IDAHO TRANSPORTATION DEPARTMENT

RESEARCH REPORT

Implementation of Balanced Asphalt Mix Design of Asphalt Mixtures Prepared with Reclaimed Asphalt Pavements and Rejuvenators for Enhanced Performance

RP 292

By

Emad Kassem, Hussain Al Hatailah,
Mohammed Abu Saq, and Fouad Bayomy
University of Idaho

and

Yang Lu and Amanda Mullins
Boise State University

Prepared for

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The use of Reclaimed Asphalt Pavement (RAP) promotes and integrates sustainable solutions into civil engineering practices. Many transportation agencies limit the RAP content to a small percentage. Despite the environmental benefits and cost savings of incorporating RAP into asphalt mixtures, it may result in stiffer mixtures, especially at a higher RAP content, that could be prone to premature cracking. Virgin binder grade adjusting is typically followed to account for the stiffening effect of RAP which may require the use of softer binders. This could increase the cost of Hot Mix Asphalt (HMA) production due to the limited availability of such softer binders in practice. This study examined the use of rejuvenators to improve the performance of asphalt mixtures, with different RAP contents, through a balanced mix design approach to ensure sufficient resistance to cracking and rutting. Rejuvenators have the potential to restore the rheological properties of aged binders. Seven different commercially available rejuvenators were acquired and included in the testing program of this study. The results demonstrated that the use of rejuvenators in asphalt mixtures with RAP is beneficial and could offer environmental benefits and cost savings. However, it is more cost effective to incorporate rejuvenators in asphalt mixtures at high RAP content (e.g., 50 or 70 percent). The cracking performance of mixtures with certain rejuvenators and high RAP content could be comparable to that of the virgin mixture (0 percent RAP) with additional cost savings. The use of tall oil and waste vegetable oil were found effective in improving the cracking resistance and providing cost savings compared to other rejuvenators. The results of this study clearly demonstrated the importance of implementing a balanced mix design approach to optimize the design of asphalt mixtures prepared with RAP and rejuvenators to provide adequate performance in terms of cracking and rutting resistance. The balanced mix design should be supplemented by conducting cost analysis to compare different alternatives that provide acceptable performance. Furthermore, this study evaluated the cracking and rutting performance of 23 different asphalt mixtures produced and used in Idaho. The results demonstrated that these mixtures are expected to exhibit good cracking and rutting performance. In addition, the current practice followed by ITD of using anti stripping agents was found effective in resisting moisture damage.		
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Technical Advisory Committee

Each research project is overseen by a Technical Advisory Committee (TAC), which is led by an ITD project sponsor and project manager. The TAC is responsible for monitoring project progress, reviewing deliverables, ensuring that study objectives are met, and facilitating implementation of research recommendations, as appropriate. ITD's Research Program Manager appreciates the work of the following TAC members in guiding this research study.

- Project Sponsor: Chad Clawson
- Project Manager: Mike Copeland
- TAC Members: John Arambarri, Chad Clawson, Kyle Holman, Ben Ward, Randy Durland
- FHWA-Idaho Advisor: Kyle Holman, P.E.

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List of Abbreviations and Acronyms

FHWA .... Federal Highway Administration

ITD .... Idaho Transportation Department

TAC .... Technical Advisory Committee

IDT .... Indirect Tensile Strength

AASHTO....................... American Association of State Highway and Transportation Officials

AASHTO....................... American Association of State Highway and Transportation Officials

HWTT .... Hamburg Wheel Tracking Test

APA .... Asphalt Pavement Analyzer

HMA............................ Hot Mix Asphalt

NMAS .... Nominal Maximum Aggregate Size

UI .... University of Idaho

BSU .... Boise State University

IDEAL-CT_{Index} .... Indirect Tension Asphalt Cracking Test

RAP .... Reclaimed Asphalt Pavement

BMD .... Balanced Mix Design

COV .... Coefficient of Variation

ASTM .... American Standards for Testing and Materials

NCAT .... National Center for Asphalt Technology

OBC .... Optimum Binder Content

NCHRP......................... National Cooperative Highway Research Program

MTS .... Material Testing System

HSD .... Honestly Significant Difference Test

Executive Summary

Many State Departments of Transportation (DOTs) allow incorporation of Reclaimed Asphalt Pavement (RAP) into asphalt mixtures. The use of RAP promotes and integrates sustainable solutions into civil engineering practices. The amount of virgin aggregates and asphalt binders can be reduced by using RAP in asphalt mixtures which offers environmental benefits and cost savings. Many transportation agencies limit the RAP content to a small percentage. For several years, the Idaho Transportation Department (ITD) allowed a RAP content of over 50 percent as selected by the contractor. Currently, ITD only allows up to 30 percent RAP Binder Replacement (RAPBR) in asphalt mixtures. Despite the environmental benefits and cost savings of incorporating RAP into asphalt mixtures, it may result in stiffer mixtures, especially at a higher RAP content, that could be prone to premature cracking. Adjusting the virgin binder grade (i.e., softer binder) is the most common method used to account for the stiffening effect of the RAP in the asphalt mixture. This could increase the production cost of the Hot Mix Asphalt (HMA) due to the limited availability of such softer binders in practice.

Rejuvenators have been used mainly in surface treatment emulsions to improve the properties of existing asphalt surface layers. Rejuvenators have the potential to restore the rheological properties of aged binders. This study examined the use of rejuvenators to improve the performance of asphalt mixtures, with different RAP contents, through a balanced mix design approach to ensure sufficient resistance to cracking and rutting. Seven different commercially available rejuvenators were acquired and included in the testing program. These rejuvenators included tall oil, aromatic extract, bio-based forestry, engineered product, triglycerides and fatty acids product, bio-based oil, petroleum-based oil for rejuvenators R1 through R7, respectively. Asphalt mixtures prepared with different doses of each rejuvenator were also examined. Furthermore, the researchers prepared and tested asphalt mixtures at different binder contents (i.e., optimum binder content [OBC] and OBC+0.5 percent) and binder grades.

This study also evaluated the cracking and rutting performance of asphalt mixtures currently produced and used in the state. Loose asphalt mixtures from 23 projects were obtained and tested. The mixtures included different mix designs, binder grades, RAP content, and percent RAP binder replacement. The researchers evaluated the performance of the test mixtures based on the performance thresholds developed in RP 261 (Kassem et al. 2019) and the ones proposed in the respective standards and literature. The cracking resistance was evaluated for all test mixtures using the Indirect Tensile (IDT) strength test and calculation of IDEAL-CT_{Index}. The researchers also calculated additional cracking parameters including $IDT_{Strength}$ and WeibullCRI. The Hamburg Wheel Tracking Test (HWTT) was conducted using the Asphalt Pavement Analyzer JR. (APA Jr.) to evaluate the rutting performance and moisture susceptibility of test mixtures. In addition, the researchers measured the creep compliance and strength for selected test mixtures at low temperatures to evaluate the thermal cracking performance.

Key Findings

The key findings of this study are summarized below:

- The cracking resistance decreased with the increase of RAP content for all RAP examined in this study. Both IDEAL-CT_{Index} and $Weibull_{CRI}$ decreased with the increase of RAP content which demonstrates reduced cracking resistance. Meanwhile, the $IDT_{Strength}$ increased with the increase of RAP content which demonstrates that the mixtures become stiffer with the addition of RAP.
- The use of rejuvenators in mixtures with low RAP content (e.g., 25 percent), especially for mixtures with good cracking performance, did not improve the cracking resistance (i.e., did not increase IDEAL-CT_{Index}). It was observed that the addition of rejuvenators could be detrimental to the cracking resistance at low RAP content for mixtures with good cracking resistance.
- Mixtures prepared with 70 percent RAP had lower IDEAL-CT_{Index} values compared to the ones without RAP (0 percent RAP) irrespective of the binder grade.
- The favorable effect of rejuvenators in asphalt mixtures is observed in mixtures with higher RAP content (e.g., 70 percent) for different RAP sources evaluated in this study. In some cases (e.g., RAP No. 2 and RAP No. 3), it was possible to produce mixtures prepared with 70 percent RAP and rejuvenators that provided comparable cracking performance to the mixture without RAP.
- Increasing the rejuvenator dose does not necessarily improve the cracking resistance (i.e., R4 and R6). In fact, in some cases, it could adversely impact cracking performance.
- The use of rejuvenator R1 (tall oil) and rejuvenator R5 (waste vegetable oil) with mixtures with high RAP contents provided the best performance compared to other rejuvenators examined in this study, and these mixtures had comparable cracking performance to the virgin mixture (i.e., 0 percent RAP).
- Rejuvenator R4 (engineered product) at a higher dose improved the cracking performance of laboratory mixtures with RAP; however, these mixtures failed the rutting criteria prematurely (i.e., the mixtures were too soft). These results demonstrated the importance of the balanced mix design approach to satisfy both cracking and rutting criteria.
- Increasing the binder content was found to increase the cracking resistance for some mixtures with or without RAP. This further emphasizes the effectiveness of the balanced mix design approach.
- The use of rejuvenator R1 (tall oil) and rejuvenator R5 (waste vegetable oil) provided higher creep compliance compared to the virgin mixture (0 percent RAP) and control mixture (70 percent RAP) which demonstrated improved cracking resistance at a low temperature.

- Some rejuvenators (e.g., R1 and R5) were effective in improving the cracking performance at higher RAP content which offers significant environmental and economic benefits. Furthermore, these rejuvenators enhanced the thermal cracking performance.

- The use of rejuvenators in asphalt mixtures with RAP is beneficial and could offer environmental benefits and cost savings. However, it is more cost effective to incorporate rejuvenators in mixtures with high RAP content (i.e., 50 or 70 percent).

- Most of the field mixes (18 out of 23) had IDEAL-CT_{Index} values of 73.7 or higher which indicates that these mixtures are expected to exhibit good cracking resistance in the field. Four projects were within the moderate cracking performance range, while only one project had an IDEAL-CT_{Index} less than the minimum threshold of 26.4 which demonstrates poor cracking resistance.

- The HWTT rut depth for the field mixes ranged from 1.12 mm to 4.41 mm after 20,000 passes. Therefore, all the mixtures had a rut depth way below the maximum threshold of 12.5 mm after 20,000 passes.

- The Pearson correlation results demonstrated that $Weibull_{CRI}$ and IDEAL-CT_{Index} had a strong correlation (r = 0.964); however, $Weibull_{CRI}$ had lower variability in the test results (average COV = 6.6 percent) compared to IDEAL-CT_{Index} (average COV = 18.8 percent) which is consistent with the results of ITD RP 280 (Kassem et al. 2021).

1. Introduction

Problem Statement

Many State Departments of Transportation (DOTs) allow incorporation of Reclaimed Asphalt Pavement (RAP) into asphalt mixtures. The use of RAP promotes and integrates sustainable solutions into civil engineering practices. The amount of virgin aggregates and asphalt binders can be reduced by using RAP in asphalt mixtures which offers environmental benefits and cost savings. Many transportation agencies limit the RAP content to about 25 percent. For several years, the Idaho Transportation Department (ITD) allowed a RAP content of over 50 percent as selected by the contractor. Currently, ITD only allows up to 30 percent RAP in asphalt mixtures. Despite the environmental benefits and cost savings of incorporating RAP into asphalt mixtures, it may result in stiffer mixtures, especially at a higher RAP content, that could be prone to premature cracking. Furthermore, the addition of RAP may adversely affect thermal cracking even if a small amount of RAP is used. Virgin binder grade adjusting is typically followed to account for the stiffening effect of the RAP. The current adjustment process is performed using modified AASHTO M 323 where a blending chart is used for virgin binder selection if the RAP content exceeds 30 percent. If the RAP content is between 17 percent and 30 percent, one grade softer virgin binder is typically selected. There is no need to change the virgin binder grade if the RAP content is less than 17 percent. The use of softer binders may increase the cost of Hot Mix Asphalt (HMA) production due to the limited availability of such softer binders in practice.

Rejuvenators have been used mainly in surface treatment emulsions to improve the properties of existing asphalt surface layers. Rejuvenators have the potential to restore the chemical and rheological properties of aged binders. The ratio of maltenes to asphaltenes is reduced due to oxidative aging, and rejuvenators contain maltenes to restore the original ratio. There is a need to investigate the use of rejuvenators to improve the performance of asphalt mixtures containing different percentages of RAP (i.e., 25, 50, and 70 percent) using a balanced mix design approach that aims to produce mixtures with adequate performance in terms of cracking and rutting resistance based on the performance thresholds developed in RP261 (Kassem et al. 2019).

RP 261 conducted a comprehensive testing program that included laboratory-mixed laboratory-compacted, plant-mixed laboratory-compacted test specimens, and cores extracted from the field. The laboratory testing included two rutting tests (i.e., Hamburg Wheel Tracking Test [HWTT] and Asphalt Pavement Analyzer [APA]) and three monotonic cracking tests (i.e., indirect tension test, semi-circle bending flexibility index test, semi-circle bending Jc test), in addition to a dynamic cracking test. The researchers examined more than 20 performance indicators to evaluate the cracking and rutting performance of asphalt mixtures in Idaho. Based on the results, RP 261 proposed performance thresholds to ensure adequate resistance to cracking, rutting, and moisture damage. Performance thresholds for HWTT as well as APA rutting tests were proposed. In addition, the researchers developed performance thresholds for selected cracking tests including IDEAL-CT_{Index}, N_{flex} factor, and $Weibull_{CRI}$. ITD has recently selected and implemented HWTT and IDEAL-CT_{Index} to evaluate the resistance of asphalt mixtures to rutting and cracking, respectively. The developed performance thresholds in RP 261 especially for IDEAL-CTIndex and HWTT need to be further evaluated using additional asphalt mixtures currently produced in Idaho and revised as needed.

Objectives

The main objectives of this study are:

- Evaluate the effect of rejuvenators on improving the performance of asphalt mixtures containing different percentages of RAP and reducing the need for softer binders which are more costly to obtain as compared to rejuvenators.
- Apply a balanced (engineered) mix design approach and performance thresholds, developed in RP 261, to optimize the mix design of asphalt mixtures prepared with RAP and rejuvenators for improved performance.
- Evaluate the performance thresholds developed in RP 261 especially for IDEAL-CT_{Index} and HWTT using additional asphalt mixtures currently produced in the state.
- Study the economic savings of using rejuvenators and RAP in asphalt mixtures as compared to the control mixtures.
- Develop recommendations on incorporating rejuvenators and RAP into asphalt mixtures that provide comparable or superior performance with respect to the control mixtures.

Tasks

The researchers conducted five main tasks to achieve the objectives of this research study. These tasks are discussed in detail in this section.

Task 1: Literature review

In this task, the researchers conducted a literature review of previous published research studies and collected pertinent information on the following subjects:

- Different types of rejuvenators and recycling agents used in asphalt mixtures prepared with RAP,
- Cracking and rutting performance of asphalt mixtures with RAP and rejuvenators,
- Effect of rejuvenators on binder performance grade,
- Methods used to select rejuvenator dose,
- Economic benefits of using rejuvenators in asphalt mixtures,
- Current practices of incorporating RAP in asphalt mixtures,
- Review of proposed balanced mix design and performance measures of RAP mixtures, and
- Test methods and associated performance thresholds to assess the cracking and rutting performance of asphalt mixtures.

Task 2: Select and procure testing materials

Under this task, the research team selected and procured local materials including aggregates, virgin binders, RAP, and rejuvenators, as well as loose asphalt mixtures. The test materials included the following:

- Virgin aggregates: two sources of river gravel were used; one in Lewiston and another one in Boise, Idaho.
- Asphalt binders: five binder grades were included (i.e., PG 58-34, PG 58-28, PG 64-28, PG 64-34, and PG 70-28).
- RAP materials: four sources of RAP were examined. Three were obtained from asphalt plants in Idaho, in addition to an artificial RAP that was produced in the laboratory.
- Rejuvenators: seven rejuvenators were obtained from different sources and included in the laboratory evaluation.
- Plant mixtures: a total number of 23 loose mixtures were collected from ITD paving projects with different characteristics including different mix designs, binder grades, percent of RAP content, and percent of RAP binder replacement.

Task 3: Prepare asphalt mixture test specimens

Under this task, the team prepared asphalt mixture test specimens needed to execute the testing program. They prepared laboratory-mixed, laboratory-compacted specimens with the following characteristics.

- Different RAP content (e.g., 0, 25, 50, 70, and 75 percent).
- Seven different rejuvenators. Their doses to obtain optimum cracking and rutting performance varied.
- Five binder grades (e.g., PG 58-28, PG 58-34, PG 64-28, PG 64-34, and PG 70-28).
- Different binder content (Optimum binder content (OBC) and OBC +0.5 percent).

In addition, the researchers prepared plant-mixed, laboratory-compacted specimens to evaluate the performance thresholds developed in RP 261 with the focus on IDEAL-CT_{Index} and HWTT tests. The IDEAL-CT_{Index} test specimens are 150 mm in diameter and 62 mm in height and don't need to be cut or notched which is an advantage over the semicircular test specimens. The HWTT test specimens are 150 mm in diameter and 60 mm in height.

Task 4: Conduct laboratory testing

Under this task, the researchers conducted laboratory testing to evaluate the properties of test specimens. The following characteristics were evaluated.

- Rutting resistance and moisture susceptibility using HWTT. The HWTT is conducted in accordance with AASHTO T324. Cylindrical test specimens are subjected to accelerated reciprocating wheel loading. HWTT applies 705 N load on the surface of test specimens at a constant moving rate of 52 pass/minute. A set of four test specimens are used in each run. The test specimens are submerged in water for at least one hour before testing at a specified temperature (e.g., 50 °C). This test is used to assess the resistance to rutting as well as moisture susceptibility. The test is completed when the test specimen achieves a certain rut depth (e.g., 12.5 mm) or the specified number of passes (e.g., 20,000 passes) is applied.
- Fatigue cracking resistance (e.g., IDEAL-CT_{Index} and WeibullCRI). IDEAL-CT_{Index} and WeibullCRI values can be calculated from the same load-displacement curve obtained using the indirect tensile test (IDT). The IDT uses a circular specimen which is subjected to a compressive loading at 50 mm/min and the test is conducted at 25 °C. The IDEAL-CT_{Index} was proposed by the researchers

at Texas A&M (ASTM D8225 – 19), while WeibullCRI was developed in Idaho in RP 261. Higher IDEAL-CT_{Index} and WeibullCRI values indicate better resistance to cracking. IDEAL-CT_{Index} is calculated as a function of fracture energy, post-peak slope, and strain tolerance. The WeibullCRI describes the entire load-displacement curve.

- Thermal cracking resistance at low temperature. The creep compliance and strength test are conducted in accordance with AASHTO T 322. The test is conducted at three temperatures (i.e., -20, -10, and 0 °C) where a vertical static load is applied on the test specimen for 100 sec to produce a horizontal deformation between 0.00125 to 0.0190 mm to ensure that the test specimen is in the linear viscoelastic range. Once the creep compliance test is completed at all temperatures, the tensile strength test is conducted at a testing temperature of -10 °C by applying a vertical load rate of 12 mm/min until failure.

Task 5: Analyze the laboratory testing results

Under this task, the researchers analyzed the laboratory testing results to evaluate the performance of the asphalt mixtures. The researchers examined the cracking and rutting performance as well as the low-temperature cracking of mixtures with different characteristics including RAP source and content, rejuvenator type and content, and binder grade and content. The results for mixtures prepared with RAP collected from four different sources (e.g., RAP Source No. 1 through RAP Source No. 4) were carefully discussed. The cracking resistance was evaluated for all mixtures using the IDT test and calculations of IDEAL-CT_{Index}. The researchers calculated additional cracking parameters including $IDT_{Strength}$ and $Weibull_{CRI}$. The Hamburg Wheel Tracking Test (HWTT) was conducted using the Asphalt Pavement Analyzer JR. (APA Jr.) to evaluate the rutting performance of the test mixtures. The effect of RAP content, rejuvenator type, and rejuvenator doses on the performance was examined for each RAP source separately. Furthermore, the researchers conducted statistical analysis of the test results using Tukey's Honestly Significant Difference (Tukey's HSD). The Tukey's HSD is a one-way analysis of variance (ANOVA) and is performed at 95 percent confidence interval (i.e., $\alpha = 0.05$). Tukey's HSD can identify test means with significant difference.

Task 5 also evaluated the cracking and rutting performance of loose mixtures collected from new paving projects. These loose mixtures were collected from different districts in Idaho and have different properties (mix design, binder grade, binder content, RAP, etc.). The researchers calculated different cracking and rutting performance parameters and compared to performance thresholds proposed and used in previous ITD studies (Kassem et al. 2019 and Kassem et al. 2021). Furthermore, the researchers examined the coefficient of variation of various cracking performance indicators of the field projects along with their correlations.

Task 6: Conduct cost analysis to assess economic savings

Under this task, the researchers conducted cost analysis to assess economic savings associated with using rejuvenators with high RAP content in asphalt mixtures without compromising the performance (i.e., cracking and rutting resistance). In addition, the researchers examined the benefits and cost savings associated with increasing the binder content at different RAP contents. The use of RAP can cut down the percent of virgin binder added leading to cost savings. In addition, the current practice is to use one grade softer virgin binder if the RAP content between 17 percent to 30 percent and the blending chart to select the grade of softer virgin binder if RAP content exceeds 30 percent. The use of softer binder costs more than the conventional virgin binder due to its limited availability. Therefore, the use of rejuvenators may eliminate or reduce the need for softer binders.

Task 7: Develop recommendations and guidelines

Under this task, the researchers developed recommendations on incorporating RAP and rejuvenators in asphalt mixtures for improved performance and cost savings. Furthermore, the researchers provided recommendations on implementing a balanced mix design approach using the performance thresholds for cracking and rutting proposed in RP 261 and further evaluated in this study. Also, the researchers provided recommendations on future studies for implementation.

Task 8: Prepare the final report

The researchers prepared a final report that includes the research methodology, results, analysis, findings, and recommendations.

Report Organization

This report consists of seven chapters and five appendices. Chapter 1 provides an overview, objectives, tasks, and report organization. Chapter 2 provides a literature review of previous studies and summarizes the main findings. Chapter 3 discusses the material properties, testing matrix, and laboratory experimental design used and conducted in this study. Chapter 4 discusses the performance of asphalt mixtures prepared with different amounts of RAP and rejuvenators. Chapter 5 discusses the cracking and rutting performance of asphalt mixtures collected from various paving projects across the state based on performance thresholds developed in RP 261. Chapter 6 provides cost analysis to assess economic savings associated with using rejuvenators and high RAP content in asphalt mixtures. Chapter 7 provides a summary of the main findings of this study and associated recommendations. The appendices provide additional information and figures that were cited and discussed in this report.

2. Literature Review

Introduction

Many State Departments of Transportation (DOTs) allow incorporation of RAP into asphalt mixtures. The use of RAP promotes and integrates sustainable solutions into civil engineering practices. The amount of virgin aggregates and asphalt binders can be reduced by using RAP in asphalt mixtures which offers environmental benefits and cost savings. The benefits of using RAP in asphalt mixtures include, but are not limited to, reducing production energy consumption and associated emissions, preserving natural resources, and reducing production cost (Yin et al., 2017). To ensure the pavement performance is not compromised due to the use of RAP, rejuvenators or recycling agents are often recommended in asphalt mixtures containing RAP. Recycling agents, also known as rejuvenators, are organic or petroleum products with chemical and physical properties that help to restore the rheological properties of aged asphalt binders. Rejuvenators were first introduced in 1960’s as a pavement preservation practice. RAP binders are often aged and stiffer with less flexibility and ductility due to the oxidization process experienced by the pavement during service. The asphalt binder is often modeled as a colloidal material with two phases, asphaltene and maltene. The ratio of maltenes to asphaltenes is reduced due to oxidative aging, which results in stiffer asphalt pavements that are susceptible to cracking (Kaseer et al. 2019a). Rejuvenators contain maltenes to restore the original ratio of maltenes to asphaltenes which improves the flexibility and resistance of asphalt mixtures to cracking.

Recently, the pavement community and industry are moving towards a Balanced Mix Design (BMD) approach to complement current Superpave method for asphalt mixture design with improved performance (Meroni et al. 2020 and Lombardo et al. 2020). The current Superpave mix design is primarily based on volumetrics. As the pavement community gravitates towards incorporating more recycled materials, the Superpave process fails to consider the interactions between virgin materials and recycling agents (NCAT 2019). The goal of BMD is to design a mix that meets the specifications according to the purpose the pavement will serve. BMD includes specific tests to evaluate pavement performance against specific distresses, most commonly resistance to rutting and cracking. The goal of BMD is to define testing criteria that are simple, affordable, and accurate enough to ensure acceptable performance (Taylor and West 2019). BMD should accurately simulate realistic climate and aging conditions, loading expectations, temperature variation, and other factors.

Rejuvenators

The American Standards for Testing and Materials (ASTM) developed a standard (ASTM D4552) that classifies recycling agents into six groups based on their viscosity at 60^{o}C as shown in Table 1Table 1. In 2014, the National Center for Asphalt Technology (NCAT) divided the rejuvenators into five categories: 1) paraffinic oil (refined used lubricating oil), 2) aromatic extract (refined crude oil products with polar aromatic oil components), 3) naphthenic oils (engineered hydrocarbons for asphalt modification), 4) triglycerides and fatty acids (derived from vegetable oils), and 5) tall oils (byproducts from the paper industry) as shown in Table 2 (NCAT 2014).

Table 1. Physical Properties of Recycling Agents (ASTM D4552)

		RA1	RA1	RA5	RA5	RA25	RA25	RA75	RA75	RA250	RA250	RA500	RA500
Test	ASTM Test Method	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Viscosity at 140ºF, cSt	D 2170 or D2171	50	175	176	900	901	4500	4501	12500	12501	37500	37501	60000
Flash point, COC, °F	D92	425	---	425	---	425	---	425	---	425	---	425	---
Saturates, wt%	D2007	---	30	---	30	---	30	---	30	---	30	---	30
Tests on residue from RTFO or TFO oven 325 °F	D 2872 or D 1754												
Viscosity Ratio	-	---	3	---	3	---	3	---	3	---	3	---	3
Wt. change ± %	-	---	4	---	4	---	4	---	4	---	4	---	4
Specific gravity	D70 or D 1298	Report		Report		Report		Report		Report		Report	

Table 2: Recycling Agent Types (NCAT 2014)

Category	Examples	Description
Paraffinic Oils	• Waste Engine Oil (WEO) • Waste Engine Oil Bottoms (WEOB) • Valero VP 165® • Storbit®	Refined used lubricating oils
Aromatic Extracts	• Hydrolene® • Reclamite® • Cyclogen L® • ValAro 130A®	Refined crude oil products with polar aromatic oil components
Nathenic Oils	• SonneWarmix RJ™ • Erogon Hyprene®	Engineered hydrocarbons for asphalt modification
Triglycerides & Fatty Acids	• Waste Vegetable Oil • Waste Vegetable Grease • Brown Grease • Delta S*	Derived from vegetable oils *Has other key chemical elements in addition to triglycerides and fatty acids.
Tall Oils	• Sylvaroad™ RP1000 • Hydrogreen®	Paper Industry byproducts Some chemical family as liquid antistrip agents and emulsifiers

Cracking Performance of Asphalt Mixtures with RAP and Rejuvenators

Many research studies examined the effect of recycling agents and rejuvenators on the performance of RAP mixtures. Zaumanis et al. (2013, 2015) evaluated the effect of different rejuvenators in restoring the performance of 100 percent RAP mixtures. They examined included plant oils, waste-derived oils, engineered products, and traditional and nontraditional refinery base oil. They evaluated the low temperature cracking performance of the test mixtures using the creep compliance and tensile strength tests as shown in Figure 1 and Figure 2. The results demonstrated that all mixtures showed improvements in their low temperature cracking performance when compared to the control RAP mixture. The waste vegetable oil improved the creep compliance of the RAP mixture to that of the virgin mix (i.e., 0 percent RAP). The results of tensile strength, conducted at -10℃, showed that certain rejuvenators such as aromatic extract increased the strength when compared to the control RAP mixture (i.e., without rejuvenator) while others including waste engine oil reduced the tensile strength.

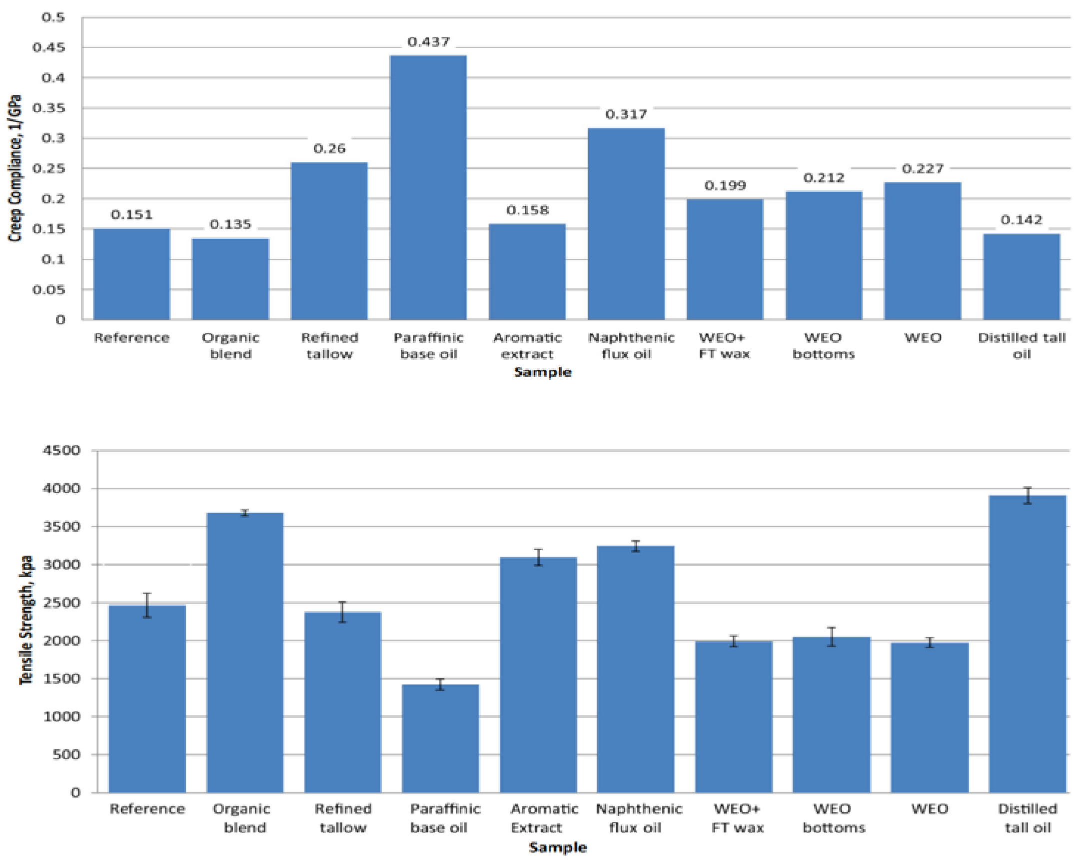


Figure 1. Effect of Rejuvenators on Creep Compliance and Tensile Strength at -10℃ (Zaumanis et al. 2013)

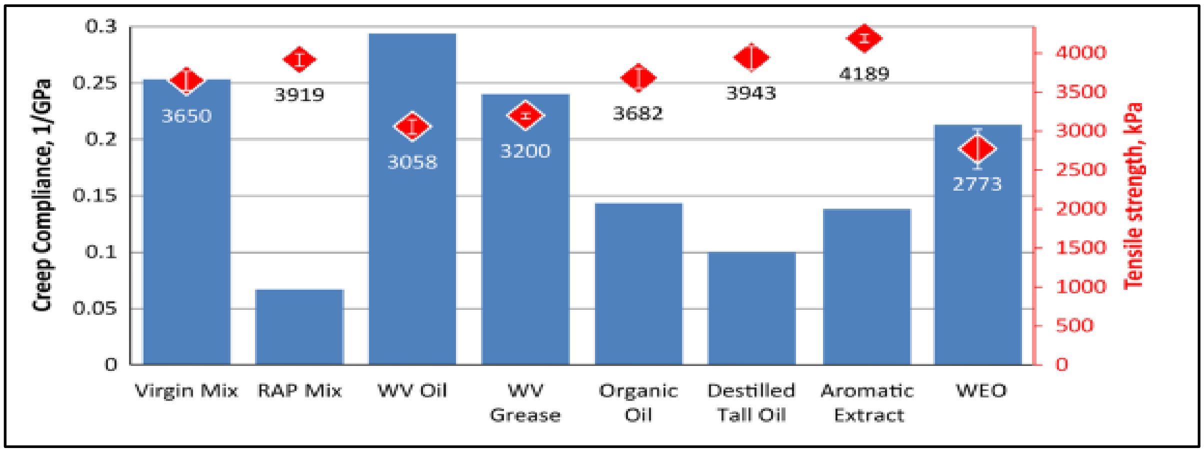


Figure 2. Creep Compliance and Tensile Strength at -10 °C (Zaumanis et al. 2015)

Nabizadeh et al. (2017) studied the effect of various rejuvenators on asphalt mixtures and Fine Aggregate Matrix (FAM) with 65 percent RAP. The study evaluated three unique rejuvenators including petroleum-tech based, green-tech based, and agriculture-tech based rejuvenators. They compared the performance of asphalt mixtures and FAM prepared with the selected rejuvenators to that of the control mix. The control mix contained 65 percent RAP and 35 percent virgin aggregates. All mixes had nominal maximum aggregate size of 12.5 mm and used PG 64-34 binder. The FAM mixtures used the same gradation as the original asphalt mixtures without aggregates larger than 1.18 mm. The results presented in Figure 3 and Table 3 showed that the petroleum-tech based rejuvenator or aromatic extract (CR1) had the highest cracking resistance followed by agriculture-tech based rejuvenator or soybean oil (CR3), green-tech based rejuvenator or tall oil (CR2). All mixtures exhibited better cracking resistance as compared to the control mix (C).

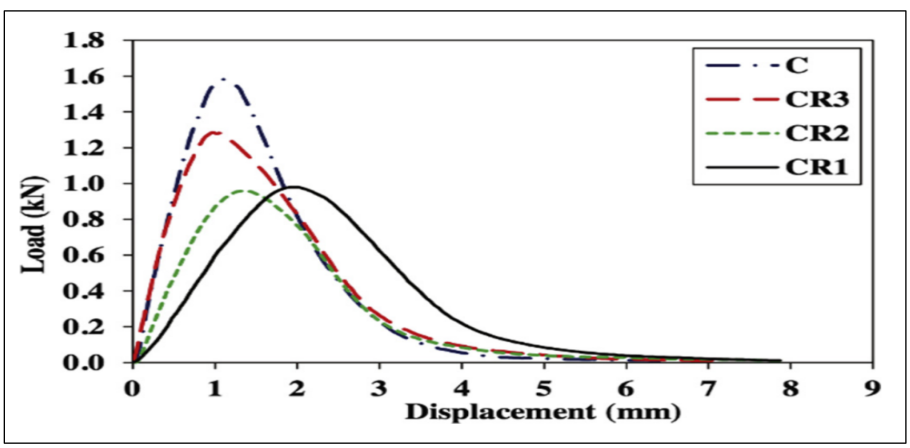


Figure 3. Effect of Different Recycling Agents on IDT Load-Displacement Curve (Nabizadeh et al. 2017)

Table 3. Semi-Circular Bending Fracture Test Results (Nabizadeh et al. 2017)

Mixture ID	Upward Slope	Downward Slope at Inflection Point	Fracture Energy (J/m²)	Flexibility Index (FI)
C	1.472	-1.11	942	8.5
CR1	0.593	-0.50	919	18.4
CR2	0.735	-0.63	685	10.9
CR3	1.276	-0.67	878	13.1

Kaseer et al. (2020) evaluated the performance of asphalt mixtures with high RAP content and rejuvenators. They evaluated the performance of both field cores and laboratory mixes. The field mixtures were extracted from five different states in the United States to cover different climate and mixture properties. In addition, laboratory mixes were prepared using raw materials collected from the source of each field project. Each field project had two sections, one designed with the maximum allowed percentage of RAP without recycling agent per the DOT specifications of that state, and the other designed similarly with the addition of rejuvenator. In the case of Texas field and laboratory mixtures, they used a replacement binder ratio of 28 percent and two different recycling agents: tall oil at two different doses and one dose of aromatic extract. The results of this study indicated that for both Short-Term Oven Aged (STOA) and Long-Term Oven Aged (LTOA) the rejuvenated lab mixtures showed a better cracking performance as shown in in Figure 4 (Kaseer et al. 2020). However, the rejuvenated field cores exhibited a lower cracking resistance compared to the cores without recycling agents.

