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Determining the Effect on Asphalt Mixture Performance by Increasing New Asphalt Binder Content Due to Inactive RAP Binder in the Mixture

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16. Abstract

The project aimed to determine the impact of adding additional virgin binders in consideration of recycled binder availability (RBA) on the performance of asphalt mixtures containing reclaimed asphalt pavements (RAP). To that end, a literature review was first conducted to select a suitable RBA value (i.e., 80%) for RBA mixtures in Florida, followed by a laboratory testing plan to characterize the performance properties of RAP mixtures and their corresponding extracted asphalt binders, with and without RBA adjustment. Overall, the results indicated that adding additional virgin binders in consideration of reduced RAP binder availability improved the cracking resistance but reduced the rutting resistance of RAP mixtures (and extracted binders), and these impacts were more pronounced at 40% RAP content than at 20% RAP content. With RBA adjustment, the 20% RAP mixtures with a Performance Grade (PG) 76-22 polymer-modified binder had similar cracking resistance but significantly better rutting resistance than the 40% RAP mixtures with a PG 52-28 binder. The performance diagram analysis showed that the 20% RAP mixtures at the RBA-adjusted optimum binder content had balanced rutting and cracking resistance while the 40% RAP mixtures had inadequate rutting resistance. Nevertheless, the 40% RAP mixtures may not necessarily be prone to rutting in the field because they are not used in the surface layer. A cost-benefit analysis was conducted to determine the required pavement life extension to offset the cost of adding additional virgin binders in consideration of RBA for RAP mixtures. Based on these results and findings, it is suggested that the Florida Department of Transportation implement 80% RBA for mix design and production of RAP mixtures to improve the long-term cracking performance and longevity of asphalt pavements in Florida.

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EXECUTIVE SUMMARY

The Florida Department of Transportation (FDOT) is interested in improving the durability and cracking performance of asphalt mixtures containing reclaimed asphalt pavements (RAP) by addressing recycled binder availability (RBA). RBA is defined as "the amount of recycled binder from RAP, or reclaimed asphalt shingles (RAS) if used, that activates and contributes to the total effective binder content in an asphalt mixture" and is often expressed as a percentage ranging from 0% to 100%. To compensate for the "inactivated" asphalt binder in RAP, additional virgin binder needs to be added to the mixture, which can improve its cracking resistance and durability. The amount of additional virgin binder added depends on the RBA value, the RAP content of the mixture, and the asphalt binder content of the RAP. For a given RAP mixture, a lower RBA value requires more virgin binder to be added and vice versa.

This project aimed to determine the impact of adding additional virgin binders in consideration of reduced RAP binder availability on the rutting resistance, cracking resistance, and overall durability of RAP mixtures in Florida. To that end, a literature review on RBA was first conducted to select an appropriate RBA value for the RAP materials in Florida, followed by a laboratory testing plan to characterize the performance properties of the RAP mixtures and their extracted asphalt binders, with and without considering RBA.

A critical review of the existing literature on RBA suggested that 80% is an appropriate RBA value for the RAP mixtures in Florida, which indicates that during mixture production, 80% of the asphalt binder in RAP can be "activated," while the other 20% remains "inactivated" and behaves as "black rock." With 80% RBA, approximately 0.23% and 0.45% additional virgin binders were added respectively into the 20% and 40% RAP mixtures used in the project for performance evaluation.

The laboratory testing plan covered mixture performance testing and extracted binder testing. The former included the Indirect Tensile Asphalt Cracking Test (IDEAL-CT), Overlay Test (OT), and Cantabro Test for cracking resistance and durability evaluation; and the Hamburg Wheel Tracking Test (HWTT), Asphalt Pavement Analyzer (APA), and Indirect Tensile Asphalt Rutting Test (IDEAL-RT) for rutting evaluation. Overall, the results showed that adding additional virgin binders in consideration of reduced RAP binder availability improved the cracking resistance and durability but reduced the rutting resistance of RAP mixtures. These impacts were more pronounced for the 40% RAP mixtures than the 20% RAP mixtures, which was expected considering the amount of additional virgin binders added in these mixtures. The mixture performance results also showed that after increasing the optimum binder content in consideration of RBA, the 20% RAP mixtures with a Performance Grade (PG) 76-22 polymer-modified asphalt (PMA) binder and the 40% RAP mixtures with a PG 52-28 unmodified binder had similar cracking resistance and durability, but the 20% RAP mixtures were significantly more rutting resistant than the 40% RAP mixtures, which can be attributed to the PG 76-22 PMA binder. The mixture performance diagram analysis [using FDOT's HWTT criterion and the suggested IDEAL-CT and OT criteria from the top-down cracking group experiment at the National Center for Asphalt Technology (NCAT) Test Track] indicated that the 20% RAP mixtures had balanced rutting and cracking resistance, while the 40% RAP mixtures had inadequate rutting resistance likely due to the soft PG 52-28 unmodified binder used. Nevertheless, the 40% RAP mixtures may not necessarily be prone to rutting in the field because they are placed in the pavement structure at least one or two layers below the surface and, thus, are not generally as exposed to high pavement in-service temperatures as the surface layer.

The extracted binder testing plan included the Superpave PG, Multiple Stress Creep Recovery (MSCR), Linear Amplitude Sweep (LAS), and Frequency Sweep tests to characterize the rheological properties of extracted binders from RAP mixtures with and without considering RBA. The results showed that adding additional virgin binder had an overall softening impact on the extracted binder. For all the RAP mixtures evaluated in the project, the extracted binders corresponding to the RBA-adjusted optimum binder content (A-OBC) had reduced rutting resistance, improved fatigue resistance and ductility, and similar elastic properties and aging susceptibility as those at the volumetric optimum binder content (V-OBC).

Upon completing the laboratory testing plan, a cost-benefit analysis was conducted to determine the required pavement life extension to offset the cost of adding additional virgin binders in consideration of reduced RAP binder availability for RAP mixtures in Florida. The analysis showed that for a 3-inch mill-and-resurface project on a 2-lane rural road with 5-foot paved shoulders, only a two-month extension in pavement service life (from 15 years) would be needed.

Based on the results and findings of the project, it is suggested that FDOT implement 80% RBA for mix design and production of RAP mixtures to improve the long-term cracking performance and longevity of asphalt pavements in Florida. Three potential approaches to implementing RBA into the existing mix design and production practices are suggested, including (1) adjusting N_{design} to maintain 4.0% design air voids at A-OBC, (2) adjusting design air voids at A-OBC, and (3) eliminating design air voids as an acceptance quality characteristic (AQC). Finally, recommendations for relevant future research and implementation are provided.

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$\%R_{3.2}$	Percent Recovery
$\|G^*\|$	Complex Shear Modulus
$\|G^*\|_{LVE}$	Linear Viscoelastic Complex Shear Modulus
AMPT	Asphalt Mixture Performance Tester
ANOVA	Analysis of Variance
A-OBC	RBA-adjusted Optimum Binder Content
APA	Asphalt Pavement Analyzer
BBR	Bending Beam Rheometer
BMD	Balanced Mix Design
CA	Critical Aging
COAC	Corrected Optimum Asphalt Content
CPR	Crack Progression Rate
CT_{Index}	Cracking Tolerance Index
CV	Coefficient of Variation
DelDOT	Delaware Department of Transportation
DoA	Degree of Activity
DSR	Dynamic Shear Rheometer
DWT	Dongre Workablity Testing
E*	Dynamic Modulus
EDS	Energy Dispersive X-ray Spectroscopy
FDOT	Florida Department of Transportation
FI	Flexibility Index
FN	Flow Number
FTIR	Fourier Transform Infrared Spectroscopy
GDOT	Georgia Department of Transportation
GLM	General Linear Model
GPC	Gel Permeation Chromatography
G-R	Glover-Rowe Parameter
GRN	Granite
G_{sb}	Aggregate Bulk Specific Gravity
HPG	High-temperature Performance Grade

HWTT	Hamburg Wheel Tracking Test
IDEAL-CT	Indirect Tensile Asphalt Cracking Test
IDEAL-RT	Indirect Tensile Asphalt Rutting Test
IDOT	Illinois Department of Transportation
IDT Strength	Indirect Tensile Strength
I-FIT	Illinois Flexibility Index Test
IPG	Intermediate-temperature Performance Grade
JMF	Job Mix Formula
J_{nr}	Non-recoverable Creep Compliance
KYTC	Kentucky Transportation Cabinet
LADOTD	Louisiana Department of Transportation and Development
LAS	Linear Amplitude Sweep
LMS	Limestone
LTPP	Long-Term Pavement Performance
LVECD	Layered Viscoelastic Pavement Analysis for Critical Distresses
MSCR	Multiple Stress Creep Recovery
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Project
N_f	Number of Cycles to Failure
NYSDOT	New York State Department of Transportation
ODOT	Ohio Department of Transportation
OOAC	Original Optimum Asphalt Content
OT	Overlay Test
PAV	Pressure Aging Vessel
PG	Performance Grade
PMA	Polymer-modified Asphalt
RAP	Reclaimed Asphalt Pavement
RAS	Recycled Asphalt Shingle
RBA	Recycled Binder Availability
RILEM	International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM)
RRI	Rutting Resistance Index
RTFO	Rolling Thin Film Oven

R-value	Rheological Index
SCDOT	South Carolina Department of Transportation
SEM	Scanning Electron Microscopy
SGC	Superpave Gyratory Compactor
SHA	State Highway Agency
SOP	Standard Operating Procedure
SP	Superpave
St. Dev.	Standard Deviation
STA	Short-term Aging
TCE	Trichloroethylene
TDOT	Tennessee Department of Transportation
TSR	Tensile Strength Ratio
TTI	Texas A&M Transportation Institute
V_a	Air Voids
VFA	Voids Filled with Asphalt (VFA)
VMA	Voids in Mineral Aggregate
V-OBC	Volumetric Optimum Binder Content
WMA	Warm Mix Asphalt
δ	Phase Angle
ΔT_c	Delta T_c
ω_c	Crossover Frequency

1. INTRODUCTION

1.1 Problem Statement

Since its implementation in 1980, the Florida Department of Transportation's (FDOT) asphalt pavement recycling specification has been refined to permit the use of reclaimed asphalt pavement (RAP) while ensuring the quality and performance of the resultant recycled mixtures. In general, FDOT's recycling program has been highly successful, with the average RAP content in dense-graded mixtures varying between 20% and 35%, which helps stretch their resurfacing funds while significantly conserving natural resources. Like most state highway agencies (SHAs), FDOT assumes that all the RAP binder in the mixture is "activated" to provide coating and binding of aggregates and to contribute to mixture performance as asphalt binder, which is often referred to as 100% RAP binder availability. However, previous studies have shown that the RAP binder is only partially "activated" (i.e., less than 100% RAP binder availability) when RAP is heated and mixed with virgin binder and aggregate at elevated mixing temperatures (Copeland, 2011; Coffey et al., 2013; Stroup-Gardiner, 2016). For this reason, RAP mixtures in Florida are likely to have been designed and produced with lower asphalt binder contents than what is needed to provide good cracking resistance without adversely affecting rutting resistance.

Since the adoption of the Superpave mix design system in the late 1990s, cracking and raveling have been the predominant pavement distresses in Florida. While many factors contribute to pavement performance regarding these distresses, one factor that has been garnering increasing attention among SHAs is the amount of "activated" RAP binder in the mixture. Some states address this issue by applying a recycled binder availability (RBA) factor that mathematically reduces the amount of recycled binder while increasing the new virgin binder added into the mixture to compensate for the "inactivated" recycled binder. RBA is defined as "the amount of recycled binder from RAP, or recycled asphalt shingles (RAS) if used, that activates and contributes to the total effective binder content in an asphalt mixture" and is often expressed as a percentage ranging from 0% to 100%. As an example, the Georgia Department of Transportation (GDOT) initiated a study in 2012 to address RAP binder availability, culminating in specification changes that considered only 75% of the RAP binder as "activated." This approach, known as the Corrected Optimum Asphalt Content (COAC) concept, required adding more virgin binder to compensate for the 25% "inactivated" RAP binder in the mixture. GDOT's specification was further changed in 2019, which now considers only 60% of the RAP binder as "activated". The implementation of COAC in Georgia has resulted in RAP mixtures with higher virgin (and total) asphalt binder contents and improved pavement cracking performance without rutting issues (Horan, 2020). It is worth noting that GDOT uses hydrated lime without grade bumping of virgin binders for RAP mixtures with COAC, which are known to be beneficial to pavement rutting performance.

While the benefits of adding more virgin binder to address reduced recycled binder availability have been well established with respect to cracking resistance, there are still some potential challenges associated with implementing this concept in Florida. For example, increasing the asphalt binder content above the volumetric optimum could potentially lead to an increased risk of rutting, especially for mixtures containing a softer virgin binder. Another challenge is related to the development and implementation of specification changes, which if not handled properly, can complicate the mix design development and approval process as well as production acceptance of RAP mixtures. Thus, there is a need to validate the research findings and specification changes implemented in other states for the conditions that exist in Florida.

1.2 Research Objectives

The overall objectives of this project are to: (1) determine if reducing the RAP binder contribution and replacing it with new asphalt binder will affect mixture performance in terms of rutting resistance, cracking resistance, and durability, and (2) develop strategic plans to implement the changes related to reducing RAP binder contribution into FDOT's existing mix design and production practices. Specific tasks to be accomplished in the project include:

1) Selecting an appropriate RBA value for Florida RAP mixtures through a literature review.
2) Selecting materials and developing mix designs for RAP mixtures.
3) Characterizing the performance properties of RAP mixtures with and without RBA adjustment, and their extracted/recovered asphalt binders.
4) Conducting performance comparison and cost-benefit analysis to determine the impacts of adding more virgin binder in consideration of reduced RAP binder availability on the performance and potential life-cycle cost benefits of RAP mixtures.
5) Proposing suggested revisions to FDOT specifications and operational procedures to facilitate the implementation of reduced RAP binder availability.

1.3 Organization of the Report

This report consists of five Chapters. Chapter 1 discusses the problem statement and research objectives of the project. Chapter 2 summarizes the literature review findings related to recycled binder availability. Chapter 3 discusses the experimental design of the project, including materials selection, mix designs, RBA selection for Florida RAP mixtures, and laboratory testing plan. Chapter 4 presents the test results and discussions of the project, including mix design verification, mixture cracking/durability evaluation, mixture rutting evaluation, mixture performance diagram analysis, extracted binder characterization, and cost-benefit analysis. Finally, Chapter 5 summarizes the major findings and conclusions of the project and provides recommendations for future research and implementation.

2. LITERATURE REVIEW

This chapter presents the literature review findings on (1) motivations for addressing recycled binder availability, (2) existing studies on recycled binder availability, (3) laboratory test methods for evaluating recycled binder availability, (4) impact of recycled binder availability on performance of recycled asphalt mixtures, and (5) state of practice for incorporating recycled binder availability into mix design and production. Each topic is discussed in detail as follows.

2.1 Motivations for Addressing Recycled Binder Availability

The use of RAP in asphalt mixtures provides significant economic, environmental, and engineering benefits. However, asphalt mixtures containing high RAP contents could be susceptible to pavement cracking and durability issues due to increased stiffness and embrittlement. The primary factor causing these performance issues is the lack of "activated" RAP binder to contribute to aggregate coating and binding, as well as mixture flexibility. From the binder quality perspective, the asphalt binder in RAP is significantly more aged than the virgin binder and thus, is more susceptible to fatigue and thermal cracking. From the binder quantity perspective, because of the heavily aged nature of RAP, only a portion of the RAP binder is available to blend with the virgin binder and additives (if used) in the mixture. However, many SHAs do not consider recycled binder availability when designing RAP mixtures using the volumetric mix design approach. The resultant mixtures, especially those with high RAP contents, may have poor workability and cracking resistance due to the lack of adequate "activated" asphalt binder.

The current volumetric mix design system is not sufficient to address the potential cracking and durability issues of recycled mixtures. There are limitations associated with the lack of accuracy in determining the aggregate bulk specific gravity (G_{sb}) for calculating voids in mineral aggregate (VMA), and the volumetric analysis cannot differentiate between the "activated" and "inactivated" asphalt binder in the RAP. Furthermore, mixture volumetric parameters provide no indication of the quality of RAP binder, nor its interaction with the virgin binder and additives such as recycling agents and warm mix asphalt (WMA) products. To address these limitations, balanced mix design (BMD) has recently been developed as a new mix design system for asphalt mixtures that relies on mixture performance testing in addition to (or in place of) volumetric analysis for mix design approval and production acceptance. Although BMD has great potential to address the potential cracking and durability issues of RAP mixtures, its implementation could take several years for some agencies, especially those with limited resources.

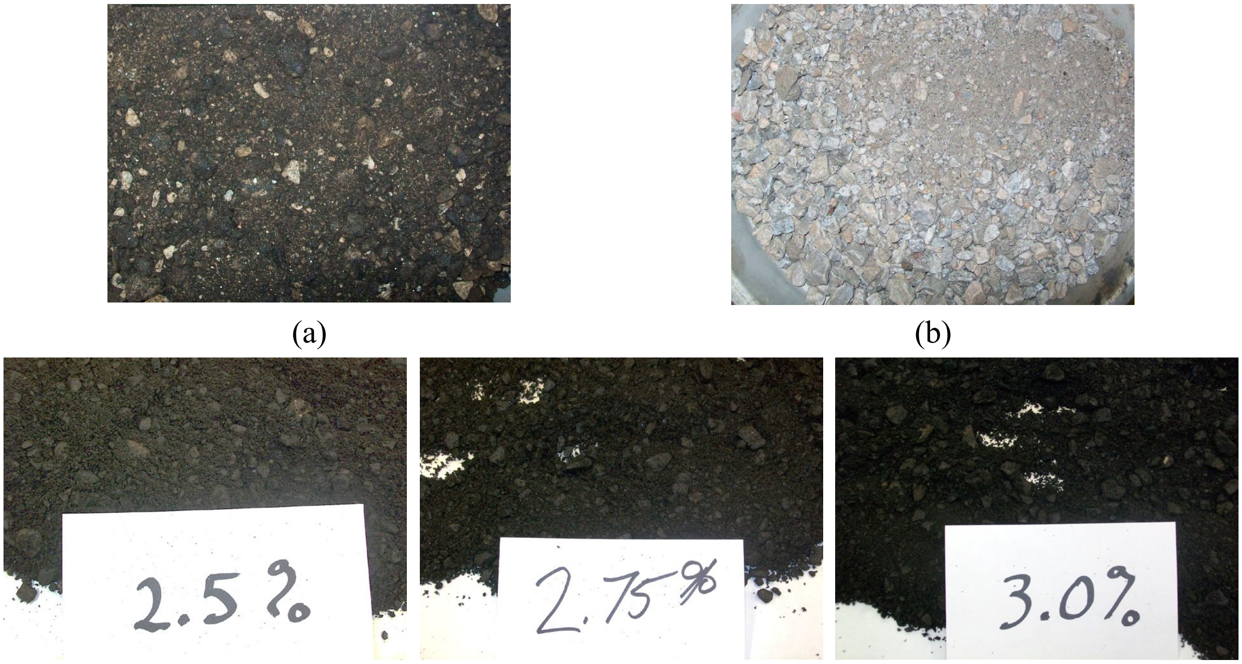
In the meantime, SHAs and the asphalt paving industry need to find short-term solutions for the potential cracking and durability issues associated with asphalt mixtures with RAP. One potential approach is to implement the recycled binder availability concept into the volumetric mix design system while simultaneously devoting efforts to better control the quality of virgin binder and RAP. Recycled binder availability is defined as "the amount of recycled binder from RAP, and/or RAS if used, that activates and contributes to the total effective binder content in an asphalt mixture" (Epps Martin et al., 2021). It is often expressed as a percentage ranging from 0% to 100% denoting the RBA value. RBA is considered an intrinsic property of the recycled mixture, which is highly dependent on the quality of RAP/RAS itself but can also be affected by other mix design variables (e.g., virgin binder grade and source, aggregate type, and asphalt additives) and mixture production conditions (e.g., production temperature and silo storage time and temperature). Implementing recycled binder availability for RAP/RAS requires more virgin binder to be added into the mixture for mix design and production, and the amount of the additional virgin binder added is dependent on the RBA value. If an excessively high RBA value is used, the resultant recycled mixtures may still have inadequate cracking resistance. Conversely, using an unreasonably low RBA value could yield mixtures with poor rutting resistance. Therefore, using an appropriate RBA value is critical to ensure good rutting and cracking performance (in other words, balanced performance) for recycled mixtures.

2.2 Existing Studies on Recycled Binder Availability

Over the years, many studies have been conducted to evaluate the recycled binder availability of asphalt mixtures containing RAP and/or RAS. These studies used different approaches to determine RBA with different sources of recycled materials, mix design variables, and simulated production conditions, and as a result, reached different conclusions. Among these studies, several notable ones include the COAC study by GDOT, a COAC verification study by the National Center for Asphalt Technology (NCAT), the National Cooperative Highway Research Project (NCHRP) project 09-58 by the Texas A&M Transportation Institute (TTI), and a recent synthesis study by TTI. These studies are briefly discussed below followed by a summary of other relevant studies worldwide.

2.2.1 GDOT COAC Study

GDOT initiated an in-house study in 2012 to determine the amount of virgin binder required to provide the “primed” coating of the RAP aggregate (Hines, 2012). RAP materials were sampled from various sources across Georgia. Each RAP source was divided into two groups for evaluation. The first group was heated in an oven at the mixing temperature for one hour [Figure 1(a)] and then photographed. The second group was processed in an ignition furnace to determine the RAP binder content and obtain the post-ignition RAP aggregate [Figure 1(b)]. The post-ignition RAP aggregate was then mixed with a virgin binder at 0.25 to 0.5% increments and then photographed as shown in Figure 1(c-e). The images of the post-ignition RAP aggregates mixed with different virgin binder contents [Figure 1(c-e)] were visually compared against that of the heated RAP [Figure 1(a)]. The amount of virgin binder required to provide a similar appearance based on the relative grey-black color contrast was then determined as the “activated” RAP binder. The “activated” RAP binder was then divided by the RAP asphalt binder content from the ignition furnace to determine the “activated” RAP binder ratio. This ratio varied between 0.4 to 0.8 among different RAP sources in Georgia, with an average of approximately 0.6. Based on these results, GDOT developed a new procedure for RAP mix design, in which the volumetric optimum binder content is adjusted based on the “activated” RAP binder ratio. The adjusted optimum binder content is referred to as the COAC. GDOT implemented the 75:25 COAC ratio in 2012, meaning only 75% asphalt binder in the RAP is activated and additional virgin binder in the amount of 25 percent of the RAP binder is added to the total mix. The 75:25 COAC ratio was first implemented to improve mixture cracking performance while minimizing the risk of rutting. Based on the success of the 75:25 COAC ratio, in 2019 GDOT implemented the 60:40 COAC ratio to further enhance pavement cracking performance in Georgia.



(a) (b)

(c) (d) (e)

Figure 1. Georgia RAP Samples: (a) Heated RAP, (b) Post-ignition RAP Aggregate, (c, d, e) Post-ignition RAP Aggregate Mixed with Different Amounts of Virgin Binder (Hines, 2012)

2.2.2 NCAT COAC Verification Study

In 2021, NCAT conducted a study to verify the COAC ratio of a 30% RAP mixture from Georgia. The test method used was based on performance testing of mixes prepared to simulate three different recycled binder availability conditions: 0% RBA, 100% RBA, and Actual Blending. Table 1 summarizes the virgin, RAP, "activated" RAP, and total asphalt binder contents of the three mixes described below:

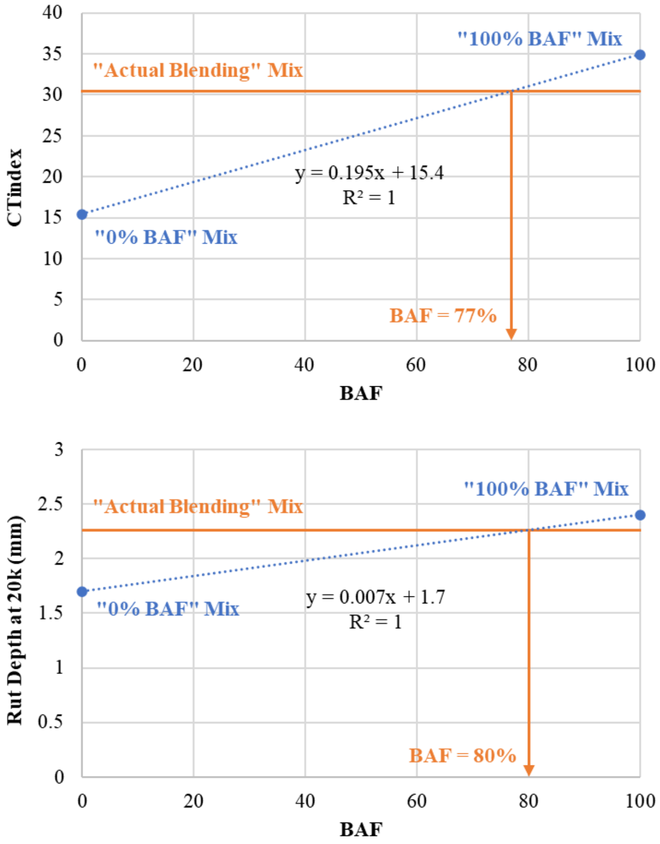
- The 0% RBA mix was prepared by mixing 3.9% virgin binder with virgin aggregate and post-ignition RAP aggregate. In this mix, no RAP binder was present.
- The 100% RBA mix was prepared by mixing 3.9% virgin binder and 1.4% extracted RAP binder with virgin aggregate and post-ignition RAP aggregate. Because of the solvent extraction and recovery process, all the RAP binder was artificially "activated" and used to mix with virgin and post-ignition RAP aggregates.
- The Actual Blending mix was prepared following the traditional mixture preparation procedure by mixing 3.9% virgin binder with virgin aggregate and RAP.

Each mix was tested with the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and Hamburg Wheel Tracking Test (HWTT). The results are also summarized in Table 1.

Table 1. Asphalt Binder Content, IDEAL-CT, and HWTT Results of a GDOT 30% RAP Mixture

Mix ID	Virgin Asphalt Binder Content (%)	RAP Asphalt Binder Content (%)	"Activated" RAP Asphalt Binder Content (%)	Total Asphalt Binder Content (%)	Average CT_{Index}	Average RD_{20k} (mm)
0% RBA	3.9	0	0	3.9	15.4	1.70
100% RBA	3.9	1.4	1.4	5.3	34.9	2.40
Actual Blending	3.9	1.4	Unknown	5.3	30.4	2.26

As expected, the 100% RBA mix had the highest average cracking tolerance index (CT_{Index}) and thus, was expected to have the best intermediate-temperature cracking resistance, followed by the Actual Blending mix and then the 0% RBA mix. The opposite trend was observed for the HWTT rut depth at 20,000 passes (RD_{20k}) results in terms of rutting resistance evaluation. Figure 2 illustrates the determination of RBA for the Actual Blending mix based on linear interpolation. As shown, the RAP in this mixture was estimated to have 77% RBA based on the IDEAL-CT results and 80% RBA using the HWTT results. These results are within the COAC ratio range previously determined by GDOT (i.e., 0.4 to 0.8).



(a)

(b)

Figure 2. RBA Determination of a GDOT 30% RAP Mixture: (a) Linear Interpolation of IDEAL-CT Results, (b) Linear Interpolation of HWTT Results

2.2.3 NCHRP Project 09-58

NCHRP Project 09-58 conducted an experiment to determine the percent “activated” RAP binder by testing a virgin and a RAP mixture. The virgin mixture was prepared with virgin binder and three distinct virgin aggregate fractions: coarse (passing ½-inch sieve and retained on ⅜-inch sieve), intermediate (passing ⅜-inch sieve and retained on No. 4 sieve), and fine (passing No. 4 sieve and retained on No. 30 sieve); while the RAP mixture was prepared by substituting the intermediate aggregate fraction of the virgin mixture with RAP, as shown in Figure 3. Both mixtures were short-term oven aged after mixing, sieved, and then the binder content of the aggregate fraction passing the ⅜-inch sieve but retained on the No. 4 sieve was determined via ignition oven. Finally, RBA was determined based on the difference in the binder content of the No.4 aggregate fraction from the virgin mixture versus the RAP mixture while assuming a linear relationship between the two extreme scenarios (i.e., 100% availability versus black rock). An example illustrating the step-by-step RBA calculation for this method can be found in Kaseer et al. (2019).

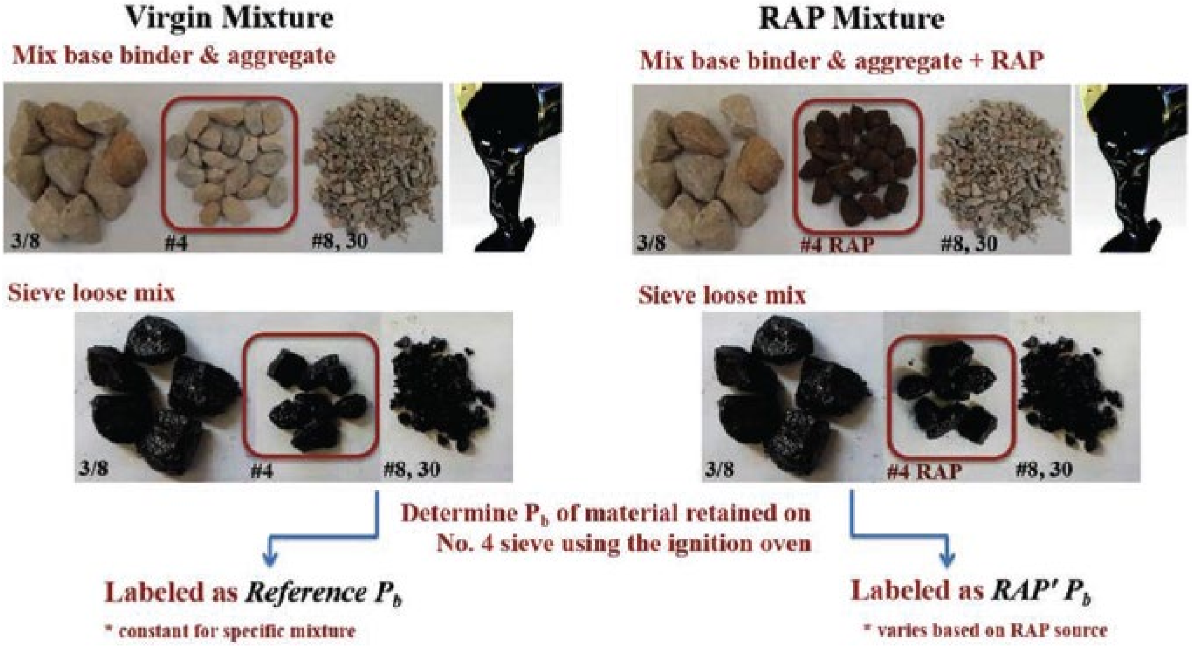


Figure 3. Illustration of Test Method for Determining RBA in NCHRP Project 09-58 (Kaseer et al., 2019)

Using this method, the project evaluated seven RAP sources from different regions of the United States, including one from Florida. Figure 4 presents the RBA results at two mixing temperatures: 140°C and 150°C. It was found that these RBA results correlated well with the high-temperature performance grade (HPG) of the extracted RAP binders, where softer (i.e., less aged) RAP binders with lower HPG had higher RBA values than stiffer (i.e., more aged) RAP binders with higher HPG. This correlation demonstrated the potential of using this correlation to estimate the RBA of an unknown RAP mixture based on its mixing temperature and HPG of the extracted RAP binder. The project also found that adding recycling agents increased the RBA of RAP mixtures in some cases but extending the short-term conditioning time did not appear to affect RBA (Epps Martin et al., 2019).

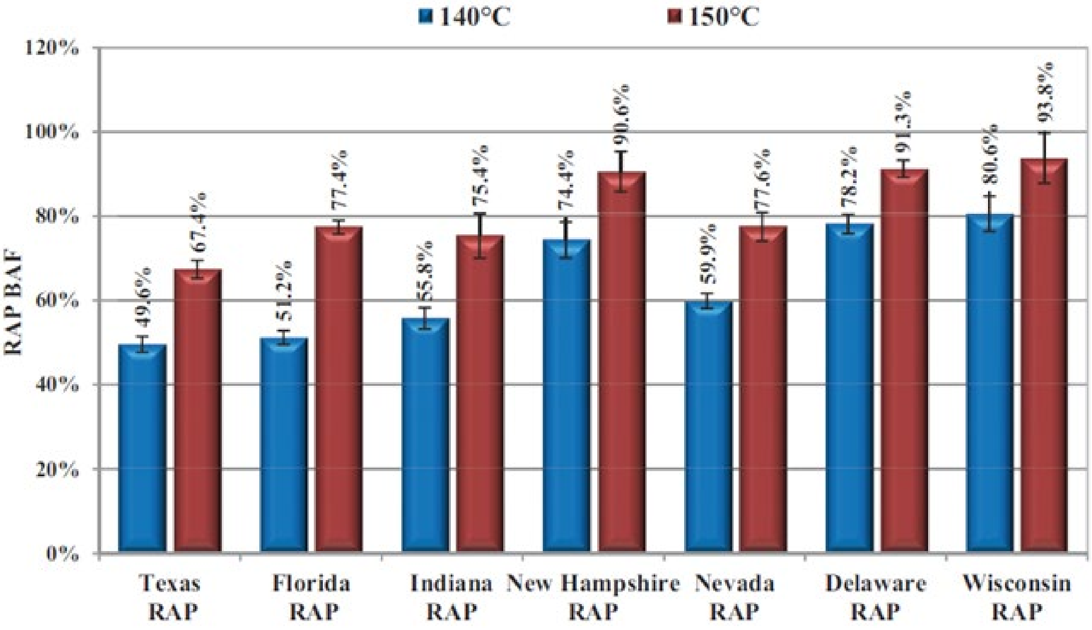


Figure 4. NCHRP Project 09-58 RBA Results of RAP from Different Sources at Two Mixing Temperatures (i.e., 140°C and 150°C) (Epps Martin et al., 2019)

2.2.4 TTI Synthesis Study

In 2021, TTI completed a synthesis study on recycled binder availability, which included a literature review, a survey to gather information on the current state of practice regarding recycled binder availability, an analysis of three different RBA methods, and revision to Texas DOT's BMD spreadsheet to incorporate recycled binder availability (Epps Martin et al., 2021). Findings from the literature review highlighted consensus regarding the occurrence of partial binder blending in recycled mixtures during production. The literature review also identified factors that could affect recycled binder availability, including (1) virgin binder grade, (2) aging condition of RAP/RAS, (3) binder content, RAP/RAS content, and gradation of the mixture, (4) presence of asphalt additives, and (5) the mixing and storage temperature. In general, higher recycled binder availability was reported for mixtures with softer virgin binders, with recycling agents and/or WMA additives, and at higher production temperatures. Furthermore, RAP was found to have more "activated" recycled binder than RAS at common mixture production temperatures.

The TTI survey identified nine states that have implemented the recycled binder availability concept, as shown in Figure 5. Among these agencies, two require RBA for RAP and RAS, two for RAP only, and five for RAS only. The RBA values used by these agencies vary from 60% to 100% for RAP, and 60% to 85% for RAS. Among these states, most reduce the credit for the RAP/RAS binder content as part of the total binder content while others increase the optimum binder content from volumetric analysis to obtain an RBA-adjusted optimum binder content by adding more virgin binder. More detailed discussions about these agencies' practices for addressing recycled binder availability are provided below.

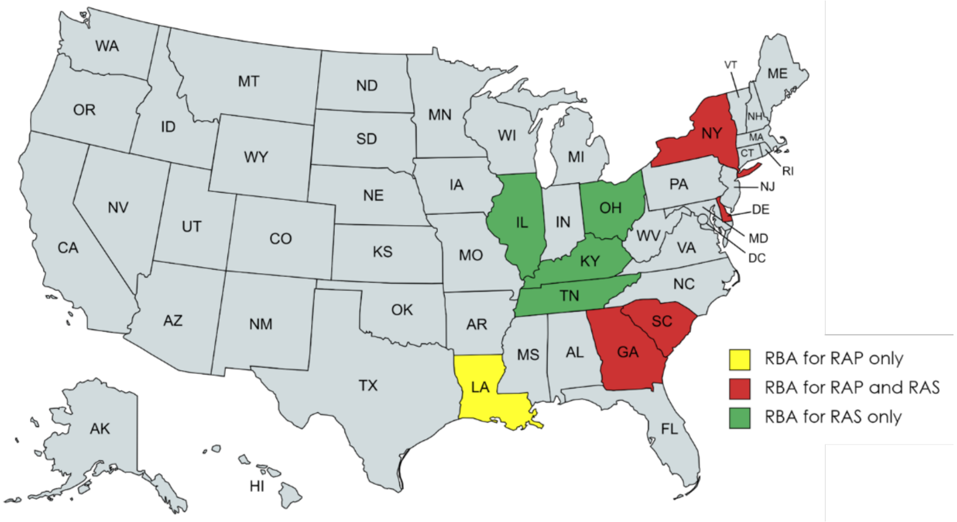


Figure 5. Map of SHAs Requiring RBA for Recycled Asphalt Mixtures (data from Epps Martin et al., 2021)

As part of this synthesis study, Epps Martin et al. (2021) evaluated three candidate methods for estimating recycled binder availability of RAP from different sources in the U.S.

