instance, an operational review conducted in NCDOT RP 2021-06 revealed inconsistencies in stockpiling, crushing frequency, and screening practices across asphalt plants. NCDOT RP 2014-05 reported that RAP binder high-temperature grades from nine stockpiles ranged from PG 82 to PG 112 (Khosla and Ramoju 2017). To establish recycled binder replacement percentage (RBR%) limits, three representative RAP binders were blended with two virgin binders (PG 64-22 and PG 58-28), but the resulting charts may not reflect the full range of recycled binder variability. Additionally, NCDOT RP 2019-21 revealed that agglomerations of RAP and RAS inhibit blending with virgin binder, contributing additional uncertainty.

Current NCDOT specifications require characterization of the recycled material asphalt content and recovered aggregate gradation for mixture design, quality assurance and quality control (QA/QC), but do not assess binder rheology, agglomeration extent, or mixture performance. To best ensure consistent and reliable performance, the NCDOT specifications should be critically evaluated to promote the consistency of recycled materials across the state.

1.1.2. Research Need Definition

Research is needed to evaluate how plant processing and stockpiling practices influence the consistency of RAP and RAS properties over time within a stockpile and across different asphalt plants. In addition, understanding how variability in recycled material characteristics and other mixture components impacts asphalt mixture performance is critical to assessing the practical implications of this variability. A critical review of existing NCDOT RBR% limits is also warranted, given the wide range of virgin and RAP binder properties observed across the state. Collectively, this research will support the development of improved specification practices to mitigate the effects of variability of RAP and RAS on asphalt mixture performance.

1.1.3. Research Objectives

The objectives of this project are to:

(1) Identify how recycled material stockpiling and processing practices affect the consistency of RAP and RAS properties within stockpiles and among plants.

(2) Evaluate the impacts of recycled material and other compositional variability on asphalt mixture performance, and

(3) Propose modifications to the NCDOT's current specifications to improve consistency within and across RAP and RAS stockpiles within North Carolina.

1.2. Summary of the Literature

A comprehensive review was conducted on state agency specifications and best practices for RAM stockpile management, quality assurance and control, and virgin binder selection. Additionally, literature addressing the impacts of RAM variability on asphalt mixture performance was examined. The full review can be found in Appendix A.

1.2.1. Stockpiling, Processing, and Fractionation

The National Asphalt Pavement Association (NAPA) provides best practices for managing RAP and RAS to minimize variability, including guidelines for collection, sorting, separation, size reduction, and stockpiling (West 2015). However, state specifications for processing, handling, storage, and usage of RAP and RAS vary significantly. Differences exist in stockpile management, processing requirements, and allowable use in surface layers.

For example, some states mandate fractionation to control asphalt content and gradation, while others do not. States like Maine, Illinois, and Georgia classify RAP stockpiles based on aggregate quality and consistency, permitting varying RAP percentages by class or specifying class requirements based on mixture designation (layer type and traffic level). Several states also require covered stockpiles to prevent moisture intrusion. For RAS, some states require pre-blending with aggregate before introduction to the plant. These variations reflect diverse approaches to managing RAP and RAS effectively across jurisdictions.

1.2.2. Quality Assurance and Control

All state agencies require routine measurement of the asphalt content and gradation of the recovered aggregate of RAP and RAS stockpiles. However, the frequency of testing varies among state agencies. Also, some states have additional requirements, such as moisture content, theoretical maximum specific gravity, and/or testing for the presence of asbestos in RAS. The methods used to determine asphalt content also differ, with some states requiring an ignition oven, others solvent extraction, and some permitting either method.

1.2.3. Recycled Binder Replacement Specifications

To mitigate the potential detrimental effects of RAP and RAS binders on cracking performance, specifications often call for the use of softer virgin binders at higher RBR% levels and impose limits on the allowable RBR%. AASHTO M 323 (2022) provides guidance on selecting virgin binder grades based on RAP content or RBR%, recommending the use of blending charts when the RBR% exceeds 25%. These blending charts estimate the performance grade (PG) of the blended binder based on the continuous grading temperatures of the RAP and virgin binders and the proportion of RAP used.

However, developing project-specific blending charts is generally impractical due to the time-consuming, hazardous, and costly nature of RAP binder extraction and recovery. As a result, most transportation agencies establish regional binder selection guidelines and maximum RAP contents based on deterministic analyses of a limited number of binder combinations and/or mixture performance. Studies consistently show that significant variability in RAP binder properties can exist within a single state. For example, NCDOT RP 2014-05 sampled across nine stockpiles showed high-temperature PG values ranging from PG 82 to PG 112 (Khosla and Ramoju 2017). Based on blending chart analysis of selected binders, the NCDOT established RBR% limits to ensure that blended binders met high- and intermediate-temperature performance requirements.

Although useful, these deterministic approaches fall short in accounting for the full variability of binder properties.

1.2.4. Impacts of RAP/RAS Variability on Performance

Several studies have evaluated the impacts of RAP source on the performance of laboratory-mixed and compacted asphalt mixtures (Hajj et al. 2009, Obaid et al. 2019, Montañez et al. 2020, Faisal et al. 2017, Izaks et al. 2015, Li et al. 2008). These studies have reported that the cracking and rutting resistance of asphalt mixtures can be substantially affected by the RAP source. This variable impact can be attributed to the inherent variability in RAP materials, which can differ in properties like gradation, asphalt content, and performance grade of their extracted and recovered binders. While asphalt content and gradation are generally measured as part of mixture design and QA/QC procedures, the RAM binder PG is not typically measured because it involves solvent extraction and recovery, which is time-consuming and impractical. Consequently, variability in the recycled binder properties is generally not accounted for in mixture design and/or QA/QC. Another factor that leads to uncertainty in the performance of high recycled content mixtures is uncertainty in the proportion of total recycled binder that is available to blend with virgin asphalt binder, known as recycled binder availability (RBA) (Pape and Castorena 2022). Recent studies have shown that not all the recycled binder in RAP is available for blending due to RAP agglomerations, which trap some of the recycled binder and make it inaccessible to blend with virgin binder during mixture production (Castorena et al. 2024, Mocelin et al. 2024). For instance, NCDOT RP 2019-21 (Castorena et al. 2022) reported recycled binder availability (RBA) values ranging from 51% to 83% across four RAP sources in North Carolina, while NCDOT RP 2021-06 (Castorena et al. 2023) found RBA values between 43% and 61% across six sources. These findings highlight significant variability in the RBA of RAP materials within the state. Failure to account for RBA in asphalt mixture design may lead to less durable asphalt mixtures, especially for those with high recycled material percentages (Mocelin and Castorena 2022).

Rahman et al. (2023) evaluated the variability of the performance of plant-produced asphalt mixtures containing RAP and RAS. They observed differences in the performance of mixtures sampled at different times during mixture production, which they speculated could be due to variations in aging caused by different silo storage times at the asphalt plant before transportation to the construction site. However, this study involved mixtures with low recycled material content, capped at 10% RAP and 3% RAS.

The incorporation of performance measures into mixture design and quality assurance procedures is one way to mitigate the potentially detrimental impacts of RAM variability on performance. Many state agencies are shifting from a solely volumetric mixture design approach to a balanced mix design (BMD) approach that incorporates measures of rutting and cracking performance into the design process (NAPA 2017, Yazdipanah et al. 2023, Newcomb 2018, West et al. 2021). However, most state agencies implementing BMD still rely on traditional compositional measures (e.g., gradation, volumetrics) as acceptance quality characteristics (AQCs) during production. Accordingly, several studies have investigated the impacts of variability in asphalt binder content and aggregate gradation on mixture performance (Bowers et al. 2023, Mogawer et al. 2019). These studies have reported that mixtures meeting performance threshold limits during the design phase can fail to meet those same thresholds during production due to variations in binder content and aggregate gradation, even when these variations are within tolerance limits. However, these investigations were conducted on laboratory-mixed and laboratory-compacted specimens, and not actual plant-produced mixtures and did not consider the impacts of variability in RAM.

1.2.5. Summary of Knowledge Gaps and Applications

A review of existing literature and specifications reveals that state agencies implement varying measures to mitigate variability in RAP and RAS. These measures differ in the characteristics assessed, testing frequency, requirements for processing and stockpiling RAM, and the specification of softer virgin binders at higher RBR% levels and limits on the allowable RBR%. The literature also highlights that variability in RAM significantly impacts asphalt mixture performance. While routine testing of RAM gradation and asphalt content helps mitigate this variability, the rheological properties of the RAM binder and RBA also affect performance.

In addition, while many states, including North Carolina, have developed RBR% specifications based on deterministic evaluation of a limited set of recycled and virgin binders, these deterministic approaches fall short in accounting for the full variability of binder properties. RBR% limits warrant a more comprehensive analysis, combining quality assurance (QA) data for virgin binders with representative RAP binder characterization to conduct a probabilistic evaluation of blended binder properties across RBR% levels. This probabilistic framework can then be used to evaluate RBR% thresholds that satisfy performance-graded specifications at a desired confidence level, offering a more risk-informed approach to setting RBR% limits. Furthermore, NCDOT RP 2014-05 (Khosla and Ramoju 2017) did not evaluate the low-temperature performance graded properties of RAP binders or RAP–virgin binder blends when establishing RBR% limits. One likely reason for this omission is the relatively large quantity of recovered binder required for Bending Beam Rheometer (BBR) testing, which can be challenging to obtain from RAP. If BBR parameters could be reliably predicted from Dynamic Shear Rheometer (DSR) measurements, the amount of binder needed for characterization would reduce significantly.

Although several studies have examined the effects of RAM variability on asphalt mixture performance, most focus on laboratory-mixed and compacted specimens. This underscores the pressing need for further research on the impacts of RAM variability in plant-produced mixtures. Such research should explore not only the asphalt content and gradation of RAM materials but also the rheological properties of extracted and recovered binders and RBA. Insights from this investigation could inform improved processing, stockpiling, and QA/QC practices, ensuring the consistent performance of asphalt mixtures with high RAM content.

1.3. Organization of the Report

This report is composed of six primary sections and five 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, experiments, and analysis methods. Section 3 presents the research results and analysis. 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 results that were used to identify contractor practices for stockpiling and processing RAP and RAS. Appendix C presents the distributions of virgin and recycled binder properties and the evaluation of the accuracy of the blending chart equations used in the probabilistic analysis of RBR% limits presented. Appendix D presents the development and verification of a method to predict low-temperature performance grading parameters from DSR test results. Appendix E presents a summary of the alternative rheological indicators of durability results for the virgin binders, RAP binders, and blends.

2. METHODOLOGY

2.1. Overview

Figure 1 provides an overview of the research approach. First, a comprehensive review was conducted to identify the best practices and strategies employed by state agencies to mitigate variability of RAP and RAS stockpiles. This review also investigated how variability in recycled materials can adversely affect asphalt mixture performance. Next, asphalt plants that would be used for the experimental portion of this study were selected based on three main criteria: (1) surface mixtures that the plant produced needed to contain a high recycled binder replacement RBR% of 25% or higher, (2) production of these mixtures had to continue throughout the project duration to allow for repeated sampling, and (3) the materials had to be sourced from different contractors and geographic regions in North Carolina to account for potential differences in aggregate mineralogies and regional practices. Once the asphalt plants were selected, a detailed asphalt plant questionnaire was distributed to understand how the different contractors operate their asphalt plants and manage their recycled asphalt materials (RAM). Subsequently, all materials (i.e., RAM, virgin binder, and plant-produced asphalt mix) were sampled multiple times at intervals spanning from several months to up to 1.5 years. The virgin binder, RAM, and plant-produced mixtures were characterized to assess the variability in their properties and performance after a prolonged time gap. The collective findings were then used to identify and propose changes to the NCDOT's current specifications to improve the consistency within and across RAP and RAS stockpiles within North Carolina.

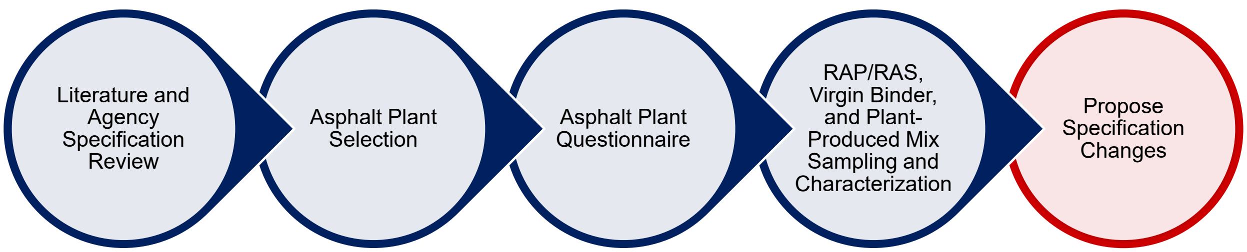


Figure 1. Overview of the research approach.

2.2. Plant Operational Review

NCDOT RP 2021-06 (Castorena et al. 2023) conducted an operational review of eight asphalt plants across North Carolina to assess RAP and RAS management practices by different contractors. Three of these plants were selected for inclusion in the present project to encompass differing stockpiling and processing practices. One major challenge, however, was the need to sample each job-mix formula (JMF) multiple times. This complication required coordination with plant supervisors to ensure that the selected JMFs would remain in production for the duration of the project to allow for repeated sampling and assessment of the variability of the performance of the plant-produced asphalt mixtures and the properties of the recycled materials over time. For that reason, four additional asphalt plants were incorporated into the present project's experimental plan after consulting with plant supervisors. In total, seven asphalt plants representing five different contractors were interviewed for the present project. The plants are designated by arbitrary letters to preserve anonymity. All participating plants completed the same questionnaire used in NCDOT RP 2021-06. The asphalt plants varied in terms of geographic location, plant type, average RAP content used, and RAS usage. The operational review focused on five key topics: (1)

general asphalt plant information, (2) recycled material sources and stockpiling, (3) recycled material processing, (4) recycled material sampling and testing, and (5) asphalt mix production and silo storage. The findings from the plant operational review provided insights into how contractors operate their asphalt plants and manage their recycled asphalt materials and highlighted potential sources of variability in RAM stockpiles properties within the state. The detailed questionnaire and responses from each plant are presented in Appendix B.

2.3. Materials

2.3.1. Job-Mix Formulas

Plant-produced surface asphalt mixtures and their constituent materials (RAM and virgin binder) were acquired and characterized from the seven asphalt plants representing five different contractors in North Carolina. All mixtures evaluated in this study have a 9.5 mm nominal maximum aggregate size (NMAS). Table 1 provides a summary of the characteristics of the plant-produced asphalt mixtures reported on the job mix formula (JMF). The RAP and RAS contents in Table 1 refer to their respective stockpile percentages. The mixtures from Plants H, A, and I are classified as RS9.5C according to NCDOT specification (NCDOT 2024) and are designed for traffic loading between 3 to 30 million equivalent single axle loads (ESALs), while the mixtures from Plant K, J, F, and W are classified as RS9.5B and are designed for traffic loading up to 3 million ESALs. For five of the seven plants, all materials (i.e., RAP, RAS, virgin binder, and plant-produced asphalt mixture) were sampled multiple times on different dates spanning from several months to up to 1.5 years apart to assess the variability in their properties and performance after a prolonged time gap. The reason for the relatively long gap was to try to encompass a gap during which the recycled material stockpiles may have been replenished with new sources.

Table 1. Characteristics of the Plant-produced Asphalt Mixtures Reported on the JMF

Plant ID	H	A	K	I	F	W	J
Mix type	RS9.5C	RS9.5C	RS9.5B	RS9.5C	RS9.5B	RS9.5B	RS9.5B
RAP (%)	35	30	30	40	40	40	30
RAS (%)	0	0	3	0	0	0	0
Total AC (%)	6.1	6.0	6.3	5.5	6.3	6.0	6.0
RBR% (%)	25	25	30	35	30	32	27
VMA (%)	16.9	17.1	18.2	16.3	18.0	17.2	17.1
Virgin PG	64-22	64-22	58-28	58-28	58-28	58-28	64-22

2.3.2. Sampling Schedule

Figure 2 presents the plant locations, and Table 2 lists the corresponding sampling dates. Plant-produced mixture and RAM were sampled on the same dates. The selected plants encompass the coastal and piedmont geologic regions in North Carolina to encompass different aggregate mineralogies and regional practices. The study did not include plants from the mountain region of North Carolina because high RAM content mixtures are not commonly used in that area. Additionally, the materials from Plants F and W were sampled only once, as these plants discontinued production of the specified JMFs during the project duration.

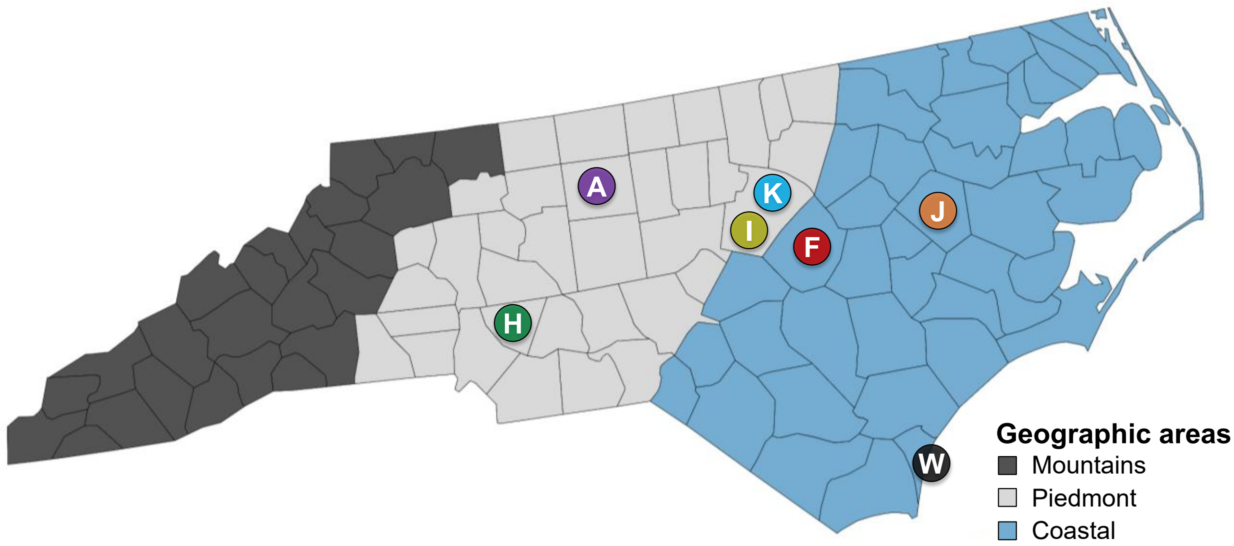


Figure 2. North Carolina map indicating the location of the asphalt plants.

Table 2. Sampling Date of the Materials.

Plant ID	Sampling date
H	October 2022 & April 2023
A	November 2022, September 2023, & March 2024
K	June 2023, September 2023, & May 2024
I	November 2023 & June 2024
F	September 2022
W	October 2023
J	June 2023, November 2023, & June 2024

2.3.3. Naming Convention

A naming convention was created to represent each mix and the different conditions at which the mixture is evaluated. An example is I-40/0-1, where "I" reflects the Plant ID, "40" denotes the RAP content, "0" denotes the RAS content, and "1" indicates this was the first sample acquired from the plant. Thus, when this mixture was resampled, the name for that sample was I-40/0-2. In sections where RAP properties are reported directly, the name may be followed with a (C)', an (F)', or a (C+F)' and in these cases, the designations indicate whether the RAP materials were from a Coarse, Fine, or Coarse + Fine stockpile. If no follow-up letter is given, then it means that the RAP is from the single stockpile available at the given plant.

2.4. Methods

A comprehensive set of tests was conducted to characterize the plant-produced surface asphalt mixtures and their constituent materials (RAP, RAS, and virgin binder), as schematically illustrated in Figure 3. Detailed descriptions of these characterization methods are provided in the subsequent sections.

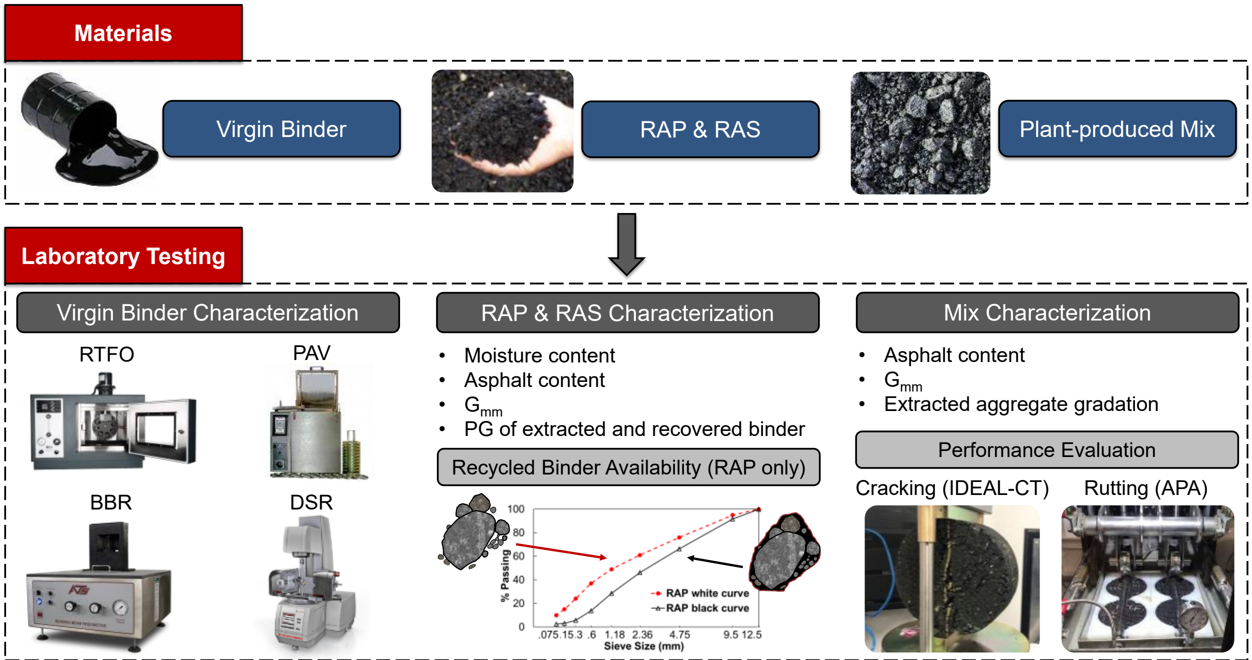


Figure 3. Summary of the tests used to evaluate the materials.

2.4.1. Recycled Asphalt Material Characterization

The RAM materials were sampled in 5-gallon buckets that were sealed and transported to the laboratory. Then, the RAM materials were oven-dried at 60°C before characterization. The mass of the RAM before and after drying was used to determine its moisture content. The RAM materials were characterized in terms of asphalt content, theoretical maximum specific gravity (G_{mm}), performance grade (PG) of extracted and recovered RAM binder, and recycled binder availability. The asphalt content of the recycled materials was measured via ignition oven according to AASHTO T 308 (2021), applying a calibration factor of 0.5% for the RAP as specified by NCDOT (2024). The G_{mm} was measured using the automatic vacuum sealing method according to ASTM D6857 (2023).

The recycled binder availability (RBA) of the RAP was determined using the sieve analysis method proposed by Pape and Castorena (2021). In summary, this method uses the gradation of the RAP itself (referred to as "black curve"), the gradation of the recovered RAP after ignition oven (referred to as "white curve"), the asphalt content of the RAP, and the aggregate specific gravity of the RAP to determine the RBA. The black curve is obtained by first subjecting the RAP sample to mechanical washing according to AASHTO T 11 (2020), then oven-drying the sample at 100°C, and finally sieving it as per AASHTO T 27 (2020). The white curve is obtained by collecting the RAP from each sieve from the previous sieve analysis and removing the binder via an ignition oven. The recovered aggregate is then subjected to mechanical washing, oven-dried at 110°C, and sieved to obtain the mass retained for each relevant size, incorporating any fines lost during the first washing. This approach to obtaining the white curve was found to provide consistent results to the standard procedure for obtaining the white curve, which does not require first washing and sieving the RAP in the ongoing National Cooperative Highway Research Program for Ideas Deserving Exploratory Analysis (NCHRP IDEA) Project 259. The proportion of recycled binder trapped within the agglomerations and, therefore, inaccessible to blend with virgin binder is inferred from the difference in surface area of the RAP and the recovered aggregate by comparing the black and white curves. Further details about the method can be found in Pape and Castorena (2021) and Castorena et al. (2024). It is important to note that the sieve analysis method does not apply to RAS materials. Currently, no practical method exists to quantify the RBA of RAS. In most but not all cases, RBA results were obtained for two replicate RAP samples. In all cases, the difference between replicates was very small (less than 2%).

2.4.2. Virgin and Recycled Binder Characterization

The recycled binders were extracted using a centrifuge extractor with trichloroethylene (TCE) as the solvent according to Method A of AASHTO T 164 (2024). The asphalt binder recovery was completed using a rotary evaporator according to ASTM D5404. The recovered RAP binders were subjected to Rolling Thin Film Oven (RTFO) aging according to AASHTO T 240 (2023) for characterization. The RAP binders were not subjected to further aging in the pressurized aging vessel (PAV) by Appendix X2 of AASHTO M 323 (2022). The RAS binders were tested after blending with virgin binder using a blend ratio that matched the plant-produced mixture. Fried et al. (2022) suggested avoiding testing RAS alone because the potentially excessive PG of RAS binders can make casting samples and obtaining reliable rheological measurements difficult. To prepare blends containing RAS, the RAS binder was preheated to 165°C and ground using a mortar and pestle. Then, the ground RAS was combined with virgin binder preheated to 140°C. The binders were blended with a power drill equipped with a paddle attachment. The virgin binders and blends were conditioned in the RTFO and PAV according to AASHTO R 28 (2022) to produce short- and long-term aged binders, respectively. No evident RAS particles persisted after blending and conditioning in the RTFO.

DSR testing was conducted on all binders at the RTFO age level according to AASHTO T 315 (2024) for high-temperature grading. Original binder testing was avoided for the RAP to ensure any residual solvent from the recovery was fully removed, which was confirmed via Fourier Transform Infrared Spectroscopy (FTIR). DSR testing was also conducted for intermediate temperature grading according to AASHTO T 315 (2024). Intermediate temperature tests were performed on RAP at the RTFO age level by Appendix X2 of AASHTO M 323 (2022) and at the PAV age level for the virgin binders and blends by AASHTO M 320 (2023). The results were analyzed to determine the standard high- and intermediate-temperature grades according to AASHTO M 320 (2023) and the continuous grading high-temperature (PGH) and continuous grading intermediate temperature (PGI) according to ASTM D7643 (2022). DSR testing was conducted at a minimum of two temperatures, one passing the AASHTO M 320 (2023) high-temperature grading criteria and one failing. In addition, testing was conducted at NC's critical climatic temperatures of 64°C for high-temperature and 25°C for intermediate temperature. Two replicate tests were initially conducted. If the results met the repeatability requirements in AASHTO T 315 (2024), testing ceased. If the requirement was not met, an additional replicate test was conducted until the requirement was satisfied.

Bending beam rheometer (BBR) testing was performed for low-temperature characterization by AASHTO T 313 (2024). RAP binders were tested at the RTFO age condition as specified in Appendix X2 of AASHTO M 323 (2022). Virgin binders were tested at the PAV age level. The RAP and RAS blends were tested at -6°C and -12°C, while the virgin binders were tested at -12°C and -18°C. All BBR tests were conducted by the NCDOT's Materials and Tests Unit.

In addition, temperature-frequency sweep (TFS) tests were carried out using the DSR at the PAV age level for the virgin binders and blends and RTFO age level for the RAP binders according to the general requirements of AASHTO T 315 (2024). For virgin binders and blends, TFS testing was implemented using the 8-mm parallel plate geometry with a 2-mm gap using test temperatures of 5°C, 20°C, 35°C, and 50°C and a frequency span of 0.1 to 15 Hz. For the RAP binders, temperatures of 10°C, 20°C, 35°C, and 50°C were used as challenges, maintaining proper adhesion was maintained at 5°C. Two replicate tests were conducted for each binder and blend. The results generally met the repeatability requirements of AASHTO T 315 (2024).

2.4.3. Plant-Produced Asphalt Mixture Characterization

The plant-produced asphalt mixtures were characterized in terms of extracted aggregate gradation, asphalt binder content, and G_{mm}. The asphalt binder content and extracted aggregate were obtained via ignition oven, and the extracted aggregate gradation was determined according to AASHTO T 30 (2021). The G_{mm} was measured according to AASHTO T 209 (2020). Additionally, all mixtures were tested for rutting and cracking susceptibility using the asphalt pavement analyzer (APA) and the indirect tensile cracking test (IDT-CT), respectively. The APA was conducted in accordance with AASHTO T 340 (2023) and NCDOT requirements on four replicate specimens with a 150 mm diameter by 75 mm tall, with a target air void of 4% at 64°C. The output of the APA test is the rut depth after 8,000-wheel passes. The IDT-CT was conducted according to ASTM D8225 (2019) on five replicate specimens measuring 150 mm in diameter and 62 mm in height, with a target air void of 7% at 25°C. It should be noted that all plant-produced asphalt mixtures were obtained in 5-gallon buckets. The loose mixes were then divided into small samples following LaCroix (2013).

2.5. Analysis

2.5.1. Blending Charts

The continuous grading temperatures of the blend of virgin and recycled binders in the plant-produced mixtures were approximated using linear blending charts by Appendix X2 of AASHTO 2M 323 (2022). For the RAP-only mixtures, the blended binder continuous grading temperatures were estimated using Equation (1). For the mixtures containing RAP and RAS, the blended binder continuous grading at high temperatures was estimated using Equation (1), inputting the continuous temperature of the blend of virgin and RAS binder as the PG_{Virgin}. The measured mixture and RAM binder contents for each sample were used to calculate the RBR% values, thereby accounting for the observed variability in mixture composition.

$$PG_{\text{Blend}} = RBR_{RAP} \times PG_{RAP} + (1 - RBR_{RAP}) \times PG_{Virgin} \quad (1)$$

where: PG_{Blend} = continuous grading temperature of the blend of recycled and virgin binder (°C); RBR_{RAP} = RAP binder recycled binder ratio, equal to the weight of RAP binder in the mix divided by total binder weight in the mix; PG_{Virgin} = virgin binder continuous grading temperature (°C).

AASHTO M 320 (2023) requires that $|G^*| \times \sin(\delta)$ is less than or equal to 6,000 kPa at 25°C for NC's climatic grade of PG 64-22. AASHTO M 320 (2023) and NCDOT specifications (2024) also require that δ must be greater than or equal to 42° when $|G^*| \times \sin(\delta)$ falls between 5,000 kPa and 6,000 kPa at this temperature. To evaluate the potential implications of the δ requirement, the blended binder δ values were estimated using Equation (2) at 25°C. None of the estimated δ values that fell below the minimum limit despite some $|G^*| \times \sin(\delta)$ values exceeding 5,000 kPa and thus, it is inferred that the $|G^*| \times \sin(\delta)$ rather than the δ criterion is most restrictive. In addition, conversations with the NCDOT Materials and Tests personnel indicate no binders have been rejected for failing the δ requirement. Consequently, the 6,000 kPa limit for $|G^*| \times \sin(\delta)$ was used as the basis for calculating continuous grading intermediate-temperatures.

$$\delta_{\text{Blend}} = RBR_{\text{RAP}} \times \delta_{\text{RAP}} + (1 - RBR_{\text{RAP}}) \times \delta_{\text{Virgin}} \quad (2)$$

where: δ_{Blend} = δ of the blend of RAP and virgin binder; δ_{RAP} = δ of the RAP binder; δ_{Virgin} = δ of the virgin binder.

The RAS blend results combined with the virgin binder results were used to estimate the RAS binder continuous high-temperature using Equation (3).

$$PG_{RAS} = \frac{PG_{Blend} - (1 - BR_{RAS}) \times PG_{Virgin}}{BR_{RAS}} \quad (3)$$

where: PG_{RAS} = continuous grading temperature of the RAS (°C); BR_{RAS} = RAS blend ratio in the blend of virgin and RAS binder, equal to the weight of RAS binder by the combined weight of RAS and virgin binder.

2.5.2. Probabilistic Analysis of RBR% Thresholds

The results of RAP binder testing herein, combined with past NCDOT RP 2014-05 and virgin binder QA data provided by the NCDOT, were also used to conduct a probabilistic evaluation of the RBR% limits specified by the NCDOT and to identify if alternatives would increase the likelihood of the blended binders in asphalt mixtures meeting intended performance-graded specifications.

The NCDOT asphalt binder specifications are based on AASHTO M 320 (2023). Accordingly, the data sets used to conduct probabilistic analysis of RBR% limits included performance-graded (PG) binder properties evaluated at the critical temperatures for North Carolina's climatic grade of PG 64-22. These properties include the DSR-derived characteristics used for high- and intermediate-temperature grading, based on measurements of the dynamic shear modulus, $|G^*|$, and phase angle, δ. Specifically, these include $|G^*|/\sin(\delta)$ at 64°C for high-temperature grading and $|G^*|\times\sin(\delta)$ at 25°C for intermediate-temperature grading. The low-temperature properties based on the BBR testing include creep stiffness at a loading time of 60 seconds, $S(60)$, and the slope of the logarithmic stiffness-time curve at a loading time of 60 seconds, $m(60)$, both measured at -12°C. Recall that AASHTO M 320 (2023) and NCDOT specifications (2024) also require that δ must be greater than or equal to 42° when $|G^*|\times\sin(\delta)$ falls between 5,000 kPa and 6,000 kPa at 25°C. However, phase angle δ was not reported in the NCDOT QA database, and thus, this additional requirement could not be directly evaluated. For the study blends, δ values were estimated at the current NCDOT RBR% limits. None of the blends had estimated δ values that fell below the minimum limit, while some had $|G^*|\times\sin(\delta)$ values exceeding 5,000 kPa, and thus, it was inferred the $|G^*|\times\sin(\delta)$ is most restrictive. Hence, the $|G^*|\times\sin(\delta)$ limit of 6,000 kPa was used within the analysis.

The data from NCDOT RP 20214-05 consists of 27 additional RAP binders (Khosla and Ramoju 2017). The high-grading temperatures for these 27 RAP binders varied from 82°C to 112°C. However, it is important to note that these additional samples include only high- and intermediate-temperature PG characterization results.

The virgin binder dataset consists of QA data acquired from 2022 to 2024. This dataset contains 273 PG 64-22 samples and 69 PG 58-28 samples. High-, intermediate-, and low-temperature PG properties were available for PG 64-22 binders. The high-temperature results utilized were acquired at the RTFO age level, whereas the intermediate and low temperature PG properties were measured after RTFO and PAV aging. The QA data for PG 58-28 binders provide only high- and intermediate-temperature data because existing low temperature measurements at -18°C do not match NC's critical climate temperature of -12°C. Thus, low-temperature properties could be evaluated for the PG 58-28 virgin binders and associated blends.

Blending charts equations were used to virtually blend RAP binders with virgin binders to generate all possible combinations of blended binder properties at a given RBR% level for a given virgin binder PG and assess the distributions of blended binder properties. This analysis yielded over 12,000 simulated binder blends, which would not be feasible to evaluate through direct experimentation. This analysis approach was chosen because the distributions of virgin and/or RAP binder value for a given parameter failed Shapiro-Wilk tests for normality in all cases at a significance level of $\alpha = 0.05$, which precluded generating distributions of blended binder properties analytically from the distributions of virgin and recycled binder properties.

High- and intermediate-temperature blended binder parameters $|G^*|/\sin(\delta)$ and $|G^*|\times\sin(\delta)$, along with the low-temperature stiffness parameter $S(60)$, were calculated using Equation (4). The blended binder parameter $m(60)$ was calculated using Equation (5). These equations were selected based on the blending charts prescribed in Appendix 2 of AASHTO M 323 (2022), which suggest a linear relationship between blended binder continuous grading temperatures and recycled binder replacement ratio (RBR) combined with the relationships between the PG parameters and temperature suggested by ASTM D7643 (2022). ASTM D7643 (2022) indicates linear relationships between the logarithm of each PG parameter and temperature, except for $m(60)$, which is assumed to vary linearly with temperature.

$$\log(P_{\mathrm{Blend}}) = RBR_{\mathrm{RAP}} \times \log(P_{\mathrm{RAP}}) + (1 - RBR_{\mathrm{RAP}}) \times \log(P_{\mathrm{Virgin}}) \tag{4}$$

where: P_{Blend} = property of the blend of RAP and virgin binder; RBR_{RAP} = RAP binder recycled binder ratio, equal to the weight of RAP binder in the mix divided by total binder weight in the mix; P_{RAP} = property of the RAP binder; and P_{Virgin}= property of the virgin binder.

$$m(60)_{\mathrm{Blend}} = RBR_{\mathrm{RAP}} \times m(60)_{\mathrm{RAP}} + (1 - RBR_{\mathrm{RAP}}) \times m(60)_{\mathrm{Virgin}} \tag{5}$$

where: $m(60)_{\mathrm{Blend}}$ = $m(60)$ of the blend of RAP and virgin binder; $m(60)_{\mathrm{RAP}}$ = $m(60)$ of the RAP binder; $m(60)_{\mathrm{Virgin}}$= $m(60)$ of the virgin binder.

Studies have noted that the blending chart equations in Appendix X2 of AASHTO M 323 (2022) can be inaccurate, especially at high RBR% levels (McDaniel and Anderson 2001). Therefore, the accuracy of the blending chart equations used was verified for select blends and properties evaluated in this study. The details of the verification materials are presented in Appendix C along with the distributions of virgin and RAP binder properties for the collective data sets. The average percent error was 8% for the high-temperature property and 3% for the intermediate-temperature property both considered acceptable given the advantages of the proposed analysis's ability to evaluate many blends compared to what would be possible through direct testing.

The distributions of blended binder properties were calculated at a range of RBR% levels to critically assess existing RBR% thresholds and identify alternative limits that would minimize the likelihood of blended binder systems failing to meet specification requirements. The PG 64-22 QA binder data set was used as a benchmark to compare the recycled binder blends against. PG 64-22 is the climatic grade specified in North Carolina for virgin mixtures. As such, it serves as a reference for the target performance properties that the recycled binder blends should achieve.

2.5.3. Analysis of Alternative Rheological Parameters

Recent research suggests alternative rheological parameters to those in the AASHTO M 320 performance graded specifications may be better indicators of cracking resistance. This study evaluated three of these parameters. The detailed results are presented in Appendix E.

The critical temperature differential (ΔT_c) is equal to the difference between the PGL_c for *S*(60) and *m*(60) criteria and has received considerable attention in recent years for capturing the effects of embrittlement on pavement cracking potential. NCHRP Project 09-60 recommended the specification of ΔT_c to control block cracking (Elwardany et al. 2022). A lower (more negative) (ΔT_c) indicates a poor ability to relax thermal stresses and is associated with higher cracking susceptibility. The ΔT_c was calculated from the continuous low-temperature performance grading temperatures obtained as described in the previous section. For blended binders, the *S*(60) and *m*(60) critical temperatures were first estimated from blending charts and then used to calculate ΔT_c.

The Glover-Rowe (G-R) parameter, $|G^*|\cos^2\delta/\sin\delta$, has been proposed as a better indicator of cracking resistance than the AASHTO M 320 intermediate-temperature parameter, $|G^*| \times \sin\delta$, for two reasons. First, the G-R parameter is an indicator of ductility and thus cracking susceptibility, for non-polymer-modified asphalts. Lower G-R values are associated with higher ductility (Glover et al. 2005). Second, an increase in G-R, along with an expected reduction in ductility, occurs due to an increase in $|G^*|$ and/or a decrease in δ, which aligns with changes imparted by oxidative aging (Anderson et al. 2011). In contrast, the AASHTO M 320 parameter suggests an improvement in cracking resistance when δ decreases, which is counterintuitive to the effects of oxidation known to induce embrittlement. The intermediate-temperature performance grading results were used to calculate the G-R parameter at 25°C and 10 rad/s, aligning with NCHRP Project 09-59 recommendations for fatigue cracking evaluation (Christensen and Tran 2020). This study proposed a maximum limit of 5,000 kPa. In addition, master curves were constructed to determine G-R at the condition of 15°C and 0.005 rad/s, which is correlated with force ductility test results for non-polymer modified binders (Rowe 2011). In both cases, Equation (4) was used to estimate blended binder G-R values.

Dynamic shear modulus ($|G^*|$) and phase angle (δ) master curves were constructed using TFS results and modeled following the recommendations of Fried and Castorena (2023). This procedure involves free shifting of the isotherms in a pair-wise approach to first construct the master curve and then employing linear regression to calculate the Christensen Anderson master curve model coefficients. The coefficient of determination (R^2) values for the resultant dynamic shear modulus master curves were all 1.00 and at least 0.99 for phase angle master curves. The results were used to determine the G-R at 15°C and 0.005 rad/s and the phase angle where $|G^*|$ = 10 MPa. Kriz (2016) found a strong correlation between the phase angle where $|G^*|$ = 8.967 MPa and the intermediate temperature cracking resistance. Subsequent researchers suggested rounding this value to 10 MPa for simplicity (Bennert et al. 2023, Mogawer et al. 2025). To obtain this parameter, the $|G^*|$ master curve model was first used to identify the reduced frequency where $|G^*|$ = 10 MPa. Subsequently, the phase angle master curve model was used to calculate the phase angle at this reduced frequency. Blended binder phase angle values were approximated, akin to the *m*-value, since both are related to the slope of the master curve using Equation (6). Higher phase angle results are associated with better cracking resistance (Mogawer et al. 2025); however, acceptance limits do not presently exist.

$$\delta_{Blend} = RBR_{RAP} \times \delta_{RAP} + (1 - RBR_{RAP}) \times \delta_{Virgin} \quad (6)$$

where: δ_{Blend} = phase angle of the blend of recycled and virgin binder (°); δ_{RAP} = phase angle of the RAP (°); δ_{Virgin} = virgin binder phase angle or blend of virgin and RAS phase angle for RAP/RAS mix case (°).

2.5.4. Prediction of Low-Temperature Performance Graded Properties from Dynamic Shear Rheometer Test Results

*S*everal previous studies have proposed methods to predict BBR results using DSR data. Among these, the approach developed by Zeng et al. (2022) is particularly notable. It relies solely on DSR testing with 8-mm parallel plates at intermediate temperatures, making it well-suited to the existing capabilities of most agency and supplier laboratories. Additionally, the method was validated using the largest dataset among the reviewed studies.

This study evaluated the applicability of Zeng et al.'s method for predicting the low-temperature grade of both virgin and recycled binders using the current dataset. Empirical calibration equations were developed to improve prediction accuracy for North Carolina materials, achieving an average absolute error in continuous low-temperature grade of just 0.7°C. The detailed methodology, results, and analysis are provided in Appendix D.

2.5.5. Statistical Analysis of the Plant-produced Mixture Variability

JMP Pro software version 17 was used to perform statistical analysis of the mixture performance test results, specifically the CT_{Index} and rut depth. Statistical tests such as analysis of variance (ANOVA) and t-test require certain assumptions, including homogeneity of variances and normality, to ensure valid inferences. The normality assumption was assessed using Q-Q plots for visual inspection and the Shapiro-Wilk test for formal evaluation (Sainani 2012). The Shapiro-Wilk test was conducted at a significance level (α) of 0.05, with the null hypothesis stating that the data is normally distributed. A p-value below 0.05 indicates the null hypothesis is rejected, suggesting the data is likely not normally distributed. Both CT_{Index} (p-value = 0.2585) and rut depth (p-value 0.2709) met the normality assumption based on the Shapiro-Wilk test and Q-Q plots.