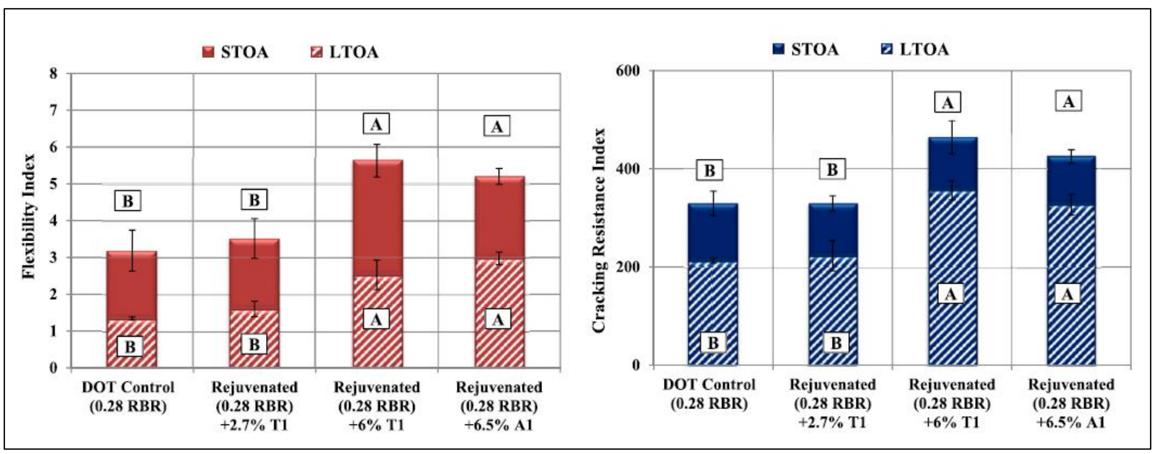


Figure 4. Effect of Rejuvenators on Flexibility Index and Cracking Resistance Index (Kaseer et al. 2020)

An ongoing research study by the National Road Research Alliance (NRRA) is currently evaluating the effect of rejuvenators on performance of asphalt mixtures. They examined the effect of seven different rejuvenators including petroleum-based and bio-based rejuvenators. They prepared and tested a total of ten mixtures. Nine mixtures had 40 percent RAP, and one mixture had 30 percent RAP. These mixtures were prepared with different rejuvenators. They compared the performance of Reheated Plant Mixtures (RPM) to Long-Term Aging (LTA) mixtures. The preliminary results (Figure 5) showed that the IDEAL-CT_{Index} decreased with the increase of aging. Therefore, the cracking resistance is expected to decrease with aging. Both RPM and LTA mixtures with bio-based rejuvenators (e.g., Soybean, Ingevity and Kraton) were able to provide better cracking resistance compared to the control mix (i.e., 40 percent RAP). In addition, it was found that certain rejuvenators had a negative impact on LTA mixtures as the cracking performance decreased compared to the control mixture after aging. They indicated that such mixtures were more susceptible to aging.

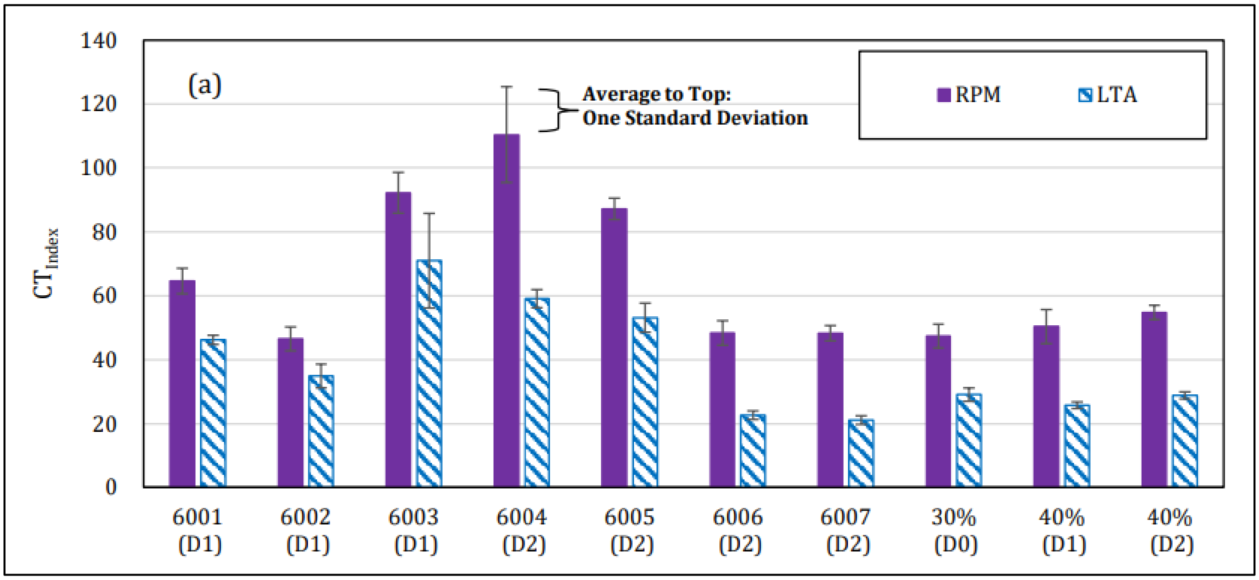


Figure 5. Effect of Rejuvenator and Aging on Cracking Performance (NRRA 2022)

Zaumanis et al. (2014) evaluated the rutting performance of rejuvenated asphalt mixtures using the HWTT. They examined six unique rejuvenators and compared the rutting performance of the virgin mixture and RAP mixture to that of the rejuvenated mixtures. The virgin mixture was prepared by burning the binder off RAP aggregates and then mixing the aggregates with a virgin binder. The results presented in Figure 6 demonstrated that the virgin mixture had the lowest rutting resistance. This could be attributed to higher binder content (5.94 percent), loss of fine materials during burning process, or moisture damage. Conversely, the RAP mixture had the highest rutting resistance due to the presence of the aged RAP binder. The results also showed that the use of rejuvenators helped to soften the materials which may resulted in increased rut depth; however, all mixtures with rejuvenators performed better that the virgin mixture and mixtures with aromatic extract, waste engine oil (WEO), and organic oil passed the rutting threshold (12.5 mm after 20,000 passes) (Zaumanis et al. 2014).

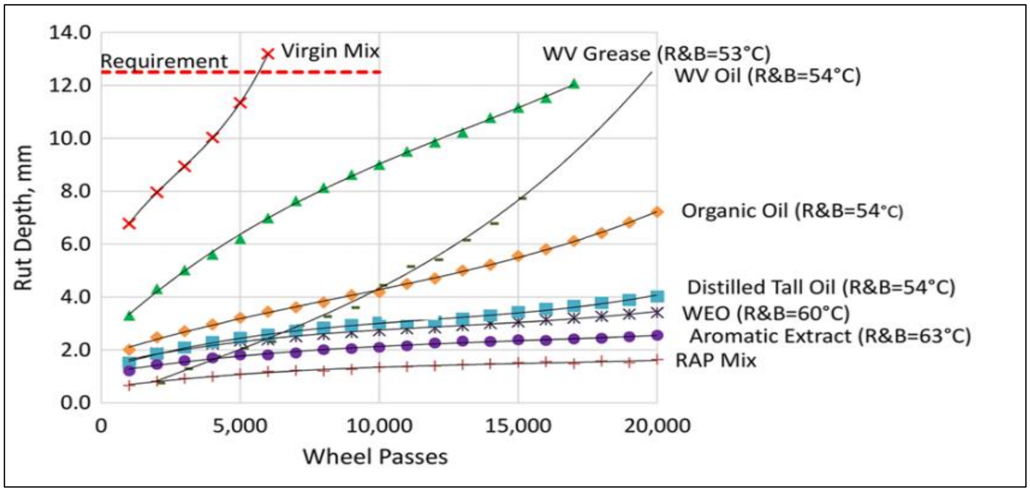


Figure 6. Effect of Rejuvenators on Rutting Performance (Zaumanis et al. 2014)

Bajaj et al. (2020) evaluated the rutting performance of asphalt mixtures prepared with six unique rejuvenators. The mixtures also included a control mix without RAP and one RAP mixture without rejuvenator. Figure 7 shows the rut depth with loading cycles. The results demonstrated that the RAP mixture without rejuvenators had the lowest rut depth which indicates better rutting resistance. All mixtures with rejuvenators passed the rutting criteria of 12.5 mm after 7500 loading cycles except the rejuvenated mixture with paraffinic recycling agent P (Bajaj et al. 2020).

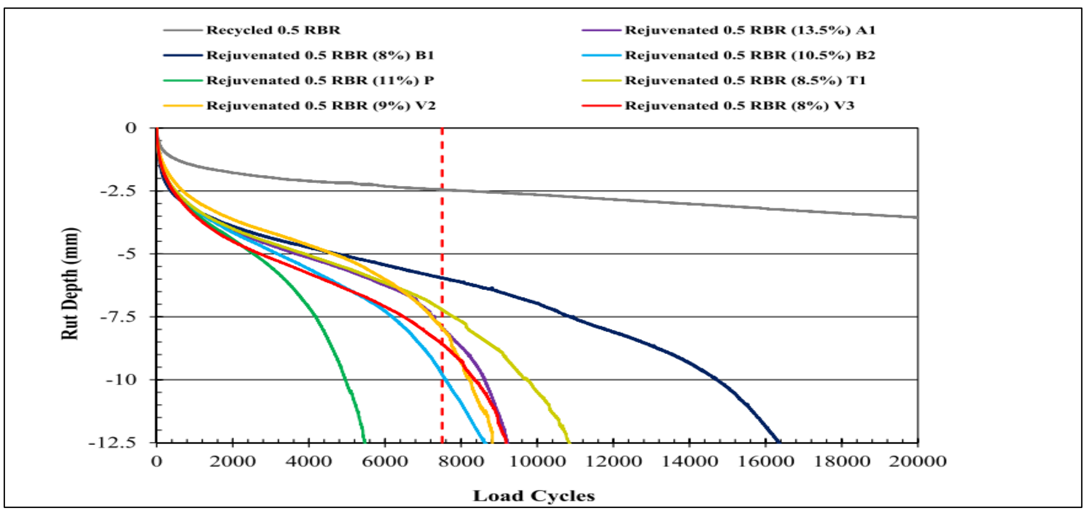


Figure 7. Effect of Rejuvenated RAP Mixture on Rutting Performance (Bajaj et al. 2020)

Kaseer et al. (2020) also evaluated the rutting performance of asphalt mixtures with rejuvenators. Asphalt mixtures were prepared in the laboratory using materials from two different states: Wisconsin and Delaware. They evaluated the rutting performance of mixtures containing two percentages of RAP (i.e., 31 and 50 percent) and modified vegetable oil rejuvenator at 5.5 and 9 percent. Figure 8 shows the number of passes for the mixtures to reach a rut depth of 12.5 mm. The results demonstrated that the addition of recycling agents increased the rutting of the mixture; however, all mixtures passed the rutting threshold (minimum of 5000 passes for binder Performance Grade PG 58-XX before reaching 12.5 mm). Also, they found that the test mixtures were susceptible to moisture damage. On the other hand, the APA test (conducted in dry conditions) showed that the rutting resistance improved compared to HWTT results with the use of rejuvenators.

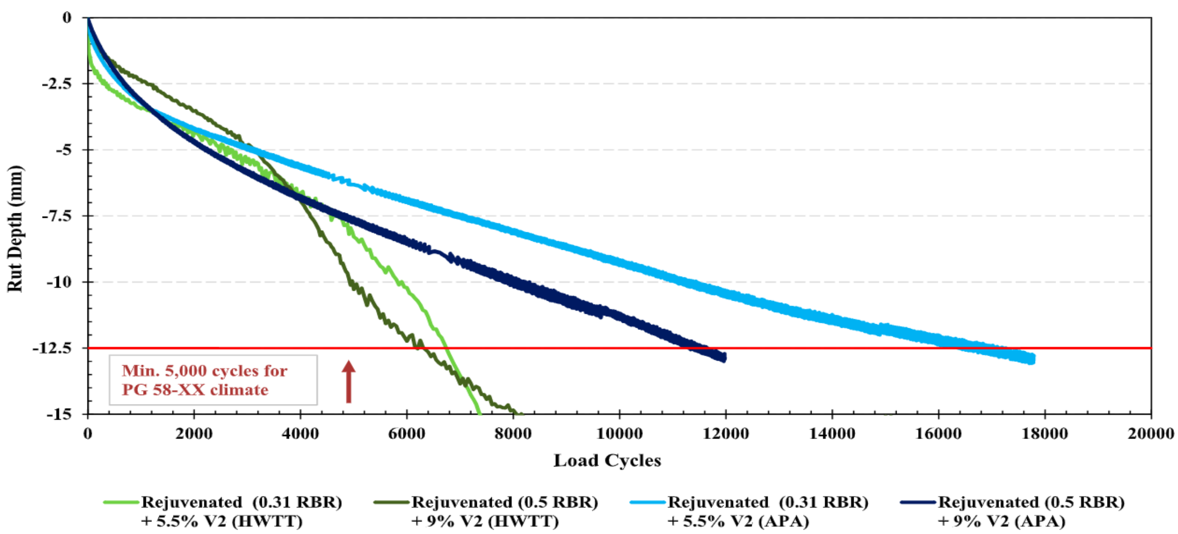


Figure 8. HWTT and APA Rutting Performance of Rejuvenated Mixtures (Kaseer et al. 2020)

Effect of Rejuvenators on Binder Performance Grade (PG)

Zaumanis et al. (2014) studied the effect of incorporating rejuvenators into asphalt mixtures on the binder performance grade (PG) of the rejuvenated asphalt binders in the mix. They extracted and recovered asphalt binders from rejuvenated asphalt mixtures and determined their PG. The results shown in Figure 9 indicated that all rejuvenated mixtures had improved low-temperature PG (PGL) compared to the RAP binder (-12 °C). The target PG was reached in all rejuvenated mixtures except mixtures with WEO rejuvenator which required a higher dose to reach the targeted PGL. None of the examined rejuvenators decreased the high-temperature PG (PGH) as compared to that of the virgin binder (Zaumanis et al. 2014).

Ali et al. (2016) investigated the impact of rejuvenator on RAP mixtures. They used five unique rejuvenators in asphalt mixtures containing 25 and 45 percent RAP at the manufacturer's recommended doses. They examined the effect of the rejuvenators on the extracted and recovered binder PG. The results demonstrated that all rejuvenators lowered the PGH. In addition, the paraffinic oil was the most effective rejuvenator in lowering the binder PG to that of the virgin binder. Other studies (Samara et al. 2022 and NRRA 2022) evaluated the effect of rejuvenators on the binder PG. They evaluated asphalt mixtures with four unique rejuvenators including crude tall oil, modified vegetable oil, corn oil and aromatic extract oil. The results on the extracted and recovered binder showed that all rejuvenators lowered the PGH by at least one grade. Furthermore, all rejuvenators lowered the PGL. They also concluded that increasing the rejuvenator dose resulted in lower PGH.

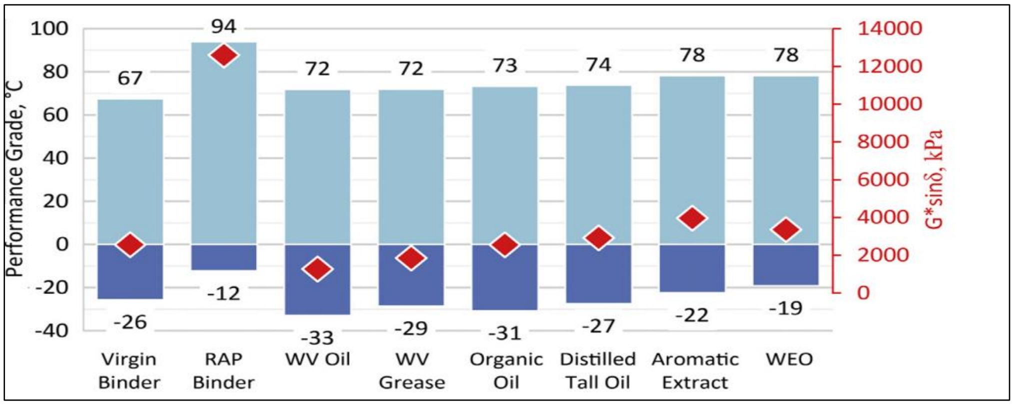


Figure 9. Effect of Rejuvenators on Performance Grade (Zaumanis et al. 2014)

Effect of Rejuvenators on Asphalt Mixture Workability

Limited studies were conducted on the effect of rejuvenators on the workability of asphalt mixtures. Zaumanis et al. (2014) evaluated the workability of rejuvenated mixtures using different rejuvenators. They recorded the number of gyrations to reach 8 percent air voids. The results demonstrated that the virgin mixture had the highest workability while the RAP mixture had the lowest workability. The workability of all mixtures with rejuvenators was enhanced by the addition of rejuvenators as shown in Figure 10.

Another study evaluated the effect of rejuvenators on workability through characterizing binder properties. Majidifard et al. (2019) investigated the effect of rejuvenators on the workability of asphalt mixtures by measuring binder stiffness. They examined the workability of the binder extracted and recovered from rejuvenated mixtures with waste cooking oil. The study concluded that the waste cooking oil was able to reduce the stiffness of the RAP binder and thus improve the mixture workability.

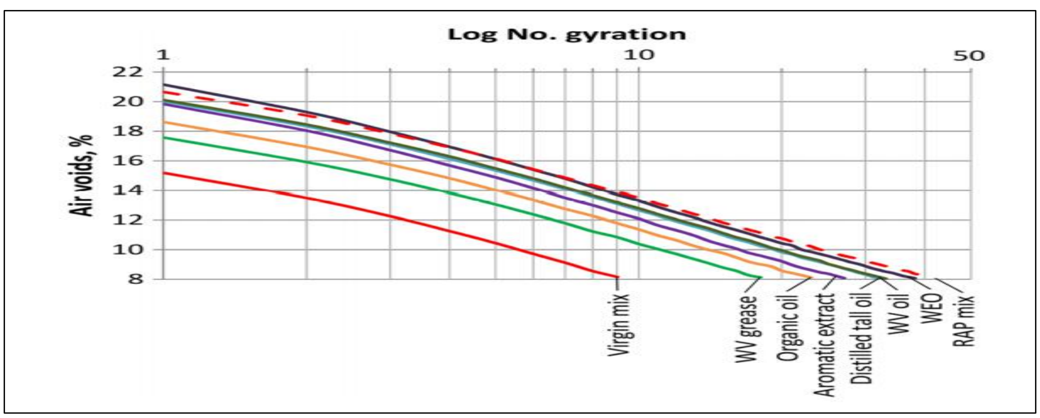


Figure 10. Effect of Rejuvenators on Workability of RAP Mixtures (Zaumanis et al. 2014)

Rejuvenator Dose Selection

Several studies have been conducted to establish a method to select a proper dose of rejuvenators. Arámbula-Mercado et al. (2017) evaluated the selection of proper recycling agent dose and incorporation method into asphalt mixtures with high RAP and Recycled Asphalt Shingles (RAS). In their study, they evaluated three methods for dose selection and their effect on the performance of asphalt mixtures with high RAP/RAS content. The three methods included 1) restoring PGL and verifying PGH, 2) achieving a temperature difference in Bending Beam Rheometer (BBR), ΔT_c of -5 °C, and 3) restoring the PGH. For the first method, they used a PG 70-22 binder and determined an optimum dose of 4.5 percent of weight of total binder, which was found to meet the PGL and then verified the PGH as shown in Figure 11 (Arámbula-Mercado et al. 2017). The second method was to achieve a maximum ΔT_C of -5 °C after 20 hours of PAV aging. They found that a dose of 12.5 percent was enough to reach the target ΔT_C for PG 58-32 and 14.5 percent for PG 68-32. The third selection method suggested that an optimum rejuvenator dose of 6 percent to reach continuous the PGH (i.e., 70 °C).

The results of the three selection methods demonstrated that the first method improved the stiffness and phase angle, but such improvement decreased with long-term aging. The second method showed that the stiffness and phase angle were improved as well; however, the stiffness reduction was excessive and had a negative effect on the mixture rutting performance. The third method provided better results over the other two methods. The researchers demonstrated that the rejuvenator dose should be carefully selected as the rutting resistance could be reduced while the cracking resistance improved. The dose selection is affected by many factors such as binder source and grade, aging level of recycled materials, and their proportions in the mix.

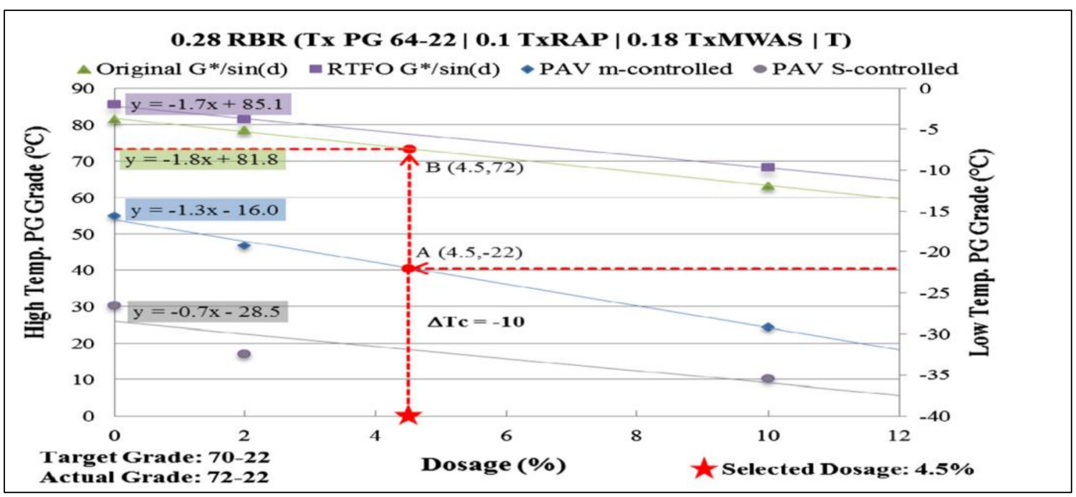


Figure 11. Performance Grade blending Chart (Arámbula-Mercado et al. 2017)

Zaumanis et al. (2014) also proposed a procedure to determine the optimum rejuvenator dose based on Superpave PG specifications. They used extracted RAP binder with PG 94-12 which had penetration of 1.9 mm. Their target PG for the region was PG 64-22. Six rejuvenators were evaluated in their study. Two rejuvenators were petroleum products and the other four were organic products. The petroleum products were aromatic extract and waste engine oil. The organic products included waste vegetable oil, organic oil, waste vegetable grease, and distilled tall oil. They evaluated two doses for organic products (i.e., 6 percent and 12 percent) and two doses for petroleum products (i.e., 12 percent and 18 percent). They conducted several binder tests including penetration test at 25°C, Dynamic Shear Rheometer (DSR), and Bending Beam Rheometer (BBR) on extracted and recovered asphalt binders. The results demonstrated that both PGH and PGL reduced linearly, while the penetration increased exponentially with the increase of the rejuvenation dose as shown in Figures 12 and 13. Overall, organic-based products required a lower dose than petroleum-based products.

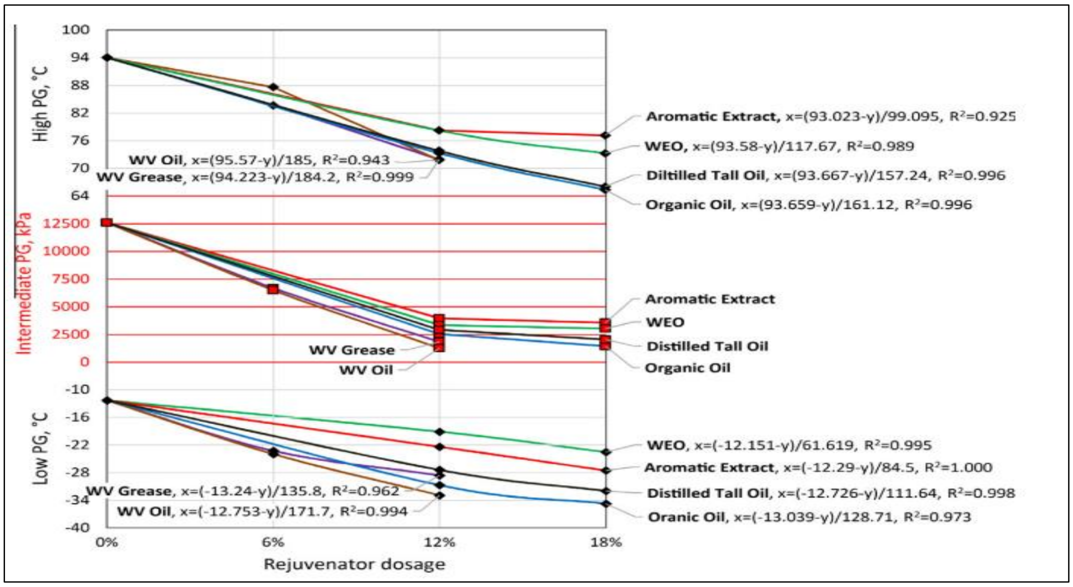


Figure 12. High, Low, and intermediate PG for Rejuvenated Extracted Binder (Zaumanis et al. 2014)

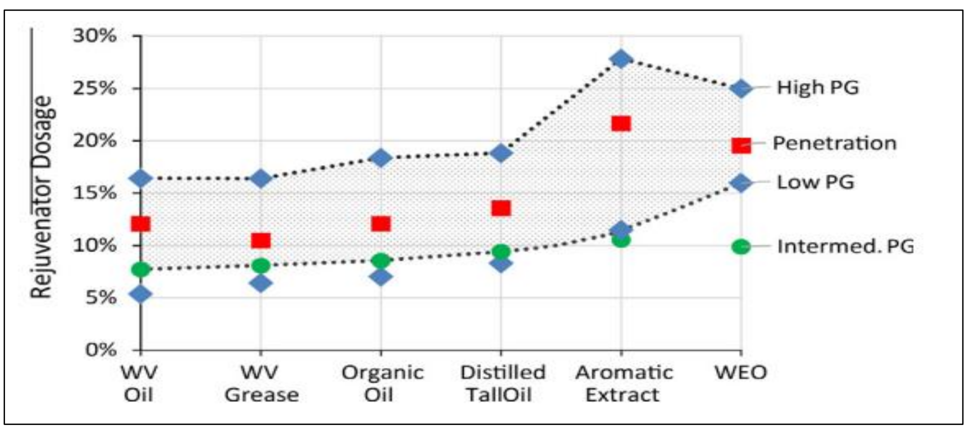


Figure 13. Minimum Rejuvenator Dose (Zaumanis et al. 2014)

Sánchez et al. (2020) examined three methods to select the optimum dose of a palm oil rejuvenator. They conducted several tests including penetration, softening point, and PGH. The PGH resulted in the lowest dose, while the softening point required the highest dose. The optimum dose was 3, 4.5 and 5.5 percent based on the PGH, penetration, and softening point, respectively (Sánchez et al. 2020).

Other researchers evaluated the optimum rejuvenator dose through the balanced mix design approach. S. Im et al. (2016) examined dose selection for three recycling agents including 1) Hydrogreen, 2) Road Science, and 3) Arizona Chemical. They determined the rejuvenator dose range per binder weight, then determined the optimum asphalt content and optimized the content for each rejuvenator used in their study. First, they determined a range of rejuvenator content based on the binder PG and Glover-Rowe (G-R) parameter. Based on the binder test results, they established the rejuvenator dose range and validation table for the three recycling agents as well as the manufacturer recommended dose as presented in Table 4. The dose range based on the binder PG varied from about 0.7 to 4.8 percent for high and low temperatures, respectively as shown in Figure 14. They also found that the rejuvenator content determined by the G-R parameter had a lower range (i.e., 0.7 to 2.6 percent). Based on the validation table (Table 4), they determined optimum dose ranges of 1.7 to 4.8 percent, 2.6 to 3.6 percent, and 1.8 to 3.7 percent per weight of binder for Hydrogreen, Road Science, and Arizona Chemical, respectively. To confirm the optimum dose for each rejuvenator, the study conducted a balanced mix design approach by examining the rutting and cracking of asphalt mixtures within the dose range. The optimum dose of each rejuvenator was determined based on a maximum rut depth of 9.5 mm. The results demonstrated that optimum dose was 3.2, 2.2, and 3.0 percent for Hydrogreen, Road Science, and Arizona Chemical, respectively. The Hydrogreen rejuvenator required a higher dose compared to the other two rejuvenators (i.e., Road Science and Arizona Chemical).

Table 4. Rejuvenator Content Range and Dose Validation (S. Im et al. 2016)

-	**Based on PG**	**Based on PG**	**Based on aging**	**Based on aging**	**Selected Range**	**Selected Range**	**Dose recommended by manufacturer**
Rejuvenator	High temp. max	Low temp. Min	Damage onset Min	Significant Cracking Min	Min	Max	-
Hydrogreen	4.8%	1.7%	1.0%	1.7%	1.7%	4.8%	2.9%
Road Science	3.6%	0.7%	0.8%	2.6%	2.6%	3.6%	2.0%
Arizona Chemical	3.7%	1.1%	0.7%	1.8%	1.8%	3.7%	2.3%

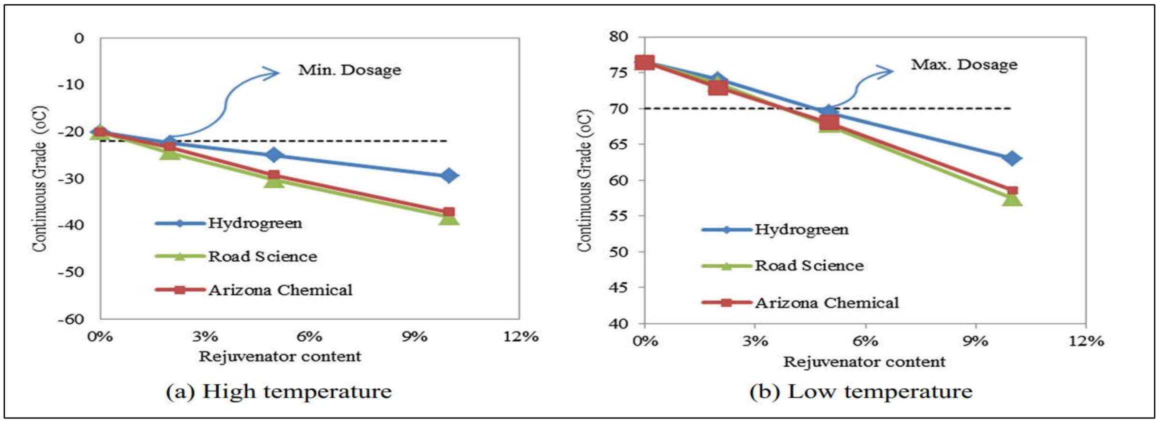


Figure 14. High and Low Temperature Performance Grade for Rejuvenated Mixtures (S. Im et al. 2016)

Economic Benefits of Rejuvenators in RAP Mixtures

Many studies evaluated the economic benefits of incorporating rejuvenators along with high RAP content in asphalt mixtures. Martin et al. (2019) studied the likelihood of cost savings of using rejuvenators when RAP content increased from 20 to 40 percent. They considered two scenarios including low economic incentive and high economic incentive. The low economic scenario assumed that the recycling agent and RAP are relatively high in price and the amount of binder available in the RAP is low, while the high economic incentive assumed that the amount of binder available in the RAP is high and the price of recycling agent and RAP are relatively low. They found that increasing the RAP content from 20 to 40 percent resulted in 4.9 percent savings in the production cost for the low economic incentive and 17 percent savings for the high economic incentive assumption. In addition, they found that the cost saving associated with 40 percent RAP is about 12 and 35 percent for the low and high economic incentive, respectively.

S. Im et al. (2014) conducted cost analysis on the benefits of using rejuvenators with asphalt mixtures containing RAP content of 19 percent. They calculated the cost (per ton) of virgin mix (i.e., 0 percent RAP), RAP mixture containing 19 percent of RAP, and rejuvenated RAP mixture containing 19 percent RAP. The outcome of their study demonstrated that a ton of virgin mix cost $47.2 while a ton of a similar mix containing 19 percent RAP cost $38.9 which resulted in cost reduction of 21 percent. However, the rejuvenated RAP mixture roughly increased the cost of the RAP mix by $0.3 per ton which resulted in cost reduction of 20 percent compared to the virgin mix. Zaumanis et al. (2014) evaluated the cost of asphalt mixtures prepared with and without RAP. The study indicated that the location of where the mixture was made derived the cost as some locations may or may not have RAP materials accessible where other locations may have extra RAP materials. Their study assumed that only the material cost will be impacted by rejuvenators and other costs would remain constant. The cost saving associated with using 100 percent RAP and rejuvenators resulted in cost reduction of about 50 to 70 percent as shown in Figure 15.

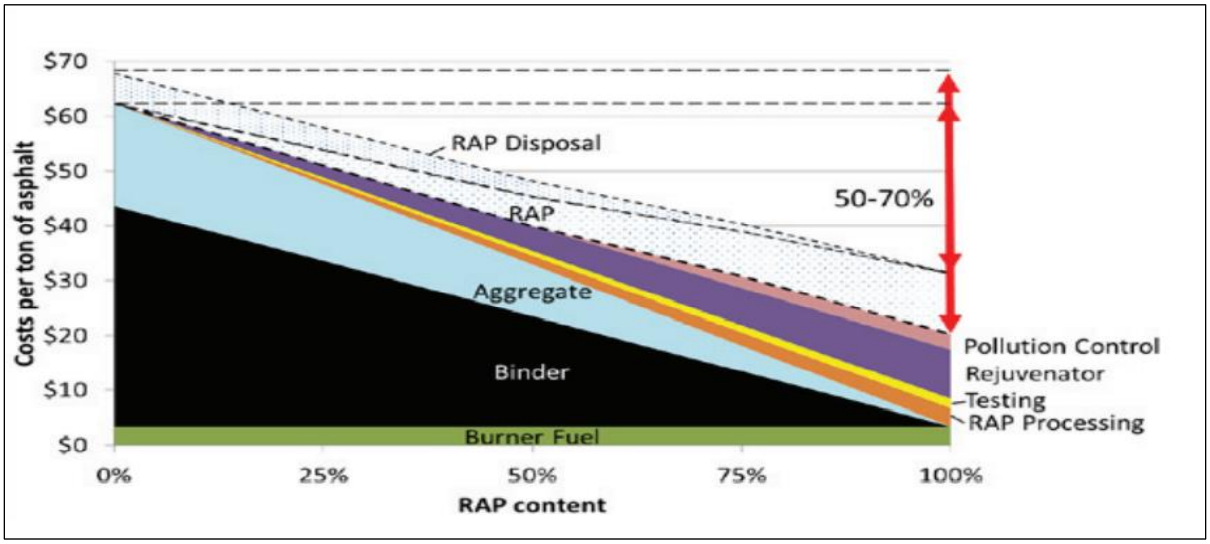


Figure 15. Cost Saving Potential Associated with Incorporating RAP and Rejuvenator Zaumanis et al. 2014)

Incorporating RAP in Asphalt Mixtures

Transportation agencies incorporate RAP into asphalt mixtures for its environmental and economic benefits. A survey conducted by the National Asphalt Pavement Association (NAPA) demonstrated the favorable impact of RAP on decreasing the cost of pavement construction and greenhouse gas emissions (NAPA 2021). Figure 16 shows the amount of RAP and the average percentage of RAP used by different transportation agencies from 2009 to 2021. The average percent of RAP increased from 21.1 percent in 2019 to about 21.9 percent in 2021 for all industry sectors. Figure 17 shows the average percentage of RAP used in various states. The number of states using 20 percent RAP or grater increased to 32 states in 2021 compared to only 10 states in 2009. Idaho is among the leading states by allowing higher RAP content (up to 30 percent). Table 5 shows the amount of RAP mixes that incorporate softer binders and/or recycling agents in each state. Most states (28 out of 32) using 20 percent RAP or more reported using rejuvenator and/or softer binders in their asphalt mixtures. The rest of states (four) don’t use any rejuvenators and/or softer binders in the asphalt mixtures with 20 percent or more RAP (NAPA 2021).