- The first method was the one developed in NCHRP project 09-58, which was discussed previously in Section 1.2.3.
- The second method was based on the multiple-temperature indirect tensile (IDT) strength testing of 100% RAP samples, which was developed by the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) Technical Committee 264 (TC264-RAP) Task Group 5 (Menegusso Pires et al., 2021; Sobieski et al., 2021). This method yielded a parameter called the Degree of Activity (DoA), which was defined as “the minimum amount of recycled binder that is active without the effects of additives”. The detailed test procedure of this RILEM method is provided subsequently in Section 2.3.10.
- The third method was based on the Dongre Workablity Testing (DWT) of 100% RAP samples. The DWT test was performed by subjecting a given amount of loose RAP samples to a constant ram displacement rate without gyrations in the Superpave Gyratory Compactor (Dongre et al., 2021). The test generated a compressive stress versus volumetric strain curve, of which the slope at 600 kPa corresponded to the DWT value. A higher DWT value was desired for RAP with better workability and thus, was expected to yield a higher RBA value when used in asphalt mixtures.

Table 2 summarizes the RBA, DoA, and DWT results from this experiment. The study concluded that in general, the NCHRP 9-58 method and RILEM method provided moderately consistent rankings of RAP from different sources in terms of recycled binder availability, while the DWT results did not correlate with the RBA and DoA results.

Table 2. Recycled Binder Availability Results of RAP Materials from Different Sources (data from Epps Martin et al., 2021)

RAP Source	NCHRP 9-58 Method (RBA, %)		RILEM Method (DoA, %)	DWT Method (DWT Value, kPa)
	Mixing at 140°C	Mixing at 150°C		
Delaware	78.2	91.3	79.9	165
Florida	51.2	77.4	74.3	180
Indiana	55.8	75.4	39.2	157
New Hampshire	74.4	90.6	62.7	175
Nevada	59.9	77.6	n/a	168
Wisconsin	80.6	93.8	99.9	169
Texas 1	49.6	67.4	n/a	n/a
Texas 2	n/a	n/a	67.5	n/a

2.2.5 Other Relevant Studies

Table 3 provides a summary of other relevant studies on evaluating the recycled binder availability of asphalt mixtures containing RAP/RAS; more details of each study can be found elsewhere (Epps Martin et al., 2021; Rodezno et al., 2021). These studies used different test methods and reported a wide range of RBA results varying from 16 to 100% for RAP and 36 to 61% for RAS.

Table 3. Summary of Previous Research Studies on Recycled Binder Availability

Reference	RAP/RAS Source	Reported RBA Value
Shirodkar et al., 2011	1 RAP source from New Jersey	70 to 90%
Coffey et al., 2013	3 RAP sources from New Jersey	85 to 90%
Zhao et al., 2015	1 RAP and 1 RAS from Tennessee	24 to 100% (RAP) 36 to 61% (RAS)
Yu et al., 2017	1 RAP source from China	20 to 85%
Epps Martin et al., 2019	7 RAP sources from Delaware, Florida, Indiana, Nevada, New Hampshire, Texas, and Wisconsin	50 to 96%
Gottumukkala et al., 2018	1 RAP source from India	16 to 87%
Jiang et al., 2018	1 RAP from China	42 to 98%
Sreeram et al., 2018	1 RAP from China	35 to 65%
Epps Martin et al., 2021	5 RAP sources from Delaware, Florida, Indiana, New Hampshire, and Wisconsin	40 to 100%
Sobieski et al., 2021	42 RAP sources from 10 countries	5 to 100% depending on temperature
Page and Castorena, 2022	4 RAP sources from North Carolina	50 to 90%

2.3 Laboratory Test Methods for Evaluating Recycled Binder Availability

[1]This section discusses the different test methods used in previous research to evaluate the recycled binder availability of RAP/RAS in recycled mixtures. Some of the methods focus on qualitatively assessing the occurrence of blending and diffusion between the virgin and RAP/RAS binders, while others seek to quantitatively determine the RBA of the mixture. At the end of this section, a summary is provided to discuss the advantages and potential limitations of each method.

2.3.1 Performance Testing of RAP/RAS Mixtures at Various RBA Conditions

This method was developed by Coleri et al. (2018) based on performance testing of RAP/RAS mixtures prepared with three RBA values. The "0% RBA" mixture was prepared by mixing the virgin binder, virgin aggregate, and extracted (or post-ignition) RAP/RAS aggregate. Because this mixture required no extracted RAP/RAS binder, it treated RAP/RAS as "black rock" with 0% RBA. The "100% RBA" mixture was prepared by mixing the virgin binder, virgin aggregate, extracted RAP/RAS aggregate, and extracted RAP/RAS binder. This mixture used solvent extraction and recovery to artificially activate all the RAP/RAS binder, yielding a 100% RBA condition. The "Actual Blending" mixture was prepared following the traditional procedure by mixing the virgin binder, virgin aggregate, and RAP/RAS to simulate the production of recycled mixtures at the asphalt plant. Because of the difference in the "activated" RAP/RAS binder content, the three mixtures had different rutting and cracking resistance. The relative difference in the performance test results of these mixtures was then used to estimate the RBA of the "Actual Blending" mixture. This method was successfully used in the NCAT COAC verification study discussed in Section 1.2.2.

2.3.2 Ignition Oven of Virgin Mixture versus RAP Mixture

As briefly described in Section 1.2.3, Kaseer et al. (2019) proposed a method to estimate the percent "activated" RAP binder by preparing asphalt mixtures with three distinct aggregate fractions: coarse (passing ½-inch sieve and retained on ⅜-inch sieve), intermediate (passing ⅜-inch sieve and retained on No. 4 sieve), and fine (passing No. 4 sieve and retained on No. 30 sieve). A virgin mixture was produced with virgin aggregates without RAP, and a recycled mixture substituted the intermediate aggregate fraction with RAP. The mixtures were short-term oven aged after mixing, sieved, and then the binder content of each aggregate fraction was determined via ignition oven. Finally, RBA was determined by comparing the binder contents of the virgin and RAP intermediate aggregate fractions while assuming a linear relationship between the two extreme scenarios (i.e., 100% availability versus 0% availability "black rock"). This method provided a direct measure of the amount of "activated" RAP binder in the mixture. Despite some limitations, this method was verified using laboratory-prepared artificial RAP and was found effective in discriminating RAP from different sources in NCHRP project 09-58 (Figure 4).

2.3.3 Extracted Binder Testing of Coarse-aggregate, Fine-RAP Mixture

This method was developed by Huang et al. (2005) and required the preparation of a mixture using fine RAP particles (passing No. 4 sieve) and coarse virgin aggregate (retained on No. 4 sieve). After mixing, the loose mix was separated into two fractions using a No. 4 sieve. As shown in Figure 6, the finer fraction corresponded to a blend of fine RAP particles and virgin

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[1] This section is reprinted with permission from Yin et al. (2023).

binder, while the coarser fraction represented a blend of coarse virgin aggregate, virgin binder, and the "activated" RAP binder. For each fraction of the loose mix, the asphalt binder was extracted, recovered, and tested to determine its rheological properties. This method assumes that if full blending between the virgin and RAP binders occurs, the recovered binders from the two fractions would have identical properties; otherwise, the recovered binder from the finer fraction would be stiffer than that recovered from the coarser fraction due to the presence of "inactivated" RAP binder. The relative difference in the properties of the two recovered binders was used to determine the RBA of the mixture.

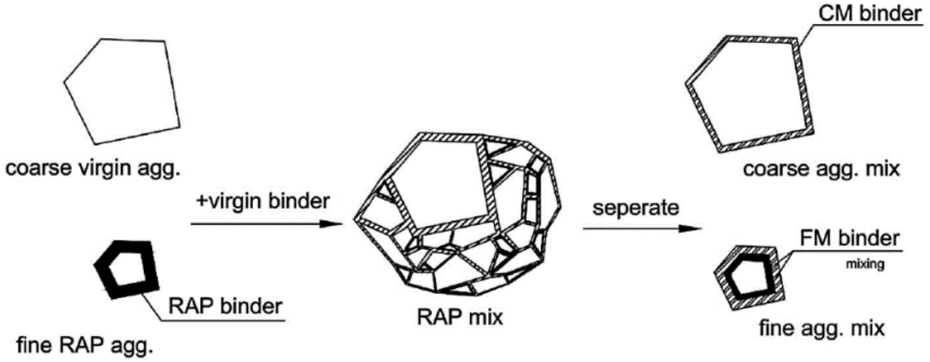


Figure 6. Schematic Illustration for the Preparation of Coarse-aggregate, Fine-RAP Mixture (Yu et al., 2017)

2.3.4 Use of Artificial Glass Beads in Virgin Aggregate as a Tracer for Extracted Binder Testing

This method was developed by Mohajeri (2015) and used borosilicate glass beads to replace a small percentage of virgin aggregates for the preparation of RAP mixtures. A normal mixing procedure was followed by mixing the virgin binder, virgin aggregate, glass beads, and RAP. After mixing, the glass beads were collected from the loose mix, as shown in Figure 7. The asphalt binder coating the surface of the glass beads was extracted, recovered, and tested to determine its rheological properties. Finally, the difference in properties between the extracted binder from the glass beads, virgin binder, and extracted RAP binder was used to estimate the RBA of the mixture.

Figure 7. Glass Beads before and after Mixing (Mohajeri, 2015)

2.3.5 Use of Titanium Dioxide in Virgin Binder as a Tracer for EDS SEM Analysis

Castorena et al. (2016) used the energy dispersive X-ray spectroscopy (EDS) scanning electron microscopy (SEM) to evaluate the blending between virgin and RAP binders. Titanium dioxide powder was preblended into the virgin binder, which allowed the delineation of virgin and RAP binders in the mixture in the EDS mapping. The locations of the virgin and RAP binders were determined by comparing the carbon and titanium EDS maps. Because titanium dioxide was present only in the virgin binder, EDS map areas with carbon but no titanium corresponded to the "inactivated" RAP binder while those with both carbon and titanium indicated a blend of the virgin binder and "activated" RAP binder. Jiang et al. (2018) adopted this method and used the element mass ratio of titanium over sulfur (Ti:S) on the EDS maps to quantitatively estimate the RBA of recycled mixtures with promising results.

2.3.6 Staged Solvent Extraction of Loose Mix Particles of RAP Mixture

This method was first developed by Zearley (1979) to assess the diffusion of asphalt binders at different aging conditions but was later adapted to evaluate blending between virgin and RAP binders in recycled mixtures (Carpenter and Wolosick, 1980; Noureldin and Wood, 1987; Huang et al., 2005). For the method adapted by Bowers et al. (2015), loose mix particles of a RAP mixture were eluted in trichloroethylene (TCE) four consecutive times. The asphalt binder was then recovered from each TCE solvent through rotary evaporation and tested with Gel Permeation Chromatography (GPC) and Fourier Transform Infrared (FTIR) Spectroscopy. The relative difference in the GPC and FTIR results among the recovered binders was used to qualitatively assess the blending between the virgin and RAP binders.

2.3.7 Comparison of Measured versus Predicted Dynamic Modulus of RAP/RAS Mixtures

This method was developed by Bonaquist (2005) to evaluate the blending of virgin and recycled binders by comparing the measured dynamic modulus (E*) of RAP/RAS mixtures versus the predicted E* from the Dynamic Shear Rheometer (DSR) testing of extracted and recovered asphalt binders. During solvent extraction and recovery, the virgin and recycled binders were forced to blend with each other. The complex shear modulus (|G*|) master curve of the extracted and recovered binder was then input into the Hirsch model to predict the mixture E* at an artificial full-blending scenario with 100% RBA. The relative difference between the measured and predicted E* was used to assess the blending between the virgin and recycled binders in the mixture. However, previous studies have reported mixed conclusions regarding the reliability of this method (Michael, 2011; Mogawer et al., 2012; Booshehrian et al., 2013; Farris, 2016).

2.3.8 Volumetric Analysis of Companion Recycled RAP Mixtures

This method was introduced by Coffey et al. (2013) based on volumetric analysis of two companion RAP mixtures. One mixture was prepared with 25% post-ignition RAP aggregates while the other mixture was prepared with 25% RAP with an assumed RBA value of 70%. For each mixture, the amount of virgin binder required to achieve the design air voids was determined. The difference in the virgin binder content of the two companion mixtures was then used to estimate the RBA.

2.3.9 Color Contrast Assessment of Loose RAP Samples

As discussed in Section 1.2.1, this method was developed by Hines (2012) to determine the amount of virgin binder required to provide the "primed" coating of the RAP aggregate. Loose RAP samples were divided into two groups for color contrast evaluation. The first group was heated in an oven at the mixing temperature for one hour and then photographed. The second group was processed in an ignition furnace to determine the RAP binder content and obtain the post-ignition RAP aggregate. The post-ignition RAP aggregate was then mixed with a virgin binder at 0.25 to 0.5% increments and then photographed. The images of the post-ignition RAP aggregates mixed with different virgin binder contents were visually compared against that of the heated RAP. The amount of virgin binder required to provide a similar appearance based on the relative grey-black color contrast was then determined as the "activated" RAP binder. Finally, the "activated" RAP binder was divided by the RAP binder content from the ignition furnace to determine the "activated" RAP binder ratio, also known as the COAC ratio.

2.3.10 Multi-temperature IDT Strength Testing of Compacted RAP Specimens

This method was developed by the RILEM TC264-RAP Task Group 5 (Menegusso Pires et al., 2021; Sobieski et al., 2021) to determine the DoA of RAP using compacted RAP specimens. For this method, the loose RAP samples were first dried in the oven for 48 hours at 40°C. Then, the material was conditioned in the oven for 4 hours prior to compaction at each of the five temperatures (70°C, 100°C, 140°C, 170°C, and 190°C) selected to represent the common production temperatures of recycled mixtures. After conditioning, the material was mixed by hand, and specimens were compacted in either the Marshall or the Superpave gyratory compactor (SGC). The IDT strength testing was then performed at room temperature and the results were used to calculate DoA using Equation 1. The higher the IDT strength of the mixture, the higher the DoA.

$$\mathrm{DoA}\ (\%) = 100 \times \frac{\mathrm{X_{RAP}(T, test)}}{\max \mathrm{X_{RAP}}} \qquad \text{Equation 1}$$

Where,

X_{RAP} = IDT strength test result of RAP conditioned at a specific temperature T; and
Max X_{RAP} = maximum value observed among the temperatures evaluated.

With increasing conditioning temperatures, the peak force and stiffness of the RAP sample increased; however, beyond a certain temperature, the peak force and stiffness decreased as shown in Figure 8. It was hypothesized that the increase in peak force was due to the increased RAP binder available at higher temperatures; conversely, the reason for the reduction in peak force after a certain conditioning temperature was likely due to a phenomenon known as clustering or the adherence of RAP particles of various sizes to each other due to increased polarity as a result of aging (Sobieski et al., 2021).

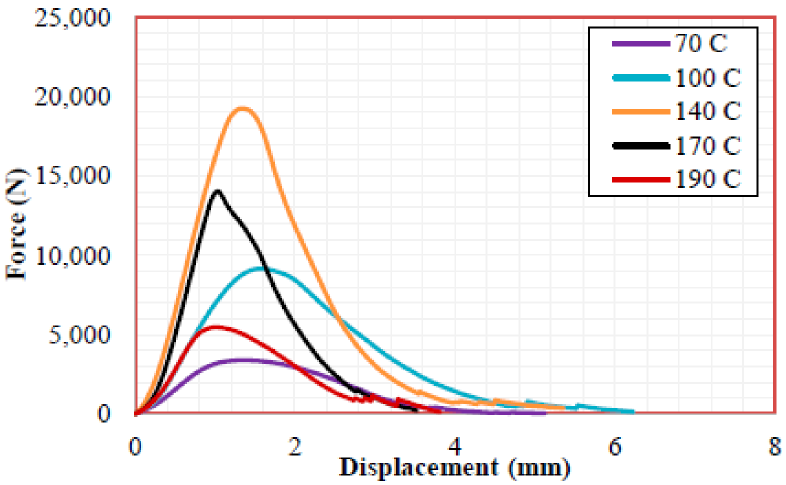


Figure 8. Typical IDT Force-displacement Curves of 100% RAP Samples at Different Conditioning Temperatures (Epps Martin et al., 2021)

2.3.11 Summary

Table 4 compares the different test methods for evaluating recycled binder availability in terms of their ability to (1) quantify RBA, either by directly measuring the volume of “activated” binder in RAP/RAS or indirectly measuring its impact on the properties of the resultant binders or mixtures; (2) evaluate mixtures with RAP only and those with RAP and RAS; (3) discriminate RAP/RAS from different sources and those with different aging conditions; (4) determine the sensitivity of RBA to mix design variables (e.g., virgin binder, RAP/RAS content, and additives) and mixture production conditions (e.g., production temperature and silo storage time); and (5) use equipment and materials available to SHAs and possibly asphalt contractors.

Table 4. Comparison of Different Test Methods for Evaluating Recycled Binder Availability

Test Method	Ability to quantify RBA	Ability to evaluate RAP and RAP/RAS mixtures	Ability to discriminate different RAP/RAS sources	Determine RBA sensitivity to mix design variables and mixture production conditions	Use widely available equipment and materials
Performance Testing of RAP/RAS Mixtures at Various RBA Conditions	✓[I]	✓	✓	✓	✓
Ignition Oven of Virgin Mixture versus RAP Mixture	✓[D]	✓	✓	✓	✓
Extracted Binder Testing of Coarse-aggregate, Fine-RAP Mixture	✓[I]	✓	✓	✓	✓
Use of Artificial Glass Beads in Virgin Aggregate as a Tracer for Extracted Binder Testing	✓[I]	✓	✓	✓	✓
Use of Titanium Dioxide in Virgin Binder as a Tracer for EDS SEM Analysis	✓[I]	✓	✓	✓	
Staged Solvent Extraction of Loose Mix Particles of RAP Mixture		✓	✓	✓	
Comparison of Measured versus Predicted E* of RAP/RAS Mixtures	✓[I]	✓	✓	✓	
Volumetric Analysis of Companion Recycled RAP Mixtures	✓[I]	✓			✓
Color Contrast Assessment of Loose RAP Samples	✓[D]		✓		✓
Multi-temperature IDT Strength Testing of Compacted RAP Specimens	✓[I]		✓		✓

[D]: *directly quantify RBA by measuring the volume of "activated" binder in RAP/RAS*

[I]: *indirectly quantify RBA by measuring its impact on the properties of RAP/RAS, resultant binders, or resultant mixtures*

2.4 Impact of Recycled Binder Availability on Performance of Recycled Asphalt Mixtures

One of the critical aspects of addressing recycled binder availability is that only the "activated" recycled binder is considered, while the "inactivated" recycled binder is compensated for by adding more virgin binder. The additional virgin binder will affect the volumetric and performance properties of recycled mixtures. Over the years, several research studies have been conducted to evaluate the performance impact of recycled binder availability based on mixture performance testing; these studies are briefly discussed below.

Yu et al. (2021) determined the RAP binder blending ratio (also known as RBA) using a gap-graded blending method through mixing fine RAP with coarse virgin aggregate and virgin binder. Then, three RAP mix designs were prepared with both the assumed 100% RBA (assuming full blending) and the measured RBA of 83% (assuming partial blending). The rutting resistance and cracking resistance of these mixtures were evaluated using HWTT and the Illinois Flexibility Index Test (I-FIT), respectively. The mixtures prepared with the partial blending method had approximately 0.4% to 0.7% more virgin binder than the mixtures prepared with the full blending method. The I-FIT results indicated that the partial blending method significantly improved the mixture cracking resistance in terms of the flexibility index (FI), as shown in Figure 9(a). The HWTT rutting resistance index (RRI) results indicated that the partial blending method slightly reduced the mixture's rutting resistance due to the additional virgin binder, as shown in Figure 9(b).

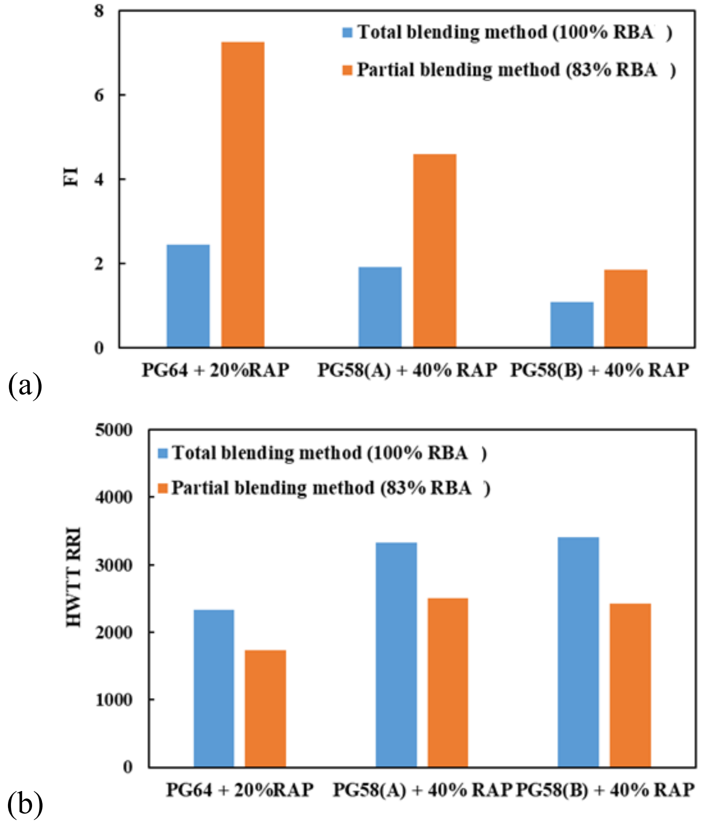
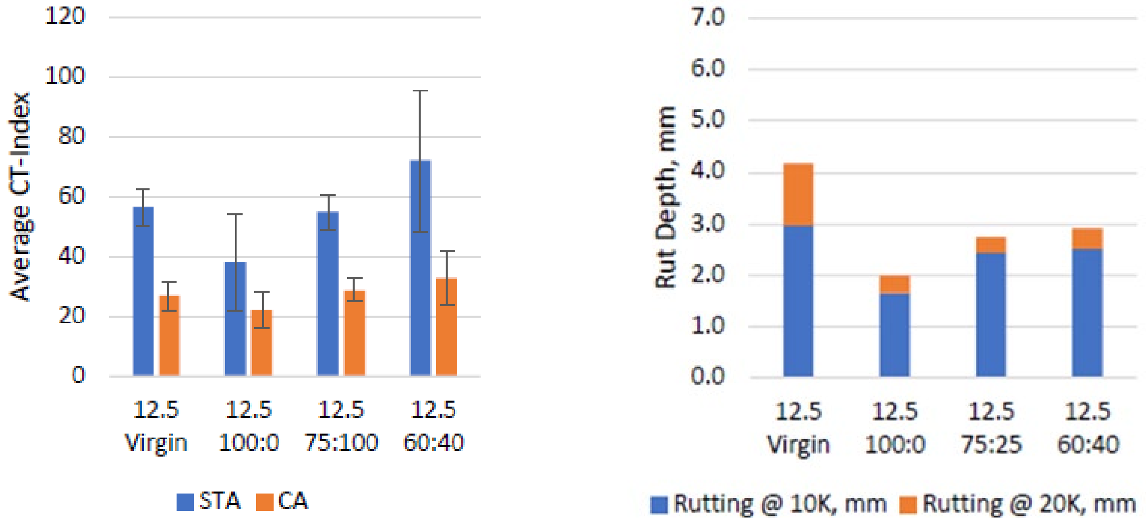


Figure 9. Effects of Implementing 83% RBA on Mixture Performance Test Results: (a) I-FIT FI, (b) HWTT RRI (data from Yu et al., 2021)

Amirkhanian et al. (2018) designed and prepared two companion RAP mixtures with and without 75:25 COAC adjustment (corresponding to 75% RBA) using materials in South Carolina. The mixtures were tested to characterize their viscoelasticity and stiffness properties using the E* test and their rutting resistance using the Flow Number (FN) test. The test results showed that the RAP mixture with 75% COAC adjustment exhibited significantly lower E* and FN values than the mixture without COAC adjustment, which indicated reduced stiffness and rutting resistance due to the additional virgin binder.

The effect of COAC adjustment on the performance properties of RAP mixtures was also investigated by Vivanco et al. (2021) using materials from Georgia. The mixture cracking and rutting resistance were evaluated by IDEAL-CT and HWTT, respectively. HWTT was conducted on short-term aged (STA) specimens while IDEAL-CT was conducted on specimens at both STA and critical aging (CA) conditions. The CA condition corresponds to STA plus additional loose mix aging for 8 hours at 135°C. In this study, four mixture types with and without RAP were included: 9.5 mm Type II Superpave (SP), 12.5 mm SP, 19.0 mm SP, and 25.0 mm SP mixtures. For each mixture type, the RAP mixtures were designed with three different COAC ratios of 100:0, 75:25, and 60:40, which corresponded to 100%, 75%, and 60% RBA, respectively. For all the mixture types, the IDEAL-CT results showed that the CT_{Index} increased as the RBA value decreased at both STA and CA conditions, which indicated improved intermediate-temperature cracking resistance due to COAC adjustment. This observation was expected because of the additional virgin binder added to the mixture to account for COAC adjustment. The HWTT rut depth also increased as the RBA value decreased, but all the RAP mixtures with COAC adjustment showed good rutting resistance with a maximum rut depth of 7.0 mm after 20,000 passes. Figure 10 presents the IDEAL-CT and HWTT results of 12.5 mm SP mixtures [with 30% RAP and a Performance Grade (PG) 64-22 virgin binder], and the test results for the other mixture types can be found elsewhere (Vivanco et al., 2021). Finally, the study concluded that the COAC adjustment was effective in improving the cracking resistance of RAP mixtures in Georgia while maintaining good rutting resistance. These findings agree with those of Yu et al. (2021).

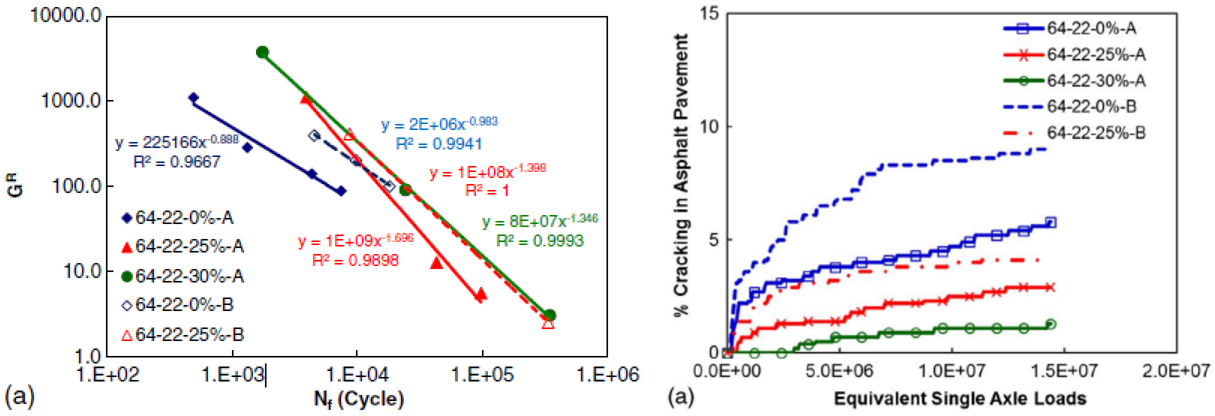


(a) (b)

Figure 10. Impact of COAC Adjustments on Performance Test Results of 12.5-mm SP Mixtures in Georgia: (a) IDEAL-CT CT_{Index}, (b) HWTT Rut Depth (Vivanco et al., 2021)

Kim et al. (2018) benchmarked the rutting and moisture resistance of RAP mixtures with 75:25 COAC adjustment in Georgia using HWTT. The mixtures were selected to cover four aggregate sources. For each aggregate source, five types of RAP mixtures were designed and tested, including 4.75 mm SP, 9.5 mm SP, 12.5 mm SP, 19.0 mm SP, and 25.0 mm SP mixtures. The HWTT results showed that all RAP mixtures with COAC adjustment regardless of mixture type exhibited excellent rutting resistance with a maximum rut depth of 5.0 mm after 20,000 passes in HWTT. In addition, no stripping failure was observed for any of the mixtures, which indicated excellent moisture resistance. Based on these results, the study concluded that 75:25 COAC adjustment was able to maintain good rutting and moisture resistance of RAP mixtures despite the additional virgin binder added.

Norouzi et al. (2017) evaluated the fatigue resistance of 12.5 mm SP mixtures using two aggregate sources in Georgia. For each aggregate source, three mix designs were included: a virgin mix, a 25% RAP mix with 75:25 COAC ratio, and a 30% RAP mix with 75:25 COAC ratio. In addition, each mix design was tested with three virgin binders: PG 64-22, PG 67-22, and PG 76-22. All the mixtures were tested using the E* and Cyclic Fatigue tests. Data analysis was conducted using a simplified viscoelastic continuum damage model and the results were reported on the failure criterion G^R-vs-N_f plot, as shown in Figure 11(a). For all three virgin binders, the failure criterion line of RAP mixtures with COAC adjustment was located above that of the virgin mixture, which indicated better fatigue resistance for the RAP mixtures. Interestingly, a previous study by Norouzi et al. (2014) found that the virgin mixtures outperformed the RAP mixtures without COAC adjustment in terms of fatigue resistance. The findings of these two studies demonstrated the effectiveness of COAC adjustment in improving the fatigue resistance of RAP mixtures in Georgia and that better performance over virgin mixtures could be achieved because of COAC adjustment.



(a) (b)

Figure 11. Impact of 75:25 COAC Adjustment on Fatigue Resistance of 12.5-mm SP Mixtures with a PG 64-22 Virgin Binder in Georgia: (a) Cyclic Fatigue Failure Criterion Plot, (b) Predicted Fatigue Cracking Damage (Norouzi et al., 2017)

To further evaluate the effect of COAC adjustment on the fatigue performance of asphalt pavements, Norouzi et al. (2017) conducted performance simulations using the layered viscoelastic pavement analysis for critical distresses (LVECD) program, which is now known as FlexPAVE™. Figure 11(b) presents the predicted fatigue cracking for pavements with different asphalt mixtures. These results showed that the RAP mixtures with 75:25 COAC adjustment had better predicted fatigue performance (in terms of lower % cracking damage) than the virgin mixtures over 20 years of service life, which was consistent with the failure criterion results in Figure 11(a).

2.5 State of Practice for Implementing Recycled Binder Availability into Mix Design and Production Practices

As previously discussed in Section 2.2.4, the TTI survey identified nine SHAs that have implemented the recycled binder availability concept for mix design and production of asphalt mixtures containing RAP/RAS (Epps Martin et al., 2021). Among these agencies, five require RBA for RAP, eight require RBA for RAS. Table 5 summarizes the RBA values used by these agencies.

Table 5. Summary of RBA Values used by SHAs

State	RBA for RAP	RBA for RAS
Delaware	90%	80%
Georgia	60%	60%
Illinois	-	85%
Kentucky	-	75%
Louisiana	Varies	RAS not allowed
New York	Varies	60%
Ohio	-	About 60%
South Carolina	75%	75%
Tennessee	-	75%

Depending on how recycled binder availability is addressed for mix design and production, these agencies can be separated into two groups. Group 1 addresses recycled binder availability by discounting the binder content of RAP/RAS or the G_{sb} of RAP/RAS aggregate, which will decrease the total binder content and/or VMA of the recycled mixture from the mix design perspective. If the mixture fails the minimum total binder content or VMA requirements specified by the agency, it must be redesigned with more asphalt binder, which is expected to have improved durability and cracking resistance. Group 1 includes seven states: Delaware, Illinois, Kentucky, Louisiana, New York, Ohio, and Tennessee. For this approach, no modification to the existing volumetric requirements for mix design and production is needed. It is the responsibility of the asphalt contractor to develop a mix design that meets the volumetric requirements with the discounted RAP/RAS binder content or the G_{sb} of RAP/RAS aggregate.

Group 2 includes Georgia and South Carolina, which address recycled binder availability by increasing the virgin (and total) binder content of the mixture to compensate for the "inactivated" binder in RAP/RAS. For this approach, the mixture is first designed with the Superpave mix design procedure assuming 100% recycled binder availability. Once the mix design is completed, the original optimum asphalt content (OOAC) from the volumetric analysis is then increased to COAC by adding more virgin binder. The amount of virgin binder added is dependent on the RAP/RAS content of the mixture, binder content of RAP/RAS, and the selected COAC ratio. Due to the additional virgin binder, the mixture will not conform to all the existing volumetric requirements. At the minimum, the mixture will have an air voids content less than the design target, which in many cases is 4.0 percent. Furthermore, VMA, VFA, and other volumetric properties may also change due to the increased virgin (and total) binder content. The agency requires the contractor to report both OOAC and COAC for mix design approval, with COAC to be used as the target binder content for production acceptance.

2.5.1 Group 1 States

The Delaware Department of Transportation (DelDOT) has developed a spreadsheet (called the "RAP Calculator") that applies a binder availability factor of 90% for RAP and 80% for RAS (DelDOT, 2021). The spreadsheet requires inputting the actual measured RAP and/or RAS binder content, along with the PG grade and Delta Tc of the virgin binder, the total binder content of the mix, and the percent RAP and/or RAS in the mix. Due to the partial contribution of the RAP/RAS binder in the mix, additional virgin binder is added to compensate for the "inactivated" RAP/RAS binder. The spreadsheet calculates the amount of additional virgin binder required and adjusts the total binder content of the mix for the ignition oven test to account for the additional virgin binder. The spreadsheet also determines mathematically (based on linear interpolation) if the blend of recycled and virgin binders meets both the PG and Delta Tc requirements, by using statewide averages for both recycled and virgin binder characteristics. The mix with the additional virgin binder is required to meet the volumetric requirements for both mix design and production.

The Illinois Department of Transportation (IDOT) assumes 100% binder contribution for RAP and fractionated RAP by using established G_{sb} values for all RAP materials (with natural aggregate) based on the district where the project is located. These are historical average G_{sb} values determined from extracted and recovered RAP aggregates, which were then tested in accordance with AASHTO T 84 and T 85. For RAS, IDOT assumes 85% contribution of the RAS binder and makes this adjustment by reducing the G_{sb} of RAS aggregates from 2.500 to 2.300 for mix design. This reduced G_{sb} will artificially lower the VMA of the mix, which may require the mix to be redesigned for increased VMA to meet the minimum requirements and consequently add more virgin binder.

The Kentucky Transportation Cabinet (KYTC) assumes 100% binder contribution for RAP and 75% binder contribution for RAS. The total binder content of the mix is calculated using the discounted RAS binder content, which will reduce the VMA of the mix. If the mix fails to meet the minimum VMA requirements, it needs to be redesigned for increased VMA by adding more virgin binder. The discounted RAS binder content is also considered in determining the percentage of effective recycled binder content of the mix for selecting virgin binder grade, as shown in Equation 2 (KYTC, 2019). Because KYTC has recently suspended the use of re-refined engine oil bottom in the state, the use of RAS in recycled mixtures has been drastically reduced.

$$Percentage\ of\ effective\ recycled\ binder\ content = \frac{[(A \times B) + (0.75 \times C \times D)]}{E} \qquad \text{Equation 2}$$

Where,

A = Asphalt binder content of the RAP (%);
B = Percentage of RAP in the mix (%);
C = Asphalt binder content of the RAS (%);
D = Percentage of RAS in the mix (%); and
E = Effective binder content of the mix (%).

The Louisiana Department of Transportation and Development (LADOTD) addresses recycled binder availability by decreasing the binder content of the RAP measured from ignition by 0.4 percent (LADOTD, 2016). This reduced RAP binder content corresponds to approximately 92% RBA for most RAP mixtures (Epps Martin et al., 2021). If the mix with the reduced RAP binder content fails the minimum VMA requirements, it needs to be redesigned for increased VMA with more virgin binder. LADOTD does not allow the use of RAS in asphalt mixtures.

The New York State Department of Transportation (NYSDOT) accounts for the "inactivated" RAP binder in their 9.5- and 12.5-mm surface mixtures by increasing the minimum required asphalt binder content by 0.2% in all mixtures that contain over 10% RAP. All regular volumetric requirements apply both at mix design and during production (NYSDOT, 2022).