The homogeneity of variances was evaluated using Levene's and Bartlett's tests, which test the null hypothesis that variances across groups are equal. For both tests, a p-value below 0.05 suggests that variances differ significantly among the groups. The results revealed that both the CT_{Index} and rut depth failed to meet the assumption of homogeneity of variances, as both parameters yielded p-values below 0.05. Consequently, the traditional ANOVA was deemed inappropriate due to the violation of this assumption. Instead, Welch's ANOVA was conducted to identify statistically significant differences between the mixture mean CT_{Index} and rut depth values among the different mixtures and samples, as Welch's ANOVA is more robust to unequal variances. After verifying significant differences exist, the Games-Howell post-hoc test was conducted to compare all pairs of means and determine which pairs are significantly different from each other. The Games-Howell test is specifically designed for situations where the homogeneity of variances assumption is violated (Sauder and DeMars 2019). All statistical tests were conducted at a significance level (α) of 0.05.

2.5.6. Relationship between Mixture Composition and Performance

The relationship between the performance and composition of plant-produced asphalt mixtures was assessed through statistical analysis using JMP Pro software version 17. First, correlation coefficients were calculated to quantify the strength of the relationship between CT_{Index} (or rut depth) and mixture composition variables as well as binder rheological parameters. Two types of correlation coefficients were computed: (1) the Pearson correlation coefficient, which measures the strength and direction of a linear relationship between two variables, and (2) the Spearman rank correlation coefficient, which measures the strength and direction of a monotonic relationship, regardless of whether it's linear. The values of both coefficients range from -1 to +1, where -1 indicates a perfect negative correlation and +1 indicates a perfect positive correlation, and values close to zero suggest no correlation between the variables (Walpole et al. 2017, Huang et al. 2025). Second, scatterplots were used to visually identify relationships between variables with the highest correlation coefficients.

The composition of the plant-produced mixtures was interpreted in two ways: (1) according to current NCDOT procedures that assume 100% RBA and (2) using the Availability Adjusted Mixture Design (AAMD) method developed in NCDOT RP 2021-06 (Castorena et al. 2023). The AAMD method addresses RBA by attributing the unavailable recycled binder to the bulk aggregate volume of the asphalt mixture and uses the RAM black curve to reflect its gradation.

3. Results and Analysis

3.1. Key Insights from the Plant Operational Review

The detailed questionnaire and responses from each asphalt plant are presented in Appendix B. The key takeaways are summarized below:

1. The interviewed asphalt plants incorporate relatively high percentages of RAP in their mixtures, with three plants using between 20 to 30% and four plants reaching up to 40%.
2. All asphalt plants indicated that their RAP stockpile could consist of materials from state roads, private roads, parking lots, and plant waste.
3. The maximum height of recycled material stockpile varies widely across plants, ranging from 20 to 75 feet. In some cases, the maximum height depends on factors such as whether the material is processed or unprocessed, coarse or fine, or consists of RAP or RAS.
4. The duration for which RAP materials are stockpiled after crushing and before use varies significantly across plants, ranging from immediate use to being stockpiled for over a year.
5. Silo storage times for produced mixtures vary widely across plants, ranging from 10 up to a maximum of 60 hours.
6. Most asphalt plants maintain a single unprocessed RAP stockpile, except for Plant H, which has two: one stockpile with surface millings from its projects and another stockpile for all other RAP sources.
7. Plants H and F each have three processed RAP stockpiles (fine, coarse, and combined), while all others have only one.
8. Plant K is notably distinct in its operations:
   a) It is the only plant that crushes its own RAP on-site; all other plants rely on external contractors.
   b) It is the only plant equipped with an inline impact crusher for RAP during mix production.
   c) Plant K is also the only facility that grinds its own RAS on-site.
9. The three RAS plants use only manufactured waste shingles.
10. The screen size of the RAP varies across plants. Plants I, W, and J use one stockpile of single-sized RAP (-5/8”). In contrast, Plant H maintains three stockpiles: fine RAP (-1/4”), coarse RAP (½” – 5/8”), and combined. Similarly, Plant F also has three stockpiles: fine RAP (-3/8”) and coarse RAP (3/8” – 9/16”) and combined.

3.2. Recycled Materials Characterization

3.2.1. Asphalt Content, Specific Gravity, and Moisture Content

Table 3 summarizes the asphalt contents, specific gravities, and moisture contents of the RAM samples. It is important to note that the only cases that contained fractionated RAP were F-40/0-1 and H-35/0-1. Plant H used two RAP stockpiles (coarse and fine) for the first sample, but later switched to using only one combined stockpile. Consequently, only one RAP stockpile result is shown for H-35/0-2, which is compared most directly to the blend from H-35/0-1. Variability in the RAP properties is observed across the different plants, with binder contents spanning from 4.3% to 5.4% (neglecting the fractionated stockpiles) and G_{mm} values spanning from 2.451 to 2.625. However, when looking at the variability within each stockpile over time, most showed generally consistent properties, except for Plant K, where the binder content varied from 4.7% to 5.4%, and G_{mm} values ranged from 2.499 to 2.523.

According to NCDOT specifications (NCDOT 2024), if a stockpile is to be replenished with a new source of RAP or RAS and used in an existing JMF, the binder content must be within specific tolerance limits. For RAP, the acceptable difference between the approved and new RAP sources is ± 0.4% for mixtures containing between 20 to 30% RAP and ± 0.3% for mixtures with more than 30% RAP. For RAS, the allowable difference is ±2.5%. The binder content differences between the measured values obtained from the ignition oven and those listed in the JMF for RAS materials are within these limits for both the first and second samplings. For RAP, the materials from Plant A (all three samplings) and Plant K (samplings one and three) exceeded the allowable limits. Specifically, the RAP materials from Plant A showed lower binder content than that listed in the JMF, while the RAP materials from Plant K showed higher binder content than what was listed in the JMF. For all other RAP materials, the binder content differences remained within the specified limits.

NCDOT also requires measurement of moisture content in RAP and RAS at the start of production and daily during production. Monitoring moisture is important because excess moisture requires additional heating and fuel consumption for evaporation, thus increasing production costs. For this reason, NCDOT recommends covering RAP and RAS stockpiles to keep them as dry as possible, although this practice is not commonly observed in North Carolina. The moisture content varies significantly across different plants, spanning from 1.4 to 5.7 percent.

The effective specific gravity (G_{se}) was back-calculated from G_{mm} measurements, using the measured binder content and assuming a binder specific gravity of 1.02 since the stockpile specific RAP binder specific gravities were not available. All G_{mm} measurements met the repeatability precision limits. Despite the relatively long time gap between samplings, the G_{se} values for most RAP materials were very consistent, with the exception of Plant K, which exhibited the largest within-plant difference of 0.046. The second-largest difference, 0.024, was observed for Plant H. In contrast, notable differences were observed among the RAS samples from Plant K, suggesting potential changes in aggregate characteristics when the stockpile was replenished. When comparing RAP materials across different plants, G_{se} values exhibited greater variability, ranging from 2.645 to 2.796. These deviations are noteworthy given that the NCDOT does not require routine measurements of RAP G_{mm} and thus, G_{se} as part of process control.

Table 3. Properties of the RAM Samples

Mix	Recycled material	Binder content, measured (%)	Binder content, JMF (%)	Binder content difference (%)	Moisture content (%)	G_{mm}	G_{se}
F-40/0-1	Coarse RAP	4.4	3.6	0.3	3.4	2.504	2.682
F-40/0-1	Fine RAP	5.0	5.1	-0.1	4.1	2.463	2.660
F-40/0-1	Blend RAP	4.9	-	-	-	2.471	2.665
H-35/0-1	Coarse RAP	3.4	3.3	0.1	3.6	2.625	2.778
H-35/0-1	Fine RAP	4.9	4.7	0.2	4.7	2.553	2.767
H-35/0-1	Blend RAP	4.3	-	-	-	2.581	2.772
H-35/0-2	RAP	4.4	4.1	0.3	5.4	2.596	2.796
A-30/0-1	RAP	4.4	5.0	-0.6	3.8	2.538	2.724
A-30/0-2	RAP	4.5	5.0	-0.5	4.0	2.527	2.715
A-30/0-3	RAP	4.5	5.0	-0.5	5.7	2.515	2.702
K-30/3-1	RAP	5.4	4.5	0.9	1.7	2.499	2.724
K-30/3-1	RAS	17.5	18.0	-0.5	2.6	2.135	2.780
K-30/3-2	RAP	4.7	4.5	0.2	1.9	2.503	2.695
K-30/3-2	RAS	20.1	18.0	2.1	4.8	2.043	2.732
K-30/3-3	RAP	5.1	4.5	0.6	3.1	2.523	2.741
K-30/3-3	RAS	21.5	18.0	3.5	4.6	2.053	2.842
J-30/0-1	RAP	5.2	5.2	0.0	3.8	2.457	2.664
J-30/0-2	RAP	5.3	5.2	0.1	3.5	2.451	2.660
J-30/0-3	RAP	5.2	5.2	0.0	1.4	2.470	2.677
I-40/0-1	RAP	4.8	4.8	0.0	4.0	2.455	2.645
I-40/0-2	RAP	4.7	4.8	-0.1	4.2	2.472	2.659
W-40/0-1	RAP	4.7	4.8	-0.1	5.4	2.486	2.674

Note: red cells indicate that the difference in binder content between the measured values and those specified in the JMF exceeds the allowable limits.

3.2.2. Recycled Binder Availability

Figure 4 shows the recycled binder availability (RBA) results from sieve analysis of the RAP materials. It is important to note that all RAP materials are non-fractionated, except for F-40/0-1 (C) and H-35/0-1 (C), which are the coarse fraction of fractionated RAP. Plant H used two RAP stockpiles (coarse and fine) for the first sampling, but later switched to using only one RAP stockpile (fine). Consequently, only fine RAP results are shown for H-35/0-2. For cases where fractionated RAP was sampled (Plants F and H), the combined RBA was mathematically calculated from the individual RBA values of the coarse and fine RAP fractions, weighted according to their proportions in the mixture. The RBA results spanned from 43 to 67 percent, and an average of 56%. These results are in agreement with a previous study conducted by Castorena et al. (2023) as part of NCDOT RP2021-06, where 11 stockpiles were evaluated, and the availability results ranged from 44 to 62 percent, with an average of 55%. Additionally, when comparing the variability within plants for each set of RAP, the results were generally consistent. The largest difference observed was 12% between the first and second samples of Plant H, followed by an 11% difference between the first and second samples of Plant A. The H-35/0-1 coarse RAP exhibited a considerably lower RBA compared to the H-35/0-2 fine RAP. However, when considering both the coarse and fine RAP materials from H-35/0-1 and their relative proportions in the mix, the results showed only marginal differences. Thus, the maximum difference between samples from a given plant is considered to be 11%. This 11% difference would cause a marginal difference in the interpreted asphalt content of an asphalt mixture, given current NCDOT RBR% limits and current tolerance limits for asphalt content during production, which permit individual sample deviations of ±0.7% from the JMF. For example, for the extreme case of a mixture with an RBR% of 40% and a relatively high total asphalt content of 6.5%, a difference in RBA of 11% results in a change in the calculated asphalt content of the mixture of less than 0.3%.

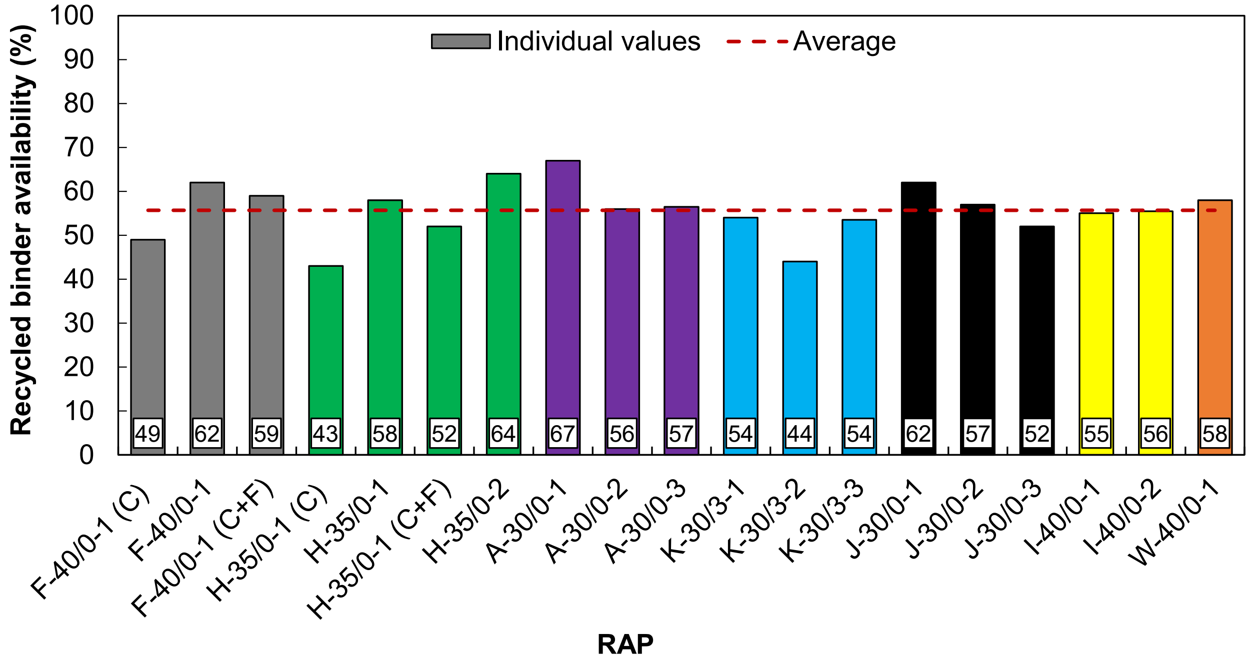


Figure 4. RBA results from sieve analysis.

3.2.3. Gradation

Figure 5 shows the gradation curves of the RAP materials, where WC stands for white curve and BC stands for black curve. In all cases, the black curves are coarser than their corresponding white curves. Additionally, black curves have minimal material passing the 0.075 mm sieve compared to white curves, which is attributed to the mastic coating on the RAP particles. When comparing the variability of the fine RAP curves within plants, the results are generally quite similar, with the curves exhibiting similar shapes, especially the RAP from Plants A and K. According to NCDOT specifications (NCDOT 2024), if a stockpile is to be replenished with a new source of RAP and used in an existing JMF, the gradation must fall within the specified tolerance limits outlined in Table 4. It can be observed that as the RAP content in the mixture increases, the gradation tolerances become more stringent. For instance, the tolerance for the 0.075 mm sieve narrows from ±4% to ±1.5% as the RAP content in the mixture increases from 0 to 20% to over 30%. Additionally, the 0.075 mm sieve has stricter tolerance limits compared to the other sieves. Previous studies indicate that milling and crushing processes tend to produce a high fine particle content, which can limit the amount of RAP incorporated into asphalt mixtures (Copeland 2011, Tarsi et al. 2020). Table 5 reveals that RAP gradations often exceed tolerance limits in the finer sieves, except for the RAP from Plant H, which exceeded tolerances in the coarser sieves, likely because of switching from fractionated RAP to a combined RAP stockpile. Notably, the RAP from Plants A and K consistently met NCDOT gradation requirements, demonstrating the greatest consistency over time.

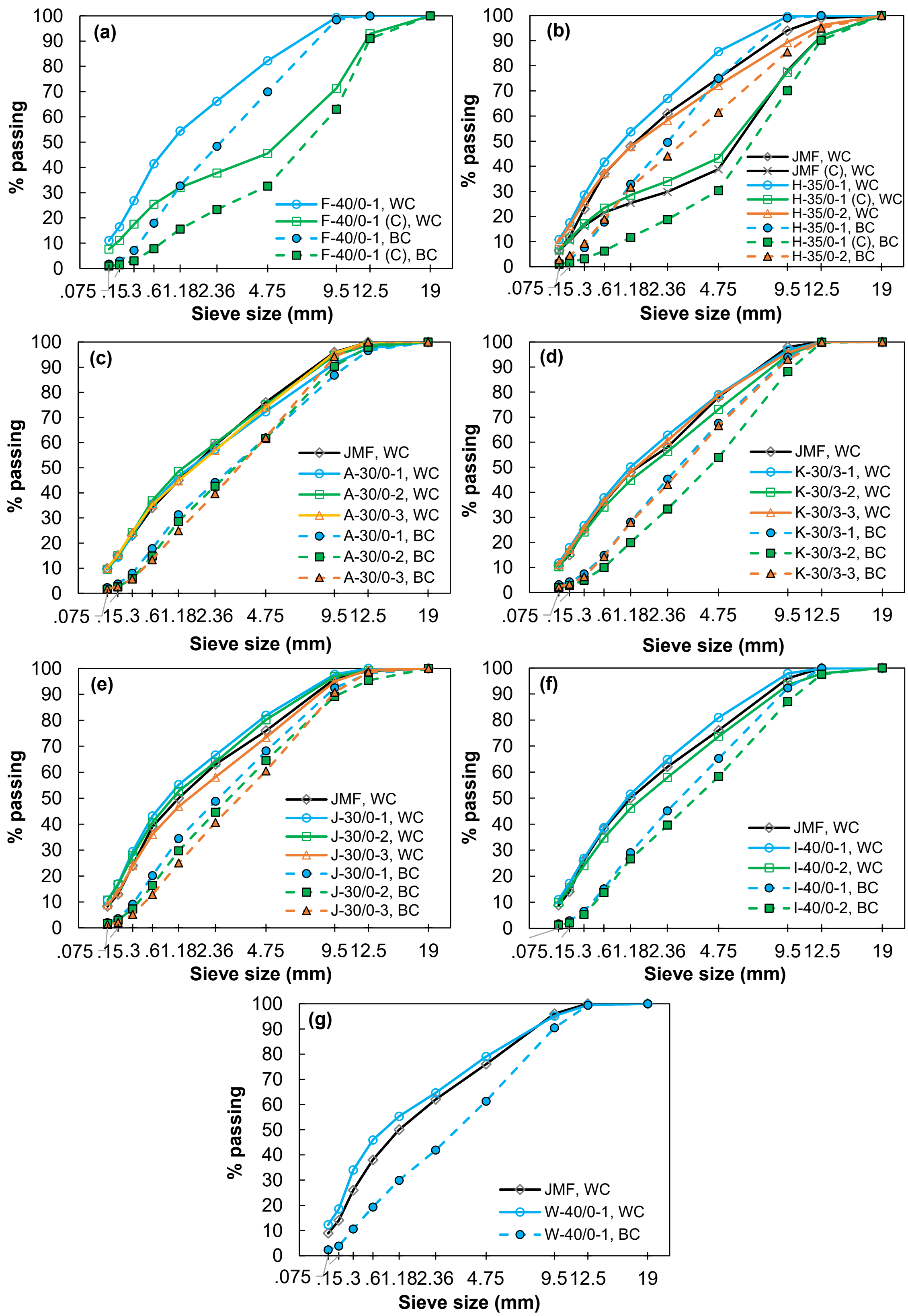


Figure 5. White and black curves of the RAP materials: (a) plant F, (b) plant H, (c) plant A, (d) plant K, (e) plant J, (f) plant I, and (g) plant W.

Table 4. New Source RAP Gradation Tolerances for Surfaces Asphalt Mixtures (NCDOT 2024)

Sieve size (mm)	0 – 20% RAP	20 - 30% RAP	> 30% RAP
19.0	-	-	-
12.5	±6	±3	±2
9.5	±8	±5	±4
4.75	±10	±7	±5
2.36	±8	±5	±4
1.18	±8	±5	±4
0.3	±8	±5	±4
0.15	±8	±5	±4
0.075	±4	±2	±1.5

Note: Tolerances applied to mix design data.

Table 5. Percent Passing Difference between Individual Test Results and the Values Listed in the JMF for the White Curve of the RAP Materials

RAP	% passing difference between measured values and those listed in the JMF								
	Sieve size (mm)								
	19.0	12.5	9.50	4.75	2.36	1.18	0.3	0.15	0.075
H-35/0-1 (Blend RAP)	0	0.6	3.1	8.2	5.3	4.7	3.7	3.5	2.9
H-35/0-2	0	-2.9	-4.7	-2.8	-2.7	-0.2	3.1	4.3	3.6
A-30/0-1	0	-2.4	-4.5	-3.7	-1.7	1.6	0.3	-0.6	-0.4
A-30/0-2	0	-1.2	-1.4	-1	0.7	3.5	1.2	0	-0.3
A-30/0-3	0	0	-0.3	-1.9	-2.1	-0.2	1.3	0.3	0.1
K-30/3-1	0	0	-1.2	1	4.8	2.1	1.7	2.9	1.1
K-30/3-2	0	0	-3.3	-4.9	-1.8	-3.2	-0.9	1	-0.4
K-30/3-3	0	0	-2.3	0.7	2.6	0.1	0.7	2.2	0.4
J-30/0-1	0	1	1.7	5.9	3.6	5.2	5.4	4	2.4
J-30/0-2	0	0.2	0.9	4.2	0.9	2.7	3.8	3.7	2.4
J-30/0-3	0	0.4	-1	-2.6	-4.9	-3.2	-0.1	0.8	0.6
I-40/0-1	0	-0.2	1.9	4.9	2.8	1.5	0.8	3.2	2.1
I-40/0-2	0	-0.8	-1.9	-1.3	-3.3	-3.3	-1.8	1.6	1
W-40/0-1	0	-0.5	-0.9	3	2.6	5.3	8	4.5	3.4

Note: red cells indicate that the difference in percent passing between individual test results, and the target (mix design data) exceeds the tolerances specified in Table 4.

3.2.4. Relationships between the Operational Review Results and Observed Variability

The relationship between the observed variability in gradation and asphalt content and the operational review results was investigated. Correspondingly, Figure 6 shows the differences in binder content between the values measured using the ignition oven and those listed in the JMF, along with the crushing frequency and method. These differences were calculated by subtracting the JMF value from the measured value. Plant A was the only plant where the measured binder content was lower than the binder content reported on the JMF (negative values). Plant K shows higher binder content differences compared to the JMF (positive values), with absolute values exceeding all other plants. When evaluating binder content differences over time within each plant, Plant K also exhibits greater variability than the other plants. Figure 6 also includes the RAP crusher type and RAP crushing frequency per year at each plant. Notably, Plant K stands out for its unique practices, being the only plant that uses a jaw crusher and performs RAP crushing monthly. All other plants use an impact crusher and crush RAP between one and four times per year. By using more frequent crushing, Plant K appears to introduce new sources of RAP into its processed RAP stockpile more frequently than other plants. This practice may help explain the higher variability in asphalt content observed in its processed RAP. Additionally, impact crushing is generally considered the best practice because jaw and other compression-type crushers are more prone to clogging when handling wet or warm RAP (West et al. 2015). Compression-type crushers also tend to produce more fines compared to impact crushers.

Gradation consistency over time could not be tied to the operational review results. Recall that Plants A and K had the most consistent gradation results over time. However, these two plants have notably distinct RAP processing practices. Plant A uses an external contractor to crush its RAP using an impact crusher once per year, and the material is stockpiled for six months to one year. In contrast, as discussed, Plant K crushes its own RAP using a jaw crusher monthly and utilizes the material immediately. Additionally, Plant K employs an inline impact crusher during mix production.

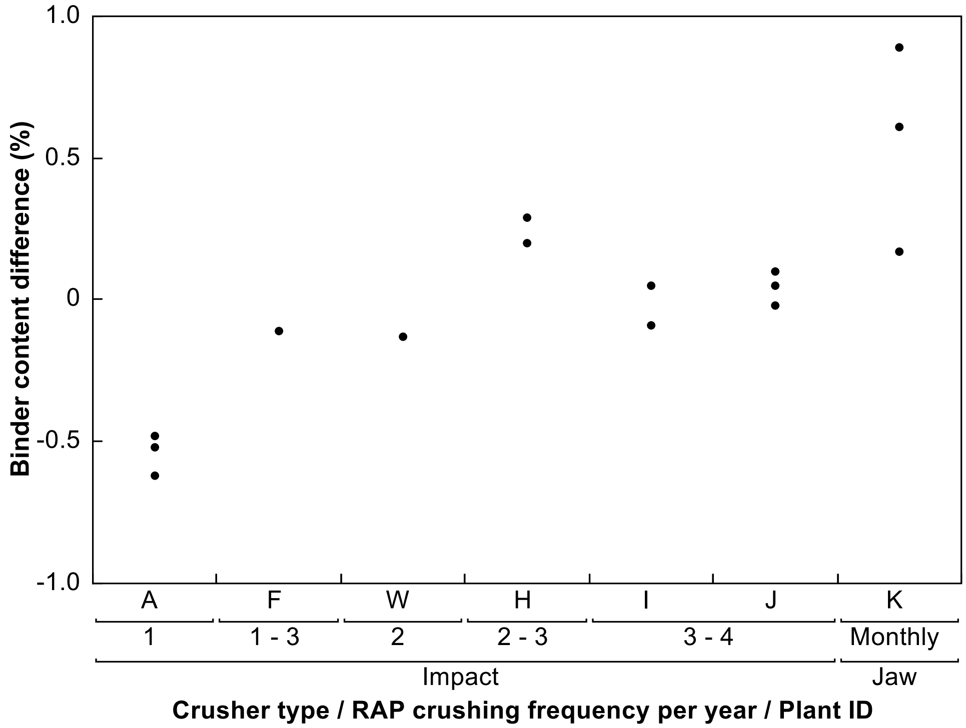


Figure 6. Binder content difference of fine RAP in relation to RAP processing practices, including crusher type, RAP crushing frequency per year, and plant ID.

3.3. Virgin and Recycled Binder Characterization

Figure 7 presents the AASHTO M 320 continuous grading high-temperatures (PGHs) of the study (a) recycled, (b) virgin, and (c) estimates for the blended binders. Figure 7 (a) shows that the PGH values of the RAP binders are also often consistent within a given plant. However, notable variability is observed in some cases with a maximum within-plant difference of 6.9°C. The RAS binders from Plant K exhibit a particularly large difference of nearly 20°C between the first and second samples. Additionally, the PGH values vary more significantly across plants than within plants, ranging from 94.3°C at Plant K to 109.3°C at Plant J, a total span of 15°C. This variability may necessitate different virgin binder grades to achieve the desired blended binder grade at high RBR% levels. However, current specifications do not account for this variability, as they are agnostic to the specific properties of the RAP binder.

Figure 7 (b) shows that the virgin binders' PGH values comply with the specified high-temperature PGs listed in Table 1. The virgin binders from Plants H, A, and J have a PGH exceeding 64°C, while the binders from Plants F, K, I, and W have values that exceed 58°C. The PGH values of the PG 64-22 virgin binders fall within a relatively narrow span of 67.5°C to 69.8°C. Similarly, the PGH values of the PG 58-28 virgin binders fall within a span of 60.2°C to 62.3°C. The virgin binder results are even more consistent within a plant, with a maximum difference in PGH between samples from a given plant of 1.6°C. Note that, unfortunately, the K-30/3-3 virgin binder was only tested in a blend with RAS and not isolated. However, this result still allowed for inference of the blended binder properties of K-30/3-3.

Figure 7 (c) shows the estimated blended binder PGH values, derived from the PGH values of virgin and RAM binders combined with the mixture RBR%. All blended binder PGH values greatly exceed the critical climatic grade temperature of 64°C, indicating adequate rutting resistance is expected. All estimated blended binder properties for the K-30/3 mixture are based on the combination of virgin binder, RAS binder, and RAP binder.

Figure 8 shows the continuous grading intermediate-temperatures (PGIs) for the (a) RAP binders, (b) virgin binders, and (c) estimates for the blended binders. The PGIs were all calculated as the temperature where $|G^*|\times\sin(\delta)$ is equal to 6,000 kPa as discussed in Section 2.5.1 because all blends had δ values that exceeded 42° despite some blends having $|G^*|\times\sin(\delta)$ values exceeding 5,000 kPa at 25°C; thus, the δ criterion does not dicate the intermediate temperature grade. Figure 8 (a) shows that the PGI values of the RAP binders generally follow similar trends across and within plants to the PGH values. The within-plant differences in PGI reach up to 5.9°C, and values across all plants range from 28.8°C to 42.3°C. Figure 8 (b) shows that the virgin binders IGH values comply with the specified PGI requirements based on the grades listed in Table 1, with the PGI values for the PG 64-22 virgin binders for Plants H, A, and J falling below 25°C and the PG values for the PG 58-28 virgin binders for Plants F, K, I, and W falling below 19°C. Figure 8 (c) shows that the estimated blended binder PGI values for some mixtures with PG 64-22 virgin binder (all samples from Plant J along with H-35/0-1) fall above the intended limit of 25°C for NC's PG 64-22 climate, suggesting that a lower RBR% limit for PG 64-22 virgin binder may be necessary to comply with the intended PGI requirements. In contrast, all mixtures with PG 58-28 virgin binder (Plants F, K, I, and W) all have PGI values falling below 25°C.

Figure 9 shows the continuous grading of low-temperatures (PGLs) for the (a) RAP binders, (b) virgin binders, and (c) estimates for the blended binders. Figure 9 (a) shows that the PGL values for RAP binders span from -8.8°C to -20.4°C, with the maximum difference within a given plant of 5.1°C. It is noted that the RAP binder from J-30/0-1 was too brittle for BBR testing at -12°C, as the sample fractured immediately upon loading. As a result, no result is available. Figure 9 (b) shows that the virgin binders' PGL values comply with the specified grade listed in Table 1. That is, the PGL values for Plants H, A, and J fall below -22°C and those for Plants F, K, I, and W fall below -28°C. Figure 9 (c) shows that most blended binder PGLs comply with the intended PGL, with values falling below -22°C. However, sample J-30/0-2 has an PGL of -20.7°C and thus, exceeds the intended PGL, suggesting a softer virgin binder may have been warranted. It is also noteworthy to mention that two of the Plant K samples (K-30/3-1 and K-30/3-3) fall into a lower grade category of -28°C rather than the required -22°C, suggesting it may have been possible to use a PG 64-22 virgin binder in this mixture and still achieve the intended blended PG.

This situation arises because of the peculiarities of the Plant K mix and how those align with the NCDOT specification, which requires a PG 58-28 virgin binder when the RBR% exceeds 30% for RAP mixtures or 20% for RAP/RAS mixtures. For mixtures with RAS binders having PGs that greatly exceed those of RAP binders, this approach may yield consistent blended binder characteristics across RAP and RAP/RAS mixtures. However, the Plant K RAP and RAS were both relatively soft. This behavior, coupled to the fact that Plant K has a total RBR% of 30%, which is only marginally higher than the RAP mixtures with PG 64-22 binder, results in this distinct PGL result. This finding underscores the potential impacts of variability in recycled binder properties that are not accounted for in the selection of virgin binder grades.

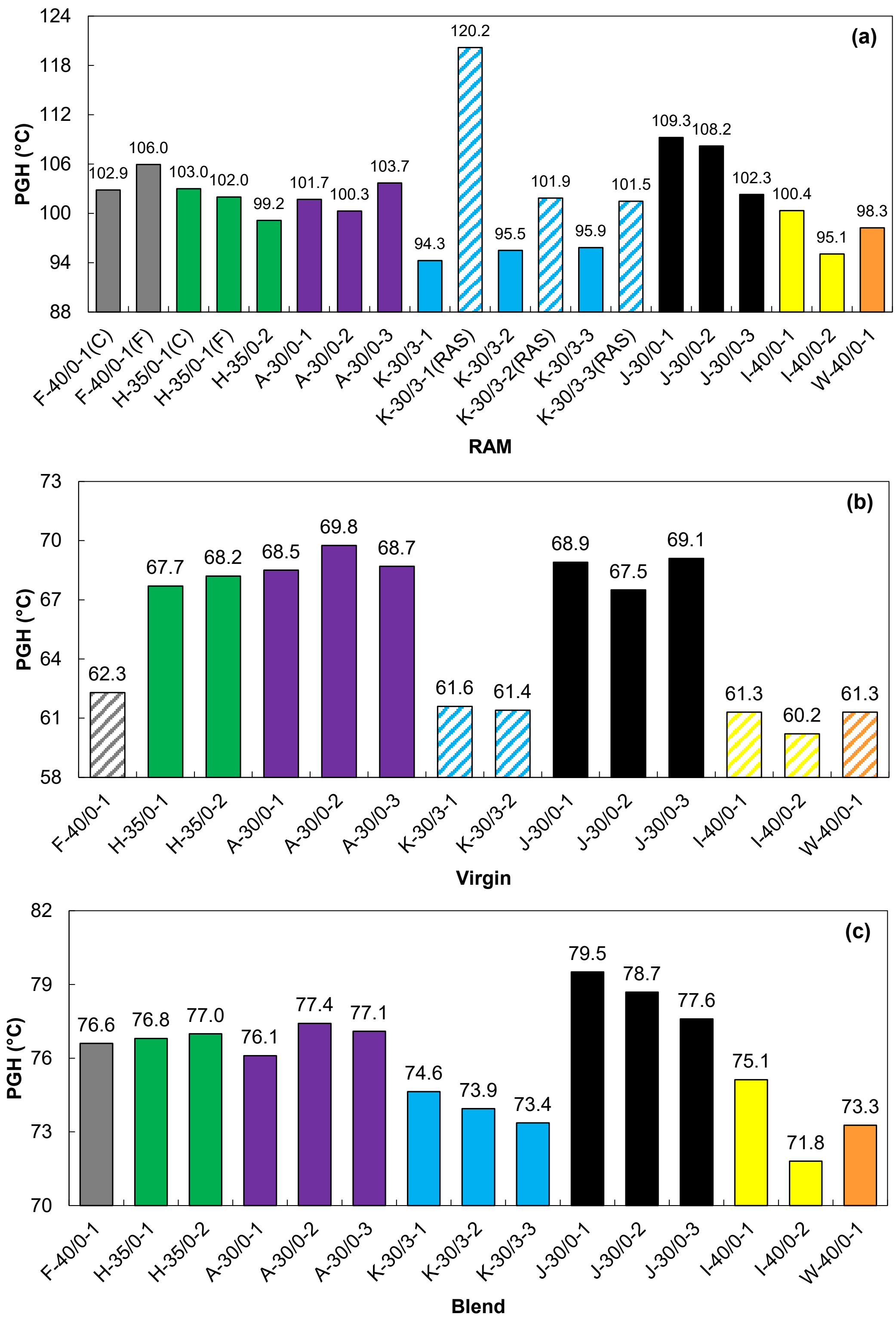


Figure 7. Continuous high grading temperatures for (a) RAM binders, (b) virgin binders, and (c) blended binders. In part (a), solid bars = RAP and dashed = RAS. In part (b), solid bars = PG 64-22 and dashed bars = PG 58-28.

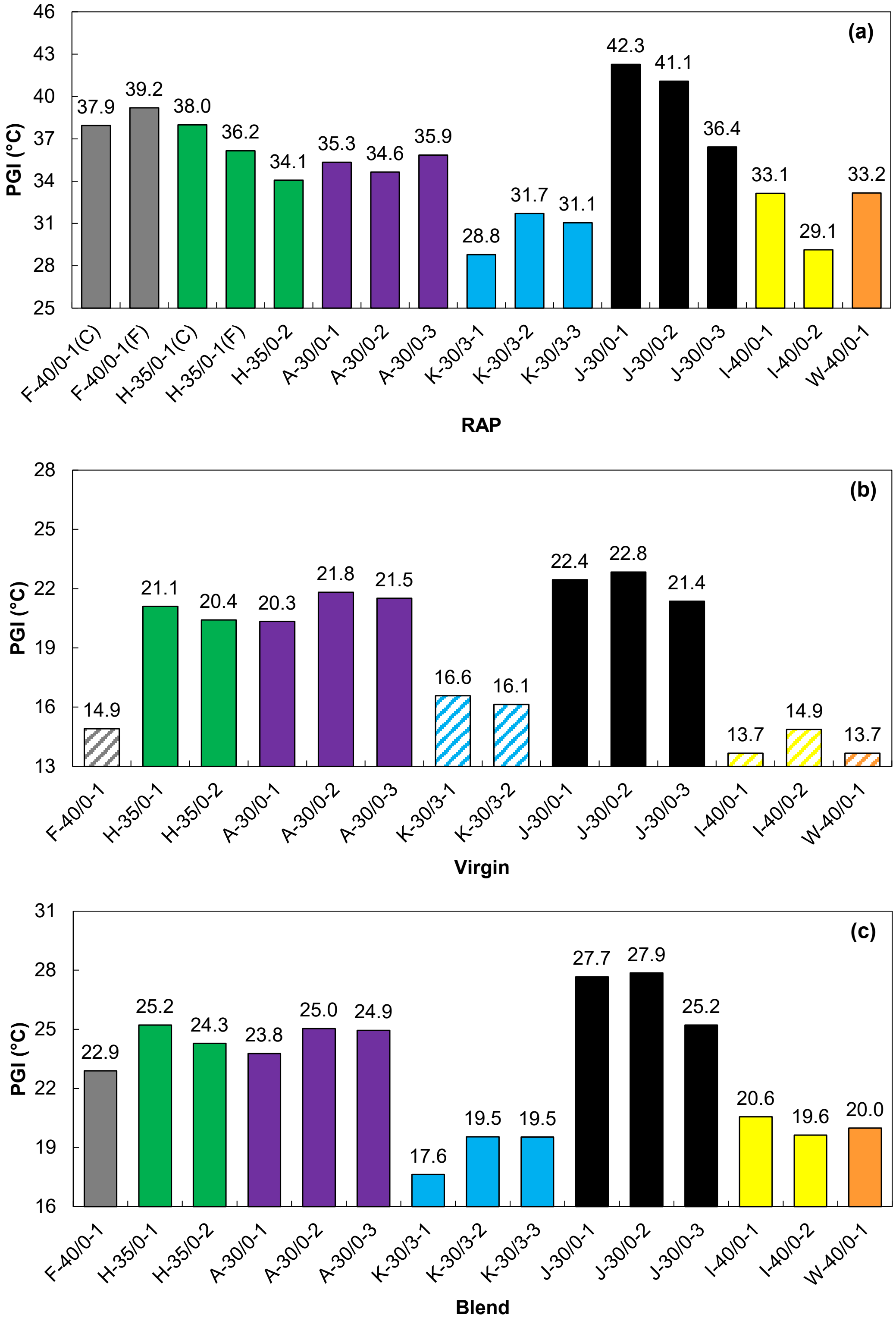


Figure 8. Continuous intermediate grading temperatures for (a) RAP binders, (b) virgin binders, and (c) blended binders. In part (b), solid bars = PG 64-22 and dashed bars = PG 58-28.

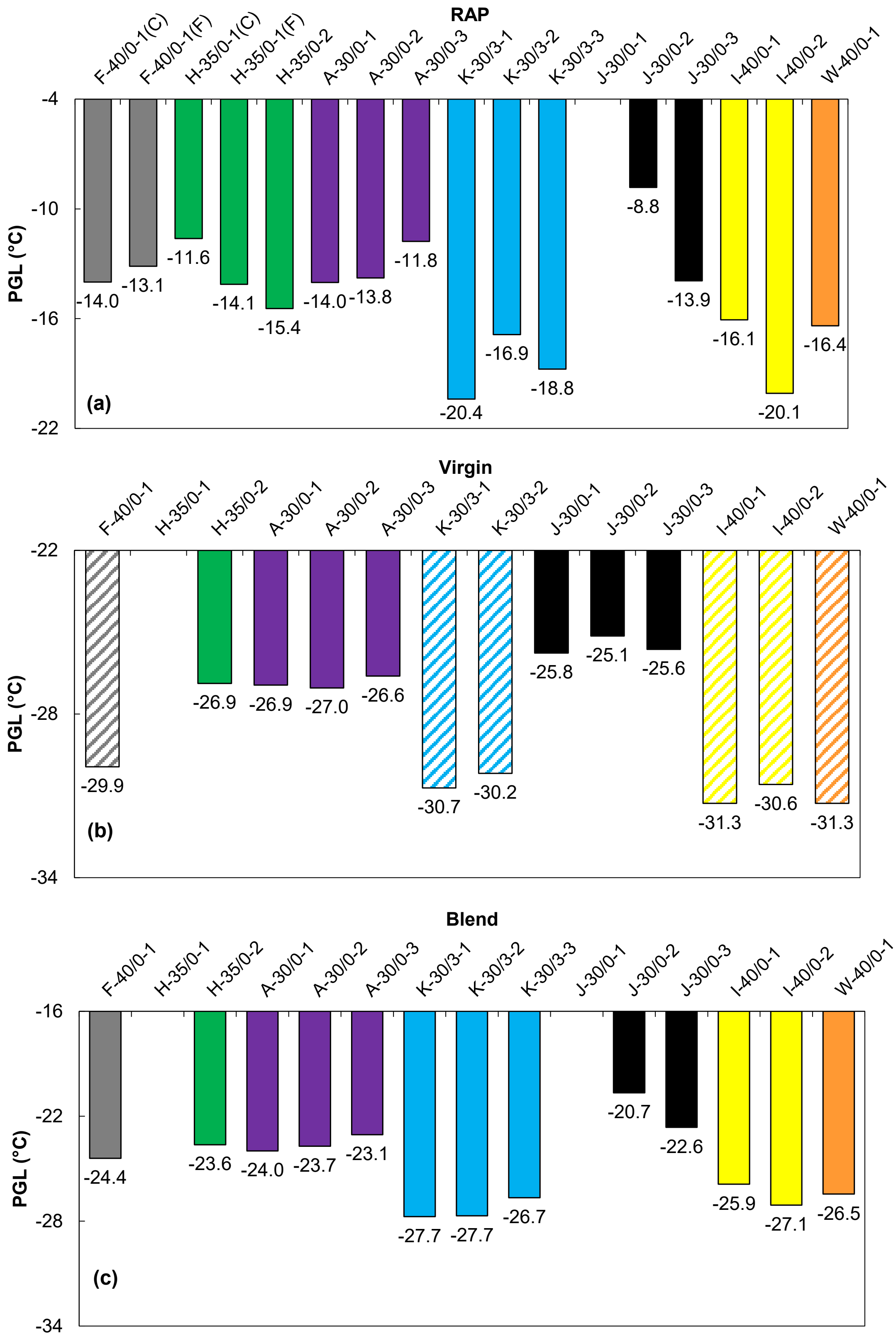


Figure 9. Continuous low grading temperatures for (a) RAP binders, (b) virgin binders, and (c) blended binders. In part (b), solid bars = PG 64-22 and dashed bars = PG 58-28.