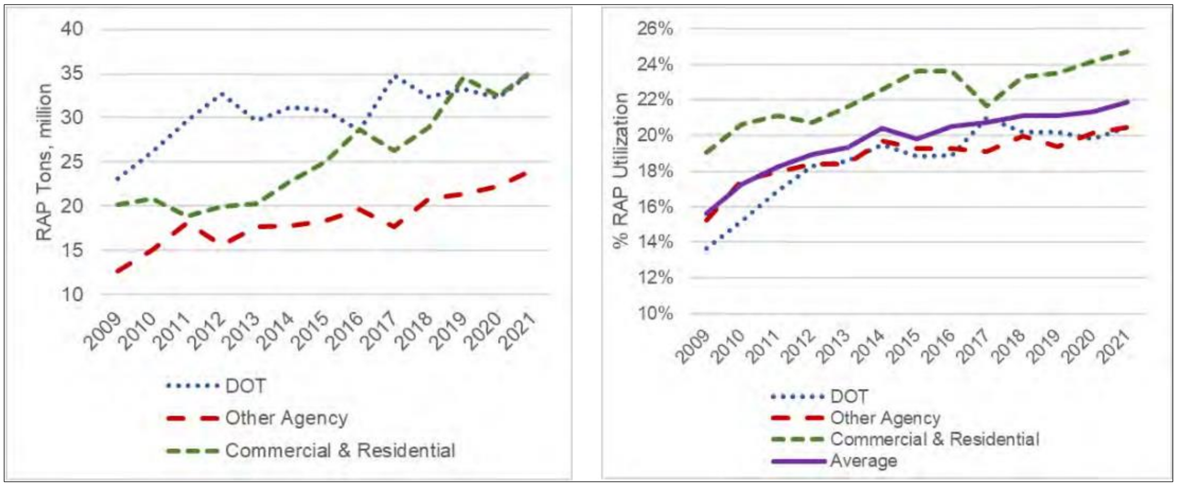


Figure 16. RAP Use by Sector (Million Tons) and Average Percent RAP Used by Sector (NAPA 2021)

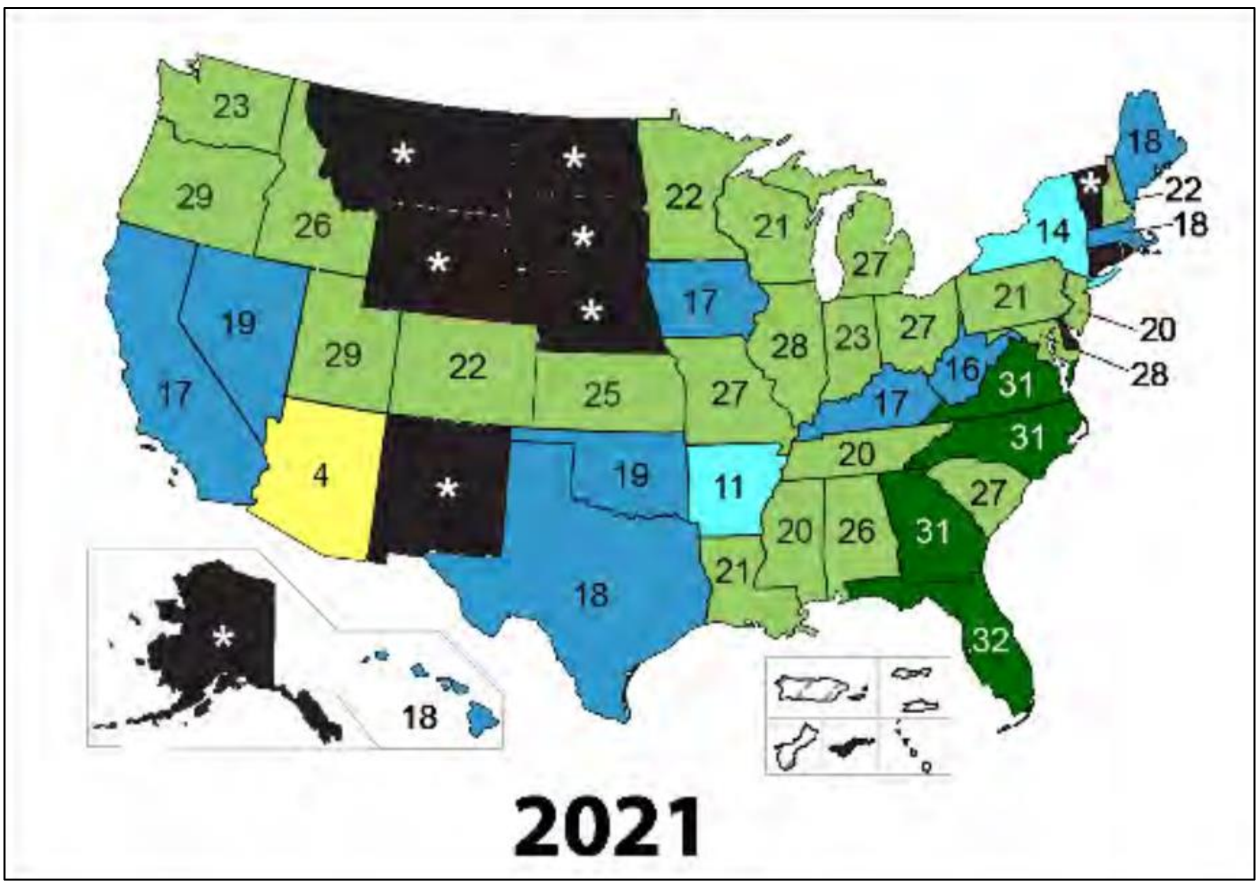


Figure 17. Average Estimated RAP Content in Asphalt Mixes by State (NAPA 2021)

Table 5. Percent of RAP Mixes Using Softer Binder and/or Recycling Agents by State (NAPA 2021)

State	Reported Tons Stockpiled (Million) in 2020	Reported Tons Stockpiled (Million) in 2021	Estimated Tons Stockpiled (Million) in 2020	Estimated Tons Stockpiled (Million) in 2021
Alabama	0.76	1.26	2.13	1.62
Alaska	*	*	*	*
American Samoa	NCR	NCR	NCR	NCR
Arizona	0.58	1.02	1.02	2.13
Arkansas	0.45	0.32	0.93	0.7
California	2.08	0.99	4.33	2.92
Colorado	0.86	0.31	1.57	0.77
Connecticut	*	*	*	*
Delaware	*	*	*	*
District of Columbia	*	*	*	*
Florida	3.62	2.04	5.43	5.21
Georgia	3.31	2.25	6.07	5.03
Guam	NCR	NCR	NCR	NCR
Hawaii	*	0.13	*	0.24
Idaho	0.65	0.59	1.56	1.39
Illinois	2	1.16	3.43	2.39
Indiana	2.35	3.71	4.07	5.05
Iowa	0.53	0.65	1.45	1.83
Kansas	0.79	0.8	1.15	1.31
Kentucky	0.58	0.96	1.36	1.98
Louisiana	0.05	0.21	0.35	1.02
Maine	0.37	0.29	0.37	0.29
Maryland	2.65	2.27	3.63	4.49
Massachusetts	0.69	0.92	1.56	3.67
Michigan	14.98	2.28	22.17	3.77
Minnesota	3.96	1.88	6.62	2
Mississippi	0.61	0.46	0.63	0.74
Missouri	0.42	0.46	1.76	1.47
Montana	*	*	*	*
Nebraska	0.12	*	0.9	*
Nevada	0.12	0.29	0.34	0.65
New Hampshire	0.32	0.29	0.46	0.3
New Jersey	2.3	9.59	4.69	26.89
New Mexico	*	*	*	*
New York	0.89	0.65	2.79	2.65
North Carolina	5.6	4.39	6.78	6.35
North Dakota	*	*	*	*
No. Mariana Isl.	NCR	NCR	NCR	NCR
Ohio	3.81	3.09	5.81	3.46
Oklahoma	1.2	1.21	1.61	1.21
Oregon	0.94	0.69	2.34	2.05
Pennsylvania	0.85	0.88	2.57	3.09
Puerto Rico	NCR	NCR	NCR	NCR
Rhode Island	*	*	*	*
South Carolina	1.42	1.68	3.11	1.68
South Dakota	*	*	*	*
Tennessee	1.85	1.67	4.32	2.59

Table 5. Percent of RAP Mixes Using Softer Binder and/or Recycling Agents by State (NAPA 2021) (Continued)

State	Reported Tons Stockpiled (Million) in 2020	Reported Tons Stockpiled (Million) in 2021	Estimated Tons Stockpiled (Million) in 2020	Estimated Tons Stockpiled (Million) in 2021
Texas	0.99	2.14	6.69	11
U.S. Virgin Islands	NCR	NCR	NCR	NCR
Utah	0.46	1.08	0.52	1.45
Vermont	*	*	*	*
Virginia	2.56	2.37	3.68	4.15
Washington	1.15	0.73	1.22	0.98
West Virginia	0.34	0.36	4.33	0.65
Wisconsin	2.14	2.7	2.67	4
Wyoming	*	*	*	*
Total	71.48	59.82	135.3	137.45

NCR No Companies Responding for the State Survey
* Fewer than 3 Companies Reporting
Total Includes Values from State with Fewer than 3 Companies

Several researchers examined the amount of RAP that can be used in asphalt mixes without detrimental effects on performance (McDaniel et al. 2012; Beeson et al. 2011; Sondag et al. 2002). McDaniel et al. (2012) demonstrated that asphalt mixtures with up to 50 percent RAP can meet the Superpave design criteria. They reported that asphalt mixtures with more than 20 percent RAP increased the stiffness which could impact the cracking resistance at low temperature (McDaniel et al. 2012). Beeson et al. (2011) demonstrated that 22 percent of RAP can be used without changing the PGL of the tested binder. In addition, the virgin binder PG should be reduced by one grade for up to 40 percent RAP. On the other hand, Mogawer et al. (2020) demonstrated that using more than 15 percent RAP impacts the PGL significantly. Sondag et al. (2002) also documented that Iowa DOT requires the virgin binder PG to be reduced by one grade for RAP exceeding 20 percent. ITD limits the maximum RAP content to 30 percent. For mixtures with less than 17 percent RAP, no binder PG adjustment is required; however, either the blending chart is required or lowering the high and low designated temperatures by one grade for mixtures with more than 17 percent RAP. Tables 6 and 7 summarize the ITD specifications for the binder grade adjustment and typical adjusted binder grades (ITD 2018). ITD RP 280 provides additional information about incorporating RAP into asphalt mixtures including characterization of RAP, mix design considerations of RAP mixtures, amount of RAP in asphalt mixtures, laboratory, and field evaluation of mixes with high RAP contents, and state of practice at different DOTs (Kassem et al. 2021).

Table 6. Grade Adjustment for RAP (ITD Specification 2018)

Level	RAP binder content by weight of the total binder in the mixture, percent	Binder Grade Adjustment to compensate for the stiffness of the asphalt binder in the RAP
1	0 to 17	No binder grade adjustment is made.
2	> 17 to 30	The selected binder grade adjustment for the binder grade specified on the plans is one grade lower for the high and the low temperatures designated. Or determine the asphalt binder grade adjustment using a blending chart. Note: See AASHTO M 323 for recommended blending chart procedure.

Table 7. Typical Adjusted Binder Grades (ITD Specification 2018)

Binder Grade Specified in Contract	Adjusted Binder Grade (Level2)	Adjusted Binder Grade (Level1)
58-28	58-34	No Adjustment Needed
58-34	No Adjustment Needed	No Adjustment Needed
64-28	58-34	No Adjustment Needed
64-34	58-34	No Adjustment Needed
70-28	64-34	No Adjustment Needed
76-28	70-34	No Adjustment Needed

Balanced Mix Design Approach

Zhou et al. (2006) proposed a method to improve the mix design of asphalt mixtures that relies on balancing the cracking and rutting performance, which is known as a balanced or engineered mix design (BMD). Asphalt mixtures prepared with low binder content have better resistance to rutting; however, they are prone to cracking. On the other hand, asphalt mixtures prepared with high binder content have better resistance to cracking; however, they may be prone to rutting. Therefore, a procedure was introduced for determining the optimum binder content that would balance rutting and cracking resistance (Zhou and Scullion 2006). This procedure is proposed for asphalt mixtures used in wearing courses (i.e., surface layer). Figure 18 shows an example of balancing rutting and cracking resistance.

The most common tests used in BMD to assess cracking performance are Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and the Semi-Circular Bending Illinois Flexibility Index Test (SCB-IFIT), while the Hamburg Wheel Tracking Test (HWTT) and Asphalt Pavement Analyzer (APA) are used to evaluate the rutting performance (Kassem at al. 2019). Other tests used in BMD also include Texas Overlay to assess cracking performance. Based on previous ITD research studies (Kassem et al. 2019 and Kassem et al. 2021), this study used IDEAL-CT and HWTT to assess the cracking and rutting performance, respectively. In addition, HWTT can be used to assess moisture susceptibility of the asphalt mixtures since it is conducted in wet conditions (Kassem et el. 2019).

ITD RP 261 proposed three performance thresholds for the IDEAL-CT: good cracking resistance (IDEAL-CT > 73.7), fair cracking resistance (26.4 ≤ IDEAL-CT ≤ 73.7), and poor cracking resistance (IDEAL-CT < 26.4). The proposed thresholds for some performance indicators were comparable to the ones proposed by other researchers (Kassem et al. 2019). In addition, ITD RP 261 proposed a maximum rut depth of 10 mm for HWTT after 15,000 passes or 12.5 mm for HWTT after 20,000 passes to ensure adequate resistance to rutting. Also, the HWTT thresholds can be used to ensure adequate resistance to moisture damage. Similar thresholds were also used and adopted by several transportation agencies (Kassem et al. 2019).

Table 8 summarizes the most promising intermediate temperature cracking performance indicators and their associate testing standards (Alkuime et al. 2020). ITD RP 261 provides comprehensive review of cracking and rutting tests used by various states as well as various performance indicators and proposed thresholds (Kassem et al. 2019). The following section provides an overview of cracking and rutting tests selected in this study and proposed thresholds from the literature.

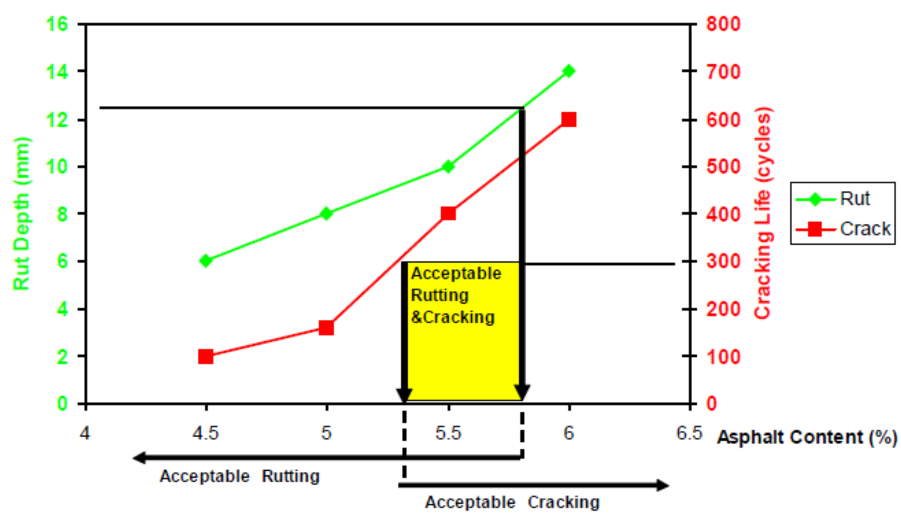


Figure 18. An example of balancing rutting and cracking resistance (Zhou et al. 2006)

Table 8. Intermediate temperature cracking most promising performance indicators and its associate testing standards after (Alkuime et al. 2020)

No.	Name	Symbol	Equation	Standard No.
1	Total Fracture Energy	$G_{fracture}$	$G_{Fracture}^{Total} = \frac{W_{Fracture}^{Total}}{crack\ face\ area}$	ASTM-D6931-07 & ASTM D8225-19
2	Cracking Resistance Index	CRI	$CRI = \frac{G_{Fracture}^{Total}}{P_{peak}}$	ASTM-D6931-07 & ASTM D8225-19
3	Flexibility Index	FI	$FI = \frac{G_{Fracture}^{Total}}{\lvert m_{inflection}^{Post-Peak} \rvert}$	ASTM-D6931-07 & ASTM D8225-19
4	IDEAL-CT_{Index}	IDEAL-CT_{Index}	$IDEAL - CT_{Index} = \frac{G_{Fracture}^{Total}}{\lvert m_{75\%Post-peak} \rvert} \times \frac{t}{62} \times \varepsilon_{v\ tolerance}$	ASTM-D6931-07 & ASTM D8225-19
5	N_{flex} Factor	N_{flex}	$N_{flex} = \frac{Toughness}{m_{inflection}^{Post-Peak}}$	ASTM-D6931-07 & ASTM D8225-19
6	IDT Modulus	$IDT_{Modulus}$	$IDT_{Modulus} = \frac{\sigma_{Tensile}^{IDT}}{L_{Peak\ Load}}$	ASTM-D6931-07 & ASTM D8225-19
7	$Weibull_{CRI}$	$Weibull_{CRI}$	$Weibull_{CRI} = \left(\frac{\eta}{\beta}\right) \times \log[A]$	ASTM-D6931-07 & ASTM D8225-19

Indirect Tensile Asphalt Cracking Test

IDEAL-Cracking Test Index [IDEAL-CT_{Index}]

IDEAL-CT_{Index} is a cracking resistance index recently developed by Zhou et al. (2017). IDEAL-CT_{Index} utilizes the load-displacement curve obtained from the IDT test. This index is a function of the total fracture energy, 75 percent post-peak slope m_{75}, and the strain tolerance parameter (Equation 1). This index is measured in accordance with ASTM D8225-19 "Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature". Several researchers evaluated this index as a cracking resistance measure. Zhou et al. (2017) found the index to be sensitive to the key components of asphalt mixtures such as, but not limited to, binder grade, RAP content, binder content, and air voids. Dong et al. (2019) found the IDEAL-CT_{Index} to be sensitive to binder content and the use of emulsion. Bennert et. al (2018) evaluated the index as a quality control tool in New Jersey, and they found that IDEAL-CT_{Index} correlated very well with overlay tester (OT) lower variability.

$$\mathrm{IDEAL} - \mathrm{CT}_{\mathbf{Index}} = \frac{G_{Total\ Fracture}}{\left|m_{75\%\ Post-peak}\right|} \times \frac{\mathrm{t}}{62} \times \varepsilon_{v\ tolerance} \quad (1)$$

where:

IDEAL-CT_{Index} = Cracking test index

$G_{Total\ Fracture}$ = Total fracture energy (J/m^2)

$m_{75\%\ Post-peak}$ = Post-peak slope at 75 percent of the peak load

t = Specimen thickness (mm)

$\varepsilon_{v\ tolerance}$ = Strain tolerance

Since the development of IDEAL-$CT_{Index,}$ several researchers and DOTs have proposed thresholds for cracking performance. Zhou et al. (2020) proposed an IDEAL-CT_{Index} criteria based on a strong correlation with the OT. They proposed a minimum criterion of 90 for Superpave mixes, 55 for TxDOT dense-graded mixes, and 135 for stone matrix asphalt mixtures (SMA). West et al. (2021) suggested a minimum threshold of 40 and 80 for Superpave, SMA mixes, respectively. ARDOT adopted a minimum preliminary threshold of 50. Kassem et al. (2019) proposed three performance thresholds for the IDEAL-CT: good cracking resistance (IDEAL-CT > 73.7), fair cracking resistance (26.4 ≤ IDEAL-CT ≤ 73.7), and poor cracking resistance (IDEAL-CT < 26.4). Diefenderfer et al. (2019) proposed CT_{Index} of 80 as an initial minimum criterion for VDOT. Similarly Cross et al. (2019) proposed a minimum threshold of 80 for Oklahoma mixes. Yin et al. (2021) demonstrated that TDOT considers a minimum of 100 for interstate and controlled access state routes and a minimum of 50 for non-controlled access state routes with less than 10,000 Average Daily Traffic (ADT) and 75 for an ADT greater than 10,000.

$Weibull_{CRI}$

The $Weibull_{CRI}$ is another cracking resistance indicator that was developed in RP 261 (Kassem et al. 2019). Similar to the IDEAL-CT_{Index}, this indicator utilizes the IDT load-displacement curve. However, the $Weibull_{CRI}$ describes the entire load-displacement curve, while other monotonic cracking indicators (e.g., IDEAL-CT_{Index}) uses one or more elements of the load-displacement curve. The $Weibull_{CRI}$ uses the Weibull probability density function's fitting parameters to calculate the cracking resistance index. The $Weibull_{CRI}$ is calculated using Equation 2. Kassem et al. (2019) found $Weibull_{CRI}$ to have less variability in the test results compared to IDEAL-CT_{Index}.

$$\mathrm{Weibull_{CRI}} = \left(\frac{\eta}{\beta}\right) \times \log(\mathrm{A}) \tag{2}$$

where:

η	= Scale parameter
β	= Shape parameter (Weibull slope)
A	= Scaling factor equals to the area under the load-displacement curve

IDT Strength

The $IDT_{strength}$ is also another performance indicator that is used in the literature (Kassem et al. 2019). This indicator is calculated by dividing the IDT peak load by the specimen geometry. The $IDT_{strength}$ is calculated using Equation 3. Additional cracking resistance indices are described in Table 8.

$$\mathrm{IDT_{strenght}} = \frac{2000 \times \mathrm{P_{Peak}}}{\pi \times \mathrm{t} \times \mathrm{D}} \tag{3}$$

where:

$IDT_{strength}$	= Tensile strength (kPa) determined from IDT test
P_{Peak}	= Peak load (N)
t	= Specimen thickness (mm)
D	= Specimen diameter (mm)

Creep-Compliance and Strength Test as low Temperature

The creep-compliance and strength test are two parameters used to evaluate the low-temperature cracking performance (thermal cracking) of asphalt mixtures. The test is conducted in accordance with AASHTO T322 “Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device”. The creep compliance is calculated using Equation 4. Further discussion of the test is provided in Chapter 3 of this report. This test was used in several studies to evaluate the low-temperature cracking performance of asphalt mixtures. Krcmarik et al. (2016) demonstrated that mixtures with stiffer binder resulted in a higher low-temperature IDT strength which indicates higher thermal cracking susceptibility. Another study by Zaumanis et al. (2015), concluded that mixtures with higher creep-compliance and lower thermal tensile strength tend to have better cracking resistance than mixtures with lower creep and higher strength.

$$D(t)_{avg} = \frac{\Delta X_{tm} \times D_{avg} \times b_{avg}}{P_{avg} \times GL} \times C_{Cmpl} \tag{4}$$

$$C_{Cmpl} = 0.6354 \times \left(\frac{X}{Y}\right)^{-1} - 0.332$$

where:

D(t) = Creep compliance at time t (kPa)

GL = Gauge length in (mm)

D_{avg} = Average diameter of the test specimen (mm)

B_{avg} = Average thickness of the test specimen (mm)

P_{avg} = Average creep load (kN)

ΔX_{tm} = Trimmed mean of the normalized horizontal deformations

(X/Y) = Absolute value normalized trimmed mean of the horizontal deformation ratio

Hamburg Wheel-Tracking Test

The Hamburg Wheel-Tracking Test (HWTT) is used to assess the rutting performance as well as moisture susceptibility of asphalt mixtures. The HWTT has steel wheel rollers that move back and forth over cylindrical asphalt specimens. The wheels are 17 mm wide and apply 705 N force. The test samples are submerged in a water bath at a controlled temperature of 50 °C. The rut depth is measured along the roller path during the test, and generally the test is performed for 20,000 passes. The test is conducted in accordance with AASHTO T324 "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures". Table 9 provides information on the rutting performance standards along with HWTT rutting performance thresholds established by various DOTs including Texas Department of Transportation (TxDOT), Washington State Department of Transportation (WSDOT), Colorado Department of Transportation (CODOT), Louisiana Department of Transportation (LADOT), and Montana Department of Transportation (MTDOT). ITD RP 261 proposed a maximum rut depth of 10 mm for HWTT after 15,000 passes or 12.5 mm for HWTT after 20,000 passes to ensure adequate resistance to rutting. Also, the HWTT thresholds can be used to ensure adequate resistance to moisture damage. In addition, other HWTT parameters such as Stripping Inflection Point (SIP) can also be calculated to evaluate moisture damage (Yin et al. 2014).

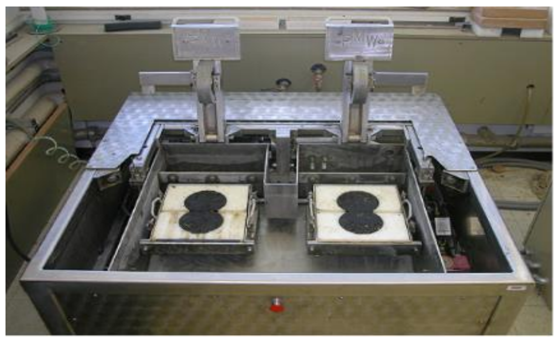


Figure 19. Hamburg wheel tracking test setup (Kassem et al. 2011)

Figure 20. APA Jr. for Hamburg wheel tracking test

Table 9. HWTT rutting performance threshold (after: Kassem at al. 2019)

DOT	Test procedure	PG grading/Mixture Type	Rutting performance threshold (minimum # of passes)
TXDOT	Tex-242-F	-	Limits, @12.5mm rut depth tested at 50 ℃
TXDOT	Tex-242-F	<=PG 64	10000
TXDOT	Tex-242-F	PG 70	15000
TXDOT	Tex-242-F	=>PG 76	20000
WSDOT	AASHTO T 324	-	15,000 Passes @10 mm rut depth tested at 50 ℃
CODOT	CP-L 5112	-	10,000 @ 4 mm rut depth tested at 50 ℃
LADOT	AASHTO T 324	Incidental Paving and ATB	10 mm @ 10,000 passes tested at 50 ℃
LADOT	AASHTO T 324	Wearing and Binder Course level 1	10 mm @ 20,000 passes tested at 50 ℃
LADOT	AASHTO T 324	Wearing and Binder Course level 2	6 mm @ 20,000 passes tested at 50 ℃
MTDOT	MT 334-14	Mix design	13 mm @ 10,000 passes
MTDOT	MT 334-14	Plant	13 mm @ 15,000 passes
ITD	AASHTO T 324	-	12.5 mm @ 20,000 passes tested at 50 ℃

3. Material Description and Experimental Design

Chapter 3 provides information about the testing materials (e.g., RAP, virgin aggregates, binders, rejuvenators). In addition, it documents the methods and procedures used by the researchers to evaluate the performance of the asphalt mixtures including intermediate temperature cracking performance, thermal cracking performance, rutting performance, and moisture susceptibility. Also, it discusses the preparation of test laboratory mixtures, loose mixtures obtained from the field, as well as the testing program.

Material Description

Reclaimed Asphalt Pavement

The researchers obtained RAP materials from four different sources and acquired virgin aggregates from two sources. The first source of RAP (i.e., RAP No. 1) was an “artificial RAP”. This RAP was prepared in the lab using loose mixtures obtained from an ITD paving project that is described later in this section. The second source of RAP (i.e., RAP No. 2) and third source of RAP (i.e., RAP No. 3) were obtained from two different asphalt plants in Lewiston, Idaho. The last source of RAP (i.e., RAP No. 4) was obtained from an asphalt plant in Boise, Idaho. The first source of virgin aggregate was river gravel obtained from a quarry in Lewiston, Idaho, while the second source of virgin aggregate was also a river gravel obtained a quarry in Boise, Idaho.

The first source of RAP (i.e., RAP No. 1) was an “artificial RAP” that was aged in the laboratory. The mixture was obtained from a paving project in District 2, and the materials were sampled and delivered by ITD to the laboratory at University of Idaho in 50-lb boxes. The Nominal Maximum Aggregate Size (NMAS) of this mixture was 12.5 mm, the binder grade was PG 64-28, and the binder content was 5.3 percent. The loose mixture was placed in an oven at 135 °C for 3 days to simulate long-term field aging. This method was used by researchers in a previous study and was found to simulate field aging (Sirin et al. 2020). Figure 21 shows the RAP gradations for all examined RAP (i.e., RAP No. 1 through RAP No. 4).

Figure 22 shows the RAP binder content from different sources. RAP No. 2 and RAP No. 3 had an asphalt content of 5.37 percent and 4.3 percent, respectively. The first three sources of RAP materials (RAP No. 1, 2, and 3) were used in the laboratory testing at the University of Idaho. RAP No. 2 and 3 were fractionated into two different sizes: coarse (i.e., retained on Sieve No. 4) and fine (i.e., passing Sieve No. 4). RAP No. 4 had an asphalt content of 5.3 percent, and similar to RAP No. 2 and RAP No. 3, it was fractionated into coarse and fine piles. RAP No. 4 was used in the laboratory evaluation at Boise State University. Appendix A provides more information about the RAP materials of different sources acquired and used in this study.

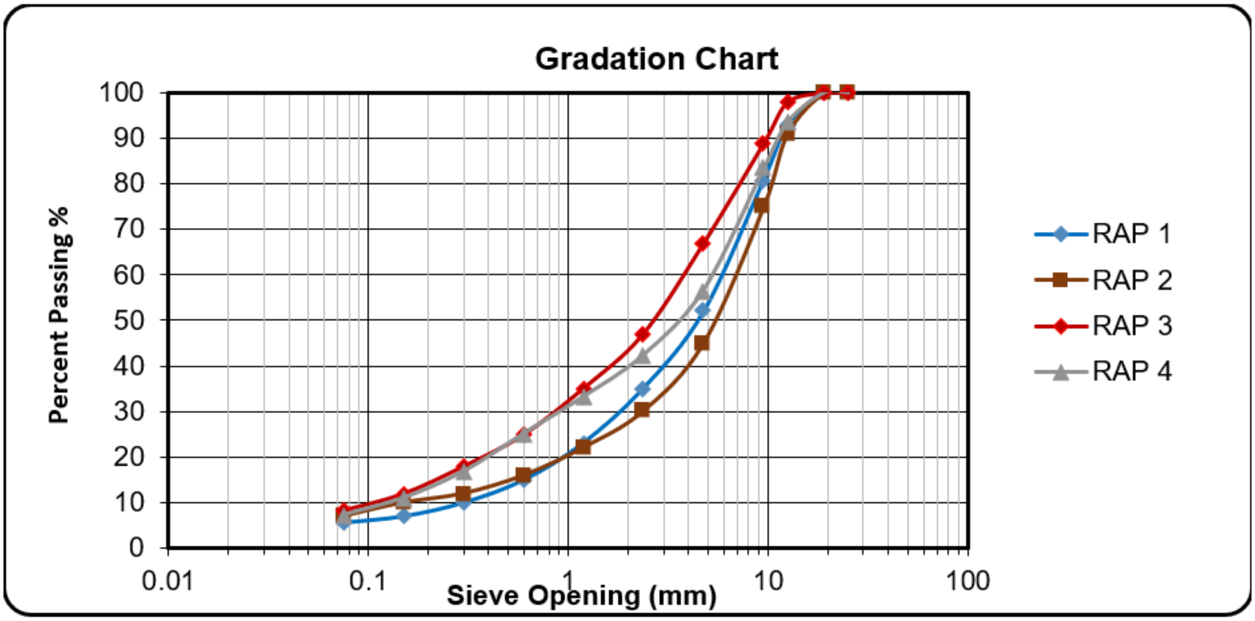


Figure 21. RAP Gradations

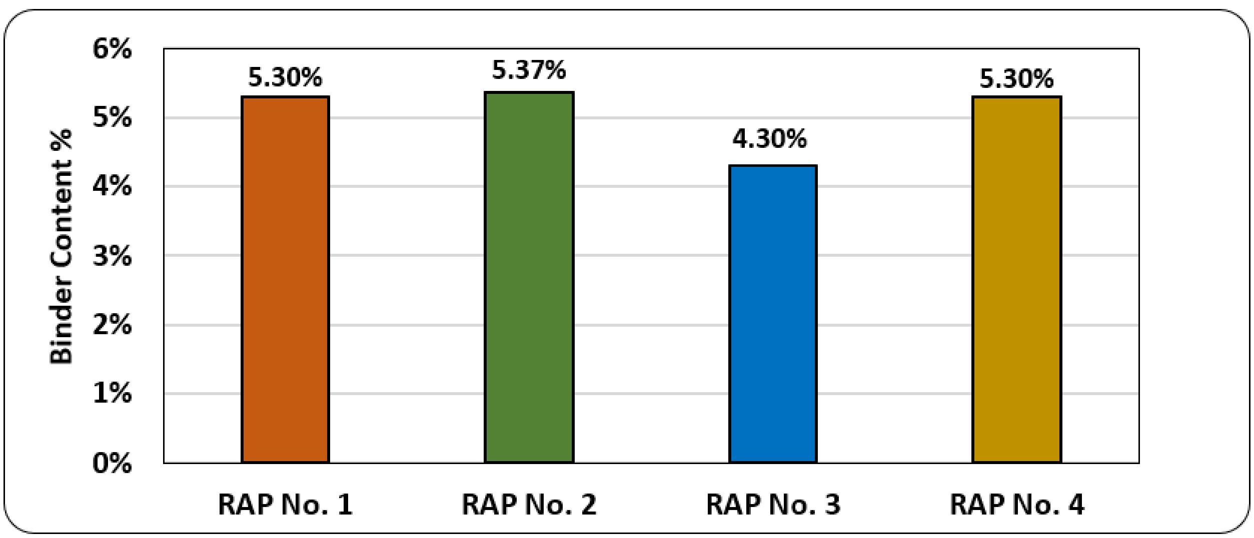


Figure 22. RAP Binder Content

Rejuvenators

In this project, seven unique commercially available rejuvenators were used. Five rejuvenators (R1 through R5) were used at the University of Idaho (UI) and the other two rejuvenators (i.e., R6 and R7) were used at Boise State University (BSU). Figures 23 and 24 show the examined rejuvenators in this study.

The first rejuvenator (R1) is categorized as a tall oil. This rejuvenator is derived from a crude tall oil which is a by-product of the paper industry and tends to have a clear yellowish color. The first rejuvenator (R1) was obtained from a company in the United Kingdom. The second rejuvenator (R2) is categorized as an aromatic extract which is a refined crude oil product obtained from a company in the U.S. This rejuvenator is a dark brown color with a petroleum odor. The third rejuvenator (R3) is considered as a bio-based forestry product which was also obtained from another company in the U.S. This rejuvenator tends to have a dark brown color. The fourth rejuvenator (R4) is an engineered product by a company in the U.S. This rejuvenator tends to have a dark brown color with a petroleum odor too. The fifth rejuvenator (R5) is considered as a triglycerides and fatty acids rejuvenator, and it is derived from waste vegetable oil obtained from a company in the U.S. This rejuvenator tends to have a light brown color. The sixth (R6) and seventh (R7) rejuvenators were obtained from a company in the U.S. too. The sixth rejuvenator (R6) is a bio-based oil, and it has an orange hue oil. The seventh rejuvenator (R7) is a petroleum-based oil and has a clear liquid look as shown in Figure 24. Table 10 summarizes the examined doses of various rejuvenators. These doses were within the recommended values by the manufacturers.