The Ohio Department of Transportation (ODOT) assumes 100% binder contribution for RAP based on the extracted asphalt binder content of the RAP, and a reduced binder contribution for RAS. ODOT assumes that RAS has a constant binder content of 12% regardless of its type and source (Biehl, 2020; ODOT, 2022), which corresponds to 60% RBA for RAS with a binder content of 20% (Epps Martin et al., 2021). From the mix design perspective, the reduced RAS binder content will decrease the total binder content and VMA of the mix, which may require the mix to be redesigned for more virgin binder if it fails ODOT's minimum virgin binder content and VMA requirements.

The Tennessee Department of Transportation (TDOT) applies a maximum active binder availability factor to RAS materials. Their specifications limit the active binder available for mixing with virgin aggregates to 75% of the RAS binder content determined by AASHTO T 164 (TDOT, 2021). This active RAS binder content is determined by the contractor and is submitted on the mix design for agency approval. For example, if the measured RAS binder content was 20.0%, the active binder content used on the mix design would be reported as 20.0 × 0.75 = 15.0%. All volumetric requirements at design remain the same except requiring the 75% binder availability factor for RAS. During production, TDOT uses the undiscounted total binder content of the mix as the target; since TDOT limits RAS to a maximum of 3% by weight of the mix, the production tolerances are wide enough so that the difference in the target total binder content for mix design versus production does not result in pay reductions for the contractor. TDOT assumes 100% effective binder availability for RAP.

2.5.2 Group 2 States

As discussed in Section 1.2.1, GDOT conducted an in-house study in early 2012 to determine the amount of asphalt binder from RAP that could blend with the virgin asphalt within the recycled mixture. Based on the findings of this study, GDOT developed the COAC approach to reduce the allowable RAP binder contribution for asphalt mix design. GDOT then worked with the Georgia Asphalt Pavement Association to develop a multi-phase process for implementing the COAC approach in the state (Horan, 2020). In 2012, the 75:25 COAC ratio was first implemented, meaning only 75 percent of the asphalt binder in RAP was credited to the total asphalt binder in the mix. Thus, additional virgin asphalt binder in the amount of 25 percent of the RAP binder was added to the volumetric (original) optimum binder content (i.e., OOAC) determined at 4.0 percent design air voids per AASHTO R 35-09. Based on the positive effect of this change in improving pavement cracking performance in Georgia, GDOT started implementing the 60:40

COAC ratio in 2019, requiring more virgin asphalt binder in the amount of 40% of the RAP binder to be added to the volumetric optimum binder content for mix production (GDOT, 2019).

Before the implementation of the COAC approach in 2012, all GDOT mix designs were required to have a design gradation within the gradation requirements and an optimum asphalt binder content within the range specified in Section 828, *Hot Mix Asphaltic Concrete Mixtures*, of GDOT's *Standard Specifications Construction of Transportation Systems*. In addition, all the Superpave mix designs were required to meet the volumetric requirements, including maximum %G_{mm} @ N_{ini}, minimum voids filled with asphalt (VFA) @ N_{des}, fines to effective asphalt binder ratio, minimum film thickness, and minimum VMA (determined based on G_{se}).

To implement the COAC approach, Section 828 of the GDOT specifications and GDOT's Standard Operating Procedure (SOP) 2 for *Control of Superpave Bituminous Mixture Designs* were revised as follows:

- The optimum binder content is first determined based on the volumetric requirements specified in Section 828 and called the OOAC.
- The OOAC is then adjusted to account for the inactive asphalt binder content in the RAP. The adjusted asphalt binder content is higher than the OOAC and is called the COAC.
- As an example, a 20% RAP mix (with 5% binder in the RAP) is designed at 4.0% air voids with a total binder content (OOAC) of 5%, which includes 4% virgin binder and 1% RAP binder. Based on the 60:40 COAC ratio, only 60% of the RAP binder is considered active. Thus, in this example, the "activated" RAP binder content of the mix is 0.6%, and the "inactivated" RAP binder content is 0.4%. To account for the "inactivated" RAP binder, an additional virgin binder content of 0.4% is added to the total binder content, resulting in a COAC of 5.4%, which includes 4.4% virgin binder, 0.6% "activated" RAP binder, and 0.4% "inactivated" RAP binder.
- After the mix design has been approved, plant mix can be produced, and acceptance testing is conducted for gradation and asphalt binder content (based on the extraction or ignition method) without volumetric requirements. Thus, the implementation of the COAC approach requires no changes to acceptance testing.

The implementation of the COAC approach has significantly increased the total binder content of plant produced mixtures in Georgia that are now easier to compact to specified in-place density. The COAC approach is believed to have the most positive impact on mix durability as compared to other changes made to the specifications by GDOT (Horan, 2020).

Following the successful implementation of the COAC approach by GDOT, the South Carolina Department of Transportation (SCDOT) implemented the 75:25 COAC in 2017 (Hand and Aschenbrener, 2021). The approach taken by SCDOT is similar to that of GDOT in which the volumetric binder content is first determined and then increased to account for the 25% "inactivated" binder in RAP/RAS. Using the same example above, the "activated" RAP binder content of the mix is 0.75%, and the remaining 0.25% RAP binder is considered "inactivated". Thus, 0.25% virgin binder needs to be added to the mix, resulting in a COAC of 5.25%, which consists of 4.25% virgin binder, 0.75% "activated" RAP binder, and 0.25% "inactivated" RAP binder. As with GDOT, SCDOT requires production acceptance based only on asphalt binder content and gradation. The volumetric requirements are for mix design approval only. Thus, no changes are needed for acceptance testing.

3. EXPERIMENTAL DESIGN

This chapter discusses the experimental design of the project to determine the effects of adding additional virgin binder in consideration of reduced RAP binder availability on the performance properties of RAP mixtures and the extracted/recovered asphalt binders. The experimental design includes three parts: 1) materials selection and mix designs, 2) RBA selection for Florida RAP mixtures, and 3) laboratory testing plan.

3.1 Materials Selection and Mix Designs

Per request from FDOT, four Superpave SP-12.5 mix designs were selected for research evaluation in the project, as summarized in Table 6. Two mix designs use granite (GRN) virgin aggregate and GRN-based RAP material, while the other two use limestone (LMS) virgin aggregate and LMS-based RAP material. The two mixtures with the same aggregate type include two RAP contents: 20% and 40%. The 20% RAP mixtures use a PG 76-22 polymer-modified asphalt (PMA) binder, and the 40% RAP mixtures use a softer PG 52-28 unmodified binder. The two GRN mix designs correspond to FDOT mix design ID: 19036A and 20064A, and the two LMS mix designs correspond to FDOT mix design ID: 17-15483C and 17-15612A. The 20% RAP LMS mix was initially designed with 100 gyrations, which was reduced to 75 gyrations for mix design verification per request from FDOT.

Table 6. Selected SP-12.5 Mix Designs in the Project

Mixture ID	Aggregate Type	RAP Type	RAP Content	Virgin Binder
20% RAP GRN	GRN	GRN-based	20%	PG 76-22 PMA
40% RAP GRN	GRN	GRN-based	40%	PG 52-28
20% RAP LMS	LMS	LMS-based	20%	PG 76-22 PMA
40% RAP LMS	LMS	LMS-based	40%	PG 52-28

3.2 RBA Selection for Florida RAP Mixtures

This section discusses three candidate approaches to selecting a suitable RBA value for Florida RAP mixtures based on the literature review findings in Chapter 2. Each approach is discussed in detail below.

3.2.1 Approach 1: Follow GDOT's COAC Practice

As discussed in Section 2.2.1, GDOT developed and implemented the COAC concept to improve the cracking resistance and durability of RAP mixtures in Georgia. The average COAC ratio determined in the GDOT in-house study was 60:40, which indicated that 60% of the RAP binder was considered "activated" for coating and binding aggregate as well as contributing to mixture performance, while the other 40% was considered "inactivated." In terms of implementation, GDOT took a two-step approach where they first adopted the 75:25 COAC ratio in 2012 to evaluate the impacts of this change on field performance and then implemented the more aggressive 60:40 COAC ratio in 2019. The major outcome of implementing COAC for mix design and production of RAP mixtures is that more virgin binder is added to the mixture to account for the "inactivated" RAP binder, which has been proven effective in improving the cracking resistance of Georgia RAP mixtures without compromising rutting resistance (Vivanco et al., 2021). The COAC verification study at NCAT (see Section 2.2.2) found that a 30% RAP mixture with a PG 67-22 virgin binder had an RBA value of 75% to 80%, which appeared to suggest that the 75:25 (or 80:20) COAC ratio might be more appropriate for RAP mixtures in

Georgia than the 60:40 COAC ratio. Given the reasonably similar geographical locations [i.e., both states in the Wet, No-Freeze Long-Term Pavement Performance (LTPP) climate zone] and materials used in Georgia and Florida, FDOT could adopt GDOT's COAC approach to address RAP binder availability, but strategically use the 75:25 (or 80:20) COAC ratio for initial implementation as a conservative approach to minimize the potential risk of rutting.

3.2.2 Approach 2: Follow RBA Recommendations from NCHRP Project 09-58

As discussed in Section 2.2.3, NCHRP project 09-58 determined the RBA results of seven RAP sources from different regions of the United States, including one from Florida. The project found that the measured RBA results using the *Ignition Oven of Virgin Mixture versus RAP Mixture* method (see Section 2.3.2) correlated well with the HPG of the extracted RAP binders, as shown in Figure 12. These correlations highlighted the potential of estimating the RBA of an unknown RAP mixture based on its mixing temperature (i.e., 140°C or 150°C) and HPG of the extracted RAP binder. A recent FDOT analysis from 2020 and 2021 showed that the extracted binder from RAP in Florida had an HPG ranging from 86.5°C to 107.8°C with an average of 95.6°C, as shown in Figure 13. These results support the selection of 95°C as the most representative HPG of the extracted binder for RAP in Florida.

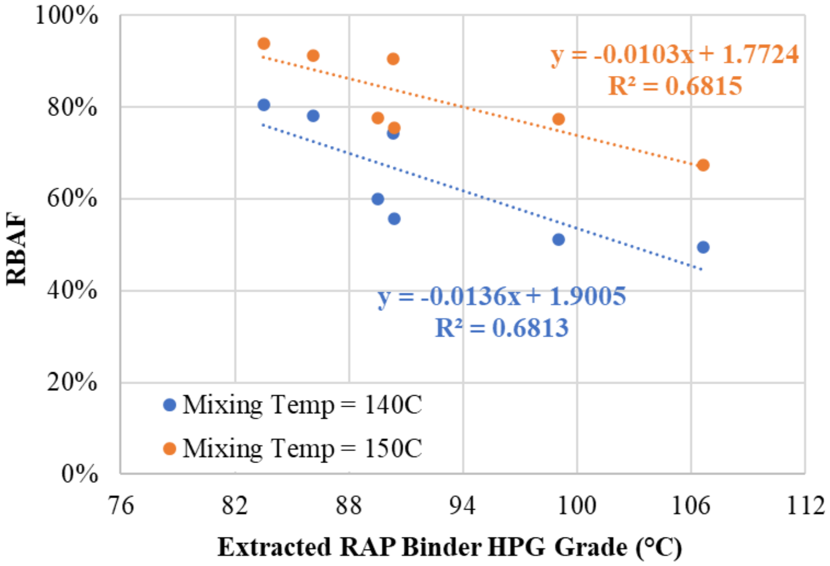


Figure 12. Correlation between Measured RBA and HPG of Extracted RAP Binder from NCHRP Project 09-58 (data from Epps Martin et al., 2019)

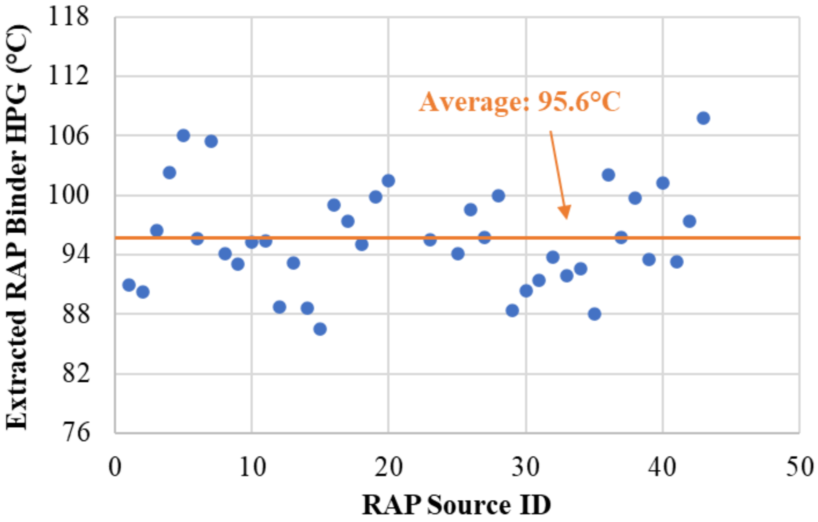


Figure 13. FDOT 2020/2021 Data of Extracted RAP Binder HPG (FDOT, 2022)

In October 2021, NCAT conducted a survey of asphalt contractors in Florida to identify the most representative mixing temperature of 20% RAP mixtures with a PG 76-22 PMA binder and 40% RAP mixtures with a PG 52-28 binder. Responses received from eight contractors indicated that the 20% RAP mixture was most often produced at 163°C (325°F) and the 40% RAP mixture at 149°C (300°F). These responses were also confirmed by FDOT (2022). Therefore, the correlation corresponding to a mixing temperature of 150°C in Figure 12 appears to be more suitable for use in estimating the RBA of RAP mixtures in Florida. With a selected mixing temperature of 150°C and a HPG of the extracted RAP binder of 95°C, the RBA is estimated to be 79.4% ($-0.0103 \times 95 + 1.7724 = 0.794$). Therefore, FDOT could adopt an RBA value of 80% to address RAP binder availability.

3.2.3 Approach 3: Follow DoA Results from TTI Study

As previously discussed in Section 2.2.4, the TTI synthesis study determined the DoA of selected RAP sources in NCHRP Project 09-58 based on the multiple-temperature IDT strength testing of compacted RAP specimens. The results are presented in Figure 14. As shown, the DoA results were able to discriminate RAP from different sources across the United States, but they did not strongly correlate to the RBA results obtained using the *Ignition Oven of Virgin Mixture versus RAP Mixture* method. The RAP sample from Florida had a DoA of 74.3% at a conditioning temperature of 70°C. Assuming this RAP sample is representative of the RAP in Florida, FDOT could adopt a DoA of 75% to address recycled binder availability for RAP mixtures.

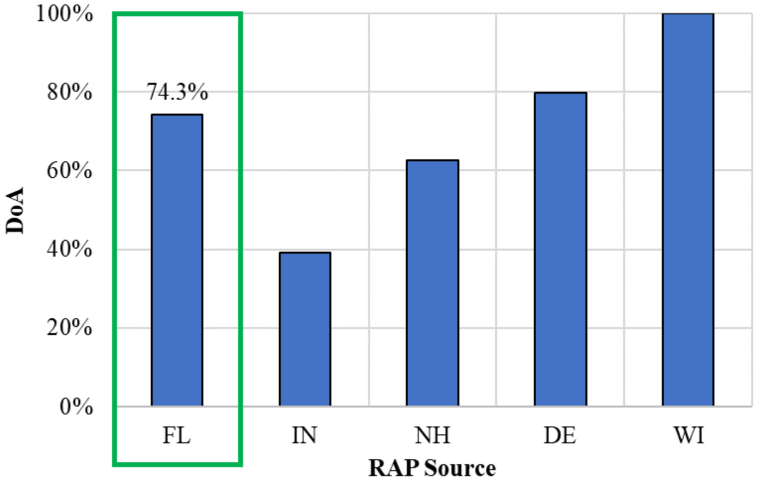


Figure 14. 70°C DoA Results of RAP from Different Sources (data from Epps Martin et al., 2021)

3.2.4 Summary

Based on the three approaches discussed above, 80% appears to be an appropriate RBA value for RAP mixtures in Florida. Therefore, this RBA value was further evaluated in the project to determine the impact of adding additional virgin binder in consideration of reduced RAP binder availability on the performance of RAP mixtures.

3.3 Laboratory Testing Plan

Figure 15 presents the laboratory testing of the four selected SP-12.5 mix designs in the project. Each mixture design was tested at two binder contents: (1) volumetric optimum binder content (V-OBC) from the Superpave volumetric analysis, and (2) RBA-adjusted optimum binder content (A-OBC) after adding additional virgin binder in consideration of reduced RAP binder availability on top of the V-OBC. As shown in Equation 3, the A-OBC was calculated based on the V-OBC, the RAP content of the mixture by weight of total aggregate (%RAP), the aggregate content of the mixture (P_s), the asphalt binder content of the RAP (RAP-P_b), and the selected RBA value of 80%. For example, a mixture has 40% RAP by weight of total aggregate and has 5.5% V-OBC from the volumetric analysis. The asphalt binder content of the RAP is 6.0%. With 80% RBA, the A-OBC of the mixture is calculated to be 5.95% [= 5.5% + 40% * (1-5.5%) * 6.0% * (1-80%)], following Equation 3.

$$\text{A-OBC} = \text{V-OBC} + \%\text{RAP} * P_s * \text{RAP-}P_b * (1-\text{RBA}) \qquad \text{Equation 3}$$

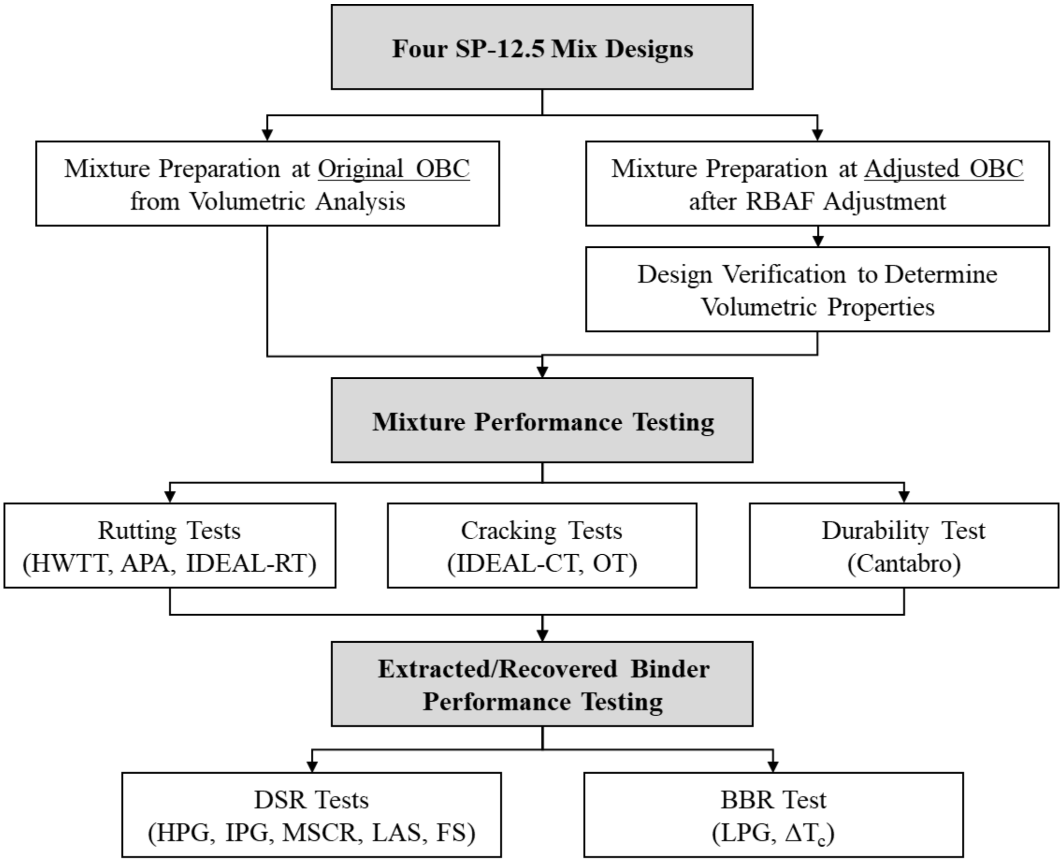


Figure 15. Laboratory Testing Plan of the Project

The laboratory testing plan on the mixture level covered the evaluation of rutting resistance, cracking resistance, and durability. The rutting evaluation included the HWTT per AASHTO T 324, the Asphalt Pavement Analyzer (APA) per AASHTO T 340, and the Indirect Tensile Asphalt Rutting Test (IDEAL-RT) per ASTM D8360. The cracking and durability evaluation included the IDEAL-CT per ASTM D8225, the Texas Overlay Test (OT) per Tex-248-F, and the Cantabro test per AASHTO T 401. All the rutting tests and the Cantabro test were conducted on specimens that were STA for 2 hours at 135°C per AASHTO R 30. To consider the impact of asphalt aging on the cracking resistance evaluation, the IDEAL-CT and OT tests were conducted at two aging conditions: (1) STA for 2 hours at 135°C per AASHTO R 30, and (2) STA plus CA for an additional 8 hours at 135°C following the recommendations of recent NCAT aging studies (Chen et al., 2018; Chen et al., 2020). The CA protocol is expected to simulate approximately 4 to 6 years of surface aging in the southeastern United States, which have been validated on the NCAT Test Track (Chen et al., 2020).

The laboratory testing plan also included rheological characterization of the extracted binders from the RAP mixtures at V-OBC versus A-OBC. The asphalt binders were extracted and recovered following AASHTO T 164 and ASTM D5404. The extracted and recovered binders were tested with the DSR and Bending Beam Rheometer (BBR) to determine the Superpave PG and Delta Tc (ΔT_c). The binders were also tested with the Multiple Stress Creep Recovery (MSCR) test per AASHTO T 350 for evaluating elastic response and rutting resistance; the Linear Amplitude Sweep (LAS) test per AASHTO T 391 for evaluating fatigue resistance; and the Frequency Sweep test followed by master-curve analysis for evaluating ductility and block cracking resistance.

Table 7 and Table 8 summarize the mixture performance tests and binder rheological tests, respectively, in the laboratory testing plan. For each test, the associated performance property, test parameters, aging condition, and test standard are provided.

Table 7. Summary of Mixture Performance Tests in the Laboratory Testing Plan

Mixture Test	Performance Property	Aging Condition	Test Temperature	Test Parameters	Test Standard
HWTT	Rutting resistance	STA	50°C	Rut depth	AASHTO T 324
APA			64°C	Rut depth	AASHTO T 340
IDEAL-RT			50°C	Rutting tolerance index (RT_{Index})	ASTM D8360
IDEAL-CT	Cracking resistance	STA, STA plus CA	25°C	CT_{Index}	ASTM D8225
Texas OT			25°C	Crack progression rate (CPR), Number of cycles to failure (N_f)	Tex-248-F
Cantabro	Durability	STA	25°C	Mass loss	AASHTO TP 108

Table 8. Summary of Binder Rheological Tests in the Laboratory Testing Plan

Binder Test	Performance Property	Aging Condition	Test Parameters	Test Standard
Superpave HPG	Rutting resistance	Extracted from STA mixtures	$\|G^*\|/\sin(\delta)$	AASHTO T 315 (M 320)
Superpave Intermediate-temperature Performance Grade (IPG)	Fatigue resistance		$\|G^*\|\sin(\delta)$	AASHTO T 315 (M 320)
MSCR	Elastic response, rutting resistance		Non-recoverable creep compliance ($J_{nr3.2}$), Percent recovery ($\%R_{3.2}$)	AASHTO T 350 (M 332)
Frequency Sweep	Ductility, block cracking resistance	Extracted from STA plus CA mixtures	*G-R* parameter	AASHTO T 315
LAS	Fatigue resistance		Number of cycles to failure (N_f)	AASHTO T 391
BBR	Thermal cracking resistance, stress relaxation property		Stiffness, m-value, ΔT_c	AASHTO T 313 (M 320)

4. TEST RESULTS AND DISCUSSIONS

This chapter presents the test results and data analysis in the following order: mix design verification, mixture cracking/durability evaluation, mixture rutting evaluation, mixture performance diagram analysis, extracted binder characterization, and cost-benefit analysis.

4.1 Mix Design Verification

The first step in the mix design verification process was to homogenize, dry, and characterize a representative sample of RAP for each selected mixture design. RAP samples for characterization were split out using Method A from AASHTO R 76. RAP samples were dried to a constant mass prior to running AASHTO T 308 to determine the RAP asphalt binder content. Post-ignition samples were then tested for washed sieve analysis per AASHTO T 30. The post-ignition gradation results for the GRN and LMS RAP stockpiles are shown in Table 9 and Table 10, respectively.

Table 9. Post-Ignition RAP Gradation Comparison for GRN Mix Designs

Sieve (in.)	Sieve (mm)	RAP Gradation (JMF)	RAP Gradation (NCAT Post-Ignition)	Difference
3/4"	19.0	100	100.0	0.0
1/2"	12.5	99	99.0	0.0
3/8"	9.5	94	95.0	1.0
#4	4.75	75	78.2	3.2
#8	2.36	58	61.0	3.0
#16	1.18	47	48.8	1.8
#30	0.600	39	40.3	1.3
#50	0.300	29	30.9	1.9
#100	0.150	15	17.7	2.7
#200	0.075	9.1	10.3	1.2

Table 10. Post-Ignition RAP Gradation Comparison for LMS Mix Designs

Sieve (in.)	Sieve (mm)	RAP Gradation (JMF)	RAP Gradation (NCAT Post-Ignition)	Difference
3/4"	19.0	100	100.0	0.0
1/2"	12.5	100	99.8	-0.2
3/8"	9.5	94	98.1	4.1
#4	4.75	75	86.8	11.8
#8	2.36	59	71.9	12.9
#16	1.18	48	60.1	12.1
#30	0.600	39	51.3	12.3
#50	0.300	31	39.4	8.4
#100	0.150	15	20.3	5.3
#200	0.075	7.0	10.1	3.1

The sampled GRN RAP was slightly finer than the gradation provided in the job mix formula (JMF), with a maximum departure of 3.2% on the #4 sieve. The dust content for the verification sample was 1.2% higher than given in the JMF. The overall differences between the JMF gradation and the verification gradation were considered reasonable and did not warrant major corrections to the aggregate gradation for the mix designs. However, the ignition RAP asphalt binder content from ignition was considerably higher than provided in the JMF (5.94% for the verification test versus 5.3% from the JMF). Because of this difference, the total asphalt binder content of the mixture for the NCAT verification samples were calculated using the verified RAP asphalt binder content from ignition instead of the JMF value.

The sampled LMS RAP was significantly finer than the gradation provided in the JMF. The #4, #8, #16, and #30 sieves all had departures of approximately 12% from the JMF values. Additionally, the verification sample was 3.1% higher on dust than the JMF. These differences would necessitate a significant correction to the virgin aggregate gradation to keep the overall blend gradation near the overall blend gradation on the JMF for the two LMS mix designs. Furthermore, the RAP asphalt binder content from ignition was considerably higher than provided in the JMF (6.09% for the verification test versus 5.4% from the JMF). The total asphalt content of the mixture for the NCAT verification samples were calculated using the verified RAP asphalt binder content instead of the JMF value.

A summary of the individual design verifications is presented below. In each case, the JMF stockpile percentages and asphalt binder contents were used as a starting point for verification. Based on the results obtained, adjustments were made to the blend, when needed, to get reasonable volumetric results for each mix design.

4.1.1 20% RAP GRN Mix Design

A summary of the 20% RAP GRN mix design verification is shown in Table 11. For the initial verification, the same stockpile percentages as the JMF along with the NCAT-measured RAP asphalt binder content were used to calculate the virgin asphalt binder content. Specimens were prepared at an N_{des} of 75 gyrations at two asphalt binder contents for the initial verification: 5.1% and 5.3%.

Table 11. 20% RAP GRN Mix Design Verification Summary

Blend	Aggregate Proportions (%)						N_{des}	AC (%)	G_{mm}	G_{mb}	V_a (%)
	RAP	C44	F22	F20	Sand	BHF					
JMF	20	25	20	20	15	0	75	5.1	2.477	2.377	4.0
NCAT Initial Blend (JMF)	20	25	20	20	15	0	75	5.1	2.480	2.314	6.7
	20	25	20	20	15	0	75	5.3	2.472	2.318	6.2
NCAT Adjusted Blend	20	30	25	16	8	1	75	5.1	2.475	2.356	4.8
	20	30	25	16	8	1	75	5.6	2.456	2.363	3.8

G_{mm} = maximum specific gravity; G_{mb} = bulk specific gravity; V_a = air voids.

The initial verification (using JMF stockpile percentages) showed good agreement between the JMF and NCAT G_{mm} values, but the G_{mb} values were significantly lower. This led to 6.7% air voids at the JMF V-OBC of 5.1%. Troubleshooting of potential causes led to a sieve analysis performed on the GRN sand, and the results are shown in Table 12. The two JMFs for the 20% RAP and 40% RAP GRN mix designs reported different gradations for this sand. The average percent passing the #50 sieve from the 20% RAP and 40% RAP JMFs was 40%. However, the verification sieve analysis showed the NCAT sample of this sand had 74% passing the #50 sieve (a 34% difference on the finer side).

Table 12. GRN Sand Gradation Comparison

Sieve (in.)	Sieve (mm)	20% RAP JMF	40% RAP JMF	JMF Average	NCAT Test	Difference
3/4"	19.0	100	100	100	100	0
1/2"	12.5	100	100	100	100	0
3/8"	9.5	100	100	100	100	0
#4	4.75	100	100	100	100	0
#8	2.36	100	100	100	100	0
#16	1.18	100	100	100	99	-1
#30	0.600	98	98	98	96	-2
#50	0.300	30	50	40	74	34
#100	0.150	18	8	13	17	4
#200	0.075	1	1	1	1	0

Given the large departure in the sand gradation from the JMF, the stockpile percentage of this sand was reduced from 15% to 8% with corresponding changes to other stockpile percentages. Additionally, 1% GRN baghouse fines (BHF) were added to help close the void structure. The adjusted blend results are summarized in Table 11. For this blend, 4.8% air voids content was obtained at the JMF V-OBC of 5.1%, with 4.0% air voids falling closer to 5.4% asphalt binder content. Based on these results, 5.4% was used as the verified V-OBC for performance testing.

4.1.2 40% RAP GRN Mix Design

A summary of the 40% RAP GRN mix design verification is shown in Table 13. For the initial verification, the same stockpile percentages as the JMF along with the NCAT-measured RAP asphalt binder content were used to calculate the virgin asphalt binder content. Specimens were prepared at an N_{des} of 75 gyrations at four asphalt binder contents: 5.3%, 5.5%, 5.8%, and 6.0%.

The initial verification (using JMF stockpile percentages) yielded an average 4.6% air voids content at the JMF V-OBC of 5.3%. Additionally, the G_{mm} and G_{mb} were both within AASHTO between-lab D2S of the JMF values. Based on these results, FDOT approved the JMF blend while recommending using 5.4% as the verified V-OBC for performance testing. This was requested to bring the air voids closer to 4.0% and to match the V-OBC of the 20% RAP GRN mix design discussed above.

Table 13. 40% RAP GRN Mix Design Verification Summary

Blend	Aggregate Proportions (%)					N_{des}	AC (%)	G_{mm}	G_{mb}	V_a (%)
	RAP	C44	F22	F20	Sand					
JMF	40	25	15	10	10	75	5.3	2.471	2.371	4.0
NCAT Initial Blend (JMF)	40	25	15	10	10	75	5.3	2.473	2.360	4.6
	40	25	15	10	10	75	5.5	2.466	2.374	3.7
	40	25	15	10	10	75	5.8	2.455	2.386	2.8
	40	25	15	10	10	75	6.0	2.448	2.390	2.4

4.1.3 20% RAP LMS Mix Design

A summary of the 20% RAP LMS mix design verification is shown in Table 14. For the initial verification, the same stockpile percentages as the JMF along with the NCAT-measured RAP asphalt binder content were used to calculate the virgin asphalt binder content. Specimens were prepared at an N_{des} of 75 gyrations at two asphalt binder contents for the initial verification: 6.0% and 6.3%. As discussed previously, the JMF used an N_{des} of 100 gyrations, but a reduced N_{des} of 75 gyrations was used for mix design verification to be consistent with the other mix designs used in the project.

The initial verification (using JMF stockpile percentages) showed that the NCAT G_{mm} value was slightly higher than the JMF G_{mm}, but the G_{mb} values were significantly lower, leading to 7.0% air voids at the JMF V-OBC of 6.0%. This higher air voids content was likely caused by the gradation of the provided RAP sample being significantly finer than the gradation provided in the JMF, as discussed previously (Table 10). For the adjusted blend, the gradation of the virgin aggregate was coarsened to offset the finer RAP sample. Additionally, 1% LMS BHF was added to help close the void structure of the blend. As shown in Table 14, the adjusted blend had 3.8% air voids at 6.3% asphalt binder content. These results were deemed reasonable given that the JMF was based on 100 gyrations and the verification was with 75 gyrations. Based on these results, FDOT approved the adjusted blend and recommended using 6.2% as the verified V-OBC for performance testing.

Table 14. 20% RAP LMS Mix Design Verification Summary

Blend	Aggregate Proportions (%)						N_{des}	AC (%)	G_{mm}	G_{mb}	V_a (%)
	RAP	C41	C51	C54	F22	BHF					
JMF	20	18	10	12	40	0	100	6.0	2.375	2.280	4.0
NCAT Initial Blend (JMF)	20	18	10	12	40	0	75	6.0	2.400	2.231	7.0
	20	18	10	12	40	0	75	6.3	2.390	2.246	6.0
NCAT Adjusted Blend	20	18	16	12	33	1	75	6.3	2.377	2.287	3.8
	20	18	16	12	33	1	75	6.8	2.360	2.301	2.5

4.1.4 40% RAP LMS Mix Design

A summary of the 40% RAP LMS mix design verification is shown in Table 15. For the initial verification, the same stockpile percentages as the JMF along with the NCAT-measured RAP asphalt binder content were used to calculate the virgin asphalt binder content. Specimens were prepared at an N_{des} of 75 gyrations at two asphalt binder contents: 6.0% and 6.5%. Like the 20% RAP LMS mix design, the initial verification yielded unreasonably high air voids, which was caused by the finer RAP sample and the fact that RAP comprised 40% of this blend. A blend adjustment was then made using the same approach as for the 20% RAP design discussed above. The aggregate blend was coarsened to compensate for the finer RAP and 1% LMS BHF were added to help close the voids structure of the blend. As shown in Table 15, the adjusted blend yielded a 4.2% air voids at 6.2% asphalt binder content. FDOT approved the adjusted blend and recommended using 6.2% as the verified V-OBC for performance testing.

Table 15. 40% RAP LMS Mix Design Verification Summary

Blend	Aggregate Proportions (%)					N_{des}	AC (%)	G_{mm}	G_{mb}	V_a (%)
	RAP	C41	C51	F22	BHF					
JMF	40	13	11	36	0	75	6.0	2.379	2.285	4.0
NCAT Initial Blend (JMF)	40	13	11	36	0	75	6.0	2.411	2.228	7.6
	40	13	11	36	0	75	6.5	2.394	2.251	6.0
NCAT Adjusted Blend	40	16	18	25	1	75	6.0	2.389	2.280	4.6
	40	16	18	25	1	75	6.2	2.382	2.283	4.2
	40	16	18	25	1	75	6.5	2.372	2.293	3.3
	40	16	18	25	1	75	6.7	2.365	2.305	2.5

4.1.5 Summary of Selected Asphalt Binder Contents for Performance Testing

Table 16 summarizes the V-OBC and A-OBC (and the corresponding RAP binder ratios) of the four verified mix designs in the project. The A-OBC was calculated following Equation 3. As shown, the A-OBC of the two 20% RAP mix designs was slightly over 0.2% higher than the V-OBC. For the two 40% RAP mix designs, the A-OBC was approximately 0.45% higher than the V-OBC. Because of the additional virgin binder added, the RAP binder ratio at the V-OBC was slightly lower than at the A-OBC.

Table 16. V-OBC versus A-OBC of Verified Mix Designs

Mixture ID	RAP Content (%)	RAP Binder Content (%)	V-OBC (%)	A-OBC (%)	RAP Binder Ratio at V-OBC (%)	RAP Binder Ratio at A-OBC (%)
20% RAP GRN	20	1.19	5.40	5.62	22.1	21.2
40% RAP GRN	40	2.38	5.40	5.85	44.0	40.7
20% RAP LMS	20	1.22	6.20	6.43	19.6	18.9
40% RAP LMS	40	2.44	6.20	6.66	39.3	36.4

4.2 Mixture Cracking/Durability Evaluation

This section presents the test procedure and data analysis of the mixture cracking/durability tests conducted in the project, including the IDEAL-CT, OT, and Cantabro test.