3.4. Probabilistic Evaluation of Recycled Binder Replacement Percentage Specifications

3.4.1. Summary of Existing NCDOT Specifications

While the previous section offers a deterministic analysis of the recycled binder blends for the study materials, it may not account for the full variability of binder properties in the state. Therefore, this section presents a probabilistic evaluation of NCDOT RBR% specifications aimed at identifying thresholds that would increase the likelihood of blended binder properties meeting intended PG properties. Pertinent to the analysis, Table 6 summarizes the maximum RBR% limits currently specified by the NCDOT (2024). For surface mixtures, the NCDOT limits the RBR% to 40%, except for those requiring a PG 76-22 binder, used in high-volume surface layers and open-graded friction courses (OGFC), for which the maximum RBR% is restricted to 18%. For intermediate and base mixtures, a higher maximum RBR% of 45% is permitted. Table 7 presents the virgin binder grades specified by the NCDOT. PG 64-22 is required when the RBR% is 30% or less, except for S9.5D surface mixtures designed for traffic levels exceeding 30 million equivalent single axle loads (ESALs) and OGFC mixtures. When the RBR% exceeds 30%, a softer PG 58-28 binder is specified.

Table 6. Maximum RBR% Limits Specified by the NCDOT (NCDOT 2024)

Mix Type	Surface Mixes	Intermediate and Base Mixes	Mixes Using PG 76-22
Maximum RAP Content	40%	45%	18%

Table 7.Virgin Binder Grades Specified by the NCDOT (NCDOT 2024)

Mix Type	RBR% ≤ 20%	21% ≤ RBR% ≤ 30%	RBR% > 30%
S4.75A, S9.5B, S9.5C, I19.0C, B25.0C	PG 64-22	PG 64-22	PG 58-28
S9.5D, OGFC	PG 76-22	n/a	n/a

To critically assess these specifications, the distributions of blended binder properties were calculated using all possible virgin and RAP binder combinations from the RAP binder characterization herein, NCDOT RP 2014-05 RAP binder characterization, and NCDOT QA data for virgin binders, at a range of RBR% levels to critically assess existing thresholds and identify alternative limits that would minimize the likelihood of blended binder systems failing to meet specification requirements. For each RBR% level evaluated, histograms of performance indices were generated. The analysis focused on NCDOT mixtures that do not specify PG 76-22, as those mixtures are subject to more restrictive RBR% limits.

3.4.2. Evaluation of Blends of PG 64-22 Virgin Binder and RAP

Table 7 shows that the NCDOT specifies the use of PG 64-22 virgin binder when RBR% is less than or equal to 30% for the mixture designations under consideration herein. To evaluate the effectiveness of the 30% threshold for PG 64-22 virgin binders and explore alternatives that may reduce the risk of failing AASHTO M 320 (2023) intermediate and low temperature specifications, the distribution of blended binder (i.e., RAP + PG 64-22 virgin binder) properties was assessed at RBR% levels of 20% and 30%, with PG 64-22 virgin binder included as a benchmark. Figure 10 presents the corresponding histograms of $|G^*| \times \sin(\delta)$ for these blends along with PG 64-22 virgin binders. As the RBR% increases, the histograms shift to the right, confirming that RAP binders increase the blended binder $|G^*| \times \sin(\delta)$.

AASHTO M 320 (2023) requires that $|G^*| \times \sin(\delta)$ is less than or equal to 6,000 kPa. AASHTO M320 and NCDOT specifications also require that δ must be greater than or equal to 42° when $|G^*| \times \sin(\delta)$ falls between 5,000 kPa and 6,000 kPa. However, phase angle δ was not reported in the NCDOT QA database, and thus, this additional requirement could not be directly evaluated. To evaluate the potential implications of the δ requirement, the blended binder δ values were estimated for the study blends (i.e., those presented in Section 3.3) using a linear blending chart at the current NCDOT RBR% limits. None of the estimated δ values fell below the minimum limit despite some having $|G^*| \times \sin(\delta)$ values above 5,000 kPa, and thus, it is inferred that the upper $|G^*| \times \sin(\delta)$ limit rather than the δ criterion is most restrictive. Consequently, the 6,000 kPa limit was used for the analysis herein. At the current RBR% threshold of 30%, only 74% of the blended binders meet this requirement. In contrast, reducing the RBR% to 20% increases compliance to 96%, suggesting that a lower RBR% threshold for PG 64-22 may better ensure conformance with the intermediate-temperature specification. Recall, from Figure 8, that half of the study blended binders with PG 64-22 virgin binder had PGI values exceeding NC's climate condition of 25°C, further supporting the need to lower the current RBR% threshold.

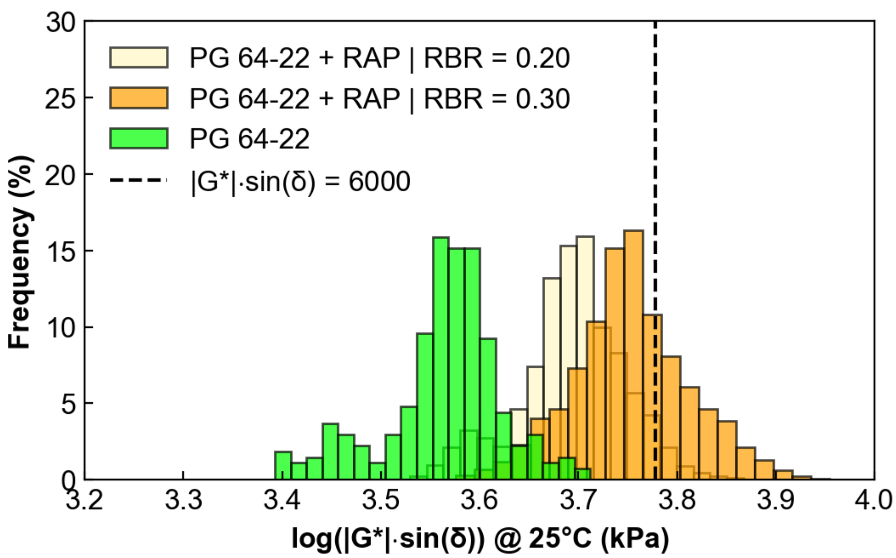


Figure 10. Histogram of log ($|G^*| \times \sin(\delta)$) at 25°C for blends of PG 64-22 and RAP at various RBR levels compared to PG 64-22 virgin binder.

Figure 11 and Figure 12 show the histograms of the *S*(60) and *m*(60) at -12°C for the blended binders at RBR% levels of 20% and 30% alongside PG 64-22 virgin binder as a reference. Figure 11 shows that 97% of blends meet the maximum *S*(60) limit of 300 MPa specified by AASHTO M 320 (2023) at the NCDOT's current RBR% limit of 30%. When the RBR% is reduced to 20%, the compliance rate increases to 99%. Figure 12 demonstrates that only 76% of blended binders exceed the minimum *m*(60) requirement of 0.3 at the current RBR% limit of 30%, suggesting that the low-temperature grades of the blends tend to be *m*-controlled rather than *S*-controlled. Reducing the RBR% to 20% improves the pass rate to 95%.

Collectively, the results indicate that reducing the maximum RBR% limit for PG 64-22 virgin binder from 30% to 20% increases the likelihood that blended binders will meet AASHTO M 320 (2023) intermediate- and low-temperature specifications to approximately 95%, thereby reducing the probability of cracking. However, an important consideration when evaluating this potential change is whether using a softer PG 58-28 at an RBR% of 20% would negatively impact rutting resistance.

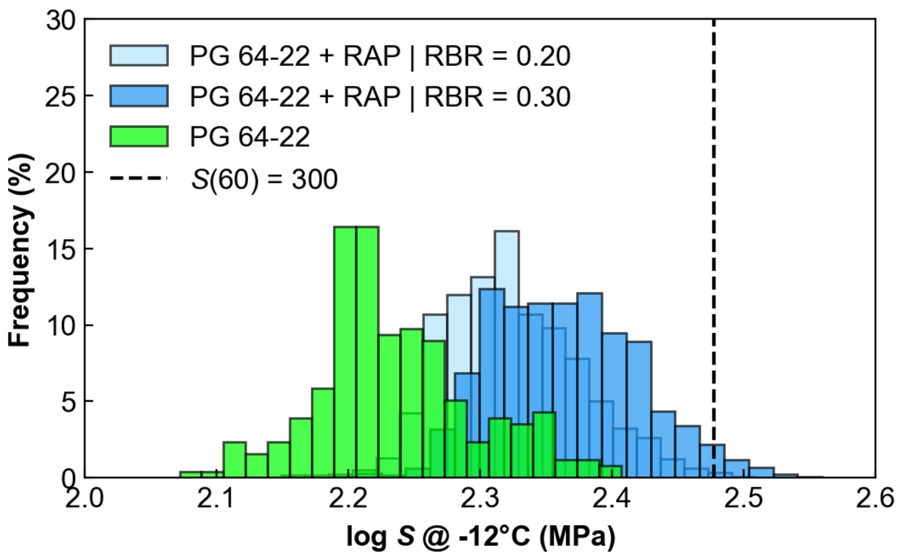


Figure 11. Histogram of log *S*(60) at -12°C for blends of PG 64-22 and RAP at various RBR levels compared to PG 64-22 virgin binder.

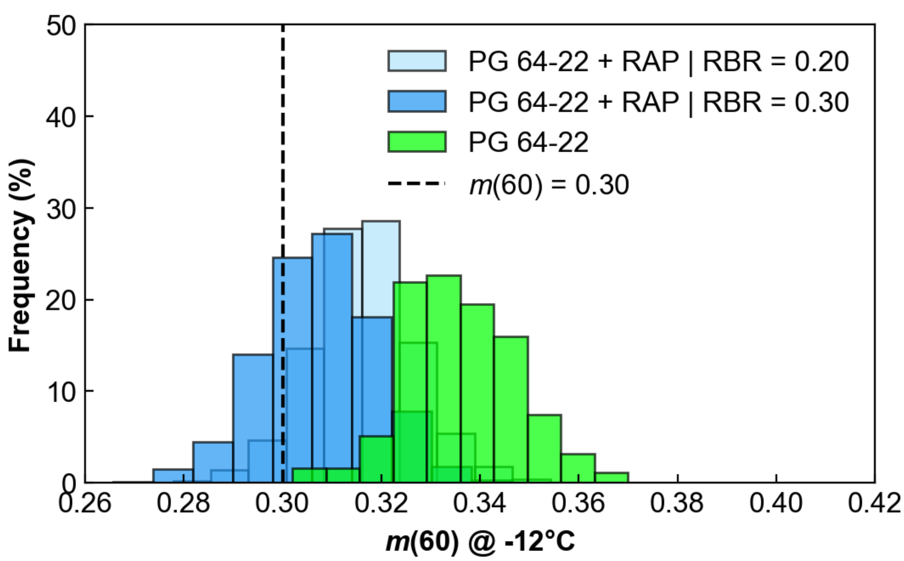


Figure 12. Histogram of *m*(60) at -12°C for blends of PG 64-22 and RAP at various RBR levels compared to PG 64-22 virgin binder.

3.4.3. Evaluation of Blends of PG 58-28 Virgin Binder and RAP

NCDOT specifies the use of PG 58-28 virgin binder when the RBR% exceeds 30%, with a maximum allowable RBR% of 40% for surface layers and 45% for intermediate and base layers.

To evaluate the effectiveness of these thresholds and to explore the potential impact of lowering the minimum RBR% at which PG 58-28 is used to 20%, the properties of blended binders (i.e., RAP + PG 58-28 virgin binder) were assessed. These blended binder properties were benchmarked against those of PG 64-22 virgin binders and the criteria specified in AASHTO M 320 (2023).

Figure 13 shows histograms of $|G^*|/\sin(\delta)$ at 64°C for blends of RAP and PG 58-28 at RBR% levels of 20% and 30% along with PG 64-22 virgin binders. The results reveal that 100% of blended binders exceed the minimum limit specified by AASHTO M 320 (2023) at both 0.2 and 0.3 RBR levels. Therefore, reducing the minimum RBR% where PG 58-28 virgin binder is used to 20% maintains adequate rutting resistance. Moreover, at an RBR% of 20%, the blended binder distribution becomes very similar to that of PG 64-22 virgin binders.

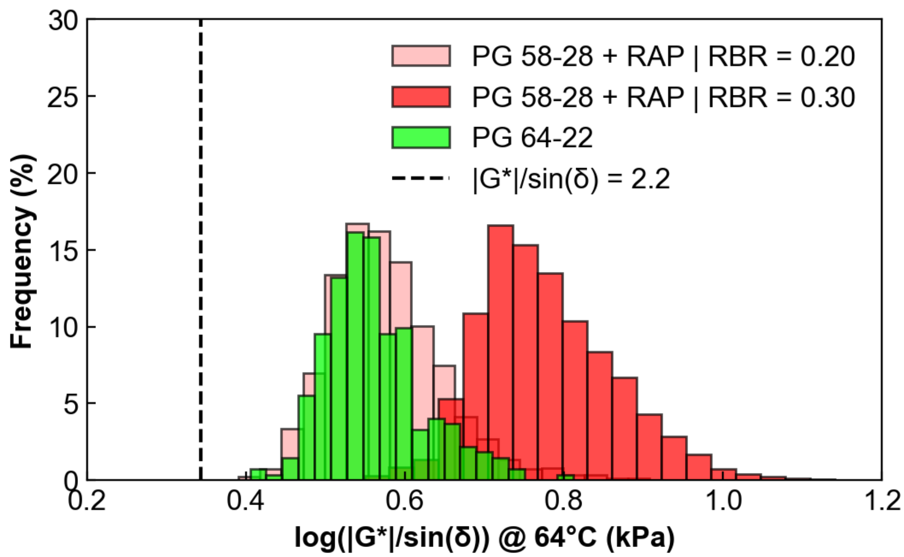


Figure 13. Histogram of log ($|G^*|/\sin(\delta)$) at 64°C for blends of PG 58-28 and RAP at various RBR levels compared to PG 64-22 virgin binder.

The maximum RBR% limits for using PG 58-28 virgin binder are 40% for surface layers and 45% for intermediate and base layers. To evaluate the effectiveness of these limits, the distribution of $|G^*|\times\sin(\delta)$ at 25°C for blended binders containing PG 58-28 at these RBR% levels, along with 20% was evaluated. These distributions were compared to PG 64-22 virgin binders and the AASHTO M 320 (2023) specification limit. Figure 14 shows the corresponding histograms. At an RBR% level of 45%, 93% of blended binders fall below the maximum $|G^*|\times\sin(\delta)$ limit of 6,000 kPa. This compliance rate increases to 99% when the RBR% is reduced to 40%, indicating the current maximum RBR% limits yield a high probability of compliance with the intermediate-temperature binder specifications. At an RBR% of 20%, the distribution of blended binder properties shifts to the left, indicating these blends are softer than PG 64-22 virgin binder.

Interestingly, the distribution $|G^*|\times\sin(\delta)$ at 25°C values for blended binders at an RBR% of 40% is like that of PG 64-22 virgin binders. This finding contrasts with the results for $|G^*|/\sin(\delta)$ at 64°C, where the blended binder properties most closely aligned with PG 64-22 virgin binder at an RBR% of 20%. Unfortunately, the effectiveness of the maximum RBR% limits in ensuring compliance with low temperature properties could not be fully evaluated, as QA data for PG 58-28 binders was only available at –18°C.

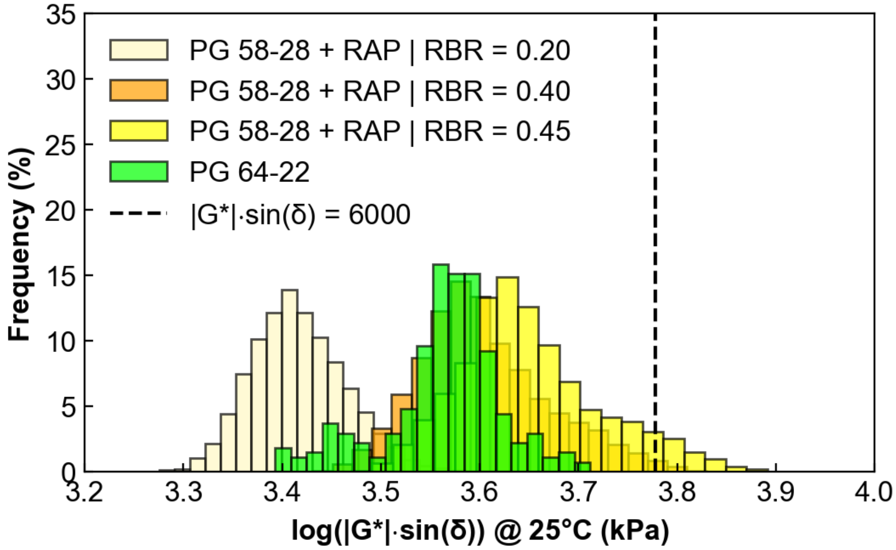


Figure 14. Histogram of log (|G^*|×sin(δ)) at 25°C for blends of PG 58-28 and RAP at various RBR levels compared to PG 64-22 virgin binder.

3.4.4. Probabilistic Evaluation of RBR% Limits

This section presents a probabilistic approach to inform the selection of RBR% limits. The properties of all possible combinations of virgin and RAP binder blends were calculated, akin to those shown in the previous sections, using fine increments of RBR. At each RBR level, the percentage of blends with a given virgin binder PG that met the AASHTO M 320 (2023) specification criteria was determined. These results were used to generate plots showing the percentage of blends meeting a given specification requirement as a function of RBR. Such plots, when paired with an agency's target probability for compliance, can be used to select an RBR% threshold. For demonstration purposes herein, a 90% compliance probability was selected arbitrarily as a benchmark for identifying potential RBR% limits. However, the NCDOT could select an alternative benchmark if desired.

Figure 15 shows the relationship between the percentage of blends meeting the intermediate-temperature specification for |G^*|×sin(δ) and RBR. The vertical arrows indicate the RBR levels at which 90% of the blends meet the specification. The results show that achieving at least 90% compliance with intermediate-temperature thresholds requires limiting the RBR% to 24% for PG 64-22 virgin binder and 47% for PG 58-28 virgin binder. It is noted that the 47% limit closely aligns with NCDOT's current maximum RBR% limit of 45% for using PG 58-28 in intermediate and base layers. However, the analysis suggests a 24% limit for PG 64-22 binders, which is notably lower than NCDOT's current limit of 30%.

Figure 15 also shows the sharp contrast over a narrow RBR% range when the virgin binder grade is changed. For example, at an RBR% of 30% (when PG 64-22 would be allowed) the data suggests that only approximately 75% of the blends would have a passing intermediate-temperature grade, whereas at an RBR% of 31% (when a PG 58-28 would be required) 100% of the blends would have a passing intermediate grade. The RBR% could be as high as approximately 55% with a PG 58-28 to achieve the same 75% passing rate that exists when a PG 64-22 is used with a blend having an RBR% of 30%, highlighting the significant impact of virgin binder grade. However, only considering blended binder properties does not guarantee that a mixture prepared at that RBR% level would have adequate performance.

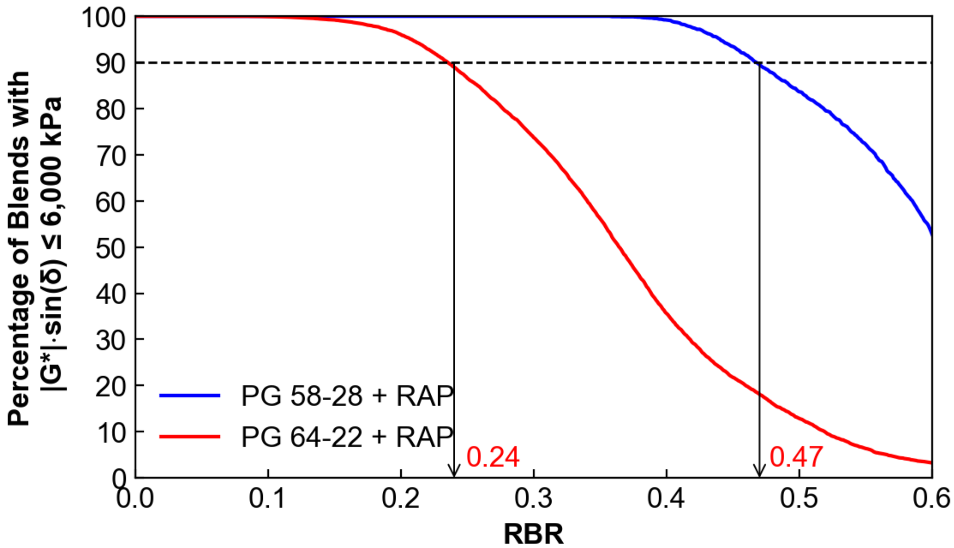


Figure 15. Selecting RBR limits to achieve a 90% probability of meeting the |*G|×sin(*δ*) specification.**

Figure 16 presents the relationship between the percentage of blends meeting the high-temperature specification for |*G**|/sin(*δ*). Since the PG 64-22 virgin binders exceed the minimum |*G**|/sin(*δ*) and, adding RAP increases the value further, high temperature requirements are met at all RBR levels for this virgin binder grade. For blends with PG 58-28, 90% of the blends meet the minimum limit for |*G**|/sin(*δ*) at an RBR% of 12%. At an RBR% level of 17%, all blends of PG 58-28 and RAP meet the high-temperature specification.

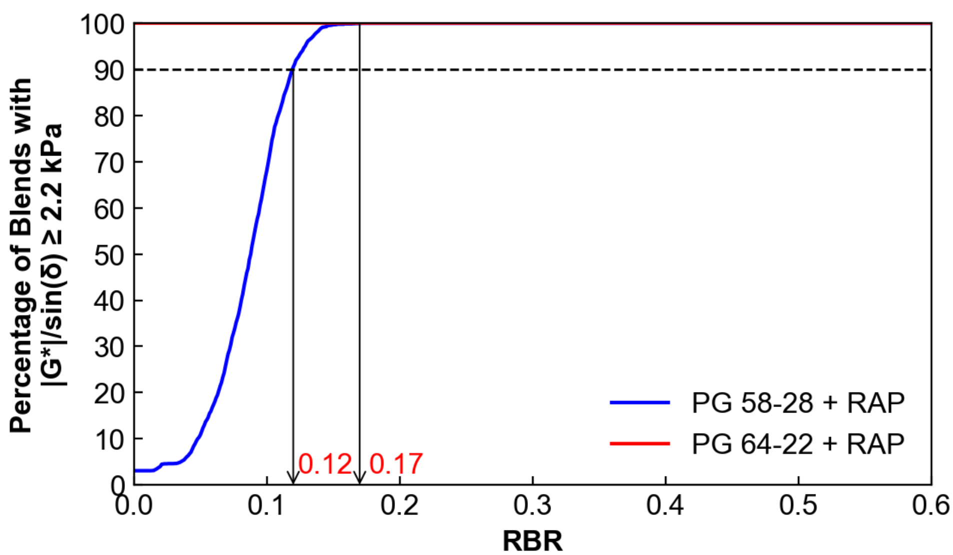


Figure 16. Selecting RBR limits to achieve a 90% probability of meeting the |*G|/sin(*δ*) specification.**

Figure 17 shows the relationship between the percentage of blends incorporating PG 64-22 virgin binder that meet low-temperature specifications for both *S*(60) and *m*(60), plotted as a function of RBR. To achieve a 90% probability of meeting the specifications, the RBR% must be less than 38% based on the *S*(60) criterion and less than 21% based on the *m*(60) criterion. These results indicate that the *m*(60) is the controlling specification parameter at low temperature. Furthermore, the results indicate that to achieve a 90% probability of compliance with the m(60) specification, the maximum allowable RBR% limit for PG 64-22 should be reduced from the current value of 30%.

Collectively, the example probabilistic analysis presented herein suggests that lowering the RBR% threshold for specifying PG 58-28 from 30% to 20%, while maintaining a maximum RBR% limit of 45%, results in greater than a 90% probability of meeting the intended blended binder performance properties.

It is important to note that selecting appropriate RBR% limits involve many additional considerations, and satisfying asphalt binder specifications alone does not guarantee adequate mixture performance. Furthermore, it is important to note that RBA lowers the effective RBR% of an asphalt mixture (Castorena et al. 2023). Thus, the performance implications of incorporating RBA when interpreting RBR% merit further investigation in the context of refining RBR% specifications.

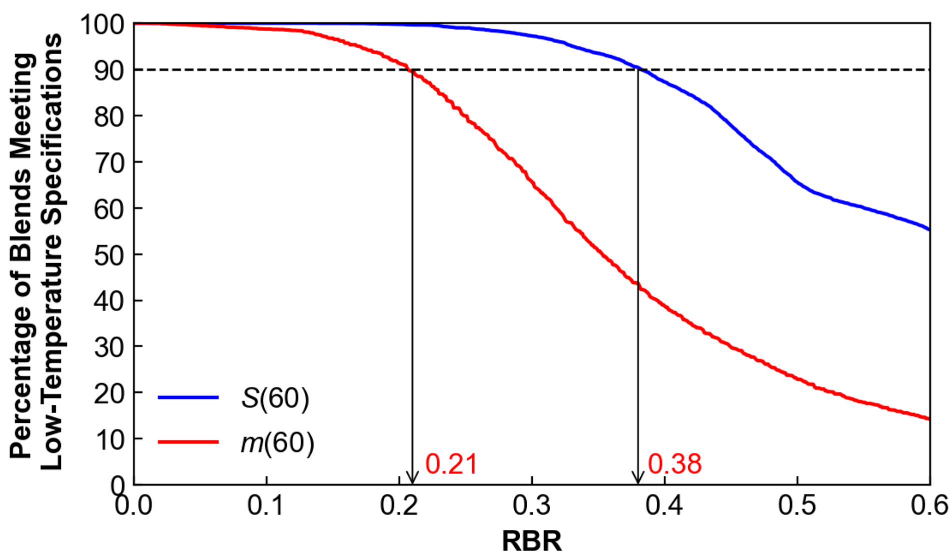


Figure 17. Selecting RBR limits to achieve a 90% probability of meeting the low-temperature specifications when PG 64-22 virgin binder is used.

3.5. Plant-Produced Asphalt Mixture Characterization

3.5.1. Gradation Results

Figure 18 presents the extracted aggregate gradations for the plant-produced asphalt mixtures along with the reported gradations on the corresponding JMF. It is important to note that all mixtures are classified as fine-graded according to AASHTO M 323 (2022), which defines fine-graded mixtures as those with gradations falling above the primary control sieve (PCS) control point. For mixtures with a nominal maximum aggregate size (NMAS) of 9.5 mm, the PCS control point is defined as 47% passing the 2.36 mm sieve.

According to NCDOT specifications, the difference between individual test results and the JMF must fall within ±8.0% for the 2.36 mm sieve and ±2.5% for the 0.075 mm sieve as part of plant mix quality control. Among the mixtures analyzed, only H-35/0-2 mixture failed these requirements, with a difference of 3.2% at the 0.075 mm sieve. This result suggests that, overall, the extracted aggregate gradations of the mixtures remain consistent over time. Table 8 shows the percent passing control points for asphalt mixtures as per NCDOT criteria. The mixtures from Plants I and W were the only ones to satisfy all control point requirements. The remaining mixtures failed to meet at least one of those control points, commonly at the 12.5 mm, 2.36 mm, or the 0.075 mm sieve. The largest deviations observed were as follows: 1.0% at the 12.5 mm sieve for H-35/0-2, 4.3% at the 2.36 mm sieve for K-30/3-3, and 1.7% at the 0.075 mm sieve for H-35/0-2. As previously shown in Table 5, six RAP sources exceeded the tolerance limits at the 0.075 mm sieve. Nevertheless, only the H-35/0-2 mixture failed to meet the control points at the 0.075 mm sieve.

For further comparison purposes, the collective extracted aggregate gradations are shown together in Figure 19. The largest observed difference in percent passing a given sieve size among all curves is 14.1%, coinciding with the difference between J-30/0-1 and F-40/0-1 at the 0.3 mm sieve. The second largest difference is 10.8%, observed between J-30/0-1 and I-40/0-1. This result reveals relatively consistent gradations across all plants compared to the wide range permitted by the band specification limits.

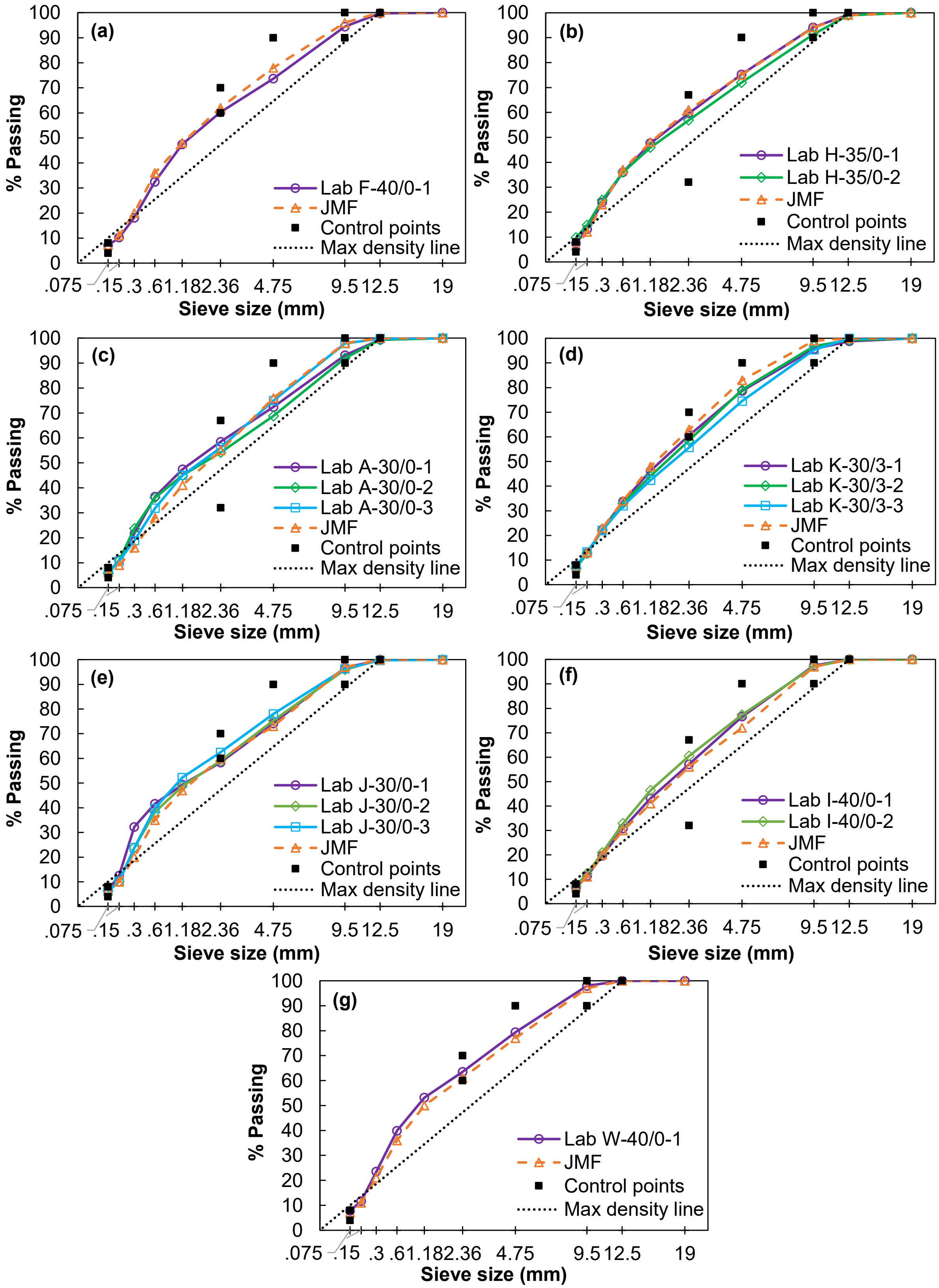


Figure 18. Extracted aggregate gradation of the plant-produced asphalt mixtures: (a) plant F, (b) plant H, (c) plant A, (d) plant K, (e) plant J, (f) plant I, and (g) plant W.

Table 8. NCDOT Aggregate Gradation Criteria (Percent Passing Control Points)

Sieve Size	Mix Type			
	9.5C		9.5B	
mm	Min	Max	Min	Max
12.5	100.0	-	100.0	-
9.5	90.0	100.0	90.0	100.0
4.75	-	90.0	-	90.0
2.36	32.0	67.0	60.0	70.0
0.075	4.0	8.0	4.0	8.0

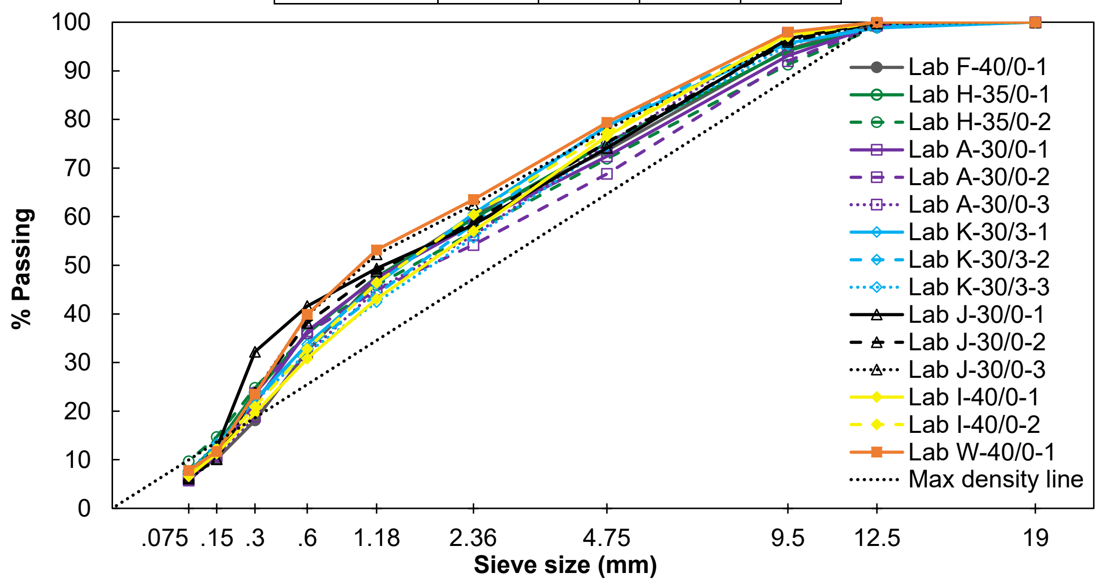


Figure 19. Collective extracted aggregate gradation.

3.5.2. IDT-CT and Asphalt Content Results

Figure 20 shows the CT_{Index} results along with the asphalt contents of the plant-produced asphalt mixtures. The vertical error bars represent the standard deviation in the CT_{Index} among the test replicates. The NCDOT specification requires the difference in asphalt content between individual test results and the JMF to fall within ±0.7% as part of plant mix quality control. All mixtures met this requirement. Despite the differences in asphalt content being deemed marginal based on NCDOT requirements, the CT_{Index} demonstrated clear trends with asphalt content when assessing within-plant variability. For instance, K-30/3-1 had a CT_{Index} of 77.3 and an asphalt content of 6.6%. In comparison, K-30/3-2 from the same plant had a lower asphalt content of 6.3% and a corresponding CT_{Index} of 59.9. Finally, K-30/3-3 had an asphalt content of 6.8% and a CT_{Index} of 87.1. These results align with past studies, which have shown that the CT_{Index} is highly sensitive to asphalt binder content, and reducing binder content leads to a decrease in CT_{Index} (Bowers et al. 2023, Zhou 2019). A lower CT_{Index} represents poorer expected cracking performance. It is noteworthy that five mixtures (i.e., H-35/0-1, A-30/0-1, K-30/3-2, J-30/0-2, and W-40/0-1) all have the same binder content, but the K-30/3-2 mixture has a visually distinct CT_{Index} result. This suggests that factors other than binder content may influence CT_{Index} values, such as binder rheological properties, gradation, and aggregate mineralogy. K-30/3-1 and K-30/3-3 also display a notably higher CT_{Index} than the mixtures from the other plants. The relatively high CT_{Index} results of the Plant K mixtures are attributed to their softer virgin binder grade of PG 58-28, which resulted in a softer blended matrix despite containing RAS. Plant K mixtures also had among the highest binder contents of the study mixtures. Previous studies have also shown that CT_{Index} is sensitive to asphalt binder grade (Zhou 2019). Moreover, the RAP binders from Plant K have lower PGH values compared to those from most other plants and the RAS PGH values were relatively close to those of RAP binders from other plants. These factors may also have contributed to the high CT_{Index} values observed in Plant K mixtures. Conversely, Plant J mixtures had the lowest average CT_{Index} values across all plants, despite having relatively high binder contents comparable to those from Plant K. A plausible explanation is the stiffness of the extracted and recovered RAP binders from Plant J, which, as shown in Figure 7 through Figure 9 resulted in a stiffer blended binder matrix than other plants.

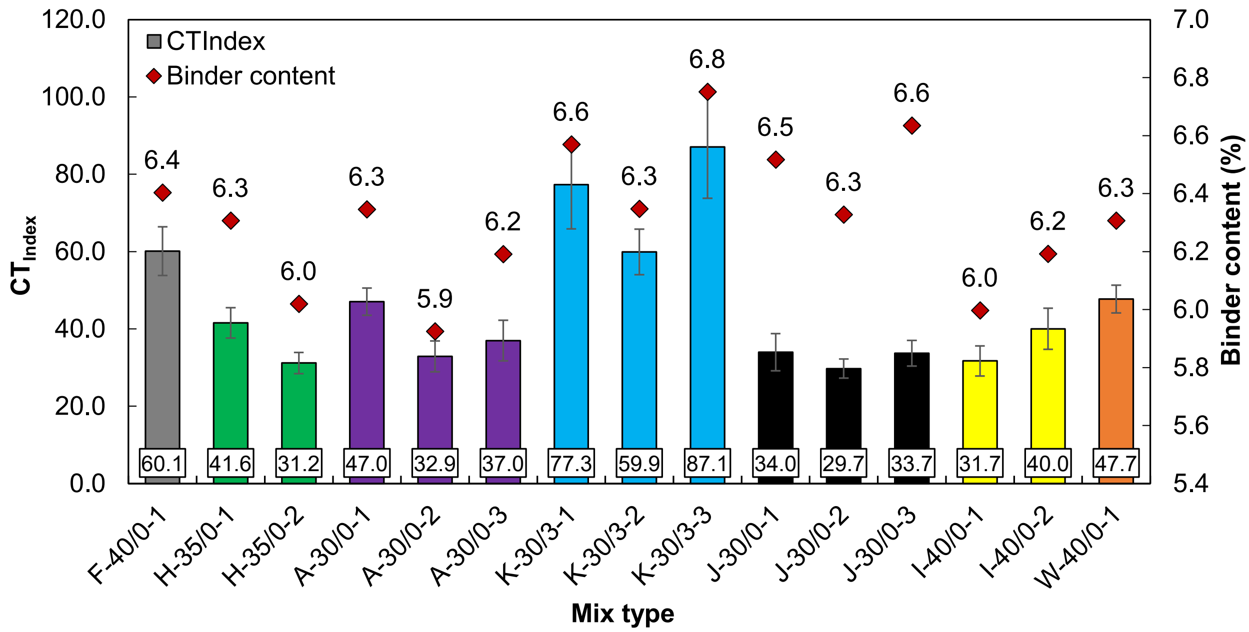


Figure 20. Cracking performance and asphalt content of the plant-produced asphalt mixtures.

To complement the visual inferences regarding the cracking performance, Table 9 presents the grouping information for the mean CT_{Index} of the plant-produced asphalt mixtures, based on the outcomes of the Games-Howell post-hoc test. Means that do not share a letter are significantly different. The Games-Howell test results indicate five distinct statistical groups; however, there is considerable overlap among groups, suggesting some of the differences between groups, while statistically significant, are marginal. Variation between plants is higher than within a given plant. The statistical results support the visual inferences, indicating that the mixtures from Plant K exhibited the best cracking performance overall, and mixtures from Plant J exhibited the worst cracking performance overall. This is evident as the mixtures from Plant K rank highest in the table and do not share a letter with those from other plants, meaning statistically significant differences. Furthermore, many of the mixtures share the same letters, such as groups D and E, indicating no statistically significant differences. The variation among plants suggests that current

NCDOT mixture design procedures can yield differences in cracking performance, suggesting a potential need to integrate cracking testing into mixture design. However, the only case where the CT_{Index} values from a given plant fall in distinct groups is Plant A, where the A-30/-1 result is not in an overlapping group with A-30/0-2, suggesting that monitoring CT_{Index} as part of routine process control may be unnecessary.

Table 9. Grouping Information Using the Games-Howell Method for the CT_{Index}

Mix Type	Mean CT_{Index}	Grouping				
K-30/3-3	87.1	A				
K-30/3-1	77.3	A	B			
F-40/0-1	60.1	A	B			
K-30/3-2	59.9	A	B			
W-40/0-1	47.7		B	C		
A-30/0-1	47.0		B	C		
H-35/0-1	41.6			C	D	
I-40/0-2	40.0			C	D	E
A-30/0-3	37.0			C	D	E
J-30/0-1	34.0			C	D	E
J-30/0-3	33.7				D	E
A-30/0-2	32.9				D	E
I-40/0-1	31.7				D	E
H-35/0-2	31.2				D	E
J-30/0-2	29.7					E

To further evaluate the variation within a given plant, Figure 21 shows the differences in asphalt content and CT_{Index} for mixture pairs produced by the same asphalt plant. A general trend is observed: larger differences in binder content tend to be associated with larger differences in CT_{Index}. This trend is particularly evident for A-30/0-1 versus A-30/0-2, as well as the differences between K-30/3-2 and the other Plant K mixtures. Although only the A-30/0-1 and A-30/0-2 case showed a statistically significant difference based on the Games-Howell test, the observed asphalt content difference of just 0.4% is notably smaller than the current production tolerance of ±0.7% from the JMF. This result suggests that mixtures produced with asphalt contents near the limits of the allowable range may still exhibit significant differences in cracking performance. Accordingly, NCDOT may consider tightening asphalt content tolerance limits and/or implementing CT_{Index} testing during production when asphalt content deviates beyond a threshold narrower than the current ±0.7%, to better control variability in cracking resistance. It is also noteworthy that while the variability in asphalt content at Plant K may be attributed to its high fluctuations in RAP and RAS binder content relative to other plants, RAP binder content at Plant A varied by no more than 0.1% across samples. This suggests that the observed variability in the A-30/0 mixture asphalt content was likely not caused by RAP binder content variation.

It should also be noted that the pattern between asphalt content differences and CT_{Index} differences does not hold for all plants. For example, mixtures from Plant J show that even with noticeable differences in asphalt content, the corresponding differences in CT_{Index} can remain relatively small. Specifically, the pair J-30/0-2 and J-30/0-3 has a binder content difference of 0.3%, but the CT_{Index} differs by only 4.0. Based on these findings, it can be concluded that while there is a general association between higher binder content differences and greater CT_{Index} differences, this relationship is not universally consistent. The results suggest that other factors, such as aggregate gradation and mineralogies, aggregate absorption characteristics, binder rheological properties, or volumetric properties, may also influence CT_{Index} values. Moreover, operational variables at the asphalt plant, such as excessive silo storage time leading to mixture aging, could also contribute to smaller CT_{Index} differences despite larger variations in binder content.