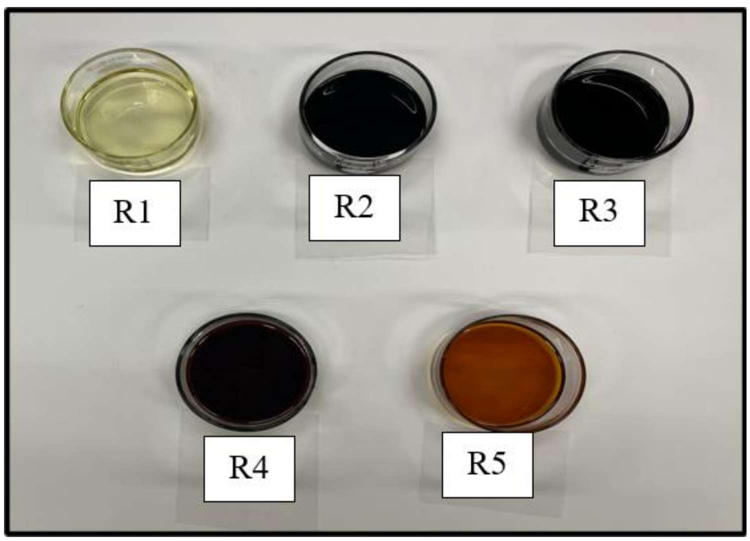


Figure 23. Rejuvenators evaluated at UI

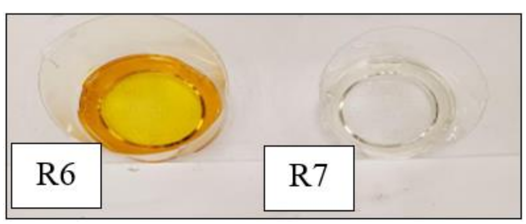


Figure 24. Rejuvenators evaluated at BSU

Table 10. Rejuvenator Test Doses

Rejuvenator No.	Examined Doses	Dose Description
R1	3.5%, 5%, and 7%	By weight of total binder
R2	6%, 10%, and 12%	By weight of reclaimed binder
R3	12.5% and 15%	By weight of reclaimed binder
R4	1% and 2%	By weight of RAP
R5	12% and 16%	By weight of reclaimed binder
R6	6.6% and 8.3%*	By weight of reclaimed binder
R7	11.3%+	By weight of reclaimed binder

Notes:
The doses of R6 and R7 were further checked using the blending charts, see Appendix B
+Only one dose was evaluated.
*Only 8.3 percent was used to evaluate both cracking and rutting performance, while 6.6 percent was used to evaluate the cracking performance

Laboratory-Mixed Laboratory-Compacted (LMLC) Test Specimens

The researchers prepared Laboratory-Mixed, Laboratory-Compacted (LMLC) asphalt mixtures with different RAP materials and rejuvenators. The laboratory experiments at UI included three different sources of RAP, five rejuvenators, three binder grades, two binder contents, different RAP contents, and different rejuvenator doses as discussed in detail later in this section. Similarly, the team at BSU prepared LMLC with one source of RAP, two rejuvenators, two binder grades, one binder content, different RAP contents, and different rejuvenator doses as discussed also later in this section.

The LMLC mixtures were prepared and tested to evaluate the cracking and rutting performance of asphalt mixtures with RAP and rejuvenators. The testing matrix at UI included LMLC mixes that were prepared using three different sources of RAP (i.e., RAP No. 1, RAP No. 2, and RAP No. 3). Each mixture was prepared using different RAP content. For RAP No. 1, different RAP contents were included (i.e., 0, 25, 50, 75 percent), while mixtures with RAP No. 2 examined the RAP contents of 0, 25, 50, 70 percent. Mixtures with RAP No. 3 included higher RAP content of 70 percent and control mix (i.e., 0 percent RAP). Furthermore, different rejuvenator doses were examined at each RAP content. Table 11 summarizes the testing matrix at UI, and Chapter 4 provides detailed information and performance results on examined mixtures. The mix designs of asphalt mixtures prepared and tested in this study are provided in Appendix B.

Similarly, the testing matrix at BSU included LMLC mixes that were prepared using one source of RAP. Each mixture was prepared using different RAP contents (i.e., 0, 25, 50, and 70 percent). In addition, the mixtures were prepared using two different rejuvenators at two different doses. Table 12 summarizes the testing matrix at BSU. The mixing and compaction temperatures for the LMLC specimens were obtained from the job mix formula. Prior to compaction, all mixes were short-term aged for four hours at a temperature of 135 °C in accordance with AASHTO R30-02. The LMLC specimens were compacted using a SuperPave Gyratory compactor to a target air void of 7±0.5 percent.

Table 11. Laboratory-Mixed, Laboratory-Compacted Testing Matrix at UI

RAP %	0	25	50	≥70	-
RAP Source	1	2	3	-	-
Air Void %	7%	-	-	-	-
Binder Grade	PG 70-28	PG 64-28	PG 58-34	PG 58-28*	-
Binder Content %	OBC	OBC+0.5%	-	-	-
Rejuvenators	R1	R2	R3	R4	R5

*Only used with the 3rd source of RAP.

Table 12. Laboratory-Mixed, Laboratory-Compacted Testing Matrix at BSU

RAP %	0	25	50	70
RAP Source	4	-	-	-
Air Void %	7%	-	-	-
Binder Grade	PG 70-28	PG 64-34	-	-
Binder Content %	OBC	-	-	-
Rejuvenators	R6	R7	-	-

Plant-Mixed Laboratory-Compacted (PMLC) Test Specimens

In this project, the researchers prepared Plant-Mixed Laboratory-Compacted (PMLC) test specimens obtained from new ITD paving projects. Loose asphalt mixtures from 23 projects were obtained and delivered to UI to evaluate the cracking and rutting performance of asphalt mixtures currently produced and used in the state. These projects were distributed across all six districts of the state (District 1 to District 6). The loose mixtures were delivered in boxes, and each box weighed 50 lbs. Also, the boxes received were labeled with the necessary information and mix composition (e.g., binder content, project number, compaction temperature, etc.). The main properties of PMLC are summarized in Table 13, which include mix design, binder grade, RAP content, and RAP binder replacement. These mixtures included two different mix types (SP3 and SP5), four different virgin binder grades (PG 58-34, PG 64-28, PG 64-34, and PG 70-28), different percent of RAP content (ranging from 0 to 35 percent by weight of the mix), and 10 different percent of RAP binder replacement (e.g., 8, 15, 17, 20, 22, 25.4, 26.3, 27.3, 29.3, and 29.7 percent). Appendix D provides the mix design for the loose mixtures evaluated in this study. The PMLC specimen were reheated at the compaction temperature specified in the job mix formula for two hours and shoveled to avoid segregation. All PMLC specimens were compacted at a target air void of 7±0.5 percent using a SuperPave gyratory compactor.

Table 13. PMLC Properties

#	District	Mix Type	Specified Binder PG	Virgin Binder PG	Binder Content Pb (%)	RAP (%)	RAP Binder Replacement (RBR %)	NMAS mm	Theoretical Specific Gravity (G_{mm})	Dust Proportion	Effective Binder Content P_{be}	Project Key No.
1	D5 &6	SP-3	PG 58-34	PG 58-34	5	30	29.4	19	2.423	1.2	4.44	20590
2	D4	SP-3	PG 70-28	PG 70-28	6.2	0	NA	9.5	2.377	1.4	5.12	19863
3	D4	SP-3	PG 70-28	PG 64-34	5.6	30	26.3	12.5	2.396	1.1	4.8	18737
4	D4	SP-3	PG 64-34	NA	5.8	17	15	19	2.420	1.2	4.56	19404
5	D4	SP-2	PG58-28	PG58-34	5.7	35	29.7	12.5	2.402	1.2	4.8	19312
6	D4	SP-3	PG 64-34	NA	5.8	17	15	19	2.409	1.2	4.56	19699
7	D4	SP-3	PG70-28	PG 64-34	5.6	30	26.3	12.5	2.402	1.1	4.8	20180
8	D4	SP-3	PG 64-34	NA	5.4	NA	NA	12.5	2.392	1.3	4.74	19130
9	D3	SP3	PG 64-34	PG 58-34	5.5	20	20	12.5	2.497	1.3	4.75	20508
10	D2	SP-3	PG 64-28	PG 58-34	5.7	30	25	12.5	2.491	1.4	4.73	20436
11	D3	SP-3	PG 70-28	PG 64-34	5.33	31	29.3	12.5	2.418	0.8	4.7	13932
12	D3	SP-3	PG 64-34	PG 58-34	5.34	31	29.3	12.5	2.382	1.2	4.53	20714
13	D6	SP-5	PG 64-34	PG 58-34	4.9	29	NA	12.5	2.458	0.9	4.5	19812
14	D3	SP-3	PG 64-28	PG 58-34	5.3	32	NA	12.5	2.441	1.4	4.33	19112
15	D2	SP-3	PG 64-28	PG 58-34	5.2	30	25.4	12.5	2.602	1.4	4.2	19261
16	D2	SP-3	PG 64-28	NA	5.6	10	8	12.5	2.555	1.4	4.66	20193
17	D4	SP-5	NA	NA	5.2	NA	NA	12.5	2.285	NA	NA	20559
18	D4	SP-5	PG 70-28	NA	5.7	19	17	19	2.298	1.3	4.44	19086
19	D5	SP-3	PG 64-34	PG 58-34	5	20	27.3	19	2.466	1.3	3.94	20051
20	D2	SP-3	PG 70-28	NA	5.9	NA	NA	12.5	2.536	1.4	4.76	19373
21	D4	SP-3	PG 64-34	NA	5.8	17%	15	19	2.407	1.2	4.56	18742
22	D5	SP-3	PG 58-34	NA	4.8	NA	22	19	2.467	0.96	3.96	20051
23	*								2.423			20003

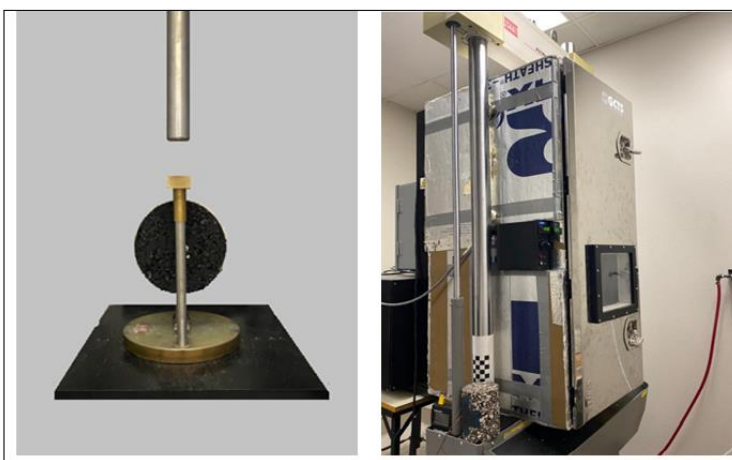
*Note: Project No. 23 (key 20003) was the only one without proper identification

Laboratory Testing

The researchers conducted various laboratory tests to evaluate the cracking and rutting performance of the test mixtures. The cracking tests included the Indirect Tensile (IDT) Strength Test in accordance with ASTM D8225 "*Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature*" to evaluate the intermediate cracking resistance. In addition, the researchers evaluate the low temperature cracking performance of selected mixtures in accordance with AASHTO T 322 "*Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device*". Furthermore, the team examined the rutting performance of the test mixtures in accordance with AASHTO T 324 "*Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures*". This section describes the laboratory tests conducted in this study.

Evaluation of Cracking Performance

The researchers evaluated the intermediate temperature cracking performance of the test asphalt mixtures using the Indirect Tensile (IDT) Strength Test in accordance with ASTM D8225. The IDT was conducted at UI using a servo-hydraulic Material Testing System (MTS-810) as shown in Figure 25. The test specimens were placed inside an environmental chamber at a temperature of 25 °C for two hours for condition before testing. The IDT conducted at BSU used a counter-top IDT apparatus at room temperature. The IDT test specimens are 6 inches (150 mm) in diameter and 2.45 inches (62 mm) thick and compacted to have 7 plus/minus 0.5 percent air voids. The IDT test is conducted at a constant compressive axial loading rate of 2 inches per minute (50 plus/minus 5 mm per minute) until failure. Figure 25 shows the test setup at UI.



a. Test Setup

b. MTS 810 and Environmental Chamber

Figure 25. IDT Test Setup

The researchers evaluated low temperature cracking (i.e., thermal cracking) of selected asphalt mixtures using the creep-compliance and strength test in accordance with AASHTO T 322. The creep compliance test was conducted using a servo-hydraulic Material Testing System equipped with an environmental chamber as shown in Figure 26b. The creep-compliance test specimens are 6 inches (150 mm) in diameter and 1.7 inches (43 mm) thick and compacted to have 7 plus/minus 0.5 percent air voids (Figure 26). The test is conducted at three different temperatures (i.e., -20, -10, and 0 °C), and the specimens are conditioned at the test temperatures for three hours before testing. In this test, a vertical static load is applied on the test specimen for 100 sec to produce a horizontal deformation between 0.00125 to 0.0190 mm to ensure that the test specimen is in the linear viscoelastic range. Both horizontal and vertical deformations are recorded during the test. Once the creep compliance test is completed at all temperatures, the tensile strength test is conducted. The tensile strength test is performed at the middle testing temperature (i.e., -10 °C) by applying a vertical load rate of 12 mm/min until failure.

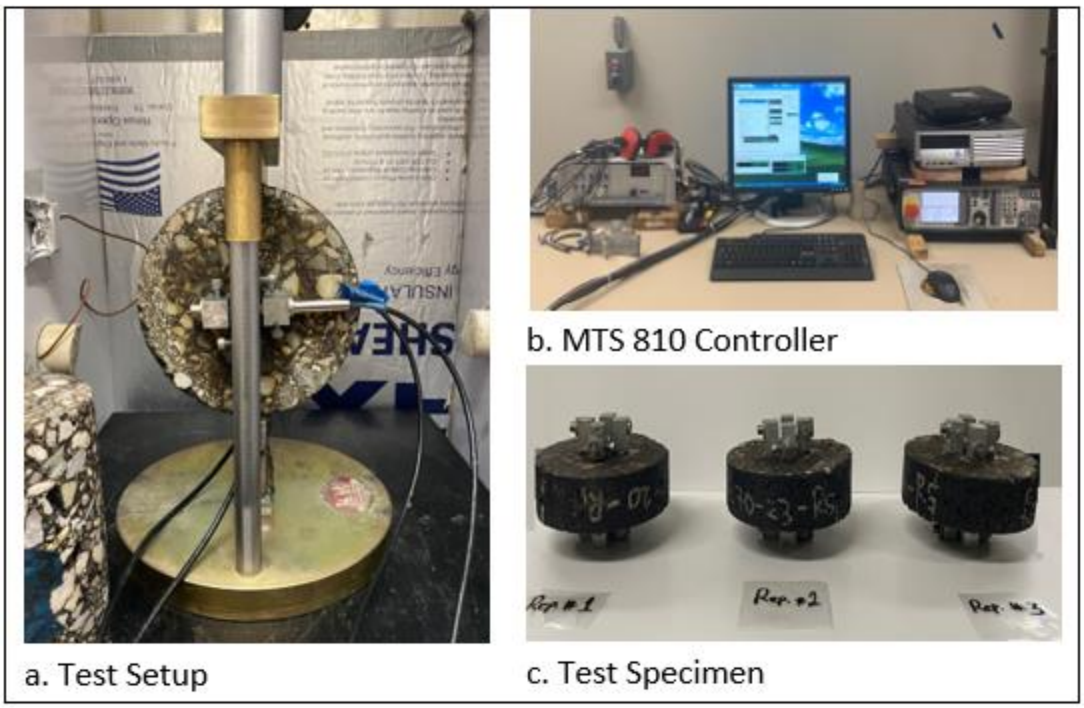


Figure 26. Creep-Compliance Test specimen

Evaluation of Rutting Performance

The researchers evaluated the rutting performance of the mixtures by conducting the Hamburg Wheel Tracking Test (HWTT) in accordance with AASHTO T324. Figure 27 shows the Asphalt Pavement Analyzer Jr. (APA Jr.) at UI. Four test specimens were used from each mixture for the HWTT testing. The HWTT test specimens are 6 inches (150 mm) in diameter and 2.36 inches (60 mm) thick and compacted to have 7 plus/minus 0.5 percent air voids. The specimens were sawed and placed in the testing molds as shown in

Figure 27a. The specimens were conditioned in a water bath at a temperature of 50 °C for 30 minutes before the test started. The HWTT wheels apply 705 N load directly on the surface of the test specimens at a constant rate of 52 pass/minute. The test is terminated after 20,000 passes or after an average rut depth of 12.5 mm is achieved. The rut depth is measured at 11 different locations along the pass of the HWTT wheels on the test specimens.

a. Test Setup b. Asphalt Pavement Analyzer Jr.

Figure 27. APA Jr. and HWTT Test Specimen and Setup

4. Evaluation of the Performance of Rejuvenators Incorporated in Mixtures with High RAP Content

This chapter presents and discusses the results of the laboratory testing program conducted to evaluate the cracking and rutting performance as well as the low-temperature cracking of mixtures with different characteristics including RAP source and content, rejuvenator type and content, and binder grade and content. The cracking resistance was evaluated for all mixtures using the IDT test and calculations of IDEAL-CT_{Index}. The IDEAL-CT_{Index} is proposed by Zhou et al. (2017) and is calculated from the IDT load-displacement curve as discussed in Chapter 2 using Equation 1. The IDEAL-CT_{Index} is a function of the fracture energy (Gf) and the post peak slope (m_{75}) at which the load after the peak equals to three quarters of the maximum load. The IDEAL-CT_{Index} is an indicator that measures the resistance of asphalt mixtures to intermediate-temperature cracking. The higher the IDEAL-CT_{Index} the higher the resistance to cracking. In addition, the researchers evaluated the low-temperature cracking performance using the creep-compliance and strength test. Creep compliance is used to evaluate the cracking performance of mixtures at low temperatures. The test is conducted in accordance with AASHTO T 322 as discussed in Chapter 2 using Equation 4. Safi et al. (2018) concluded that the lower the compliance the stiffer the mix and thus more prone to thermal cracking and vice versa. At least three replicates were tested for each cracking test (i.e., IDT and creep compliance) to minimize the variation of the test results.

The rutting performance was evaluated in this study using Hamburg Wheel Tracking Test (HWTT) conducted using the Asphalt Pavement Analyzer JR. (APA Jr.). The rut depth is measured at eleven different locations along the wheel pass and the average rut depth is recorded. The test is conducted for 20,000 passes or until 12.5 mm rut depth is achieved as discussed in Chapter 2.

The statistical analysis of the test results for cracking and rutting evaluation was conducted using Tukey's Honestly Significant Difference (Tukey's HSD). The Tukey's HSD is a one-way analysis of variance (ANOVA) and is performed at 95 percent confidence interval (i.e., α = 0.05). It can identify test means with significant difference. In this study, the researchers used Minitab software (Minitab 2019) to conduct the statistical analysis. In this chapter, the researchers discussed the results for mixtures prepared with various RAP sources separately. RAP materials from four different sources were utilized in this study as discussed in Chapter 3.

Evaluation of Asphalt Mixtures Prepared with RAP No. 1

The source of RAP No. 1 was a loose mixture (PMLC) obtained from an ITD paving project. The loose mixture was aged in the laboratory by placing the mixture in an oven at 135 °C for 3 days to simulate aged RAP materials as discussed in Chapter 3. Therefore RAP No. 1 was an artificial RAP. The researchers conducted this control experiment using artificial RAP to eliminate the effect of RAP variability (e.g., gradation, binder content, etc.) on the test results when other parameters were evaluated such as rejuvenator type and content. Different amounts of RAP (i.e., 0, 25, 50, and 75 percent), four different rejuvenators (R1, R2, R3, and R4) and two different doses from each rejuvenator were evaluated. The examined doses were based on the manufacturers' recommendations and literature as discussed in Chapter 3 in Table 10. The recommended dose for R1 is between 3.5 to 7.0 percent by weight of total binder. The recommended dose of R2 depends on RAP content (i.e., for less than 30 percent RAP, 5 to 7 percent by weight of reclaimed binder and for more or equal to 30 percent RAP, 9 to 12 percent by weight of reclaimed binder). For the third rejuvenator (R3), the recommended dose is between 12.5 to 15 percent by weight of reclaimed binder. For rejuvenator No. 4 (R4), the recommended dose is between 1 to 3 percent of weight of RAP, while it is between 12 to 16 percent by weight of reclaimed binder for R5. For R6 and R7, the examined doses were 6.6 and 8.3 percent by weight of reclaimed binder for R6 and 11.3 percent by weight of reclaimed binder for R7.

Effect of RAP Content

Figure 28 shows the effect of RAP content (i.e., 0, 25, 50, and 75 percent) on cracking performance using IDEAL-CT_{Index}. Figure 28 also includes performance thresholds proposed in ITD RP 261 (Kassem et al. 2019) where the red dotted line represents the higher threshold (IDEAL-CT_{Index} of 73.7), and the solid blue line shows the minimum threshold (IDEAL-CT_{Index} of 26.4). Mixtures with IDEAL-CT_{Index} greater than 73.7 are expected to exhibit good cracking resistance, while mixtures with IDEAL-CT_{Index} less than 26.4 are expected to have poor resistance to cracking. Mixtures with IDEAL-CT_{Index} between 26.4 and 73.7 are expected to exhibit moderate or fair cracking performance. Tukey's HSD was also conducted to compare the IDEAL-CT_{Index} values for the examined mixtures. The statistical analysis results (Tukey's HSD groups) are included in the form of capital letters on each bar. If the mixtures share the same capital letters (e.g., A, B, C, D, etc.) then, there was no significant difference between the means.

The results of Figure 28 demonstrate that the control mix (i.e., 0 percent RAP) had higher IDEAL-CT_{Index} which indicates good cracking performance. The addition of 25 percent RAP decreased the IDEAL-CT_{Index} but still the mixture is expected to exhibit good cracking performance, and there was no statistically significant difference in the IDEAL-CT_{Index} results between mixtures without RAP (0 percent RAP) and with 25 percent RAP. Mixtures with 50 percent and 75 percent RAP showed lower IDEAL-CT_{Index} and are expected to exhibit poor cracking performance (average IDEAL-CT_{Index} was less than 26.4). In addition, mixtures with 50 percent and 75 percent RAP share the same letter "B" which indicate that there was no statistically significant difference in the IDEAL-CT_{Index} results between these two mixtures. However, there was statistically significant difference in IDEAL-CT_{Index} results between these mixtures (i.e., mixtures with 50 percent and 75 percent RAP) and mixtures without RAP and 25 percent RAP.

Figures 29 and 30 show the $IDT_{Strength}$ and $Weibull_{CRI}$ results for mixtures prepared at different RAP contents using RAP No. 1. The results showed that the $IDT_{Strength}$ increased with the increase of RAP content which demonstrates that the mixtures are stiffer with the addition of RAP. Meanwhile, mixtures with 70 percent RAP had slightly lower stiffness compared to 50 percent; however, such difference was not statistically significant. Furthermore, the results $Weibull_{CRI}$ were consistent with that of IDEAL-CT_{Index} and the cracking performance decreased from good ($Weibull_{CRI} > 4.7$) to poor ($Weibull_{CRI} < 3.6$) with increasing RAP content. Therefore, the researchers focused on the results of IDEAL-CT_{Index} in this section and provided the $IDT_{Strength}$ and $Weibull_{CRI}$ results in Appendix E.

The results of this section clearly demonstrated the detrimental effect of increasing RAP content on the cracking performance of asphalt mixtures prepared with RAP No. 1. Increasing the amount of RAP in asphalt mixtures resulted in stiffer mixtures with reduced resistance to cracking as expected. Next, the researchers evaluated the use of rejuvenators to improve the cracking resistance of these mixtures.

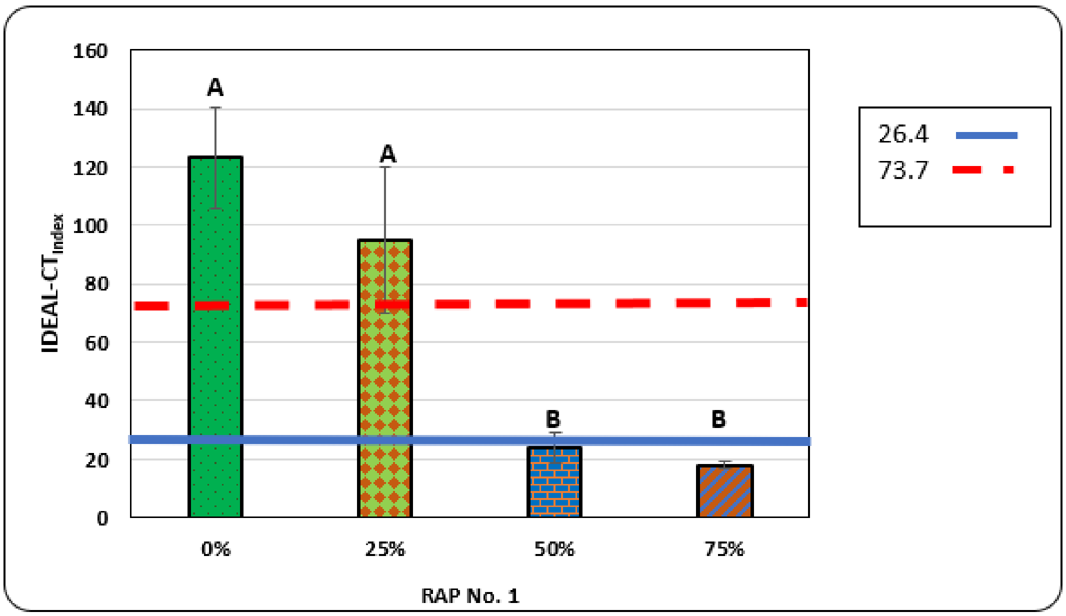


Figure 28. Effect of RAP Content on Cracking Performance for RAP No. 1

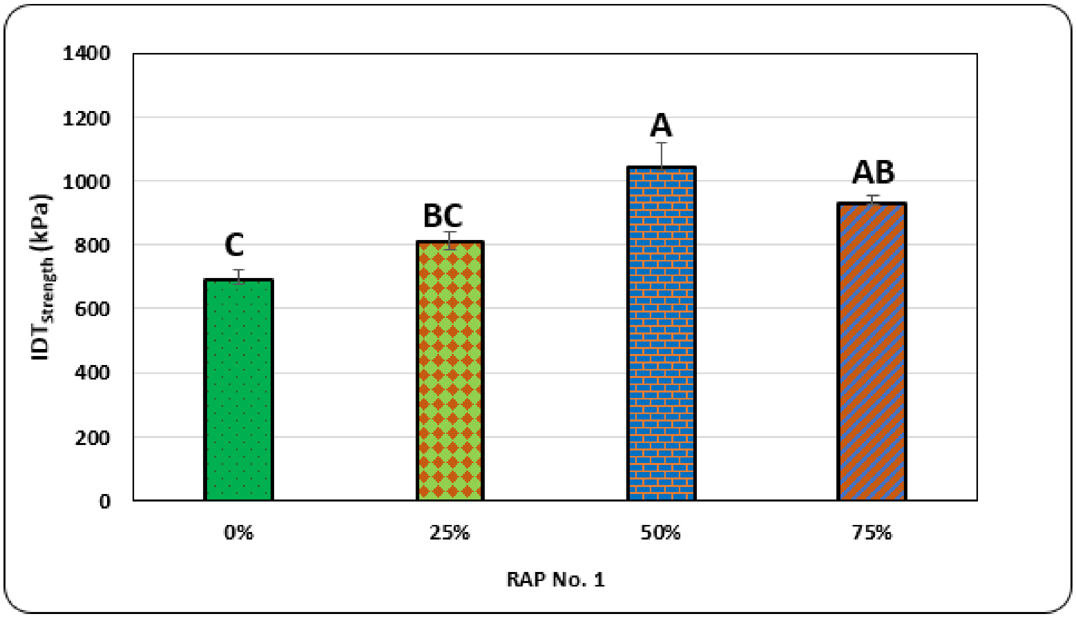


Figure 29. Effect of RAP Content of RAP No. 1 on IDT$_{Strength}$

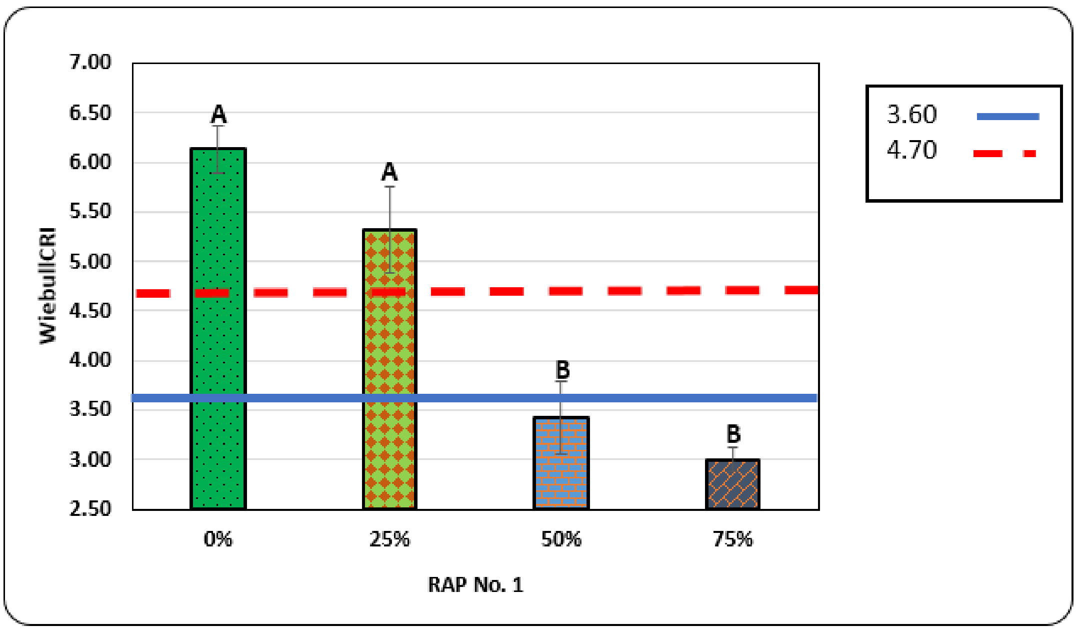


Figure 30. Effect of RAP Content of RAP No. 1 on Weibull$_{CRI}$

Effect of Rejuvenator Type

The researchers evaluated the use of rejuvenators to improve the cracking resistance of mixtures prepared with different RAP contents and the results were compared to the control mix (i.e., without RAP). Figures 31, 32, and 33 show the effect of the first dose (lower end) of different types of rejuvenators for mixtures with RAP content of 25, 50, and 75 percent, respectively. For RAP No. 1, the researchers evaluated four different rejuvenators 1) tall oil (R1) at 3.5 percent by weight of total binder for 25 and 50 percent RAP and 5 percent for 75 percent RAP; 2) aromatic extract (R2) at 6 percent by weight of the reclaimed binder for the 25 percent RAP and 10 percent by weight of reclaimed binder for 50 percent and 75 percent RAP, 3) bio-based forestry oil (R3) at 12.5 percent by weight of reclaimed binder, and 4) engineered product (R4) at 1 percent of weight of RAP. These doses were discussed in Chapter 3.

As shown earlier from Figure 28, mixtures with 25 percent RAP showed good cracking performance based on proposed IDEAL-CT_{Index} thresholds. The results of Figure 31 demonstrated that adding rejuvenators didn't significantly impact the cracking performance except mixtures with R2 (25 percent plus R2) compared to mixtures with 25 percent RAP. The use of R2 resulted in reduced cracking resistance. For mixtures with 50 percent RAP (Figure 32), the addition of rejuvenators R2 and R4 showed improvements to cracking resistance; however, R1 and R3 didn't have significant improvement on cracking resistance compared to mixtures with 50 percent RAP. Unlike mixtures with 25 percent RAP, R2 improved the cracking performance from poor to good and this is attributed to increased rejuvenator dose as specified for mixtures with 30 percent RAP or higher. The dose was increased as specified for R2 (i.e., for less than 30 percent RAP, 5 to 7 percent by weight of reclaimed binder and for more or equal to 30 percent RAP, 9 to 12 percent by weight of reclaimed binder). Mixtures with R4 also exhibited improved cracking resistance from poor to good cracking performance. Rejuvenators R1 and R3 improved the cracking resistance slightly but there was no statistically significant difference in the results compared to that of mixtures with 50 percent RAP.

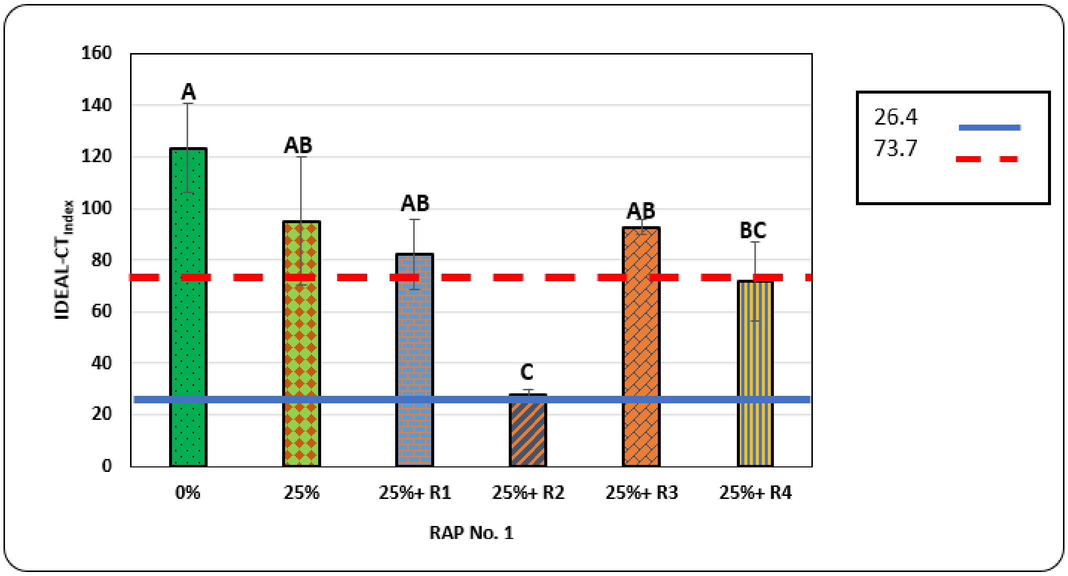


Figure 31. Effect of Rejuvenator Type on Cracking Performance at 25% RAP No. 1

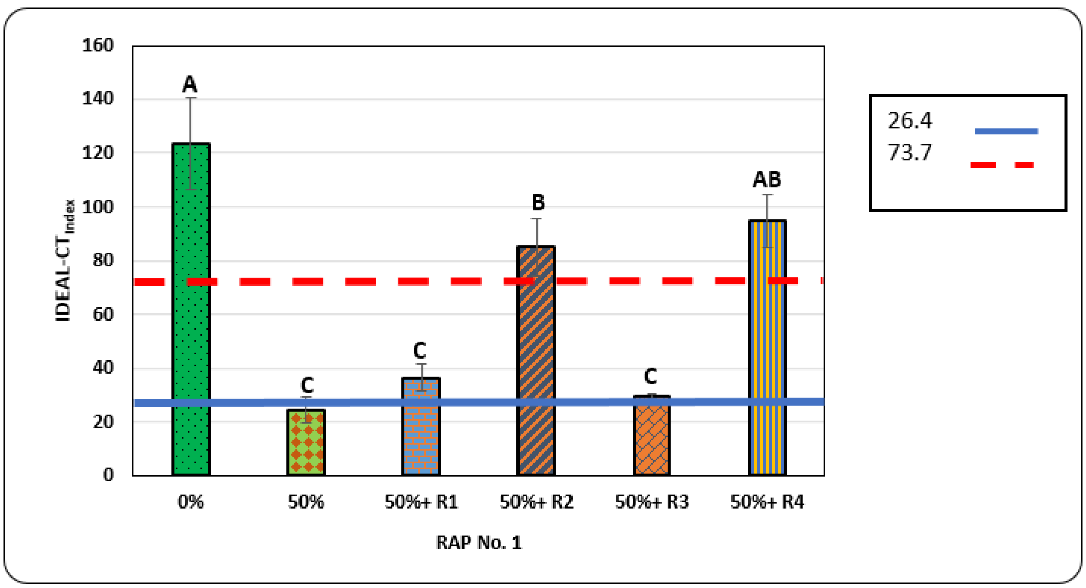


Figure 32. Effect of Rejuvenator Type on Cracking Performance at 50% RAP No. 1

Figure 33 shows the effect of rejuvenator type on the cracking performance for mixture prepared with 75 percent RAP. The results demonstrated that the use of R1, R2 and R4 improved the cracking resistance from poor to fair; however, the results of IDEAL-CT$_{Index}$ for R2 and R4 were not statistically significant different from the control mix (i.e., 75 percent RAP). Also, rejuvenator R3 improved the performance slightly but such improvement was not statistically significant.