4.2.1 Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

The IDEAL-CT was conducted to evaluate mixture resistance to intermediate-temperature cracking. Testing was performed at 25°C and in accordance with ASTM D8225. For this test, a minimum of four 62-mm tall gyratory specimens were prepared to a target air voids level of 7.0 ± 0.5%. Specimens were loaded monotonically in indirect tension at a rate of 50 mm/min until failure while load line displacement (LLD) was recorded. Testing was performed using a device capable of sampling load and displacement data at a rapid rate (40 Hz), and a plot of load versus LLD was generated for each specimen (Figure 16). This plot is then analyzed to determine the CT_{Index}. A higher CT_{Index} is desired for asphalt mixtures with better intermediate-temperature cracking resistance.

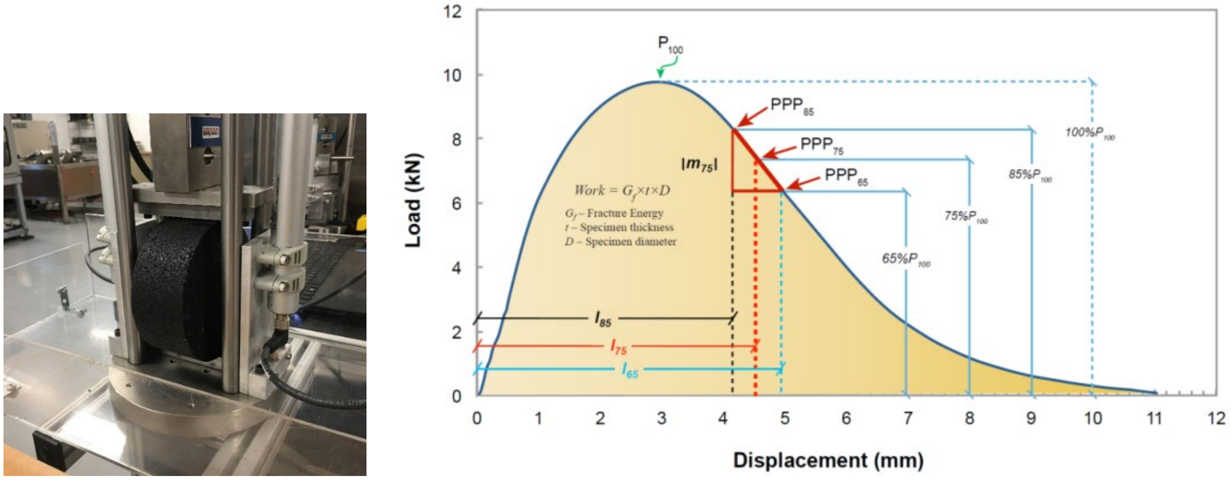


Figure 16. IDEAL-CT Test Setup (left) and Plot of Load versus LLD (right) (Zhou et al., 2017)

Table 17 summarizes the IDEAL-CT results of the four mixtures evaluated in the project. The same results are presented graphically in Figure 17, highlighting the comparisons of V-OBC versus A-OBC for each mixture. The columns represent the average CT_{Index} results, and the error bars represent plus and minus one standard deviation from the average. At both aging conditions, the average CT_{Index} of all the mixtures increased as the asphalt binder content increased from V-OBC to A-OBC, indicating improved intermediate-temperature cracking resistance. At the STA condition, the increase in CT_{Index} from V-OBC to A-OBC was more pronounced for the 40% RAP mixtures than for the 20% RAP mixtures. This was expected given that the A-OBC adjustment in consideration of reduced RAP binder availability for the 40% RAP mixtures was almost double that of the 20% RAP mixtures. At the CA condition, the results follow similar trends as the STA results, but the CA results fall in a much narrower range with the average CT_{Index} varying from 10.7 to 20.2 across all the mixtures. The CA results also showed that three out of the four mixtures passed the suggested CT_{Index} criterion (i.e., minimum 15) from the NCAT top-down cracking group experiment (West et al., 2021) at the A-OBC, but they all failed at the V-OBC.

Table 17. IDEAL-CT Result Summary

Mixture ID (Virgin Binder)	Mixture Aging	Asphalt binder content	V_a (%)	FE (J/m^2)	Slope (kN/mm)	l_{75} (mm)	CT_{Index}		
			Avg.	Avg.	Avg.	Avg.	Avg.	St. Dev.	CV (%)
20% RAP GRN (PG 76-22)	STA (2 hours at 135°C)	V-OBC (5.40%)	6.9	7,734	4.421	4.244	50.0	7.3	14.6
		A-OBC (5.62%)	6.7	8,020	3.903	4.607	64.0	10.2	15.9
40% RAP GRN (PG 52-28)		V-OBC (5.40%)	6.8	5,054	4.170	3.586	29.1	2.2	7.7
		A-OBC (5.85%)	6.8	5,499	2.903	4.145	53.7	11.9	22.2
20% RAP LMS (PG 76-22)		V-OBC (6.20%)	7.0	7,757	5.088	4.038	41.3	4.3	10.5
		A-OBC (6.43%)	7.0	7,755	4.354	4.425	53.6	11.2	20.9
40% RAP LMS (PG 52-28)		V-OBC (6.20%)	7.1	4,512	3.744	3.559	28.9	4.0	13.8
		A-OBC (6.66%)	6.7	4,729	3.147	4.038	40.9	6.4	15.6
20% RAP GRN (PG 76-22)	STA plus CA (8 hours at 135°C)	V-OBC (5.40%)	6.6	7,023	11.284	2.550	10.7	1.6	14.6
		A-OBC (5.62%)	6.8	7,037	8.499	2.841	16.0	3.7	23.0
40% RAP GRN (PG 52-28)		V-OBC (5.40%)	6.8	5,560	8.155	2.749	13.2	3.9	29.6
		A-OBC (5.85%)	7.0	5,424	5.577	3.063	20.2	4.0	19.6
20% RAP LMS (PG 76-22)		V-OBC (6.20%)	6.9	6,657	12.022	2.768	10.5	2.4	22.9
		A-OBC (6.43%)	6.9	6,820	8.455	2.919	15.9	2.7	16.8
40% RAP LMS (PG 52-28)		V-OBC (6.20%)	7.3	5,006	8.067	2.564	10.7	1.2	11.5
		A-OBC (6.66%)	6.6	5,106	6.656	2.733	14.0	1.1	8.1

Avg. = average; St. Dev. = standard deviation; CV = coefficient of variation.

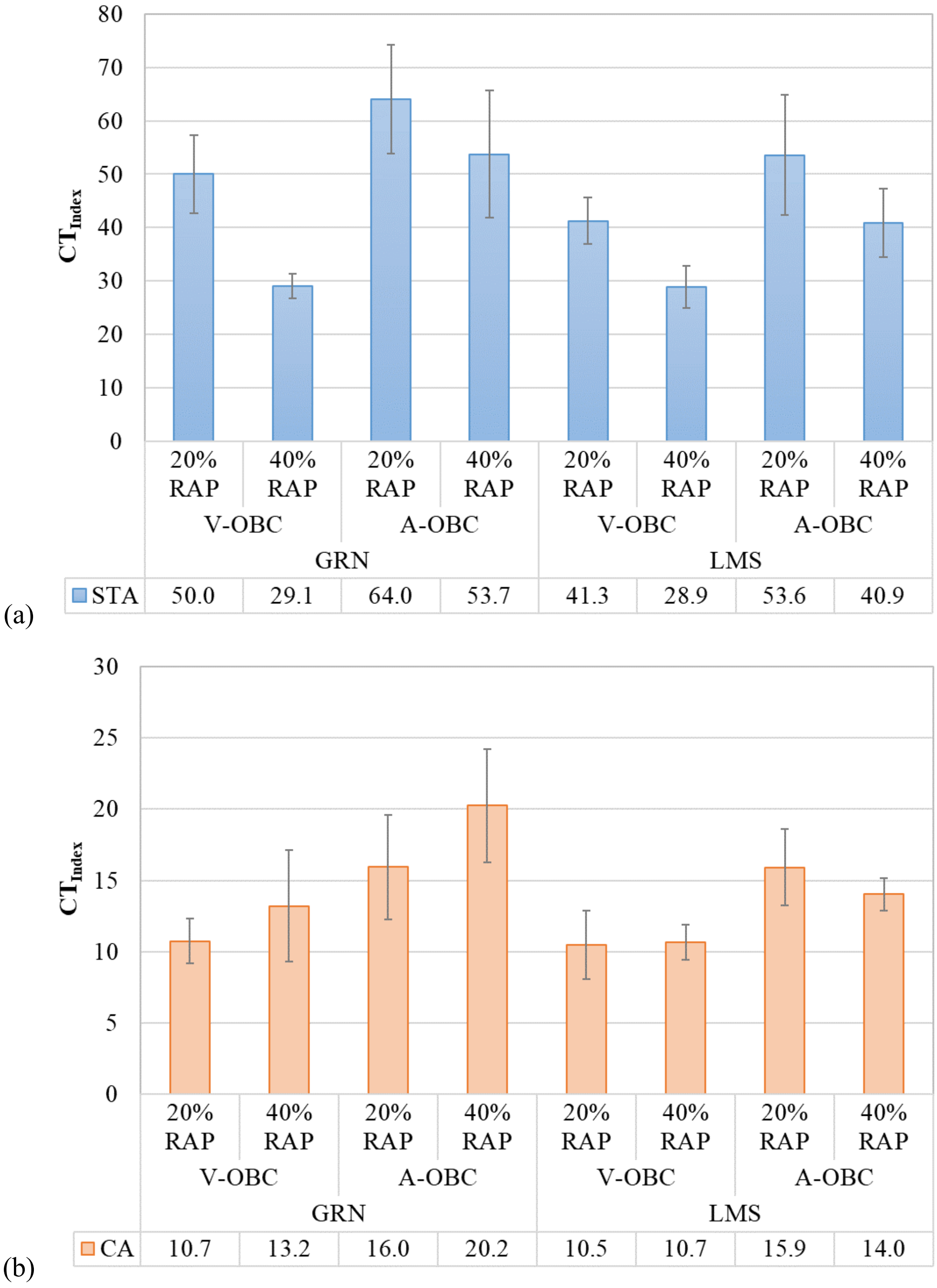


Figure 17. IDEAL-CT Results: (a) STA Condition, (b) CA Condition

The IDEAL-CT results in Figure 17 also showed that at the STA condition, the 20% RAP mixtures had consistently higher average CT_{Index} values and thus, are expected to have better intermediate-temperature cracking resistance than the corresponding 40% RAP mixtures with the same aggregate type, but the difference tended to decrease as the asphalt binder content increased from V-OBC to A-OBC. At the CA condition, the 20% and 40% RAP mixtures had comparable CT_{Index} results if considering the variability of the test. Overall, the IDEAL-CT results indicated that the 20% RAP mixtures with a PG 76-22 PMA binder were more resistant to intermediate-temperature cracking than the 40% RAP mixtures with a PG 52-28 unmodified binder at the STA condition, but the difference diminished after aging and after adding additional virgin binder in consideration of reduced RAP binder availability.

Finally, the General Linear Model (GLM) analysis was conducted to determine the significant factors affecting the IDEAL-CT results. The Analysis of Variance (ANOVA) results are summarized in Table 18 and the GLM output report from Minitab is presented in the Appendix. All the individual factors, including mixture aging (i.e., STA vs. CA), asphalt binder content (AC level) (i.e., V-OBC vs. A-OBC), RAP content [i.e., 20% RAP (with PG 76-22 binder) vs. 40% RAP (with PG 52-28 binder)], and aggregate type (i.e., GRN vs. LMS) were found to significantly affect the IDEAL-CT results. In addition, the two-way interactions for mixture aging versus AC level, RAP content, and aggregate type were also identified as significant factors for the IDEAL-CT results. Overall, the GLM analysis confirmed that increasing the asphalt binder content from V-OBC to A-OBC in consideration of reduced RAP binder availability significantly improved the intermediate-temperature cracking resistance of the four RAP mixtures in the project.

Table 18. ANOVA Summary for IDEAL-CT Results

Factor	DF	Adj SS	Adj MS	F-value	P-value
Mixture Aging	1	19788.9	19788.9	551.12	0.000
AC Level	1	2312.9	2312.9	64.41	0.000
RAP Content	1	827.8	827.8	23.05	0.000
Aggregate Type	1	534.0	534.0	14.87	0.000
Mixture Aging × RAP Content	1	1202.9	1202.9	33.50	0.000
Mixture Aging × AC Level	1	534.2	534.2	14.88	0.000
Mixture Aging × Aggregate Type	1	172.8	172.8	4.81	0.031

4.2.2 Overlay Test (OT)

The OT was conducted to evaluate mixture cracking resistance under cyclic loading. Testing was performed following Tex-248-F. Three SGC specimens were compacted to a target height of 125 mm. Each SGC specimen was then cut and trimmed into two OT specimens at the following dimensions: 150 mm x 76 mm x 38 mm, yielding a total of six specimens for each mixture. The air voids of the OT specimens were controlled at 7.0 ± 0.5%. The OT specimens were glued to the OT fixture for testing in the Asphalt Mixture Performance Tester (AMPT), as shown in Figure 18(a). During the test, one side of the OT fixture remained fixed while the other side moved in a displacement-controlled mode applying a sawtooth form once per 10 second cycle (5 seconds of loading followed by 5 seconds of unloading). Testing was conducted at 25°C with a maximum displacement of 0.635 mm. The peak load of each cycle was recorded. The test was terminated when the peak load reached a 93% reduction from the initial peak load, and the corresponding number of cycles was recorded as the number of cycles to failure (N_f). The OT results were analyzed using the crack progression rate (CPR) for evaluating cracking resistance. CPR is defined as the reduction in load required to propagate cracking under the cyclic loading condition, which is determined by fitting a power equation to the curve of the normalized peak load versus the number of cycles and taking the absolute value of the exponent coefficient b, as shown in Figure 18(b). A lower CPR is desired for asphalt mixtures with better cracking resistance.

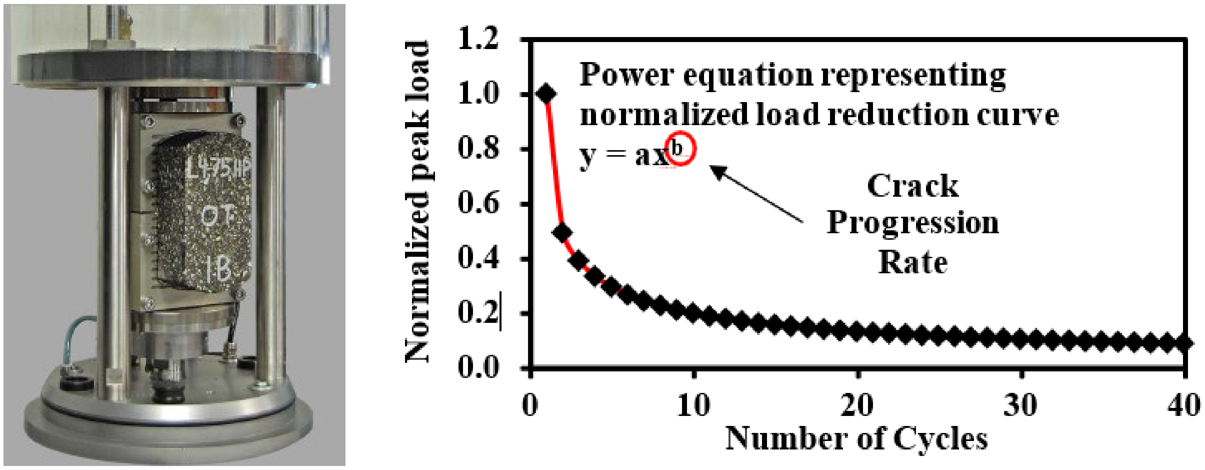


Figure 18. OT Test: (a) Test Setup in AMPT, (b) Illustration of CPR Determination

Table 19 summarizes the OT results at both the STA and CA conditions. The CPR results are presented graphically in Figure 19, highlighting the comparisons of V-OBC versus A-OBC for each of the four mixtures included in the project. The columns represent the average CPR results, and the error bars represent plus and minus one standard deviation from the average. For all the mixtures, the average CPR decreased as the asphalt binder content increased from V-OBC to A-OBC, indicating improved cracking resistance under cyclic loading. This improvement was significantly more pronounced for the 40% RAP mixtures than for the 20% RAP mixtures, which was expected considering that the A-OBC adjustment in consideration of reduced binder availability for the 40% RAP mixtures was almost double that of the 20% RAP mixtures. At both aging conditions, the 20% RAP mixtures had notably lower average CPR values than the corresponding 40% RAP mixtures at the V-OBC, but they had comparable average CPR values at the A-OBC. This indicates that the A-OBC adjustment yielded RAP mixtures with equivalent cracking resistance despite the different RAP contents and different virgin binders used. The OT results in Figure 19(b) also showed that all the mixtures at the A-OBC passed the suggested CPR criterion (i.e., maximum 1.75) from the NCAT top-down cracking group experiment (West et al., 2021); therefore, they are expected to have satisfactory top-down cracking performance in the field when used as surface mixtures.

The OT N_f results in Figure 20 show the same trends as the CPR results discussed above. For each of the four mixtures, increasing the asphalt binder content from V-OBC to A-OBC improved its cracking resistance at the STA condition, as indicated by a notable increase in the average N_f. However, this improvement diminished at the CA condition, especially for the two 20% RAP mixtures. After the A-OBC adjustment, the 40% RAP mixtures with a softer PG 52-28 binder had comparable N_f results as the 20% RAP mixtures with a PG 76-22 PMA binder, and thus, are expected to have similar cracking resistance despite doubling the RAP content.

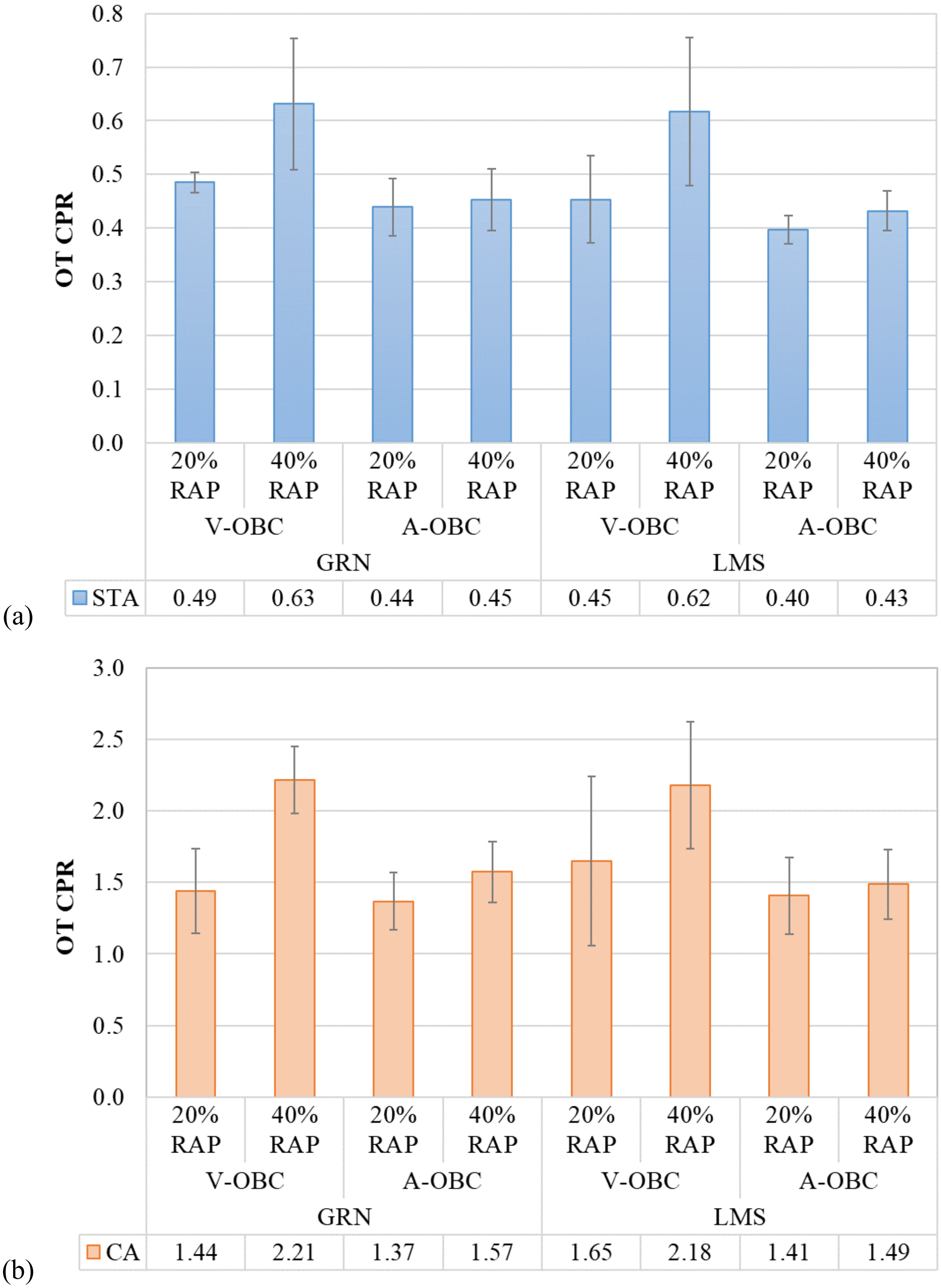


Figure 19. OT CPR Results: (a) STA Condition, (b) CA Condition

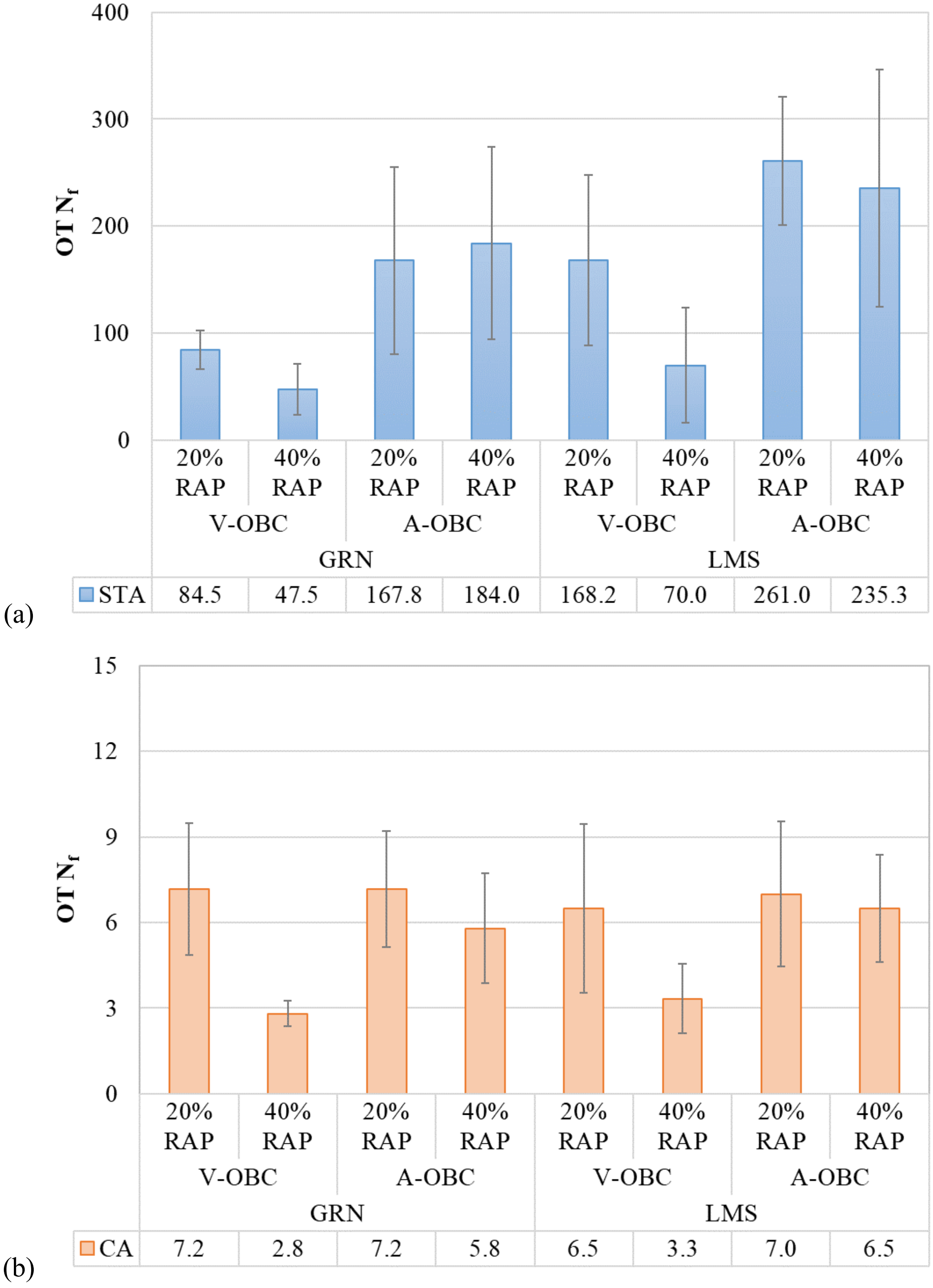


Figure 20. OT N_f Results: (a) STA Condition, (b) CA Condition

Table 19. OT Result Summary

Mixture ID (Virgin Binder)	Mixture Aging	Asphalt Binder Content	V_a (%)	N_f			CPR		
			Avg.	Avg.	St. Dev.	CV (%)	Avg.	St. Dev.	CV (%)
20% RAP GRN (PG 76-22)	STA (2 hours at 135°C)	V-OBC (5.40%)	7.2	84.5	17.9	21.2	0.49	0.02	3.8
		A-OBC (5.62%)	7.0	167.8	87.6	52.2	0.44	0.05	12.1
40% RAP GRN (PG 52-28)		V-OBC (5.40%)	7.1	47.5	23.6	49.7	0.63	0.12	19.3
		A-OBC (5.85%)	6.9	184.0	89.9	48.9	0.45	0.06	12.6
20% RAP LMS (PG 76-22)		V-OBC (6.20%)	6.5	168.2	80.0	47.6	0.45	0.08	17.9
		A-OBC (6.43%)	6.5	261.0	59.8	22.9	0.40	0.03	6.6
40% RAP LMS (PG 52-28)		V-OBC (6.20%)	6.8	70.0	53.6	76.6	0.62	0.14	22.3
		A-OBC (6.66%)	6.5	235.3	110.7	47.0	0.43	0.04	8.6
20% RAP GRN (PG 76-22)	STA plus CA (8 hours at 135°C)	V-OBC (5.40%)	6.7	7.2	2.3	32.3	1.44	0.30	20.5
		A-OBC (5.62%)	6.6	7.2	2.0	28.5	1.37	0.20	14.5
40% RAP GRN (PG 52-28)		V-OBC (5.40%)	6.7	2.8	0.4	16.0	2.21	0.23	10.6
		A-OBC (5.85%)	6.5	5.8	1.9	33.2	1.57	0.21	13.4
20% RAP LMS (PG 76-22)		V-OBC (6.20%)	6.5	6.5	2.9	45.4	1.65	0.59	35.9
		A-OBC (6.43%)	6.6	7.0	2.5	36.1	1.41	0.27	19.2
40% RAP LMS (PG 52-28)		V-OBC (6.20%)	7.3	3.3	1.2	36.3	2.18	0.45	20.5
		A-OBC (6.66%)	7.2	6.5	1.9	28.8	1.49	0.24	16.4

Finally, the GLM analysis was conducted to determine the significant factors affecting the OT CPR results. The N_f results were not analyzed via GLM because of the high variability among the replicates (COV ranging from 16% to 76.6% as shown in Table 19). The ANOVA results are summarized in Table 20 and the GLM output report from Minitab is presented in the Appendix. As shown, mixture aging (STA vs. CA), RAP content [i.e., 20% RAP (with PG 76-22 binder) vs. 40% RAP (with PG 52-28 binder)], and asphalt binder content (i.e., V-OBC vs. A-OBC) were found to significantly affect the OT results while aggregate type (i.e., GRN vs. LMS) did not; as a result, it was excluded from the analysis. In addition, the two-way interactions among mixture aging, RAP content, and asphalt binder content were also identified as significant factors for the OT results. Overall, the GLM analysis confirmed that increasing the asphalt binder content from V-OBC to A-OBC in consideration of reduced RAP binder availability significantly improved the cracking resistance of the RAP mixtures used in the project, especially the two 40% RAP mixtures.

Table 20. ANOVA Summary for OT CPR Results

Factor	DF	Adj SS	Adj MS	F-value	P-value
Mixture Aging	1	32.3868	32.3868	555.95	0.000
RAP Content	1	1.3751	1.3751	23.60	0.000
AC Level	1	1.6142	1.6142	27.71	0.000
Mixture Aging × RAP Content	1	0.5446	0.5446	9.35	0.003
Mixture Aging × AC Level	1	0.4990	0.4990	8.57	0.004
RAP Content × AC Level	1	0.5870	0.5870	10.08	0.002

4.2.3 Cantabro Test

The Cantabro test was conducted in accordance with AASHTO T 401. Testing was performed on the gyratory specimens produced for the mix design verification, which were compacted after STA for 2 hours at 135°C per AASHTO R 30. These specimens were compacted to N_{des} (75 gyrations) at multiple asphalt binder contents. For the Cantabro test, the initial mass of the specimen is obtained prior to testing. The specimen is then placed in the LA Abrasion machine for 300 revolutions at 30-33 rpm with no additional charges in the drum. The specimen is then removed from the drum and the final mass is recorded. The percent mass loss relative to the initial mass is then calculated. Figure 21 shows the LA Abrasion machine as well as a specimen after the Cantabro testing.

Figure 21. LA Abrasion Machine for Cantabro Testing (left) and Post-testing Cantabro Specimen (right)

Figure 22 presents the plot of Cantabro mass loss versus asphalt binder content for the four mix designs in this project. For each mix design, N_{des} specimens at multiple asphalt binder contents were tested. As shown, the Cantabro mass loss decreased as the asphalt binder content increased, indicating improved overall mixture durability. A linear trendline was fitted to the mass loss vs. asphalt binder content relationship for each mix design, as shown in Figure 22. The mass loss at the V-OBC and A-OBC were calculated based on linear interpolation, and the results are summarized in Table 21. For both GRN and LMS mix designs, increasing the RAP content from 20% to 40% shifted the curves up (with higher Cantabro mass loss indicating reduced overall mixture durability) with some convergence as the asphalt binder content increased. At the V-OBC, the 40% RAP mixtures had over 1% higher Cantabro mass loss than the corresponding 20% RAP mixtures. However, the 20% and 40% RAP mixtures had similar Cantabro mass loss (within 0.6% difference) at the A-OBC. Overall, the Cantabro test results indicated that increasing the asphalt binder content from V-OBC to A-OBC in consideration of reduced RAP binder availability improved the overall mixture durability and this improvement was more pronounced for the 40% RAP mixtures than the 20% RAP mixtures.

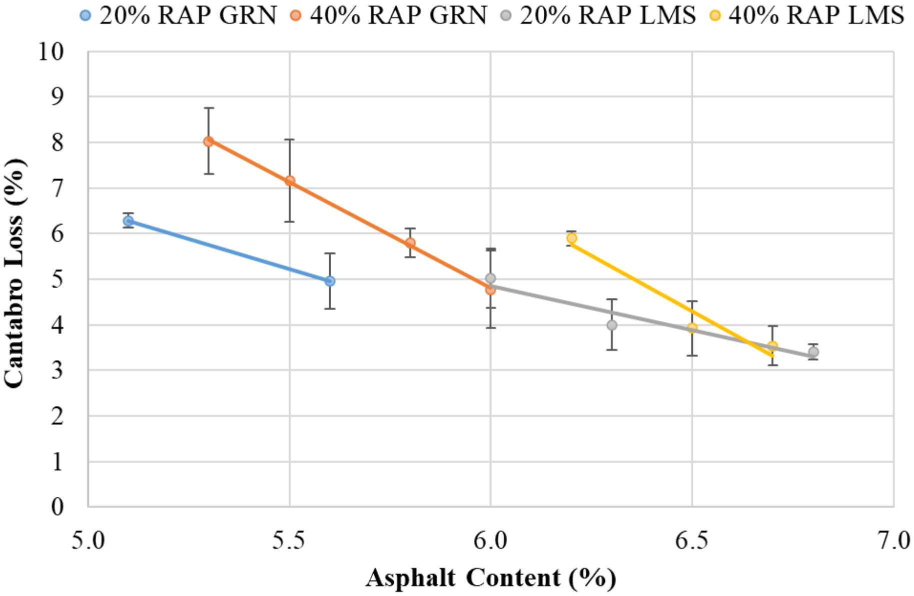


Figure 22. Cantabro Mass Loss versus Asphalt Binder Content

Table 21. Cantabro Mass Loss Results at V-OBC versus A-OBC

Mixture ID (Virgin Binder)	Asphalt Binder Content	Cantabro Loss (%)
20% RAP GRN (PG 76-22)	V-OBC (5.40%)	5.5
	A-OBC (5.62%)	4.9
40% RAP GRN (PG 52-28)	V-OBC (5.40%)	7.6
	A-OBC (5.85%)	5.5
20% RAP LMS (PG 76-22)	V-OBC (6.20%)	4.5
	A-OBC (6.43%)	4.0
40% RAP LMS (PG 52-28)	V-OBC (6.20%)	5.7
	A-OBC (6.66%)	3.5

4.2.4 Cracking/Durability Correlation Analysis

Figure 23 presents the correlation of the IDEAL-CT, OT, and Cantabro results across all the mixtures evaluated in the project. Note that the IDEAL-CT and OT results are presented for both the STA and CA conditions while the Cantabro results are presented only for the STA condition. As shown, the three tests did not strongly correlate with each other, with R^2 values varying from 0.14 to 0.69. This lack of correlation can be attributed to the different mechanisms and loading conditions of the tests; specifically, the IDEAL-CT and OT are intended to evaluate the cracking resistance of asphalt mixtures under monotonic loading and cyclic loading, respectively, while the Cantabro test is intended to evaluate the overall durability of asphalt mixtures.