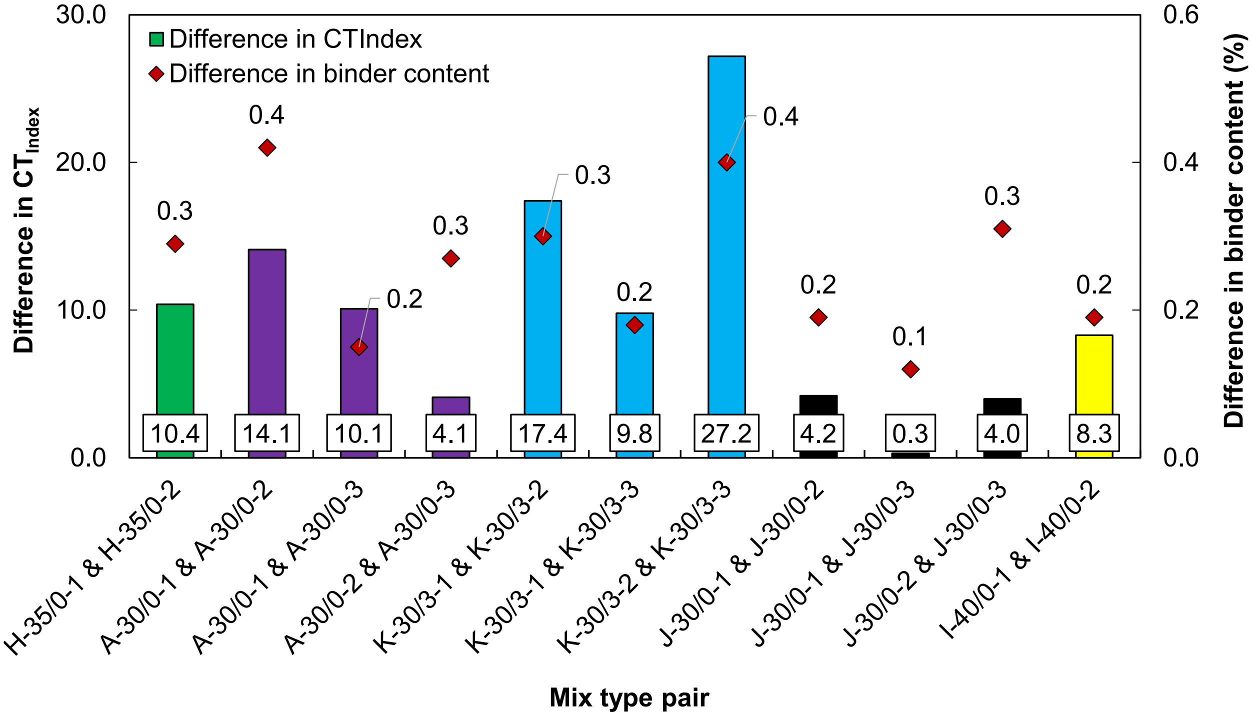


Figure 21. Within-plant variability of asphalt content and CT_{Index}

Figure 22 illustrates the IDT-CT interaction diagram, which plots the fracture energy (G_f) of the mixtures against the ratio of the displacement at 75% the peak load after the peak (l_{75}) to the absolute value of the post-peak slope ($|m_{75}|$), denoted as $l_{75}/|m_{75}|$. The G_f represents the toughness of the mixture, while $l_{75}/|m_{75}|$ is an indication of its ductility. Higher values of both G_f and $l_{75}/|m_{75}|$ lead to a higher CT_{Index} (Leavitt et al. 2023, Yin et al. 2023). The interaction diagram includes contour curves, represented by black dashed lines, where data points along the same curve share the same CT_{Index}, but differ in their G_f and $l_{75}/|m_{75}|$ values. Most of the mixtures in this experimental plan fall within the zone between the CT_{Index} contour curves of 30 and 45, with W-40/0-1 and A-30/0-1 slightly outside this range.

The interaction diagram points out that $l_{75}/|m_{75}|$ is the primary driver of the CT_{Index}. For example, all mixtures from Plant K exhibit relatively low G_f values, but not outside the span of the other mixtures. In contrast, the Plant K mixtures display significantly higher $l_{75}/|m_{75}|$ values, resulting in higher CT_{Index} values. Additionally, while G_f values among Plant K mixtures are relatively consistent, variations in $I_{75}/|m_{75}|$ predominantly influenced their CT_{Index}. Furthermore, the diagram reveals that mixtures with the same CT_{Index} can differ notably in G_f and $I_{75}/|m_{75}|$ values. For instance, along the CT_{Index} contour curve of 30, the I-40/0-1 mixture has a CT_{Index} of 31.7, G_f of 6,160.6 J/m^2, and $I_{75}/|m_{75}|$ of 0.76, whereas J-30/0-3 mixture has a CT_{Index} of 33.7, Gf of 11,013.0 J/m^2, and $I_{75}/|m_{75}|$ of 0.46. As previously mentioned, Plant J mixtures generally had the lowest CT_{Index} values across all plants. Interestingly, these mixtures also had the lowest $I_{75}/|m_{75}|$ values, which predominantly contributed to their poorer performance, despite having the highest G_f values of all mixtures.

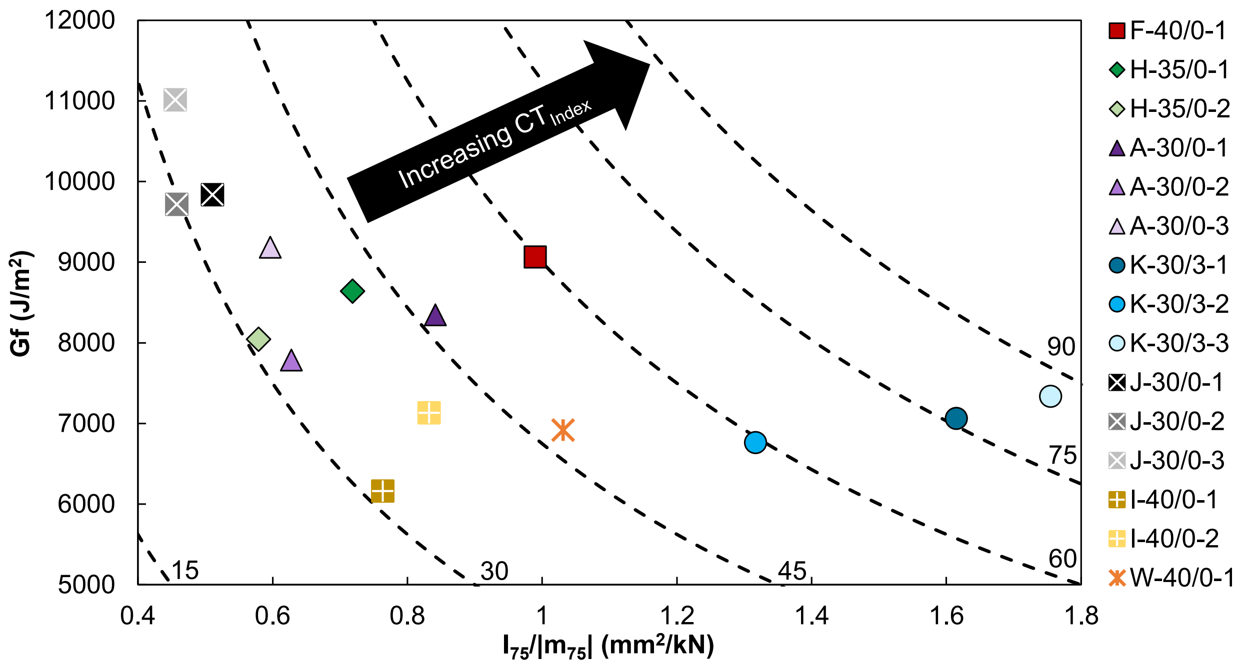


Figure 22. IDT-CT interaction diagram.

3.5.3. APA Results

Figure 23 presents the APA rut depth results for the plant-produced mixtures. Again, the asphalt contents are shown for comparison. A higher rut depth represents a poorer rutting performance. According to NCDOT specifications, the maximum allowable rut depth at mix design is 6.5 mm for RS9.5C mixes and 9.5 mm for RS9.5B mixes. The rut depth values of all mixtures fall below these limits. The Plant K mixtures exhibit similar rut depths to the other mixtures despite having distinct CT_{Index} values, suggesting that characteristics of the asphalt binder had a smaller impact on rutting compared to cracking. In most cases, higher APA rut depths within a given plant correspond to higher binder contents. However, there are a few exceptions. For example, K-30/3-3 has the lowest rut depth among the Plant K samples but the highest binder content. Similarly, the Plant A APA results do not follow a clear trend with respect to binder content.

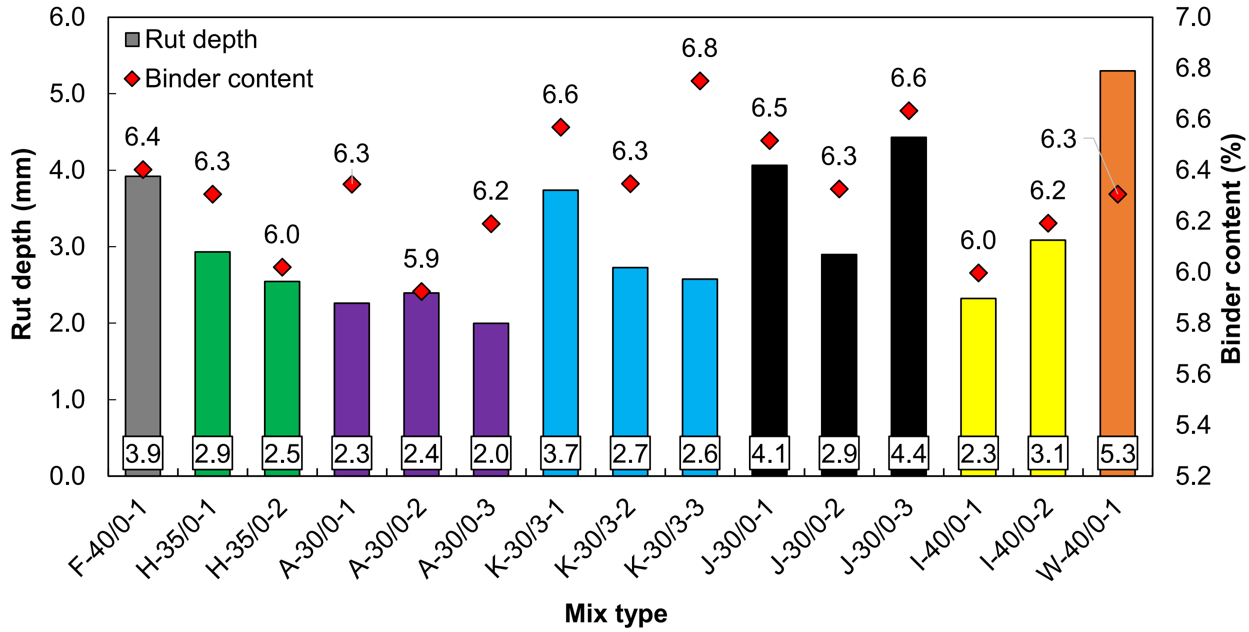


Figure 23. Rutting performance and asphalt content of the plant-produced asphalt mixtures.

Table 10 presents the grouping information for the mean rut depth of the plant-produced asphalt mixtures, based on the outcomes of the Games-Howell post-hoc test. Means that do not share a letter are significantly different. The statistical analysis reveals a wide range of groups, labeled from A to H, indicating greater variability in rut depth results compared to the CT_{Index} results. Despite this variability, all mixtures met the NCDOT specifications for the maximum allowable rut depth by a large margin. The maximum APA rut depth limits for RS9.5C and RS9.5B mixtures are 6.5 and 9.5 mm, respectively. Consequently, the practical significance of the observed differences, particularly within a given plant, is unknown. The statistical findings also align with the visual inferences, suggesting that the mixtures from Plant K exhibited similar rutting performance to those from other mixtures.

Table 10. Grouping Information Using the Games-Howell Method for the Rut Depth

Mix Type	Mean Rut Depth (mm)	Grouping							
W-40/0-1	5.3	A							
J-30/0-3	4.4	A	B						
J-30/0-1	4.1		B						
F-40/0-1	3.9		B						
K-30/3-1	3.7		B	C					
I-40/0-2	3.1			C	D				
H-35/0-1	2.9			C	D	E			
J-30/0-2	2.9			C	D	E	F		
K-30/3-2	2.7				D	E	F	G	
K-30/3-3	2.6						F	G	
H-35/0-2	2.5						F	G	
A-30/0-2	2.4					E	F	G	H
I-40/0-1	2.3				D	E	F	G	H
A-30/0-1	2.3							G	H
A-30/0-3	2.0								H

3.5.4. Effects of Mixture Type and Virgin Performance Grade on IDT-CT and APA Results

Figure 24 shows box-and-whisker plots comparing CT_{Index} and rut depth by mix type and virgin binder grade. For CT_{Index}, RS9.5B mixes exhibit greater variability, as indicated by the larger interquartile range. The mean CT_{Index}, represented by the "x" markers inside the boxes, is also higher for RS9.5B mixes compared to RS9.5C mixes. A similar trend is observed when comparing by virgin binder grade, where mixtures produced with PG 58-28 show higher variability and mean CT_{Index} values than those with PG 64-22. Rut depth follows the same trend by mix type, with RS9.5B mixtures showing both greater variability and higher mean values than RS9.5C mixtures. However, when comparing rut depth results among the virgin binder grades, the mean values are similar for both PG grades. This suggests that rutting performance may be less sensitive to the binder grade than cracking performance.

A two-way ANOVA was conducted to evaluate the effects of mix type, virgin binder grade, and their interaction on CT_{Index} and rut depth. For CT_{Index}, all three factors, mixture type, virgin binder, and their interaction, were statistically significant ($p < 0.0001$). In contrast, for rut depth, only mix type was statistically significant ($p < 0.0001$), while virgin binder ($p = 0.656$) and the interaction term ($p = 0.160$) were not. It is noted that there were only three RS9.5C JMFs and four RS9.5B JMFs included in this study, and thus, the findings here should be verified using a broader data set in the future.

The mixtures containing PG 64-22 virgin binder were generally near the RBR% threshold of 30%, above which PG 58-28 is currently specified. As discussed in Section 3.3, mixtures using PG 58-28 binder exhibited softer blended binder properties, often due to only slightly higher RBR% than those with PG 64-22. Since the choice of virgin binder grade does not significantly influence rutting performance, and PG 58-28 is associated with improved cracking resistance, these findings support the consideration of lowering the RBR threshold at which PG 58-28 is required. This recommendation is further reinforced by the probabilistic evaluation of RBR% limits presented in Section 3.4.

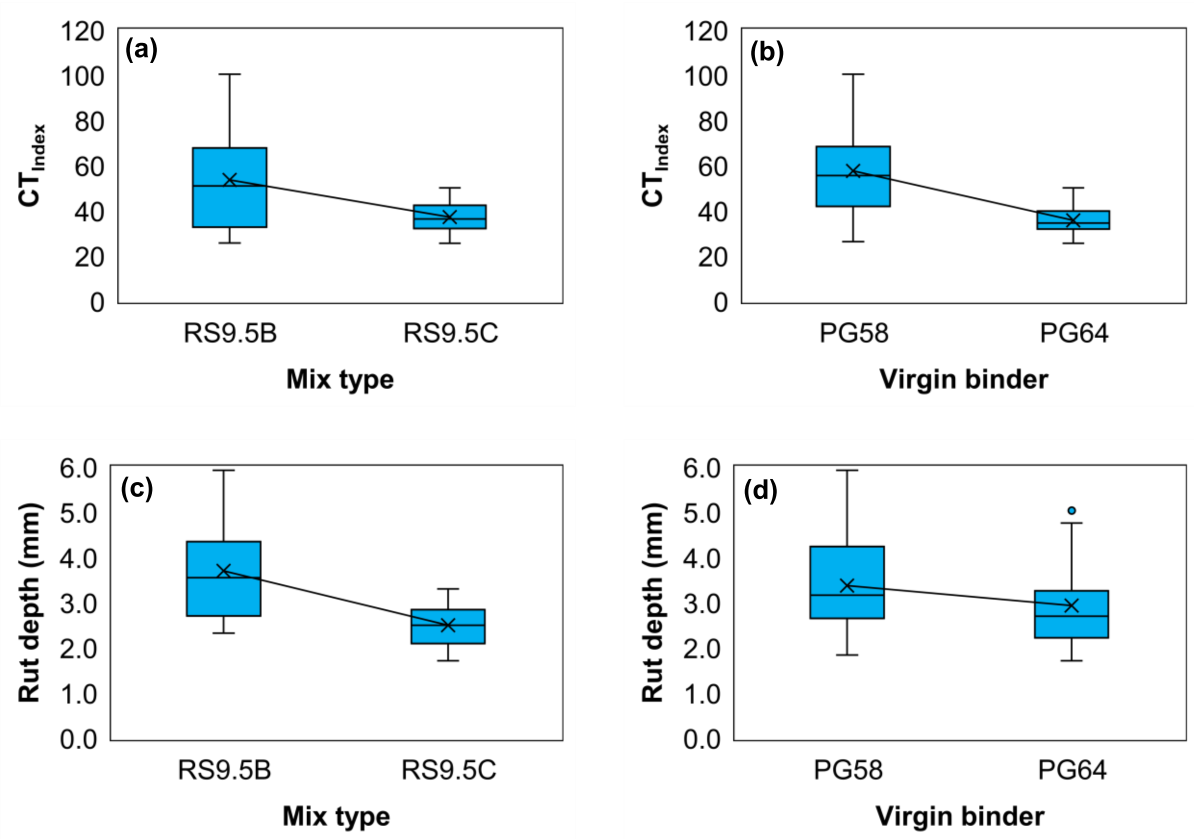


Figure 24. Box-and-whisker plots comparing CT_{Index} by: (a) mix type and (b) virgin binder, and rut depth by: (c) mix type and (d) virgin binder.

3.5.5. Relationship between Plant-Produced Asphalt Mixture Performance and Composition

The correlations between the performance test results and mixture compositional parameters and blended binder rheological properties were investigated to further understand the variation in plant-produced mixture performance. The composition of the plant-produced mixtures was interpreted in two ways: (1) according to current NCDOT procedures that assume 100% RBA and (2) using the AAMD method developed in NCDOT RP 2021-06 (Castorena et al. 2023). The AAMD method addresses RBA by attributing the unavailable recycled binder to the bulk aggregate volume of the asphalt mixture and uses the RAM black curve to reflect its gradation. However, incorporating RBA into the analysis generally did not improve the correlations between mixture performance and composition; in some cases, it even resulted in weaker relationships. This outcome contrasts with the findings from NCDOT RP 2021-06, where stronger relationships were observed between volumetric properties calculated using AAMD and cracking performance in laboratory-mixed, laboratory-compacted samples. One potential explanation is that incorporating RBA into volumetric property calculations requires accurate knowledge of the RAP binder content and gradation in the asphalt mixture. For plant-produced mixtures, this was estimated by assuming the RAP stockpile proportion matches that specified in the JMF. However, plants sometimes adjust proportions based on observed trends in AQCs to maintain compliance with specifications. Any deviations from the actual RAP content during production may have introduced errors into the adjusted volumetric calculations, thereby weakening the observed correlations with performance. It is also possible that the plant mixture production increased RBA beyond what was observed in the laboratory setting. These findings highlight that additional research is needed to identify if and how RBA should be incorporated into process control. For brevity, only the analysis using compositional properties calculated according to the NCDOT's current procedures is presented in the main body of the report. The correlation strengths ranged from extremely weak to extremely strong, categorized in intervals of 0.2 in accordance with Huang et al. (2025). It is also worth noting that Pearson and Spearman coefficients were typically very similar. Therefore, the discussion focuses on Pearson coefficients for brevity.

Figure 25 summarizes the correlation coefficients between CT_{Index} and mixture composition variables and blended binder rheological parameters. Binder content and VMA exhibited positive correlations with CT_{Index}, with Pearson coefficients of 0.63 and 0.82, respectively, indicating strong and extremely strong correlations. All the binder rheological parameters showed negative correlation with CT_{Index}, with PGI blend having the strongest correlation, with a Pearson coefficient of -0.69, indicating a strong negative relationship. In contrast, the gradation of the plant-produced asphalt mixtures, expressed as the percentage passing a given size, exhibited only weak to extremely weak correlations with CT_{Index}.

Figure 27**Error! Reference source not found.** presents the scatterplots of CT_{Index} versus selected mixture composition variables and blended binder rheological parameters, integrating results from all the plants and samples. Based on the correlation results, binder content, VMA, and PGI blend were selected due to their stronger correlations, allowing for potential visual patterns to be identified. G-R at 25°C and 10 rad/s was also included because it has been proposed in the literature as a good indicator of binder ductility and cracking resistance (Duarte and Faxina 2022, Bajaj et al. 2020). A positive trend is observed for both binder content and VMA, indicating that as these variables increase, the CT_{Index} tends to increase as well, which corresponds to an expected improvement in cracking performance. This trend becomes more pronounced when the data points corresponding to Plant J mixtures are excluded from the analysis, resulting in R^2 values above 0.9 for both variables. The mixtures from Plant J deviate from this pattern, as they have high binder content but relatively low CT_{Index} values. If Plant J mixtures are excluded from the correlation analysis, the Pearson coefficients for CT_{Index} versus binder content and VMA increase to 0.94 and 0.95, respectively, both indicating extremely strong correlations.

One plausible explanation for this deviation is the properties of the recovered RAP binders from Plant J, which tend to have higher PG values compared to the other RAP sources. Previous studies have also shown that CT_{Index} is sensitive to asphalt binder grade (Zhou, 2019). A negative trend is observed between CT_{Index} and both G-R at 25°C and phase angle at the condition where $|G^*| = 10$ MPa. The negative trend between CT_{Index} and both G-R at 25°C is expected as lower G-R values are associated with better cracking resistance. However, the negative relationship between CT_{Index} and phase angle is unexpected since higher phase angles at a constant modulus are generally associated with a better stress relaxation ability and thus, better cracking resistance. These results highlight the importance of assessing the properties of both virgin and recycled asphalt binders on cracking performance. It is well recognized that determining the performance grade of recycled binders is impractical in routine practice due to the time-consuming extraction and recovery process. Therefore, integrating asphalt mixture cracking testing into mixture design and potentially quality assurance is necessary to mitigate variability in the performance of high recycled content mixtures.

Figure 26 summarizes the correlation coefficients between rut depth and mixture composition variables and blended binder rheological parameters. Gradation appears to have the strongest correlation with rut depth, as indicated by the Pearson correlation coefficients for the percentage passing 2.36 mm and 1.18 mm sieves, which are 0.88 and 0.86, respectively, both indicating extremely strong correlations. In contrast, other properties such as binder content, VMA and blended binder rheological parameters exhibit only moderate to extremely weak correlations with rut depth.

Figure 28 presents scatterplots of rut depth versus mixture composition variables and blended binder rheological parameters. The percentages passing 2.36 mm and 1.18 mm sieves were selected due to their stronger correlations. Additionally, binder content and PGH were included to represent a volumetric and binder property, respectively. A positive trend is observed for mixture gradation, specifically in terms of the percentage passing the 2.36 mm and 1.18 mm sieves. As the percentage passing increases, the rut depth also tends to increase, implying finer gradations at these sieves increase rutting susceptibility. No clear trends are observed between PGH or binder content and rut depth when all data is considered despite the clear relationship between binder content and rut depth within samples from specific plants in many cases.

CT_{Index}	Pearson coefficient	Spearman coefficient
AC	0.63	0.59
P_{be}	0.65	0.55
VMA	0.82	0.66
%Passing 9.5 mm	0.00	-0.01
%Passing 4.75 mm	0.26	0.24
%Passing 2.36 mm	0.08	0.25
%Passing 1.18 mm	-0.29	-0.12
%Passing 0.6 mm	-0.39	-0.30
%Passing 0.3 mm	-0.24	-0.36
%Passing 0.075 mm	0.08	0.37
$G_{mm, mix}$	0.21	0.26
$G_{sb, mix}$	0.53	0.43
RBR	0.48	0.28
PGI blend	-0.69	-0.70
G-R at 15°C & 0.005 rad/s	-0.45	-0.53
G-R at 25°C & 10 rad/s	-0.59	-0.61
Phase angle	-0.61	-0.53
G*sin(δ)	-0.65	-0.63

Range	Correlation
$1 \geq r > 0.8$	Extremely strong
$0.8 \geq r > 0.6$	Strong
$0.6 \geq r > 0.4$	Moderate
$0.4 \geq r > 0.2$	Weak
$0.2 \geq r \geq -0.2$	Extremely weak
$-0.2 > r \geq -0.4$	Weak
$-0.4 > r \geq -0.6$	Moderate
$-0.6 > r \geq -0.8$	Strong
$-0.8 > r \geq -1$	Extremely strong

Figure 25. Pearson correlation coefficient and spearman rank correlation coefficient between CT_{Index} and mixture composition variables.

Rut depth	Pearson coefficient	Spearman coefficient
AC	0.45	0.50
P_{be}	0.39	0.56
VMA	0.26	0.46
%Passing 9.5 mm	0.31	0.15
%Passing 4.75 mm	0.53	0.56
%Passing 2.36 mm	0.88	0.86
%Passing 1.18 mm	0.86	0.80
%Passing 0.6 mm	0.64	0.58
%Passing 0.3 mm	0.38	0.42
%Passing 0.075 mm	0.06	0.34
$G_{mm, mix}$	-0.48	-0.52
$G_{sb, mix}$	-0.40	-0.45
RBR	0.21	0.22
PGH	-0.05	-0.04
$G^*/\sin(\delta)$	-0.05	-0.07

	Correlation
$1 \geq r > 0.8$	Extremely strong
$0.8 \geq r > 0.6$	Strong
$0.6 \geq r > 0.4$	Moderate
$0.4 \geq r > 0.2$	Weak
$0.2 \geq r \geq -0.2$	Extremely weak
$-0.2 > r \geq -0.4$	Weak
$-0.4 > r \geq -0.6$	Moderate
$-0.6 > r \geq -0.8$	Strong
$-0.8 > r \geq -1$	Extremely strong

Figure 26. Pearson correlation coefficient and spearman rank correlation coefficient between rut depth and mixture composition variables.

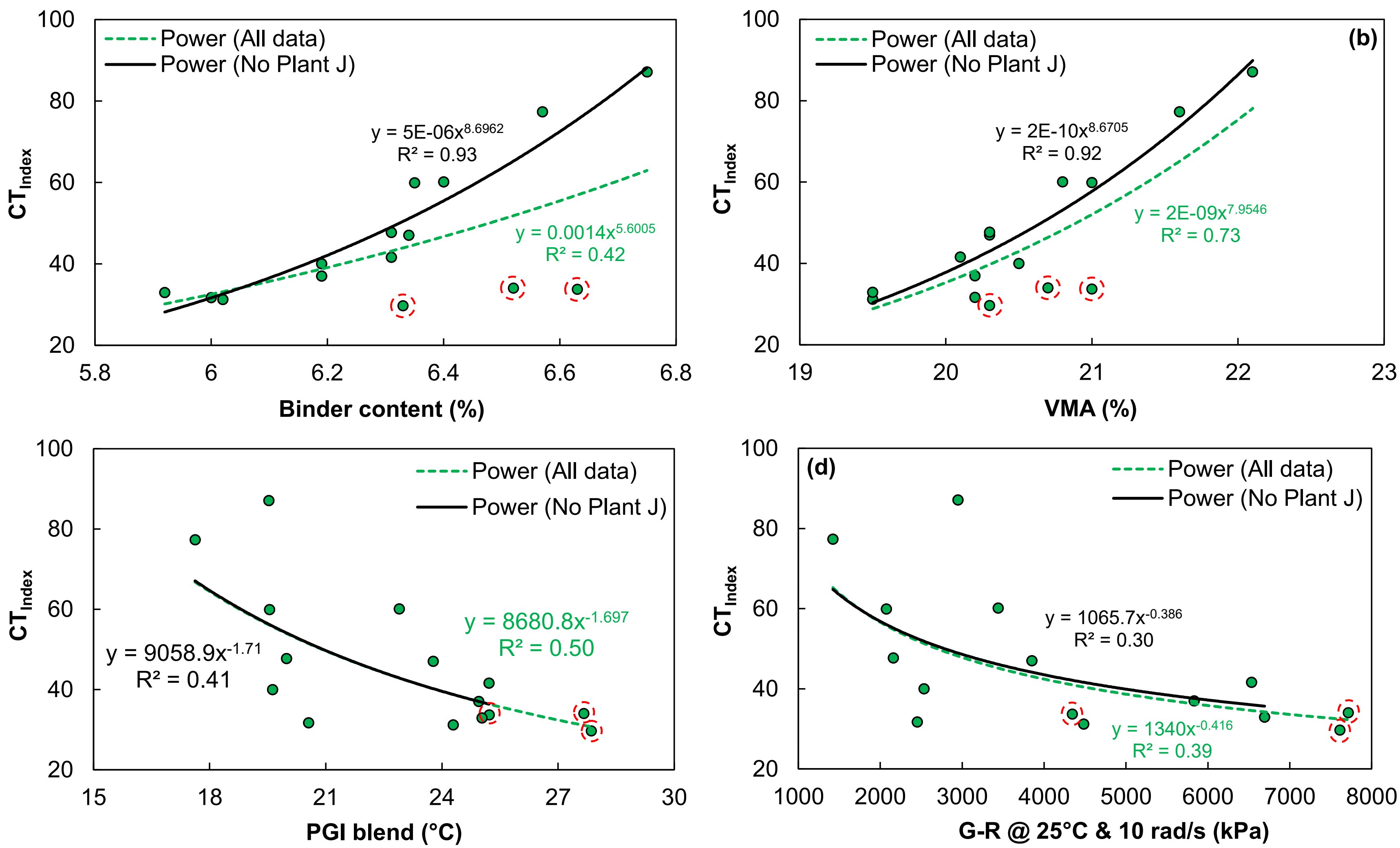


Figure 27. Scatterplots of CT_{Index} versus: (a) binder content, (b) VMA, (c) PGI blend (°C), and (d) G-R at 25°C & 10 rad/s (kPa). The circled data points correspond to plant J.

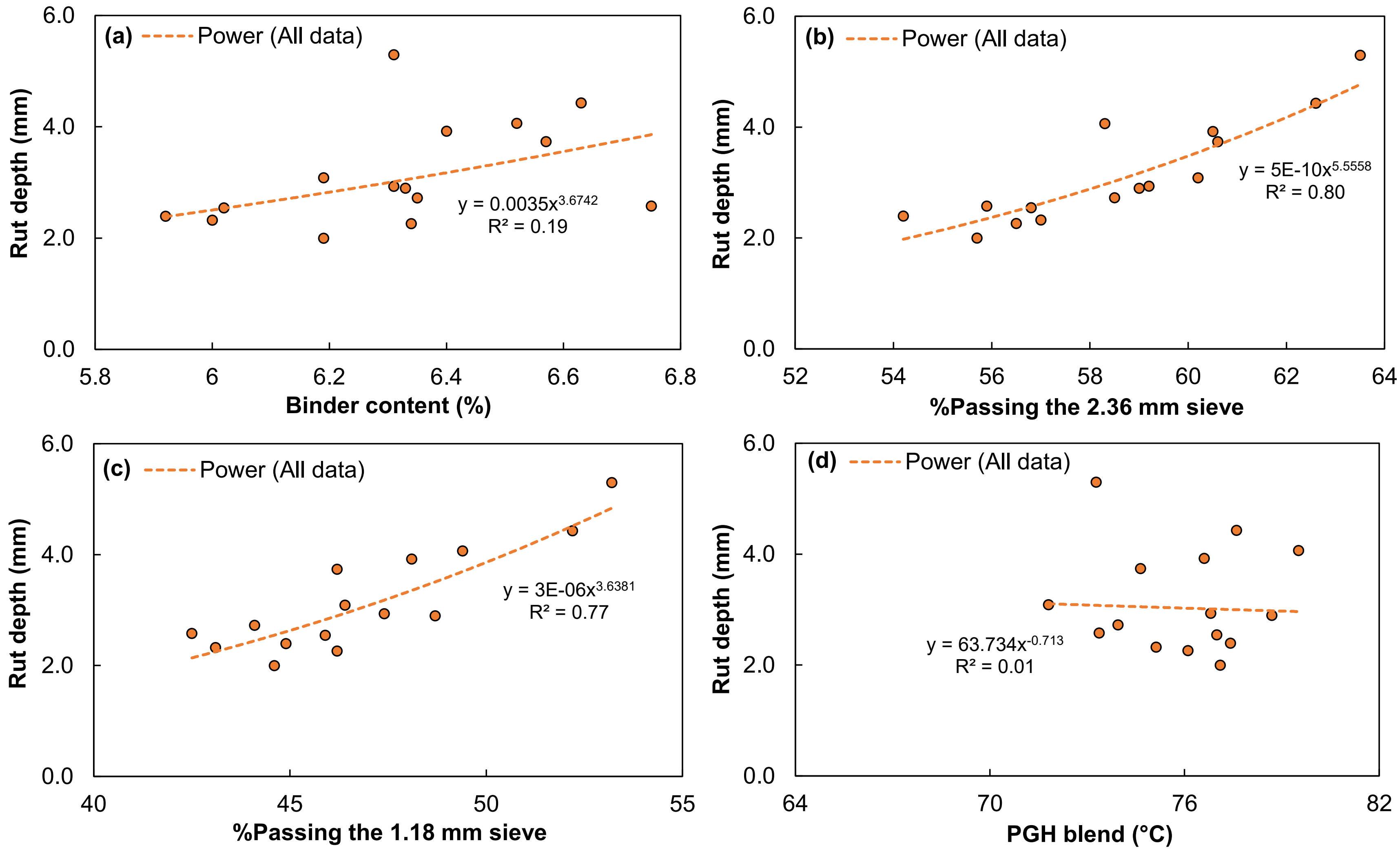


Figure 28. Scatterplots of rut depth versus: (a) binder content, (b) %passing the 2.36 mm sieve, (c) %passing the 1.18 mm sieve, and PGH blend (°C).

Figure 29 presents the relationship between rut depth and percentage passing the 2.36 mm sieve, highlighting individual plants and identifying the B mixtures. As previously discussed, when considering the results of all plants, rut depth tends to increase with a higher percentage passing the 2.36 mm sieve. Interestingly, this trend also often holds within individual plants, such as Plants K, I, and H. Plants A and J generally follow this trend as well, except for one data point each.

The 2.36 mm sieve plays a particularly critical role, as defined in NCDOT specifications (NCDOT 2024), where it serves as the boundary between coarse and fine aggregates. Material retained on the 2.36 mm sieve is categorized as coarse, while material passing through it is considered fine. Based on the results, finer gradations, reflected by a higher percentage passing the 2.36 mm sieve, tend to result in increased rut depths, which correspond to poorer expected rutting performance. These findings underscore the importance of closely monitoring and controlling aggregate gradation during mixture design and plant mix production, particularly at the 2.36 mm sieve, to ensure a balanced aggregate skeleton and improved rutting resistance.

The NCDOT mix design procedure establishes the percent passing control points at the 2.36 mm sieve. For RS9.5C mixtures, the allowable range is between 32% and 67%, while for S9.5B, the specification is more stringent, requiring between 60% and 70% passing. As shown in Figure 29, mixtures with more than 60% passing the 2.36 mm sieve tend to exhibit higher rut depths. Notably, the B mixes that showed better rutting resistance had percentages just below the minimum threshold of 60%, while those above it had the highest rut depth values, suggesting that lowering the minimum limit for the percent passing the 2.36 mm sieve for RS9.5B mixtures may offer a means to lower APA rut depths.

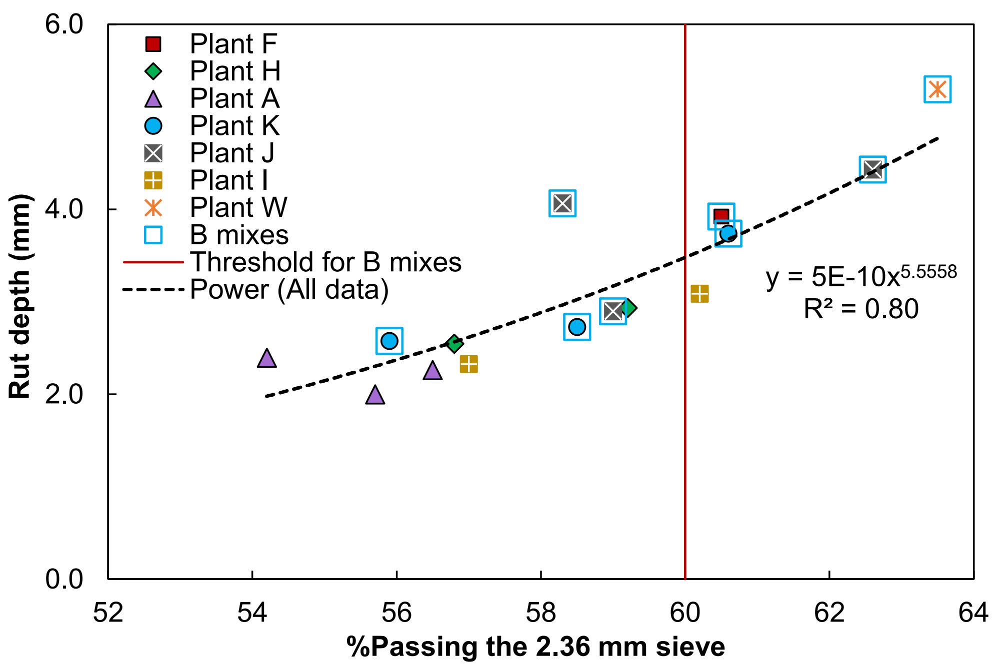


Figure 29. Rut depth versus %passing the 2.36 mm sieve for all mixtures.

3.6. Summary

The experimental program provides a comprehensive evaluation of recycled material variability and its effects on asphalt mixture performance. The findings support potential updates to mixture design and specification practices that could improve material consistency and long-term pavement performance, particularly as the use of high-RAP and RAS mixtures increases. The following summarizes the key findings drawn from the results of this study and their potential implications for NCDOT specifications.

RAP properties varied more across plants than within a single plant over time. Asphalt content ranged from 4.3% to 5.4%. While many plants maintained consistent properties, measured values sometimes exceeded allowable deviations from the JMF. Plant K, which crushed RAP in-house monthly using a jaw crusher, exhibited the largest fluctuations in RAP binder content and corresponding CT_{Index} values than the other plants that outsourced crushing to contractors using impact crushers on a less frequent basis. Consequently, it is suggested that the NCDOT require that RAP and RAS asphalt contents remain within tolerance limits relative to the JMF whenever a processed stockpile is replenished, even if no new unprocessed material is added. It is also suggested that the NCDOT further investigate the influence of crusher type on RAP consistency.

RAS stockpiles showed greater variability over time than RAP, with nearly a 20°C range in continuous high-temperature grade and a 2.6% change in asphalt content. This variability influenced blended binder properties and contributed to larger CT_{Index} variation in RAP/RAS mixtures than in RAP-only mixtures.

Evaluation of study binders and probabilistic analysis using QA data indicated that lowering the maximum RBR% limit for PG 64-22 mixtures from 30% to 20% increases the likelihood of meeting performance grade requirements. The plant-produced asphalt mixtures with PG 58-28 virgin binder exhibited higher average CT_{Index} values than those with PG 64-22, further suggesting that lowering the RBR% limit for PG 64-22 binder could potentially improve cracking performance and consistency. At 20% RBR%, blends of RAP binder with PG 58-28 mixtures maintained compliance with high-temperature requirements. Furthermore, the APA rut depths of the mixtures with PG 64-22 and PG 58-28 were statistically similar, suggesting that lowering the RBR% threshold where PG 58-28 is specified is unlikely to harm rutting performance. The current maximum RBR% limits for PG 58-28 provide a high probability of meeting intermediate-temperature PG requirements; therefore, no change is recommended.

Plant-produced, laboratory-compacted asphalt mixture CT_{Index} and APA rut depth values varied significantly among plants but were more consistent within a given plant over time. CT_{Index} was most strongly associated with VMA, asphalt content, and blended binder properties. APA rut depth was primarily influenced by the percentage passing the 2.36 mm and 1.18 mm sieves. Softer binders and higher VMA generally improved CT_{Index}, while finer gradations increased rut depths. RS9.5B mixtures had higher CT_{Index} and APA rut depths on average than RS9.5C mixtures, but all rut depths were well below NCDOT limits.

The large variation in CT_{Index} across plants, attributable in part to variation in recycled binder properties, indicates a need for a cracking or durability performance test in mixture design, given the impracticality of routine recycled binder grading. Furthermore, lowering the minimum percent passing limit for the 2.36 mm sieve in RS9.5B mixtures could promote a coarser aggregate structure and improve rutting resistance. Notably, NCDOT RP 2021-06 (Castorena et al. 2023) also recommended relaxing the tight gradation band at the 2.36 mm sieve, highlighting that the current specification restricts a designer's ability to effectively adjust VMA. Taken together, the findings from both studies suggest that lowering the lower gradation limit at the 2.36 mm sieve would provide mixture designers with greater flexibility to optimize gradation for balanced cracking and rutting performance, an especially important consideration should NCDOT implement cracking performance testing in future specifications.

Statistically significant differences in CT_{Index} and APA rut depth were observed within a given plant over time. Differences in the CT_{Index} over time corresponded with changes in asphalt content. An increase in asphalt content improved CT_{Index}. A 0.4% change in asphalt content, though within current NCOT tolerance limits, produced statistically significant CT_{Index} differences. Given that such tight control of asphalt content may not be feasible operationally, NCDOT could consider implementing an asphalt content threshold that triggers cracking performance testing during production. APA rut depth changes were found to be more closely associated with gradation differences, and thus, tightening tolerance limits for the 2.36 mm and 1.18 mm sieves during production may help minimize variability in rutting performance.