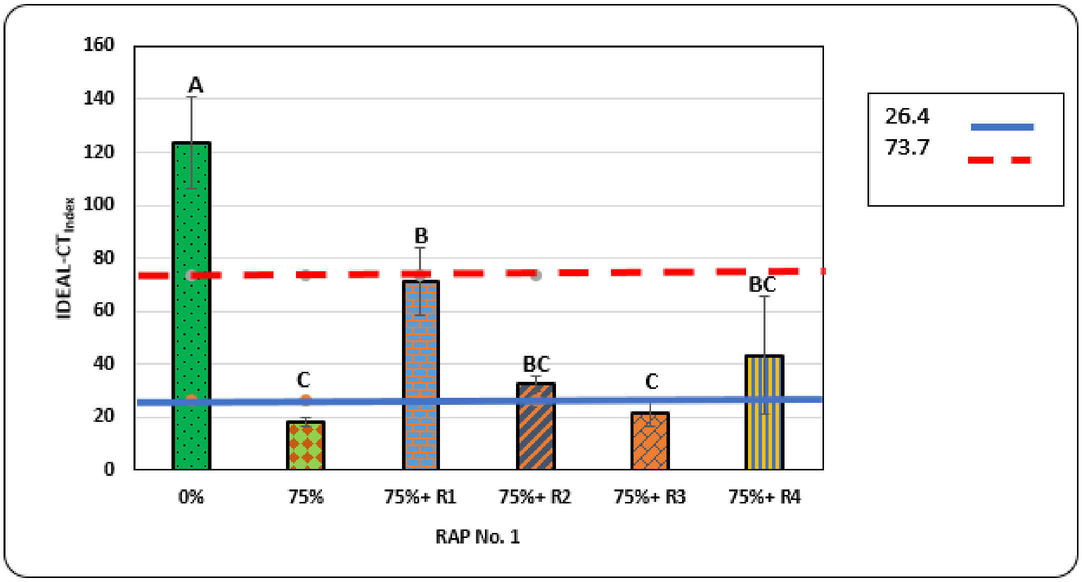


Figure 33. Effect of Rejuvenator Type on Cracking Performance at 75% RAP No. 1

Effect of Rejuvenator Dose

Figure 34 shows the effect rejuvenator dose on the IDEAL-CT$_{Index}$ results for mixtures prepared with 75 percent RAP. The researchers increased the dose for three rejuvenators (i.e., R2, R3, and R4). Two doses were evaluated for R2 (i.e., 10 and 12 percent by weight of reclaimed binder), two doses for R3 (i.e., 12.5 and 15 percent by weight of reclaimed binder), and two doses for R4 (i.e., 1 and 2 percent of weight of RAP). Increasing the rejuvenator dose for R2 improved the cracking performance, while it showed slight improvement for R3. On the other hand, the second dose of R4 adversely impacted the cracking resistance; however, such detrimental effect was not significant. These results clearly demonstrate that increasing the rejuvenator dose doesn't necessarily improve the cracking resistance. In some cases, it could adversely impact the cracking performance.

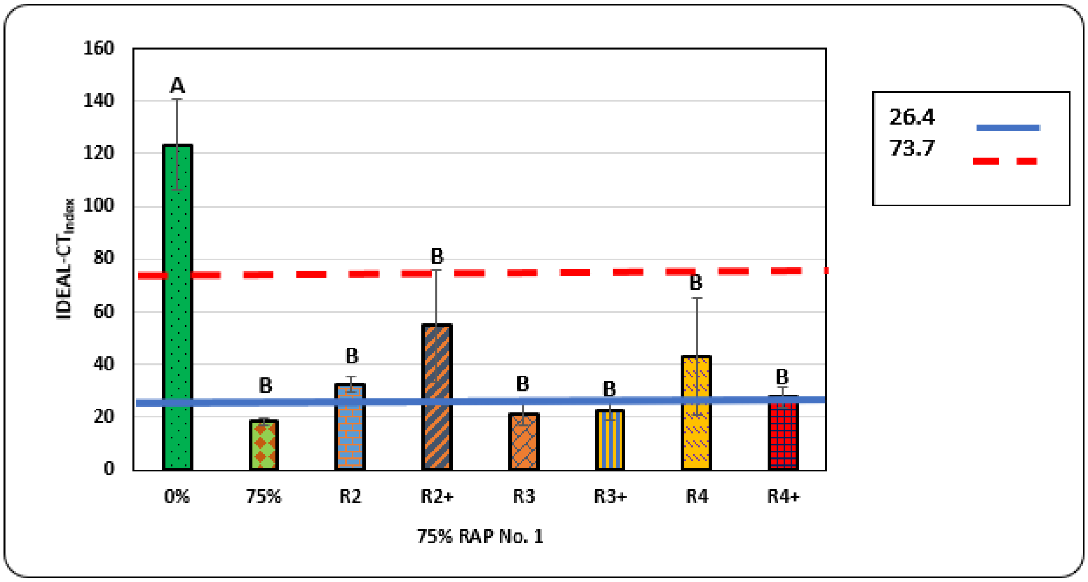


Figure 34. Effect of Rejuvenator Dose on Cracking Performance for RAP No. 1

Evaluation of RAP No. 2 Mixtures

RAP No.2 was obtained from an asphalt plant in Lewiston, Idaho. The researchers prepared and tested asphalt mixtures in the laboratory prepared using RAP No. 2 to evaluate the cracking performance at various RAP contents (i.e., 0 percent [control], 25 percent, 50 percent, and 70 percent), three different binder grades (i.e., PG 58-34, PG 64-28, and PG 70-28), two different binder contents (i.e., optimum binder content [OBC] and OBC+0.5 percent), five different rejuvenators (i.e., R1, R2, R3, R4, and R5), and two different doses of each rejuvenator. For R1, the researchers evaluated two doses of 5 percent and 7 percent by weight of total binder. For R2, two doses of 6 percent and 7 percent by weight of reclaimed binder for mixtures with 25 percent RAP, and 10 percent and 12 percent by weight of reclaimed binder for mixtures with 50 and 70 percent RAP. Also, two doses of 12.5 percent and 15 percent by weight of reclaimed binder were evaluated for R3. For R4, the researchers evaluated two doses of 1 percent and 2 percent by weight of RAP incorporated in the mixture. Finally, two doses of 12 percent and 16 percent by weight of reclaimed binder were examined for R5. Furthermore, the researchers conducted the creep compliance test to evaluate the low-temperature cracking as well as rutting testing for selected mixtures that exhibited good cracking performance.

Effect of RAP Content

Figure 35 shows the results of IDEAL-CT$_{Index}$ for test mixtures prepared with different RAP contents of RAP No. 2. The results demonstrated that IDEAL-CT$_{Index}$ decreased with the increase of RAP content. This trend is consistent with the results of RAP No. 1 (artificial RAP). The mixture without RAP (0 percent) had higher

IDEAL-CT_{Index} and fair cracking resistance (26.4 < IDEAL-CT_{Index} > 73.7) compared to mixtures prepared with RAP No. 2. Mixture with 25, 50, and 70 percent RAP which had poor cracking resistance (26.4 > IDEAL-CT_{Index}). In addition, there was a statistically significant difference in IDEAL-CT_{Index} results of control mixture compared to mixtures with 50 and 70 percent RAP. Also, there was no statistically significant difference in IDEAL-CT_{Index} for mixtures prepared with various RAP contents (i.e., 25, 50, and 70 percent RAP).

Figures 36 and 37 show the $IDT_{Strength}$ and $Weibull_{CRI}$ results for mixtures prepared at different RAP contents using RAP No. 2, respectively. The results showed that the $IDT_{Strength}$ consistently increased with the increase of RAP content which demonstrated that the mixtures became stiffer with the addition of RAP similar to the results of RAP No. 1. Furthermore, the results of $Weibull_{CRI}$ were consistent with that of IDEAL-CT_{Index} and the cracking performance decreased from fair (3.6 < $Weibull_{CRI}$ > 4.7) to poor ($Weibull_{CRI}$ < 3.6) with increasing RAP content. In this section, the researchers focused on the results of IDEAL-CT_{Index} and provided the $IDT_{Strength}$ and $Weibull_{CRI}$ results in Appendix E.

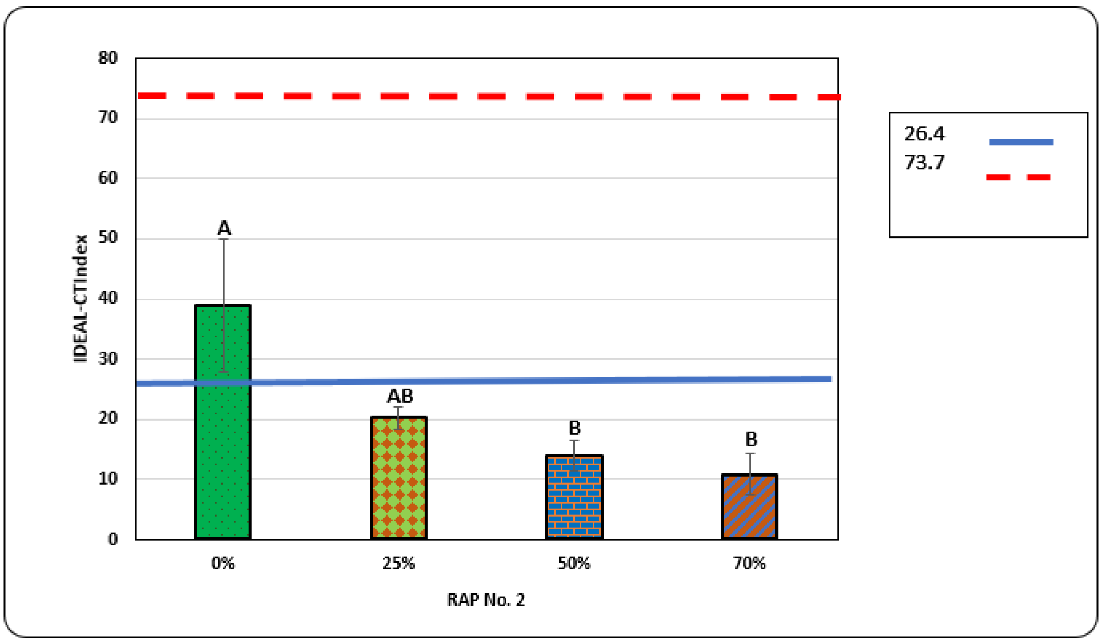


Figure 35. Effect of RAP Content on Cracking Performance for RAP No. 2

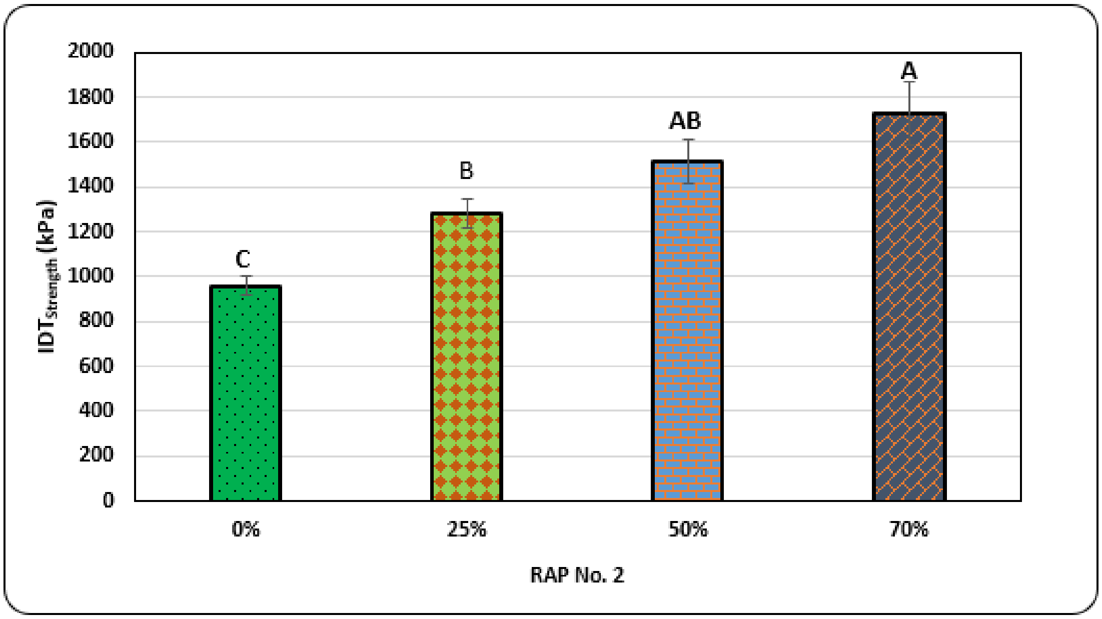


Figure 36. Effect of RAP Content of RAP No. 2 on $IDT_{Strength}$

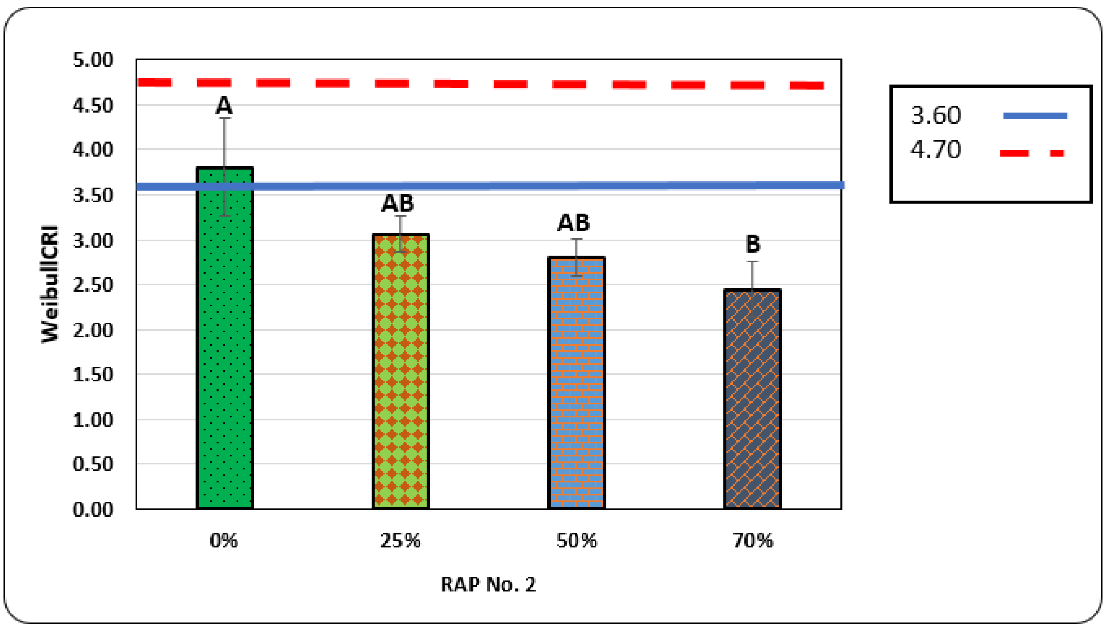


Figure 37. Effect of RAP Content of RAP No. 2 on $Weibull_{CRI}$

Effect of Rejuvenator Type

The researchers examined the effect of rejuvenator type at different doses on IDEAL-CT_{Index}. Figures 38, 40, and 41 show the effect of rejuvenators (i.e., R1, R2, R3, R4, and R5) at the first dose of each rejuvenator at 25, 50, and 70 percent RAP, respectively. The first dose was 5 percent by weight of total binder for R1, 10 percent by weight of reclaimed binder for R2, 12.5 percent by weight of reclaimed Binder weight for R3, 1 percent by weight of RAP for R4, and 12 percent by weight of reclaimed binder for R5. In addition, the researchers evaluated the mixtures at two different binder contents (i.e., OBC and OBC+0.5 percent). For mixtures with 25 percent of RAP No. 2 (Figure 38), the use of different rejuvenators results in improved cracking performance of higher IDEAL-CT_{Index} compared to mixtures with 25 percent RAP. Also, increasing the binder content by 0.5 percent above the optimum binder content increased the IDEAL-CT_{Index}. Meanwhile, the statistical analysis demonstrated that such improvement was not statistically significant. Also, increasing the binder content by 0.5 percent above the optimum binder content for mixtures without RAP (0 percent RAP) resulted in good cracking resistance (IDEAL-CT_{Index} > 73.7) compared to mixtures without RAP at optimum binder content which had fair cracking resistance (26.4<IDEAL-CT_{Index} > 73.7) and the difference in IDEAL-CT_{Index} results was statistically significant.

Similarly, all rejuvenators improved the cracking resistance for mixtures prepared with 50 percent RAP; however, such improvement was not statistically significant as shown in Figure 39. Meanwhile, R3 and R4 provided fair cracking performance comparable to the mixture without RAP (i.e., 0 percent RAP). Figure 40 shows the cracking performance at higher RAP content of 70 percent. All mixtures with rejuvenators had better cracking resistance (i.e., higher IDEAL-CT_{Index}) compared to the control mixture (i.e., mixture with 70 percent RAP without rejuvenators). Mixtures with R4 exhibited statistically significant improvements compared to the control mixture. Also, increasing the binder content by 0.5 percent at 70 percent RAP increased IDEAL-CT_{Index} and improved the cracking performance from poor to fair. Next, the researchers evaluated the effect of different rejuvenator doses at various RAP contents as discussed in the following section.

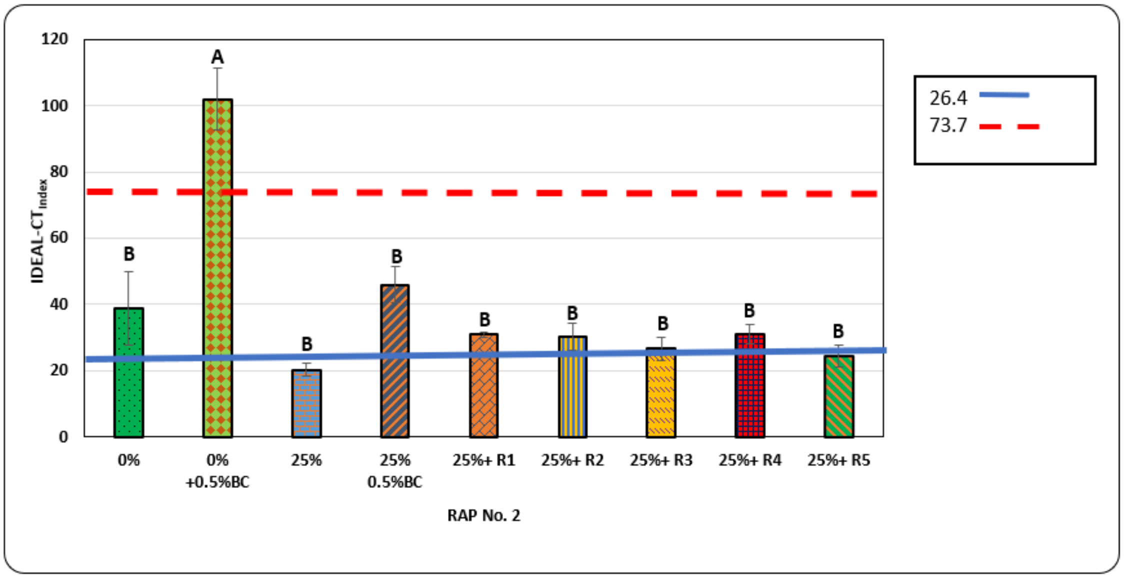


Figure 38. Effect of Rejuvenator Type on Cracking Performance at 25% RAP No. 2

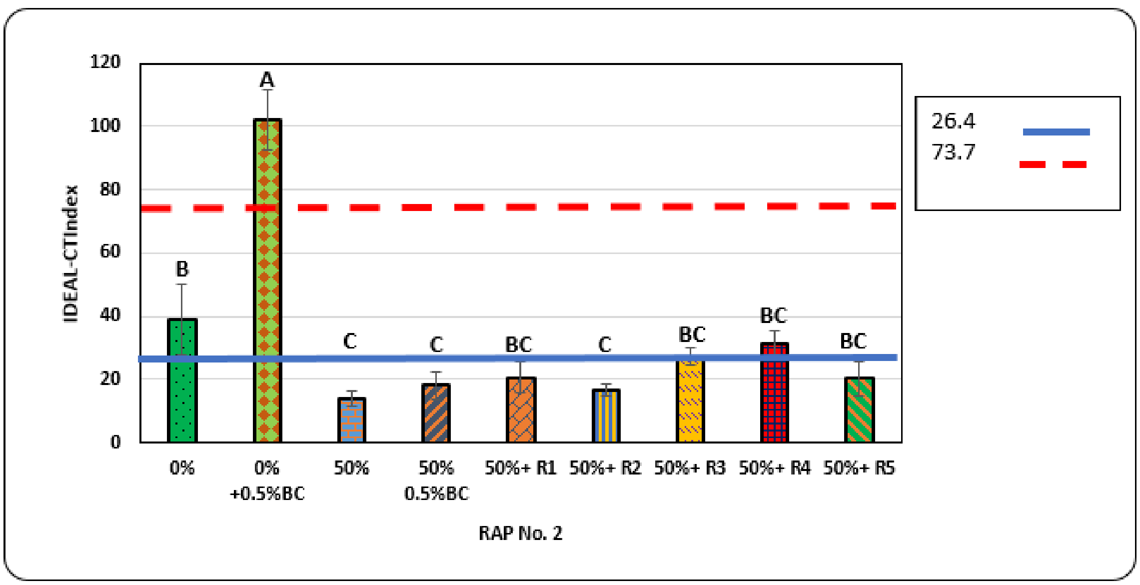


Figure 39. Effect of Rejuvenator Type on Cracking Performance at 50% RAP No. 2

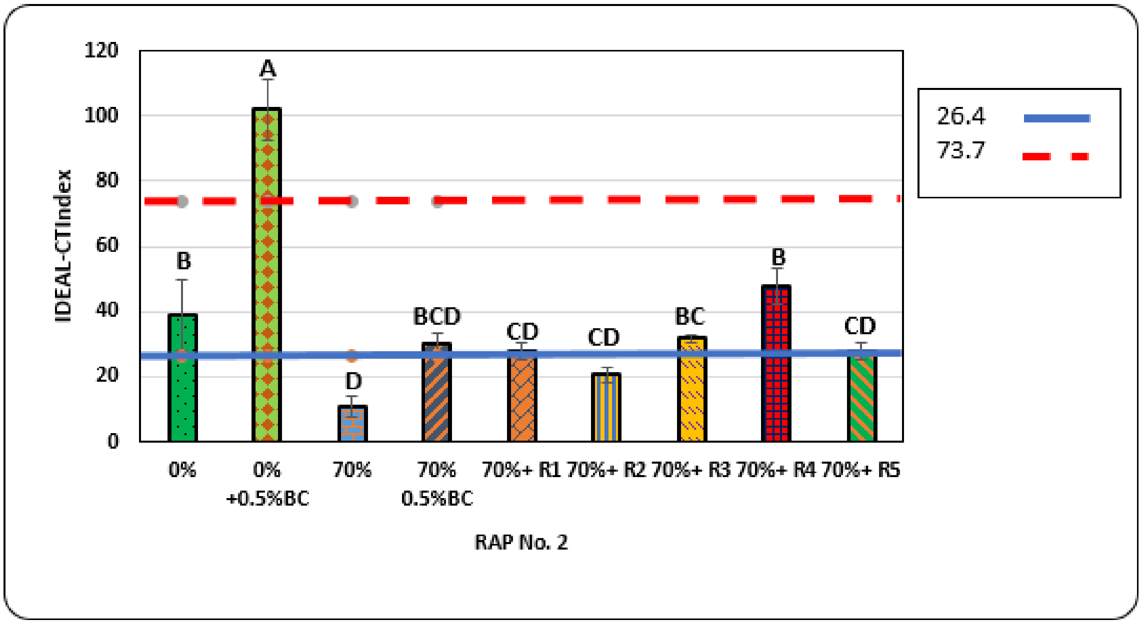


Figure 40. Effect of Rejuvenator Type on Cracking Performance at 70% RAP No. 2

Effect of Rejuvenator Dose

The researchers evaluated the effect of various rejuvenator doses at different RAP contents. The researchers increased the dose for five rejuvenators (i.e., R1, R2, R3, R4, and R5). Two doses were evaluated for each rejuvenator as follows: R1 (5 percent and 7 percent by weight of total binder), R2 (6 percent and 7 percent by weight of reclaimed binder for mixtures with 25 percent RAP, and 10 percent and 12 percent by weight of reclaimed binder for mixtures with 50 and 70 percent RAP), R3 (12.5 and 15 percent by weight of reclaimed binder), R4 (i.e., 1 and 2 percent of weight of RAP), and R5 (12 and 16 percent by weight of reclaimed binder). Figures 41, 42, and 43 show the IDEAL-CT_{Index} results for mixtures prepared with 25, 50, and 70 percent RAP, respectively. The following findings were found.

- Mixtures prepared with 25 percent RAP showed improved performance at higher rejuvenator dose (i.e., R1+, R2+, R3+, and R4+) compared to the control mixture with 25 percent RAP at optimum binder content (OBC). Also, the difference in IDEAL-CT_{Index} results was statistically significant for R1 at higher dose (R1+) and R3 at higher dose (R3+).
- Mixtures prepared with 50 percent RAP showed improved performance at higher rejuvenator dose compared to the first dose and compared to the control mixture with 50 percent without rejuvenators. The use of R1+, R3+, and R4+ improved the cracking resistance from poor cracking performance (26.4 > IDEAL-CT_{Index}) for the control mixture (i.e., 50 percent RAP) to moderate cracking performance (IDEAL-CT_{Index} between 26.4 and 73.7). The IDEAL-CT_{Index} of R4 at a higher dose was statistically significantly different compared to the control mixture and provided the best cracking performance among all examined rejuvenators.

- Mixtures prepared with 70 percent RAP showed improved performance at higher rejuvenator dose (i.e., R1+, R3+, R4+, and R5+) compared to the first dose and compared to the control mixture prepared with 70 percent RAP, for all rejuvenators except for R2. Also, the results demonstrated that R4 at higher dose exhibited the best performance among all examined rejuvenators at different doses, even better than the mixture without RAP. However, this mixture was relatively wet (i.e., soft) and it failed in rutting as discussed later in this chapter. These results demonstrated the importance of the balanced mix design approach to satisfy both cracking and rutting criteria. Also, R1 and R5 improved the cracking resistance significantly when compared to the control mix (70 percent RAP) and provided comparable cracking performance to the mixture without RAP.

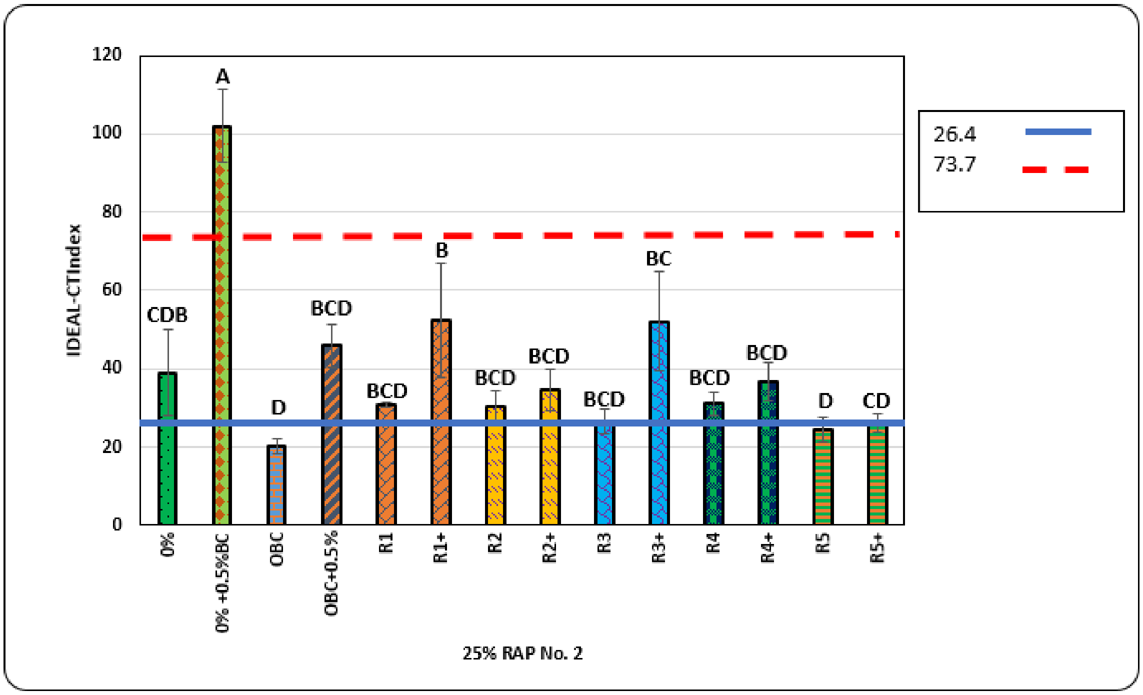


Figure 41. Effect of Rejuvenator Dose on Cracking Performance at 25% on RAP No. 2

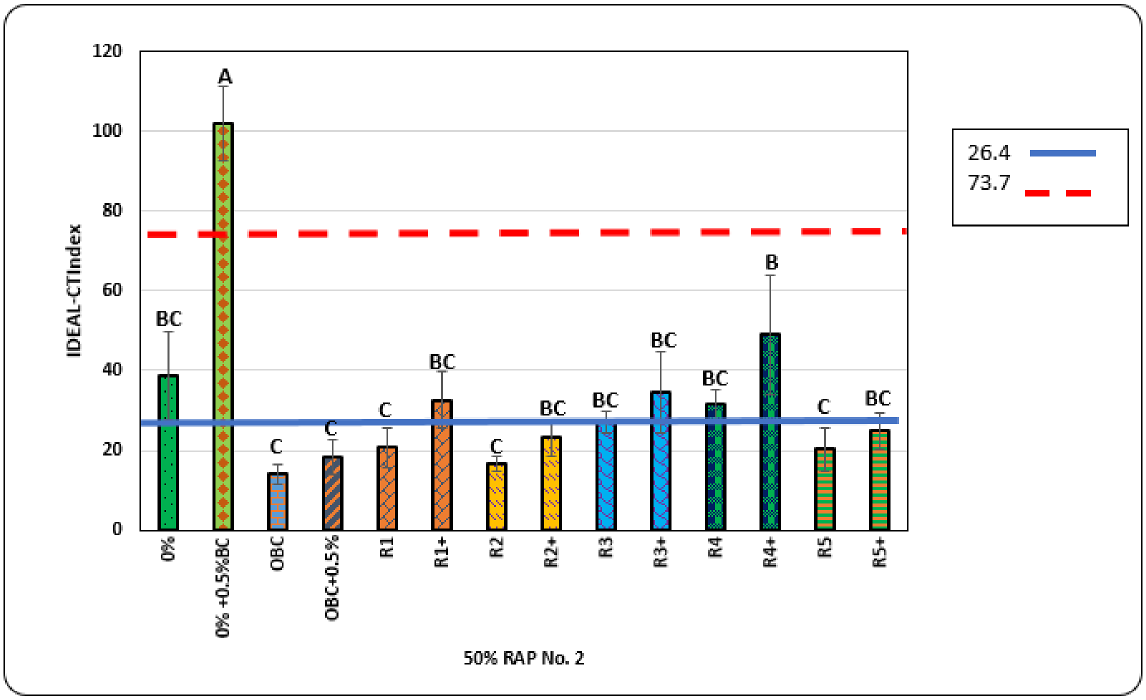


Figure 42. Effect of Rejuvenator Dose on Cracking Performance at 50% on RAP No. 2

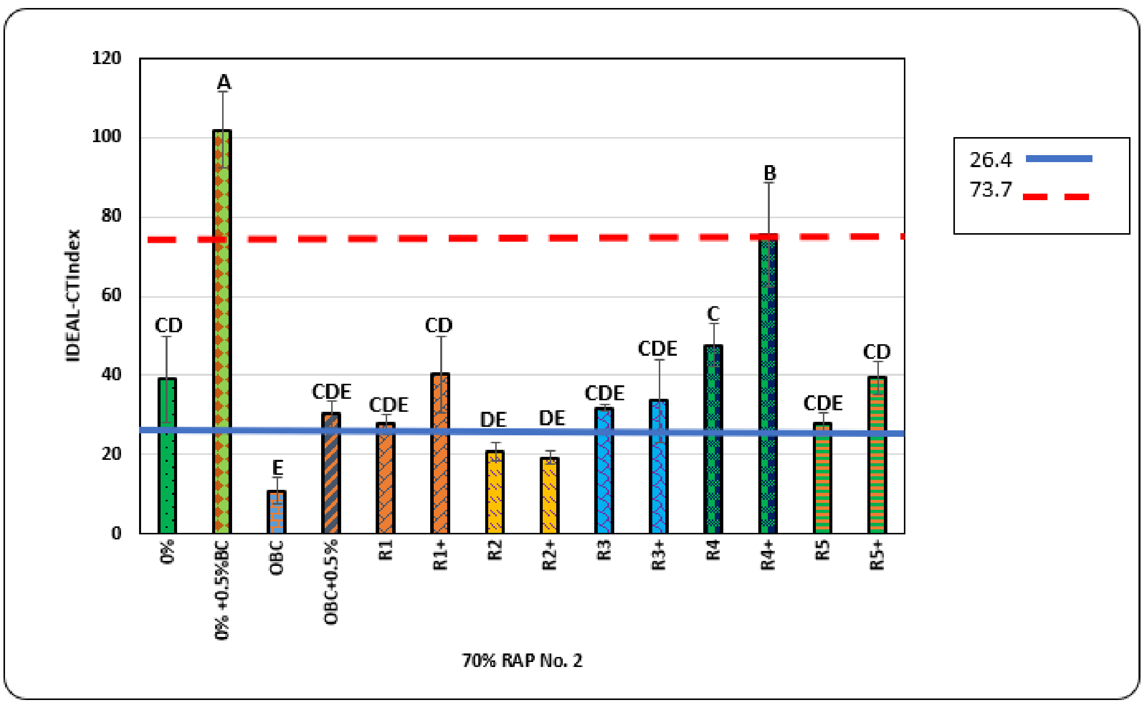


Figure 43. Effect of Rejuvenator Dose on Cracking Performance at 70% on RAP No. 2

Effect of Rejuvenator on Cracking Performance of Mixtures with Different Binder Grades

Based on the results of the previous section, R1 and R5 were selected for further evaluation at higher dose with different binder grades (i.e., PG 58-34, PG 64-28, and PG 70-28). The objective of this evaluation was to assess the positive impact of these two rejuvenators at higher doses for mixtures prepared with different binder grades. It should be noted that R4 also provided good cracking performance but produced relatively softer mixtures susceptible to rutting; therefore, it was not included in this additional evaluation.