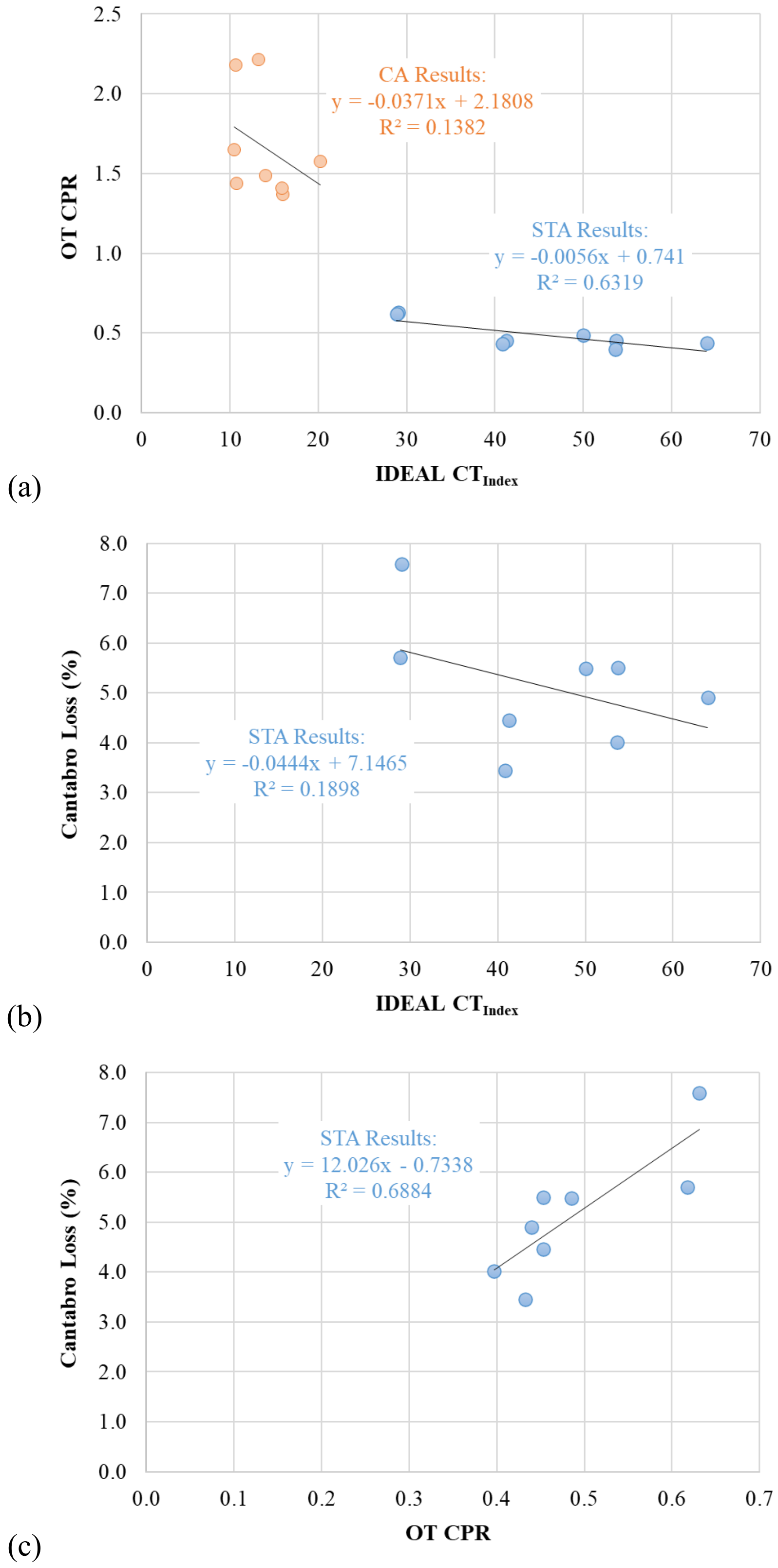


Figure 23. Correlation of Cracking/Durability Test Results: (a) IDEAL-CT vs. OT, (b) IDEAL-CT vs. Cantabro Test, (c) OT vs. Cantabro Test

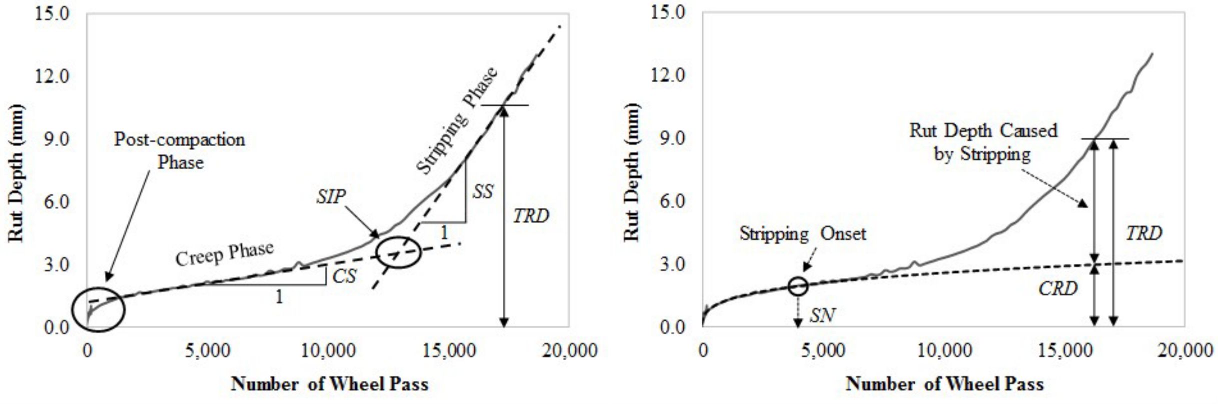
4.3 Mixture Rutting Evaluation

This section presents the test procedure and data analysis of the mixture rutting tests conducted in the project, including the HWTT, APA, and IDEAL-RT.

4.3.1 Hamburg Wheel Tracking Test (HWTT)

The HWTT was conducted in accordance with AASHTO T324. Specimens were loaded for a maximum of 20,000 passes with a 158-pound wheel load while submerged in a 50°C water bath (Figure 24). Two specimens were trimmed and loaded together in the machine as a single replicate. Four specimens (two replicates or wheel tracks) were tested per mixture. Prior to testing, the specimens were conditioned in the water bath at the test temperature for 45 minutes. The output of the test was a plot of rut depth versus number of wheel passes, which typically consists of three phases: post-compaction consolidation, creep phase, and stripping phase, as shown in Figure 25(a). In this project, two HWTT parameters were used to assess rutting resistance: total rut depth (TRD) and corrected rut depth (CRD). CRD represents the rut depth caused by the permanent deformation of the mixture, which is isolated from the rut depth due to stripping, as shown in Figure 25(b) (Yin et al., 2014; Yin et al., 2020). Compared to TRD, CRD allows a more accurate evaluation of the mixture's rutting resistance without the confounding impact from moisture damage. For HWTT results with stripping failure, CRD is lower than TRD at 20,000 passes, while CRD and TRD are equal for HWTT results without stripping failure. Moisture susceptibility was evaluated using the stripping inflection point (SIP), which represents the number of passes at which the HWTT curve transits from the creep phase into the stripping phase. A lower TRD and CRD are desired for better rutting resistance while a higher SIP is desired for better moisture resistance. As of December 2022, 14 states have established HWTT criteria for assessing the rutting resistance, and in some cases moisture resistance, of asphalt mixtures, but the criteria vary greatly from state to state (NAPA, 2023). FDOT uses a maximum rut depth of 12.5 mm at 20,000 passes as the criterion for research purposes, but HWTT testing is not required for mix design approval or production acceptance.

Figure 24. HWTT Device



(a) (b)

Figure 25. HWTT Results: (a) Typical Three-phase Rutting Curve, (b) Illustration of CRD versus TRD (Yin et al., 2020)

Table 22 summarizes the HWTT results including the TRD and CRD at 20,000 passes, number of passes to 12.5 mm rut depth ($N_{12.5}$), and SIP. Figure 26 and Figure 27 present the average HWTT rutting curves of the GRN and LMS mixtures, respectively, to highlight the impact of the A-OBC adjustment in consideration of reduced RAP binder availability. As shown in Figure 26, increasing the asphalt binder content from V-OBC to A-OBC had minimal impact on the 20% RAP GRN mixture but led to more rutting and earlier stripping for the 40% RAP GRN mixture (with an increase of 1.8 mm rut depth in CRD, a reduction of 3,800 passes in $N_{12.5}$, and a reduction of 4,500 passes in SIP). The two LMS mixtures also showed a notable deterioration in the HWTT results at the A-OBC versus V-OBC. For the 20% RAP LMS mixture, the A-OBC adjustment increased the TRD from 2.8 to 6.5 mm and the CRD from 2.6 to 3.4 mm, indicating reduced rutting resistance. The mixture also showed a late low-severity stripping failure (with a SIP of 17,000 passes) at the A-OBC. For the 40% RAP LMS mixture, the A-OBC adjustment decreased the $N_{12.5}$ by 5,300 passes, decreased the SIP by 4,375 passes, and increased the CRD by 1.8 mm, indicating reduced rutting and moisture resistance.

Table 22. HWTT Result Summary

Mixture ID (Virgin Binder)	Asphalt Binder Content	V_a (%)	TRD at 20,000 Passes (mm)	CRD at 20,000 Passes (mm)	$N_{12.5}$ (passes)	SIP (passes)
20% RAP GRN (PG 76-22)	V-OBC (5.40%)	6.9	3.1	2.5	>20,000	>20,000
	A-OBC (5.62%)	6.6	2.9	2.7	>20,000	>20,000
40% RAP GRN (PG 52-28)	V-OBC (5.40%)	7.2	>12.5	4.4	15,600	12,250
	A-OBC (5.85%)	7.0	>12.5	6.2	11,800	7,750
20% RAP LMS (PG 76-22)	V-OBC (6.20%)	7.0	2.8	2.6	>20,000	>20,000
	A-OBC (6.43%)	7.0	6.5	3.4	>20,000	17,000
40% RAP LMS (PG 52-28)	V-OBC (6.20%)	7.0	>12.5	5.5	13,600	9,875
	A-OBC (6.66%)	6.8	>12.5	7.3	8,300	5,500

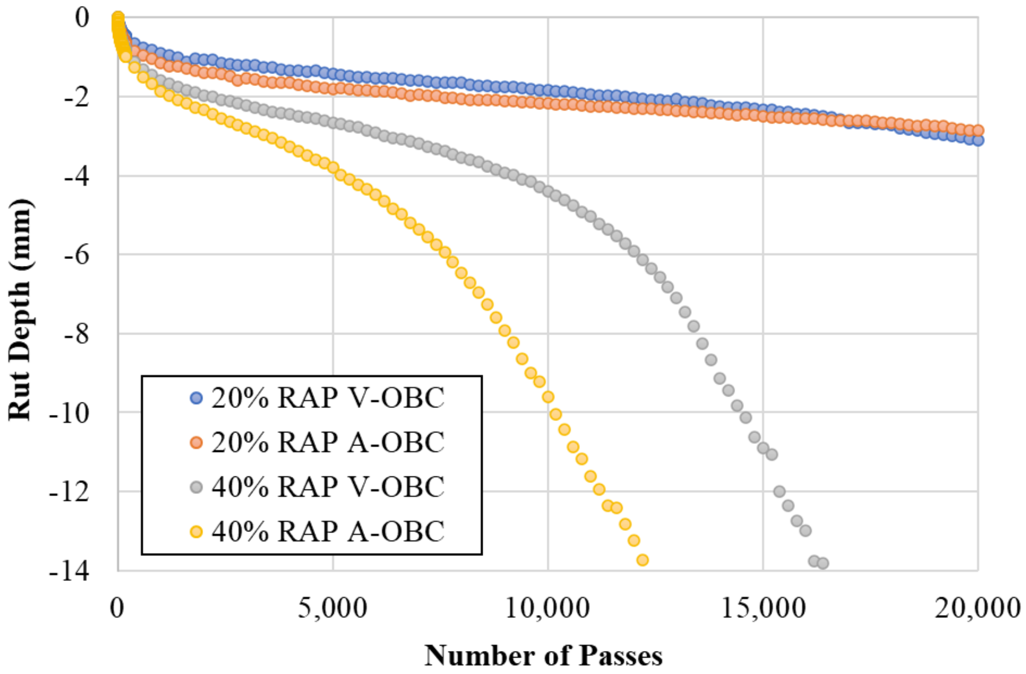


Figure 26. HWTT Rutting Curves of GRN Mixtures at V-OBC and A-OBC

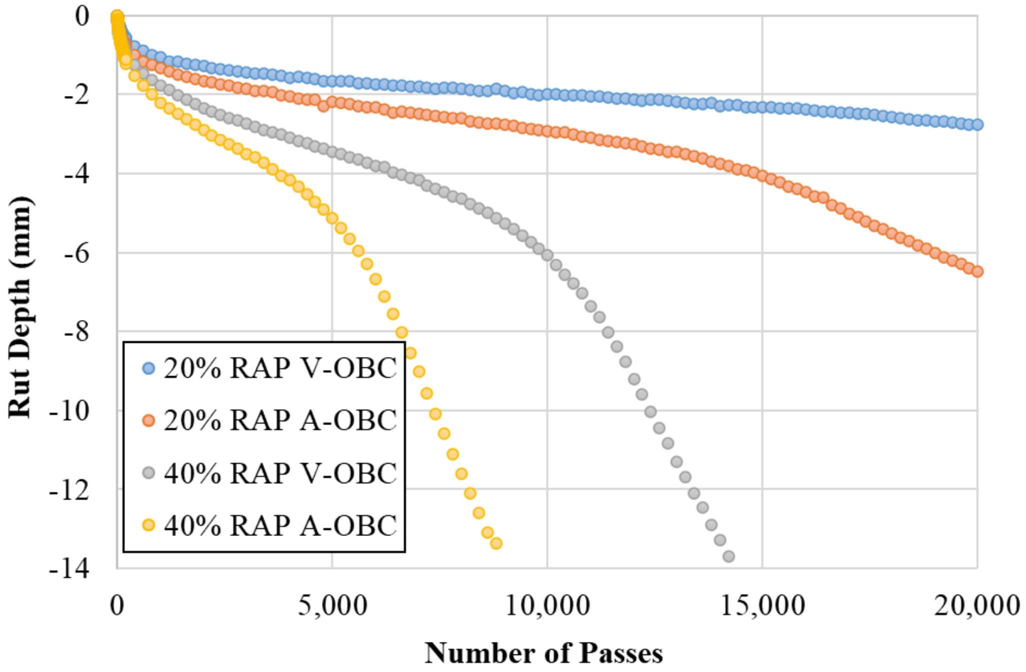


Figure 27. HWTT Rutting Curves of LMS Mixtures at V-OBC and A-OBC

The two 20% RAP mixtures (with a PG 76-22 PMA binder) at both the V-OBC and A-OBC passed FDOT's HWTT criterion and thus are expected to have adequate rutting and moisture resistance. Conversely, the two 40% RAP mixtures with a PG 52-28 unmodified binder failed the HWTT criterion, indicating potential rutting and moisture damage concerns. However, it should be noted that the 40% RAP mixtures are placed in the pavement structure at least one or two layers below the surface, so they are not likely to be exposed to the same high pavement in-service temperatures as the surface layer. Historical temperature data from FDOT's accelerated pavement testing facility shows that the temperature difference between the pavement surface and 4 inches below the surface could vary up to 15 to 20°C in summertime. Therefore, these mixtures may not necessarily be susceptible to rutting despite the unsatisfactory performance in the HWTT. It is also worth noting that asphalt pavements in Florida do not have a permeability issue, so stripping failure is not likely to occur in the field. Nevertheless, adding hydrated lime or liquid anti-strip or using a PG 58-22 or PG 58-28 binder in lieu of a PG 52-28 binder are potential strategies to improve the HWTT results of the 40% RAP mixtures.

4.3.2 Asphalt Pavement Analyzer (APA)

The APA test was conducted in accordance with AASHTO T 340. For each mixture, six specimens were prepared to a height of 75 mm and a target air void level of 7.0 ± 0.5% air voids. Two specimens were tested per APA wheel track, as shown in Figure 28. The test applies a repeated load to the specimens via a loaded wheel on top of inflated rubber hoses. The test was conducted at 64°C, and the wheel load and hose pressure were set to 100 lbs. and 100 psi, respectively. Prior to testing, the specimens were conditioned in the testing chamber for six hours at 64°C. Several states have established APA criteria for assessing the rutting resistance of asphalt mixtures (NAPA, 2023). These criteria vary from state to state depending on the test temperature and other factors such as mixture type and traffic level. For example, FDOT requires that mixtures used in District 3 have a maximum rut depth of 4.5 mm at 8,000 cycles (or 16,000 passes). Previous studies at the NCAT Test Track suggest that a rut depth of less than 5.5 mm in the APA would yield a rut-resistant mixture on the NCAT Test Track (Tran et al., 2009; West et al., 2012).

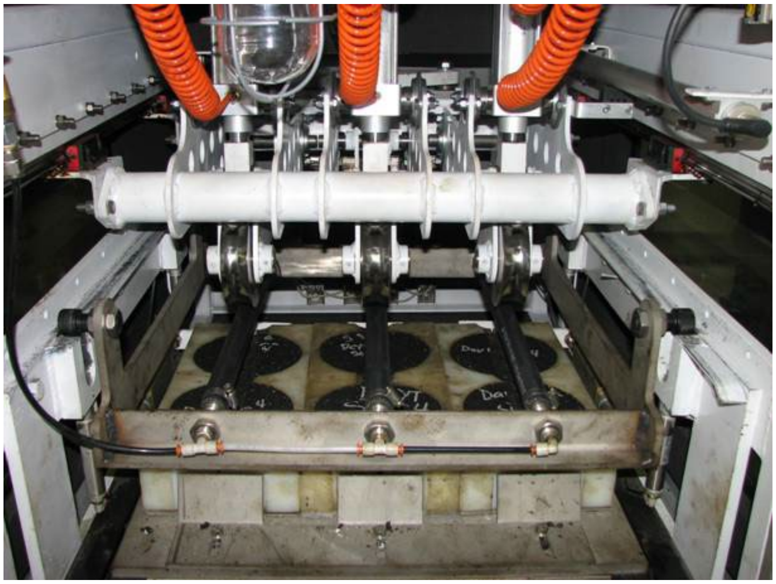


Figure 28. APA Test Device and Specimen Setup

Table 23 summarizes the APA results of the four RAP mixtures in the project. Figure 29 and Figure 30 present the average rutting curves of the GRN and LMS mixtures, respectively, for visual comparisons. Figure 31 presents the same results highlighting the V-OBC versus A-OBC comparisons, where the columns represent the average rut depth, and the error bars represent plus and minus one standard deviation from the average. For all the mixtures, increasing the asphalt binder content from V-OBC to A-OBC did not significantly affect the APA results, if considering the variability of the test. A potential explanation for these results is that the APA is not sensitive to moderate changes in asphalt binder content (i.e., no more than 0.5%) and thus, the test did not manifest the impact of the A-OBC adjustment in consideration of reduced RAP binder availability for the mixtures evaluated in the project. The 20% RAP mixtures at both the V-OBC and A-OBC met FDOT District 3's APA criterion, but the 40% RAP mixtures failed. Nevertheless, the 40% RAP mixtures may not necessarily be susceptible to rutting in the field because they are placed in the pavement structure at least one or two layers below the surface, and thus, are not likely to be exposed to the same high pavement in-service temperatures as the surface layer is. The APA results also show that the 20% RAP mixtures with a PG 76-22 PMA binder had consistently lower rut depths than the 40% RAP mixtures with a PG 52-28 binder, indicating better rutting resistance. This agrees with the HWTT results discussed previously and demonstrates the benefits of polymer modification on the rutting resistance of asphalt mixtures.

Table 23. APA Result Summary

Mixture ID (Virgin Binder)	Asphalt Binder Content	V_a (%)	Automated Rut Depth (mm)		
		Avg.	Avg.	St. Dev.	CV (%)
20% RAP GRN (PG 76-22)	V-OBC (5.40%)	7.1	3.8	0.3	7.7
	A-OBC (5.62%)	7.2	3.9	0.8	21.0
40% RAP GRN (PG 52-28)	V-OBC (5.40%)	7.0	5.9	0.7	11.7
	A-OBC (5.85%)	7.1	5.8	1.0	16.7
20% RAP LMS (PG 76-22)	V-OBC (6.20%)	7.0	3.7	0.5	13.5
	A-OBC (6.43%)	7.1	3.9	0.4	9.0
40% RAP LMS (PG 52-28)	V-OBC (6.20%)	6.8	5.6	1.6	28.6
	A-OBC (6.66%)	7.1	6.6	0.6	9.3

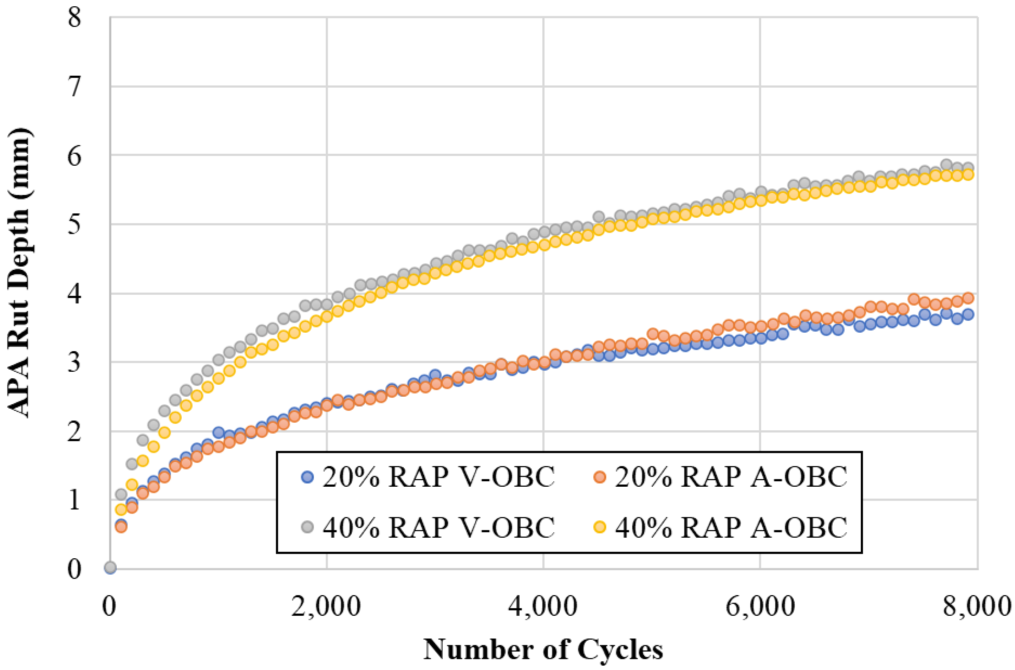


Figure 29. APA Automated Rut Depth Curves of GRN Mixtures

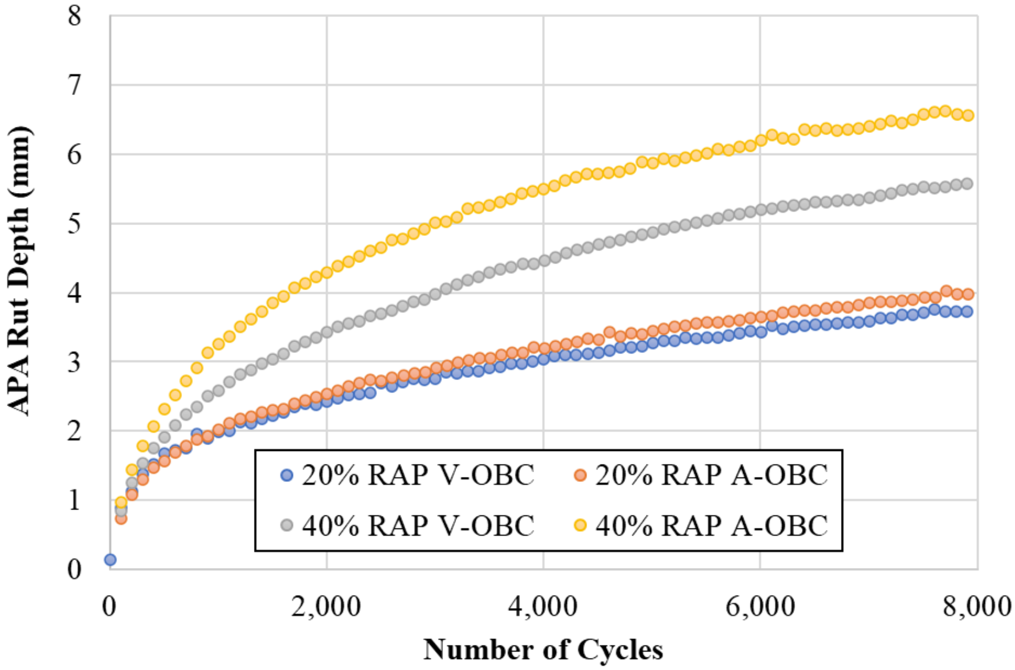


Figure 30. APA Automated Rut Depth Curves of LMS Mixtures

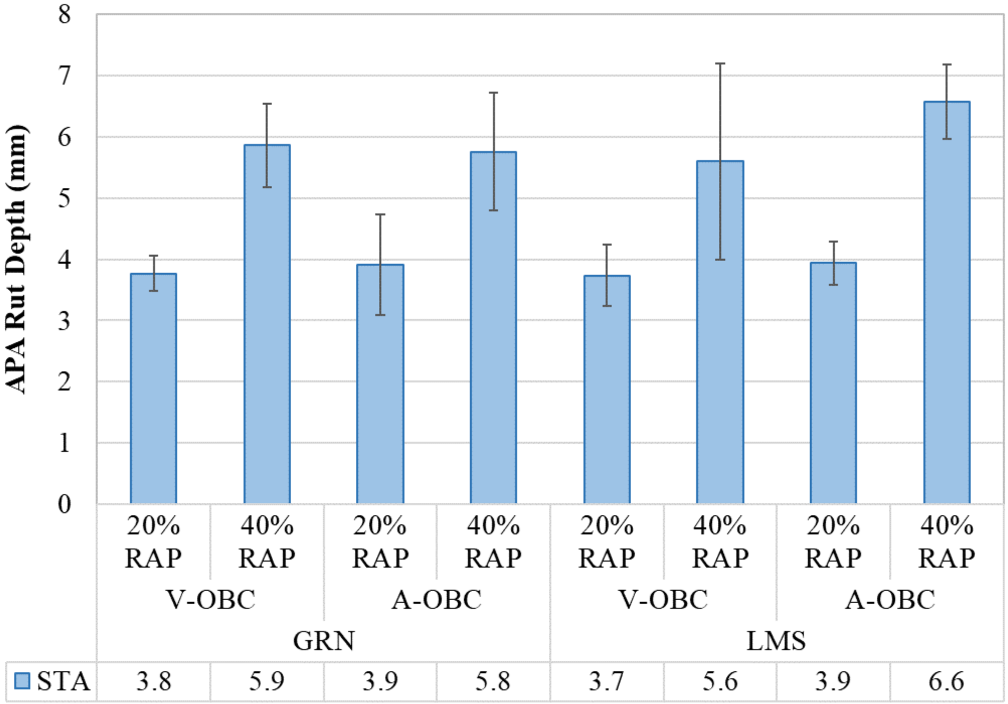


Figure 31. APA Automated Rut Depth Results

Finally, the GLM analysis was conducted to determine the significant factors affecting the APA results. The ANOVA showed that RAP content [i.e., 20% RAP (with PG 76-22 binder) vs. 40% RAP (with PG 52-28 binder)] was the only significant factor, while asphalt binder content (i.e., V-OBC vs. A-OBC) and aggregate type (i.e., GRN vs. LMS) did not affect the APA results. The GLM output report from Minitab is provided in the Appendix.

4.3.3 Indirect Tensile Asphalt Rutting Test (IDEAL-RT)

The IDEAL-RT was performed in accordance with ASTM D8360. This test requires a cradle attachment for the standard indirect tension breaking head to create two shear planes within the specimen (Zhou et al., 2019), as shown in Figure 32. Testing was performed using a Marshall style load frame (50 mm/min loading rate) on specimens conditioned at 50°C for 1 hour in a water bath prior to testing. A minimum of three specimens prepared to 62 mm tall and 7.0 ± 0.5% air voids were tested for each mixture. The rutting tolerance index (RT_{Index}) is calculated using Equation 4, where a higher RT_{Index} is indicative of better rutting resistance. The suggested RT_{Index} criteria by Zhou et al. (2021) are summarized in Table 24. Based on these criteria, a minimum RT_{Index} of 65 seems appropriate for Florida mixtures as Florida is largely a PG 70-xx state per LTPPBind.

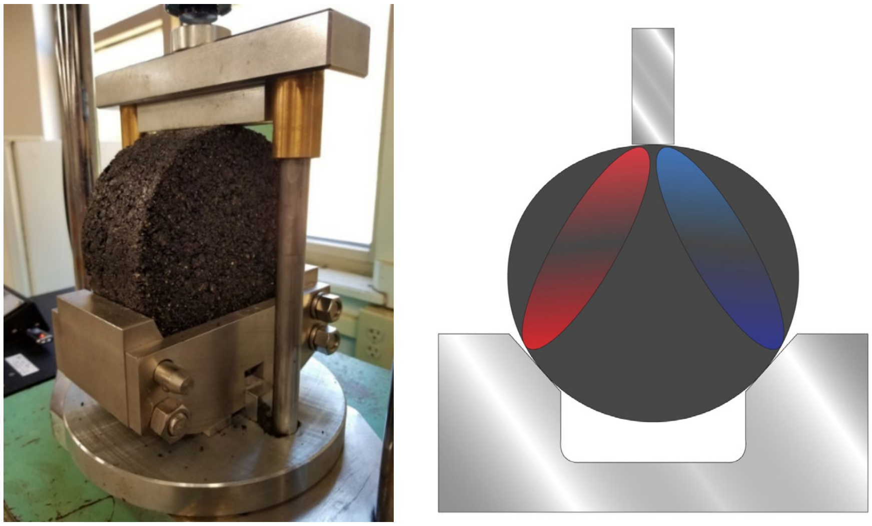


Figure 32. IDEAL-RT Test Setup in Marshall Press (left) and Illustration of Shear Planes within the Specimen (right)

$$PRT_{Index} = 6.618\ x\ 10^{-5}\ x\ \frac{\left[0.356\ x\ \frac{P_{Max}}{(t\ x\ w)}\right]}{1\ Pa} \qquad \text{Equation 4}$$

Where,

RT_{Index} = rutting tolerance index;
P_{Max} = peak load (N);
t = specimen thickness (m); and
w = width of upper loading strip (0.0191 m).

Table 24. Suggested RT_{Index} Criteria by Zhou et al. (2021)

Climate Binder Grade	Minimum RT_{Index}
PG 64-xx or lower (with 95% confidence)	60
PG 70-xx (with 95% confidence)	65
PG 76-xx or higher (with 95% confidence)	75

Table 25 summarizes the IDEAL-RT results and Figure 33 presents a graphical comparison of the RT_{Index} results at the V-OBC versus A-OBC, where the columns represent the average RT_{Index}, and the error bars represent plus and minus one standard deviation from the average. As expected, rutting resistance as measured by the RT_{Index} decreased as the asphalt binder content increased from V-OBC to A-OBC. At the V-OBC, all the mixtures met the suggested RT_{Index} criterion of 65, indicating adequate rutting resistance. At the A-OBC, the two 20% RAP mixtures passed the RT_{Index} threshold while the two 40% RAP mixtures failed marginally with an average RT_{Index} of 64.4 and 62.9. This indicated that the A-OBC adjustment in consideration of reduced RAP binder availability could yield 40% RAP mixtures (with a PG 52-28 unmodified binder) with inadequate rutting resistance. However, it should be noted that the IDEAL-RT is still relatively new and the suggested criteria in Table 24 were developed based on correlation with the HWTT (Zhou et al., 2021); therefore, further validation of these criteria versus field rutting performance is needed in future research. The results in Figure 33 also showed that the 20% RAP mixtures with a PG 76-22 PMA binder had consistently higher RT_{Index} and are expected to have better rutting resistance than the corresponding 40% RAP mixtures with a PG 52-28 unmodified binder. This again highlights the benefits of polymer modification in improving the rutting resistance of asphalt mixtures.

Table 25. IDEAL-RT Result Summary

Mixture ID (Virgin Binder)	Asphalt Binder Content	V_a (%)	Peak Load (lbf)	RT_{Index}		
		Avg.	Avg.	Avg.	St. Dev.	CV (%)
20% RAP GRN (PG 76-22)	V-OBC (5.40%)	6.8	1,173	104.4	3.8	3.6
	A-OBC (5.62%)	7.2	1,056	93.9	3.3	3.5
40% RAP GRN (PG 52-28)	V-OBC (5.40%)	6.8	904	80.4	4.8	6.0
	A-OBC (5.85%)	6.8	724	64.4	3.0	4.6
20% RAP LMS (PG 76-22)	V-OBC (6.20%)	7.0	1,314	116.9	7.9	6.8
	A-OBC (6.43%)	6.9	1,195	106.3	10.3	9.7
40% RAP LMS (PG 52-28)	V-OBC (6.20%)	7.0	915	81.4	3.5	4.3
	A-OBC (6.66%)	6.8	707	62.9	5.2	8.2

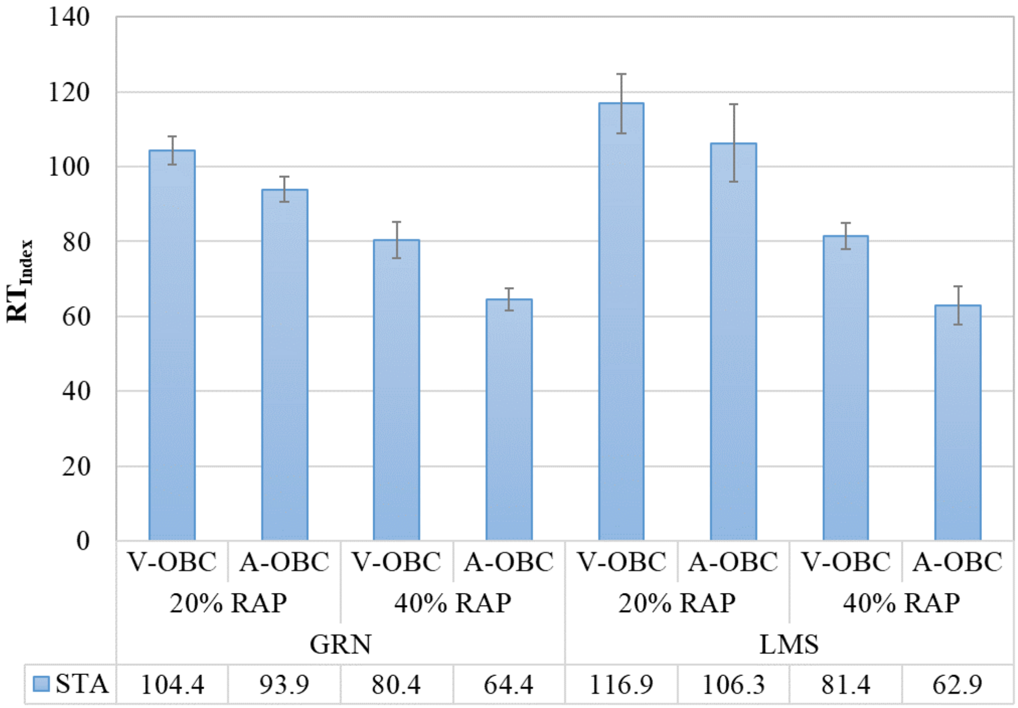


Figure 33. IDEAL-RT Results

Finally, the GLM analysis was conducted to determine the significant factors affecting the IDEAL-RT results. The ANOVA results are summarized in Table 26 and the GLM output report from Minitab is presented in the Appendix. As shown, RAP content [i.e., 20% RAP (with PG 76-22 binder) vs. 40% RAP (with PG 52-28 binder)], asphalt binder content (i.e., V-OBC vs. A-OBC), and aggregate type (i.e., GRN vs. LMS) were found to significantly affect the IDEAL-RT results. In addition, the two-way interaction between RAP content and aggregate type was also identified as a significant factor. Overall, the GLM analysis confirmed that increasing the asphalt binder content from V-OBC to A-OBC in consideration of reduced RAP binder availability reduced the rutting resistance of the RAP mixtures in the project.

Table 26. ANOVA Summary for IDEAL-RT Results

Factor	DF	Adj SS	Adj MS	F-value	P-value
RAP Content	1	8151.4	8151.36	266.20	0.000
AC Level	1	1422.2	1422.24	46.45	0.000
Aggregate Type	1	251.2	251.24	8.20	0.008
RAP Content × Aggregate Type	1	304.7	304.74	9.95	0.004

4.3.4 Rutting Correlation Analysis

Figure 34 presents the correlation of HWTT, APA, and IDEAL-RT results across all the mixtures evaluated in the project. Note that the HWTT results are presented using the CRD parameter to avoid the confounding impact from stripping. As shown, the three tests had strong correlations with each other, with R^2 values varying from 0.85 to 0.94. This indicates that the HWTT, APA, and IDEAL-RT are reasonably comparable in assessing the rutting resistance of asphalt mixtures.