The RBA of combined RAP ranged from 44% to 67%, averaging 56%, with within-plant variation up to 11%. This within-plant variability has marginal impacts on effective binder content under current RBR% and asphalt content tolerances, suggesting that while RBA may aid in mixture design, routine measurement for process control is likely unnecessary. Adjusting volumetric properties using RBA requires assumptions about RAP content during production, introducing uncertainty. This likely contributed to weaker performance correlations between compositional properties adjusted for RBA compared to NCDOT's current practice of assuming 100% RBA, underscoring challenges of incorporating RBA into process control and the potential need for performance testing in quality assurance processes.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

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

- RAP stockpile properties varied significantly among plants across the state. Continuous high-temperature grades of recovered binders differed by up to 15°C, and low-temperature grades by up to 12°C. Binder contents ranged from 4.3% to 5.4%. While individual stockpiles generally showed relatively consistent properties over time, some plants exhibited notable discrepancies between measured RAP asphalt content and gradation and those reported in their respective JMFs, with differences occasionally exceeding specification limits.
- Plant K showed greater variation in RAP binder content over time than the other plants. Unlike other plants, which outsource crushing to contractors using impact crushers, Plant K performs monthly in-house crushing using a jaw crusher. This approach results in more frequent replenishing of their processed RAP stockpile compared to other plants. Despite higher variability in asphalt content, Plant K maintained among the most consistent RAP gradations.
- The RAS stockpile evaluated showed comparatively higher variability over time than RAP, with a near 20°C change in continuous high-temperature grade of the recovered binder and a 2.6 percent change in asphalt content. The corresponding mixture containing both RAP and RAS demonstrated a greater change in CT_{Index} over time than the RAP-only mixtures.
- The extracted aggregate gradations of the plant-produced asphalt mixtures were generally consistent with the values reported in the corresponding JMFs. Although some RAP sources exceeded the tolerance limits at the 0.075 mm sieve, this did not broadly translate to noncompliance in the plant-produced mixtures. Only one mixture failed to meet NCDOT's tolerance limits at the 0.075 mm sieve.
- NCDOT's maximum RBR% limits of 40% and 45% for RAP mixtures yield greater than 90% probabilities of blended binders meeting intermediate-temperature grading requirements.
- Reducing the maximum RBR% limit for RAP mixtures using PG 64-22 virgin binder from 30% to 20% increases the probability of the blended binder meeting AASHTO M 320 intermediate- and low-temperature requirements from approximately 75% to 95%. At this lower RBR% limit, high-temperature requirements are met by using a PG 58-28 virgin binder.
- Significant variation in CT_{Index} values and APA rut depths was observed among the plant-produced mixtures, with greater variation across compared to within a given plant over time.
- On average, the CT_{Index} values and APA rut depths of RS9.5B mixtures were higher than those for RS9.5C mixtures. All APA rut depths of the plant-produced mixtures fell well below established limits for mixture design for RS9.5B and C designations, with average values of 3.7 mm and 2.5 mm, respectively.
- Asphalt mixtures produced with PG 58-28 binder exhibited higher average CT_{Index} values and greater variation across plants than those with PG 64-22. In contrast, virgin binder grade did not significantly affect APA rut depth.
- Differences in the CT_{Index} of a given plant-produced mixture over time corresponded with changes in asphalt content. An increase in asphalt content improved CT_{Index}. While these changes were often statistically insignificant, there was an instance where statistically significant changes occurred even when the variations in binder content were well within acceptable limits. In contrast, differences in APA rutting over time for a given plant showed

less consistent correlation with changes in asphalt content. While some cases exhibited a relationship, the trend was not as clear or pronounced as that observed for CT_{Index}.

- The CT_{Index} across all plant-produced mixtures was most strongly correlated with VMA and blended binder properties. Higher VMA, along with the associated increase in asphalt content, softer binder properties and lower phase angle values, were associated with improved CT_{Index}.
- APA rut depth across all plant-produced mixtures was most strongly correlated with the percent passing the 2.36 mm and 1.18 mm sieves. Finer gradations were associated with increased rut depths.
- The RBA of combined RAP ranged from 44% to 67%, averaging 56%, with within-plant variation up to 11%. This within-plant variability has marginal impacts on effective binder content under current RBR% and asphalt content tolerances. Adjusting volumetrics for RBA introduces uncertainty due to the required assumptions about RAP content, likely weakening correlations with performance compared to assuming 100% RBA. This highlights the challenges of using RBA in process control and the potential need for performance testing in quality assurance processes.

4.2. Recommendations

Based on these conclusions, the research team makes the following recommendations:

- **RBR% Limits**. Lower the maximum allowable RBR% for mixtures using PG 64-22 virgin binder from 30% to 20%. For mixtures exceeding this revised threshold, specify the use of PG 58-28 virgin binder. The results of this study suggest that lowering the RBR% limit for PG 64-22 would increase the probability of compliance with intended performance graded properties and enhance cracking performance. Additionally, the performance implications of incorporating RBA into RBR% calculations merit evaluation.
- **Mixture Design.** Given the substantial variation in asphalt mixture CT_{Index} values across plants, attributable in part to differences in recycled binder properties, it is recommended that a cracking or durability performance test be incorporated into the mixture design process. Furthermore, it is recommended that NCDOT lower the minimum percent passing limit for the 2.36 mm sieve in RS9.5B mixtures. Lower percent passing values at this sieve were associated with reduced APA rut depths, and expanding the allowable gradation range at this size would provide greater flexibility to adjust VMA. Since VMA is positively correlated with CT_{Index}, this change would enhance the ability of mixture designers to optimize both cracking and rutting performance, supporting a more balanced design approach.
- **Quality Assurance**. Tighten asphalt content tolerance limits during production. A 0.4% change in asphalt content resulted in a statistically significant difference in CT_{Index} in one of the study mixtures, despite falling within current production tolerances. While tighter control may not be feasible operationally, NCDOT could consider implementing an asphalt content threshold that triggers cracking performance testing during production. Additionally, reducing tolerance limits for the 2.36 mm and 1.18 mm sieves during production may help minimize variability in rutting performance.
- **RAP and RAS Stockpile Management.** Ensure that the asphalt content of RAP and RAS remains within established tolerance limits relative to the JMF whenever the processed stockpile is replenished, even if new sources have not been added to the unprocessed stockpile. This practice will help maintain material consistency during production. Investigate the influence of RAP crusher type on the consistency of RAP. Also, this study indicates that recycled binder properties affect asphalt mixture cracking performance. Because solvent

extraction and recovery are not practical for routine use, future research should be conducted to develop practical and efficient methods for characterizing RAP and RAS binder properties to enable routine measurements. The procedure presented in Appendix D, which estimates low-temperature PG properties from DSR results, offers a promising starting point for reducing reliance on extracted and recovered binders.

5. IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

The Materials and Tests Unit of the NCDOT is the primary user of the outcomes of this research. The recommendations above can be integrated into NCDOT specifications for a mixture of design and quality assurance. The research team suggests that the NCDOT considers allocating resources to support the following follow-up activities:

- Expand the number of plant-mixed, laboratory-compacted mixtures tested to get better coverage of contractors, regions, and RBR%s;
- Evaluate the relationship between plant-mixed, laboratory-compacted and laboratory-mixed, laboratory-compacted IDT-CT and APA test results to identify if separate limits are required for mixture design and production.
- Evaluate the performance impacts of lowering the minimum limit for the percent passing the 2.36 mm sieve in RS9.5B mixtures as a potential means for mixture designers to improve rutting resistance and adjust VMA.
- Assess the impacts of crushing frequency and crusher type to identify measures to promote RAP consistency.
- Explore practical approaches for quantifying RAP and RAS binder properties.

6. CITED REFERENCES

AASHTO. 2024. *Quantitative extraction of asphalt binder from hot mix asphalt (HMA) (T 164)*. American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 222. *Accelerated aging of asphalt binder using a pressurized aging vessel (PAV) (R 28).* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2022. *Determining the flexural creep stiffness of asphalt binder using the bending beam rheometer (BBR) (T 313).* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2024. *Determining the rheological properties of asphalt binder using a dynamic shear rheometer (DSR) (T 315).* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2023. *Effect of heat and air on a moving film of asphalt binder (rolling thin-film oven test) (T 240).* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2020. *Standard method of test for materials finer than 75-µm (No. 200) sieve in mineral aggregates by washing (T 11).* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2020. *Standard method of test for sieve analysis of fine and coarse aggregates (T 27).* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2020. *Standard method of test for theoretical maximum specific gravity (Gmm) and density of asphalt mixtures (T 209).* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2021. *Standard method of test for determining the asphalt binder content of asphalt mixtures by the ignition method (T 308).* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2021. *Standard method of test for mechanical analysis of extracted aggregate (T 30).* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2022. *Standard specification for Superpave volumetric mix design (M 323).* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2023. *Standard method of test for determining rutting susceptibility of asphalt mixtures using the Asphalt Pavement Analyzer (APA) (T 340).* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2023. *Performance-graded asphalt binder (M 320).* American Association of State Highway and Transportation Officials, Washington, D.C.

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

ASTM International. 2019. *Standard test method for determination of cracking tolerance index of asphalt mixture using the indirect tensile cracking test at intermediate temperature (D 8225).* West Conshohocken, PA.

ASTM International. 2023. *Standard test method for maximum specific gravity and density of asphalt mixtures using automatic vacuum sealing method (D 6857).* West Conshohocken, PA.

ASTM International. 2022. *Standard practice for determining continuous grading temperatures for performance-graded asphalt binders (D 7643).* West Conshohocken, PA.

ASTM International. 2010. *Standard practice for recovery of asphalt binder from solution using the rotary evaporator (D 5404).* West Conshohocken, PA.

Bajaj, A., A. E., Martin, G. King, C. Glover, F. Kaseer, E. Arambula-Mercado. 2020. "Evaluation and classification of recycling agents for asphalt binders." *Construction and Building Materials*, 260 (119864). https://doi.org/10.1016/j.conbuildmat.2020.119864

Bennert, T., N. Garg, C. Ericson, and N. Cytowicz. 2023. "Evaluation of Test Methods to Identify 21 Asphalt Binders Prone to Surface-initiated Cracking." *Transportation Research Record*, 2677(3), 897- 22 910.

Bowers, B. F., T. Lynn, F. Yin, N. Moore, S. Diefenderfer, and I. Boz. 2023. *Impact of production variability on balanced mix designs in Virginia.* VTRC Rep. 23-R20. Virginia Transportation Research Council, Charlottesville, VA.

Castorena, C., B. S. Underwood, Y. R. Kim, D. Mocelin, M. Isied, M. C. A. Alvis, and A. Kusam. 2023. *Modifying existing asphalt mix design procedures for RAP/RAS surface mixtures.* FHWA/NC-2021-06. North Carolina Department of Transportation, Raleigh, NC.

Castorena, C., R. Costa, M. C. A. Alvis, D. Mocelin, M. Isied, and A. Kusam. 2024. *A practical method to determine reclaimed asphalt pavement (RAP) binder availability.* NCHRP IDEA Project 236. Transportation Research Board, Washington, D.C.

Christensen, D.W. and N. Tran. 2022. *Relationships between the fatigue properties of asphalt binders 10 and the fatigue performance of asphalt mixtures*. NCHRP Report 982, Washington, DC.

Copeland, A. 2011. *Reclaimed asphalt pavement in asphalt mixtures: State of the practice.* Rep. FHWA-HRT-11-021. Federal Highway Administration, Washington, D.C.

Duarte, G. M., and A. L. Faxina. 2022. "Low-Temperature and Fatigue Properties of Asphalt Binders Modified with Crumb Rubber from Discarded Tires and Recycled Low-Density Polyethylene." *Journal of Materials in Civil Engineering*, 34 (9). https://doi.org/10.1061/(ASCE)MT.1943-5533.0004365

Elkashef, M., S. S. Hung, J. T. Harvey, and D. Jones. 2020. Assessing the Use of Blending Charts to Estimate the Allowable Reclaimed Asphalt Pavement (RAP) Binder Content for Mixes Containing Rap from Different Sources. *Journal of Testing and Evaluation*, 49(5), 3132–3147. https://doi.org/10.1520/JTE20200106

Elwardany, M. D., J.P. Planche, and G. King. 2022. "Proposed Changes to Asphalt Binder Specifications to Address Binder Quality-Related Thermally Induced Surface Damage." *Transportation Research Record*, 2676(5), 176-191. https://doi.org/10.1177/03611981211065428

Faisal, H. M., U. A. Mannan, A. S. M. Asifur Rahman, M. M. Hasan, and R. A. Tarefder. 2017. "Effects of RAP Sources for Performance Testing of Asphalt Concrete." In *International Conference on Highway Pavements and Airfield Technology*, 119–128. https://doi.org/10.1061/9780784480939.011.

Fried, A., L. G. Xue, S. Gulzar, J. Preciado, B. S. Underwood, and C. Castorena. 2022. "Evaluation of Recycling Agent and Extender Dosage Selection Procedures to Restore the High-Temperature Climatic Performance Grade." *Transportation Research Record* 2676(6): 302–314. https://doi.org/10.1177/03611981221074361.

Fried, A., and C. Castorena. 2023. "Practical Methods to Construct Asphalt Binder Master Curves and Calculate Christensen-Anderson Model Parameters." *Transportation Research Record* 2677(12): 647-660.

Glover, C. J., R. R. Davison, C. H. Domke, Y. Ruan, P. Juristyarini, D. B. Knorr, and S. H. Jung. *Development of a New Method for Assessing Asphalt Binder Durability with Field Validation*. 2005. Report No. FHWA/TX-05/1872-2. College Station, Texas.

Hajj, E. Y., P. E. Sebaaly, and R. Shrestha. 2009. "Laboratory Evaluation of Mixes Containing Recycled Asphalt Pavement (RAP)." *Road Materials and Pavement Design* 10: 495–517. https://doi.org/10.3166/rmpd.10.495-517.

Huang, S., D. Chen, S. Niu, X. Ren, and X. Liu. 2025. "Insights into the Micro-Modification Mechanism, Thermal Stability, and Rheological Property of SBS/TB Rubber Crumb Modified Asphalt Binder." *Construction and Building Materials* 482: 141670.

Izaks, R., V. Haritonovs, I. Klasa, and M. Zaumanis. 2015. "Hot Mix Asphalt with High RAP Content." *Procedia Engineering* 114: 676–684. https://doi.org/10.1016/j.proeng.2015.08.009.

Khosla, N. P., and S. Ramoju. 2017. *Characterization of Different RAP Sources.* FHWA/NC/2014-05. North Carolina Department of Transportation, Raleigh, NC.

Kriz, P., D. Grant, N. Boussad, D. Gausson, F. Cointe, C. Toulemonde, and R. Shirts. 2016. Assessment of performance specification tests for rheologically simple bitumens. In Proc., *6th 3 Eurasphalt 4 and Eurobitume Congress*. Brussels, Belgium: Foundation Eurasphalt. https://doi. org/10.14311/EE.

LaCroix, A. 2013. "Performance Prediction of the NCAT Test Track Pavements Using Mechanistic Models." Doctoral dissertation. North Carolina State University, Raleigh, NC.

Leavitt, A. E., E. Martin, and E. Arámbula-Mercado. 2023. "Mitigation Strategy Selection for Asphalt Mixtures with High Reclaimed Asphalt Pavement Content." *Transportation Research Record* 2677(11): 602–614.

Li, X., M. O. Marasteanu, R. C. Williams, and T. R. Clyne. 2008. “Effect of Reclaimed Asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures.” *Transportation Research Record* 2051: 90–97. https://doi.org/10.3141/2051-11.

Mocelin, D. M., and C. Castorena. 2022. “Impacts of Recycled Binder Availability on Volumetric Mixture Design and Performance.” *International Journal of Pavement Engineering*, 1–17. https://doi.org/10.1080/10298436.2022.2046276.

Mocelin, D. M., M. M. Isied, R. F. Costa, and C. Castorena. 2024. “Availability-Adjusted Mix Design Method as a Tool to Mitigate the Adverse Effects of RAP on Performance of Asphalt Mixtures.” *Construction and Building Materials* 422: 135813. https://doi.org/10.1016/j.conbuildmat.2024.135813.

Mogawer, W., G. Rowe, I. Abdalfattah, and A. Austerman. 2025. “Evaluating Asphalt Binder Quality: Point and Shape Rheological Parameters for Assessing Intermediate Temperature Cracking Susceptibility.” Accepted for publication in *Transportation Research Record*.

Montañez, J., S. Caro, D. Carrizosa, A. Calvo, and X. Sánchez. 2020. “Variability of the Mechanical Properties of Reclaimed Asphalt Pavement (RAP) Obtained from Different Sources.” *Construction and Building Materials* 230: 116968. https://doi.org/10.1016/J.CONBUILDMAT.2019.116968.

National Center for Asphalt Technology. 2017. *Moving Towards Balanced Mix Design for Asphalt Mixtures. Asphalt Technology News* 29(1): 1–5. https://www.odot.org/materials/asph_tchnl_info/BALANCED_DESIGN.pdf.

Newcomb, D., and P. Investigator. 2018. *Balanced Design of Asphalt Mixtures.* MN/RC 2018-22. Minnesota Department of Transportation.

North Carolina Department of Transportation. 2024. *Standard Specifications for Roads and Structures*. Raleigh, NC.

Obaid, A., M. D. Nazzal, L. Abu Qtaish, S. S. Kim, A. Abbas, M. Arefin, and T. Quasem. 2019. “Effect of RAP Source on Cracking Resistance of Asphalt Mixtures with High RAP Contents.” *Journal of Materials in Civil Engineering* 31: 0002817. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002817.

Pape, S., and C. Castorena. 2022. “Application of Sieve Analysis to Estimate Recycled Binder Availability.” *Transportation Research Record* 2676: 170–181. https://doi.org/10.1177/03611981211073324.

Rahman, M., J. Harvey, J. Buscheck, J. Brotschi, A. Mateos, D. Jones, and S. Pourtahmasb. 2023. “Laboratory Performance and Construction Challenges for Plant-Produced Asphalt Mixes Containing RAP and RAS.” *Construction and Building Materials* 403: 133082. https://doi.org/10.1016/j.conbuildmat.2023.133082.

Roberts, R. E., et al. 2025. *Probability & Statistics for Engineers & Scientists: MyStatLab Update* (9th ed.). Pearson.

Rowe. 2011. "Evaluation of the Relationship Between Asphalt Binder Properties and Non-Load Related Cracking." *Journal of the Association of Asphalt Paving Technologists*, Prepared Discussion, 80, 615–664.

Tarsi, G., P. Tataranni, and C. Sangiorgi. 2020. "The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review." *Materials* 13(18): 116968. https://doi.org/10.3390/ma1318116968.

Walpole, R. E., R. H. Myers, S. L. Myers, and K. Ye. 2017. *Probability & Statistics for Engineers & Scientists: MyStatLab Update* (9th ed.). Pearson.

Yazdipanah, F., M. Khedmati, and H. F. Haghshenas. 2023. *Nebraska Balanced Mix Design—Phase I.* SPR-FY22(002). Nebraska Department of Transportation.

Zeng, Z., B. S. Underwood, and C. Castorena. 2022. "Low-Temperature Performance Grade Characterisation of Asphalt Binder Using the Dynamic Shear Rheometer." *International Journal of Pavement Engineering* 23(3): 811–823. https://doi.org/10.1080/10298436.2020.1774766.

Zhou, F. 2019. *Development of an IDEAL Cracking Test for Asphalt Mix Design, Quality Control and Quality Assurance.* NCHRP IDEA Project 195. Transportation Research Board, Washington, D.C.

APPENDIX A: DETAILED LITERATURE REVIEW

A.1. Introduction

The literature review intended to identify best practices and state agency specifications for RAP and RAS stockpile management, quality control/assurance, and virgin binder selection. In addition, research was reviewed on the impacts of RAP and RAS variability on the performance of asphalt mixtures. This literature review encompasses papers, reports, and a representative set of state specifications. Figure 30 depicts the 18 state agency specifications about RAP and RAS that were reviewed. The selection of states provides geographic coverage of the U.S. and includes all states surrounding North Carolina.

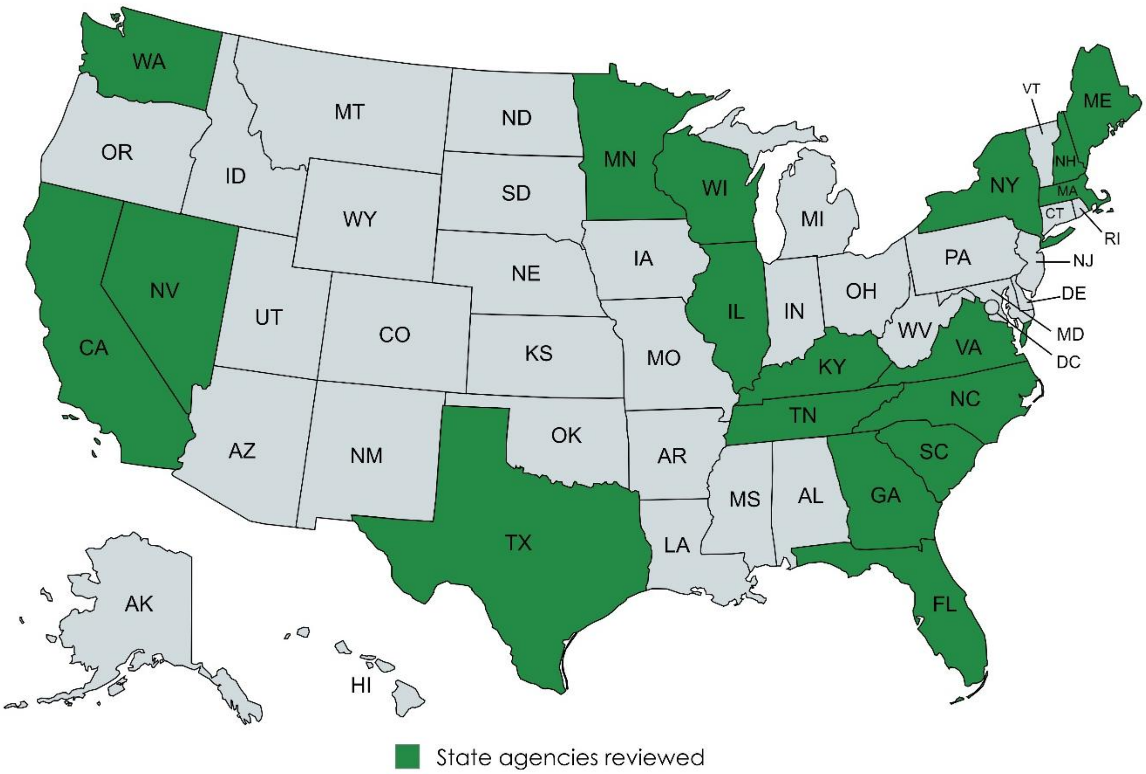


Figure 30. State agencies reviewed for RAP and RAS stockpile management

A.2. Quality Control Practices for RAP and RAS

To ensure the consistency of RAP materials, West et al. recommend measuring the asphalt content and recovered aggregate gradation for each 1,000 tons of RAP used, a frequency higher than that typically required for virgin aggregates (West 2015). West 2015. suggested maximum standard deviations for quality control (QC) of 0.5 percent for asphalt content and 5 percent for both the material passing the median sieve and 1.5 percent for the material passing the 0.075 mm sieve. The NCDOT Asphalt Quality Management System (QMS) manual requires one set of asphalt content and gradation measurements of RAP and RAS at the start of production and weekly thereafter (NCDOT 2024a). Table 12 andTable 13 summarize the RAP properties, RAS properties, and sampling frequency requirements for QC in the 18 states surveyed. Note that not all the states surveyed permit RAS. The survey results demonstrate that all the other states surveyed require gradation and asphalt content measurements for RAP and RAS. Some states have additional requirements, and sampling frequency requirements vary. Nevada (NDOT 2014), California (Caltrans 2023), Florida (FDOT 2024), and New Hampshire (NHDOT 2016) do not allow RAS in asphalt mixtures.

New York (NYDOT 2022, NYDOT 2015) and South Carolina (SCDOT 2007) include other testing requirements, such as moisture content, as part of the RAP and RAS characterization requirements. Similarly, Illinois (IDOT 2021) and Florida (FDOT 2024) require routine theoretical maximum specific gravity (G_{mm}) testing. Texas (TxDOT 2024) and Nevada (NDOT 2014) further include requirements for measuring the recycled material gradation, also known as the black curve, but only for processed RAS (in Texas, using dry sieve analysis under Tex-200-F) and RAP material (in Nevada). Furthermore, Nevada (NDOT 2014) requires analysis of the aggregate extracted from the RAP material gradation by test method AASHTO T 30. Texas (TxDOT 2024) also incorporates testing of decantation and plasticity index for the RAP and RAS materials. Georgia (GDOT 2021), Virginia (VDOT 2020), Washington (WSDOT 2024), and Tennessee (TDOT 2021) require additional testing to detect the presence of asbestos in RAS.

Table 11. RAP Property Requirements by State

STATE DOT	RAP gradation	Binder content	Recovered aggregate gradation	Moisture content	G_{mm}	Decantation
Nevada	X	X	X			
New York		X	X	X		
Georgia		X	X			
New Hampshire		X	X			
Texas		X	X			X
South Carolina		X	X	X		
North Carolina		X	X			
Virginia		X	X			
California		X	X			
Illinois		X	X		X	
Florida		X	X		X	
Massachusetts		X	X			
Minnesota		X	X			
Maine		X	X			
Kentucky		X	X			
Tennessee		X	X			
Wisconsin		X	X			
Washington		X	X			

Table 12. RAS Property Requirements by State

STATE DOT	RAS gradation	Binder content	Recovered aggregate gradation	Moisture content	G_{mm}	Asbestos containing material	Decantation
New York		X	X	X			
Georgia		X	X			X	
Texas	X	X	X				X
South Carolina		X	X	X			
North Carolina		X	X	X			
Virginia		X	X			X	
Illinois		X	X		X		
Minnesota		X	X				
Kentucky		X	X				
Tennessee		X	X			X	
Wisconsin		X	X				
Washington		X	X			X	

Table 13. Sampling Frequency Requirements by State

STATE DOT	RAP	RAS
	Minimum Sampling Frequency	Minimum Sampling Frequency
Nevada	1 sample per 500 tons	NA
New York	1 sample per day during production	1 sample per day during production
Georgia	1 sample per 1000 tons	1 sample per 1000 tons
New Hampshire	1 sample per 1000 tons	NA
Texas	As directed by Engineer	As directed by Engineer
South Carolina	1 sample per 1000 tons, 2 moisture content per day	1 sample per 1000 tons, 2 moisture content per day
North Carolina	Beginning of production and weekly thereafter	Beginning of production and weekly thereafter
Virginia	Minimum 1 sample per stockpile	Minimum 1 sample per stockpile, PLM 1 per 750 tons

STATE DOT	RAP	RAS
	Minimum Sampling Frequency	**Minimum Sampling Frequency**
California	1 per lot (500 tons)	NA
Illinois	1 sample per 500 tons (for the first 2000 tons), later 1 sample per 2000 tons	1 sample per 200 tons (for the first 1000 tons), later 1 sample per 500 tons, or 1 per week
Florida	1 sample per 1000 tons and 1 sample per 5000 tons for Gmm	NA
Massachusetts	As indicated in the QC plan	NA
Minnesota	2 samples per source	2 samples per source
Maine	1 sample per 500 tons	NA
Kentucky	Every two lots of mixture produced	Every two lots of mixture produced
Tennessee	Beginning of a project and every 2000 tons thereafter	Beginning of a project and every 2000 tons thereafter for binder content and aggregate gradation and every 500 tons for asbestos containing material
Wisconsin	1 sample per 600 tons	1 sample per 600 tons
Washington	1 sample per 1000 tons	1 sample per 100 tons for binder content and recovered aggregate gradation and 1 sample per 500 tons for asbestos containing material

Figure 31 and Table 14 convey the method used by each state to determine the asphalt content of the recycled materials. Of the 18 investigated state agency requirements reviewed, six of them require the use of an ignition oven, in accordance with AASHTO T 308 (2021), to determine the asphalt content of the RAP and RAS materials. Only three of the states reviewed require solvent extraction, following the procedure specified in AASHTO T 164 (2024), and eight permit the use of either method to determine the asphalt content.

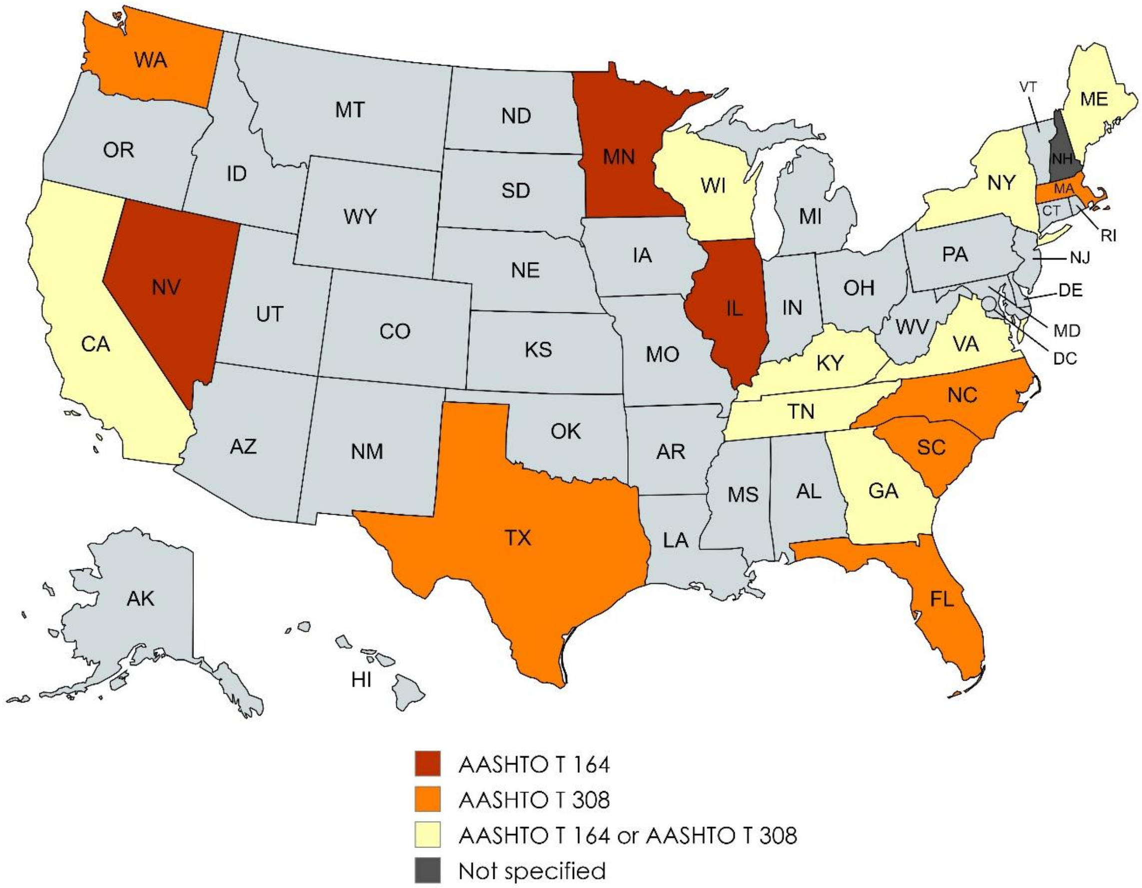


Figure 31. Asphalt content determination method for recycled materials.

Table 14. Asphalt Content Determination Method by State

STATE DOT	Asphalt Content Determination Method	
	AASHTO T 164 (Solvent Extraction)	AASHTO T 308 (Ignition Oven)
Nevada	X	
New York	X	X
Georgia	X	X
New Hampshire	Not specified	Not specified
Texas		X
South Carolina		X
North Carolina		X
Virginia	X	X
California	X	X
Illinois	X	

STATE DOT	Asphalt Content Determination Method	
	AASHTO T 164 (Solvent Extraction)	**AASHTO T 308 (Ignition Oven)**
Florida		X
Massachusetts		X
Minnesota	X	
Maine	X	X
Kentucky	X	X
Tennessee	X	X
Wisconsin	X	X
Washington		X

A.3. Stockpiling, Processing, and Fractionation

The National Asphalt Pavement Association (NAPA) best practices for RAP and RAS management were reviewed to identify key methods to reduce the RAP and RAS variability. 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 2015).

On the other hand, 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). Additionally, it is recommended that the stockpiles should be covered to avoid excessive water (Zhou et al. 2012).

Furthermore, NAPA advises that RAP and RAS should be stockpiled separately. Separating stockpiles for material sourced from a given project is recommended if possible, considering the space available at the plant. 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. Additionally, if the source of recycled material in a given stockpile changes from the one used to design the mixture, testing of the binder content and gradation should be performed to verify its compatibility with the current mix design (West 2015).

Past research with North Carolina materials has demonstrated that the properties of RAP stockpiles across the state vary significantly in terms of gradation and asphalt content (Khosla and Ramoju 2017). To reduce and control this variability, the NCDOT requires the processing of the RAP to eliminate clusters of material bigger than 25 mm, whereas RAS must be finer than 9.5 mm. Screening before crushing is required for processed RAP. In most cases, RAP is crushed and screened to either a maximum size of 1/2 in or 3/8 in to produce material with a suitable top size to use in new asphalt mixtures. Crushing to smaller max sizes will increase the dust content and limit the amount of RAP that can be used in a new mix design, which is another important consideration (Khosla and Ramoju 2017). Finally, blending or mixing of RAP sources before processing contributes to uniformity.

Additionally, NCDOT requires the fractionation of RAP into fine and coarse components when the RAP content of a mixture exceeds 30 percent (NCDOT 2024b). This fractionation process is used to minimize the segregation of RAP particle sizes. It is a practice where processed RAP is divided into different-size fractions, which yields better consistency and more flexibility to achieve blended gradation requirements.

Regarding RAP and RAS processing, handling, and storing, the range of state specifications is summarized by the examples below:

- Nevada allows one or more stockpiles of uniform, crushed and processed RAP. They require that 100 percent of the processed RAP passes the 12.5-mm sieve. Additionally, they specify that RAP may replace 5 to 15 percent by mass of the total aggregate in two types of surface mixtures (NDOT 2014).
- New York indicates that a stockpile of RAP or RAS should be on free-draining and clean bases, assuring that these materials are not contaminated. When using RAS, the maximum allowed RAS content in the mixture is 2 percent by weight of the total mixture. RAS must be uniformly blended with RAP before introduction to the plant to reduce clumping and needs to be stockpiled separately from other stockpiles (NYDOT 2022, NYDOT 2015).
- Georgia specifies that stockpiles should be separated by project sources and by aggregate types. The aggregates are divided into two groups: i) Group I, which includes limestone, dolomite, marble, or a combination thereof, and ii) Group II, which includes gravel, granite and gneissic rocks, quartzite, or a combination thereof. It is not allowed to use RAP materials that contain local sand or alluvial gravel in any mixture placed on interstate projects. For non-interstate projects, the RAP content in recycled mixtures is limited by the overall amount of alluvial gravel, which cannot exceed 5 percent of the total mix. Also, the maximum RAP content by weight of the total mixture is 40 percent for continuous drum mix-type plants and 25 percent for batch-type plants. Processed RAP material must pass the 2 in (50 mm) sieve. Regarding RAS, a maximum of 5 percent by weight of the total mixture weight is allowed. The RAS should be shredded before incorporating it into the mix to ensure that 100 percent of the shredded pieces are less than 1/2 in (12.5 mm) in any dimension (GDOT 2021).
- New Hampshire establishes different considerations for handling RAP depending on the total reused binder percentage (TRB). The TRB reflects the RAP binder content as a percentage of the total mixture weight. The maximum allowable TRB is 1.5 percent. For designs containing a TRB greater than 1 percent, RAP stockpiles must be covered by a roof and are only allowed in drum mixers, specifically for binder and base courses (NHDOT 2016).
- Texas allows the use of fractionated RAP, which is defined as a stockpile containing RAP material with at least 95 percent passing through a ½ in. sieve before burning in the ignition oven. For RAS, up to 3 percent may be used separately or as a replacement for fractionated RAP. The specification allows the processing of the RAS by ambient grinding or granulating such that 100 percent of the particles pass the 3/8 in. sieve. One important criterion in this specification is to perform sieve analysis on processed RAS material before extraction (or ignition) of the asphalt binder. Additionally, they allow adding sand or fine RAP to RAS stockpiles if needed to keep the processed material workable (TxDOT 2024).
- South Carolina requires the processing of RAP so that 100 percent of the material passes 2 in. screens before entering the plant. Also, particles retained in the 2 in. screens may be re-crushed but ensure that it does not result in further degradation of the aggregate. This specification requires the separation of stockpiles by categories, and these stockpiles may be replenished

with RAP from sources by the same category. Regarding RAS, the maximum allowed is 8% by total weight of the aggregate, and they shall be shredded shingles produced by ambient temperature grinding processes. Shingles of multiple types and sources can be combined if the blend meets the gradation requirements (SCDOT 2007).

- Virginia requires the processing of RAP to ensure that the maximum particle size is 2 in. The Engineer may require smaller-sized particles to be introduced into the mix if the RAP particles are not broken down or uniformly distributed in the mixture during heating and mixing. VDOT has distinct specifications for Tear-off RAS and manufactured waste RAS. Tear-off RAS consists of discarded shingle scrap from re-roofing projects, whereas Tabs RAS originates from the manufacturing process of roofing shingles. For Tear-off, the material shall be shredded before incorporating into the mixture, where a minimum of 99 percent shall pass a ½ in. (12.5 mm) sieve, and a minimum of 80% must pass the #4 sieve (4.75 mm). For Tabs RAS, the material shall be shredded before incorporating it into the mixture so that 100 percent shall pass ½ in. (12.5 mm) in any dimension. All materials shall be stockpiled in a way that prevents contamination. For RAS materials, the stockpiling may be either whole or partial shingles that have not been shredded or shredded shingles that meet the size particle requirements. Also, they allow the blending of the shingles with fine aggregate to prevent conglomerations upon processing (VDOT 2020).
- California allows using up to 25 percent RAP by mass of the aggregate blend. A clean, graded base in a well-drained area is required for stockpiles. If RAP is acquired from multiple sources, the RAP shall be blended thoroughly and completely before processing. For mixtures with greater than 15 percent RAP by mass of the aggregate blend, RAP must be fractionated into 2 sizes: a coarse fraction RAP retained on a 3/8-inch sieve and a fine fraction RAP passing a 3/8-inch sieve (Caltrans 2023).
- Illinois defines four types of RAP stockpiles, which are summarized in Table 15. Note that 'Class I HMA' corresponds to hot-mix asphalt (HMA) used in low and high-volume travel lanes, and aggregate type 'C' quality requirements are more stringent than type 'D' within Illinois DOT specifications. Table 15 shows that the Illinois DOT RAP types vary in terms of the sources of the RAP in a given stockpile, constituent properties before processing, and post-processing property requirements. Table 15 indicates that fractionated and homogenous types of RAP stockpiles must meet additional consistency requirements in terms of source properties and post-processing properties compared to the conglomerate types. Illinois DOT requires the use of fractionated or homogeneous RAP in surface mixtures but also allows conglomerate in intermediate and base layers. Conglomerate D is only allowed in shoulders and subbases (IDOT 2021).

Table 15. Illinois DOT RAP Stockpile Types

Type	Source Requirements	Processing Requirements
Fractionated	● Class I HMA ● May include multiple aggregate types and quality but collectively aggregate must meet C quality	● Agglomerations minimized such that all material passes max sieve size in mix design ● Fractionate by screening into a minimum of two sizes
Homogeneous	● Class I HMA ● Sources must include the same aggregate type and quality, similar gradation, and similar binder content	● Agglomerations minimized such that all material passes max sieve size in mix design
Conglomerate	● Class I HMA ● May encompass more than one aggregate type and quality ● Sources may have inconsistent gradation and asphalt content	● All RAP must pass the 5/8 in (16 mm) screen after crushing
Conglomerate D	● Class I HMA and/or HMA from shoulders, bituminous stabilized subbases ● Sources may have inconsistent gradation and asphalt content	● Achieve D quality aggregate requirements after crushing

- Florida limits the amount of RAP material used in the mix to a maximum of 20 percent by weight of the total aggregate. RAP material shall have a minimum average asphalt binder content of 4.0 percent by weight of RAP. As an exception, the minimum average asphalt binder content for the coarse portion of fractionated RAP shall be 2.5 percent (FDOT 2024).
- Massachusetts requires that RAP and RAS shall be stockpiled, separated from other aggregates, and covered to prevent the intrusion of water while allowing the flow of air. The maximum permitted RAP content in surface course mix types is 15 percent by weight of the total mixture, while for intermediate and base courses, it is 40 percent. RAS can only be used in HMA base, HMA intermediate, and HMA leveling courses, with a maximum content of 5 percent by weight of the total mixture. Only the by-product materials obtained from the roofing shingle manufacturing process are permitted and not post-consumer RAS (MassDOT 2023).
- Maine classifies the RAP into three categories (Class I, II, and III) depending on the asphalt content standard deviation, percentage passing the 0.075 mm sieve, and residual aggregate micro-deval (M-D) loss value, as shown in Table 16. According to this classification scheme, RAP is separated into stockpiles based on class. The maximum percentage of RAP by weight of the total mixture allowed depends on its category. Additionally, the specification allows the contractor to use up to two different RAP sources in any one mix design (MaineDOT 2020).

Table 16. Maine DOT RAP Content Limits

Classification	Maximum RAP Percentage Allowed	Asphalt content standard deviation	Percent passing 0.075 mm sieve standard deviation	Percent passing 0.075 mm sieve / asphalt content ratio	Residual aggregate M-D loss value
Class III	10%	≤ 1.0	N/A	≤ 4.0	≤ 18
Class II	20%	≤ 0.5	≤ 1.0	≤ 2.8	
Class I	30%	≤ 0.3	≤ 0.5	≤ 1.8	

- Minnesota allows the inclusion of RAP and RAS in plant-produced asphalt mixes. However, recycled materials are not allowed in ultra-thin bonded wearing courses, micro-surfacing, permeable asphalt stabilized stress relief courses, and permeable asphalt stabilized bases. Additionally, the RAS may be manufactured from waste scrap asphalt shingles (MWSS) or tear-off scrap asphalt shingles (TOSS), but it is required to keep separate stockpiles for MWSS and TOSS. The contractor is authorized to blend RAS with virgin sand material to minimize agglomeration (MnDOT 2020).
- Kentucky allows the use of RAP and RAS in hot mix asphalt and warm mix asphalt. The RAP must come from Department projects or other approved sources. RAS can be either pre-consumer (manufacturing waste or new) or post-consumer reclaimed shingles that have been processed to ensure all material passes through a 3/8-inch sieve. RAP and RAS of different asphalt binder content, gradation, asphalt binder properties, and aggregate properties must be kept always separated, including during stockpiling and feeding. The maximum allowable RAP content is 20 percent for surface mixtures and 30 percent for base mixtures for RAP-only mixtures. For RAS-only mixtures, the maximum allowable RAS content is 5 percent. For mixtures containing both RAP and RAS, the permissible content is 10 percent RAP and 3 percent RAS for surface mixtures, and 12 percent RAP and 4 percent RAS for base mixtures (KYTC 2019).
- Tennessee allows the use of RAP and RAS in hot mix asphalt for constructing base and surface layers. The maximum allowable RAS content is 3 percent by total weight of the mixture for both base and surface layers. On the other hand, RAP can constitute up to 35 percent of the base layer mix and 20 percent of the surface layer mix, except for 35 percent for shoulders. It's important to note that the permissible RAP content also varies depending on the specific type of mix and the processing methods the RAP has undergone, as shown in Table 17. Furthermore, the ratio of added new virgin asphalt binder to the total asphalt binder in the mix shall be 65 percent or greater for base layers and 80 percent or greater for surface layers. The RAP must be removed from the Department or other State Highway Agency projects and stored in a department approved stockpile. The RAS must be stockpiled separately from other salvage material. Manufacture waste scrap shingles (MWSS) and tear-off scrap shingles (TOSS)

should not be blended. Additionally, processed shingles should not be blended with virgin sand (TDOT 2021).