Figure 44 shows the IDEAL-CT_{Index} results for mixtures prepared without RAP (0 percent RAP) and 70 percent RAP, with and without rejuvenators (I.e., R1 and R5 at higher doses) with different binder grades. In addition, Figures 45 and 46 show the $IDT_{Strength}$ and $Weibull_{CRI}$, respectively. The main findings of the results can be summarized below.

- Mixtures prepared with 70 percent RAP had lower IDEAL-CT_{Index} values compared to the ones without RAP (0 percent RAP) irrespective of the binder grade. Mixtures with RAP had poor cracking resistance (26.4>IDEAL-CT_{Index}) compared to the control mixture with moderate cracking resistance (IDEAL-CT_{Index} between 26.4 and 73.7).
- The binder grade did not affect the IDEAL-CT_{Index} for mixtures without RAP (0 percent RAP) and those prepared with 70 percent RAP. However, the $IDT_{Strength}$ for mixtures with PG 64-28 and PG 70-28 was higher compared to the ones for PG 58-34 for the mixtures without RAP. The results of $IDT_{Strength}$ were comparable for mixtures of different binder grades at higher RAP content (70 percent RAP) which demonstrates stiffer mixtures.
- The use of R5 resulted in significantly improved the cracking performance (higher IDEAL-CT_{Index}) compared to mixtures with 70 percent RAP without rejuvenators irrespective of the binder grade. In addition, the use of R5 resulted in comparable cracking performance to the mixtures without RAP at the corresponding binder grade. The $IDT_{Strength}$ results further demonstrated that R5 was effective in reducing the mixture stiffness irrespective of the binder grade too.
- Mixtures prepared with 70 percent RAP and rejuvenator R1 showed improved cracking performance compared to mixtures at the same RAP content without rejuvenator. Also, there was significant improvement in IDEAL-CT_{Index} results for mixtures with PG 58-34 and PG 64-28. Therefore, R1 provided better results with softer binders which could be attributed to the compatibility between asphalt binders and rejuvenators. Also, the use of R1 resulted in comparable cracking performance to the mixtures without RAP for PG 58-34 and PG 64-28.
- The results of $Weibull_{CRI}$ shown in Figure 46 had the same trend as the IDEAL-CT_{Index} results, and there was good agreement between both performance indicators.
- The results of this section clearly demonstrated the effectiveness of rejuvenators in improving the cracking performance at higher RAP content which offers significant environmental and economic benefits. The associated cost savings are discussed in Chapter 6.

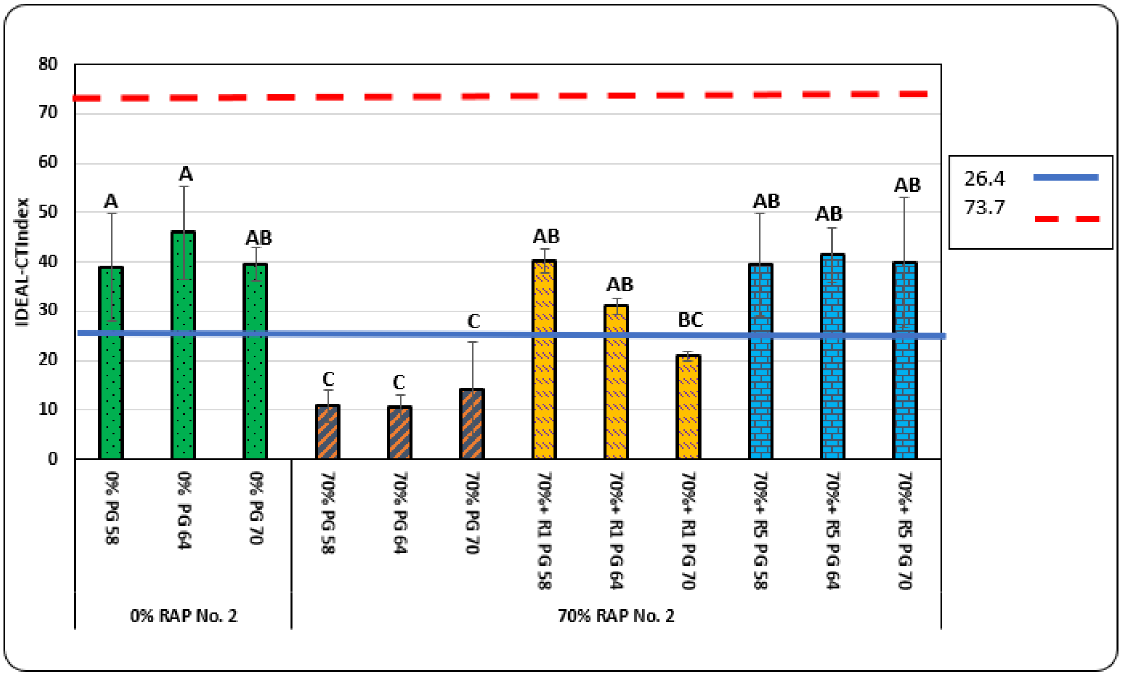


Figure 44. Effect of Rejuvenator on Cracking Performance for Different Binder Grades

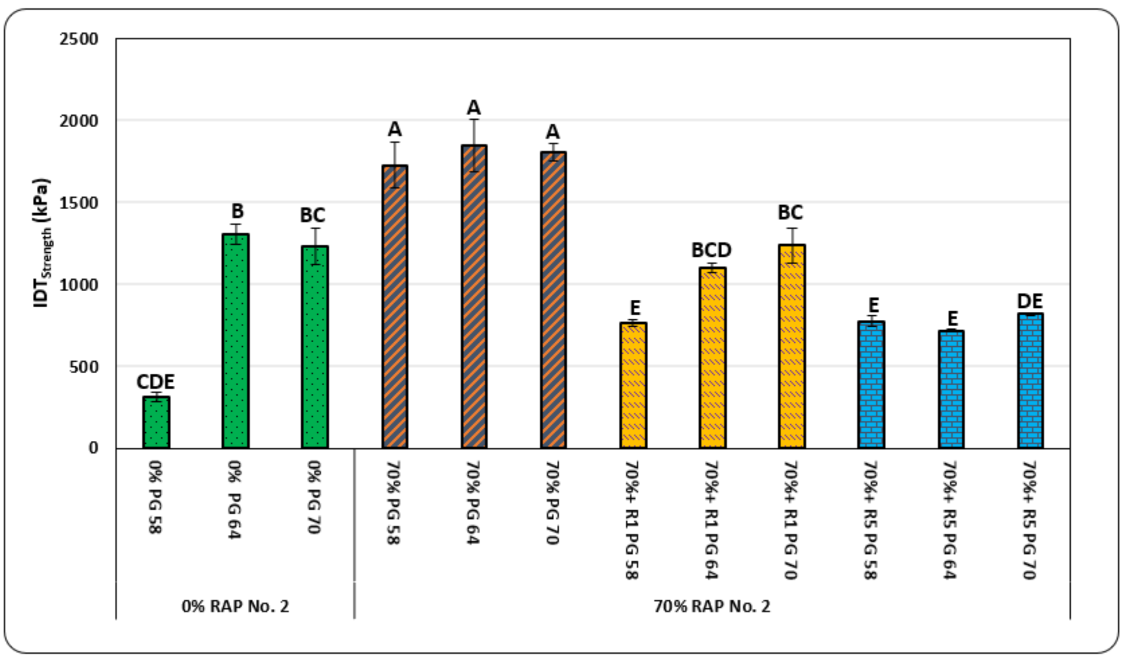


Figure 45. Effect of Rejuvenator on $IDT_{Strength}$ for Different Binder Grades

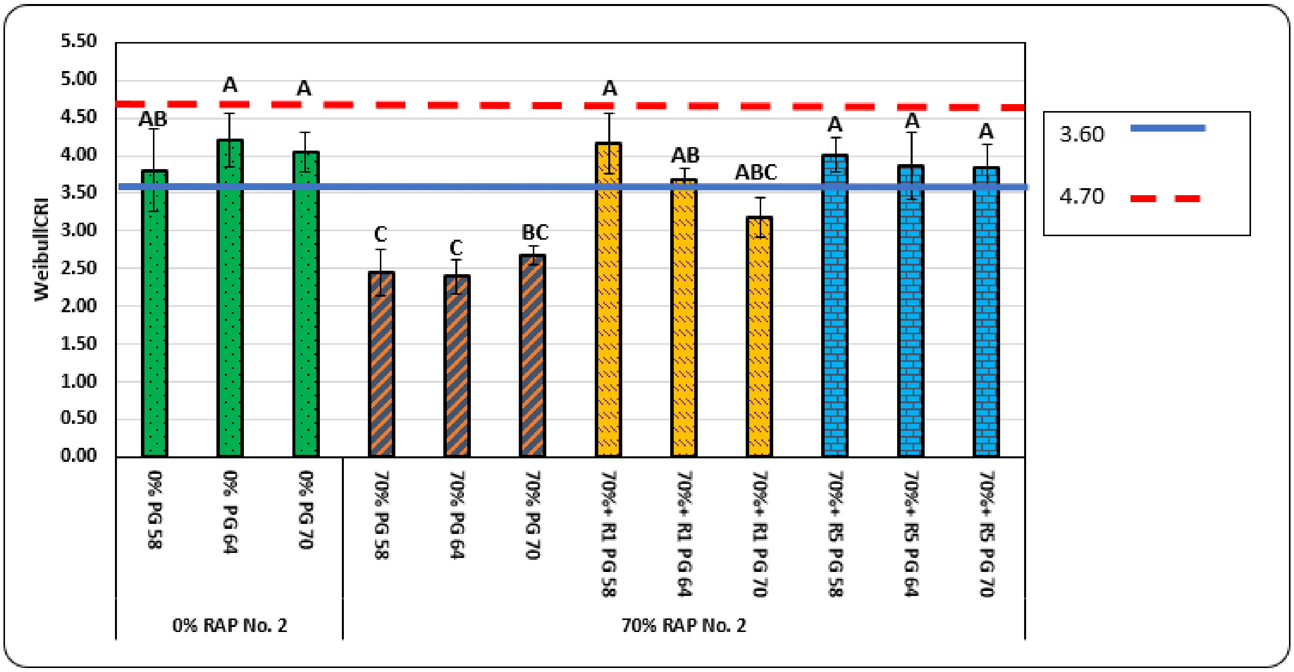


Figure 46. Effect of Rejuvenator on Weibull$_{CRI}$ for Different Binder Grades Effect of Rejuvenators

Evaluation of Rutting Performance

To ensure that mixtures prepared with RAP and rejuvenators attain good resistance to rutting, the researchers evaluated the rutting performance using the HWTT. Test mixtures prepared with RAP and rejuvenators that exhibited improved cracking performance were further evaluated for rutting performance. Mixtures without RAP (i.e., 0 percent RAP) and with 70 percent RAP, prepared without rejuvenators and with rejuvenators (i.e., R1, R4, and R5) at different rejuvenator doses (i.e., 7 percent by weight of total binder for R1, 1 percent and 2 percent by wight of RAP for R4, and 12 percent and 16 percent by weight of reclaimed binder for R5) were tested.

Figure 47 shows the HWTT rut depth results. Mixtures prepared with R4 at two different doses (i.e., R4 and R4+) failed HWTT. Mixtures with R4 at 1 percent by weight of RAP accumulated rut depth of 12.5 mm after 7060 passes, while mixtures with R4 at 2 percent by weight of RAP reached 12.5 mm rut depth after only 2470 passes. Rejuvenator R4 over softened the asphalt mixtures, and this was observed during the laboratory preparation of these mixtures. It should be noted that R4, which is an engineered commercial product, had the lowest viscosity among all test rejuvenators. All remaining test mixtures, including the ones prepared with R1 and R5, experienced very low rutting (rut depth less than 3 mm after 20,000 passes) and passed the test criteria of 12.5 mm after 20,000 passes. Mixtures prepared with R1 and R5 had comparable rutting performance to that of mixtures with RAP (70 percent RAP) and mixtures without RAP and rejuvenators. Figures 48 and 49 further illustrate the rutting performance of asphalt mixtures prepared with R4 at 1 percent dose and 2 percent dose, respectively.

The results of this section further demonstrated the importance of the balanced mix design approach to produce asphalt mixtures with adequate resistance to cracking and rutting. Some mixtures prepared with certain rejuvenators (R4 as an example) had good cracking resistance but failed the rutting resistance criteria; therefore, it is important to ensure that mixtures prepared with RAP and rejuvenators achieve balanced performance.

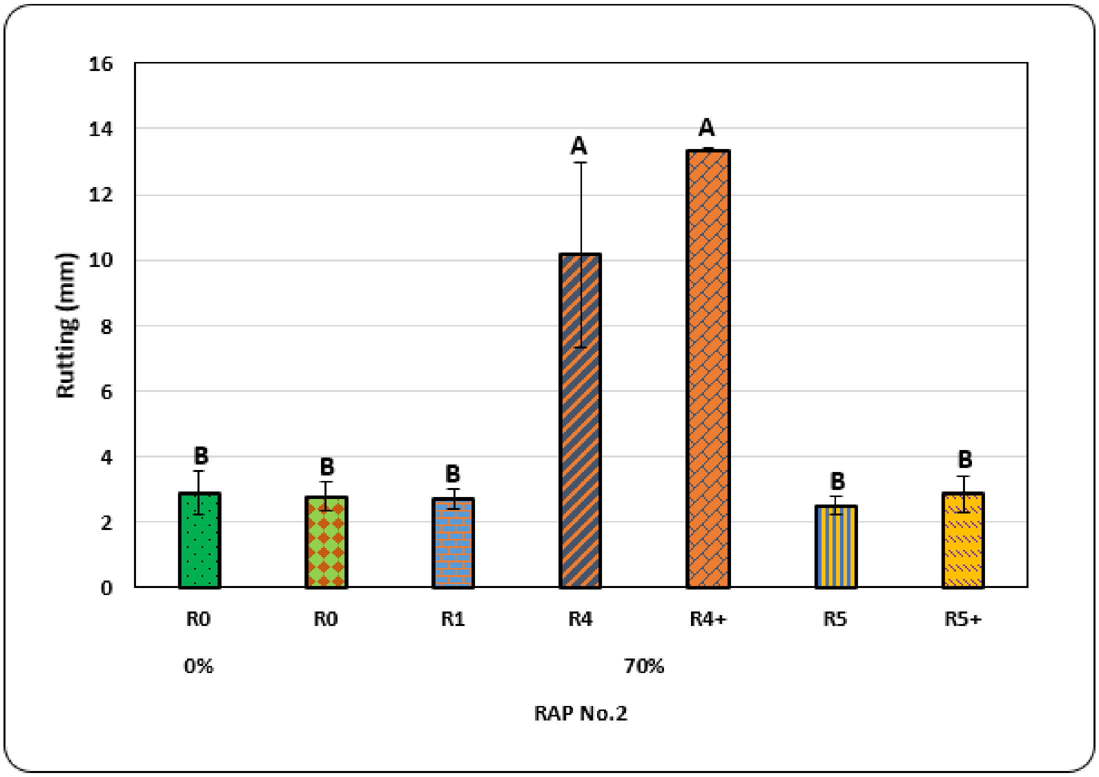


Figure 47. Evaluation of HWTT Rutting Performance of Asphalt Mixtures with RAP No. 2

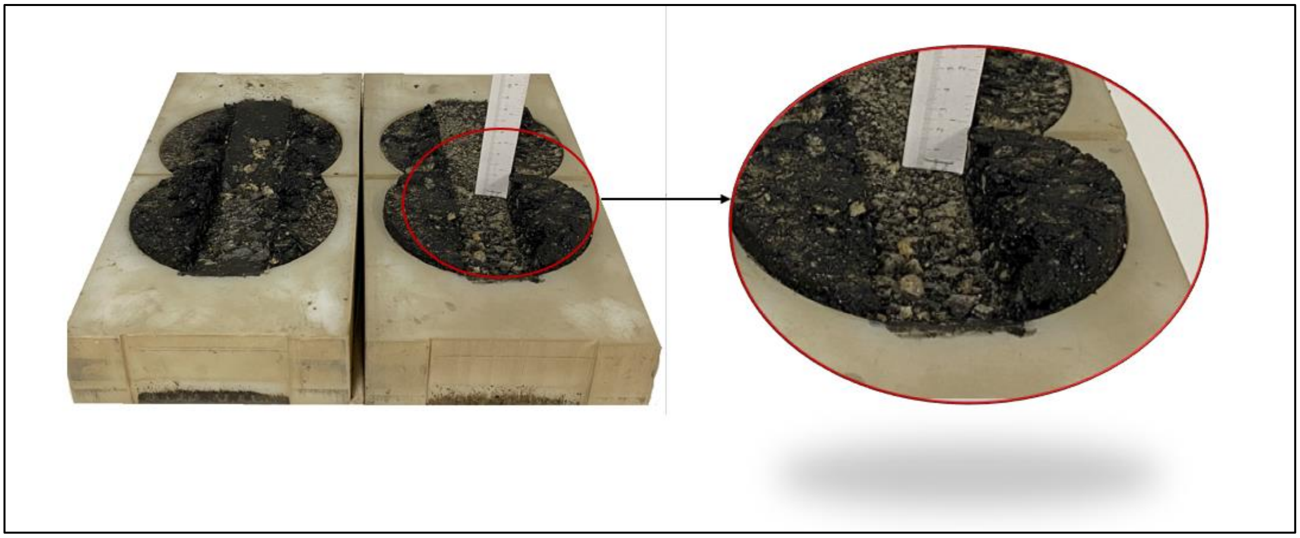


Figure 48. HWTT Test Specimens with 70% RAP and Rejuvenator 4 at 1 Percent Dose

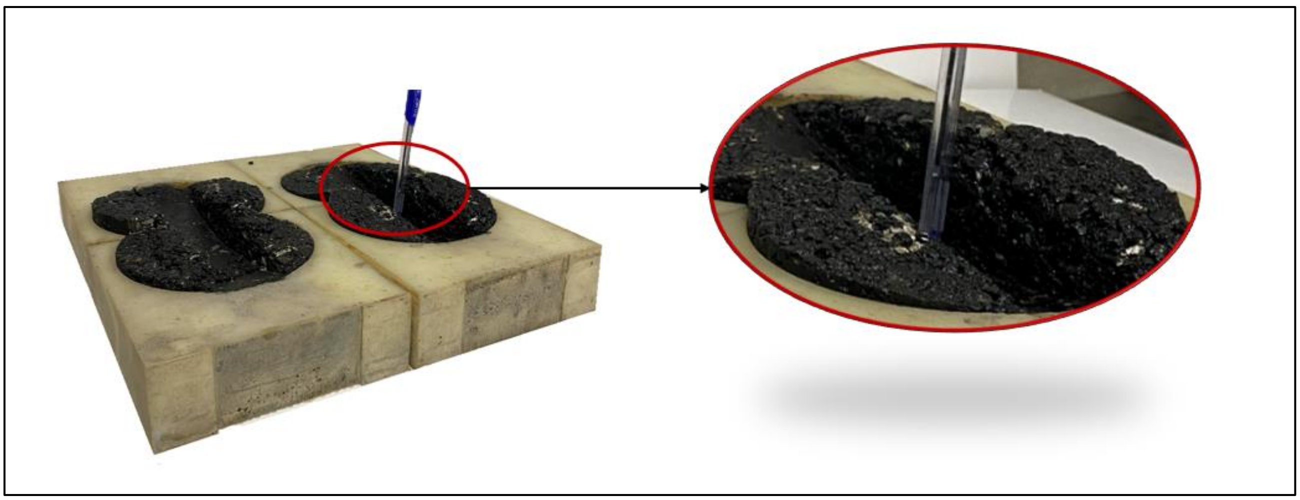


Figure 49. HWTT Test Specimens with 70% RAP and Rejuvenator 4 at 2 Percent Dose

Evaluation of RAP No. 3 Mixtures

RAP No.3 was obtained from a second asphalt plant in Lewiston, Idaho. The researchers evaluated the cracking performance of asphalt mixtures prepared without RAP (0 percent RAP), 70 percent RAP, two different rejuvenators (i.e., R1 and R5) at optimum binder content (5.8 percent of PG 58-28). For rejuvenator R1, the dose was 7 percent by weight of total binder and 16 percent by wight of reclaimed binder for R5. These doses were found to provide good cracking performance based on the testing results of mixtures prepared with RAP No. 2. In addition, the researchers evaluated the rutting performance and moisture susceptibility of test mixture using the HWTT. Furthermore, the researchers investigated the low temperature cracking performance in accordance with AASHTO T 322 "*Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device*".

Effect of RAP and Rejuvenator Type

Similar to mixtures prepared with RAP No. 1 and RAP No. 2, incorporating 70 percent RAP of RAP No. 3, resulted in stiffer mixtures with lower IDEAL-CT_{Index} compared to the control mixture without RAP. Mixtures prepared with 70 percent RAP showed poor cracking resistance (26.4 > IDEAL-CT_{Index}) while mixture without RAP had moderate performance (IDEAL-CT_{Index} between 26.4 and 73.7) as shown in Figure 50. The use of R1 and R5 increased IDEAL-CT_{Index} which indicates improved cracking performance. Both rejuvenators produced mixtures with good cracking performance (IDEAL-CT_{Index} >73.7) compared to the control mixture which exhibited moderate cracking resistance (IDEAL-CT_{Index} between 26.4 and 73.7). The results of Figure 50 further demonstrated that increasing the binder content by 0.5 percent at 70 percent RAP (70 percent + 0.5BC) increased IDEAL-CT_{Index} compared to mixtures prepared at optimum binder content and 70 percent RAP, and such improvement was statistically significant. Meanwhile, mixtures with no RAP at a higher binder content (0.5 percent above optimum binder content) provided better cracking performance compared to mixtures with no RAP at optimum binder content and compared to mixtures with 70 percent RAP at optimum binder content.

Figures 51 and 52 show the results of $IDT_{Strength}$ and $Weibull_{CRI}$, respectively. Mixtures prepared with high RAP content (i.e., 70 percent RAP) had higher $IDT_{Strength}$ compared to mixtures without RAP (0 percent RAP); however, such increased stiffness was associated with reduced cracking resistance (lower $Weibull_{CRI}$ and IDEAL-CT_{Index}). The results of loose mixtures presented in Chapter 5 showed that this an opposite correlation between $IDT_{Strength}$ and both IDEAL-CT_{Index} and $Weibull_{CRI}$. Furthermore, the results of $Weibull_{CRI}$ were consistent with that of IDEAL-CT_{Index}. Increasing the binder content and the use of rejuvenators (i.e., R1 and R5) were found to be very effective in improving the cracking resistance based on the $Weibull_{CRI}$ results.

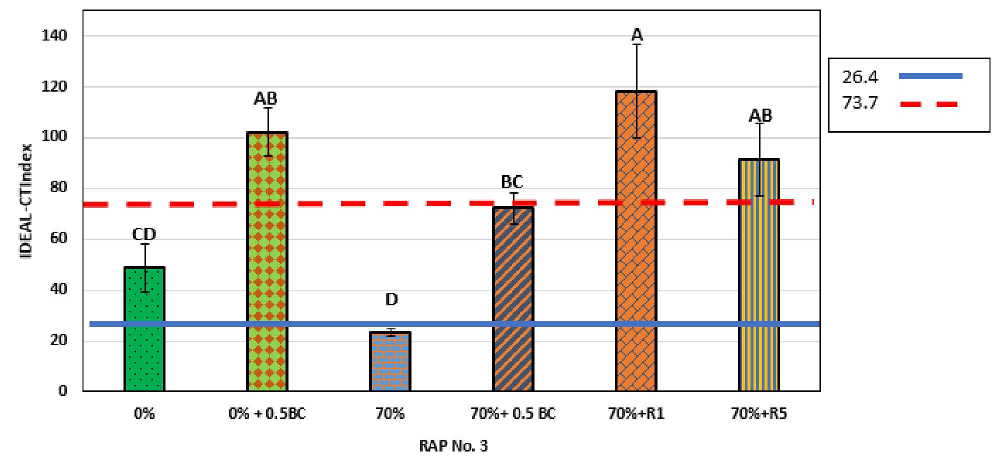


Figure 50. Effect of RAP Content and Rejuvenator Type on IDEAL-CT_{Index} for RAP No. 3

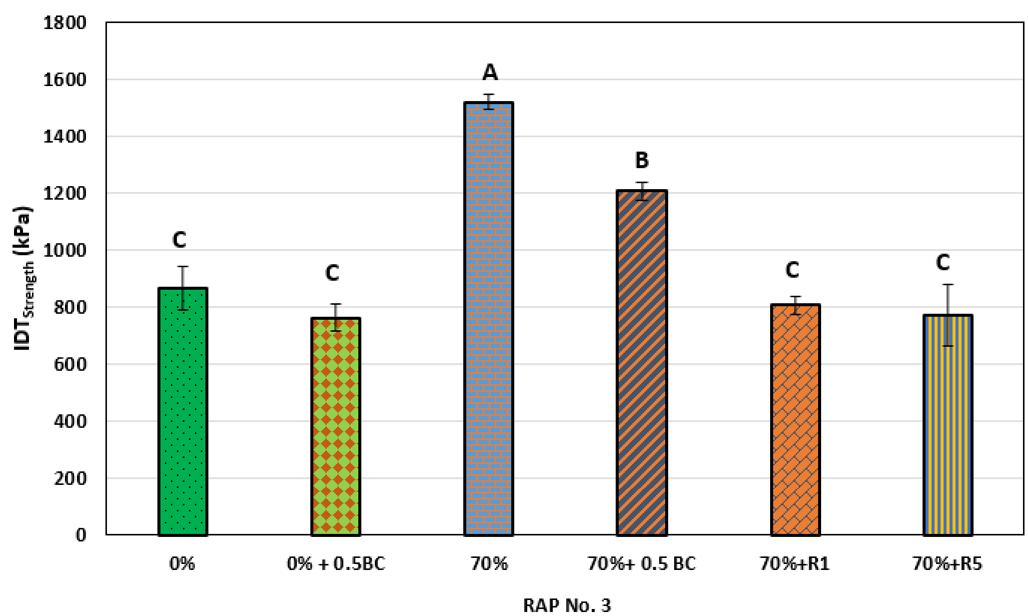


Figure 51. Effect of RAP Content and Rejuvenator Type on $IDT_{Strength}$ for RAP No. 3

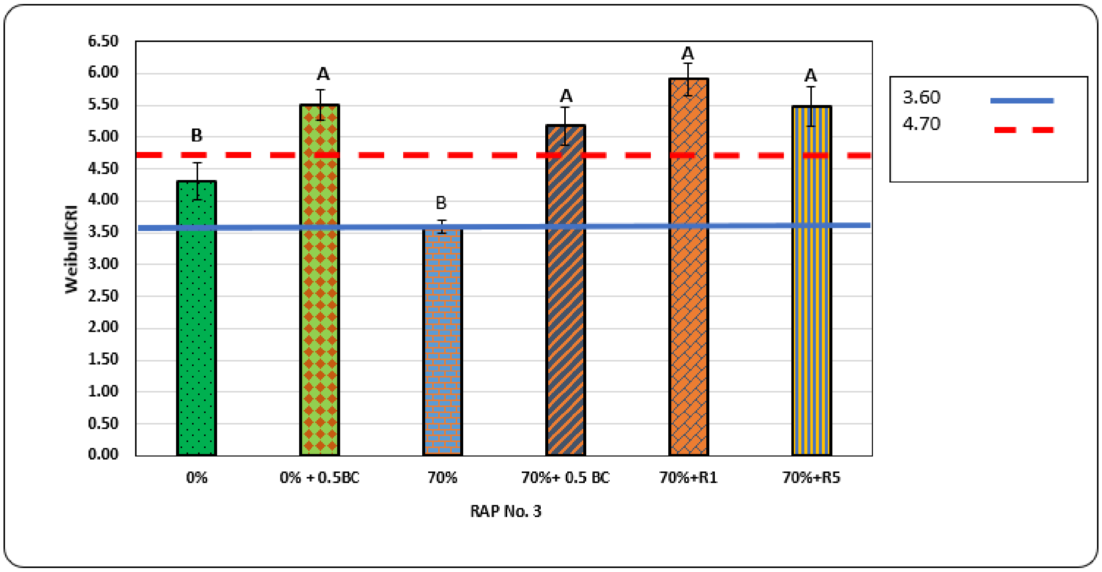


Figure 52. Effect of RAP Content and Rejuvenator Type on Weibull_{CRI} for RAP No. 3

Evaluation of Low-Temperature Cracking

Researchers further evaluated the low-temperature or thermal cracking of mixtures prepared with RAP No. 3 and rejuvenators. They evaluated mixtures without RAP (0 percent RAP), 70 percent RAP, and 70 percent RAP with rejuvenators R1 and R5. Previous study by Safi et al. (2018) showed that stiffer mixtures tend to have lower deformation and thus lower compliance. Figures 53 through 55 show the creep compliance for the test mixtures at different temperatures of -20 °C, -10 °C, 0 °C, respectively. Figure 56 shows the creep compliance at all test temperatures. Also, Figure 57 shows the $\text{IDT}_{\text{Strength}}$ for the same mixtures measured at -10 °C after the completion of creep compliance testing. The main findings of these results can be summarized below.

- Mixtures with 70 percent RAP had the lowest creep compliance compared to mixtures without RAP (i.e., 0 percent RAP), and mixtures prepared with 70 percent RAP with rejuvenators R1 and R5 (i.e., 70 percent+R1 and 70 percent+R5). Lower compliance values are associated with stiffer mixtures and less resistance to low-temperature or thermal cracking.
- Mixtures prepared with 70 percent RAP and R1 and R5 had the highest creep compliance and consequently would exhibit better resistance to thermal cracking compered to mixtures with 70 percent RAP without rejuvenators as well as mixtures without RAP and rejuvenators. Also, mixtures without RAP and rejuvenators had higher creep compliance than those of mixtures with 70 percent RAP without rejuvenators and lower creep compliance than mixtures with rejuvenators. These results demonstrated that the use of rejuvenators (i.e., R1 and R5) were

found effective in improving the thermal cracking resistance of asphalt mixtures with high RAP content (i.e., 70 percent).

- The results of $IDT_{Strength}$ measured at -10 °C demonstrated that mixtures without RAP and rejuvenators had comparable $IDT_{Strength}$ values with no statistically significant difference in the results.
- The use of rejuvenators reduced the $IDT_{Strength}$ compared to mixtures without rejuvenators (with and without RAP). Mixtures with R5 had the lowest $IDT_{Strength}$ compared to all other mixtures. In addition, the difference in $IDT_{Strength}$ results between mixtures with R5 and mixtures without rejuvenators was statistically significant.
- There is a good agreement between the results of $IDT_{Strength}$ (measured at -10 °C) and that of the creep compliance test. The results further demonstrated the favorable impact of rejuvenators on improving the performance of asphalt mixtures with high RAP content at low temperature.