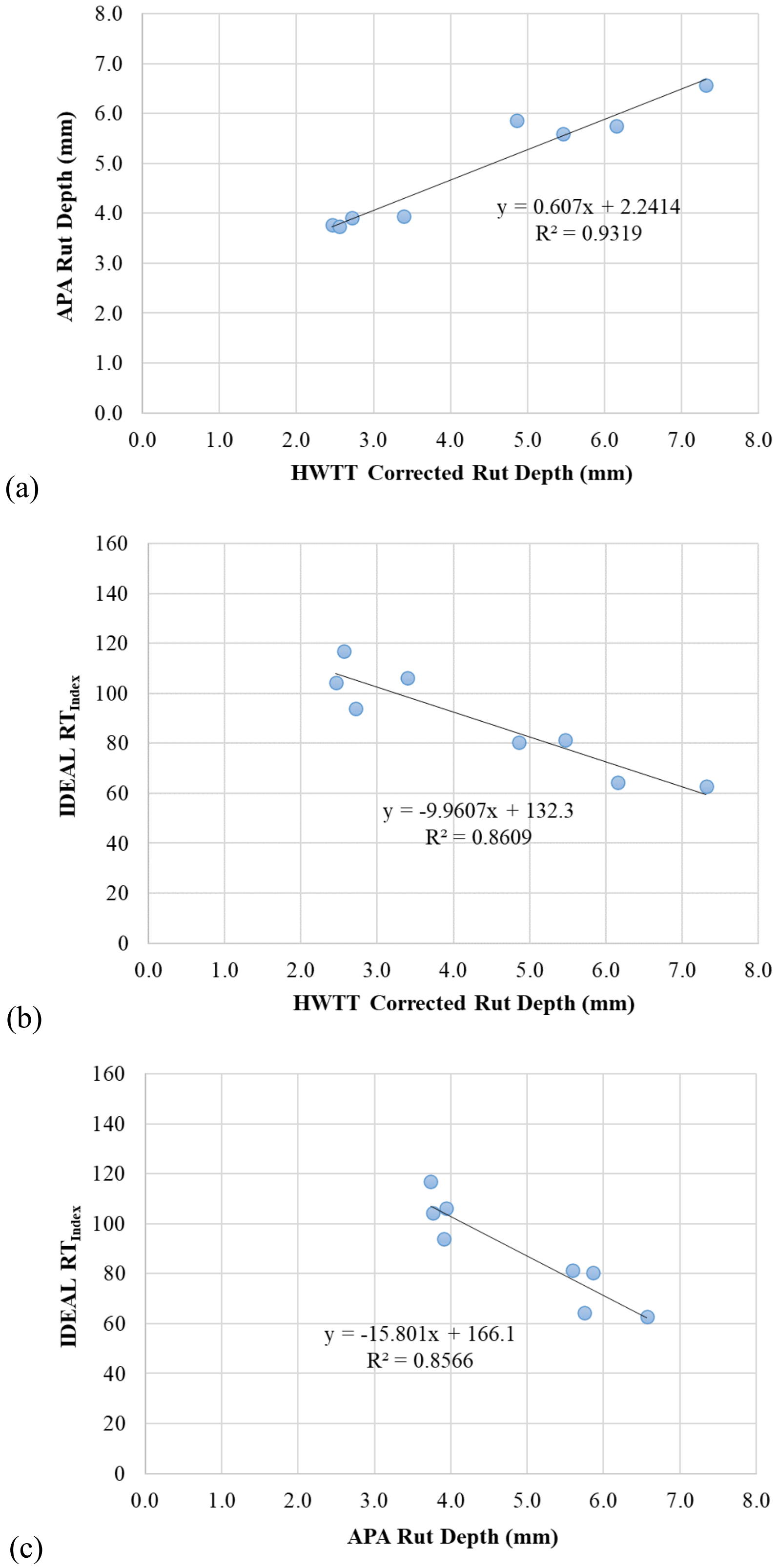


Figure 34. Correlation of Rutting Test Results: (a) HWTT vs. APA, (b) HWTT vs. IDEAL-RT, (c) APA vs. IDEAL-RT

4.4 Mixture Performance Diagram Analysis

Figure 35 and Figure 36 present the HWTT-versus-IDEAL-CT and HWTT-versus-OT performance diagrams, respectively, for the four RAP mixtures evaluated in the project. The vertical dashed lines represent FDOT's HWTT criterion of 12.5 mm rut depth at 20,000 passes but expressed using the RRI parameter to allow the comparison of HWTT results reaching 20,000 passes versus 12.5mm rut depth at the end of the test. RRI is calculated based on the rut depth and number of passes at the end of the test, following Equation 5. A higher RRI is desired for better HWTT performance, and an RRI of 10,000 corresponds to 12.5 mm rut depth at 20,000 passes. The horizontal dashed lines represent the suggested IDEAL-CT and OT criteria from the NCAT top-down cracking group experiment (i.e., $CT_{Index} \geq 15$ and $CPR \leq 1.75$ at the CA condition) (West et al., 2021). The arrows in the figures indicate the impacts of adding additional virgin binder in consideration of reduced RAP binder availability (i.e., V-OBC versus A-OBC) on the rutting and cracking resistance of RAP mixtures. The performance diagram consists of four quadrants indicating if the results pass or fail the rutting and cracking test criteria.

$$RRI = N_{max}(1 - RD_{max}) \qquad \text{Equation 5}$$

Where,

N_{max} = number of passes at the end of the test; and
RD_{max} = rut depth at the end of the test, in inches.

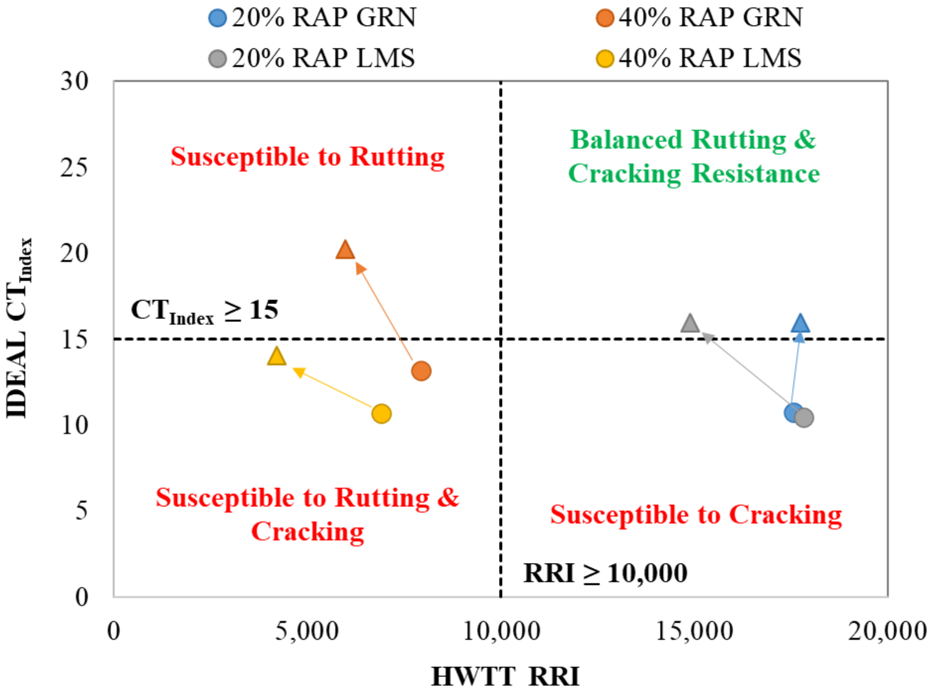


Figure 35. HWTT versus IDEAL-CT Performance Diagram (Notes: arrows indicate the impact of increasing asphalt binder content from V-OBC to A-OBC)

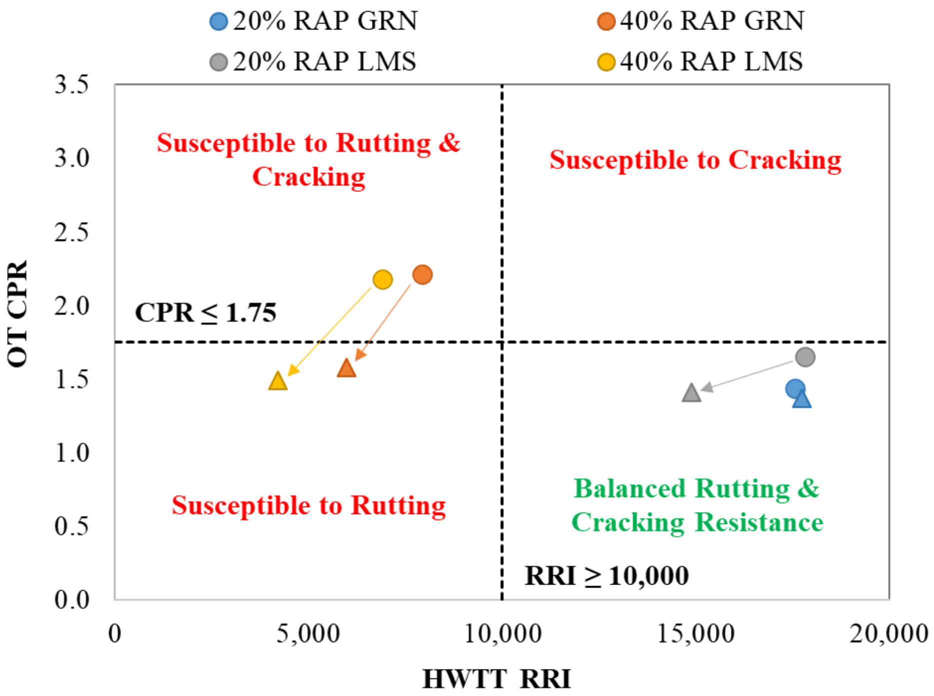


Figure 36. HWTT versus OT Performance Diagram (Notes: arrows indicate the impact of increasing asphalt binder content from V-OBC to A-OBC)

As shown in Figure 35, increasing the asphalt binder content from V-OBC to A-OBC moved the RAP mixtures toward the upper left corner of the performance diagram, indicating improved IDEAL-CT results but reduced HWTT results. The only exception was the 20% RAP GRN mixture, where adding additional virgin binder in consideration of reduced RAP binder availability improved its IDEAL-CT result but did not significantly affect the HWTT result; as a result, the mixture moved upward on the performance diagram. When compared against the HWTT and IDEAL-CT criteria, the two 20% RAP mixtures at the A-OBC fall within the ‘balanced performance’ zone and are expected to have balanced rutting and cracking resistance, but they failed the IDEAL-CT criteria at the V-OBC and thus, are located outside the ‘balanced performance’ zone. Conversely, the two 40% RAP mixtures at both the V-OBC and A-OBC are located outside the ‘balanced performance’ zone on the performance diagram because of the failing HWTT and/or IDEAL-CT results.

The HWTT-versus-OT performance diagram in Figure 36 shows similar trends as the HWTT-versus-IDEAL-CT performance diagram discussed above. Increasing the asphalt binder content from V-OBC to A-OBC in consideration of reduced RAP binder availability improved the cracking resistance but reduced the rutting resistance of the RAP mixtures except the 20% RAP GRN mixture. At both the V-OBC and A-OBC, the 20% RAP mixtures are located within the ‘balanced performance’ zone on the diagram and are expected to have balanced rutting and cracking resistance. The 40% RAP mixtures, on the other hand, fall outside the ‘balanced performance’ zone because of the failing HWTT and IDEAL-CT results at the V-OBC and the failing HWTT results at the A-OBC.

4.5 Extracted Binder Characterization

This section presents the test procedure and data analysis of the rheological tests conducted on the extracted binders in the project, which include the Superpave PG, ΔT_c, MSCR, LAS, and DSR Frequency Sweep tests. Asphalt binders from loose mixtures at the STA and CA conditions were extracted using the centrifuge method in ASTM D2172 with TCE and recovered with the rotary evaporator per ASTM D7906. The binders were then tested as extracted and recovered without additional Rolling Thin Film Oven (RTFO) or Pressure Aging Vessel (PAV) aging.

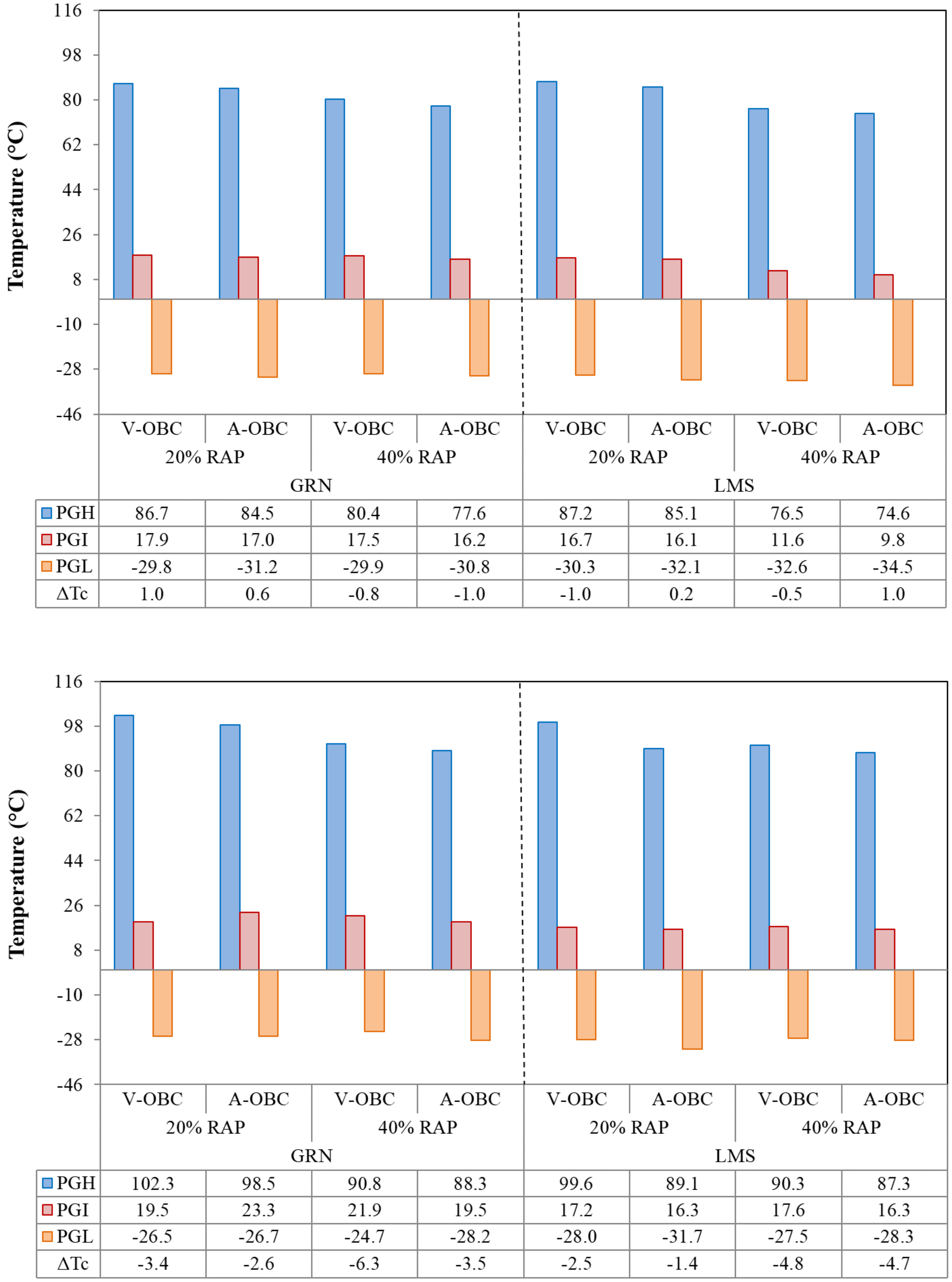
4.5.1 Superpave PG and ΔT_c Parameter

The performance grades of the extracted binders were determined following AASHTO T 315 (M 320), except that the binders were tested as extracted and recovered without additional RTFO or PAV aging. The ΔT_c was determined based on the BBR results, where ΔT_c is defined as the numerical difference between the low continuous grade temperatures determined from the BBR stiffness criterion of 300 MPa and the m-value criterion of 0.300. The ΔT_c parameter has recently been used to assess the loss of stress relaxation properties of asphalt binders. Generally, a more positive (or less negative) ΔT_c value is desired for asphalt binders with better ductility and block cracking resistance. However, it should be noted that the applicability of ΔT_c to PMA binders has been questioned (Kluttz, 2019; Elwardany et al. 2020) and warrants further investigation.

The PG and ΔT_c results are summarized in Table 27, with Figure 37 highlighting the comparisons of V-OBC versus A-OBC for each of the four mixtures in the project. As the asphalt binder content increased from V-OBC to A-OBC for all the mixtures, a decrease in the continuous true grade (i.e., pass/fail temperature) of the extracted binders was observed at high, intermediate, and low temperatures at both aging conditions. This behavior indicates an overall softening of the composite binder in the mixture as the asphalt binder content increased. The only exception was the 20% RAP GRN mixture at the CA condition, of which the extracted binder at the A-OBC had a higher intermediate continuous true grade temperature (23.3°C) than at the V-OBC (19.5°C). In most cases, increasing the asphalt binder content from V-OBC to A-OBC in consideration of reduced RAP binder availability also improved the ΔT_c of the extracted binders. In all cases except one, the extracted binders at the STA condition had the same Superpave PG at the V-OBC versus A-OBC. The only exception was the 40% RAP LMS mixture, of which the extracted binder was graded to be PG 76-28 at the V-OBC versus PG 70-34 at the A-OBC. At the CA condition, the softening effect of the A-OBC adjustment was visible for all mixtures, yielding a maximum of 6°C (i.e., one grade) change in either the high-temperature or low-temperature grade of the extracted binder.

Table 27. PG and ΔT_c Result Summary

Mixture ID (Virgin Binder)	Mixture Aging	Asphalt Binder Content	T_{cont}, High (°C)	T_{cont}, Intermediate (°C)	T_{cont}, Low S (°C)	T_{cont}, Low m-value (°C)	ΔT_c (°C)	Superpave PG
20% RAP GRN (PG 76-22)	STA (2 hours at 135°C)	V-OBC (5.40%)	86.7	17.9	-29.8	-30.8	1.0	82-28
		A-OBC (5.62%)	84.5	17.0	-31.2	-31.8	0.6	82-28
40% RAP GRN (PG 52-28)		V-OBC (5.40%)	80.4	17.5	-30.7	-29.9	-0.8	76-28
		A-OBC (5.85%)	77.6	16.2	-31.8	-30.8	-1.0	76-28
20% RAP LMS (PG 76-22)		V-OBC (6.20%)	87.2	16.7	-31.3	-30.3	-1.0	82-28
		A-OBC (6.43%)	85.1	16.1	-32.1	-32.3	0.2	82-28
40% RAP LMS (PG 52-28)		V-OBC (6.20%)	76.5	11.6	-33.1	-32.6	-0.5	76-28
		A-OBC (6.66%)	74.6	9.8	-34.5	-35.5	1.0	70-34
20% RAP GRN (PG 76-22)	STA plus CA (8 hours at 135°C)	V-OBC (5.40%)	102.3	19.5	-29.9	-26.5	-3.4	100-22
		A-OBC (5.62%)	98.5	23.3	-29.3	-26.7	-2.6	94-22
40% RAP GRN (PG 52-28)		V-OBC (5.40%)	90.8	21.9	-31.0	-24.7	-6.3	88-22
		A-OBC (5.85%)	88.3	19.5	-31.7	-28.2	-3.5	88-28
20% RAP LMS (PG 76-22)		V-OBC (6.20%)	99.6	17.2	-30.5	-28.0	-2.5	94-28
		A-OBC (6.43%)	89.1	16.3	-33.1	-31.7	-1.4	88-28
40% RAP LMS (PG 52-28)		V-OBC (6.20%)	90.3	17.6	-32.3	-27.5	-4.8	88-22
		A-OBC (6.66%)	87.3	16.3	-33.0	-28.3	-4.7	82-28



(a)

	GRN				LMS			
	20% RAP		40% RAP		20% RAP		40% RAP	
	V-OBC	A-OBC	V-OBC	A-OBC	V-OBC	A-OBC	V-OBC	A-OBC
🟦 PGH	86.7	84.5	80.4	77.6	87.2	85.1	76.5	74.6
🟥 PGI	17.9	17.0	17.5	16.2	16.7	16.1	11.6	9.8
🟧 PGL	-29.8	-31.2	-29.9	-30.8	-30.3	-32.1	-32.6	-34.5
ΔTc	1.0	0.6	-0.8	-1.0	-1.0	0.2	-0.5	1.0

(b)

	GRN				LMS			
	20% RAP		40% RAP		20% RAP		40% RAP	
	V-OBC	A-OBC	V-OBC	A-OBC	V-OBC	A-OBC	V-OBC	A-OBC
🟦 PGH	102.3	98.5	90.8	88.3	99.6	89.1	90.3	87.3
🟥 PGI	19.5	23.3	21.9	19.5	17.2	16.3	17.6	16.3
🟧 PGL	-26.5	-26.7	-24.7	-28.2	-28.0	-31.7	-27.5	-28.3
ΔTc	-3.4	-2.6	-6.3	-3.5	-2.5	-1.4	-4.8	-4.7

Figure 37. PG and ΔT_c Results: (a) STA Condition, (b) CA Condition

4.5.2 Multiple Stress Creep Recovery (MSCR)

The MSCR test per AASHTO T 350 (M 332) was used to evaluate the extracted binders' elastic response and rutting resistance. The test was conducted at 67°C on as-recovered binders. The test applied 20 loading cycles at a low-stress level of 0.1 kPa and 10 cycles at a high-stress level of 3.2 kPa. Each loading cycle consisted of 1 second of creep and 9 seconds of recovery. For data analysis, the strain responses were used to calculate the percent recovery (%R) and non-recoverable creep compliance (J_{nr}) using Equations 6 and 7, respectively. A higher %Recovery value indicates better binder elasticity, and a lower J_{nr} value indicates better rutting resistance.

$$\%R = \frac{\varepsilon_r}{\varepsilon_r + \varepsilon_{nr}} * 100\% \qquad \text{Equation 6}$$

Where,

ε_r = recoverable strain; and
ε_{nr} = non-recoverable strain.

$$J_{nr} = \frac{\varepsilon_{nr}}{\sigma} \qquad \text{Equation 7}$$

Where,

σ = creep stress.

Figure 38 presents the MSCR results. As shown in Figure 38(a), the binders extracted from the V-OBC mixtures had notably lower $J_{nr,3.2}$ values than those from the A-OBC mixtures, indicating the softening of the binders in the mixtures as the asphalt binder content increased. The only exception was the 20% RAP GRN mixture at the CA condition, of which the extracted binder at the A-OBC had a slightly lower $J_{nr,3.2}$ value than at the V-OBC (i.e., 0.02 versus 0.03 kPa^{-1}). This behavior was also observed in the intermediate-temperature PG results (Table 27 and Figure 37). As expected, the softening effect of the A-OBC adjustment in consideration of reduced RAP binder availability was significantly more pronounced for the 40% RAP mixtures than for the 20% RAP mixtures. Nevertheless, in all cases, the A-OBC adjustment did not affect the MSCR traffic rating of the extracted binders. At both aging conditions, asphalt binders extracted from the 20% RAP mixtures (with a PG 76-22 PMA binder) presented consistently lower $J_{nr,3.2}$ values than the corresponding 40% RAP mixtures (with a PG 52-28 binder), indicating better rutting resistance. This agrees with the mixture rutting results and highlights the benefits of polymer modification on the rutting resistance of asphalt binders and mixtures. At the STA condition, asphalt binders extracted from the 20% RAP mixtures had higher traffic ratings than the corresponding 40% RAP mixtures; while at the CA condition, all extracted binders were classified as "E" (extreme traffic loading) for the traffic rating.

The results in Figure 38(b) show that in all cases except one, the binders extracted from the A-OBC mixtures had slightly lower $\%R_{3.2}$ values than those from the V-OBC mixtures, but the differences were not considered practically significant considering the variability of the $\%R_{3.2}$ measurement. The 40% RAP mixtures showed significantly lower $\%R_{3.2}$ values than the 20% RAP mixtures, indicating less elastic response. This difference can be attributed to the use of a PG 76-22 PMA binder in the 20% RAP mixtures versus a PG 52-28 unmodified binder in the 40% RAP mixtures. In all cases, the extracted binder at the CA condition had a higher $\%R_{3.2}$ than at the STA condition, which may indicate improved elasticity after aging. However, this trend is not expected and should be interpreted with caution because all the extracted binders at the CA condition had exceptionally low $J_{nr,3.2}$ values, which could adversely affect the accuracy of the $\%R_{3.2}$ measurement in the MSCR test.

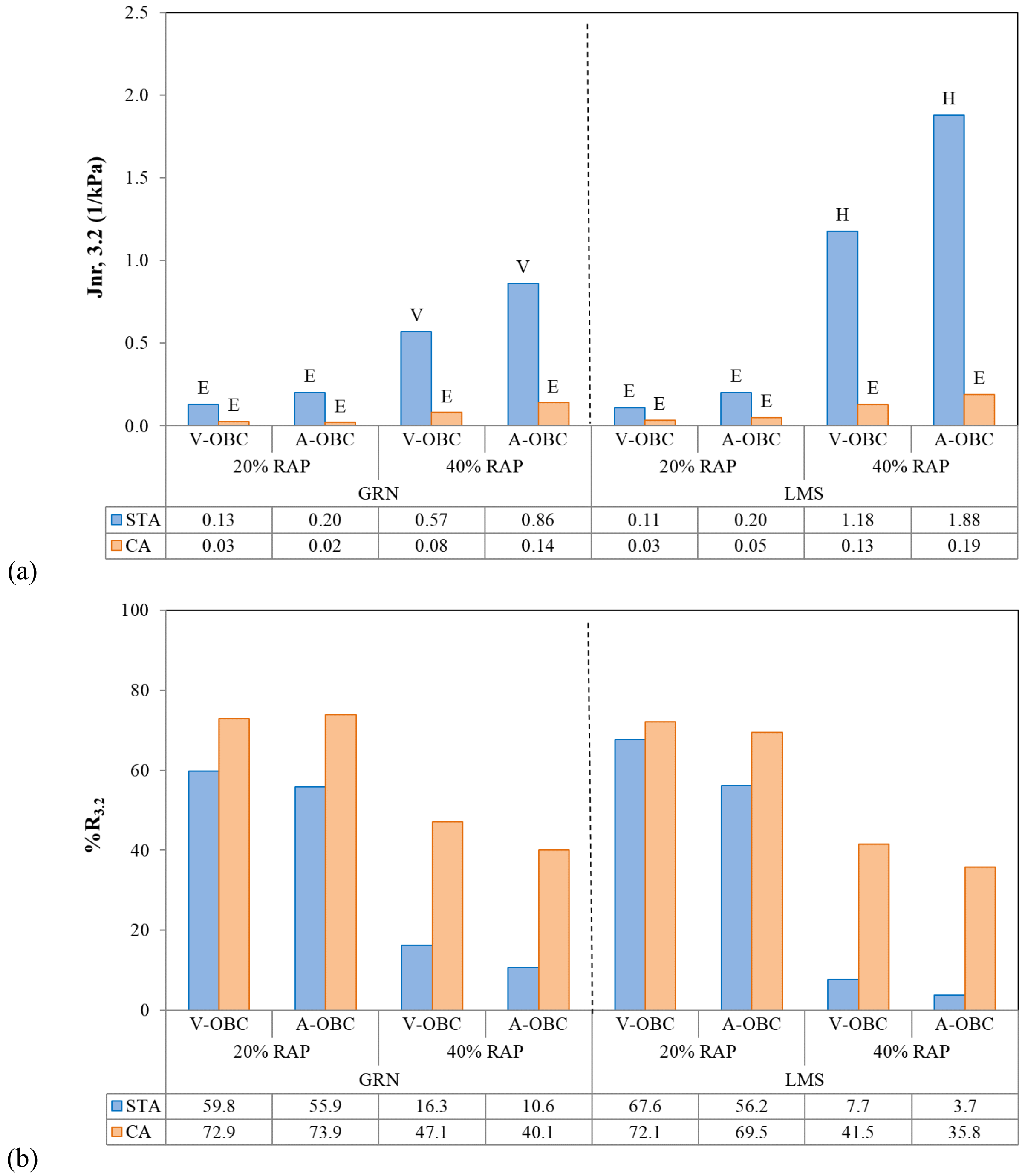


Figure 38. MSCR Results: (a) $J_{nr3.2}$, (b) $\%R_{3.2}$. Where H = heavy traffic loading (10-30 million ESALs or 20-70 km/h), V = very heavy traffic loading (>30 million ESALs or <20 km/h), E = extreme traffic loading (>30 million ESALs and <20 km/h).

4.5.3 Linear Amplitude Sweep (LAS)

The LAS test per AASHTO T 391 was utilized to evaluate the fatigue resistance of the extracted binders. The test was conducted at 13°C on as-recovered binder samples without additional RTFO or PAV aging. The test consisted of two procedures: a frequency sweep test and an amplitude sweep test. The binder was first tested in the frequency sweep test to determine its linear viscoelasticity and then tested in the amplitude sweep test, where a series of oscillatory load cycles at systematically increasing amplitudes (up to 30% applied strain) was applied to introduce accelerated fatigue damage. For data analysis, the continuum damage theory was used (Kim et al., 2006; Hintz et al., 2011). The major outcome of the test was a relationship between the fatigue parameter (N_f, normalized to 1 million ESALs) versus the applied shear strain as a pavement structure indicator (Equation 8). At a certain strain level, asphalt binders with a higher N_f value are expected to have better resistance to fatigue damage.

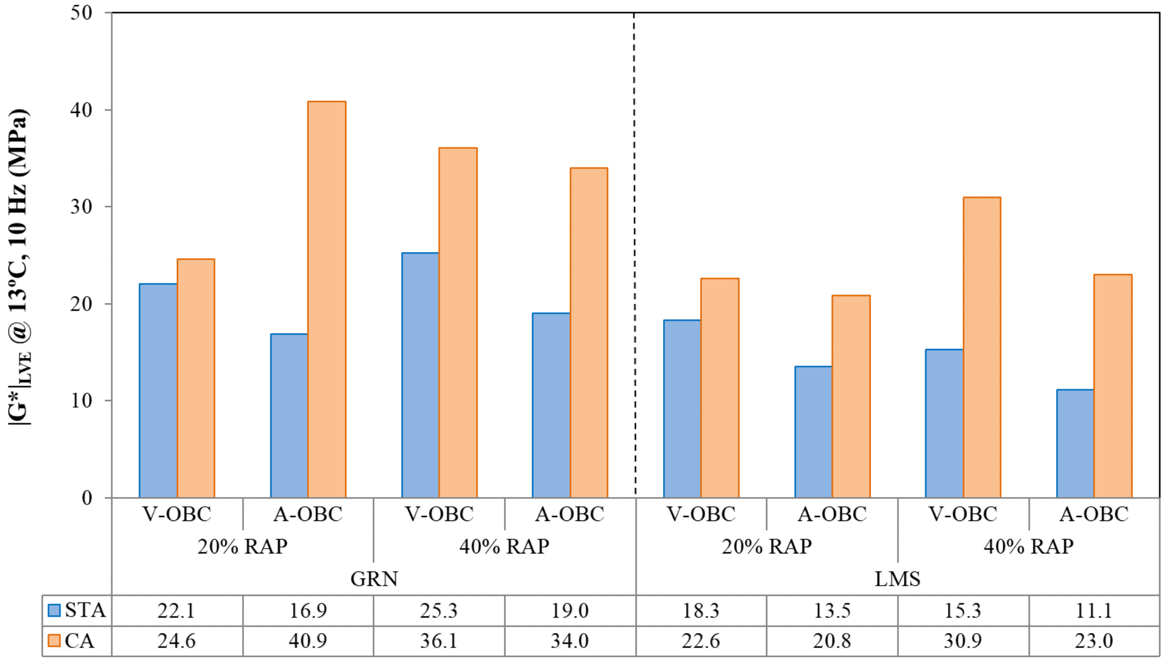
$$N_f = A_{35}(\gamma_{\max})^{-B} \qquad \text{Equation 8}$$

Where,

$\gamma_{\max}$ = the maximum expected binder strain for a given pavement structure; and

A_{35}, B = fatigue performance model parameters.

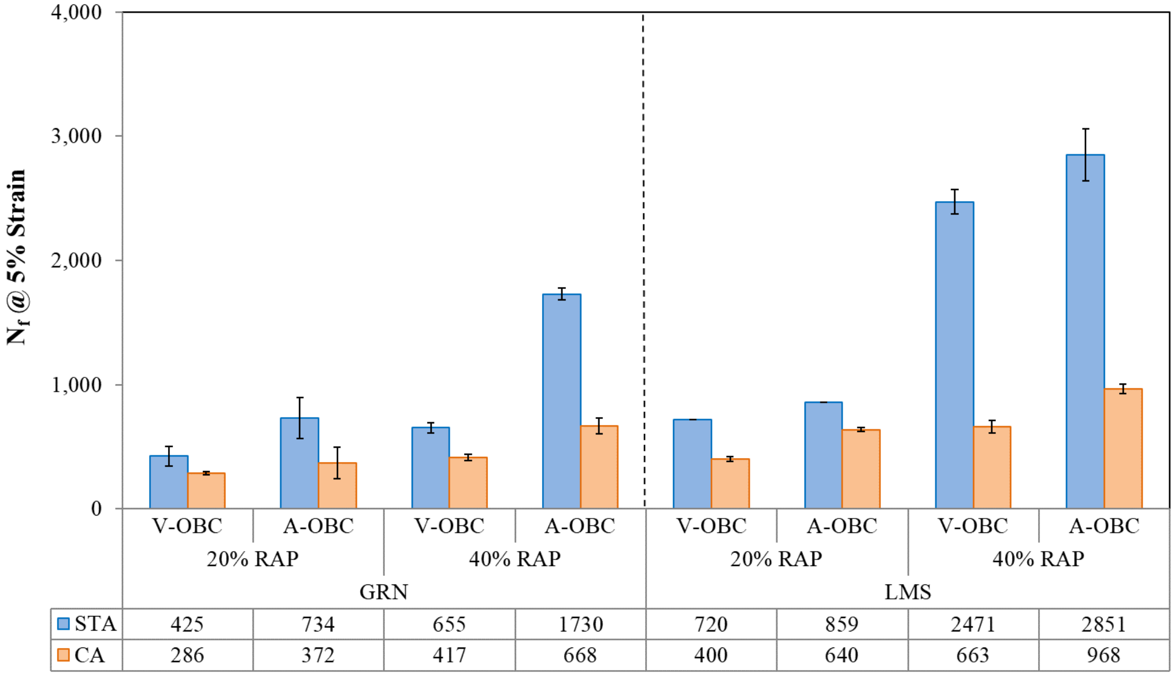
According to Safaei and Castorena (2016), cohesive fatigue cracking occurs within the asphalt binder during the LAS test if the test temperature is selected when the linear viscoelastic complex shear modulus $|G^*|_{\mathrm{LVE}}$ of the binder falls between 12 and 60 MPa at a loading frequency of 10 Hz. As shown in Figure 39, at the selected test temperature (i.e., 13°C), all the extracted binders presented $|G^*|_{\mathrm{LVE}}$ values within the desired 12- to 60-MPa range.



	V-OBC	A-OBC	V-OBC	A-OBC	V-OBC	A-OBC	V-OBC	A-OBC
	20% RAP		40% RAP		20% RAP		40% RAP	
	GRN				LMS			
🟦 STA	22.1	16.9	25.3	19.0	18.3	13.5	15.3	11.1
🟧 CA	24.6	40.9	36.1	34.0	22.6	20.8	30.9	23.0

Figure 39. $|G^*|_{\mathrm{LVE}}$ @ 13°C, 10Hz Results

Figure 40 presents the LAS N_f results of the extracted asphalt binders at the 5.0% strain level. This strain level was selected to simulate relatively thin (less than 4 inches) asphalt layers with approximately 1,000 microstrains per findings of Masad et al. (2001), Willis and Timm (2008), and Hintz et al. (2011). The columns in Figure 40 represent the average N_f, and the error bars represent plus and minus one standard deviation from the average. In all cases, the average N_f increased as the asphalt binder content increased from V-OBC to A-OBC, indicating improved fatigue resistance due to adding additional virgin binder in consideration of reduced RAP binder availability. As expected, this improvement was significantly more pronounced for the 40% RAP mixtures than for the 20% RAP mixtures, considering that the A-OBC adjustment for the 40% RAP mixtures was almost double that of the 20% RAP mixtures. At both aging conditions, the binders extracted from the 20% RAP mixtures had lower N_f values than the corresponding 40% RAP mixtures. Although these results seemed to indicate that the binders from the 20% RAP mixtures were not as fatigue resistant as the 40% RAP mixtures, caution should be exercised when interpreting these results because the ability of the LAS test to capture the benefits of polymer modification has been questioned (Keuliyan, 2022) and warrant further investigation. Overall, the LAS test results demonstrated the benefits of increased asphalt binder content in consideration of reduced RAP binder availability in improving the fatigue resistance of asphalt binders extracted and recovered from the four RAP mixtures in the project.



	GRN				LMS			
	20% RAP		40% RAP		20% RAP		40% RAP	
	V-OBC	A-OBC	V-OBC	A-OBC	V-OBC	A-OBC	V-OBC	A-OBC
🟦 STA	425	734	655	1730	720	859	2471	2851
🟧 CA	286	372	417	668	400	640	663	968

Figure 40. LAS N_f Results at 5% Strain Level and 13°C

4.5.4 G-R Parameter, Crossover Frequency, and R-value

The *G-R* parameter was used in the project to evaluate the extracted binders' ductility and block cracking potential. The DSR frequency sweep test was conducted at multiple test temperatures (i.e., 0, 10, 20, 30, 40, 50, 60, and 70°C) over an angular frequency range of 0.1 to 10 rad/s to determine the *G-R* parameter. During the test, the peak-to-peak strain of the binder sample was controlled at one percent to ensure its behavior remained in the linear viscoelastic range. For data analysis, the RHEA software was used to construct a limited DSR master curve by fitting the |G*| and phase angle (δ) data to the discrete relaxation and retardation spectra (Baumgaertel and

Winter, 1989). Then, the binder |G*| and δ at 15°C and 0.005 rad/s were determined, from which the *G-R* parameter was calculated using Equation 9. Generally, a high *G-R* parameter indicates low ductility with high susceptibility to block cracking.

$$\text{G-R Parameter} = \frac{|G^*|\, cos(\delta)^2}{sin(\delta)} \qquad \text{Equation 9}$$

Where,

|G*| = shear complex modulus at 15°C (59°F) and 0.005 rad/s; and
δ = phase angle at 15°C and 0.005 rad/s.