Table 17. Tennessee DOT RAP content limits for surface layers

Mix Type	% RAP (Non-processed)	Maximum % RAP (Processed)	Maximum % RAP (Processed and Fractionated)	Maximum Particle Size (inch)
411D (PG64-22, PG67-22)	0	15	20	½
411D (PG70-22, PG76-22, PG82-22)	0	10	15	½
411E & 411TLE (Roadway)	0	15	20	½
411E & 411TLE (Shoulder)	15	30	35	½
411TL (PG64-22, PG67-22)	0	15	15	5/16
411TL (PG70-22, PG76-22, PG82-22)	0	10	10	5/16
411TLD (PG64-22, PG67-22)	0	15	15	5/16
411TLD (PG70-22, PG76-22, PG82-22)	0	10	10	5/16

- Wisconsin allows the use of RAP and RAS in hot mix asphalt and requires the separation of RAP and RAS stockpiles from virgin materials. The maximum allowable number of recycled materials in HMA is limited by the percent binder replacement (PBR). For RAS-only mixtures, the maximum allowable PBR is 25 percent for lower layers and 20 percent for upper layers. For RAP-only mixtures, the maximum allowable PBR is 40 percent for lower layers and 25 percent for upper layers. For RAP-RAS mixtures, the maximum allowable PBR is 35 percent for lower layers and 25 percent for upper layers. Additionally, the maximum allowable percentage of RAS is 5 percent by weight of the total mixture when used in combination with RAP (WisDOT 2024).
- North Carolina states that each type of RAP/RAS material should be stockpiled separately. However, it is permissible to combine RAP/RAS from different sources when the material is processed and/or uniformly blended during the stockpiling and before its sampling and testing. In addition, the specification does not permit adding extra material to any approved RAP/RAS stockpile unless otherwise approved by the Engineer. It is also specified that the use of RAP is not allowed in open-graded friction course (OGFC) mixes or Ultra-thin bonded wearing courses (UBWC); the use of RAS is not permitted in UTBWC. The maximum allowable

number of recycled materials is limited by the recycled binder replacement percentage (RBR%) as shown in Table 18. When the RAP content exceeds 30 percent by weight of the total mixture, fractionated RAP must be used. The maximum amount of RAS material by weight of mix permitted is 6 percent, except for OGFC mixes, where the limit is 5 percent (NCDOT 2024a, NCDOT 2024b).

Table 18. North Carolina DOT RAP and RAS content limits

Maximum recycled binder replacement percentage (RBR%)			
Recycled material	**Intermediate and base mixes**	**Surface mixes**	**Mixes using PG 76-22**
RAS	23%	20%	18%
RAP or RAP/RAS combination	45%	40%	18%

- Washington classifies mix designs containing RAP and RAS into two categories: (i) low RAP/no RAS, with RAP between 0 and 20 percent and RAS equal to 0 percent, and (ii) high RAP/any RAS, with RAP between 20 percent and the maximum allowable amount, and RAS between 0 percent and the maximum allowable amount. The maximum allowable amount of RAP and/or RAS in HMA mixes is limited by the amount of binder contributed by the RAP and/or RAS, as specified in Table 19. For mix designs with high RAP/any RAS, a single stockpile for RAP and a single stockpile for RAS must be constructed and isolated from further stockpiling before beginning the development of the mix design (WSDOT 2024).

Table 19. Washington DOT RAP and RAS content limits

Maximum amount of binder contributed from the recycled material	
RAP	RAS
40% minus contribution of binder from RAS	20%

A.4. Virgin Binder Selection and RBR% Specifications

Virgin binder specification according to the recycled material content or recycled binder replacement percentage (RBR%) and/or the recycled material type is another measure used to mitigate variability in the performance of recycled asphalt mixtures. AASHTO M 323 (2022), which specifies Superpave volumetric mix design, provides the virgin binder selection guidelines presented in Table 20 for RAP mixtures. The AASHTO M 323 (2022) guidance was derived from NCHRP Project 09-12 findings from studying the impacts of RAP on blended binder and mixture performance characteristics (McDaniel and Anderson 2001) and NCHRP Project 09-46 (Wes et al. 2013). The specifications pertain to the RAP percentage by total weight of mixture or RBR%. Total RAP percentage provides less control of blended binder properties than the RBR% since RAP binder content can vary. Also, the AASHTO M 323 (2022) guidance recommends following a blending chart when the RAP content exceeds 25 percent. A blending chart is used to calculate the RBR% when virgin binder properties are known, or , to select the appropriate virgin binder grade at a specific RBR%. The blending chart is represented by Equation (7) as follows:

$$T_{\text{virgin}} = \frac{T_{\text{blend}} - (\text{RBR} \times T_{\text{RAP}})}{1 - \text{RBR}} \tag{7}$$

where: T_{virgin} = critical temperature of virgin asphalt binder (high, intermediate, or low); T_{blend} = critical temperature of blended asphalt binder (final desired) (high, intermediate, or low); RBR = weight of RAP divided by total weight of binder; T_{RAP} = critical temperature of recovered RAP binder (high, intermediate, or low).

Creating a blending chart requires the use of solvent extraction and recovery of the RAP binder with subsequent performance-graded characterization of the recovered binder properties, which is generally deemed too costly and time-consuming to be practical to perform on a routine basis. These factors are likely what is driving some of the relatively low RAP content limits imposed by states described in the previous section.

Table 20. Virgin Binder Selection for RAP Mixtures According to AASHTO M 323 (2022)

Recommended Virgin Asphalt Binder Grade	RAP Percentage
No change in binder selection	<15
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)	15 to 25
Follow recommendations from blending charts	>25

Many states have developed specific requirements for virgin binder selection according to the RBR% (defined in Equation (8)), informed by an evaluation of the properties of RAP and/or RAS binders within their state. NCDOT followed this practice, resulting in the RBR% limits shown in Table 18 and Table 21.

$$RBR = \frac{(Pb_{RAP} \times P_{RAP}) + (Pb_{RAS} \times P_{RAS})}{100 \times Pb_{total}} \tag{8}$$

where: Pb_{RAP} = binder content of the RAP; P_{RAP} = percentage of RAP by weight of mixture; Pb_{RAS} = binder content of the RAS; P_{RAS} = percentage of RAS by weight of mixture; Pb_{total} = total binder content of the mixture.

Table 18 shows that the maximum RAP or RAP/RAS RBR% allowed to use in surface mixtures is 40 percent, and only 20 percent for mixtures with only RAS. Furthermore, NCDOT specifies virgin binder grade requirements depending on the mixture type and the RBR%, as indicated in Table 21. The specification requires using a PG 64-22 for RAP only mixtures with a maximum RBR% of 30 percent, and the use of a PG 58-28 virgin binder when the RBR% exceeds 30 percent for A, B, and C mixtures. Moreover, the maximum RBR% is 18% for mixes using virgin binder

PG 76-22. The NCDOT (2024) also stipulates that when the RBR% exceeds 20 percent and the mixture contains RAS that a PG 58-28 is used.

Table 21. Virgin Binder Grade Requirements based on RBR% According to NCDOT QMS

Mix Type	RBR% ≤ 20%	21% ≤ RBR% ≤ 30%	RBR% > 30%
S4.75A, S9.5B, S9.5C I19.0C, B25.0C	PG 64-22	PG 64-22	PG 58-28
S9.5D, OGFC	PG 76-22 B	n/a	n/a

AASHTO M 323 (2022) recommended using a blending chart to set the RBR% limits and selecting virgin binders when the RAP content exceeds 25 percent. However, states have used different approaches to set their allowable RAP and RAS content limits and virgin binder grade specifications. Therefore, relevant literature was reviewed to understand how different states use various methods to establish or critically evaluate RAP and RAS content limits.

NCDOT RP 2012-04 (Khosla et al. 2015) proposed maximum RBR% limits based on the characterization of blended binders' rheological properties. The researchers selected two representative virgin binders in North Carolina, PG 64-22 and PG 58-28, and three recycled materials, including RAP, MRAS (Manufacturer Waste Recycled Asphalt Shingles), and PRAS (Post-consumer Recycled Asphalt Shingles). Binders from recycled materials were extracted and blended with two virgin binders separately in different proportions as shown in Table 22, where the percentage represents the proportion of extracted binder by weight of total blended binder. For each blended binder, rolling thin film oven (RTFO) test and pressure aging vessel (PAV) test were conducted to simulate short-term aging and long-term aging of the material. The unaged level, RTFO aged level, and PAV aged level blended binders were tested on the Dynamic Shear Rheometer (DSR) to determine their rheological properties, including dynamic shear modulus (G^*) and phase angle (δ) at varying temperatures. Blending charts were created based on these rheological properties to determine the RAP binder limits that could be used in the pavement mixtures. The minimum limit of RAP binder content was determined from the blending charts at high temperatures, using $G^*/\sin(\delta) \geq 1.0$ kPa and $G^*/\sin(\delta) \geq 2.2$ kPa for unaged and RTFO aged binders, respectively. The maximum limit was determined from the blending charts at intermediate temperatures, using $G^*\sin(\delta) \leq 5000$ kPa for PAV aged binders. From the limits determined through the blending charts, the recycled binder limits that meet the specifications of a PG 64-22 binder concerning both high and intermediate temperatures are shown in Table 23. Table 24 shows the suggested limits for S9.5B mixtures, with conservative rounding to the nearest 5%.

Table 22. Binder Blends Matrix

Virgin Binder	RAP	MRAS	PRAS
PG 58-28	25%, 40%, 100%	10%, 20%	10%, 25%
PG 64-22	25%, 40%, 100%	10%, 20%	10%, 25%

Table 23. Minimum and Maximum Limits of Recycled Binders to Meet PG 64-22

Virgin Binder	Recycled Binder	High Temperature (Minimum)	Intermediate Temperature (Maximum)
PG 58-28	RAP	21.6%	42.9%
	MRAS	23.5%	56.3%
	PRAS	5.4%	26.8%
PG 64-22	RAP	12.1%	20.5%
	MRAS	15.1%	41.9%
	PRAS	4.3%	11.1%

Table 24. Recycled Binder Limits for S9.5B Mixes

Recycled Binder	Virgin Binder	Maximum Limits (% Binder)
RAP	PG 58-28	45%
	PG 64-22	20%
MRAS	PG 58-28	55%
	PG 64-22	40%
PRAS	PG 58-28	25%
	PG 64-22	10%

The limits derived from blended binders' rheological properties were validated through performance tests on RS9.5B mixes designed and fabricated in the laboratory. These mixes contained the same content of recycled materials and corresponding virgin binder as listed in Table 24, with adjustments made to virgin aggregate and virgin binder content to account for the contributions from RAP. Each mixture was tested using the Asphalt Mixture Performance Tester (AMPT) to measure dynamic modulus, with results then input into AASHTOware Pavement ME Design software to estimate fatigue and rutting life for comparison with virgin mixtures. The recycled and virgin mixtures demonstrated satisfactory performance in the AASHTOware Pavement ME simulations, and thus, the final recycled binder limits for RS9.5B mixes remained consistent with those presented in Table 24.

NCDOT RP 2014-05 (Khosla and Ramoju 2017) further assessed the impacts of RAP binder properties in the state to inform the NCDOT's RBR% specifications. The researchers characterized the high- and intermediate-performance-graded properties of 27 RAP binders acquired from 9 different stockpiles across the state, in unaged, RTFO and PAV aged conditions. The authors leveraged the results to identify the range of acceptable RBR% levels for use with PG 64-22 and PG 58-28 virgin binders, which are listed in Table 25. The RAP binder characterized demonstrated considerable variability with continuous high temperature grades ranging from 82 to 112°C, leading to the relatively wide ranges in applicable RBR% levels in Table 15.

Table 25. Proposed RBR% Limits for RAP According to NCDOT RP 2014-05

Virgin Binder	By RBR%	By weight of Mix
PG 64-22	0% - 17.7%	0% - 21.2%
PG 58-28	8.8% - 47.3%	10.6% - 56.8%

While the past NCDOT RP 2012-04 and RP 2014-05 proposed the RBR% limits based on blended binders' rheological properties and mixture performance, NCDOT RP 2014-05 adjusted RAP RBR% limits by considering the variability of RAP binders. However, the variability of virgin binders in the state was not considered in either of these two studies.

Austerman et al. (2018, 2020) conducted a study to evaluate the variability of RAP stockpile and virgin binder properties being used in Massachusetts. Eight RAP producers and four regional virgin binder suppliers were evaluated, encompassing variation among stockpiles and year-to-year variation for specific stockpiles. Greater variabilities were observed among RAP stockpiles than within specific stockpiles. Virgin binders from four regional suppliers met the PG 64-28 grade requirements. However, the continuous low-temperature grades varied among these binders. While three suppliers provided binders with continuous low-temperature grades around -30°C, the binder from the fourth source showed a continuous low-temperature grade very close to the -28°C threshold. This near-threshold performance compromised its ability to accommodate RAP in asphalt mixtures without exceeding specified properties. The accuracy of the blending chart equation was verified by preparing four blended binders, combining one virgin binder with recovered RAP binders from four different sources. The low-temperature continuous grade was measured for each of these blended binders. Results indicated that the equation's predictions were accurate only at lower RAP percentages. Overall, considering the variability in both RAP and virgin binders, the predicted blended binder grades showed cases that failed intended property limits at currently permissible RBR% levels. Using the blending chart equation, only 71% of the blended binder combinations achieved the specified PG 64-28 grade, despite having a relatively low RAP content of 15% by dry weight of mixture.

Mogawer et al. (2016) conducted another study for MassDOT to assess the impact of higher percentages of RAP in asphalt mixtures and confirmed the benefit of softer binders for mixture performance. The study used two virgin binders, including PG 64-28, which is commonly used in the Northeast, and a softer PG 52-34. The aggregates and RAP were from the same plant. The mixtures were designed and fabricated in the laboratory, with a 9.5-mm NMAS. Different RAP contents were evaluated as shown in Table 26.

Table 26. RAP Content for Mixture Design

Binder	%RAP
PG 64-28	0% - Control
	15%
	25%
	35%
	50%
PG 52-34	35%
	50%

The study evaluated both recovered binder properties and mixture performance. Recovered binders were extracted and recovered from the RAP mixtures and thus constituted the blend of RAP and virgin binder. The study analyzed the rheological black space diagram, R-value, and crossover frequency. Results showed that using softer virgin binder helped reverse the increased cracking susceptibility observed when RAP content was increased to 35% and 50%. The aging-induced stiffness was effectively mitigated by the softer binder. Regarding mixture performance, the study conducted the Hamburg wheel tracking test and the flexural beam fatigue test. Results illustrated the impact of the softer binder in mitigating the stiffness of mixtures containing 35% and 50% RAP, as shown by increased rutting susceptibility and fatigue cracking resistance compared to the PG 64-28 mixtures. The study concluded that Superpave 9.5 mm mixtures could be designed with up to 50% RAP with the same binder content and gradation as a control mixture with 0% RAP based on volumetric design criteria. However, using the softer PG 52-34 virgin binder yielded a mixture with more rutting susceptibility at both RAP contents of 35% and 50% compared to the PG 64-28 control mixture. The mixtures with PG 52-34 binder did not meet MassDOT rutting test requirements. Therefore, the authors concluded that the use of higher percentages of RAP in HMA must be carefully developed for each specific mixture based on the properties of the RAP, the amount of RAP, and the available virgin binders.

One limitation of relying on blending charts is that the approach assumes complete blending between the recycled and virgin binder. To address this concern, Stephens et al. (2001) conducted a study for the Connecticut DOT to develop a simple physical testing procedure to determine the effective blended binder grade in asphalt mixtures with RAP. The study collected aggregate, PG 64-28 and PG 58-34 virgin binders, and RAP from a Connecticut mix plant. The determination of binder content within the RAP material and the RAP aggregate recovery was conducted using the ignition oven. One aggregate structure was chosen and maintained throughout each specimen. Half of the mix specimens contained 15% RAP, and half contained 15% reclaimed RAP aggregate. Virgin materials and reclaimed RAP aggregate were batched and mixed in the laboratory. The specimens were subjected to the indirect tension test at 28°C and 3°C for correlation with high-temperature and low-temperature blended binder grades, respectively. For high temperature grade, the study first created a plot correlating the average tensile load measured at 28°C with the high temperature grade for specimens containing only virgin binder. Then, assuming a linear relationship between the virgin specimen average tensile loads and high-temperature grade, interpolation or extrapolation was used to obtain the effective high PG grade of the combination of RAP and virgin binder. A similar process was used to infer the low temperature grade. The effects of testing temperature, RAP content, and aggregate source were also investigated to confirm that the test method is effective. The authors found that the effective PG of the mixture depends on RAP content but was not substantially impacted by aggregate source, gradation, or conditioning temperature. The authors also compared laboratory and plant mixture, which yielded unexpected trends indicating an effective PG in the plant mix exceeding what would result from complete blending. However, the authors attributed this to potential aging differences between laboratory and plant aging. While the results were not used to directly inform RBR% limits, they highlight the potential impacts of partial recycled binder contribution on effective binder properties of asphalt mixtures.

Tavakol et al. (2016) researched for the Kansas DOT to study the effect of incorporating RAP and RAS on the performance of hot-mix asphalt mixtures and tried to identify the minimum virgin binder contents (in other words, 100 – RBR%) that would result in mixture performance meeting standards. The study selected three KDOT mixture designs from two projects in Kansas as control mixtures. The first mixture design was a surface layer mixture designated as US-59-surface, which used aggregates with a 9.5-mm Nominal Maximum Aggregate Size (NMAS). The other two were intermediate course mixtures using a 19-mm NMAS, one designated as US-59-intermediate, the other designated as US-36-intermediate. All three control mixture designs contained 15% recycled materials by weight of total mixture, with US-59-surface and US-59-intermediate containing 5% RAS, while US-36-intermediate contained only RAP. To compare the impact of different recycled materials content while satisfying KDOT requirements for aggregate gradation, different percentages of recycled materials were chosen for each mixture design. The virgin binder grade was adjusted based on blending charts to achieve the intended blended binder grade, and the RBR% was calculated by considering the weight of recycled binder that was introduced into the mixture, as shown in Table 27.

Table 27. Virgin Binder Content and PG Grade in Each Mixture

Mixture Design		%RAS	RBR%	Virgin Binder Grade
US-59-surface course (SR-9.5A)	15% Rec.	5	21	64-34
	20% Rec.	5	25	64-34
	35% Rec.	5	38	58-34
US-59-intermediate course (SR-19A)	15% Rec.	5	21	64-34
	20% Rec.	5	30	64-34
	30% Rec.	5	40	58-34
US-36-intermediate course (SR-19A)	15% Rec.	0	14	70-28
	20% Rec.	5	42	64-34
	25% Rec.	5	48	58-34

The mixture performance was evaluated in terms of moisture susceptibility, rutting resistance, and fatigue cracking resistance. The testing methods included the dynamic modulus test, the Hamburg wheel tracking test, the flow number test, and the uniaxial cyclic fatigue test. The study recommended that maximum RBR% limits should be required based on mixture type because of varying performance observed for SR-9.5A and SR-19A mixtures with RAP content. For SR-9.5A, lower than 25% RBR% could lead to satisfactory performance. For SR-19A, 30% RBR% was the maximum recycled binder content to show good performance. In addition, improved fatigue performance was observed in the mixtures incorporating both RAP and RAS compared to RAP-only mixtures. While this study evaluated the impact of RAP binder on mixture performance, only a limited number of mixture designs could be included.

Roque et al. (2020) investigated the relationship between RAP content and mixture cracking performance based on the dominant aggregate size range-interstitial component (DASR-IC) theory as part of a study for Florida DOT. In this theory, the dominant aggregate size range (DASR) forms an aggregate skeleton to provide shear resistance, while the interstitial component (IC) part consists of fine aggregates, binder, and air voids, which fill the volume in the DASR to provide tension and shear resistance. The DASR porosity governs the interlocking and provides resistance to deformation and fracture. The study required DASR porosity to reach a range of 38-52% to ensure adequate interlocking and potentially good mixture performance. Eight RAP sources were selected based on their DASR porosity, recovered RAP binder stiffness, and RAP fineness for evaluation in mixtures. The RAP binder was according to the high-temperature continuous grade of the recovered RAP binder. The RAP binder stiffness was defined following the Superpave performance grading system and grouped into high (PGH>106°C), intermediate (100°C <PGH<106°C), and low (PGH<100°C). The RAP fineness was determined from the percentage passing No. 16 sieve (1.18 mm) and grouped into coarse (<40%), intermediate (40-50%), and fine

(>50%). IC mixes were designed using the eight RAP sources at four RAP contents of 0%, 20%, 30%, and 40%. IC mixes were evaluated using the interstitial component direct tension (ICDT) test because the specimen preparation and testing required less effort than a full-scale mixture test.

From the test, a parameter called interstitial component fracture energy (FE_{IC}) was used to evaluate cracking resistance and estimate preliminary allowable RAP content for each source. FE_{IC} is defined as the area under the stress-strain curve. The study observed that FE_{IC} generally decreases as RAP content increases because the highly aged, stiff RAP binder within RAP material can lead to lower FE_{IC}. FE_{IC} is also influenced by RAP fineness because finer RAP results in more RAP in the IC portion of the mixture than coarse and intermediate RAP at the same RAP content, leading to lower FE_{IC}. The result shows that even at 20% RAP content, all three IC mixes with fine RAP exhibited distinctively lower FE_{IC}. Therefore, the study used coarse and intermediate RAP sources to estimate preliminary maximum RAP content and generated a preliminary guideline for maximum allowable RAP content in PMA mixture based on RAP binder stiffness and RAP fineness. After the verification using IDT test, it is concluded that for course (<40% passing No. 16) and low stiffness RAP, the maximum RAP content can be up to 40%.

Table 28 summarizes the pros and cons of the different approaches identified in the literature to evaluate and inform maximum RAP and RAS contents. Some studies have focused on blended binder testing, but this approach lacks mixture-level validation, critical given the potential for partial recycled binder contribution. Additionally, the extraction and recovery process is labor-intensive, limiting the number of blends that can be evaluated. Mixture testing addresses this gap but is more time-consuming, typically restricting the number of conditions that can be studied compared to binder-level testing. Florida's ICDT method offers an alternative by testing the fine mortar fraction of the mix. While initial results are promising, standardized procedures for IC mix design and testing are still lacking. A common limitation across past studies is the narrow range of RAP, virgin binder, and RBR% combinations evaluated. Future approaches could leverage large binder property databases (e.g., virgin binder QA data) to develop probabilistically informed RBR% limits, with mixture testing used to validate selected scenarios.

Table 28. Summary of Pros and Cons for Different Approaches.

Relevant State	Approach	Pros	Cons
North Carolina	Binder characterization	• Direct measurement of blended binder properties. • Well-established testing protocols with acceptable thresholds. • Follows traditional binder specifications, familiar to industry.	• Binder extraction and recovery are time-consuming. • RAP impact on mixture performance remains unknown. • Variability of virgin binder is not considered.
Kansas	Mixture performance evaluation	• RAP impact on mixture performance is directly evaluated. • Accounts for aggregate structure effects, not just binder properties. • Eliminates assumptions about binder blending and interaction.	• Limited mixture design scenarios are evaluated. • Performance tests can be highly variable. • Difficult to tie findings directly to influence of the binder.
Massachusetts	Binder and mixture evaluation	• Considers impacts of RAP on both binder and mixture properties.	• Extensive testing requirements limit the number of mixtures/RAP sources that can be evaluated.
Connecticut	Comparison of mixtures prepared with RAP and RAP aggregate to binder properties	• Do not need extraction and recovery. • Considered partial blending between RAP and virgin binders. • Can be easily implemented by agencies.	• Requires validation against established methods.
Florida	New method for IC mix specimen evaluation	• IC mix specimen preparation and testing require less effort than full scale mixture and capture	• Requires validation. • IC preparation is not practical.

		interactions between binder and aggregate.	

A.5. Impacts of RAP and RAS Variability on Asphalt Mixture Performance

The previous sections of this literature review have highlighted the varying requirements set by state agencies across the United States for the incorporation of RAP and RAS in asphalt mixtures. The maximum allowable RAP content varies significantly, ranging from 10 to 40 percent by weight of mixture, whereas for RAS, it spans from 2 to 6 percent. Furthermore, the maximum allowable content of RAM is also dependent upon the specific pavement layer (i.e., surface, intermediate, base), with surface layers having stricter limitations due to their greater exposure to traffic and environmental factors. State agencies impose these restrictions due to concerns about potential long-term pavement performance issues, particularly related to cracking and raveling.

One of the major obstacles hindering state agencies from incorporating higher amounts of RAM in asphalt mixtures is the inherent variability in RAM properties. These properties can vary within a given stockpile over time, and even more so across stockpiles within a state, leading to inconsistencies in the properties and performance of asphalt mixtures (Zaumanis et al. 2018, Bonaquist 2011, Hajj et al. 2009). Studies have shown that RAP stockpile properties, such as the theoretical maximum specific gravity (G_{mm}), asphalt content, gradation, and performance grade (PG) of extracted and recovered binder, can vary greatly across different regions within a state and even within a single stockpile over time (Austerman et al. 2020, Khosla and Ramoju 2017). While state agencies require the measurement of some of these RAM properties as part of quality assurance and control procedures, the PG is typically not included because it involves solvent extraction and recovery of the RAM binder, which is time-consuming and impractical. Consequently, variability in the recycled binder properties is generally not accounted for. Accordingly, several studies have evaluated the impacts of RAP source on the performance of laboratory-mixed and compacted asphalt mixtures (Montañez et al. 2020, Obaid et al. 2019, Faisal et al. 2017, Izaks et al. 2015, Hajj et al. 2009, Li et al. 2008). These studies have reported that the cracking and rutting resistance of asphalt mixtures can be substantially affected by the RAP source. This can be attributed to the inherent variability in RAP materials, which can differ in properties like gradation, asphalt content, and performance grade of their extracted and recovered binders.

Another factor that leads to uncertainty in the performance of high recycled content mixtures is uncertainty in the proportion of total recycled binder that is available to blend with virgin asphalt binder, known as recycled binder availability (RBA) (Pape and Castorena 2022). Recent studies have shown that not all the recycled binder in RAP is available for blending due to RAP agglomerations, which trap some of the recycled binder and make it inaccessible to blend with virgin binder during mixture production (Castorena et al. 2024, Mocelin et al. 2024, Al-Qadi 2007). For instance, NCDOT RP 2019-21 (Castorena et al. 2022) reported recycled binder availability (RBA) values ranging from 51 to 83 percent across four RAP sources in North Carolina, while NCDOT RP 2021-06 (Castorena 2023) found RBA values between 43 and 61% across six sources. These findings highlight significant variability in the RBA of RAP materials within the state. Failure to account for RBA in asphalt mixture design may lead to less durable asphalt mixtures, especially for those with high recycled material percentages (Mocelin and Castorena 2022).

The incorporation of performance measures into mixture design and quality assurance procedures is one way to mitigate the potentially detrimental impacts of RAM variability on performance. Many state agencies are shifting from a solely volumetric mixture design approach to a balanced mix design (BMD) approach that incorporates measures of rutting and cracking performance into the design process (Yazdipanah et al. 2023, West et al. 2021, Newcomb and Zhou 2018, NCAT 2017). However, most state agencies implementing BMD still rely on traditional compositional measures (e.g., gradation, volumetrics) as quality acceptance characteristics (AQCs) during production. Thus, understanding the impacts of variability in the composition of asphalt mixtures on their performance is crucial to ensure adequate controls are implemented during production to mitigate performance variability. Accordingly, several studies have investigated the impacts of variability in asphalt binder content and aggregate gradation on mixture performance (Bowers et al. 2023, Mogawer et al. 2019, Austerman et al. 2018). These studies have reported that mixtures meeting performance threshold limits during the design phase can fail to meet those same thresholds during production due to variations in binder content and aggregate gradation, even when these variations are within tolerance limits. However, these investigations were conducted on laboratory-mixed and laboratory-compacted specimens, and not actual plant-produced mixtures and did not consider the impacts of variability in the RAM. Rahman et al. 2023 evaluated the variability of the performance of plant-produced asphalt mixtures containing RAP and RAS. They observed differences in the performance of mixtures sampled at different times during mixture production, which they speculated could be due to variations in aging caused by different silo storage times at the asphalt plant before transportation to the construction site. However, this study involved mixtures with low recycled material content, capped at 10% RAP and 3% RAS.

A.6. Summary and Identification of Knowledge Gaps

The key findings of this literature review are summarized as follows:

Quality Control and Assurance Practices for RAP and RAS:

The frequency of testing for RAP and RAS properties like gradation and asphalt content varies among state agencies. Some states have additional requirements, such as moisture content, theoretical maximum specific gravity, or testing for the presence of asbestos in RAS. The methods used to determine asphalt content also differ, with some states requiring an ignition oven, others solvent extraction, and some permitting either method.

Stockpiling, Processing, and Fractionation:

The National Asphalt Pavement Association (NAPA) outlines best practices for managing RAP and RAS to minimize variability. These include proper collection, sorting, separation, size reduction, and stockpiling methods. State specifications regarding the processing, handling, storage, and usage of RAP and RAS vary widely, with differences in stockpile management, processing requirements, the type of surface layer where they can be used, and the allowable amount of RAP and RAS that can be used in asphalt mixtures. Some states, such as Maine, Illinois, and Georgia, have different classes of RAP based on their characteristics and consistency, while others require covering stockpiles to prevent moisture intrusion.

Virgin Binder Selection:

Choosing the appropriate type of virgin binder, considering the amount of recycled material used or the percentage of recycled binder replacing virgin binder, as well as the specific type of recycled material, is one way of reducing inconsistencies in the performance of recycled asphalt mixtures.

AASHTO M 323 (2022) provides guidelines for virgin binder selection based on RAP percentage. Many states, such as North Carolina, have developed their requirements for virgin binder selection based on RBR% through evaluation of region-specific RAP and/or RAS binder properties. Other states have implemented various approaches to establish or critically evaluate RAP and RAS content limits: Kansas used mixture performance evaluation, Massachusetts employed both binder and mixture evaluation, Connecticut compared mixtures prepared with RAP and RAP aggregate to binder properties, and Florida evaluated the fine mortar fraction of the mix.

Impacts of RAP and RAS Variability on Asphalt Mixture Performance:

The variability of RAP and RAS properties can impact the performance of asphalt mixtures, particularly those with a high percentage of recycled materials. Studies conducted on laboratory-mixed and laboratory-compacted asphalt mixtures have demonstrated that variations in RAP stockpile properties can affect both the cracking and rutting resistance. The incorporation of performance measures into mixture design and quality assurance procedures is one way to mitigate the potential detrimental impacts associated with the variability of RAP and RAS.

The following knowledge gaps have been identified:

This literature review highlights the significant influence that the variability in RAP and RAS properties can have on the performance of high recycled content asphalt mixtures. Although several studies have investigated these impacts, most have focused on laboratory-mixed and laboratory-compacted specimens. This underscores a critical need for further research to bridge the gap between laboratory findings and real-world production scenarios. Further research should also aim to identify the factors contributing to the variability observed in the performance of plant-produced high recycled content mixtures, considering not only asphalt content and gradation of the RAM materials, but also rheological measures of extracted and recovered binder. Finally, the reviewed studies assumed complete blending of the virgin and RAM binders. However, in practice, partial RBA occurs. Thus, it is recommended that future investigations incorporate partial RBA when evaluating the properties of high recycled content asphalt mixtures.

In addition, while many states, including North Carolina, have developed RBR% specifications based on deterministic evaluation of a limited set of recycled and virgin binders, these deterministic approaches fall short in accounting for the full variability of binder properties. RBR% limits warrant a more comprehensive analysis, combining quality assurance (QA) data for virgin binders with representative RAP binder characterization to conduct a probabilistic evaluation of blended binder properties across RBR% levels. This probabilistic framework can then be used to evaluate RBR% thresholds that satisfy performance-graded specifications at a desired confidence level, offering a more risk-informed approach to setting RBR% limits. Furthermore, NCDOT RP 2014-05 (Khosla and Ramoju 2015) did not evaluate the low-temperature performance graded properties of RAP binders or RAP–virgin binder blends when establishing RBR% limits. One likely reason for this omission is the relatively large quantity of recovered binder required for Bending Beam Rheometer (BBR) testing, which can be challenging to obtain from RAP. If BBR parameters could be reliably predicted from Dynamic Shear Rheometer (DSR) measurements, the amount of binder needed for characterization would be significantly reduced, facilitating broader evaluation of RAP binder low-temperature properties.

References

AASHTO. 2022. *Standard Specification for Superpave Volumetric Mix Design, AASHTO M 323 (2022)-22*. Washington, DC: American Association of State Highway and Transportation Officials.

Al-Qadi, I. L., M. Elseifi, and S. H. Carpenter. 2007. *Reclaimed Asphalt Pavement – A Literature Review*. Report No. FHWA-ICT-07-001. Urbana, IL: Illinois Center for Transportation.

Austerman, A. J., W. S. Mogawer, and K. D. Stuart. 2020. "Variability of Reclaimed Asphalt Pavement (RAP) Properties within a State and Its Effects on RAP Specifications." *Transportation Research Record* 2674 (6): 73–84. https://doi.org/10.1177/0361198120917679.

Austerman, A. J., W. S. Mogawer, and K. D. Stuart. 2018. "Influence of Production Considerations on Balanced Mixture Designs." *Transportation Research Record* 2672 (28): 426–437. https://doi.org/10.1177/0361198118786826.

Bonaquist, R. 2011. *Effect of Recovered Binders from Recycled Shingles and Increased RAP Percentages on Resultant Binder PG*. Report No. WHRP 11-13. Sterling, VA: Asphalt Institute.

Bowers, B. F., T. Lynn, F. Yin, N. Moore, S. Diefenderfer, and I. Boz. 2023. *Impact of Production Variability on Balanced Mix Designs in Virginia*. Report No. FHWA/VTRC 23-R20. Charlottesville, VA: Virginia Transportation Research Council.

California Department of Transportation. *Standard Specifications*. Sacramento, CA. 2023.

Castorena, C., R. Costa, M. C. A. Alvis, D. Mocelin, M. Isied, and A. Kusam. 2024. *A Practical Method to Determine Reclaimed Asphalt Pavement (RAP) Binder Availability*. NCHRP IDEA Project 236.

Castorena, C., B. S. Underwood, Y. R. Kim, D. Mocelin, M. Isied, M. C. A. Alvis, and A. Kusam. 2023. *Modifying Existing Asphalt Mix Design Procedures for RAP/RAS Surface Mixtures*. Report No. FHWA/NC2021-06. Raleigh, NC: North Carolina Department of Transportation.

Castorena, C., S. Pape, G. L. Xue, D. Mocelin, M. C. A. Alvis, and M. Ravichandran. 2022. *Improving the Design of RAP and RAS Mixtures*. Report No. FHWA/NC/2019-21. Raleigh, NC: North Carolina Department of Transportation.

Florida Department of Transportation. *Standard Specifications for Road and Bridge Construction*. Tallahassee, FL. 2024.

Faisal, H. M., U. A. Mannan, A. S. M. Asifur Rahman, M. M. Hasan, and R. A. Tarefder. 2017. "Effects of RAP Sources for Performance Testing of Asphalt Concrete." Paper presented at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

Georgia Department of Transportation. *Standard Specifications Construction of Transportation Systems*. Atlanta, GA. 2021.

Hajj, E. Y., P. E. Sebaaly, and R. Shrestha. 2009. "Laboratory Evaluation of Mixes Containing Recycled Asphalt Pavement (RAP)." *Road Materials and Pavement Design* 10 (3): 495–517. https://doi.org/10.3166/rmpd.10.495-517.

Illinois Department of Transportation. *Special Provision for Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS)*. Springfield, IL. 2021.

Izaks, R., V. Haritonovs, I. Klasa, and M. Zaumanis. 2015. "Hot Mix Asphalt with High RAP Content." *Procedia Engineering* 114: 676–684. https://doi.org/10.1016/j.proeng.2015.08.009.

Kentucky Transportation Cabinet. *Standard Specifications for Road and Bridge Construction*. Frankfort, KY. 2019.

Khosla, N. P., and S. S. Ramoju. 2017. *Characterization of Different RAP Sources*. Report No. FHWA/NC/2014-05. Raleigh, NC: North Carolina Department of Transportation.

Li, X., M. O. Marasteanu, R. C. Williams, and T. R. Clyne. 2008. "Effect of Reclaimed Asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures." *Transportation Research Record* 2051: 90–97. https://doi.org/10.3141/2051-11.

Maine Department of Transportation. *Standard Specifications*. Augusta, ME. 2020.

Massachusetts Department of Transportation. *Standard Specifications for Highways and Bridges*. Boston, MA. 2023.

McDaniel, R., and R. M. Anderson. 2001. *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual*. NCHRP Report 452. Washington, DC: Transportation Research Board.

Minnesota Department of Transportation. *Standard Specifications for Construction. Volume 1*. St. Paul, MN.

Mocelin, D. M., and C. Castorena. 2022. "Impacts of Recycled Binder Availability on Volumetric Mixture Design and Performance." *International Journal of Pavement Engineering*: 1–17. https://doi.org/10.1080/10298436.2022.2046276.

Mocelin, D. M., M. M. Isied, R. F. Costa, and C. Castorena. 2024. "Availability Adjusted Mix Design Method as a Tool to Mitigate the Adverse Effects of RAP on the Performance of Asphalt Mixtures." *Construction and Building Materials* 422: 135813. https://doi.org/10.1016/j.conbuildmat.2024.135813.

Mogawer, W. S., A. J. Austerman, T. Pauli, S. Salmans, and J.-P. Planche. 2016. *Determination of the Binder Grade and Performance of High Percentage RAP-HMA Mixes*. Report No. SPRII-15-57946. Fall River, MA: Massachusetts Department of Transportation.

Mogawer, W. S., K. D. Stuart, A. J. Austerman, F. Zhou, and P. Romero. 2019. "Balanced Mix Design Sensitivity to Production Tolerance Limits and Binder Source." *Journal of the Association of Asphalt Paving Technologists* 88.

National Center for Asphalt Technology. 2017. "Moving Towards Balanced Mix Design for Asphalt Mixtures." *Asphalt Technology News* 29 (1): 1–5.

Nevada Department of Transportation. *Standard Specifications for Road and Bridge Construction*. Carson City, NV. 2016.

New Hampshire Department of Transportation. *Standard Specifications for Road and Bridge Construction, Document 502*. Concord, NH. 2016.

New York Department of Transportation. *Quality Control and Quality Assurance Procedure for Asphalt Mixture Production*. Albany, NY. 2022.

New York Department of Transportation. *The Use of Reclaimed Asphalt Shingles (RAS) in the Production of Asphalt Mixtures*. Albany, NY. 2015.

Newcomb, D., and F. Zhou. 2018. *Balanced Design of Asphalt Mixtures*. Report No. MN/RC 2018-22. St. Paul, MN: Minnesota Department of Transportation.

North Carolina Department of Transportation. *Asphalt Quality Management System*. Raleigh, NC. 2024a.

North Carolina Department of Transportation. *Standard Specifications for Roads and Structures*. Raleigh, NC. 2024b.

Obaid, A., M. D. Nazzal, L. Abu Qtaish, S. S. Kim, A. Abbas, M. Arefin, and T. Quasem. 2019. "Effect of RAP Source on Cracking Resistance of Asphalt Mixtures with High RAP Contents." *Journal of Materials in Civil Engineering* 31 (10): 1–7. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002817.

Pape, S., and C. Castorena. 2022. "Application of Sieve Analysis to Estimate Recycled Binder Availability." *Transportation Research Record* 2676 (6): 170–181. https://doi.org/10.1177/03611981211073324.

Rahman, M., J. Harvey, J. Buscheck, J. Brotschi, A. Mateos, D. Jones, and S. Pourtahmasb. 2023. "Laboratory Performance and Construction Challenges for Plant Produced Asphalt Mixes Containing RAP and RAS." *Construction and Building Materials* 403: 133082. https://doi.org/10.1016/j.conbuildmat.2023.133082.

Ramoju, S. S., N. P. Khosla, and N. Prabu. 2015. *Determining Recycled Asphalt Binder Limits Contributed by Waste Materials*. NCDOT Project 2012-04. Raleigh, NC: North Carolina Department of Transportation.

Roque, R., B. Park, J. Zou, and G. Lopp. 2020. *Enhanced Characterization of RAP for Cracking Performance*. Publication BDV31-977–70. Gainesville, FL: University of Florida.

South Carolina Department of Transportation. *Standard Specifications for Highway Construction*. Columbia, SC. 2007.

Stephens, J. E., J. Mahoney, and C. Dippold. 2001. *Determination of the PG Binder Grade to Use in a RAP Mix*. Publication JHR 00-278. Storrs, CT: Connecticut Department of Transportation.

Tavakol, M., and M. Hossain. 2016. *Minimum Virgin Binder Limits in Recycled Superpave Mixes in Kansas*. Report No. K-TRAN: KSU-13-5. Manhattan, KS: Kansas Department of Transportation.

Tennessee Department of Transportation. *Standard Specifications for Road and Bridge Construction*. Nashville, TN. 2021.

Texas Department of Transportation. *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges*. Austin, TX. 2024.

Virginia Department of Transportation. *Road and Bridge Specifications*. Richmond, VA. 2020.

Washington State Department of Transportation. *Standard Specifications for Road, Bridge, and Municipal Construction, M 41-10*. Publication No. 1151. Olympia, WA. 2024.

West, R., J. R. Willis, and M. N. Marasteanu. 2013. *Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content*. NCHRP Report 752. Transportation Research Board, Washington, D.C.

West, R., F. Yin, C. Rodezno, and A. Taylor. 2021. *Balanced Mixture Design Implementation Support*. Auburn, AL: National Center for Asphalt Technology.

West, R. C. 2015. *Best Practices for RAP and RAS Management*. Report No. QIP 129. Lanham, MD.

Wisconsin Department of Transportation. *Standard Specifications for Highway and Structure Construction*. Madison, WI. 2024.

Yazdipanah, F., M. Khedmati, and H. F. Haghshenas. 2023. *Nebraska Balanced Mix Design - Phase I*. Report No. SPR-FY22(002).

Zaumanis, M., J. Oga, and V. Haritonovs. 2018. "How to Reduce Reclaimed Asphalt Variability: A Full-Scale Study." *Construction and Building Materials* 188: 546–554. https://doi.org/10.1016/j.conbuildmat.2018.08.137.

Zhou, F., J. W. Button, and J. Epps. 2012. *Best Practice for Using RAS in HMA*. Report No. FHWA/TX-12/0-6614-1. College Station, TX: Texas Transportation Institute.

APPENDIX B: PLANT OPERATIONAL REVIEW RESULTS

This appendix contains the operational review questionnaire and the detailed responses from each interviewed plant. To ensure participant anonymity, the plants are labeled as H, A, K, I, F, W, and J.