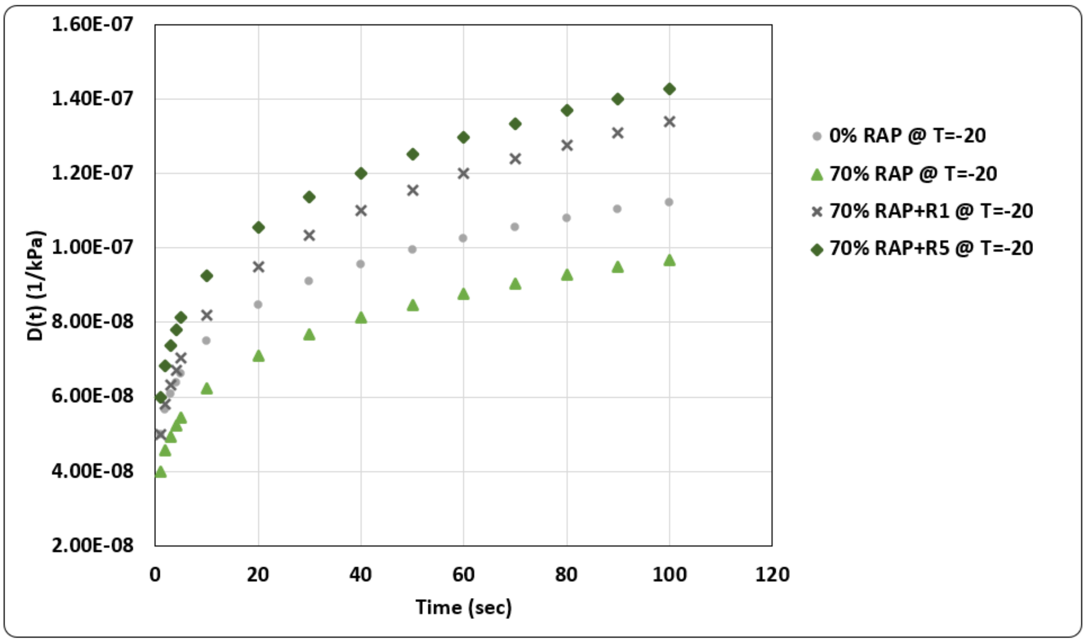


Figure 53. Creep Compliance Results at -20 °C

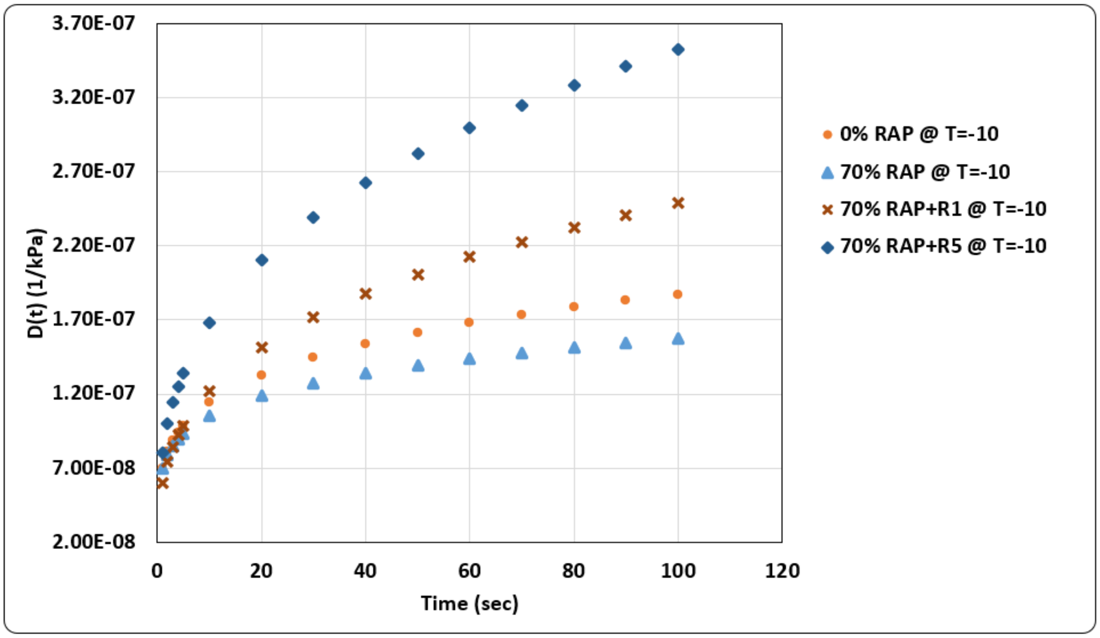


Figure 54. Creep Compliance Results at -10 °C

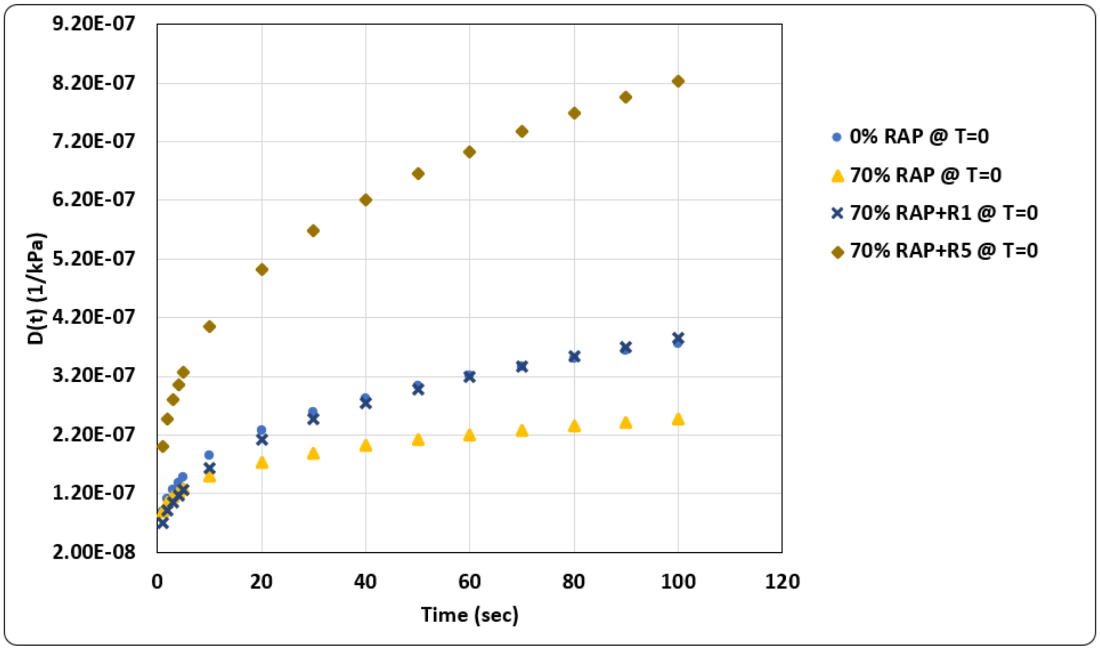


Figure 55. Creep Compliance Results at 0 °C

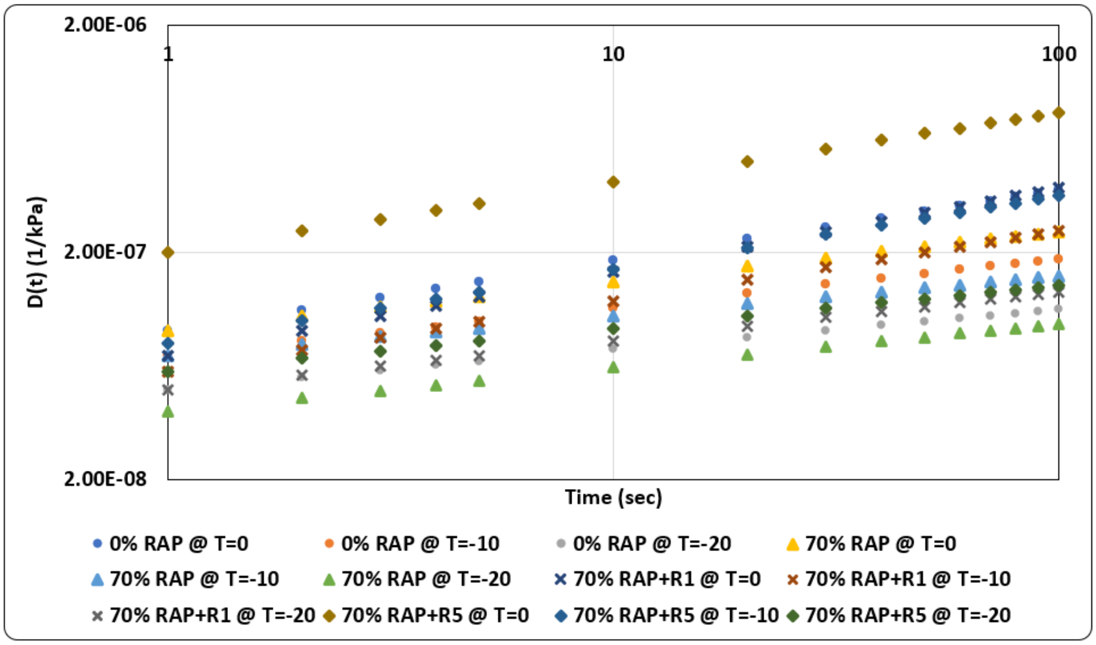


Figure 56. Creep Compliance Results at Different Temperatures

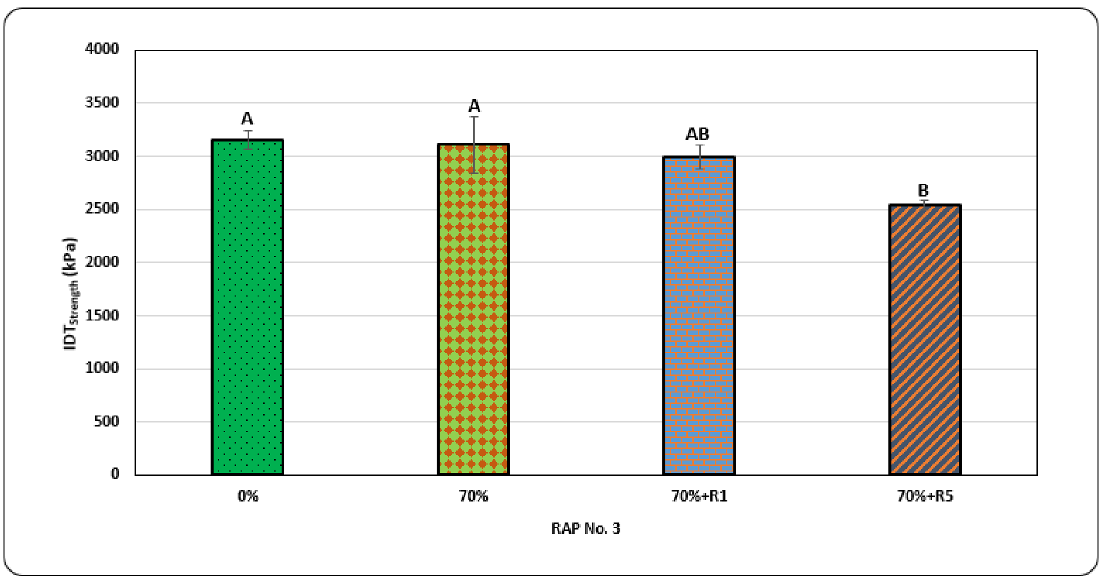


Figure 57. Measured $IDT_{Strength}$ of Test Mixtures at -10 °C

Evaluation of Rutting Performance

Mixtures prepared with 70 percent of RAP No. 3 and rejuvenators R1 and R5 all passed HWTT rutting criteria. The rut depth values after 20,000 passes were way below the rutting threshold of 12.5 mm as shown in Figure 58. Furthermore, there was no sign of moisture damage. In addition, the results showed that there was no statistically significant difference in the rut depth results between mixtures with rejuvenators and high RAP content of 70 percent and the control mixture with no RAP. These results demonstrated that the use of rejuvenators R1 and R5 at high RAP content of 70 percent produced mixtures with good resistance to intermediate-temperature as well as low-temperature cracking. In addition, these mixtures exhibited good resistance to rutting and moisture damage.

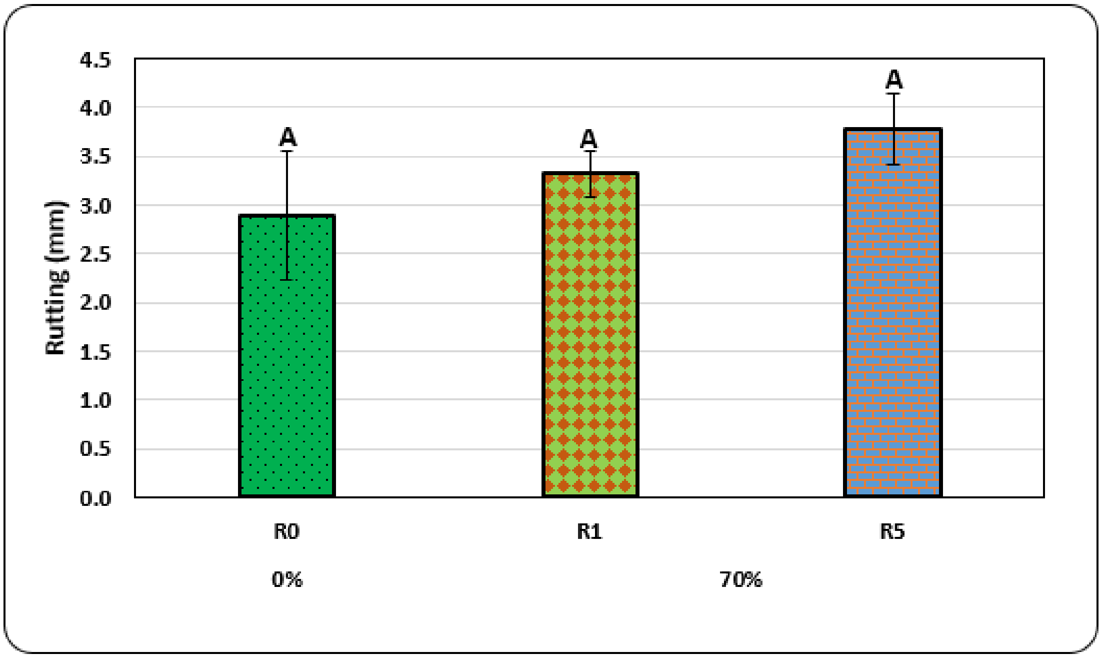


Figure 58. Evaluation of Rutting Performance of Mixtures with RAP No. 3

Evaluation of RAP No. 4 Mixtures

The researchers evaluated the performance of asphalt mixtures prepared with a fourth source of RAP (i.e., RAP No. 4). This RAP was obtained from an asphalt plant in Boise, Idaho. The asphalt mixtures were prepared at different RAP contents (i.e., 0, 25, 50 and 70 percent) as well as rejuvenator type and doses. Two rejuvenators (i.e., R6 and R7) were used at 6.6 percent and 8.3 percent by weight of RAP binder for R6 and 11.3 percent by weight of RAP binder for R7. Rejuvenator R6 is a bio-based product while R7 is petroleum-based product as discussed in Chapter 3.

The researchers conducted the IDT and HWTT to assess the intermediate temperature cracking and rutting performance, respectively and this section discusses the results of these tests.

Effect of RAP Content

Figure 59 shows the effect of RAP content on IDEAL-CT_{Index}. Mixtures without RAP had higher IDEAL-CT_{Index} and it decreased with the increase of RAP content. There is a statistically significant difference in the IDEAL-CT_{Index} results for mixtures prepared without and with RAP. Based on the results of Figure 59, mixtures without RAP had good cracking performance (IDEAL-CT_{Index} > 73.7), mixtures with 25 and 50 percent RAP had moderate cracking performance (IDEAL-CT_{Index} between 26.4 and 73.7), while mixtures with 70 percent RAP had poor cracking resistance (26.4>IDEAL-CT_{Index}). These results are consistent with the other sources of RAP (i.e., RAP No. 1, 2, and 3) where increasing RAP content resulted in decreased cracking performance.

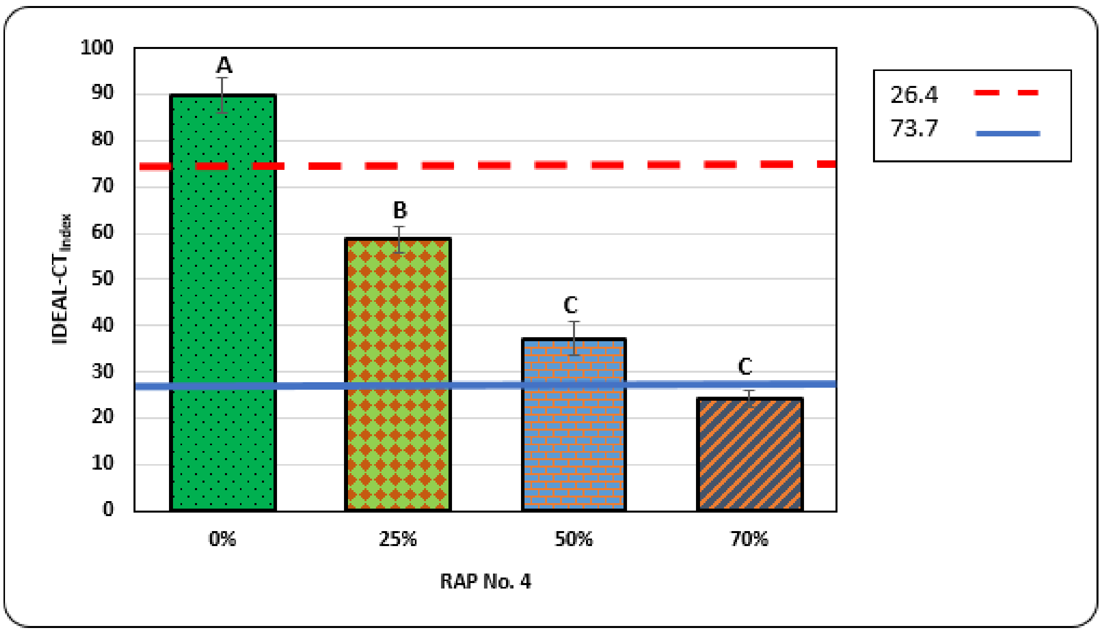


Figure 59. Effect of RAP Content on Cracking Performance of Mixtures Prepared with RAP No. 4

Effect of Rejuvenator Type

Figure 60 shows the effect of rejuvenator type and first dose on the IDEAL-CT_{Index} results. Mixtures prepared with different RAP contents (i.e., 0, 25, 50, and 70 percent) and two types of rejuvenators (i.e., R6 and R7). The following findings can be summarized from these results.

- The use of rejuvenators R6 and R7 didn't affect the IDEAL-CT_{Index} significantly at 25 percent RAP. It should be noted that mixtures with 25 percent RAP had good cracking performance. These results are consistent with the results of other RAP sources where the use of rejuvenators at low RAP content didn't improve the cracking performance.
- The use of softer binder PG 64-34 at 25 percent RAP did not affect IDEAL-CT_{Index} compared to mixtures prepared with 25 percent RAP and PG 70-28 and there was no statistically significant difference in the results.
- Similar to mixtures prepared with 25 percent RAP, the IDEAL-CT_{Index} results of mixtures prepared with 50 percent RAP did not exhibit improved cracking performance when rejuvenators R6 and R7 were used at the lower dose (i.e., 6.6 percent by weight of reclaimed binder for R6 and 11.3 percent by weight of reclaimed binder for R7). It should be noted that the results of other RAP sources demonstrated that some rejuvenators were effective at 50 percent RAP which might be attributed to the compatibility between asphalt binders and rejuvenators.
- The IDEAL-CT_{Index} for mixtures prepared with 70 percent RAP further demonstrated that the use of both rejuvenators, R6 and R7 improved the cracking resistance from poor cracking performance to moderate performance; however, there was no statistically significant difference mixtures with 70 percent RAP with and without rejuvenator.

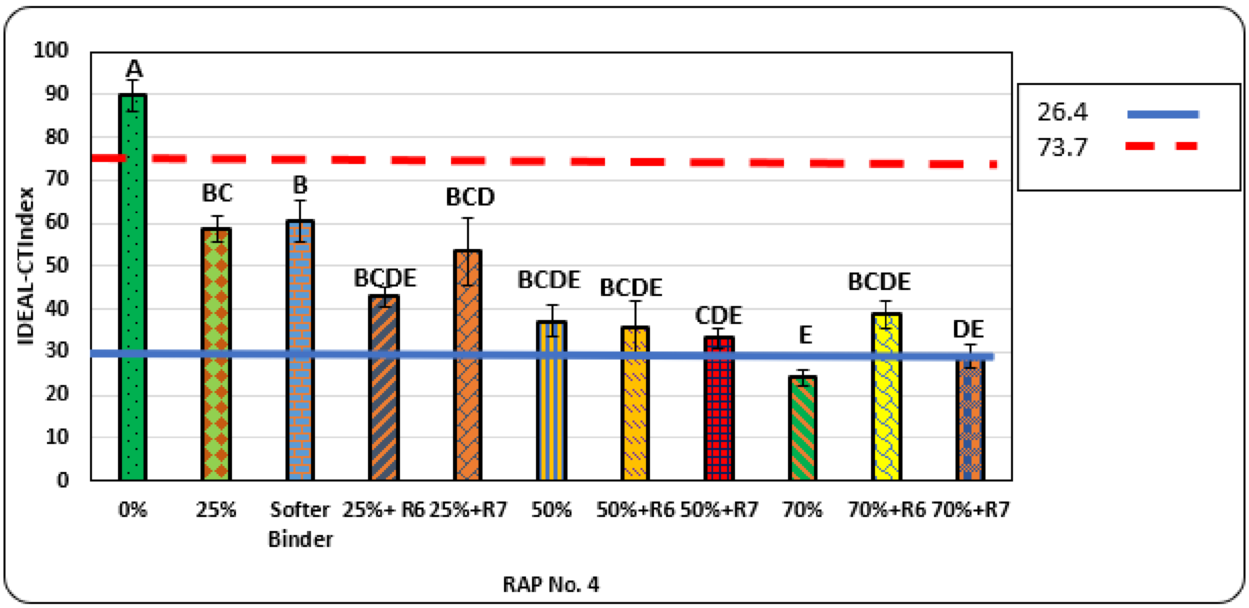


Figure 60. Effect of Rejuvenator Type on 25% RAP No. 4

Effect of Rejuvenator Dose

The researchers examined a higher dose of 8.3 percent by weight of reclaimed binder for R6 only. Figure 61 shows the IDEAL-CT_{Index} results of the tested mixtures at different doses of R6 (i.e., 6.6 and 8.3 percent by weight of reclaimed binder) and different RAP contents (i.e., 0, 25, 50, and 70 percent RAP). The following observations can be drawn from the results shown in Figure 61.

- The increase of rejuvenator dose from at 6.6 to 8.3 percent by weight of RAP binder for R6 at 25 and 50 percent RAP increased the cracking performance; however, the IDEAL-CT_{Index} was comparable to mixtures prepared with 70 percent RAP without rejuvenators. In other words, there was no favorable effect for R6 on the cracking performance at both 25 and 50 percent RAP at different doses.
- For mixtures prepared with 70 percent RAP and R6 at 6.6 percent by weight of reclaimed binder showed improved cracking resistance compared to mixtures with the same RAP content (i.e., 70 percent). The IDEAL-CT_{Index} increased from 25, which indicates poor cracking resistance (26.4 >IDEAL-CT_{Index}) to IDEAL-CT_{Index} of 39, which indicates fair or moderate cracking resistance (IDEAL-CT_{Index} between 26.4 and 73.7). The increase of dose from 6.6 to 8.3 percent of R6 had an inverse effect on the cracking resistance (decreased IDEAL-CT_{Index}); however, such reduction was not statistically significant. These results demonstrated the need to evaluate different doses of the same rejuvenator to select the one that provides optimum performance at the mixture level. Also, an increase in rejuvenator's dose does not necessarily translate into improved mixture performance.

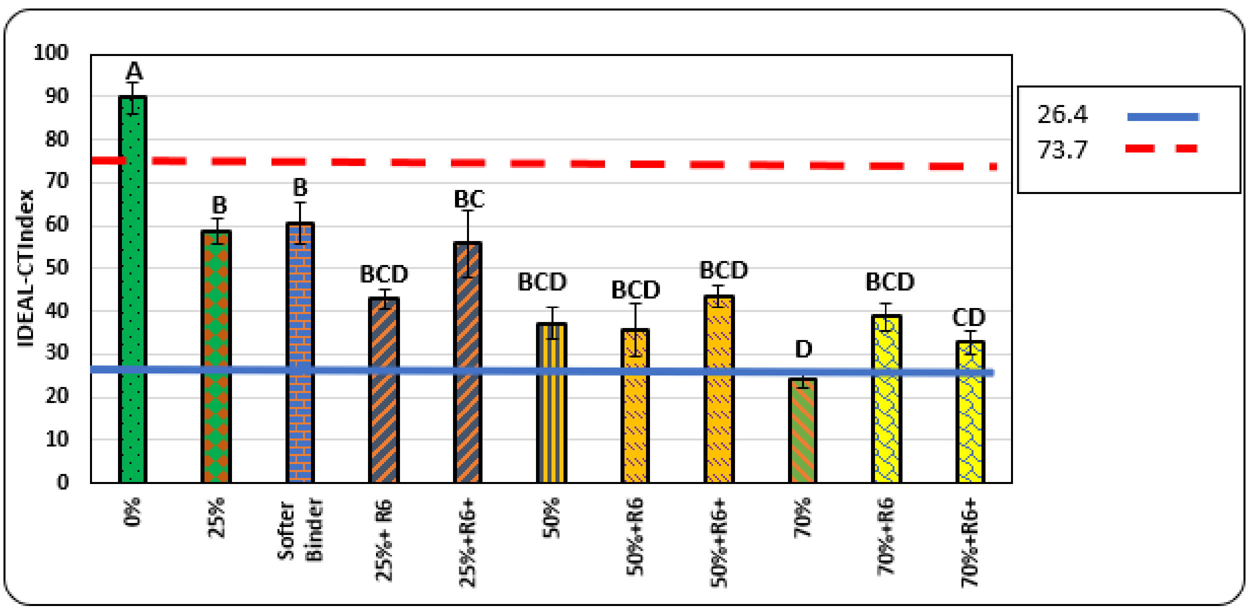


Figure 61. Effect of Rejuvenator Dose on 25% RAP No. 4

Evaluation of Rutting Performance

The researchers evaluated the rutting performance of all test mixtures prepared using RAP No. 4. Figure 62 shows the effect of RAP content on HWTT rut depth. Test mixtures prepared with RAP had less rutting compared to mixtures without RAP; however, all the mixtures had rut depths way below the threshold of 12.5 mm after 20,000 passes. Furthermore, mixtures prepared with rejuvenators also satisfied the rutting performance as shown in Figure 63.

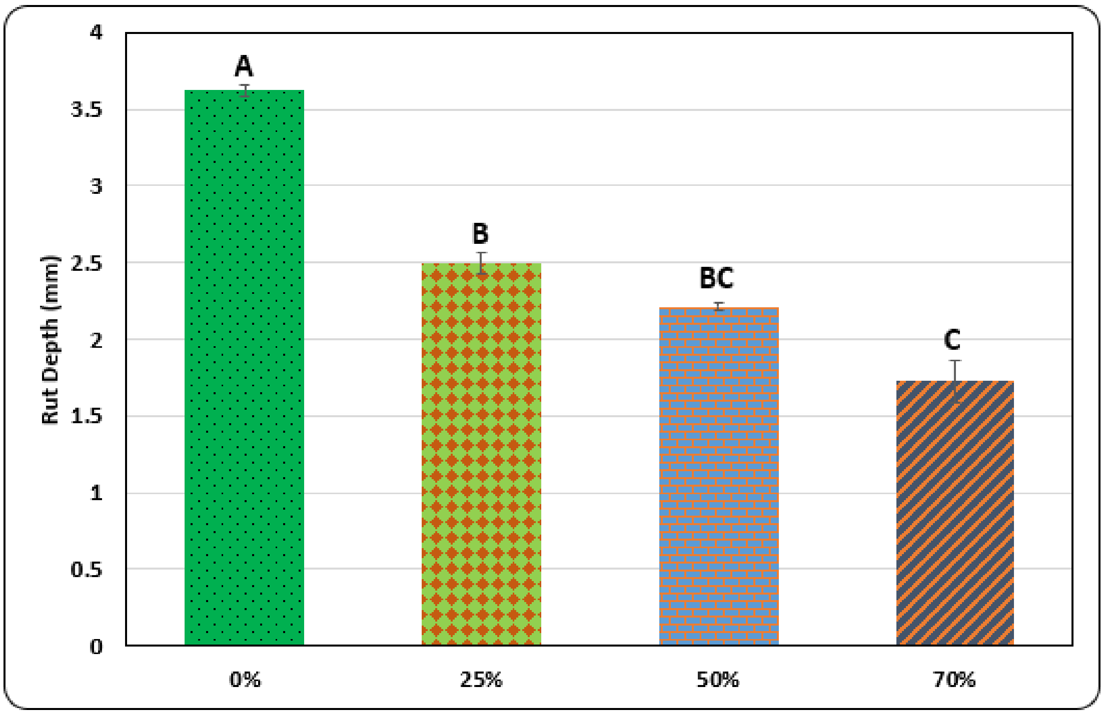


Figure 62. Evaluation of Rutting Performance on RAP No. 4

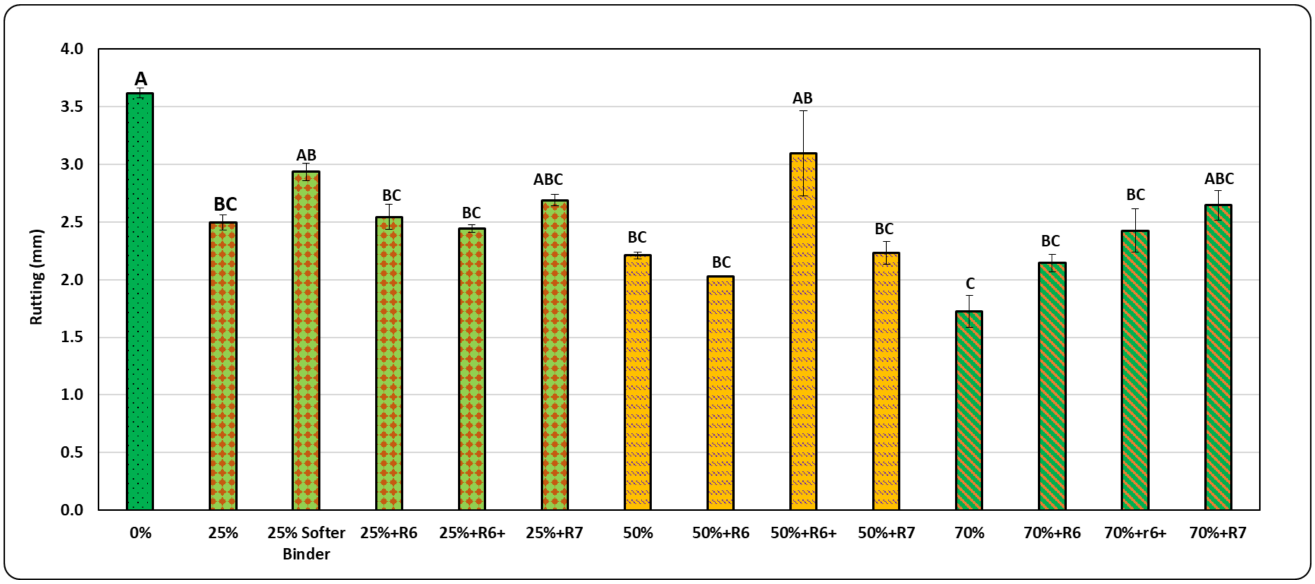


Figure 63. Effect of Rejuvenator Type and Dose on Rutting Performance of RAP No. 4

5. Evaluation of Field Mixes

Chapter 5 evaluates the cracking and rutting performance of loose mixtures collected from new paving projects. These loose mixtures were collected from different districts in Idaho and have different properties (mix design, binder grade, binder content, RAP, etc.) as discussed in Chapter 3. The researchers calculated different cracking and rutting performance parameters and compared to performance thresholds proposed and used in previous ITD studies (Kassem et al. 2019 and Kassem et al. 2021). Furthermore, the researchers examined the coefficient of variation of various cracking performance indicators of the field projects along with their correlations.

Cracking and Rutting Performance Thresholds

Kassem et al. (2019) proposed monotonic performance thresholds for various performance indicators to assess the cracking and rutting performance for asphalt mixtures produced in Idaho. The cracking performance indicators included IDEAL-CT_{Index}, $Weibull_{CRI}$, N_{flex} factor, Cracking Resistance Index (CRI), and Flexibility Index from IDT test (FI[IDT]). They proposed a minimum and maximum threshold for each cracking performance indicator. Table 14 summarizes the recommended thresholds for each indicator that were proposed by Kassem et al. (2019). Mixtures with cracking performance below the minimum thresholds are expected to exhibit poor cracking resistance, while mixtures with cracking performance above the maximum thresholds are expected to exhibit good cracking resistance. Mixtures with performance between the minimum and maximum thresholds are expected to show fair or moderate cracking resistance.

Table 14. Proposed Thresholds for Monotonic Cracking Performance Indices (after Kassem at al. 2019)

	Poor	Fair/Moderate	Good
IDEAL-CT_{Index}	<26.4	26.4 ≤ IDEAL-CT_{Index} ≤ 73.7	>73.7
$Weibull_{CRI}$	<3.60	3.60 ≤ WeibullCRI ≤ 4.70	>4.70
N_{flex}	<0.40	0.40 ≤ Nflex≤ 0.70	>0.70
CRI (IDT)	<466	466 ≤ CRI (IDT) ≤ 614	>614
FI (IDT)	<11.4	11.4 ≤ FI (IDT) ≤ 22.6	>22.6

Kassem et al. (2019) reviewed the HWTT rutting depth thresholds used in different DOTs (i.e., TxDOT, WSDOT, CODOT, LADOT, and MTDOT). All DOTs performed the HWTT test at 50°C. ITD RP 261 proposed a maximum rut depth of 10 mm after 15,000 passes or 12.5 mm after 20,000 passes to ensure adequate resistance to both rutting and moisture damage (Kassem et al. 2019). TxDOT specifies a max rut depth of 12.5 mm at different number of HWTT passes based on the binder grade (i.e., ≤ PG 64 required a minimum of 10,000 passes, PG 70 required a minimum of 15,000, and ≥ PG 76 required a minimum of 20,000). WSDOT specifies a maximum rut depth of 10 mm at 15,000 passes. In addition, CODOT specifies a maximum rut depth of 4 mm at 10,000 passes while LADOT specifies a maximum rut of 10 mm at different number of passes based on the mixture type (i.e., Incidental Paving and ATB required at least 10,000 passes, while Wearing and Binder Course required at least 20,000 passes). MTDOT specifies a maximum rut depth of 13 mm and a minimum number of passes based on the mix design (i.e., the mix design required a minimum of 10,000 passes and the plant mix required a minimum of 15,000 passes). Table 9, in Chapter 2, summarizes the HWTT rutting performance thresholds used by different DOTs.

Evaluation of Cracking Resistance of Field Mixes

IDEAL-CT_{Index} is one of the monotonic cracking performance indicators that is obtained from the IDT load-displacement curve. This index can be used to evaluate the cracking resistance for a given asphalt mixture. Mixtures with higher IDEAL-CT_{Index} exhibit higher cracking resistance and vice versa. The IDEAL-CT_{Index} is calculated using Equation 1. The researchers calculated IDEAL-CT_{Index} for all PMLC specimens. Figure 64 shows the results of the IDEAL-CT_{Index} for 23 different mixes that were collected from different districts. Most of the PMLC mixes (18 out of 23) in Figure 64 exceeded the maximum threshold of 73.7 which indicate that these mixtures are expected to exhibit good cracking resistance in the field based on the proposed threshold by Kassem e al. (2019). Four projects were within the moderate cracking performance range including Project No.7, No.12, No.14, and No. 23. Only one project (Project No. 11) had an IDEAL-CT_{Index} less than the minimum threshold of 26.4.

It was observed that some mixtures with good cracking resistance used a higher binder content or lowered down the binder grade if they included high RAP content. For instance, Project No. 10 and Project No. 15 had a good cracking resistance with 5.7 percent and 5.2 percent binder content, respectively. Both projects had 30 percent RAP and lowered the binder PG by one grade to PG 58-34. In addition, Project No. 21 found to have a good resistance to cracking had 5.8 percent biner content, 17 percent RAP, and the specified binder grade of PG 64-28. Project No. 2 had the highest binder content of 6.2 percent, 0 percent RAP, and PG76-28 among other projects which provided a good cracking resistance. On other hand, Project No. 7 had a moderate cracking resistance and had PG 64-34, 30 percent RAP, and 5.6 percent binder content. Moreover, Project No. 12 used 32 percent RAP, 5.3 percent binder content, and PG 58-34 and showed moderate cracking resistance which could be attributed to RAP sources as some may have been aged more than others. Project No. 11 with poor cracking resistance had RAP content of 31 percent, binder content of 5.3 percent, and PG 64-34. The researchers observed that this mix (i.e., Project No. 11) was relatively drier and has more fines compared to other projects.

The Tukey's HSD analysis classified the mixes into five statistical groups (A, B, C, D, and E). The statistical analysis showed that there was a statistically significant difference between Project No. 11 compared to

Project No. 4, No. 8, No. 10, No. 15, No.16, No. 17, No. 19, and No. 21, while there was no significant difference between Project No. 11 and the remaining projects.

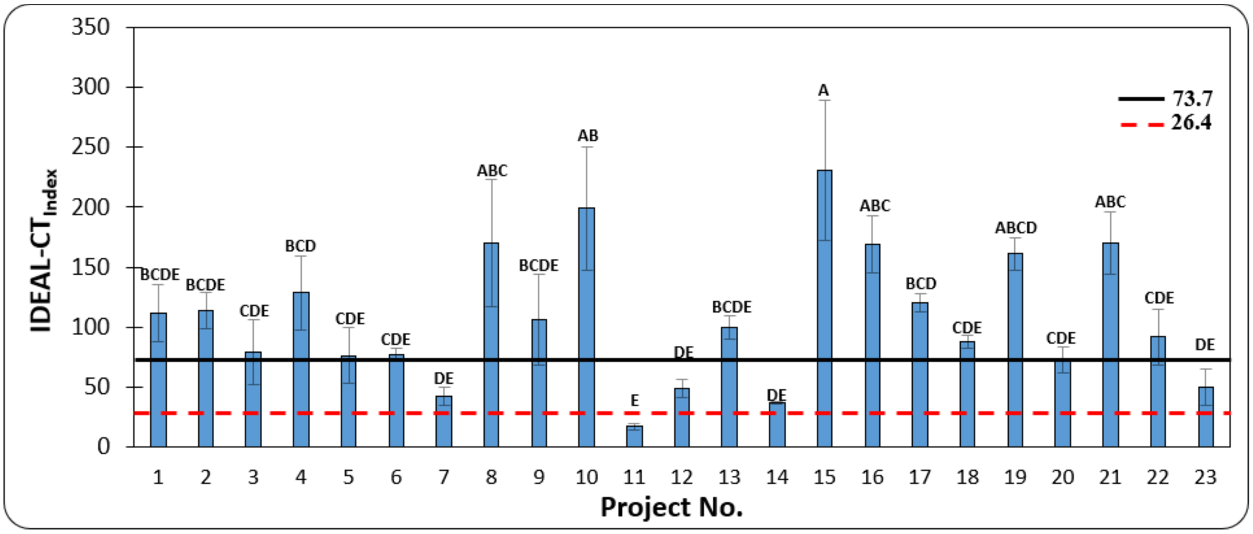


Figure 64. IDEAL-CT_{Index} for PMLC Mixes

$Weibull_{CRI}$ is another cracking performance indicator that was examined in this study. $Weibull_{CRI}$ is calculated from the IDT test by fitting the entire load-displacement curve as discussed in Chapter 2. The higher the $Weibull_{CRI}$ value the better cracking resistance and vice versa. Figure 65 shows the $Weibull_{CRI}$ values for the examined 23 mixes. The figure includes the maximum (i.e., 4.7) and minimum (i.e., 3.6) thresholds for the $Weibull_{CRI}$ cracking performance indicator. The results demonstrated that 18 field projects were above the maximum threshold and are expected to exhibit good resistance to cracking. Four projects (i.e., Project No.7, No.12, No.14, and No. 23) are expected to show fair cracking resistance, while only one project (i.e., Project no. 11) is expected to exhibit poor cracking resistance ($Weibull_{CRI} < 3.6$). These results are consistent with the results of IDEAL-CT_{Index}. However, the Tukey's HSD analysis classified the mixes into eight statistical groups (A, B, C, D, E, F, G, and H). This could be due to the lower coefficient of variation for $Weibull_{CRI}$ compared to IDEAL-CT_{Index} as discussed later in this section. A higher number of statistical groups helps to distinguish between more mixes in terms of cracking resistance. The statistical analysis showed that there was a statistically significant difference between Project No. 11 and all the projects except those with fair cracking resistance (i.e., Project No.7, No.12, No.14, and No. 23). These results demonstrated that $Weibull_{CRI}$ was able to distinguish between more projects in terms of cracking resistance compared to IDEAL-CT_{Index}. Based on the cracking performance results of IDEAL-CT_{Index} and $Weibull_{CRI}$ and the corresponding thresholds proposed in RP 261, there is no concern with the expected cracking performance of most asphalt mixtures currently produced in Idaho.