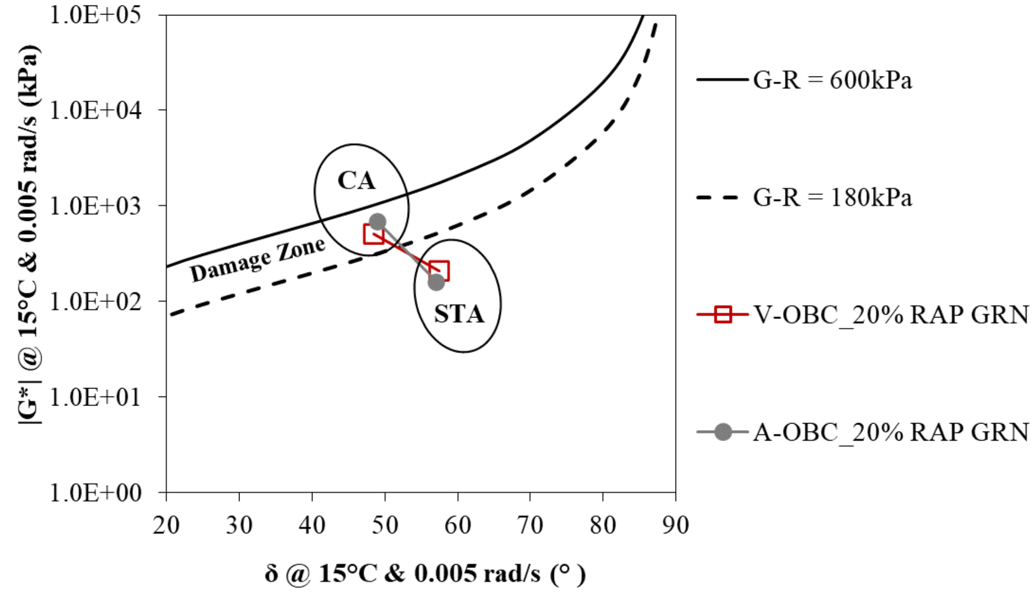
In addition to the *G-R* parameter, the crossover frequency (ω_c) and rheological index (R-value) were also determined from the DSR master curve. The ω_c is defined as the reduced frequency at which the δ is 45°, which is a measure of the overall hardness of an asphalt binder. As ω_c decreases, the binder's hardness increases. The R-value is the log of the glassy modulus of the binder minus the log of the |G*| where the δ is 45°. As R-value increases, the master curve becomes flatter, indicating a more gradual transition from elastic behavior to steady-state flow.

Table 28 summarizes the |G*| and δ at 15°C and 0.005 rad/s, and the *G-R* parameter results. In all cases except one, increasing the asphalt binder content from V-OBC to A-OBC in consideration of reduced RAP binder availability decreased the *G-R* parameter of the extracted binders, which was mainly due to the reduced |G*| (i.e., stiffness) with minimal impact on δ. The only exception was the 20% RAP GRN mixture at the CA condition, which showed a higher *G-R* for the extracted binder at the A-OBC than V-OBC. This behavior was also observed in the intermediate-temperature PG and MSCR results discussed previously. The decrease in the *G-R* parameter indicates that the A-OBC adjustment improved the ductility and block cracking resistance of the overall binders in the RAP mixtures.

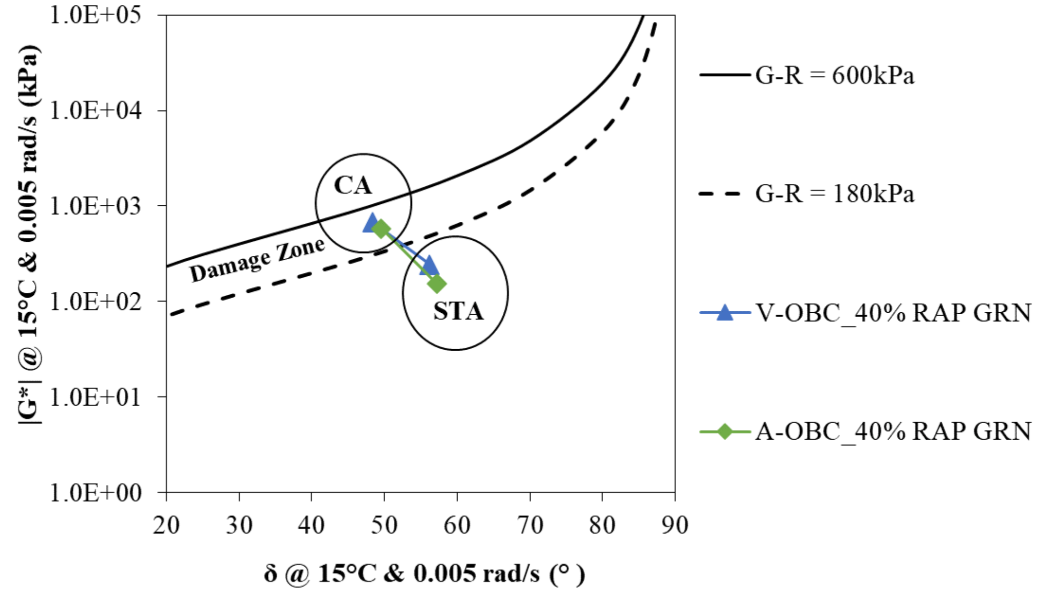
Table 28. *G-R* Parameter Results at 15°C, 0.005 rad/s

Aggregate Type	RAP Content (%)	Asphalt Binder Content	STA Condition			CA Condition		
			|G*| (kPa)	δ (°)	*G-R* (kPa)	|G*| (kPa)	δ (°)	*G-R* (kPa)
GRN	20% RAP	V-OBC	211.1	57.4	72.8	507.3	48.4	298.7
		A-OBC	161.1	57.0	56.8	693.8	48.9	397.7
	40% RAP	V-OBC	244.0	56.2	91.0	674.2	48.4	398.4
		A-OBC	153.9	57.2	53.8	582.4	49.6	321.5
LMS	20% RAP	V-OBC	197.5	55.8	75.7	380.7	50.6	198.6
		A-OBC	118.9	57.9	39.6	311.6	51.5	154.6
	40% RAP	V-OBC	128.3	57.5	44.1	540.7	48.5	316.3
		A-OBC	77.4	59.7	22.8	346.4	50.7	179.3

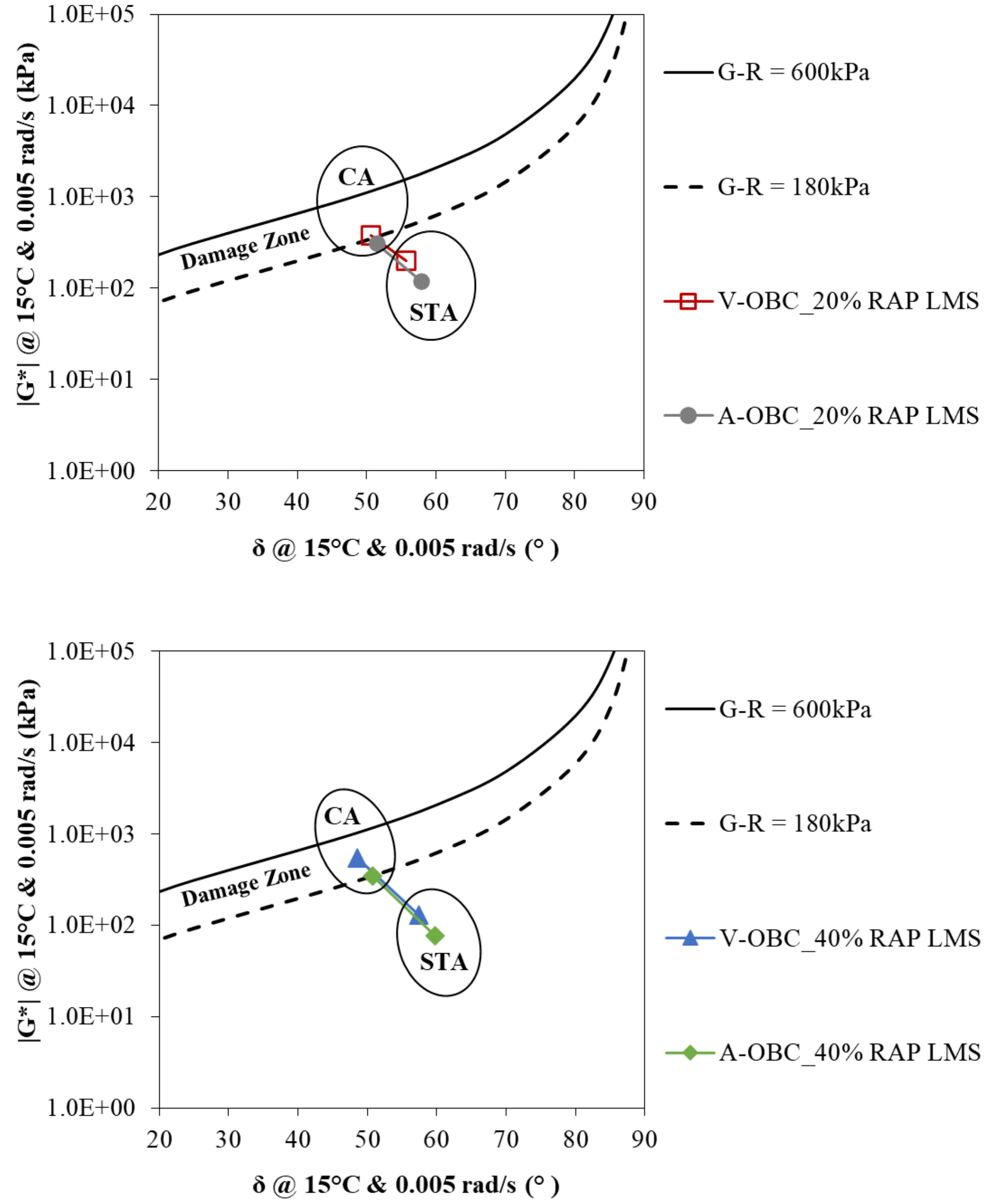
Figure 41 presents the *G-R* parameter results on a black space diagram, where the binder |G*| at 15°C and 0.005 rad/s is plotted on the y-axis versus δ at the same condition on the x-axis. The dashed and bold curves represent the two preliminary *G-R* parameter criteria of 180 kPa and 600 kPa for the onset of block cracking and visible surface cracking, respectively. All the extracted binders at the STA condition remained outside the cracking damage zone. At the CA condition, only the binders extracted from the 20% and 40% RAP LMS mixtures did not reach the cracking damage zone, while the rest fell inside the cracking damage zone with *G-R* values between 180 and 600 kPa. The aging susceptibilities of the extracted binders at the V-OBC versus A-OBC were comparable based on the slopes and aging pathways in black space.



(a)



(b)



(c)

(d)

Figure 41. *G-R* Parameter Results on Black Space Diagram: (a) 20% RAP GRN Mixture, (b) 40% RAP GRN Mixture, (c) 20% RAP LMS Mixture, (d) 40% RAP LMS Mixture

Table 29 summarizes the R-value and ω_c results. The extracted binders from the V-OBC and A-OBC mixtures exhibited notably different rheological properties. Specifically, the A-OBC adjustment in consideration of reduced RAP binder availability generally increased the ω_c and decreased the R-value of the binders, indicating reduced binder stiffness and elastic-to-steady-state transition potential. Figure 42 presents the ω_c-versus-R-value plots on a black space diagram. For all the extracted binders, the ω_c decreased while R-value increased after CA, which indicated that the binders became more brittle and prone to block cracking after oxidative aging. Overall, the R-value and ω_c results demonstrated the benefits of increasing the asphalt binder content from V-OBC to A-OBC in decreasing the age hardening of the extracted binders, as it moved the data points towards the upper left corner on the black space diagram, as shown in Figure 42.

Table 29. ω_c and R-value Results

Aggregate Type	RAP Content (%)	Asphalt Binder Content	STA Condition		CA Condition	
			R-value	ω_c (rad/s)	R-value	ω_c (rad/s)
GRN	20% RAP	V-OBC	3.3	1.910	5.4	0.020
		A-OBC	3.2	2.570	3.8	0.024
	40% RAP	V-OBC	2.6	0.559	4.3	0.030
		A-OBC	2.2	1.178	4.0	0.047
LMS	20% RAP	V-OBC	3.7	1.251	4.8	0.072
		A-OBC	3.0	5.250	4.8	0.174
	40% RAP	V-OBC	2.3	1.203	4.1	0.043
		A-OBC	1.8	2.756	3.7	0.092

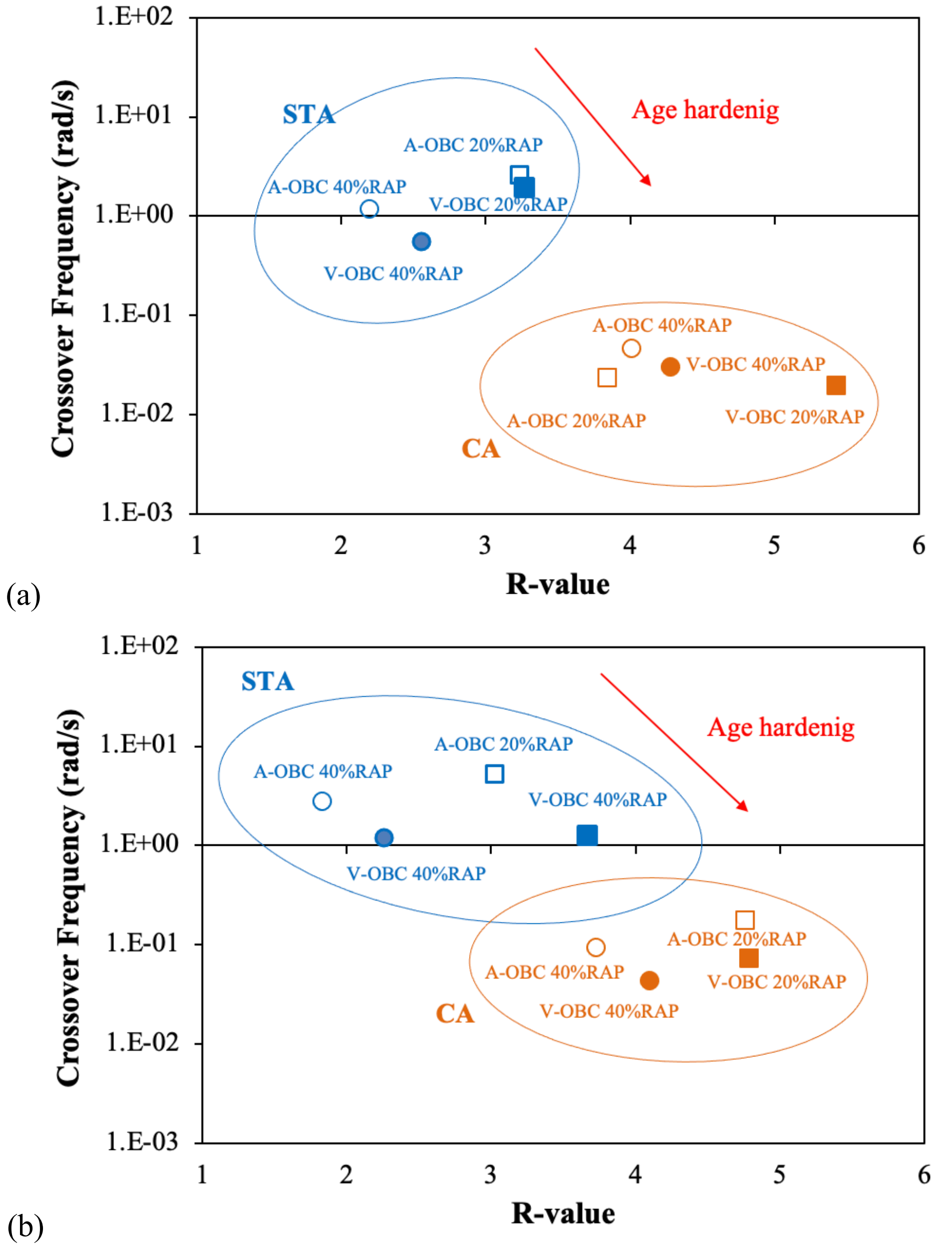


Figure 42. ω_c-versus-R-value Plots on Black Space Diagram: (a) GRN Mixtures, (b) LMS Mixtures

4.6 Cost-benefit Analysis

A cost-benefit analysis was conducted to determine the required pavement life extension to offset the cost of adding additional virgin binder associated with implementing 80% RBA for RAP mixtures in Florida. The analysis followed the method developed by FDOT in comparing the cost savings of high polymer (HP) versus PMA binders (FDOT, 2021). Specific inputs for the cost-benefit analysis are provided below:

- Project description: A 2-lane rural road with 5-foot paved shoulders will be milled to a depth of 3 inches (1.5 inches on the shoulders) and then resurfaced with 1.5 inches of FC-

12.5 mixtures (totaling 1,645.6 tons per roadway mile) over 1.5 inches of SP-12.5 mixtures (totaling 1,161.6 tons per roadway mile).

- Expected pavement service life: 15 years.
- Discount rate: 4%
- FC-12.5 mix design
  - 20% RAP mixture with a PG 76-22 PMA binder
  - RAP asphalt binder content: 6.0% (average of the two RAP stockpiles used in the project)
  - V-OBC: 5.8% (average V-OBC of the four RAP mixtures in the project)
  - RBA: 80%
- SP-12.5 mix design: 30% RAP mixture with a PG 58-22 unmodified binder
  - 30% RAP mixture with a PG 58-22 unmodified binder
  - RAP asphalt binder content: 6.0% (average of the two RAP stockpiles used in the project)
  - V-OBC: 5.8% (average V-OBC of the four RAP mixtures in the project)
  - RBA: 80%
- Asphalt mixture cost (per FDOT Item Average Unit Cost from January 2023 to June 2023)
  - FC-12.5 (traffic C, PG 76-22 PMA binder): $177.15/ton
  - SP-12.5 (traffic C, PG 58-22 unmodified binder): $148.04/ton
- Asphalt binder cost (per FDOT Asphalt Price Index from August 2023)
  - PG 76-22 PMA binder: $733/ton
  - PG 58-22 unmodified binder: $600/ton

Scenario 1: Not Considering Reduced RAP Binder Availability

Based on the Costs per Mile Models from the FDOT State Estimates Office, the estimated cost of milling and resurfacing the project is $737,437 per mile (Table 30). Annualizing this initial cost based on a projected life expectancy of 15 years (or 180 months) at a discount rate of 4.0% results in an annualized cost of $66,326 per year.

Scenario 2: Considering Reduced RAP Binder Availability

If the reduced RAP binder availability is considered, approximately 0.23% additional virgin binder would be required in the FC-12.5 mixture, and 0.34% additional virgin binder required in the SP-12.5 mixture, which are calculated following Equation 3. These additional virgin binders would increase the total cost of the project by $5,144, including $2,774 (= 0.23% x $733/ton x 1,645.6 tons) for the FC-12.5 mixture and $2,370 (= 0.34% x $600/ton x 1,161.6 tons) for the SP-12.5 mixture.

- If the projected pavement life expectancy remains at 15 years, the annualized cost would increase to $66,789, which corresponds to a 0.7% increase from Scenario 1.
- If the projected pavement life expectancy is increased to 15.17 years (a two-month extension from 15 years), the annualized cost would reduce to $66,250, which corresponds to a 0.1% decrease from Scenario 1.

Therefore, to breakeven on the cost of the additional virgin binder in consideration of reduced RAP binder availability from the life-cycle cost perspective, the pavement life would only need to be increased by two months.

Table 30. Estimated Project Cost using FDOT Costs per Mile Models

Pay Item	Description	Total Quantity	Unit	Weighted Avg. Unit Price	Total Amount
102-1	MAINTENANCE OF TRAFFIC	1.00	LS		$44,806.48
101-1	MOBILIZATION	1.00	LS		$49,287.12
104-11	FLOATING TURBIDITY BARRIER	100.00	LF	$12.00	$1,200.00
104-12	STAKED TURBIDITY BARRIER- NYL REINF PVC	100.00	LF	$6.70	$670.00
107-1	LITTER REMOVAL	1.20	AC	$30.00	$36.00
107-2	MOWING	1.20	AC	$46.00	$55.20
327-70-6	MILLING EXIST ASPH PAVT, 1.5" AVG DEPTH (SHOULDER)	5866.67	SY	$3.92	$22,997.35
327-70-4	MILLING EXIST ASPH PAVT, 3" AVG DEPTH (MAINLINE)	14080.00	SY	$3.92	$55,193.60
337-7-83	ASPHALT CONCRETE FRICTION COURSE, TRAFFIC C, FC-12.5, PG 76-22	1645.60	TN	$177.15	$291,518.04
334-1-13	SUPERPAVE ASPHALTIC CONC, TRAFFIC C	1161.60	TN	$148.04	$171,963.26
546-72-1	GROUND-IN RUMBLE STRIPS, 16"	2.00	GM	$1,200.00	$2,400.00
570-1-2	PERFORMANCE TURF, SOD	5866.67	SY	$2.30	$13,493.34
700-1-11	SINGLE POST SIGN, F&I GM,	10.00	AS	$440.00	$4,400.00
700-1-12	SINGLE POST SIGN, F&I GM, 12-20 SF	14.00	AS	$1,400.00	$19,600.00
700-1-50	SINGLE POST SIGN, RELOCATE	2.00	AS	$260.00	$520.00
700-1-60	SINGLE POST SIGN, REMOVE	12.00	AS	$43.00	$516.00
700-2-14	MULTI- POST SIGN, F&I GM, 31-50 SF	2.00	AS	$5,800.00	$11,600.00
700-2-60	MULTI- POST SIGN, REMOVE	2.00	AS	$910.00	$1,820.00
706-1-3	RAISED PAVMT MARK, TYPE B	135.00	EA	$3.80	$513.00
710-11-101	PAINTED PAVT MARK, STD, WHITE, SOLID,6"	4.00	GM	$1,100.00	$4,400.00
710-11-131	PAINTED PAVT MARK, STD, WHITE, SKIP, 6"	2.00	GM	$520.00	$1,040.00
711-15-101	THERMOPLASTIC, STD-OP, WHITE, SOLID, 6"	2.00	GM	$5,300.00	$10,600.00
711-15-131	THERMOPLASTIC, STD-OP, WHITE, SKIP, 6"	1.00	GM	$1,700.00	$1,700.00
999-25	INITIAL CONTINGENCY AMOUNT (DO NOT BID)	1.00	LS	$27,107.92	$27,107.92
				Sum	**$737,437**

5. FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Findings and Conclusions

The major findings and conclusions of the project are summarized below:

- A critical review of the literature on recycled binder availability suggested that 80% is an appropriate RBA value for RAP mixtures in Florida.
- To accommodate the reduced RAP binder availability with 80% RBA, an increase in the virgin binder content of approximately 0.23% and 0.45% were required for the 20% RAP and 40% RAP mixtures used in the project, respectively.
- The IDEAL-CT, OT, and Cantabro tests consistently showed that increasing the asphalt binder content from V-OBC to A-OBC in consideration of reduced RAP binder availability improved the cracking resistance and durability of RAP mixtures in the project and that the improvement was more pronounced for the 40% RAP mixtures than the 20% RAP mixtures. The results also showed that the A-OBC adjustment in consideration of reduced RAP binder availability yielded 20% and 40% RAP mixtures with similar cracking resistance and durability despite the different RAP contents and different virgin binders used.
- There was not aa strong correlation between the IDEAL-CT, OT, and Cantabro test results. This lack of correlation can be attributed to the different mechanisms and loading conditions of the tests; specifically, the IDEAL-CT and OT are intended to evaluate the mixture cracking resistance of asphalt mixtures under monotonic loading and cyclic loading, respectively, while the Cantabro test is intended to assess the overall mixture durability.
- The HWTT and IDEAL-RT tests consistently showed that increasing the asphalt binder content from V-OBC to A-OBC in consideration of reduced RAP binder availability reduced the rutting resistance of RAP mixtures in the project, especially the 40% RAP mixtures with a PG 52-28 unmodified binder. However, all the RAP mixtures had comparable APA results at the V-OBC versus A-OBC. Despite the lower RAP content, the 20% RAP mixtures with a PG 76-22 PMA binder had significantly better HWTT, APA, and IDEAL-RT results than the 40% RAP mixtures with a PG 52-28 unmodified binder, indicating better rutting resistance. This highlights the benefits of polymer modification in improving the rutting resistance of asphalt mixtures.
- Strong correlations existed among the HWTT, APA, and IDEAL-RT results, indicating the three tests are reasonably comparable in assessing the rutting resistance of asphalt mixtures.
- The mixture performance diagram analysis showed that with the A-OBC adjustment in consideration of reduced RAP binder availability, the 20% RAP mixtures with a PG 76-22 PMA binder had balanced rutting and cracking resistance, while the 40% RAP mixtures with a PG 52-28 unmodified binder had inadequate rutting resistance. Nevertheless, the 40% RAP mixtures may not necessarily be prone to rutting in the field because they are placed in the pavement structure at least one or two layers below the surface and, thus, are not exposed to high pavement in-service temperatures as the surface layer.
- The extracted binder results showed an overall softening of the binder in the RAP mixture because of the additional virgin binder added in consideration of reduced RAP

binder availability. The extracted binders at the A-OBC exhibited reduced rutting resistance, improved fatigue resistance and ductility, and similar elastic properties and aging susceptibility as those at the V-OBC.
- The cost-benefit analysis showed that for a 3-inch mill-and-resurface project on a 2-lane rural road with 5-foot paved shoulders, only a two-month extension in pavement service life (from 15 years) would be needed to justify the cost of the additional virgin binders added in consideration of reduced RAP binder availability for the resurfacing RAP mixtures.

5.2 Recommendations for Future Research and Implementation

Based on the results and findings of the project, it is suggested that FDOT implement 80% RBA for mix design and production of RAP mixtures to improve the long-term cracking performance and longevity of asphalt pavements in Florida. There are three potential approaches to incorporating reduced RAP binder availability into the existing mix design and production practices: (1) adjusting N_{design} to maintain 4.0% design air voids at A-OBC, (2) adjusting design air voids at A-OBC, and (3) eliminating design air voids as an acceptance quality characteristic (AQC). The description of each approach and the required revisions to the FDOT Standard Specifications for Road and Bridge Construction are provided below.

Approach 1. Adjusting N_{design} to Maintain 4.0% Design Air Voids at A-OBC

This approach requires adjusting N_{design} to maintain 4.0% design air voids at the A-OBC for mix design and acceptance. After completing the volumetric mix design while meeting FDOT's current design criteria at the V-OBC, the mix designer needs to determine the A-OBC based on the V-OBC, the RAP content of the mixture by weight of total aggregate (%RAP), the aggregate content of the mixture (P_s), the asphalt binder content of the RAP (RAP-P_b), and the recommended RBA value of 80%. Then, the mix designer needs to mix and compact three SGC samples with the *initial* N_{design} at the A-OBC and analyze the compaction data to determine the *adjusted* N_{design} corresponding to 4.0% air voids for the SGC samples. The mix designer may also need to mix and compact three additional SGC samples with the *adjusted* N_{design} to verify that the samples at the A-OBC have air voids reasonably close to 4.0%. After that, the mix designer needs to determine the VMA, voids filled with asphalt (VFA), and dust-to-binder ratio of the mix design at the A-OBC and with the *adjusted* N_{design}. Production acceptance will follow the current specification requirements, with three exceptions: (1) using A-OBC as the target asphalt binder content, (2) using the *adjusted* N_{design} to accept air voids, and (3) using the G_{mm} at the A-OBC to accept field density.

This approach requires the following revisions to Section 334 of the FDOT Standard Specifications for Road and Bridge Construction:

- 334-3.2.1 General: Add a new paragraph, preferably with a calculation example, to illustrate how to calculate the A-OBC and select the *adjusted* N_{design}.
- 334-3.2.5 Design Criteria: Clarify these requirements apply to the V-OBC.
- 334-3.2.7 Additional Information
  - Item 1: Provide the *initial* N_{design} for V-OBC and the *adjusted* N_{design} for A-OBC.
  - Item 7: Provide the V-OBC and A-OBC.
  - Item 9: Provide the physical properties at both the V-OBC and A-OBC.

- <u>334-5.4 QC Sampling and Testing</u>
    - Table 334-6: Clarify the asphalt binder content target should be the A-OBC from the mix design; clarify the field density should be calculated based on the G_{mm} at the A-OBC.
- <u>334-8 Basis of Payment</u>
    - Table 334-8: Clarify the field density should be calculated based on the G_{mm} at the A-OBC.
    - Table 334-9: Clarify the asphalt binder content target should be the A-OBC from the mix design; clarify the field density should be calculated based on the G_{mm} at the A-OBC.

Table 31 summarizes the *initial* N_{design} versus *adjusted* N_{design} for the four RAP mixtures evaluated in the project. The difference between the *initial* N_{design} and *adjusted* N_{design} vary from 16 to 22 gyrations for the 20% RAP mixtures, and 40 to 41 gyrations for the 40% RAP mixtures. Despite the very limited number of data, there is a strong linear relationship between the difference between the *initial* N_{design} and *adjusted* N_{design} and the difference between the V-OBC and A-OBC, as shown in Figure 43. According to the fitted trendline, for every 0.1% increase in the asphalt binder content from the V-OBC, the *initial* N_{design} will decrease by approximately 8 to 9 gyrations. However, this relationship should be interpreted with caution because it is only based on the four RAP mixtures evaluated in the project (all having an *initial* N_{design} of 75 gyrations), which could vary for RAP mixtures with different N_{design} levels, aggregate types, aggregate gradations, and RAP materials.

Table 31. Comparison of Initial N_{design} for V-OBC versus Adjusted N_{design} for A-OBC

Mixture ID	V-OBC (%)	Initial N_{design}	A-OBC (%)	Adjusted N_{design}
20% RAP GRN	5.40	75	5.62	59
40% RAP GRN	5.40	75	5.85	34
20% RAP LMS	6.20	75	6.43	53
40% RAP LMS	6.20	75	6.66	35

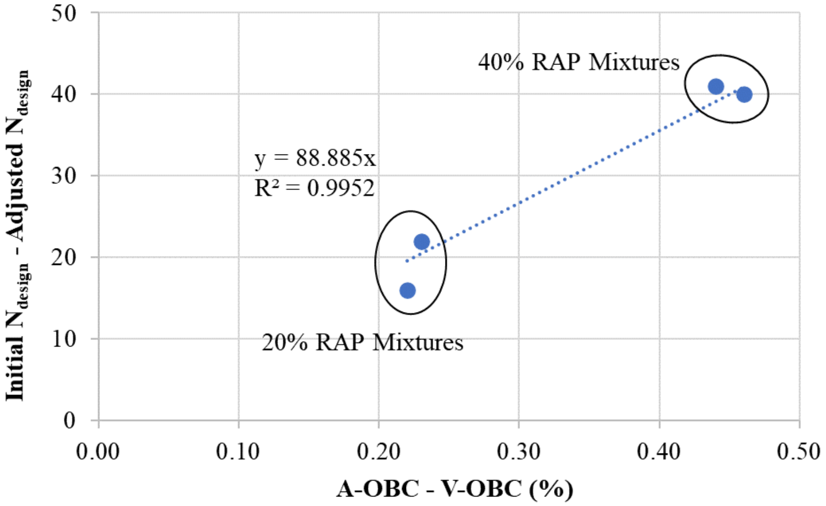


Figure 43. Difference between *Initial* N_{design} and *Adjusted* N_{design} versus Difference between V-OBC and A-OBC

Approach 2. Adjusting Design Air Voids at A-OBC

This approach requires adjusting the design air voids at the A-OBC for mix design and acceptance. After completing the volumetric mix design while meeting FDOT's current design criteria at the V-OBC, the mix designer needs to determine the A-OBC based on the V-OBC, the RAP content of the mixture by weight of total aggregate (%RAP), the aggregate content of the mixture (P_s), the asphalt binder content of the RAP (RAP-P_b), and the recommended RBA value of 80%. Then, the mix designer needs to mix and compact three SGC samples at the A-OBC to determine the adjusted air voids, VMA, VFA, and dust-to-binder ratio. Production acceptance will follow the current specification requirements, with three exceptions: (1) using A-OBC as the target asphalt binder content, (2) using the adjusted air voids at the A-OBC as the production target, and (3) using the G_{mm} at the A-OBC to accept field density.

This approach requires the following revisions to Section 334 of the FDOT Standard Specifications for Road and Bridge Construction:

- 334-3.2.1 General: Add a new paragraph, preferably with a calculation example, to illustrate the determination of the A-OBC.
- 334-3.2.5 Design Criteria: Clarify these requirements apply to the V-OBC.
- 334-3.2.7 Additional Information
  - Item 7: Provide the V-OBC and A-OBC.
  - Item 9: Provide the physical properties at both the V-OBC and A-OBC.
- 334-5.4 QC Sampling and Testing
  - Table 334-6: Clarify the asphalt binder content target should be the A-OBC from the mix design; revise the master production range for air voids because of the change of the design target from 4.0%; clarify the field density should be calculated based on the G_{mm} at the A-OBC.
- 334-8 Basis of Payment
  - Table 334-8: Clarify the field density should be calculated based on the G_{mm} at the A-OBC.
  - Table 334-9: Clarify the asphalt binder content target should be the A-OBC from the mix design; revise the air voids target from 4.0% to the adjusted air voids at the A-OBC; clarify the field density should be calculated based on the G_{mm} at the A-OBC.

Table 32 summarizes the air voids at V-OBC versus A-OBC for the four RAP mixtures in the project. Despite the very limited number of data, there is a strong linear relationship between the reduction in air voids from V-OBC to A-OBC and the difference between V-OBC and A-OBC, as shown in Figure 44. According to the fitted trendline, for every 0.1% increase in the asphalt binder content from the V-OBC, the design air voids will decrease by approximately 0.3%. However, this relationship should be interpreted with caution because it is only based on the four RAP mixtures evaluated in the project (all having an N_{design} of 75 gyrations), which could vary for RAP mixtures with different N_{design} levels, aggregate types, aggregate gradations, and RAP materials.

Table 32. Comparison of Air Voids at V-OBC versus A-OBC

Mixture ID	V-OBC (%)	Air Voids (%)	A-OBC (%)	Air Voids (%)
20% RAP GRN	5.40	4.2	5.62	3.8
40% RAP GRN	5.40	4.1	5.85	2.8
20% RAP LMS	6.20	4.3	6.43	3.6
40% RAP LMS	6.20	4.1	6.66	2.8

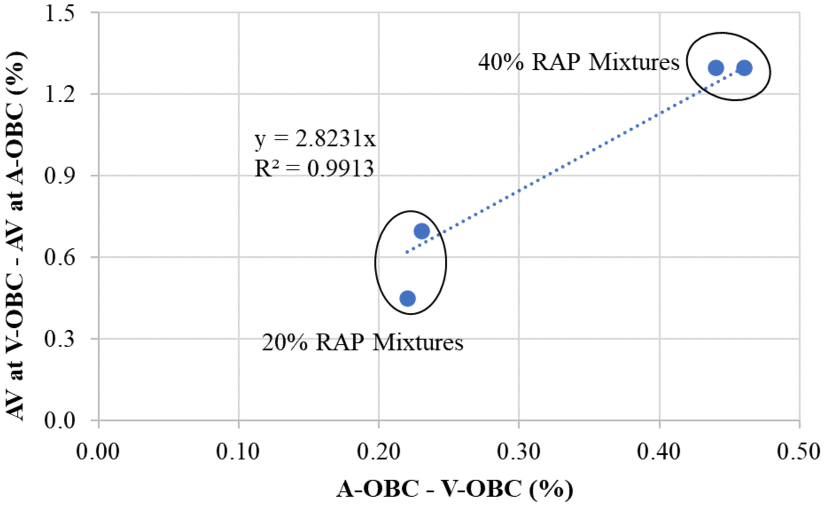


Figure 44. Reduction in Air Voids from V-OBC to A-OBC versus Difference between V-OBC and A-OBC

Approach 3. Eliminating Design Air Voids as an AQC

This approach requires eliminating air voids as an AQC for acceptance. The mix design process will be the same as Approach 2. Production acceptance will follow the current specification requirements, with three exceptions: (1) using A-OBC as the target asphalt binder content, (2) eliminating air voids as an AQC, and (3) using the G_{mm} at the A-OBC to accept field density. This approach requires the following revisions to Section 334 of the FDOT Standard Specifications for Road and Bridge Construction:

- 334-3.2.1 General: Add a new paragraph, preferably with a calculation example, to illustrate the determination of the A-OBC.
- 334-3.2.5 Design Criteria: Clarify these requirements apply to the V-OBC.
- 334-3.2.7 Additional Information
    - Item 7: Provide the V-OBC and A-OBC.
    - Item 9: Provide the physical properties at both the V-OBC and A-OBC.
- 334-5.4 QC Sampling and Testing
    - Table 334-6: Clarify the asphalt binder content target should be the A-OBC from the mix design; eliminate the master production range for air voids; clarify the field density should be calculated based on the G_{mm} at the A-OBC.
- 334-5.5 Verification Testing
    - Table 334-7: Eliminate the between-laboratory precision values for G_{mb} (gyratory compacted specimens)

- <u>334-8 Basis of Payment</u>
    - Table 334-8: Eliminate the deviation ranges for air voids; clarify the field density should be calculated based on the G_{mm} at the A-OBC.
    - Table 334-9: Clarify the asphalt binder content target should be the A-OBC from the mix design; eliminate the specification limits for air voids; clarify the field density should be calculated based on the G_{mm} at the A-OBC.
    - Item 334-8.3 Composite Pay Factor (CPF): Exclude air voids from calculating the composite pay factor; adjust the weighting factors for density, asphalt binder content, passing No. 200, and passing No. 8 to total 100% for the composite pay factor or possibly add a third gradation sieve and adjust the weighting factors of each AQC.