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 an RAP collar approximately 1/3 of the distance down the mixing drum)?
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, what?
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 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 the 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 29. Topic 1 - General Asphalt Plant Information

Plant	H	A	K	I	F	W	J
Location	Piedmont	Piedmont	Piedmont	Piedmont	Coastal	Coastal	Coastal
Plant type	Counter flow	Counter flow	Double barrel	Double barrel	Double barrel	Double barrel	Counter flow
How is RAP introduced	Rap collar approx 10 feet from flame	Rap collar, approx 15' from flame	RAP collar and introduces into chute with raw aggregate material	RAP collar approximately 3/4 the distance down the drum	Rap collar in outer drum above flame	RAP collar approximately 3/4 the distance down the drum	RAP collar approximately 3/4 the distance down the drum
Number of liquid tanks	3	3	2	3	2	1 (split tank)	2
Binder grades	64 and 76	58 and 64	58 and 64	58 and 64	58 and 64	58 and 64	58 and 64
Typical RAP contents	20-30%	20-30%	≤ 30%	30-40%, usually to minimize the virgin aggregate and AC	30-40%	30-40%, usually to minimize the virgin aggregate and AC	30-40%, usually to minimize the virgin aggregate and AC
# of RAP/RAS cold feed bins	3	2	2 (1 for RAP and 1 for RAS)	2	2	1	2
RAS uses?	no	yes	yes	No	No - we typically run 40% mixes at Knightdale, no need to run RAS at that plant yet	No - no need to run RAS in OGFC, we run high RAP mixes instead	Yes - in the OGFC in place of fibers

Table 30. Topic 2 - Recycled Material Sources and Stockpiling

Plant	H	A	K	I	F	W	J
Location	Piedmont	Piedmont	Piedmont	Piedmont	Coastal	Coastal	Coastal
Stockpile Sources	Only State roads,Private,Plant waste,Parking lots	State roads,Private,Parking lots,Plant waste	State-owned roads. Private roads. Parking lots. Plant waste. Manufactured waste RAS.	All RAP from any source, no RAS	Private,Parking lots, State roads,Plant waste	RAP from any source	RAP from any source, no RAS
Number of Unprocessed RAP Stockpiles	2	1	1	1	1	1	1
Explanation	One with everything and one with surface millings only from their projects			1 stockpile for millings	Unprocessed rap. About 75 -100 feet tall, collects everything	1 stockpile for millings	1 stockpile for millings
Number of Processed RAP Stockpiles	3	1	1	1	3	1	1
Explanation	Fine Rap -1/4"; Coarse 1/2 - 5/8; Combo - -5/8"			1 stockpile single sized Rap (-5/8")	Fine - -3/8"; Coarse 3/8 - 9/16; combined pile	1 stockpile single sized Rap (-5/8")	1 stockpile single sized Rap (-5/8")
Are stockpiles contaminated?	no	no	no	no	no	no	no
Explanation							
Are RAP stockpiles captive?	no	no	it depends	no	no	no	no
Explanation	replenished daily	always being replenished		we add to the existing as we crush after testing has determined it to be consistent with the old RAP. If significantly different, we will build a separate stockpile.	replenished daily	we add to the existing as we crush after testing has determined it to be consistent with the old RAP. If significantly different, we will build a separate stockpile.	we add to the existing as we crush after testing has determined it to be consistent with the old RAP. If significantly different, we will build a separate stockpile.

Table 30 (continued)

Plant	**H**	**A**	**K**	**I**	**F**	**W**	**J**
Location	Piedmont	Piedmont	Piedmont	Piedmont	Coastal	Coastal	Coastal
What efforts are made to avoid segregation of stockpiles	Crushing sub works the pile and combines material during crushing. Loader works pile daily	Loader works the pile each night	n/a	a dozer is usually used to blend millings and spread plant waste, dozer is also used to blend processed RAP and break up to be loaded into plant	Pile will be worked with a loader daily then a dozer will come in occasionally	a dozer is usually used to blend millings and spread plant waste, dozer is also used to blend processed RAP and break up to be loaded into plant	a dozer is usually used to blend millings and spread plant waste, dozer is also used to blend processed RAP and break up to be loaded into plant
Max stockpile height	50 feet	RAP-30'; Unprocessed RAP - 75'; RAS -20'	60' or less for both unprocessed and processed	generally below 30' although that is not a limit just usually based on quantities we have on hand	Fine - 30'; Coarse - 25'; Combo - 30'	generally below 20' although that is not a limit just usually based on quantities we have on hand	generally below 30' although that is not a limit just usually based on quantities we have on hand
RAS PLANTS ONLY							
Do you accept post-consumer and/or manufactured waste shingles?			Manufactured waste shingles ONLY				Manufactured waste shingles ONLY
How many RAS stockpiles are present?		1	2				1
Explanation			1 for processed and 1 for unprocessed				1 processed RAS stockpile - we do not have unprocessed RAS at this location
Are RAS stockpiles captive?		no, continuously fed by supplier	no, continuously fed				yes
Is RAS mixed with other materials when stockpiled or when introduced into plant?		no	no				no

Table 31. Topic 3 - Recycled Material Processing

Topic 3: Recycled Material Processing							
Plant	**H**	**A**	**K**	**I**	**F**	**W**	**J**
Location	Piedmont	Piedmont	Piedmont	Piedmont	Coastal	Coastal	Coastal
Who performs crushing?	Blackrock	Smith Rowe	Ourselves	Blackrock	Blackrock	Empire	Blackrock
Crusher Type	Impact	Impact	Jaw crusher with screen	Impact	Portable impact (McClosky 144v3)	Impact	Impact
How often is RAP crushed?	2-3 times a year	once a year	once a month	3-4 times per year	1-3 times a year	twice a year maybe	3-4 times per year
Is RAP fractionated?	yes	no	no	no - we crush single sized (-5/8")	yes	no - we use a single sized Rap (-5/8")	no - we produce a single size (-5/8")
Is crushing avoided in certain weather?	yes	yes	no	yes	no	yes	yes
Explanation	not in heavy rain	rain		in general not during heavy rain	any weather	in general not during heavy rain	in general not during heavy rain
Any measures in place to minimize moisture in RAP?	sloped site, not paved	sloped site	tent for RAS	no	sloped site	no	no
How long is RAP stockpiled?	used pretty immediately	6 month to a year	using right away	could be several months depending on how much production from the plant	3-4 months	possibly up to 6 months depending on plant production	could be several months depending on how much production from the plant
RAS PLANTS ONLY							
Who performs grinding of your RAS?		A1 Sand Rock	Ourselves				Premier (recycling center)
How often?		continuously by sub	two-three times a week				once every couple of years - we do not use much RAS at any of our locations
How is RAS cleaned?		Precleaned by sub. Pile is clean except for some paper	using manufactured only				during processing
What size is RAS grind?		minus 3/8"	3/8-7/16				I'm unsure
How long is RAS stockpiled?		2 months. Small pile	using right away				could be several years, stockpiles will be mixed and "fluffed" with an excavator to keep from hardening

Table 32. Topic 4 - Sampling and Testing

Plant	H	A	K	I	F	W	J
Location	Piedmont	Piedmont	Piedmont	Piedmont	Coastal	Coastal	Coastal
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.)?	cold feed belt with shovel	load face only using front end loader and NCDOT method	random, from the location the material is batched from, using front-end loader	From the loadout face with a sample laid out by the loader	load face only	From the loadout face with a sample laid out by the loader	From the loadout face with a sample laid out by the loader
How often is RAP sampled?	weekly	weekly	weekly	weekly	weekly	weekly	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	weekly per DOT specs, additionally when crushing	Not usually - we will pull additional samples if we are having mix problems and trying to identify the source of the issue	when crushing	Not usually - we will pull additional samples if we are having mix problems and trying to identify the source of the issue	Not usually - we will pull additional samples if we are having mix problems and trying to identify the source of the issue
Do you ever characterize the extracted and recovered binder properties from your recycled material stockpiles? If so, when/how often?	6-8 times. Haven't done recently	no	yes, yearly	no	no	no	no

Table 33. Topic 5 - Asphalt Mix Production and Silo Storage

Plant	H	A	K	I	F	W	J
Location	Piedmont	Piedmont	Piedmont	Piedmont	Coastal	Coastal	Coastal
How do you transfer recycled material from stockpiles to cold feed bins?	works along face of pile continuously	changes faces from day to day	from a single side	usually from the loadout face, this may change location from day to day and depends on what areas of the stockpile are accessible by the loader	works along one face	usually from the loadout face, this may change location from day to day and depends on what areas of the stockpile are accessible by the loader	usually from the loadout face, this may change location from day to day and depends on what areas of the stockpile are accessible by the loader
Is any inline plant screening and/or crushing of recycled materials performed during mix production?	yes	yes	yes	yes	yes	yes	yes
Explanation	5/8" screen deck	3/8" screen	inline impact crusher for RAP	the RAP is run across a screen deck - no in-line crusher at this location	screen deck at the end of the belt	the RAP is run across a screen deck - no in-line crusher at this location	the RAP is run across a screen deck - no in-line crusher at this location
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.	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.	no actions for RAP, tent for RAS. Production tons per hour depends and varies on moisture	the operator will adjust the speed of the plant and mix temperature to ensure the RAP is dried and fully incorporated into the mix	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.	the operator will adjust the speed of the plant and mix temperature to ensure the RAP is dried and fully incorporated into the mix	the operator will adjust the speed of the plant and mix temperature to ensure the RAP is dried and fully incorporated into the mix

Table 33 (continued)

Plant	H	A	K	I	F	W	J
Location	Piedmont	Piedmont	Piedmont	Piedmont	Coastal	Coastal	Coastal
How long do you store produced mixture in the silo? Please indicate typical and maximum allowable storage times	overnight, 70% of the time	overnight - 50% of the time	typical use right away, store 12 hours. Maximum 60 hours	silos have a heating system - mix can be stored for 12 hours without issues and up to 48 hours if they "burp" the silo (remove some of the mix from the bottom of the silo)	12-16 hours fairly often	the silos do not have heating systems so they will store mix for a maximum of 10 hours	silos have a heating system - mix can be stored for 12 hours without issues and up to 48 hours if they "burp" the silo (remove some of the mix from the bottom of the silo)
If the plant uses RAS, are processed RAS and RAP or RAS and fine aggregate combined prior to feeding into the asphalt plant?	n/a		no	n/a	n/a	n/a	if RAP/RAS combo, the RAP and RAS are combined at the shaker deck and introduced into the plant together
If the plant uses RAS, are there any measures in place to remove residual nails, fibers, or deleterious materials during production?	n/a	removed by crushing sub prior to delivery	no, its manufactured waste, no nails	n/a	n/a	n/a	no

APPENDIX C: HISTOGRAMS OF BINDER DATA AND BLENDING CHART VERIFICATION

C.1. Data Sets

The probabilistic evaluation of RBR% limits discussed in Sections 2.5.1 and 3.4 used three data sets: (1) virgin binder QA data provided by NCDOT, (2) RAP binders specifically characterized as part of this project, (3) RAP binder data from the earlier NCDOT RP 2014-05 (Khosla and Ramoju 2015). In total, these data sets encompass 44 RAP binders and 342 virgin binders.

The virgin binder dataset consisted of QA data acquired from 2022 to 2024 by the North Carolina Department of Transportation (NCDOT). This dataset contains 273 PG 64-22 samples and 69 PG 58-28 samples. High-, intermediate-, and low-temperature PG properties were available for PG 64-22 binders. The high-temperature results utilized were acquired at the rolling thin film oven (RTFO) age level, whereas the intermediate and low temperature PG properties were measured after RTFO and pressurized aging vessel (PAV) aging. The QA data for PG 58-28 binders provide only high- and intermediate-temperature data because existing low temperature measurements at -18°C do not match NC's critical climate temperature of -12°C. Thus, low-temperature properties could not be evaluated for the PG 58-28 virgin binders and associated blends.

Figure 32 shows histograms of PG 64-22 and PG 58-28 virgin binder properties in data set #1. Figure 32(a) shows that all PG 64-22 virgin binders satisfy the AASHTO M 320 (2023) requirement, that $|G^*|/\sin(\delta)$ is at least 2.2 kPa at the RTFO age level at 64°C. In contrast, most PG 58-28 binders fall below the threshold, with only two samples exceeding it. This outcome is expected because PG 58-28 binders are not designed to meet the specification at 64°C.

Figure 32(b) shows that all virgin binders satisfy the AASHTO M 320 (2023) specification that $|G^*|\times\sin(\delta)$ must not exceed 6,000 kPa at 25°C. AASHTO M320 and NCDOT specifications require that the phase angle δ must be equal to or above 42° when $|G^*|\times\sin(\delta)$ falls between 5,000 kPa and 6,000 kPa. However, the phase angle δ information was not reported in the NCDOT QA database, and thus, this additional requirement could not be evaluated for the two binders that fall within this range. Most virgin binders had values well below 5,000 kPa, with only two PG 64-22 binders falling between 5,000 kPa and 6,000 kPa. Figure 32(c) and (d) show that all PG 64-22 virgin binders meet the AASHTO M 320 (2023) requirements that require that $S(60)$ not exceed 300 MPa and $m(60)$ is at least 0.30.

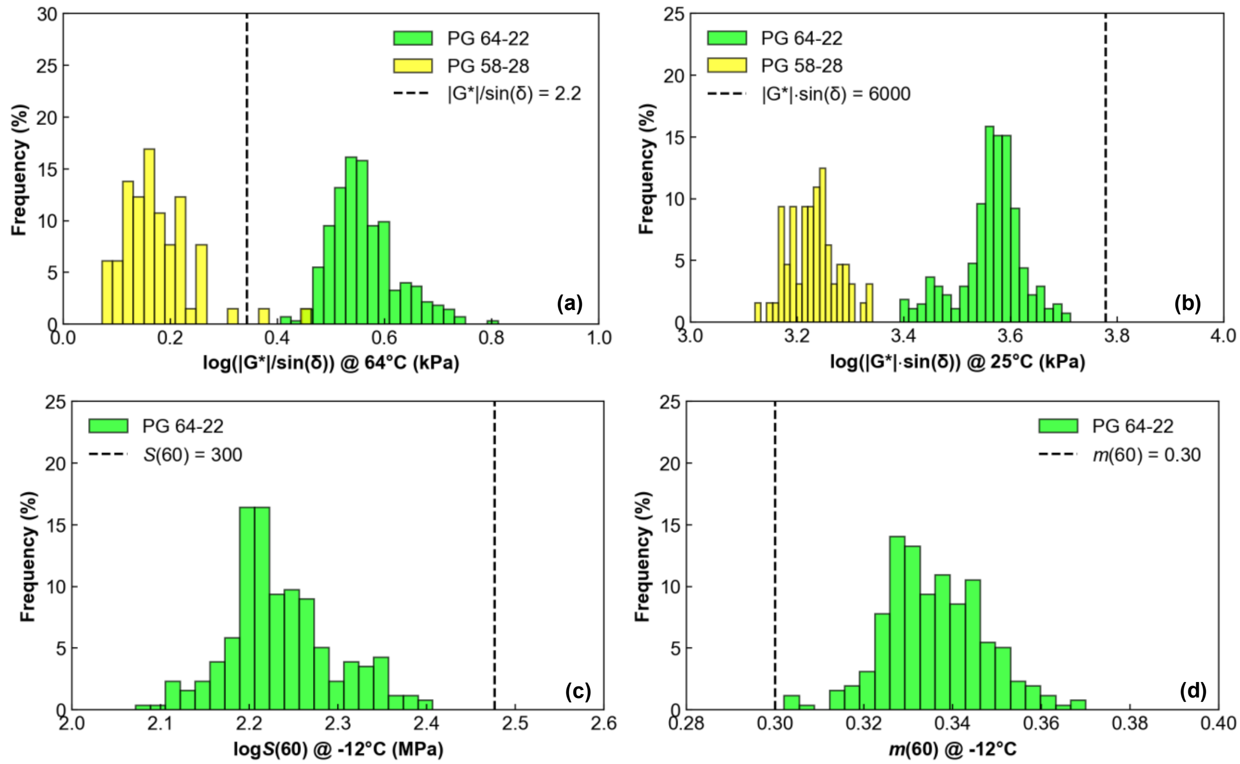


Figure 32. Histograms of PG parameters for the PG 64-22 and PG 58-28 virgin binders: (a) log (|*G|/sin(*δ*)) at 64°C, (b) log |*G**|×sin(*δ*) at 25°C, (c) *S*(60) at -12°C, and (d) m(60) at -12°C.**

Data set #2 is comprised of study materials, including 17 RAP stockpiles sampled from plants across North Carolina. Details on the extraction, recovery, and testing of these samples are provided in the subsequent section. The high temperature grades for the study RAP binders spanned from 94°C to 106°C, and the low temperature grades ranged from -4°C to -16°C.

To support a more comprehensive analysis, a second RAP data set was incorporated. Data set #3 consists of 27 additional RAP binders characterized in previous NCDOT RP 2014-05 (Khosla and Ramoju 2015. The high-grading temperatures for these 27 RAP binders varied from 82°C to 112°C. However, it is important to note that these additional samples include only high- and intermediate-temperature PG characterization results.

Figure 33 shows histograms of the collective RAP binder properties from data sets #2 and #3. Note that different property values ranges are used in Figure 33 compared to Figure 32 given the substantial differences between virgin binder and RAP binder properties. The logarithm of the 2.2 kPa minimum limit specified by AASHTO M 320 (2023) is approximately 0.34. Thus, Figure 33(a) shows that the entire distribution of RAP binder properties greatly exceeds the specification, matching expectations since RAP binders are generally highly oxidized and exhibit high stiffness. Figure 2(b), (c), and (d) show that the RAP binders all fail to meet AASHTO M 320 (2023) specification criteria at NC's critical climatic conditions corresponding to test temperatures of 25°C and -12°C, indicating greater cracking susceptibility than the virgin binders.

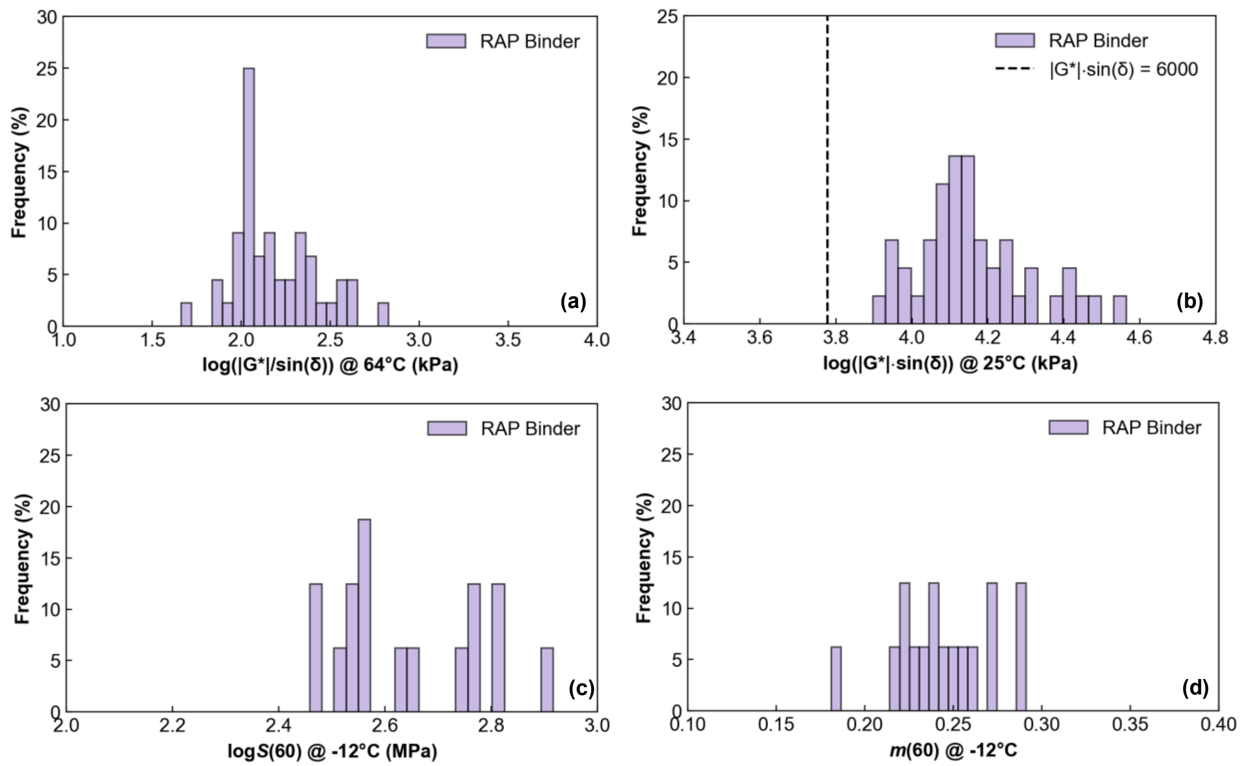


Figure 33. Histograms of PG parameters for the RAP binders: (a) log (|*G|/sin(*δ*)) at 64°C, (b) log |*G**|×sin(*δ*) at 25°C, (c) *S*(60) at -12°C, and (d) m(60) at -12°C.**

The normality of the RAP and virgin binder property distributions was assessed using the Shapiro-Wilk test to inform the appropriate methodology for generating the distribution of blended binder properties. A significance level of $\alpha = 0.05$ was used when interpreting results. While several distributions were identified as normally distributed, there are no cases where the distributions of both RAP and virgin binders for a given parameter are normally distributed, which would allow them to be combined analytically.

C.2. Blending Chart Verification

The accuracy of the blending charts' equations was verified for select blends and properties evaluated in this study. Six RAP binders encompassing the range of continuous high-grading temperatures of the study materials were physically blended with virgin binders in the laboratory at different RBR% levels as shown in Table 34. The blended binders were aged using RTFO and PAV procedures, and the high- and intermediate-temperature PG properties were evaluated using the DSR, respectively. The results were compared to the values predicted using Equation (4). Figure 34 shows the results, which yield an R^2 value of 0.99 relative to the line of equality. The data is centered along the line of equality, indicating no apparent systematic bias. The average percent error was 8% for the high-temperature property and 3% for the intermediate-temperature property,both considered acceptable given the advantages of the proposed analysis's ability to evaluate many blends compared to what would be possible through direct testing. Moreover, since the verification results are symmetrically distributed about the line of equality, the errors associated with the blending chart equations are not expected to introduce bias into the predictions.

Table 34. Virgin and RAP binders blended at different RBR levels.

Virgin Binder	RBR%	RAP PGH (ºC)
PG 64-22	20%	109.3
		95.5
PG 58-28	30%	94.5
		95.5
	40%	94.3
		108.2

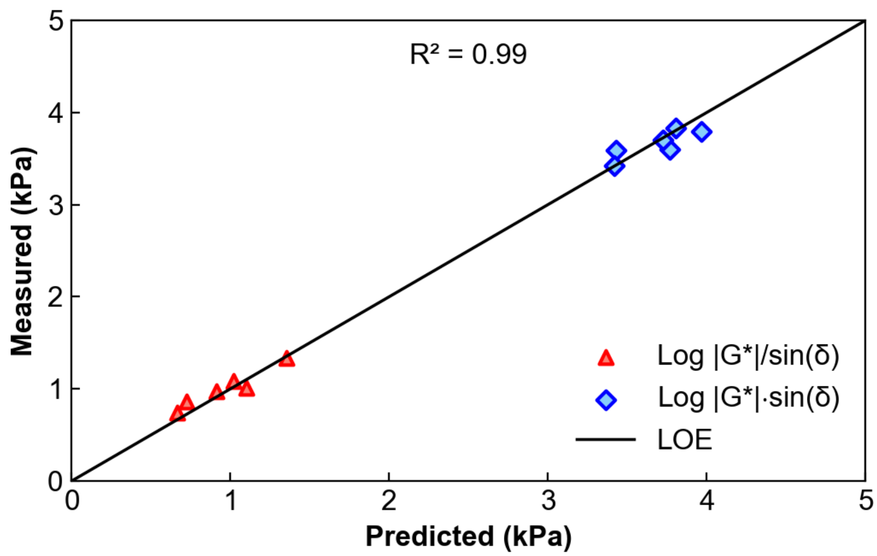


Figure 34. Comparison of blending chart predictions and measured values.

Appendix D: Prediction of BBR Properties from DSR Test Results

D.1. Introduction

Low-temperature performance evaluation plays a critical role in the asphalt performance grading system by determining the thermal crack resistance of asphalt binders. The bending beam rheometer (BBR) test currently serves as the standard method for determining these low-temperature properties. However, the BBR test requires significantly more binder than the dynamic shear rheometer (DSR) test, which poses challenges when characterizing RAM binder samples due to the extensive solvent extraction and recovery needed to obtain sufficient binder. Extraction and recovery are time-consuming and require hazardous, expensive solvents. In contrast, smaller DSR samples are more readily extracted and recovered. Furthermore, the DSR is used for high- and intermediate-temperature performance grading. Thus, eliminating the BBR would streamline the equipment required for performance grading.

Researchers have attempted to use DSR testing to evaluate low-temperature properties of asphalt binders as an alternative to BBR testing. Different geometries, including the torsion bar (Carret et al. 2015), 4 mm parallel plate (Sui et al. 2011, Lu et al. 2017, Hajj et al. 2019), and 8 mm parallel plate (Zeng et al. 2022), as well as various analytical techniques, have been investigated. However, efforts to date have focused on virgin binders and not specifically those from NC. Thus, research is needed to develop an approach for accurately obtaining low-temperature performance graded (PG) properties for both virgin and recycled binders in NC. Herein, the approach proposed by Zeng et al. (2022) is adopted. This approach uses the 8 mm parallel plate geometry at intermediate temperatures, which is compatible with equipment typically available in asphalt laboratories. Furthermore, among available analytical approaches in the literature, Zeng et al. (2022)'s approach was selected because it achieved relatively good prediction accuracy among studies in the literature and used the largest dataset for validation. This appendix evaluates and improves the accuracy of Zeng et al.'s (2022) model for obtaining the low-temperature performance graded properties from the DSR for both virgin and RAM binders in NC.

D.2. Methodology

D.2.1. Materials

The evaluation included the 29 asphalt binders characterized as part of this project from 7 plants across North Carolina, including 12 virgin binders and 17 RAM binders, of which there are 3 RAS binders and 14 RAP binders. The RAS binders were blended with the virgin binder before characterization as discussed in Section 2.4.2. The binders and BBR characterization presented herein coincide with the virgin and RAP binder characterization presented in Section 3.3.

D.2.2. Test Methods

As discussed in Section 2.4.2, the BBR test was performed for low temperature characterization by AASHTO T 313 (2022). The RAP and RAS binders were tested at -6°C and -12°C, while the virgin binders were tested at -12°C and -18°C. All BBR tests were conducted by the NCDOT's Materials and Tests Unit.

Temperature-frequency sweep (TFS) tests were performed in a DSR using the 8 mm parallel plate geometry following the general requirements in AASHTO T 315 (2024). The test temperatures were 5°C, 20°C, 35°C, and 50°C, with test frequencies that ranged from 0.1 Hz to 15 Hz for the virgin and RAS blends. The RAP binder was tested at 10°C rather than 5°C to avoid the potential debonding between the sample surface and the parallel plate. However, in Zeng et al.'s (2022) prediction method, only data from 5°C (or 10°C), 20°C, and 35°C are included. The dynamic shear modulus, $|G^*|$, and the phase angle, δ, were measured in the TFS test. Two replicate tests were initially conducted. If the results met the repeatability requirements in AASHTO T 315 (*23*), testing ceased. If the requirement was not met, additional replicate tests were conducted until the requirement was satisfied.

D.2.3. Model Framework

Zeng et al. (2022) 's model framework was applied to predict the low-temperature BBR properties, creep stiffness at 60 seconds, $S(60)$, and the absolute value of the slope of creep stiffness versus time in log space at a loading time of 60 seconds, $m(60)$, from DSR tests. Accordingly, initially, three data quality and preparation steps were conducted: raw data checking, stiffness extrapolation verification, and $|G^*|$ smoothing. The raw data quality checking ensures that results are smooth and continuous by using Cole-Cole plots and Black Space diagrams (Carret et al. 2015). The stiffness extrapolation check determines whether extrapolation is necessary because the converted highest creep stiffness from the DSR test was smaller than the maximum $S(60)$ in the reported BBR test results. To check this, Equation (9) is used to estimate $S(60)$ and the values are compared to the BBR measurements. If the maximum $S(60)$ calculated is smaller than the maximum from the BBR results, it suggests extrapolation is necessary (Zeng et al. 2022), but results can still be estimated. In this study, the blends with the three RAS binders required extrapolation because the calculated maximum $S(60)$ converted from the DSR test results was around 200 MPa, which was smaller than the BBR threshold of 300 MPa. In addition, J#1 and J#2 RAP binders had a minimum $S(60)$ value of 363 MPa and 345 MPa, requiring minor extrapolation. All other binders did not require extrapolation. While these cases where extrapolation is noted, they were analyzed in the same way as the other binders and did not demonstrate larger errors than the remaining binder samples.

$$S(t) = \frac{2(1+\nu)}{J'(\omega)} \tag{9}$$

$$\omega = \frac{2}{\pi t} \tag{10}$$

where: $S(t)$ = creep stiffness; ν = Poisson's ratio; and $J'(\omega)$ = storage shear compliance.

The $|G^*|$ smoothing was achieved by constructing master curves using two steps. First, the time-temperature shift factors for each temperature were determined using the pairwise interpolation method proposed by Fried and Castorena (2022). This approach relies on linear interpolation of $|G^*|$ versus frequency in log–log space between successive isotherms to identify the frequencies at the two isotherms that yield equivalent $|G^*|$ values. Thus, the method requires that adjacent isotherms have an overlapping span of $|G^*|$ values. These differences in these frequencies define the shift factor between the two isotherms of interest. After calculating the shift factor for each pair of isotherms, the time-temperature shift factors, a_T, are calculated relative to a selected reference temperature.

Subsequently, the E_a parameter in the Arrhenius time-temperature shift factor model in Equation (11) and the 2S2P1D model fitting parameters in Equation (12) are optimized simultaneously to minimize the sum of squared errors for storage and loss moduli.

$$\log a_T = \frac{E_a}{2.303R}\left(\frac{1}{273+T} - \frac{1}{273+T_{ref}}\right) \tag{11}$$

where: E_a = the activation energy and a material dependent constant; R = 8.314 J/(K·mol); T = temperature; and T_{ref} = the reference temperature.

$$G^*(\omega) = G_e + \frac{G_g - G_e}{1+\delta(i\omega\tau_0)^{-k} + (i\omega\tau_0)^{-h} + (i\omega\beta\tau_0)^{-1}} \tag{12}$$

where: G^* = complex shear modulus; ω = reduced frequency, equal to the actual frequency multiplied by a_T; G_g = the glassy modulus, fixed as 10^9 Pa in this study; G_e = the static modulus; and δ, τ_0, β, k and h are constant coefficients determined by optimization.

The fitting accuracy of this study was evaluated by calculating the mean absolute percentage error (MAPE). The maximum MAPE of $|G^*|$ among all binders evaluated is 4.79% and the maximum MAPE of the phase angle δ, is 3.05%, indicating good agreement between the measurements and model predictions.

These models smooth the data and enable calculation of properties at any temperature. Since DSR measurements only reach temperatures of 5-10°C, the system uses Arrhenius equation extrapolation to obtain time-temperature shift factors for BBR temperatures using Equation (11)

The general definition of the creep stiffness, $S(t)$ is given in Equation (13). Thus, translating from the above master curve model to $S(t)$ requires conversion from the unit response function $G^*(\omega)$ to $J(t)$.

$$S(t) = \frac{1}{D(t)} = \frac{2(1+\nu)}{J(t)} \tag{13}$$

where: $D(t)$ = flexural creep compliance; ν = Poisson's ratio which Zeng et. al assumed to equal 0.5; and $J(t)$ =shear creep compliance.

Two methods are used to convert from the frequency to the time domain and obtain the desired properties, one for $S(60)$ and a second for $m(60)$ determination. An approximate interconversion method is used to obtain $S(60)$ using idealized relaxation and retardation spectra. In contrast, the $m(60)$ is determined through rigorous computation involving the retardation spectrum conversion. The respective methods were found to be most accurate by Zeng et al. (2022).

The rigorous method converts from the frequency to the time domain through retardation spectrum conversion following Equation (14). The reader is referred to Zeng et al. (2022) for further details on how the $|G^*|$ master curve is used to arrive at this equation. Then, $J(t)$ is input into Equation (13) to calculate $S(t)$ and ultimately $S(60)$. In addition, $S(t)$ is calculated at 8, 15, 30, 60, 120, and 240 seconds, and a second-order polynomial is fit to the log $S(t)$ versus log t results per calculating $m(60)$ by the AASHTO T 313 procedure.

$$J(t) = J_g + \int_{-\infty}^{\infty} L(\tau)(1-e^{-t/\tau})\,d\ln\tau \tag{14}$$

where: J_g = glassy shear compliance; t = time; τ = retardation time; and $L(\tau)$ = retardation spectrum.

The approximate conversion method resembles the rigorous method except for $J(t)$ is obtained from $J'(\omega)$ in frequency domain as originally proposed by Christensen and defined in Equation (15).

$$J(t) = J'(\omega)\Big|_{\omega=\frac{2}{\pi t}} \qquad (15)$$

D.2.3. Empirical Calibration

The BBR parameters, $S(60)$ and $m(60)$, were predicted from the DSR results at each test temperature according to Zeng et al. (2022). That is, Equations (15) and (13) were used to obtain $S(t)$ for determining $S(60)$ and Equations (14) and (13) were used to determine $S(t)$ for obtaining $m(60)$. To improve the prediction of BBR properties, separate linear regression models were calibrated to relate the measured $S(60)$ and $m(60)$ properties from the BBR and those predicted from the DSR. The goal here was to provide an empirical calibration to improve accuracy.

Initially, linear regression models with interaction terms (i.e., an Analysis of Covariance (ANCOVA)) were developed for $S(60)$ and $m(60)$ using all the data. This initial regression analysis was used to assess whether there was a bias in the relationship between measured and predicted values between the virgin and RAM binders. Equation (16) shows the general form of the regression model.

$$Measured = \beta_0 + \beta_1 \times Predicted + \beta_2 \times Group + \beta_3 \times Group \times (Predicted - Mean_{Predicted}) \qquad (16)$$

where: *Measured* = measured parameter value from the BBR test; *Predicted* = predicted parameter value from the DSR test; *Group* = dataset indicator (Group 1 = virgin binders, assigned a value of 0, Group 2 = RAM binders, assigned a value of 1); $Mean_{Predicted}$ = mean predicted value among the two groups; β_0 = intercept for the virgin binder group; β_1 = slope for the virgin binder group; β_2 = change in intercept for the RAM binder group; and β_3 = change in slope for the RAM binder group.

Model significance was evaluated at a significance level of $\alpha = 0.05$. A statistically significant β_0 indicates a nonzero intercept, while a significant β_1 confirms that the slope parameter is significant. A significant β_2 suggests the intercept differs between the virgin and RAM binder groups, and a significant β_3 indicates a difference in slope between the two groups. Equations were fit to the relationship between measured and predicted properties.

Subsequently, linear regression equations were calibrated without interaction terms according to the findings of the initial regression analysis (i.e., if the slopes were found to be different between groups, separate slopes were calculated for the virgin and RAM binder groups). To enable both optimization and testing of these empirical calibrations, these regression equations were calibrated using 80% of the study binders. To ensure the verification binders are independent from the calibration binders, the binders sampled only once from a given plant were selected for verification, which means in the calibration binders, there are no binders from the same plants as the verification binders.

D.2.4. Calibrated Model Evaluation

The prediction accuracy of the calibrated models was evaluated by comparing the predicted continuous low grading temperatures (CPG) calculated according to ASTM D7643 (2022) and ΔT_c calculated according to AASHTO R118 (2023) values from DSR test results with those determined from BBR measurements. To determine these parameters, the continuous grading temperatures for

$S(60)$ and $m(60)$ are first calculated, termed $T_{c,s}$ and $T_{c,m}$, respectively. $T_{c,s}$ represents the CPG based on $S(60)$ values at two temperatures and is calculated using Equation (17). $T_c(m)$ represents the CPG based on $m(60)$ values at two temperatures and is calculated using Equation (18). Once these values are obtained, ΔT_c is calculated using Equation (19). The final CPG determination follows a conditional criterion based on the ΔT_c sign: when $\Delta T_c > 0$, CPG = $T_{c,s}$; when $\Delta T_c < 0$, CPG = $T_{c,m}$.

$$T_{c,s} = T_x + \left[\frac{(T_x - T_y) \times (\log 300 - \log S_x)}{\log(S_x) - \log(S_y)} \right] - 10 \quad (17)$$

where: T_x = a lower temperature; T_y = a higher temperature; S_x = the $S(60)$ at a specific temperature T_x; and S_y = the $S(60)$ at a specific temperature T_y.

$$T_{c,m} = T_x + \left[\frac{(T_x - T_y) \times (0.300 - m_x)}{m_x - m_y} \right] - 10 \quad (18)$$

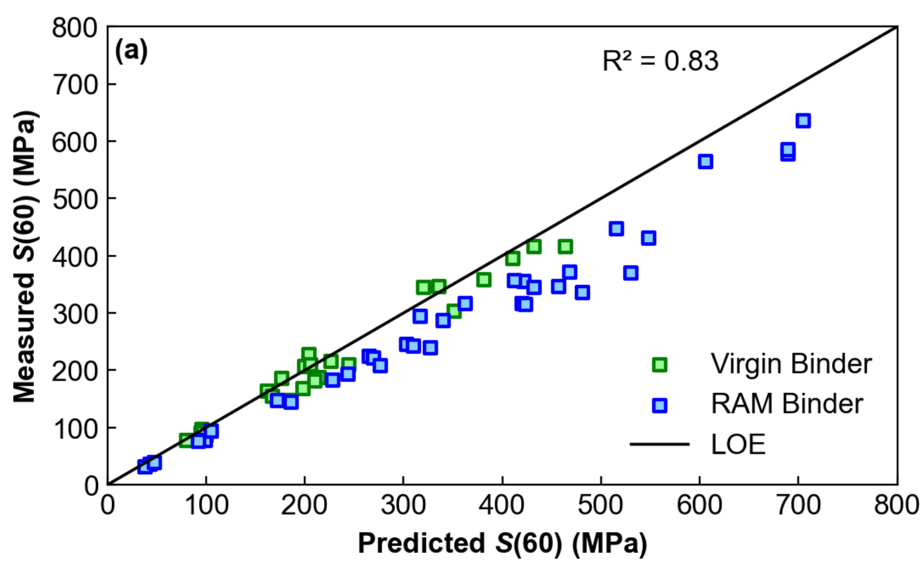
where: m_x = the $m(60)$ at a specific temperature T_x; and S_y = the $m(60)$ at a specific temperature T_y,

$$\Delta T_c = T_{c,s} - T_{c,m} \quad (19)$$

D.3. Results

D.3.1. Model Prediction without Calibration

This section presents the comparison of DSR-predicted and BBR-measured properties. The DSR-predicted values were calculated without any calibration. Figure 35 (a) and (b) show the comparison of measured and predicted $S(60)$ and $m(60)$, respectively. A small bias is visually evident between virgin binders and RAM binders when comparing the measured and predicted $S(60)$ values. The virgin binders exhibit closer agreement with the line of equality than the RAM binders. In general, the DSR-predicted $S(60)$ values tend to be higher than the measured values, while the $m(60)$ values tend to be underestimated. The coefficient of determination (R^2) concerning the line of equality for $S(60)$ and $m(60)$ is 0.83.



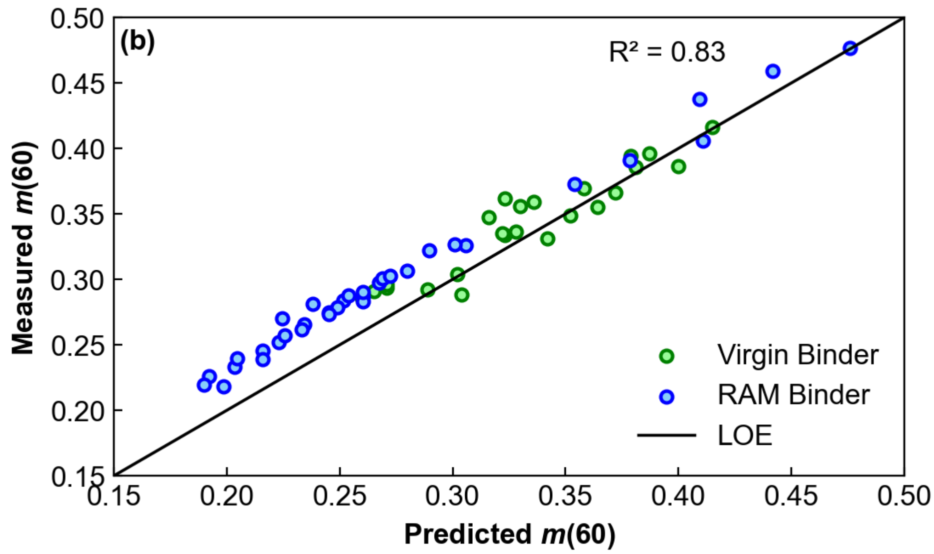


Figure 35. Comparison of *S*(60) and *m*(60) from DSR-predicted and BBR-measured; (a) *S*(60), (b) *m*(60).

Figure 36 presents the comparison of CPG values calculated based on BBR measurements and DSR predictions without calibration. The results show a bias between the virgin binder and RAM binders. Virgin binders are well aligned along the line of equality, while a bias exists for the RAM binders. However, the overall R^2 with respect to the line of equality is 0.82. The CPGs of the RAM binders were all *m*-controlled (meaning ΔT_c *is* less than zero), whereas only one virgin binder was *m*-controlled, which seems to at least partially explain the observed bias. Interestingly, there are three RAM binder results that align with those of the virgin binders. They are all RAS binders, which were blended with virgin binders before being measured. Therefore, their CPG values are closer to those of virgin binders. However, even though the RAS percentages are from 12% to 16%, the impact is still noticeable, with all RAS binders being *m*-controlled like the RAP binders.

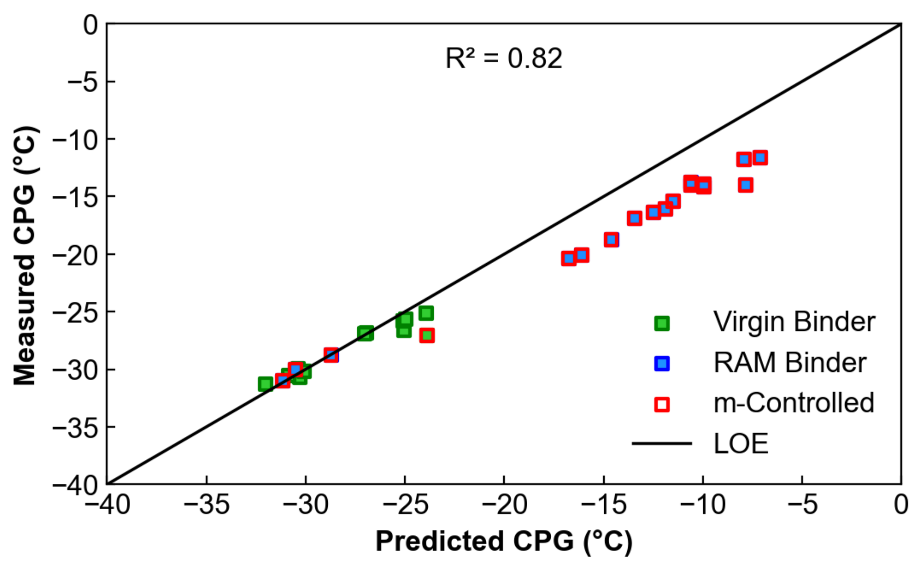


Figure 36. Comparison of CPG from DSR-predicted and BBR-measured.

Figure 37 presents the comparison of ΔT_c values calculated based on BBR measurements to those calculated based on DSR predictions. The prediction accuracy is not as good as for *S*(60), *m*(60), and CPG, with an R^2 with respect to the line of equality of 0.54. The virgin binder and RAM binder ΔT_c values are distinct. Most measured ΔT_c values of the virgin binders are greater than zero, while all RAM binders have ΔT_c values less than zero. This aligns with the virgin binders being *S*-controlled and RAM binders being *m*-controlled, as shown in Figure 36.