For research implementation, it is suggested that FDOT conduct pilot projects to evaluate the field performance of asphalt pavements using RAP mixtures designed with 80% RBA. The field performance data will be critical in quantifying the life extension benefits and life-cycle cost benefits associated with implementing reduced RAP binder availability. It is also suggested that FDOT verify the suitability and robustness of the selected RBA value in this project as the properties of RAP materials in Florida change over time and as the literature on RAP binder availability continues to evolve. Finally, future research is recommended to explore mix design strategies to improve the rutting resistance of 40% RAP mixtures without compromising their cracking resistance; potential strategies include using a PG 58-22 or PG 58-28 binder instead of a PG 52-28 binder or adding hydrated lime.

REFERENCES

Amirkhanian, S., Xiao, F., and Corley, M. (2018). Characterization of asphalt concrete dynamic modulus in South Carolina (No. FHWA-SC-18-04). South Carolina Dept. of Transportation. FHWA-SC-18-04. Published in the United States Department of Transportation, Bureau of Transportation Statistics, National Transportation Library (ROSA P).

Baumgaertel, M., and Winter, H. H. (1989). Determination of discrete relaxation and retardation time spectra from dynamic mechanical data. *Rheologica Acta*, Vol. 28(6), pp. 511-519.

Biehl, E. (2020). Ohio DOT's Experience with RAS. 99th Annual TRB Meeting, Washington D.C., January 14, 2020.

Bonaquist, R. (2005). Laboratory evaluation of hot mix asphalt (HMA) mixtures containing recycled or waste product materials using performance testing (Publication FHWA-PA-2005-006+ 98-32 (19), Pennsylvania Department of Transportation, Office of Planning and Research).

Booshehrian, A., Mogawer, W.S. and Bonaquist, R. (2013). How to construct an asphalt binder master curve and assess the degree of blending between RAP and virgin binders. *Journal of Materials in Civil Engineering*, 25(12), pp.1813-1821.

Bowers, B.F., Huang, B., He, Q., Shu, X., Jia, X. and Miller, B.C. (2015). Investigation of sequential dissolution of asphalt binder in common solvents by FTIR and binder fractionation. *Journal of Materials in Civil Engineering*, 27(8), p.04014233.

Carpenter, S.H. and Wolosick, J.R. (1980). Modifier influence in the characterization of hot-mix recycled material. *Transportation Research Record*, (777), Transportation Research Board.

Castorena, C., Pape, S. and Mooney, C. (2016). Blending measurements in mixtures with reclaimed asphalt: use of scanning electron microscopy with X-ray analysis. *Transportation Research Record*, 2574(1), pp.57-63.

Chen, C., Yin, F., Andriescu, A., Moraes, R., Mensching, D., Tran, N., Taylor, A., and West, R. (2020). Preliminary validation of the critical aging protocol for NCAT Top-down cracking experiment. *Journal of the Association of Asphalt Paving Technologists*.

Chen, C., Yin, F., Turner, P., West, R.C., and Tran, N. (2018). Selecting a laboratory loose mix aging protocol for the NCAT top-down cracking experiment. *Transportation Research Record*, 2672(28), 359-371.

Coffey, S., DuBois, E., Mehta, Y., Nolan, A., and Purdy, C. (2013). Determine the Impact of Degree of Blending and Quality of Reclaimed Asphalt Pavement on Predicted Pavement Performance using Mechanistic-Empirical Design Guide (MEPDG). In Ninth International Conference on the Bearing Capacity of Roads, Railways and Airfields, 445-454.

Coleri, E., Lewis, S. and Sreedhar, S. (2018). Quantification of Rap Binder Blending to Provide Recommendations for Asphalt Mix Design (No. 18-01228).

Copeland, A. (2011). Reclaimed asphalt pavement in asphalt mixtures: State of the practice (No. FHWA-HRT-11-021). United States. Federal Highway Administration. Office of Research, Development, and Technology.

Delaware. Department of Transportation (DelDOT). (2021). Standard Specifications for Road and Bridge Construction. Delaware Department of Transportation.

Dongré, R., Li, X., and Youtcheff, J. (2021). A Simple Test for Quality Control of RAP Piles. Proceedings of the 7th E&E Congress Eurasphalt & Eurobitume.

Elwardany, M., Planche, J.P., and King, G. (2020). Universal and practical approach to evaluate asphalt binder resistance to thermally-induced surface damage. *Construction and Building Materials*, Vol. 255, 119331.

Epps Martin, A., Arambula Mercado, E., and Abdelaziz, A. (2021). Binder Availability in Recycled Materials: Review of Literature and Available Qualification Methods. FHWA/TX-21/0-7062-R1B Draft Final Report.

Epps Martin, A., Kaseer, F., Arambula-Mercado, E., Bajaj, A., Cucalon, L.G., Yin, F., Chowdhury, A., Epps, J., Glover, C., Hajj, E.Y. and Morian, N. (2019). Evaluating the effects of recycling agents on asphalt mixtures with high RAS and RAP binder ratios. NCHRP Report 927.

Farris, D. (2016). Evaluating the Contribution of Asphalt Binder from Recycled Asphalt Shingles in Asphalt Concrete. Master's Thesis, Auburn University.

Florida Department of Transportation (FDOT). (2021). Unpublished data from FDOT Pavement Management Office – Cost benefit analysis.

Florida Department of Transportation (FDOT). (2022). Email Communication with Greg Sholar: Data Requested.

Georgia Department of Transportation (GDOT). (2019). Standard Operating Procedure (SOP) 2 - Control of Superpave Bituminous Mixture Designs.

Gottumukkala, B., Kusam, S.R., Tandon, V., and Muppireddy, A.R. (2018). Estimation of Blending of Rap Binder in a Recycled Asphalt Pavement Mix. *Journal of Materials in Civil Engineering*, 30(8), 04018181.

Hand, A. and Aschenbrener, T. (2021). Successful Use of Reclaimed Asphalt Pavement in Asphalt Mixtures, WRSC-TR-21-10, University of Nevada, Reno.

Hines, S. (2012). RAP Research: Blending Binder versus Black Rock Theory. GDOT Internal Presentation.

Hintz, C., Velasquez, R., Johnson, C., and Bahia, C. (2011). Modification and Validation of the Linear Amplitude Sweep Test for Binder Fatigue Specification. Journal of the Transportation Research Board. *Transportation Research Board*, National Academies of Sciences, Washington, D.C., pp. 96-106.

Horan, B. (2020). Georgia Addresses Pavement Performance Problems Linked to High RAP Usage. The Magazine of the Asphalt Institute, pp. 29-33.

Huang, B., Li, G., Vukosavljevic, D., Shu, X., and Egan, B.K. (2005). Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement. *Transportation Research Record*, 1929, 37–45.

Jiang, Y., Gu, X., Zhou, Z., Ni, F., and Dong, Q. (2018). Laboratory Observation and Evaluation of Asphalt Blends of Reclaimed Asphalt Pavement Binder with Virgin Binder using SEM/EDS. *Transportation Research Record*, 2672(28), 69-78.

Kaseer, F., Arámbula-Mercado, E., and Epps Martin, A. (2019). A Method to Quantify Reclaimed Asphalt Pavement Binder Availability (Effective RAP Binder) in Recycled Asphalt Mixes. *Transportation Research Record*, 2673(1), 205–216.

Kentucky Transportation Cabinet (KYTC). (2019). Standard Specifications for Road and Bridge Construction.

Keuliyan, F. (2022). Rheological and Chemical Evaluation of Aging Resistant Binder Technologies. M.Sc. Thesis, Auburn University, 2022.

Kim, S., Shen, J., and Myung Jeong, M. (2018). Effects of aggregate size on the rutting and stripping resistance of recycled asphalt mixtures. *Journal of Materials in Civil Engineering*, 30(2), 04017280.

Kim, Y., Lee, H.J., Little, D.N., and Kim, Y.R. (2006). A Simple Testing Method to Evaluate Fatigue Fracture and Damage Performance of Asphalt Mixtures. *Journal of the Association of Asphalt Paving Technologists*, Vol. 75, pp. 755-788.

Kluttz, R.Q. (2019). Prepared Discussion on Relationships Between Mixture Fatigue Performance and Asphalt Binder Properties, *Journal of the Association of Asphalt Paving Technologists*, Volume 88.

Louisiana Department of Transportation & Development (LADOTD). (2016). Application of Quality Assurance Specifications for Asphalt Concrete Mixtures. http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Materials_Lab/MatLab_Downloads/QAM%20-%20Asphalt%202016.pdf

Masad, E., Somadevan, N., Bahia, H. and Kose, S. (2001) Modeling and Experimental Measurements of Strain Distribution in Asphalt Mixes. *Journal of Transportation Engineering*, Vol. 127, No. 6, pp. 477−485.

Menegusso Pires, G., Lo Presti, D. and Airey, G.D. (2021). A practical approach to estimate the degree of binder activity of reclaimed asphalt materials. *Road Materials and Pavement Design*, 22(5), 1093-1116.

Michael, J. (2011). Evaluation of Non-Solvent Methods to Characterize Reclaimed Asphalt Pavement Binder. Master's Thesis, Auburn University.

Mogawer, W., Bennert, T., Daniel, J.S., Bonaquist, R., Austerman, A. and Booshehrian, A. (2012). Performance characteristics of plant produced high RAP mixtures. *Road Materials and Pavement Design*, 13(sup1), pp.183-208.

Mohajeri, M. (2015). Hot Mix Asphalt Recycling: Practices and Principles.

National Asphalt Pavement Association (NAPA) (2023). Balanced Mix Design Resource Guide. https://www.asphaltpavement.org/expertise/engineering/resources/bmd-resource-guide.

New York State Department of Transportation (NYSDOT) (2022). Standard Specifications.

Norouzi, A., Kim, Y.R., Kim, S.S., and Yang, J. (2017). Effect of reclaimed asphalt pavement content and binder grade on fatigue-resisting performance of asphalt mixtures in Georgia. *Journal of Materials in Civil Engineering*, 29(9), 04017115.

Norouzi, A., Sabouri, M., and Kim, Y.R. (2014). Evaluation of the fatigue performance of high RAP asphalt mixtures. Proceedings of the 12th International Society for Asphalt Pavements, Raleigh, NC.

Noureldin, A.S. and Wood, L.E. (1987). Rejuvenator diffusion in binder film for hot-mix recycled asphalt pavement. *Transportation Research Record*, (1115).

Ohio Department of Transportation (ODOT). (2019). Construction and Material Specifications. 2019 Edition, Online Version 1/21/2022.

Page, S., and Castorena, C. (2022). Application of Sieve Analysis to Estimate Recycled Binder Availability. Poster Presented at the 2022 TRB Annual Meeting, Washington, D.C.

Rodezno, C., Moraes, R., Yin, F. and Fortunatus, M. (2021). Recycled Asphalt Binder Study (No. WHRP 0092-19-04). Wisconsin Highway Research Program.

Safaei, F., and Castorena, C. (2016). Temperature effects of linear amplitude sweep testing and analysis. *Transportation Research Record*, 2574(1), 92-100.

Shirodkar, P., Mehta, Y., Nolan, A., Sonpal, K., Norton, A., Tomlinson, C., Dubois, E., Sullivan, P. and Sauber, R. (2011). A study to determine the degree of partial blending of reclaimed asphalt pavement (RAP) binder for high RAP hot mix asphalt. *Construction and Building Materials*, 25(1), pp.150-155.

Sobieski, T., Arámbula-Mercado, E. and Epps Martin, A. (2021). A method for characterizing RAP degree of binder activity. *Road Materials and Pavement Design*, 1-21.

Sreeram, A., Leng, Z., Zhang, Y., and Padhan, R.K. (2018). Evaluation of RAP binder mobilisation and blending efficiency in bituminous mixtures: An approach using ATR-FTIR and artificial aggregate. *Construction and Building Materials*, 179, 245-253.

Stroup-Gardiner, M. (2016). Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures. NCHRP Synthesis 495.

Tennessee Department of Transportation (TDOT). (2021). Standard Specifications for Road and Bridge Construction.

Tran, N.H., West, R., Powell, B., and Kvasnak, A. (2009). Evaluation of AASHTO Rut Test Procedure Using the Asphalt Pavement Analyzer. *Journal of the Association of Asphalt Paving Technologists*, Volume 78, pp. 1-24.

Vivanco, D., Tran, N., Yin, F., Bowers, B., and Chen, C. (2021). Implementation of a Mixture Cracking Test for Asphalt Mix Design and Acceptance Testing. GDOT Project Draft Final Report.

West, R., Timm, D., Willis, J.R., Powell, R., Tran, N., Watson, D., Sakhaeifar, M., Robbins, M., Brown, R., Vargas-Nordcbeck, A. and Villacorta, F.L. (2012). Phase IV NCAT Pavement Test Track Findings. NCAT Report No. 12-10.

West, W., Timm, D., Powell, B., Tran, N., Yin, F., Bowers, B., Rodezno, C., Leiva, F., Vargars, A., Gu, F., Moraes, R., and Nakhaei, M. (2021). Phase VII (2018-2021) NCAT Test Track Findings. NCAT Report No. 21-03.

Willis, R., and Timm, D. (2008). Repeatability of Asphalt Strain Measurements Under Full Scale Dynamic Loading. *Transportation Research Record*, 2087, pp. 40-48.

Yin, F., Arambula, E., Lytton, R., Martin, A.E. and Cucalon, L.G. (2014). Novel method for moisture susceptibility and rutting evaluation using Hamburg wheel tracking test. *Transportation Research Record*, 2446(1), pp.1-7.

Yin, F., Chen, C., West, R., Epps Martin, A., and Arámbula-Mercado, E. (2020). Determining the relationship among Hamburg wheel-tracking test parameters and correlation to field performance of asphalt pavements. *Transportation Research Record*, 2674(4), pp. 281-291.

Yin, F., Chen, C., Rodezno, C., Tran, N., Epps Martin, A., Arambula-Mercado, E., and Botella Nieto, R. (2023). Recycled Asphalt Materials: Binder Availability and Its Impact on Mix Performance. Phase I Interim Report.

Yu, S., Li, P., Zhang, Z., and Shen, S. (2021). Virgin Binder Determination for High RAP Content Mixture Design. *Journal of Materials in Civil Engineering*, 33(6), 04021112.

Yu, S., Shen, S., Zhang, C., Zhang, W., and Jia, X. (2017). Evaluation of the blending effectiveness of reclaimed asphalt pavement binder. *Journal of Materials in Civil Engineering*, 29(12), 04017230.

Zearley, L.J. (1979). Penetration characteristics of asphalt in a recycled mixture.

Zhao, S., Huang, B., Shu, X. and Woods, M.E. (2015). Quantitative characterization of binder blending: How much recycled binder is mobilized during mixing? *Transportation Research Record*, 2506(1), 72-80.

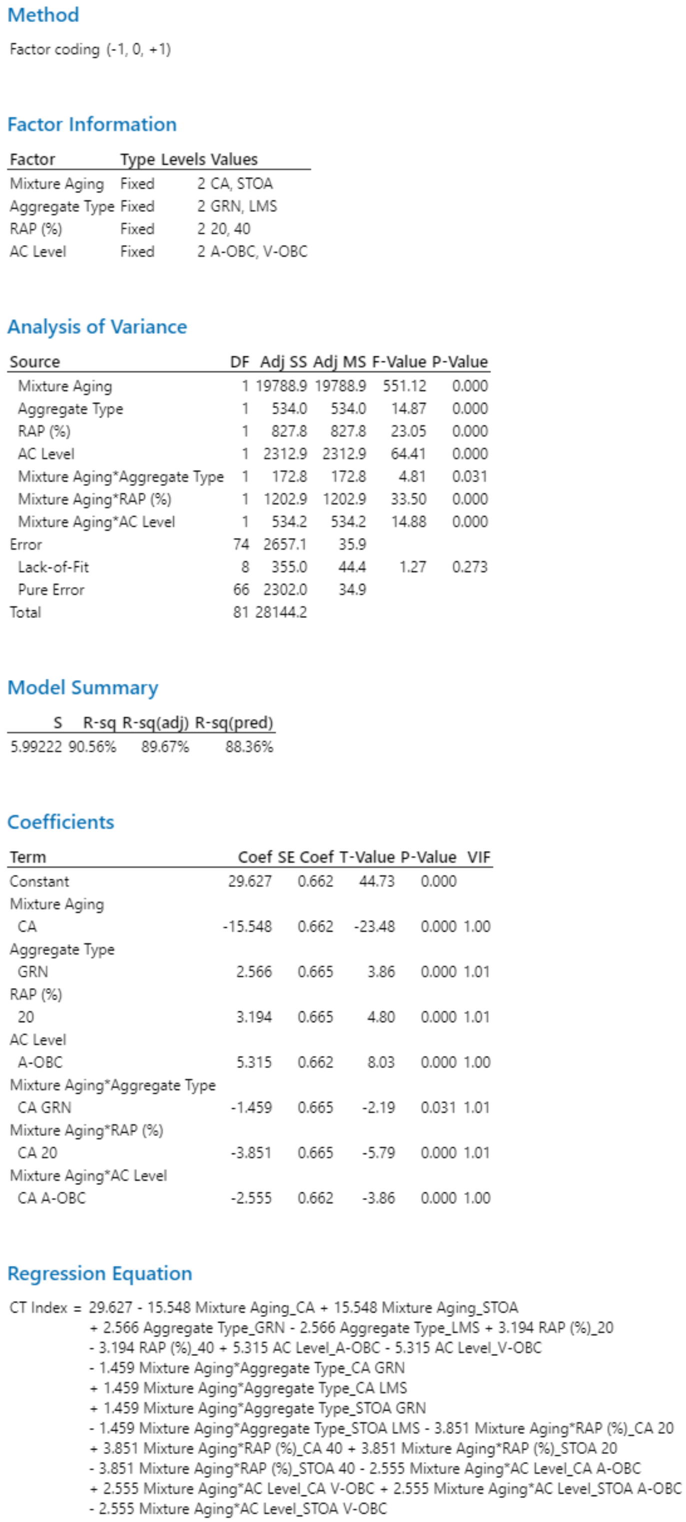
Zhou, F., Crockford, B., Zhang, J., Hu, S., Epps, J. and Sun, L. (2019). Development and Validation of an Ideal Shear Rutting Test for Asphalt Mix Design and QC/QA. *Journal of the Association of Asphalt Paving Technologists*, Volume 88, 719-749.

Zhou, F., Im, S., Sun, L., and Scullion, T. (2017). Development of an IDEAL Cracking Test for Asphalt Mix Design and QC/QA. *Journal of the Association of Asphalt Paving Technologists*, pp 549-577.

Zhou, F., Steger, R., and Mogawer, W. (2021). Development of a coherent framework for balanced mix design and production quality control and quality acceptance. *Construction and Building Materials*, 287, 123020.

APPENDIX. GENERAL LINEAR MODEL OUTPUT REPORTS

General Linear Model for IDEAL-CT Results



Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Mixture Aging	Fixed	2	CA, STOA
Aggregate Type	Fixed	2	GRN, LMS
RAP (%)	Fixed	2	20, 40
AC Level	Fixed	2	A-OBC, V-OBC

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mixture Aging	1	19788.9	19788.9	551.12	0.000
Aggregate Type	1	534.0	534.0	14.87	0.000
RAP (%)	1	827.8	827.8	23.05	0.000
AC Level	1	2312.9	2312.9	64.41	0.000
Mixture Aging*Aggregate Type	1	172.8	172.8	4.81	0.031
Mixture Aging*RAP (%)	1	1202.9	1202.9	33.50	0.000
Mixture Aging*AC Level	1	534.2	534.2	14.88	0.000
Error	74	2657.1	35.9		
Lack-of-Fit	8	355.0	44.4	1.27	0.273
Pure Error	66	2302.0	34.9		
Total	81	28144.2			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
5.99222	90.56%	89.67%	88.36%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	29.627	0.662	44.73	0.000	
Mixture Aging					
CA	-15.548	0.662	-23.48	0.000	1.00
Aggregate Type					
GRN	2.566	0.665	3.86	0.000	1.01
RAP (%)					
20	3.194	0.665	4.80	0.000	1.01
AC Level					
A-OBC	5.315	0.662	8.03	0.000	1.00
Mixture Aging*Aggregate Type					
CA GRN	-1.459	0.665	-2.19	0.031	1.01
Mixture Aging*RAP (%)					
CA 20	-3.851	0.665	-5.79	0.000	1.01
Mixture Aging*AC Level					
CA A-OBC	-2.555	0.662	-3.86	0.000	1.00

Regression Equation

```
CT Index = 29.627 - 15.548 Mixture Aging_CA + 15.548 Mixture Aging_STOA
           + 2.566 Aggregate Type_GRN - 2.566 Aggregate Type_LMS + 3.194 RAP (%)_20
           - 3.194 RAP (%)_40 + 5.315 AC Level_A-OBC - 5.315 AC Level_V-OBC
           - 1.459 Mixture Aging*Aggregate Type_CA GRN
           + 1.459 Mixture Aging*Aggregate Type_CA LMS
           + 1.459 Mixture Aging*Aggregate Type_STOA GRN
           - 1.459 Mixture Aging*Aggregate Type_STOA LMS - 3.851 Mixture Aging*RAP (%)_CA 20
           + 3.851 Mixture Aging*RAP (%)_CA 40 + 3.851 Mixture Aging*RAP (%)_STOA 20
           - 3.851 Mixture Aging*RAP (%)_STOA 40 - 2.555 Mixture Aging*AC Level_CA A-OBC
           + 2.555 Mixture Aging*AC Level_CA V-OBC + 2.555 Mixture Aging*AC Level_STOA A-OBC
           - 2.555 Mixture Aging*AC Level_STOA V-OBC
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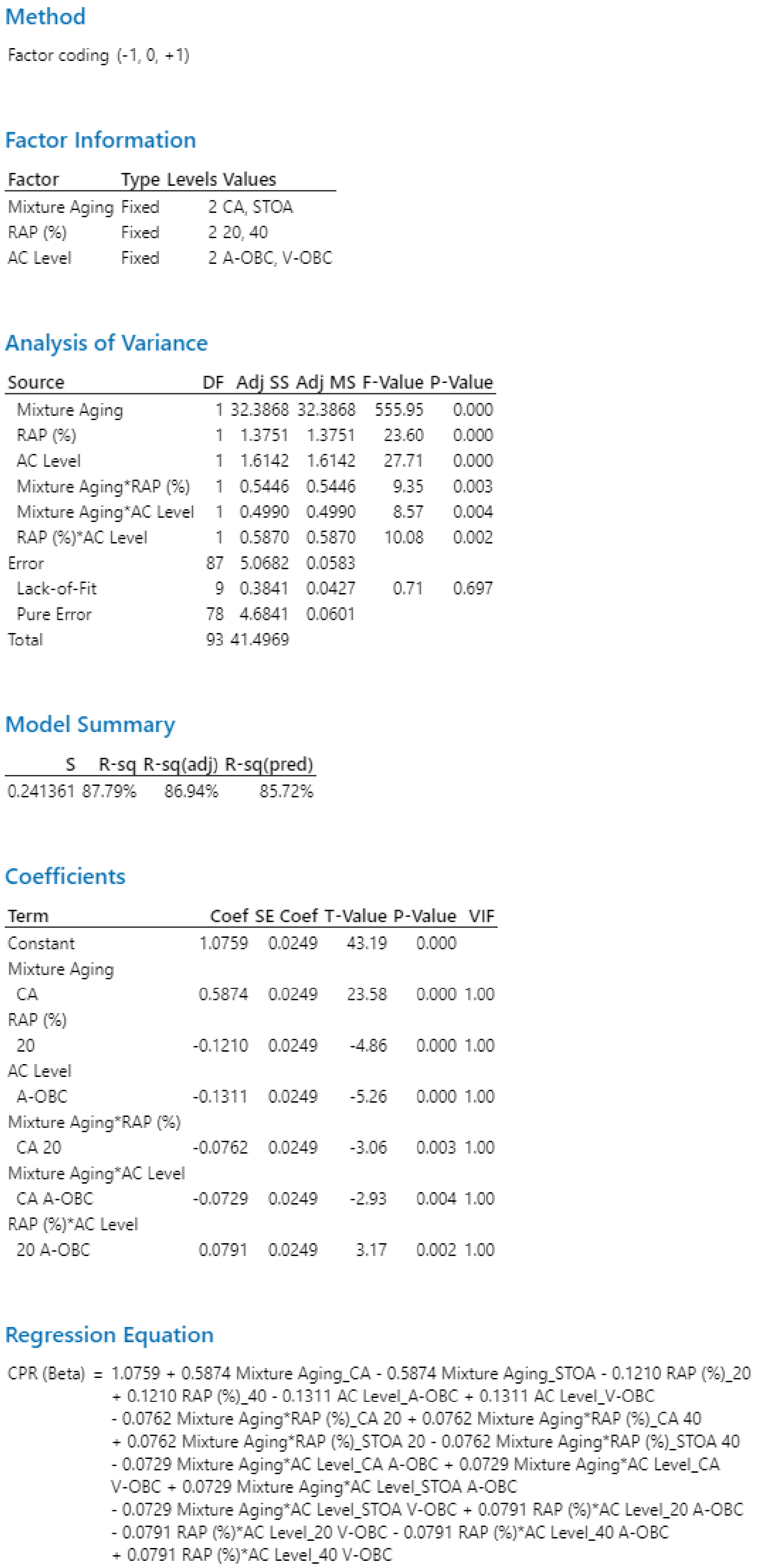
General Linear Model for OT CPR Results



Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Mixture Aging	Fixed	2	CA, STOA
RAP (%)	Fixed	2	20, 40
AC Level	Fixed	2	A-OBC, V-OBC

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mixture Aging	1	32.3868	32.3868	555.95	0.000
RAP (%)	1	1.3751	1.3751	23.60	0.000
AC Level	1	1.6142	1.6142	27.71	0.000
Mixture Aging*RAP (%)	1	0.5446	0.5446	9.35	0.003
Mixture Aging*AC Level	1	0.4990	0.4990	8.57	0.004
RAP (%)*AC Level	1	0.5870	0.5870	10.08	0.002
Error	87	5.0682	0.0583		
Lack-of-Fit	9	0.3841	0.0427	0.71	0.697
Pure Error	78	4.6841	0.0601		
Total	93	41.4969			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.241361	87.79%	86.94%	85.72%

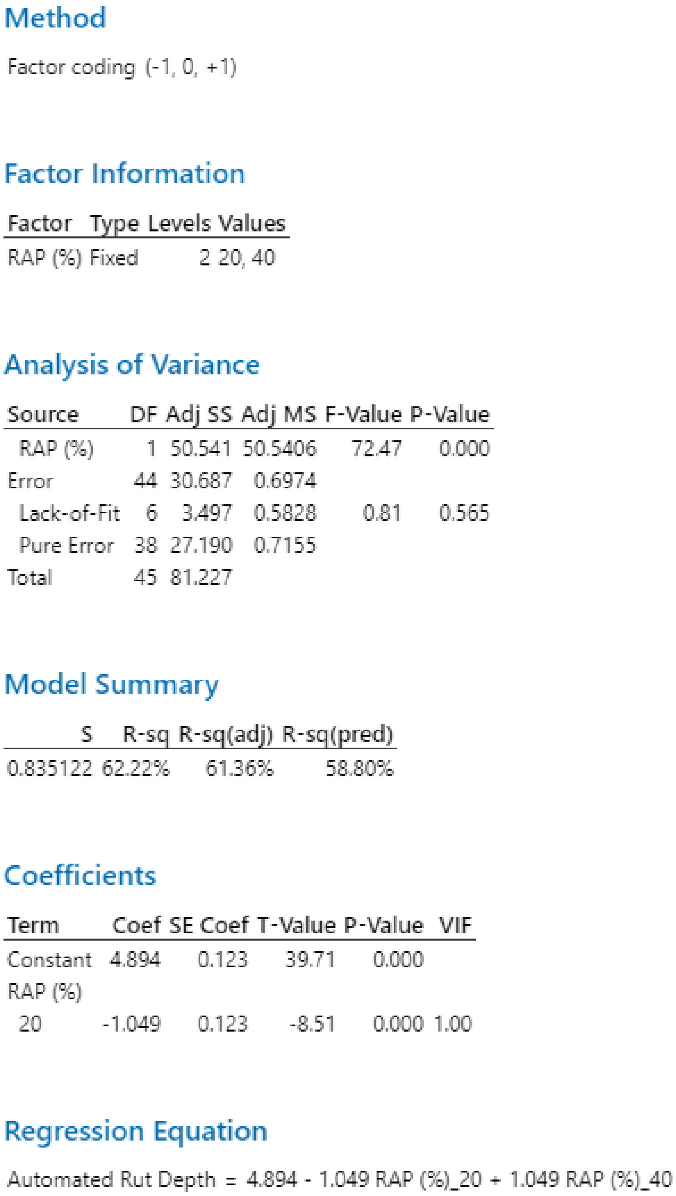
Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.0759	0.0249	43.19	0.000	
Mixture Aging					
CA	0.5874	0.0249	23.58	0.000	1.00
RAP (%)					
20	-0.1210	0.0249	-4.86	0.000	1.00
AC Level					
A-OBC	-0.1311	0.0249	-5.26	0.000	1.00
Mixture Aging*RAP (%)					
CA 20	-0.0762	0.0249	-3.06	0.003	1.00
Mixture Aging*AC Level					
CA A-OBC	-0.0729	0.0249	-2.93	0.004	1.00
RAP (%)*AC Level					
20 A-OBC	0.0791	0.0249	3.17	0.002	1.00

Regression Equation

CPR (Beta) = 1.0759 + 0.5874 Mixture Aging_CA - 0.5874 Mixture Aging_STOA - 0.1210 RAP (%)_20
+ 0.1210 RAP (%)_40 - 0.1311 AC Level_A-OBC + 0.1311 AC Level_V-OBC
- 0.0762 Mixture Aging*RAP (%)_CA 20 + 0.0762 Mixture Aging*RAP (%)_CA 40
+ 0.0762 Mixture Aging*RAP (%)_STOA 20 - 0.0762 Mixture Aging*RAP (%)_STOA 40
- 0.0729 Mixture Aging*AC Level_CA A-OBC + 0.0729 Mixture Aging*AC Level_CA
V-OBC + 0.0729 Mixture Aging*AC Level_STOA A-OBC
- 0.0729 Mixture Aging*AC Level_STOA V-OBC + 0.0791 RAP (%)*AC Level_20 A-OBC
- 0.0791 RAP (%)*AC Level_20 V-OBC - 0.0791 RAP (%)*AC Level_40 A-OBC
+ 0.0791 RAP (%)*AC Level_40 V-OBC

General Linear Model for APA Results



Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
RAP (%)	Fixed	2	20, 40

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
RAP (%)	1	50.541	50.5406	72.47	0.000
Error	44	30.687	0.6974		
Lack-of-Fit	6	3.497	0.5828	0.81	0.565
Pure Error	38	27.190	0.7155		
Total	45	81.227			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.835122	62.22%	61.36%	58.80%

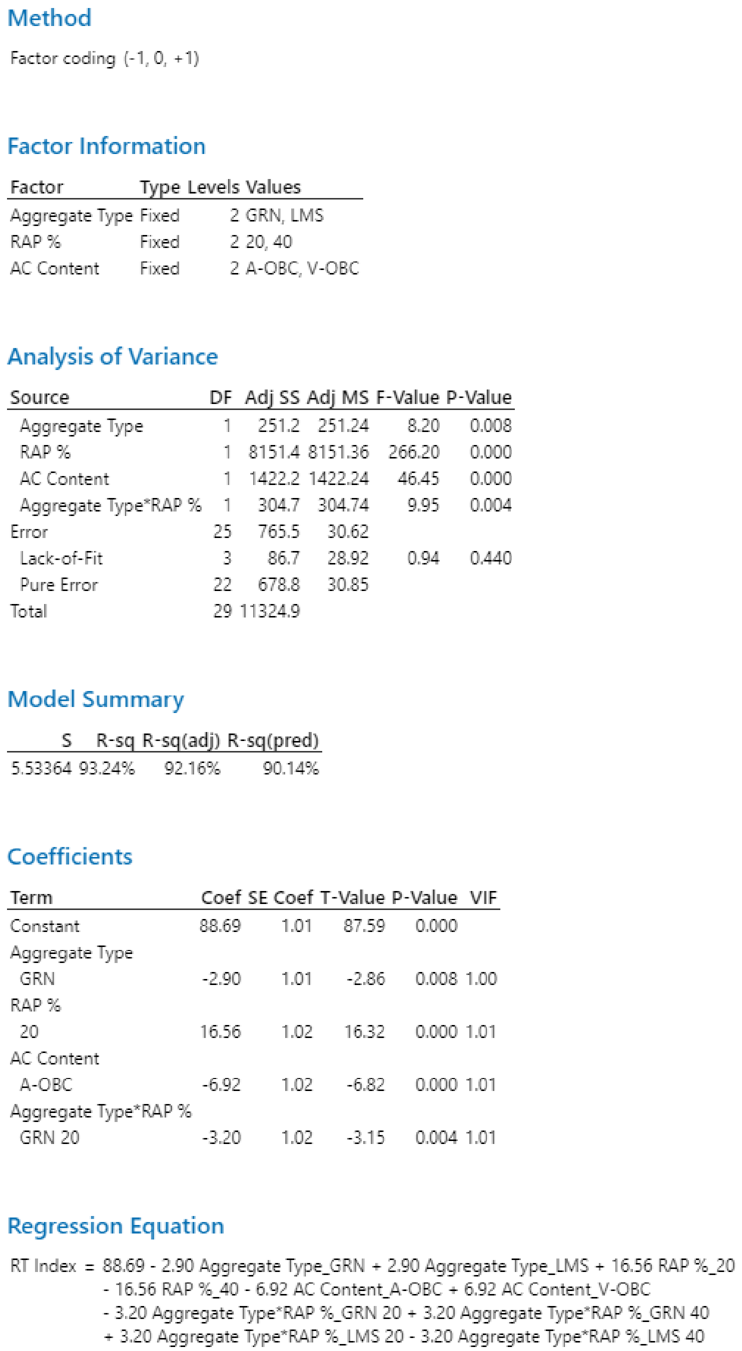
Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	4.894	0.123	39.71	0.000	
RAP (%)					
20	-1.049	0.123	-8.51	0.000	1.00

Regression Equation

Automated Rut Depth = 4.894 - 1.049 RAP (%)_20 + 1.049 RAP (%)_40

General Linear Model for IDEAL-RT Results



Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Aggregate Type	Fixed	2	GRN, LMS
RAP %	Fixed	2	20, 40
AC Content	Fixed	2	A-OBC, V-OBC

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Aggregate Type	1	251.2	251.24	8.20	0.008
RAP %	1	8151.4	8151.36	266.20	0.000
AC Content	1	1422.2	1422.24	46.45	0.000
Aggregate Type*RAP %	1	304.7	304.74	9.95	0.004
Error	25	765.5	30.62		
Lack-of-Fit	3	86.7	28.92	0.94	0.440
Pure Error	22	678.8	30.85		
Total	29	11324.9			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
5.53364	93.24%	92.16%	90.14%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	88.69	1.01	87.59	0.000	
Aggregate Type					
GRN	-2.90	1.01	-2.86	0.008	1.00
RAP %					
20	16.56	1.02	16.32	0.000	1.01
AC Content					
A-OBC	-6.92	1.02	-6.82	0.000	1.01
Aggregate Type*RAP %					
GRN 20	-3.20	1.02	-3.15	0.004	1.01

Regression Equation

```
RT Index = 88.69 - 2.90 Aggregate Type_GRN + 2.90 Aggregate Type_LMS + 16.56 RAP %_20
           - 16.56 RAP %_40 - 6.92 AC Content_A-OBC + 6.92 AC Content_V-OBC
           - 3.20 Aggregate Type*RAP %_GRN 20 + 3.20 Aggregate Type*RAP %_GRN 40
           + 3.20 Aggregate Type*RAP %_LMS 20 - 3.20 Aggregate Type*RAP %_LMS 40
```