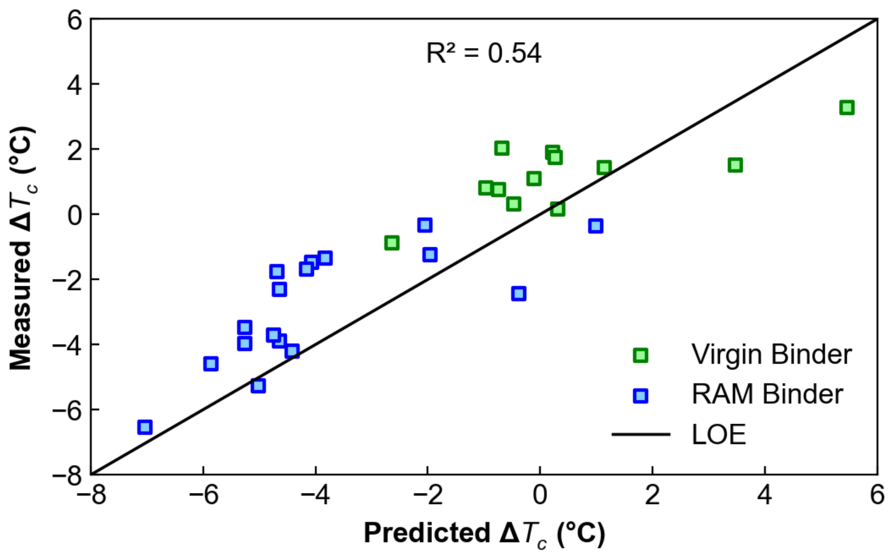


Figure 37. Comparison of ΔT_c from DSR-predicted and BBR-measured.

D.3.2. Linear Regression with Interactions

Table 35 presents the linear regression with interaction terms results obtained using Equation (16). P-values less than 0.05 are deemed significant. The results indicate that the virgin binder intercept (β_0) and slope (β_1) parameters are significant, except for the intercept term for *S*(60). Furthermore, the results indicate that both the slopes and intercepts of the relationships between BBR measurements and DSR predictions of *S*(60) values are significantly different for the virgin binder and RAM binder groups based on the interaction terms β_2 and β_3. For *m*(60) values, the slopes of the virgin and RAM binder groups do not differ significantly based on the β_3 parameter p-values, but the intercepts are different based on the β_2 p-values. Based on these results, the linear regression equations for *S*(60) and *m*(60) were fitted separately for virgin binders and RAM binders, using a consistent slope for virgin and RAM binder groups when developing the *m*(60) regression equations. In addition, given that β_0 is insignificant, linear regression equations for S(60) were evaluated using intercept terms and fixed intercepts of zero.

Table 35. Linear regression with interactions results.

Parameter	Equation Term	Estimate	p-value
S(60)	Intercept Virgin (β_0)	-3.273	0.6522
	Slope Virgin (β_1)	0.891	<0.0001
	Intercept Interaction (β_2)	-20.396	<0.0001
	Slope Interaction (β_3)	-0.0511	0.0450
	$Mean_{Predicted}$	299.726	NA
m(60)	Intercept Virgin (β_0)	0.0592	<0.0001
	Slope Virgin (β_1)	0.8693	<0.0001
	Intercept Interaction (β_2)	0.0043	0.0112
	Slope Interaction (β_3)	0.03518	0.1997
	$Mean_{Predicted}$	0.2978	NA

D.6.3. Empirical Calibrations

This section presents the linear regression equations identified to improve the accuracy of S(60) and m(60) predictions from DSR test results for virgin binders and RAM binders, respectively. To enable both optimization and testing of these empirical calibrations, the equations were fit using 80% of the study binders that were independent from others.

Figure 38 shows the best-fit lines for relating measured and predicted S(60) of virgin binders and RAM binders. For virgin binders, the slope of the measured versus predicted S(60) is 0.95, and the intercept is -5.79, while for RAM binders, the slope is 0.83, and the intercept is -2.90. Since the intercept terms are small relative to the magnitude of the measured S(60) values, and the linear regression with interaction terms suggested that the intercept is insignificant for the virgin binder group, regression equations were also fitted using a fixed intercept of zero. Given that the regression equations with and without intercept terms produced identical R^2 values relative to the line of equality for both the virgin and RAM binder groups, the intercept is deemed unnecessary.

Building on Equation (13), the calibrated $S(t)$ equations with the fixed intercept of zero can be conveyed by Equation (20). Equation (20) shows that an alternative way to implement this calibration is through an update to Poisson's ratio. Zeng et al. (2022) used a Poisson's ratio of 0.5, citing Di Benedetto et al. (2007). Di Benedetto et al. (2007) reported Poisson's ratios of asphalt binders spanning from 0.35 at low temperatures and/or high frequencies to 0.50 at high temperatures and/or low frequencies for a single 50/70 penetration-graded virgin binder.

$$S(t)_{calibrated} = \frac{2(1+\nu_{=0.5})}{J(t)} \times slope = \frac{2(1+\nu_{calibrated})}{J(t)} \tag{20}$$

Where: $S(t)_{\text{calibrated}}$ = calibrated creep stiffness prediction from the DSR test; $\nu_{=0.5}$ = Poisson's ratio, assumed to equal 0.5; *slope* = slope of the best fix line between DSR-predicted $S(t)$ without calibration and BBR measurements; and $\nu_{\text{calibrated}}$ = refined Poisson's ratio to provide equivalent $S(t)$ to that with Poisson's ratio set at 0.5 and the slope calibration.

Accordingly, the calibrated slopes of 0.93 for virgin binders and 0.82 for RAM binders in Figure 38 are equivalent to changing Poisson's ratio in Equation (13) from 0.5 to 0.40 and 0.23 for virgin and RAM binders, respectively. The trend in Poisson's ratio values is deemed reasonable among virgin and RAM binders based on the literature, which shows that stiffer asphalt binders exhibit lower Poisson's ratio values. However, it is noted that the RAM value is lower than those reported in the literature (Di Benedetto et al. 2007, Kim et al. 2025). Kim et al. (2025) showed that at –5°C, a penetration grade 30/45 asphalt binder maintained a relatively constant complex Poisson's ratio of 0.26 ± 0.04 across different frequencies. In contrast, the softer penetration grade 50/70 asphalt binder exhibited slightly higher values that varied with frequency, ranging from 0.32 ± 0.04 at 10 Hz to 0.30 ± 0.04 at 0.1Hz, near the lower end of the range reported by Di Benedetto et al. (2007). Given that these were virgin binders, it seems plausible that the RAM binders may exhibit lower values than those reported in the literature. It is recommended that the empirical calibration of *S*(60) be adopted using updates to Poisson's ratios in Equation (13).

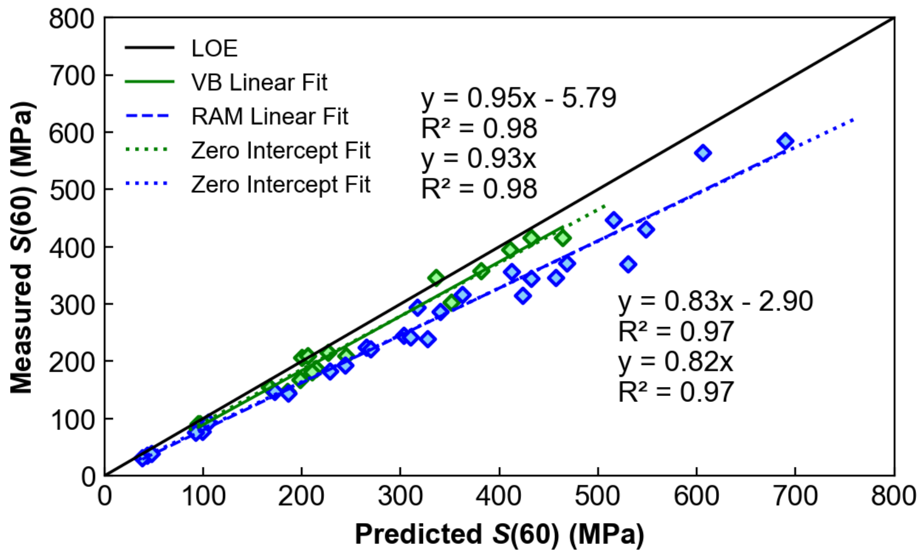


Figure 38. Linear fit equations of *S*(60) for virgin binder and RAM binder separately.

Figure 39 shows the comparison between BBR measurements and DSR predictions of *S*(60) using updated Poisson's ratios of 0.40 for virgin binders and 0.23 for RAM binders in Equation (13). The calibration improved the R^2 for the line of equality from 0.83 without calibration to 0.97. In addition, the R^2 values concerning the line of equality are similar for the calibration and verification data sets. The R^2 for the 80% study binders used to calibrate the regression equations with respect to the line of equality is 0.98, while the R^2 for the line of equality for the remaining 20% of the data used for verification is 0.96.

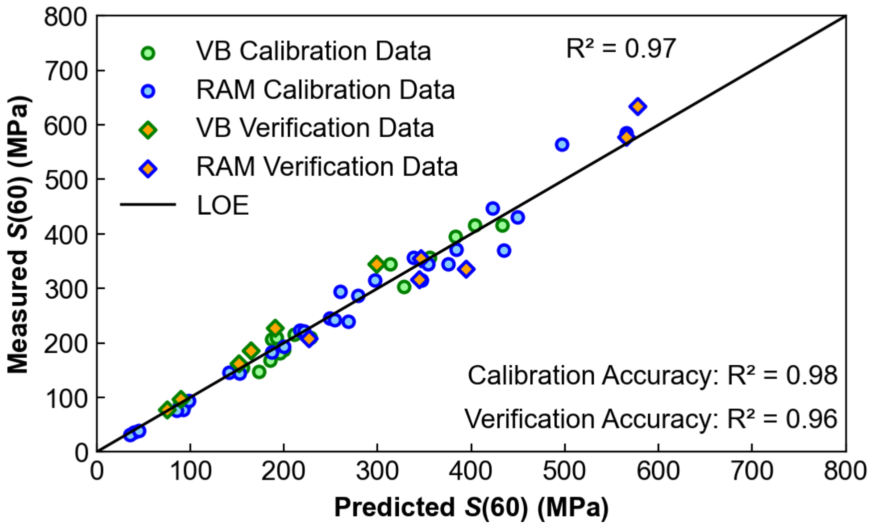


Figure 39. Comparison of predicted and measured *S*(60) with Poisson's ratio = 0.40 for virgin binders and Poisson's ratio = 0.23 for RAM binders.

Table 35 indicates that the slope of the relationship between BBR measurements and DSR predictions of *m*(60) values does not differ between virgin and RAM binders; however, the two groups exhibit different intercepts. Accordingly, the calibrated equations for predicting *m*(60) using DSR measurements were made using a common slope with distinct intercepts for each binder type. To determine these parameters, a least squares optimization was performed in which the two intercepts (for virgin and RAM binders) and a single slope parameter were simultaneously estimated. The objective function minimized the sum of squared errors between the measured *m*(60) values and those predicted by the calibrated equations for both binder groups. Figure 40 shows the resultant calibrated equations and their accuracy. This analysis yielded a slope of 0.8924 and an intercept of 0.0492 for virgin binders and 0.0563 for RAM binders. It is noted that the predicted *m*(60) value is insensitive to the chosen Poisson's ratio since *m*(*t*) is the slope of the log *S*(*t*) versus log(*t*) curve.

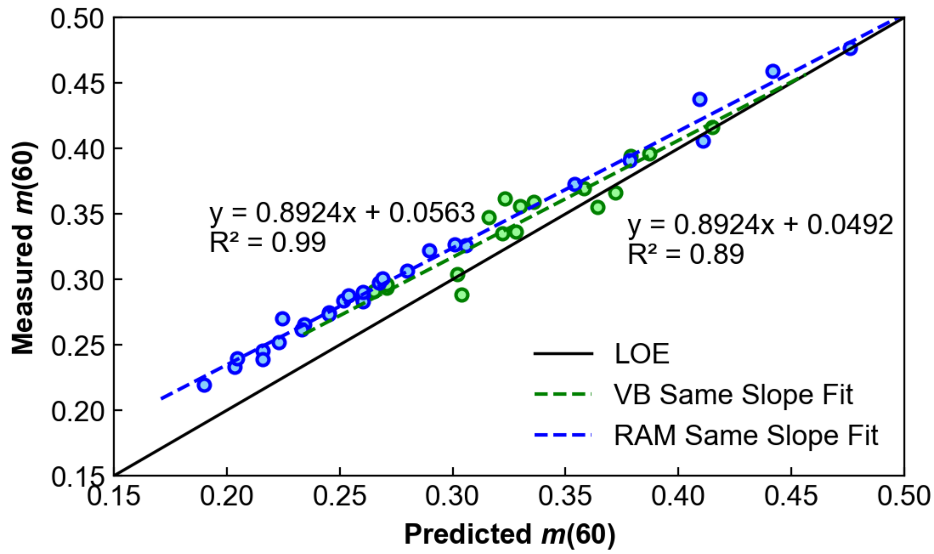


Figure 40. Linear fit equations of *m*(60) of virgin and RAM binder separately with a constrained slope.

Figure 41 shows the comparison of measured BBR *m*(60) values and those from the calibrated DSR predictions for all binders. The calibrations improved the R^2 with respect to the line of equality from 0.83 to 0.97 for the collective data. Additionally, the R^2 with respect to the line of equality is comparable for the calibration and verification data sets. 80% of the study binders used to calibrate the regression equations have an R^2 with respect to the line of equality of 0.97, while the R^2 for the line of equality for the remaining 20% of the data used for verification is 0.95.

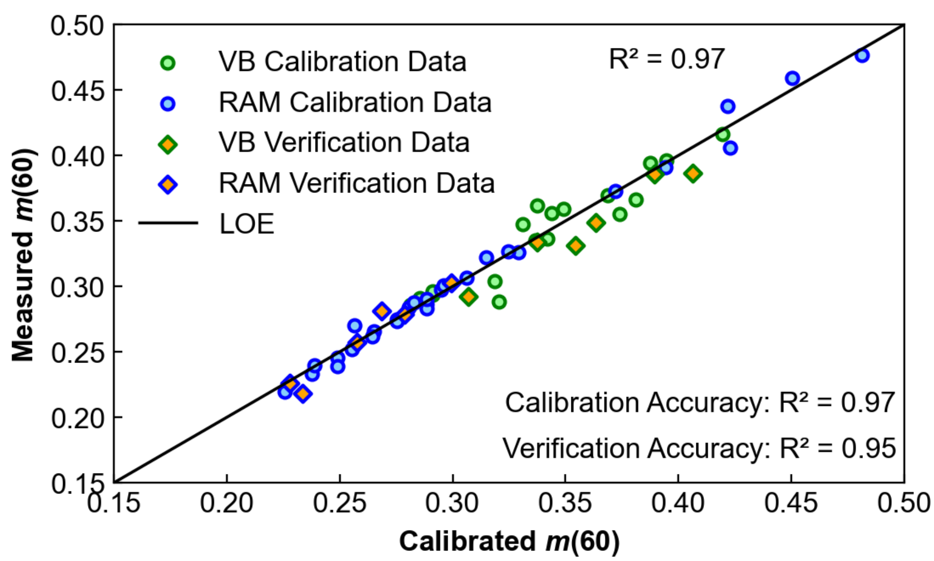


Figure 41. Comparison of linear calibrated and measured *m*(60).

D.3.4. Evaluation of the Calibrated Models

Based on the results presented in the previous section, Equation (21) is suggested for the prediction of *S*(60) using DSR test results and Equations (22) and (23) are suggested for the prediction of *m*(60) values for virgin and RAM binders, respectively, from DSR test results.

$$S(t) = \frac{2(1+\nu)}{J'\left(\omega = \frac{2}{\pi t}\right)} \tag{21}$$

where: ν = 0.40 for virgin binders and 0.23 for RAM binders.

$$m(60) = 0.0492 + 0.8924 \times m_{predicted} \tag{22}$$

$$m(60) = 0.0563 + 0.8924 \times m_{predicted} \tag{23}$$

Where: $m_{predicted}$= *m*(60) predicted from DSR test results using *S*(*t*) values calculated using Equations (13) and (14) with ν values of 0.40 and 0.23 for virgin and RAM binders, respectively, for consistency with the *S*(60) calcualtions. However, it is noted that the *m*(60) does not depend on Poisson's ratio.

Figure 42 shows the comparison between the CPG values calculated using BBR test results to those calculated based on the above equations. The R^2 with respect to the line of equality for the entire data set improved from 0.82 without calibration to 0.98 with calibration. Furthermore, the verification data set maintains a high R^2 with respect to the line of equality of 0.96. Figure 43 provides another visual means to compare CPGs determined from BBR results versus those from the calibrated DSR predictions. The average error in CPG is –0.02°C, the average absolute error is 0.69°C, and the maximum error is 2.6°C.

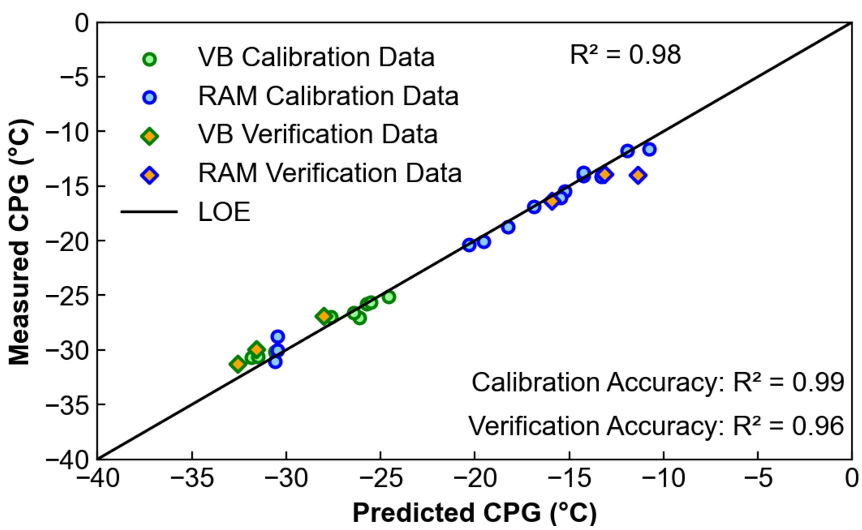


Figure 42. Comparison of calibrations, predictions and measured CPG values.

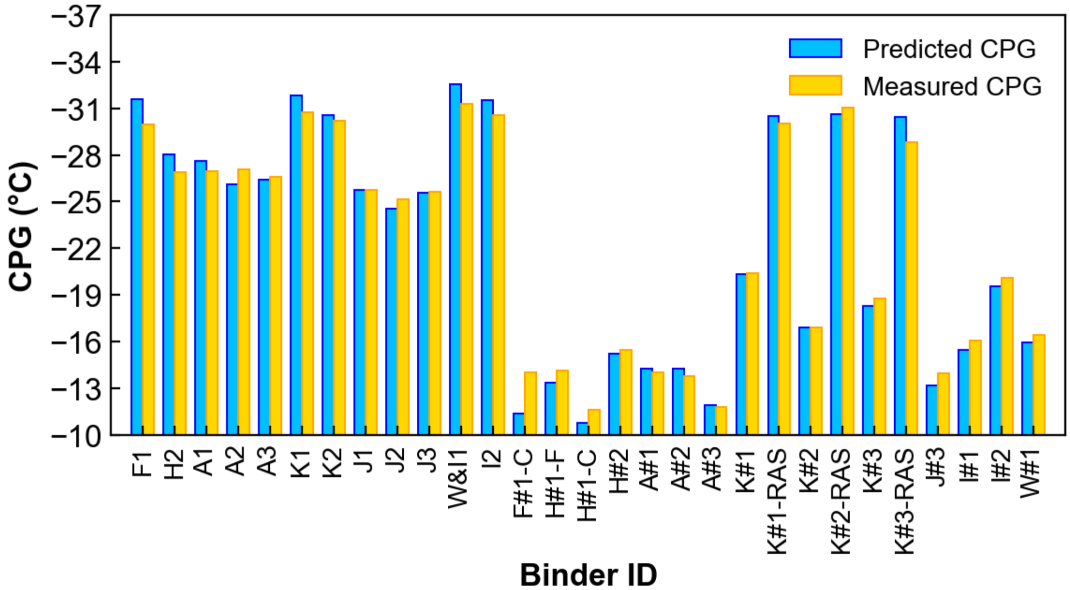


Figure 43. Comparison of calibrated, predictions and measured CPGs for each binder.

Figure 44 shows the corresponding relationships between ΔT_c determined using the BBR and calibrated DSR predictions, indicating an R^2 of 0.63 concerning the line of equality. This is a moderate improvement in the prediction of ΔT_c compared to that without any calibration, where the R^2 was 0.54, but it is still not as good as the other parameters evaluated.

To further evaluate the potential implications of the errors in ΔT_c predictions, the determination of passing vs. failing the limits established by Elwardany et al. (2022) as part of NCHRP Project 09-60 was evaluated. They proposed: (1) accepting all binders with ΔT_c > -2°C, (2) rejecting all binders with ΔT_c < -6°C, and (3) accept binders with ΔT_c values between the critical range of -6°C and 2°C only if cracking resistance is verified via the Asphalt Binder Cracking Device (ABCD) test. Correspondingly, the decision whether a binder is accepted, rejected, or in the critical range based on the calibrated DSR predictions was compared to that from BBR measurements.

The calibrated DSR predictions identified the same decision for 23 out of the 29 binders evaluated based on these criteria. One binder that failed based on the BBR measurements was identified as being in the critical range based on the calibrated DSR predictions. In addition, four binders that were accepted based on BBR results were identified as falling in the critical zone based on the calibrated DSR predictions, and one binder that fell in the critical range based on BBR results was identified as acceptable based on the calibrated DSR predictions.

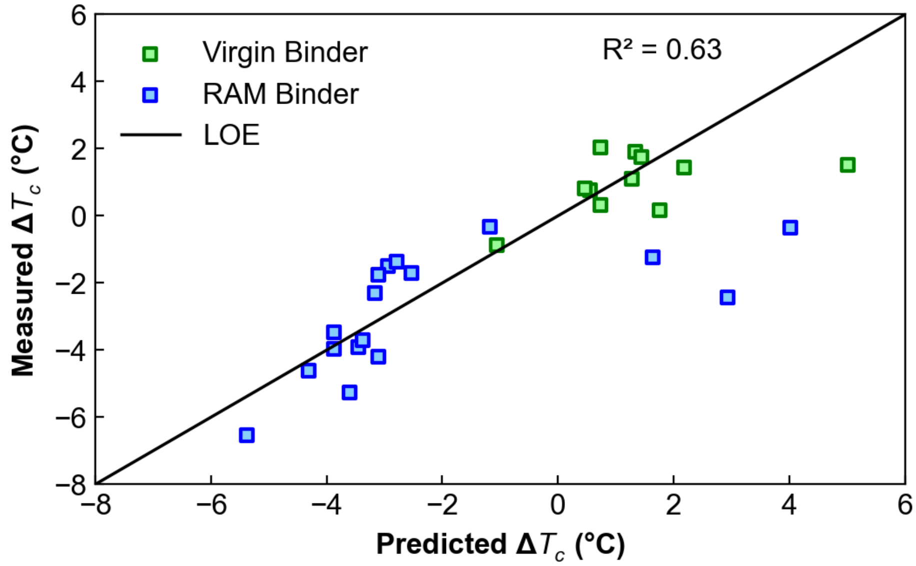


Figure 44. Comparison of the calibrated, predictions and measured ΔT_c values .

a. **Conclusions and Recommendations**

The following conclusions and recommendations are drawn from the results of this Appendix:

- Using Zeng et al.'s (2022) approach without empirical calibration, the prediction accuracy for *S*(60) and *m*(60) both achieved an R^2 of 0.83 relative to the line of equality, while the CPG accuracy yielded an R^2 of 0.82 with respect to the line of equality.
- The linear regression-based calibrations developed in this Appendix, specific to RAM and virgin binders, improved the prediction accuracy of the DSR predictions of BBR test results with an R^2 with respect to the line of equality of 0.97 for both *S*(60) and *m*(60). The average absolute error in continuous low-grading temperature predictions was 0.7°C. The empirical calibration for *S*(60) suggests that Poisson's ratio is approximately 0.40 for virgin binders and 0.23 for RAM binders at the BBR test conditions.
- Predictions of ΔT_c were poorer than those for *S*(60), *m*(60), and the continuous low grading temperature. Future research should evaluate alternative parameters that could serve as more reliable predictors than ΔT_c from DSR test results.
- The calibrated equations provide a promising means to predict BBR properties using DSR test results. It is suggested that the calibrations be validated using a broader data set. Notably, this study did not consider polymer-modified binders.

Cited References

AASHTO. 2022. *Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR) (T 313).* Washington, D.C.: American Association of State Highway and Transportation Officials.

AASHTO. 2023. *Standard Practice for Characterizing the Relaxation Behavior of Asphalt Binders Using the Delta Tc (ΔTc) Parameter (R 118).* Washington, D.C.: American Association of State Highway and Transportation Officials.

AASHTO. 2024. *Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR) (T 315).* Washington, D.C.: American Association of State Highway and Transportation Officials.

ASTM International. 2022. *Standard Practice for Determining Continuous Grading Temperatures for Performance Graded Asphalt Binders (D 7643).* West Conshohocken, PA.

Carret, J.-C., A. C. Falchetto, M. O. Marasteanu, H. Di Benedetto, M. P. Wistuba, and C. Sauzeat. 2015. "Comparison of Rheological Parameters of Asphalt Binders Obtained from Bending Beam Rheometer and Dynamic Shear Rheometer at Low Temperatures." *Road Materials and Pavement Design*, 16 (sup1): 211–227. https://doi.org/10.1080/14680629.2015.1029696.

Di Benedetto, H., B. Delapore, and C. Sauzeat. 2007. "Three-Dimensional Linear Behavior of Bituminous Materials: Experiments and Modeling." *ASCE International Journal of Geomechanics*, 7(2), 149-157. https://doi.org/10.1061/(ASCE)1532-3641(2007)7:2(149)

Elwardany, M. D., J.P. Planche, and G. King. 2022. "Proposed Changes to Asphalt Binder Specifications to Address Binder Quality-Related Thermally Induced Surface Damage." *Transportation Research Record*, 2676(5), 176-191. https://doi.org/10.1177/03611981211065428

Fried, A., L. G. Xue, S. Gulzar, J. Preciado, B. S. Underwood, and C. Castorena. 2022. "Evaluation of Recycling Agent and Extender Dosage Selection Procedures to Restore the High-Temperature Climatic Performance Grade." *Transportation Research Record* 2676 (6): 302–314. https://doi.org/10.1177/03611981221074361.

Hajj, R., A. Filonzi, S. Rahman, and A. Bhasin. 2019. "Considerations for Using the 4 Mm Plate Geometry in the Dynamic Shear Rheometer for Low Temperature Evaluation of Asphalt Binders." *Transportation Research Record: Journal of the Transportation Research Board* 2673 (11): 649–659. https://doi.org/10.1177/0361198119855332.

Kim, Y. S., J. R. Agudo, M. P. Wistuba, J. Büchner, and M. Schäffler. 2025. "Determination of Complex Poisson's Ratio of Asphalt Binders Using Torsion-Tension Tests in a Dynamic Shear Rheometer." *Road Materials and Pavement Design* 26 (2): 397–419.

Lu, X., P. Uhlback, and H. Soenen. 2017. "Investigation of Bitumen Low Temperature Properties Using a Dynamic Shear Rheometer with 4 Mm Parallel Plates." *International Journal of Pavement Research and Technology* 10 (1): 15–22. https://doi.org/10.1016/j.ijprt.2016.08.010.

Sui, C., M. J. Farrar, P. M. Harnsberger, W. H. Tuminello, and T. F. Turner. 2011. "New Low-Temperature Performance-Grading Method: Using 4-Mm Parallel Plates on a Dynamic Shear Rheometer." *Transportation Research Record: Journal of the Transportation Research Board* 2207 (1): 43–48. https://doi.org/10.3141/2207-06.

Zeng, Z., B. S. Underwood, and C. Castorena. 2022. "Low-Temperature Performance Grade Characterisation of Asphalt Binder Using the Dynamic Shear Rheometer." *International Journal of Pavement Engineering* 23 (3): 811–823. https://doi.org/10.1080/10298436.2020.1774766.

APPENDIX E: ALTERNATIVE RHEOLOGICAL INDICATORS OF DURABILITY

Figure 45 shows the G-R parameter values at 25°C and 10 rad/s for the (a) RAP binders, (b) virgin binders, and (c) estimates for the blended binders. Higher G-R parameter values are generally associated with poorer cracking resistance (Christensen and Tran 2020). The trends among binders in Figure 45 closely mirror those for PGI in Section 3.3. The AASHTO M 320 PGI parameter $|G^*|\times\sin(\delta)$ and the G-R parameter exhibit a Pearson correlation coefficient of 0.96 across the study binders, indicating they provide nearly equivalent assessments of relative cracking resistance. Notably, most of the blends incorporating PG 64-22, corresponding to Plants A, H, and J, exceed the 5,000 kPa G-R limit proposed in the NCHRP 09-59 project for controlling fatigue cracking.

Figure 46 shows the phase angle values at the condition where $|G^*|$ = 10 MPa for the (a) RAP binders, (b) virgin binders, and (c) estimates for the blended binders. Trends in this parameter differ from those observed for $|G^*|\times\sin(\delta)$ and G-R, which is consistent with previous studies reporting that the phase angle provides complementary rather than redundant information (Mogawer et al. 2025). However, some results appear counterintuitive. For instance, there is an overlap in the span of phase angle values between the virgin and RAP binder groups despite the RAP binders being more aged, with lower expected phase angle values for a given $|G^*|$ condition. Moreover, RAP binders and blends from Plant J consistently exhibit the highest phase angle values, which would typically indicate better cracking resistance. Yet, all other intermediate- and low-temperature parameters suggest these binders are among the worst performers. These inconsistencies suggest that while the phase angle at $|G^*|$ = 10 MPa may offer useful insights, its application as a standalone indicator for binder cracking resistance requires further investigation and validation.

Figure 47 shows the ΔT_c values for the (a) RAP, (b) virgin, and (c) blended binders. Figure 47 (a) shows the RAP binder ΔT_c values span from -6.5°C to 1.7°C. Many cases fall above -2°C, which was recommended as a warning limit for virgin binders in NCHRP 09-60 (Elwardany et al. 2022). Much like phase angle results, the Plant J results ΔT_c values seem to suggest potentially better relaxation properties than the other RAP samples and contradict other parameter findings. Figure 47 (b) shows the virgin binder ΔT_c values span from -0.9°C to 3.3°C, all exceeding typical limits. Figure 47 (c) shows the blended binder ΔT_c values span from -2.3°C to 1.7°C, again indicating generally acceptable values. The highest values coincide with Plant J, which aligns with phase angle findings but is in contradiction to the other intermediate- and low-temperature properties evaluated. The ΔT_c and phase angle values at the condition where $|G^*|$ = 10 MPa were moderately correlated for the virgin and RAP binders with a Pearson coefficient of 0.6.

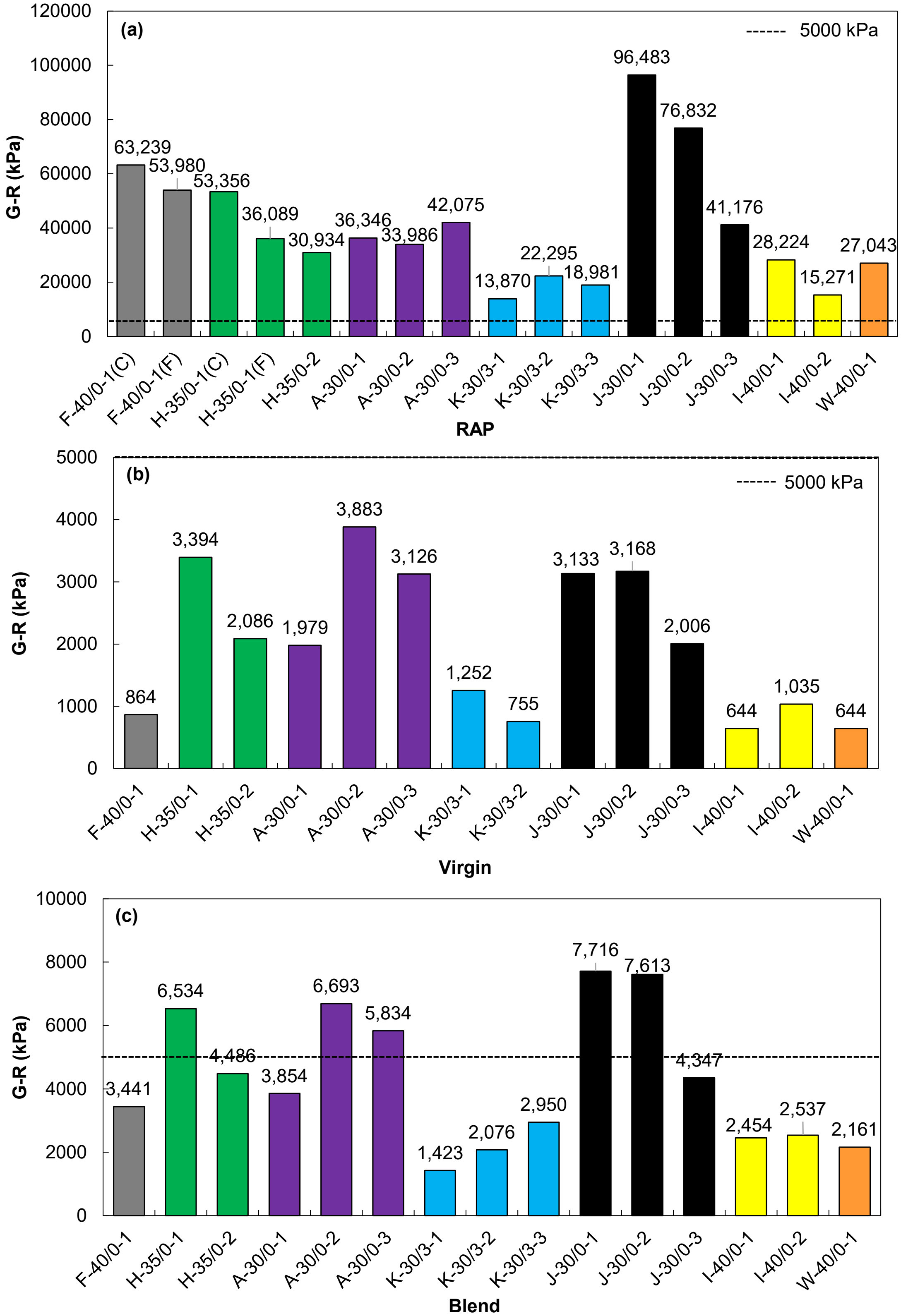


Figure 45. Glover-Rowe (G-R) parameters at 25°C for (a) RAP binders, (b) virgin binders, and (c) blended binders.

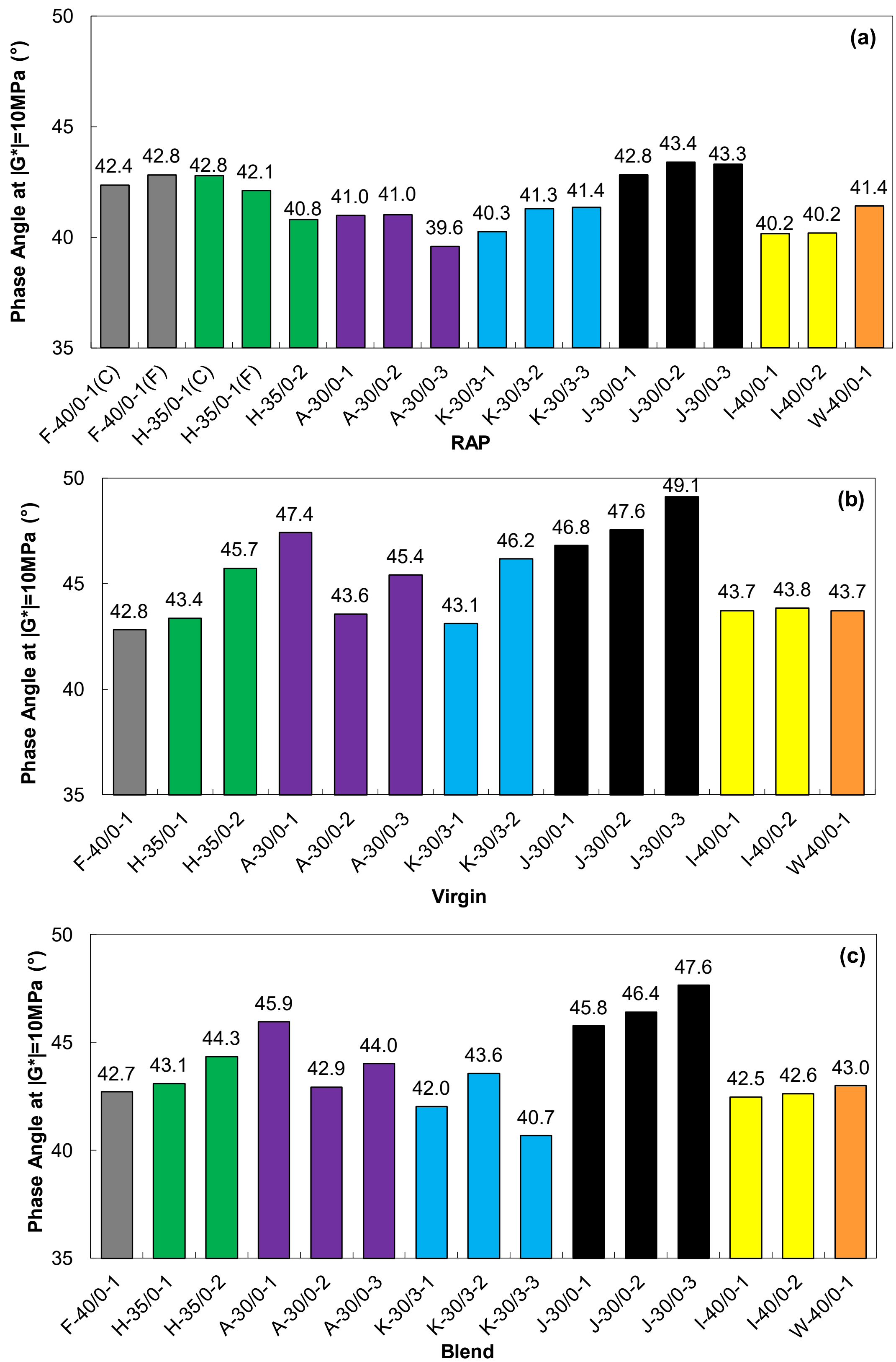


Figure 46. Phase angle at |*G| = 10 MPa for (a) RAP binders, (b) virgin binders, and (c) blended binders.**

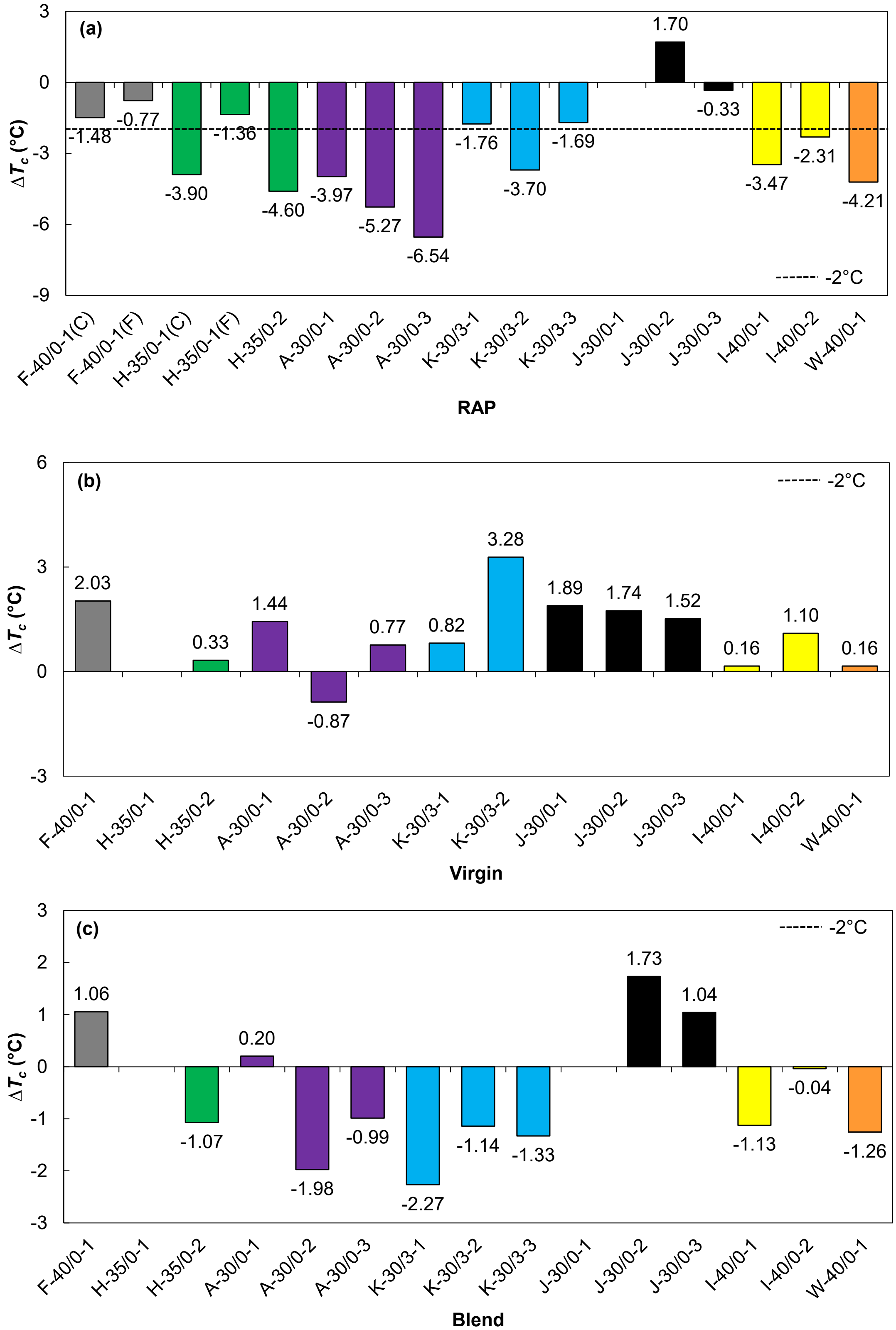


Figure 47. ΔT_c for (a) RAP binders, (b) virgin binders, and (c) blended binders.

Cited References

Elwardany, M. D., J.P. Planche, and G. King. 2022. “Proposed Changes to Asphalt Binder Specifications to Address Binder Quality-Related Thermally Induced Surface Damage.” *Transportation Research Record*, 2676(5), 176-191. https://doi.org/10.1177/03611981211065428

Mogawer, W., G. Rowe, I. Abdalfattah, and A. Austerman. 2025. “Evaluating Asphalt Binder Quality: Point and Shape Rheological Parameters for Assessing Intermediate Temperature Cracking Susceptibility.” Accepted for publication in *Transportation Research Record*.