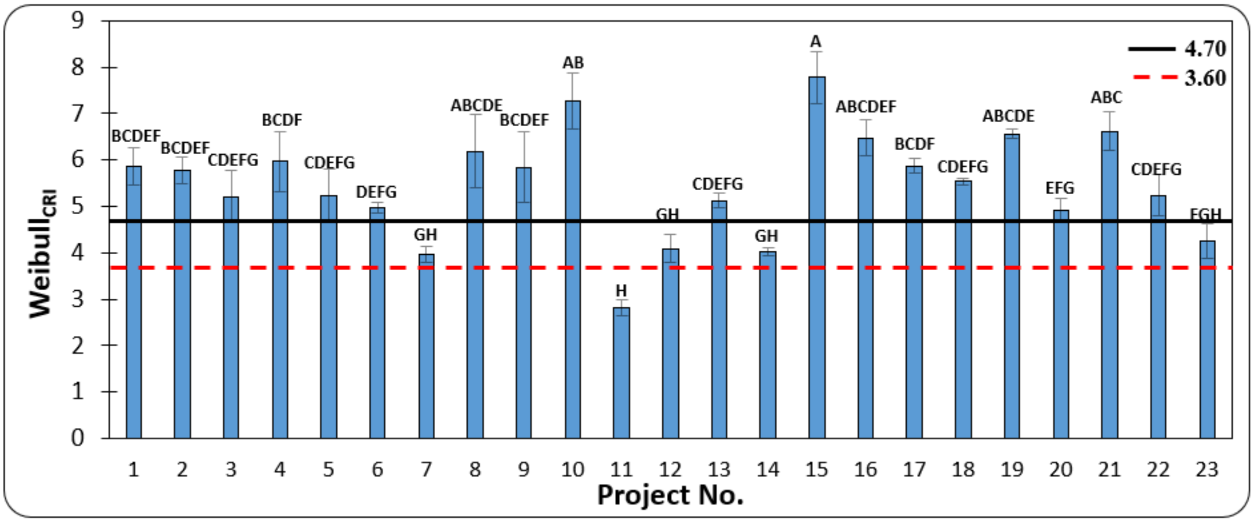


Figure 65. WeibullCRI for PMLC Mixes

Figure 66 illustrates the results of $IDT_{Strength}$ for the field projects. The $IDT_{Strength}$ is calculated from the IDT load-displacement curve as discussed in Chapter 2. Mixtures with higher $IDT_{Strength}$ are often stiffer compared to those with lower $IDT_{Strength}$ and vice versa. Stiffer mixtures often exhibit lower resistance to cracking. Based on the IDEAL-CT_{Index} and $Weibull_{CRI}$ cracking resistance for different groups (i.e., good, fair, and poor), the group of mixtures with good cracking resistance had an $IDT_{Strength}$ ranging from 872 kPa to 1004 kPa, while mixtures with fair cracking resistance had an $IDT_{Strength}$ ranging from 774 kPa to 1160 kPa. The mixture (Project No. 11) that is expected to exhibit poor cracking resistance had relatively higher $IDT_{Strength}$ of 1156 kPa. The $IDT_{Strength}$ had an opposite correlation with both IDEAL-CT_{Index} and $Weibull_{CRI}$, as discussed later in this chapter; however, such correlation is not strong. Similar to $Weibull_{CRI}$, the Tukey's HSD analysis classified the mixes, based on $IDT_{Strength}$, into eight statistical groups (A, B, C, D, E, F, G, and H). Also, there was a statistically significant difference between Project No. 11 and some projects with good cracking performance including Project No. 1, No. 2, No. 4, No. 6, No. 8, No. 9, No. 10, No. 13, No. 16, No. 19, No. 20, No. 21, and No. 22.

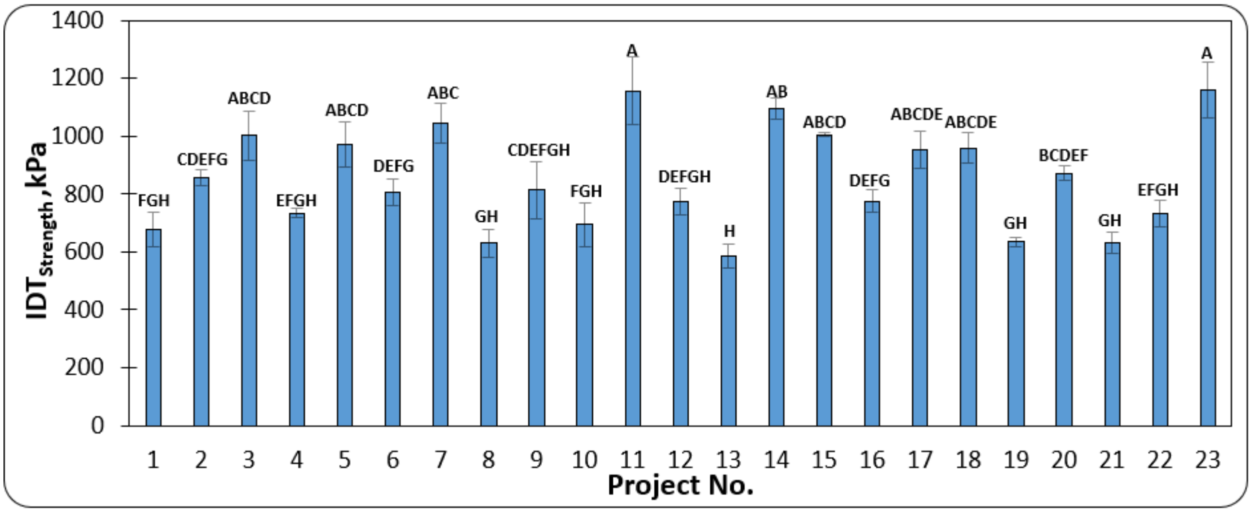


Figure 66.IDT$_{Strength}$ for PMLC Mixes

Evaluation of Correlation and Coefficient of Variation for Cracking Performance Indicators

The researchers evaluated various cracking performance indicators including IDEAL-CT$_{Index}$, Weibull$_{CRI}$, N$_{flex}$ factor, Cracking Resistance Index (CRI), and Flexibility Index from IDT test (FI[IDT]), Fracture Energy (Gf), IDT$_{Strength}$, and IDT$_{Modulus}$. All these performance indicators can be calculated from the same IDT load-displacement curve and conducted using the same testing protocol. The formulas used to calculate these indicators are summarized in Table 8 of Chapter 2.

The researchers evaluated the correlation among the above-mentioned cracking performance indicators. The Pearson coefficient is a statistical tool used in this study to examine the correlation between various cracking performance indicators. The Pearson product moment correlation coefficient (r) is used to assess the linear relationship between two indicators (Salkind 2010). The value of "r" ranges between -1 and +1. The magnitude of "r" describes the strength of the correlation between two parameters, while the sign (negative or positive) indicates whether such relationship is direct (+) or inverse (-). Higher magnitude of "r" demonstrates stronger correlation. Table 15 presents the value of r between various cracking performance indicators. The results clearly demonstrated that IDEAL-CT$_{index}$, Weibull$_{CRI}$, N$_{Flex}$, CRI, and FI had direct strong correlations ($r > 0.90$). Also, the results showed that both IDT$_{Strength}$ and IDT$_{Modulus}$ had an inverse correlation with most indicators (i.e., that IDEAL-CT$_{index}$, Weibull$_{CRI}$, N$_{Flex}$, CRI, and FI), except between each other. Fracture Energy (Gf) had poor correlations ($r < 0.5$) with all other examined performance indicators. The Pearson correlation results in Table 15 also demonstrated that WeibullCRI and IDEAL-CT$_{Index}$ had a strong correlation ($r = 0.964$); however, Weibull$_{CRI}$ had lower variability in the test results (average COV = 6.6 percent) compared to IDEAL-CT_{index} (average COV = 18.8 percent) as discussed in the section below. These results are very consistent with the results of ITD RP 280 (Kassem et al. 2021).

Table 15. Pearson Coefficient (r) for Cracking Performance Indicators

Spearman Coefficient	$Weibull_{CRI}$ (IDT)	IDEAL - CT (IDT)	N_{flex} (IDT)	CRI (IDT)	FI (IDT)	$IDT_{Strength}$	$IDT_{Modulus}$	Fracture Energy (Gf)
$Weibull_{CRI}$ (IDT)	1							
IDEAL -CT (IDT)	0.964	1						
N_{flex} (IDT)	0.971	0.983	1					
CRI (IDT)	0.989	0.963	0.983	1				
FI (IDT)	0.960	0.944	0.955	0.958	1			
IDT strength	-0.539	-0.547	-0.643	-0.632	-0.572	1		
IDTModulus	-0.741	-0.731	-0.808	-0.82	-0.756	0.937	1	
Fracture Energy (Gf)	0.494	0.428	0.341	0.392	0.411	0.445	0.147	1

Excellent Correlation ($r_s \geq 0.9$) Good Correlation ($0.7 < r_s < 0.9$) Fair Correlation ($0.5 < r_s \leq 0.7$) Poor Correlation ($0.1 < r_s \leq 0.5$) No Correlation

Figure 67 shows the coefficient of variation (COV) for each cracking performance indicator based on the results of 23 loose mixtures. The COV indicates that variability in test results in relation to the mean of the values. It is calculated as the ratio of the standard deviation to the mean. The results of COV presented in Figure 67 demonstrate that CRI, $Weibull_{CRI,}$ Nflex, FI, and IDEAL-CT_{Index} had a COV of 6.0, 6.6, 12.5, 14.7, and 18.8 percent, respectively, while Gf, $IDT_{Strength,}$ and $IDT_{Modulus}$ had a COV of 4.2, 6.3, and 11.2 percent, respectively. $Weibull_{CRI}$ had lower COV compared to IDEAL-CT_{Index} which is consistent with previous findings by Kassem et al. (2019) and Kassem et al. (2021).

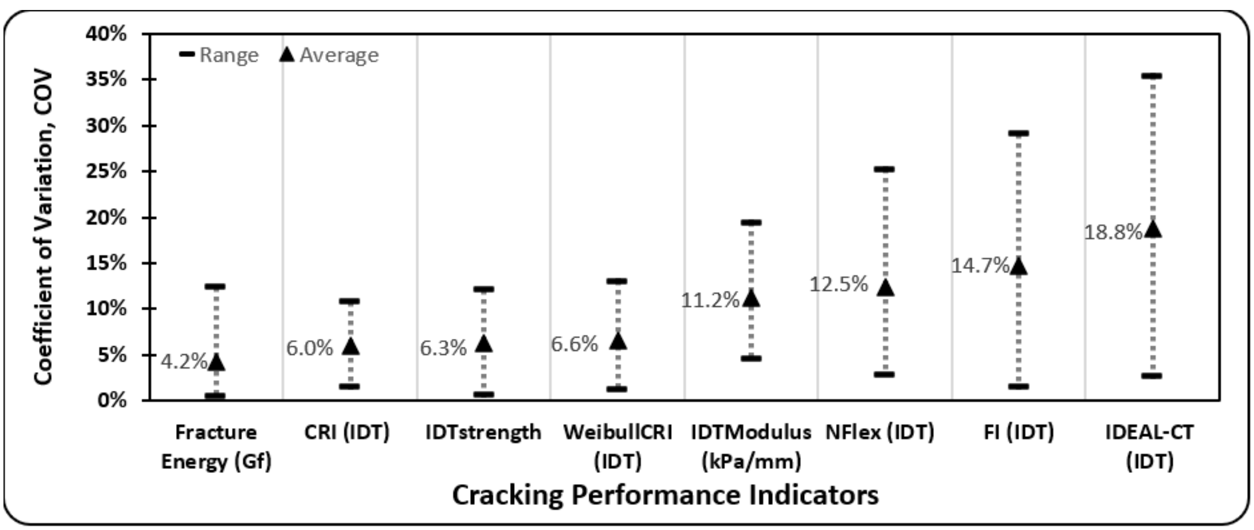


Figure 67. Coefficient of Variation of Cracking Performance Indicators for PMLC Mixes

Evaluation of Rutting Resistance of Field Mixes

Figure 68 shows the HWTT rut depth for the examined 23 field projects. Four PMLC replicates were prepared from each mixture. A total of 92 PMLC specimens were prepared to evaluate the rutting resistance of the field mixtures. The HWTT measures the rut depth at 11 different locations along the pass of the HWTT wheels on the test specimens. The test is conducted at 50°C in wet conditions where the test HWTT specimens are submerged in water; therefore, the test can be used to assess both rutting resistance as well as moisture susceptibility of asphalt mixtures. The results of the HWTT rutting depth summarized in Figure 68 demonstrate that the rut depth after 20,000 passes for all field mixtures ranged from 1.12 mm to 4.41 mm. Therefore, all the mixtures had a rut depth way below the maximum threshold of 12.5 mm after 20,000 passes, and there was no statistically significant difference in rut depth among various projects except between Project No. 11 and Project No. 12. Project No. 11 had a RAP content of 31 percent, 5.3 percent binder content, and PG 64-34. The researchers observed that this mix (i.e., Project No. 11) was relatively drier and has more fines compared to other projects. It had the maximum rut depth of 4.41 mm. Project No. 12 had RAP content of 32 percent, binder content of 5.3 percent and PG 58-34, and had the minimum rut depth of 1.18 mm. Meanwhile, Project No. 11 and Project No. 12 were way below 12.5 mm after 20,000 passes. In addition, Project No. 6, No. 9, No. 10, No. 13,No. 17, No. 20, No. 22, and No. 23 had an average rut depth from 3 mm to 4 mm. Project No. 6, No. 13, No. 9, and No. 10 had RAP content ranging from 17 percent to 30 percent with binder content ranging from 4.9 percent to 5.8 percent, while Project No. 17, No. 20, and No. 22 had binder content ranging from 4.8 percent to 5.9 percent with 0 percent RAP. Project No. 1, No. 2, No. 3, No. 4, No. 5, No. 7, No. 8, No. 14, No. 15, No. 16, No. 18, No. 19, and No. 21 had an average rut depth between 2 mm to 3 mm. These mixtures had RAP content ranging from 0 percent to 35 percent while the binder content ranged from 4.9 percent to 6.2 percent. It should be noted that Project No. 11 was found to exhibit the lowest cracking resistance among all examined projects too. The HWTT results further demonstrated that there was no sign of moisture damage. Most of the examined projects had anti-strip agents of 0.5 percent except Project No. 1 and No. 13 where 0.75 percent of anti-strip agents was used. Project No. 9 and No. 16 did not have any anti-strip agents, while Project No. 8 had 0.25 percent anti-strip agents. Based on the results of this section, there is no concern on the rutting performance of asphalt mixtures currently produced in Idaho which is consistent with the findings of RP 261 and RP 280.

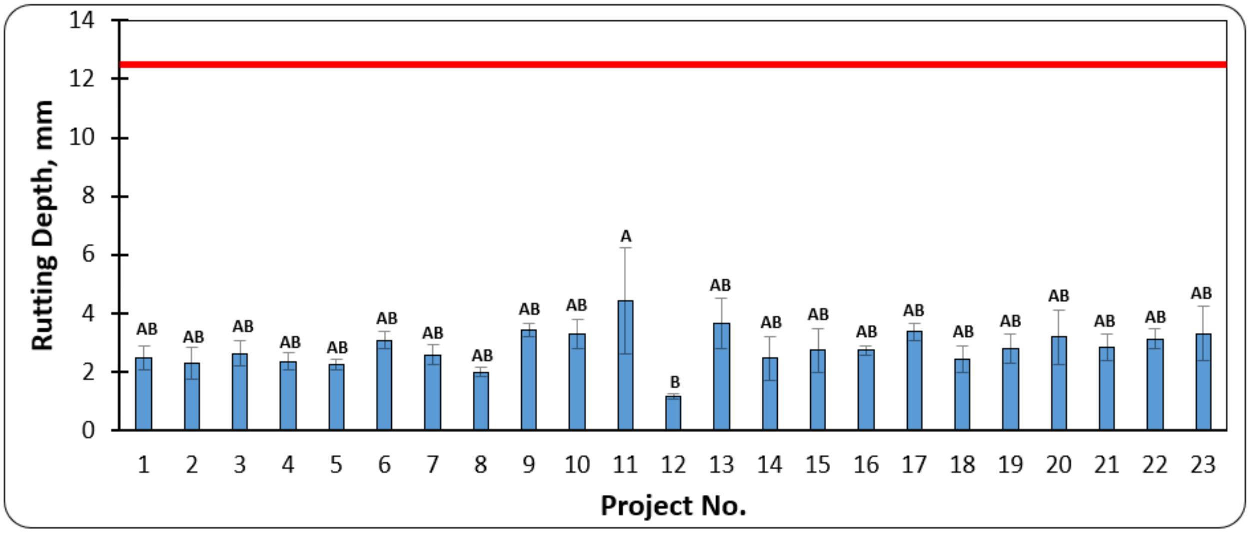


Figure 68. Hamburg Rutting Depth for PMLC Mixes

6. Cost Analysis

The researchers conducted cost analysis to assess economic savings associated with using rejuvenators with high RAP content in asphalt mixtures without compromising the performance (i.e., cracking and rutting resistance). The use of RAP can cut down the percent of virgin binder added, leading to cost savings. In addition, the current practice is to use one grade softer virgin binder if the RAP content between 17 percent to 30 percent and the blending chart to select the grade of softer virgin binder if RAP content exceeds 30 percent. The use of softer binder costs more due to its limited availability. Therefore, the use of rejuvenators may eliminate or reduce the need for softer binders.

In this study, the researchers evaluated mixtures with different sources of RAP. Some RAP sources had higher binder content (e.g., RAP No. 3 and RAP No. 4 had 5.37 and 5.3 percent, respectively) and others had lower binder content (e.g., RAP No. 3 had 4.3 percent). The researchers evaluated the cost of asphalt mixtures with and without RAP as well as RAP mixtures with and without rejuvenators. They examined the materials cost for asphalt mixtures prepared with three different RAP materials evaluated in this study (i.e., RAP No.2, RAP No. 3, and RAP No. 4) incorporating the best performing rejuvenators for each RAP source. For RAP No. 2, the researchers studied the cost associated with using two rejuvenators (i.e., R1 and R5) with different RAP contents (i.e., 25, 50,70 percent) and at different binder grades for the 70 percent RAP mixtures. For RAP No. 3, they examined the cost associated with using two rejuvenators (i.e., R1 and R5) at a higher RAP content of 70 percent. In addition, the researchers examined the cost of mixtures with no RAP (i.e., 0 percent RAP) and mixtures with higher binder content. For RAP No. 4, the researchers studied the cost associated with using two rejuvenators (i.e., R6 and R7) at different RAP content (i.e., 0, 25, 50, and 70 percent). The results of the cost analysis are presented and discussed for each RAP source separately in this chapter.

Materials Cost

The researchers conducted a cost-benefit analysis based on the cost of rejuvenators, aggregates, asphalt binders obtained from the manufacturers or literature. Martin et al. (2020) estimated the material cost at around 45 to 50 percent, plant production cost at around 35 to 40 percent, and cost of field operations (i.e., hauling, laydown, and compaction) at around 15 to 20 percent of the total in-place HMA cost. In this study, the researchers examined the cost savings associated with materials only. The cost of rejuvenators is much higher than the cost of binders, virgin aggregates, and RAP materials as summarized in Table 16. Meanwhile, the percentage of rejuvenator used in asphalt mixtures is very small and taken as a small percent of asphalt binder by weight. The tall oil rejuvenator (R1) cost ranges from $4,000 to $4,900 per ton, waste vegetable oil rejuvenator (R5) is about $3,800 per ton, the bio-based oil rejuvenator (R6) cost is about $2,200 per ton, and the petroleum-based oil rejuvenator (R7) cost is about $1,900 per ton. The cost of virgin binder ranges from $750 to $925 per ton depending on the binder grade. The virgin aggregate and RAP materials are much lower compared to the cost of rejuvenators and asphalt binders.

The cost per ton for virgin aggregates and RAP materials ranges from \$12 to \$15 and from \$5 to \$8, respectively.

Table 16. Summary Materials Cost

		$Price/ton	
Material Type	**Material Description**	**Low**	**High**
Aggregate	Virgin Aggregates	12	15
Aggregate	RAP Aggregates	5	8
Virgin Binder	PG 58-28	750	-
Virgin Binder	PG 58-34	875	-
Virgin Binder	PG 64-28	800	-
Virgin Binder	PG 64-34	925	-
Virgin Binder	PG 70-28	825	-
Rejuvenator (R1)	Tall oil	4000	4900
Rejuvenator (R5)	Waste Vegetable Oil	3800	-
Rejuvenator (R6)	Bio-Based Oil	2200	-
Rejuvenator (R7)	Petroleum-Based Oil	1900	-

Cost Comparison Associated with RAP No. 2

The researchers calculated the materials cost for mixtures prepared with different percentages of RAP No.2, rejuvenators, and binder contents as shown in Figures 69 and Table 17. Figure 69 includes two "Y" axes, the one on the left for the cost in US dollar per ton of asphalt mixtures and the axis on the right is for the IDEAL-CT_{Index}. The grey bars represent the IDEAL-CT_{Index} and the colored bars represent the cost. The percentage of cost reduction or increase, with respect to the control mix, is written on the top of each bar corresponding to mixtures with different compositions. A negative sign indicates a cost reduction, while a positive sign demonstrates a cost increase. The following observations can be made based on the cost analysis:

- The control asphalt mixture (0 percent RAP) had an IDEAL-CT_{Index} of 39 which is moderate cracking resistance according to the cracking performance thresholds proposed in RP 261 (Kassem et al. 2019). Also, the control mixture costs about \$65 per ton.
- When the binder content was increased from 5.8 percent to 6.3 percent which represents 0.5 percent increase in OBC (i.e., 0 percent RAP + 0.5 BC), the IDEAL-CT_{Index} was increased which indicates improved cracking resistance compared to the control mixture. The IDEAL-CT_{Index} increased from 39 (moderate cracking resistance) to 102 (good cracking resistance). However, this resulted in a cost increase of 6.8 percent compared to the control mix.
- Asphalt mixtures prepared with 25 percent RAP (25 percent RAP) without rejuvenators resulted in a cost reduction of \$13 per ton which is approximately 21.6 percent reduction in the cost compared to the virgin mix (0 percent RAP). However, the performance of mixtures with 25 percent RAP had a lower IDEAL-CT_{Index} (IDEAL-CT_{Index} of 20) which demonstrated reduced cracking resistance compared to the control mixture (IDEAL-CT_{Index} of 39).
- When the binder content was increased from 5.8 percent to 6.3 percent which represents 0.5 percent increase in OBC at 25 percent RAP (25 percent RAP + 0.5 BC), the cracking performance was improved (IDEAL-CT_{Index} of 46) compared to the control mixture (IDEAL-CT_{Index} of 39). In

addition, there was a net 14.8 percent reduction in the cost compared to the control mix ($9 reduction per ton). These analyses indicate that increasing the binder content at a RAP content of 25 percent could be a cost-effective approach to incorporate RAP in the mix without compromising the performance (i.e., both cracking and rutting resistance). All mixtures passed the rutting requirements as discussed in Chapter 4. This further demonstrates the importance of implementing a balanced mix design approach when incorporating RAP in asphalt mixtures. This leads to cost savings as well as producing a mixture with comparable or improved performance.

- At 25 percent RAP, the use of tall oil (25 percent RAP + R1) resulted in improved IDEAL-CT_{Index} (IDEAL-CT_{Index} of 52) compared to the mix with 25 percent RAP (IDEAL-CT_{Index} of 20) and the control mix (IDEAL-CT_{Index} of 39). However, this resulted in a 6.8 percent cost increase ($5 increase per ton) compared to the control mix.
- At 25 percent RAP, the use of waste vegetable oil (25 percent RAP + R5) resulted in slightly higher IDEAL-CT_{Index} (IDEAL-CT_{Index} of 26) compared to mixture with 25 percent RAP (IDEAL-CT_{Index} of 20); however, it was less than the control mixture (IDEAL-CT_{Index} of 39). In addition, there was an 8.5 percent cost reduction compared to the control mix.
- The cracking performance of mixtures prepared with 50 percent RAP and tall oil (50 percent RAP + R1) was comparable to the control mixture (i.e., IDEAL-CT_{Index} of 33 compared to 39 for the control mixture). In addition, there was a cost reduction of 14.6 percent compared to the control mixtures. Mixtures prepared with 50 percent RAP and waste vegetable oil (50 percent RAP + R2) had lower IDEAL-CT_{Index} (IDEAL-CT_{Index} of 25) than the control mixture (IDEAL-CT_{Index} of 39). In addition, increasing the binder content by 0.5 percent at 50 percent RAP (50 percent RAP+0.5BC) was not sufficient to improve the cracking resistance to that of the control mix. For the previous analysis, it can be concluded that using the tall oil is the most cost-effective alternative to improve the performance of asphalt mixtures prepared with 50 percent RAP compared to the other rejuvenator (waste vegetable oil) or increasing the binder content. Martin et al. (2019) reported 12 percent reduction in materials cost for mixtures prepared with 40 precent RAP which agrees with our study where there was 14.6 percent reduction in materials cost for mixtures with 50 percent RAP.
- Asphalt mixtures prepared with 70 percent RAP and rejuvenators exhibited higher cost savings than at 25 and 50 percent RAP. Asphalt mixtures with 70 percent RAP and tall oil (70 percent RAP + R1) had comparable or improved cracking performance (IDEAL-CT_{Index} of 40) compared to the control mix (IDEAL-CT_{Index} of 39). Furthermore, the use of tall oil resulted in the highest cost reduction of 30.4 percent compared to the cost of control mix. Similarly, asphalt mixtures with 70 percent RAP and waste vegetable oil (70 percent RAP + R2) also provided comparable or improved cracking performance (IDEAL-CT_{Index} of 39) compared to the control mix (IDEAL-CT_{Index} of 39). Meanwhile, the cost reduction (i.e., 23.1 percent) was less than that of the tall oil (i.e., 23.1 percent). Increasing the binder content by 0.5 percent (70 percent RAP + 0.5 BC) resulted in higher cost reduction (52.2 percent) and slightly lower cracking performance (IDEAL-CT_{Index} of 30) to the control mix (IDEAL-CT_{Index} of 39) which demonstrates that the increasing the binder content could be very beneficial in some cases. This further emphasizes the effectiveness of the balanced mix design approach.

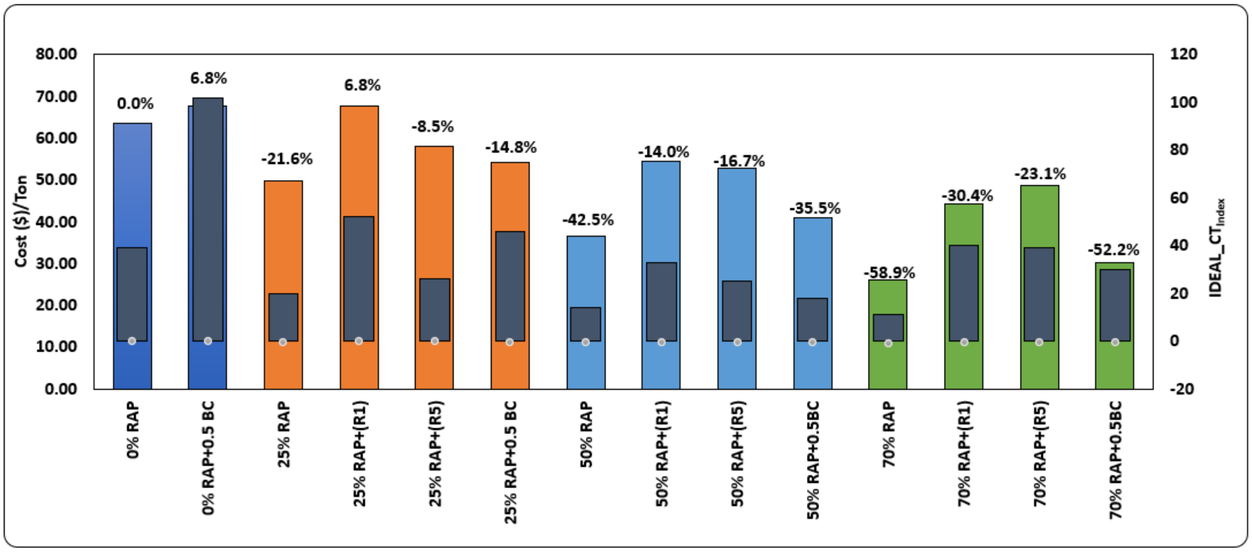


Figure 69. Cost Comparison of Mixtures with RAP No. 2 and Rejuvenators

Table 17. RAP No. 2 Cost Analysis Summary

Mix Type	Cost ($/ton)	Cost Difference ($/ton)	Performance, IDEAL-CT$_{Index}$
0% RAP	63	0	39
0% RAP +0.5 BC	67	4	102
25% RAP	50	-13	20
25%RAP +0.5 BC	54	-9	46
25% + R1	68	5	52
25% + R5	58	-5	26
50% RAP	36	-27	14
50%RAP +0.5 BC	41	-22	18
50% + R1	55	-8	33
50% + R5	53	-10	25
70% RAP	26	-37	14
70%RAP +0.5 BC	41	-22	30
70% + R1	44	-19	40
70% + R5	43	-20	39

Cost Associated with RAP No. 3

The researchers also calculated the materials cost for mixtures prepared with 70 percent RAP, two rejuvenators, and binder contents as shown in Figures 70 and Table 18. The following observations can be made based on the cost analysis:

- The control asphalt mixture (0 percent RAP) had an IDEAL-CT_{Index} of 49 which is moderate cracking resistance according to the cracking performance thresholds proposed in RP 261 (Kassem et al. 2019). Also, the control mixture costs about $56 per ton.
- When the binder content was increased from 5.8 percent to 6.3 percent which represents 0.5 percent increase in OBC (i.e., 0 percent RAP + 0.5 BC), the IDEAL-CT_{Index} was increased from 43 (moderate cracking resistance) for the control mix to 102 (good cracking resistance) which is considered a significant improvement. However, this resulted in an increase in the cost by 7 percent compared to the control mix.
- The use of 70 percent RAP decreased the cracking resistance (IDEAL-CT_{Index} of 23) which indicated poor cracking resistance according to the thresholds presented in RP 261. Although the use of 70 percent RAP resulted in higher cost savings (i.e., 48 percent reduction), the cracking performance was not acceptable (IDEAL-CT_{Index} of 23 demonstrates poor cracking resistance).
- Increasing the binder content from 5.8 percent to 6.3 percent which represents 0.5 percent increase in OBC) combined with the use of 70 percent RAP (i.e., 70 percent RAP + 0.5 BC), resulted in improved cracking resistance (IDEAL-CT_{Index} of 72) compared to the control mix (IDEAL-CT_{Index} of 49). This approach resulted in a higher cost reduction of 42 percent.
- The use of both rejuvenators (i.e., tall oil and waste vegetable oil) improved the cracking resistance from poor performance for 70 percent RAP (IDEAL-CT_{Index} of 23) to good performance (IDEAL-CT_{Index} of 118 for tall oil and IDEAL-CT_{Index} of 92 for waste vegetable oil) which is better than the control mix (IDEAL-CT_{Index} of 49) at optimum binder content (0 percent RAP) and even to the virgin mix at higher binder content (0 percent RAP + 0.5 BC). The use of tall oil and waste vegetable oil resulted in cost reductions of 16 and 15 percent, respectively. These results further demonstrate the effectiveness of the use of rejuvenators at higher RAP contents which are consistent with the cost analysis of RAP No. 2.

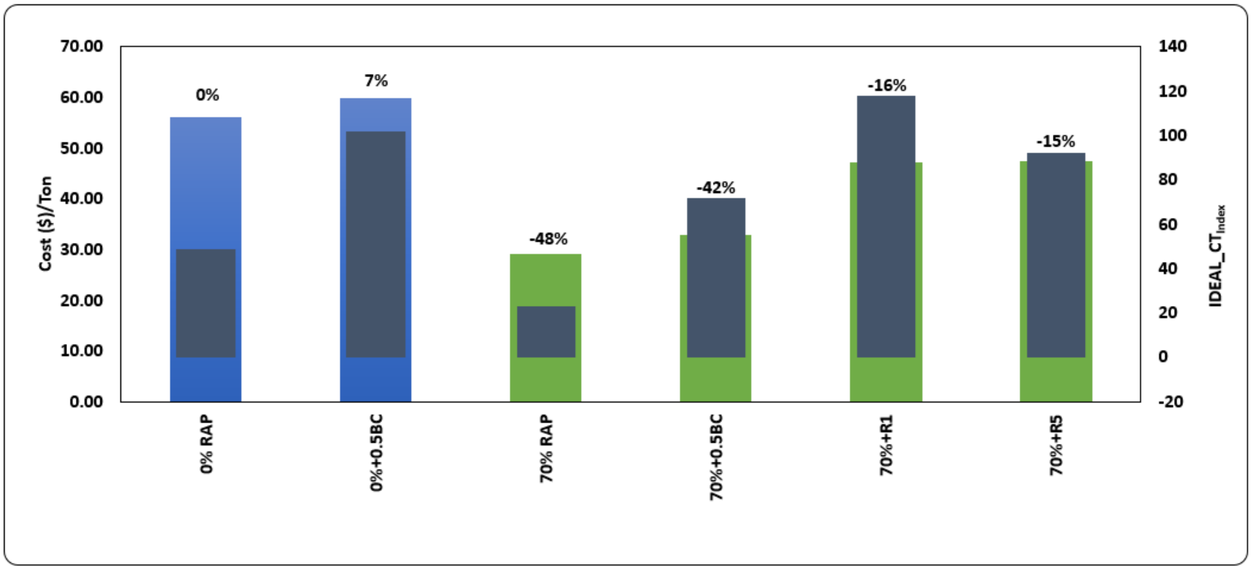


Figure 70. Cost Comparison of Mixtures with RAP No. 3 and Rejuvenators

Table 18. RAP No. 3 Cost Analysis Summary

Mix Type	Cost ($/ton)	Cost Difference ($/ton)	Performance, IDEAL-CT_{Index}
0% RAP	56	0	49
0% RAP +0.5 BC	60	4	102
70% RAP	29	-27	23
70%RAP +0.5 BC	33	-23	72
70% + R1	47	-9	118
70% + R5	48	-8	92

Cost Associated with RAP No. 4

The researchers also calculated the materials cost for mixtures prepared with different percentages of RAP No. 4 (i.e., 0, 25, 50, and 70 percent), two rejuvenators (i.e., R6 and R7), and one binder content as shown in Figures 71 and Table 19. In addition, the cost of mixtures prepared with 25 percent of RAP with softer binder (i.e., PG 64-34) was included. The following observations can be made based on the cost analysis:

- The control mix (i.e., 0 percent RAP) had an IDEAL-CT_{Index} of 90 which illustrates good cracking resistance according to the cracking performance thresholds proposed in RP 261 (Kassem et al. 2019) and costs about $57 per ton.

- Mixtures prepared with 25 percent RAP without rejuvenators resulted in 22 percent reduction in the cost; however, these mixtures had lower cracking resistance (IDEAL-CT_{Index} of 59) compared to control mixture (IDEAL-CT_{Index} of 90).
- The addition of rejuvenators R6 (at two doses of 6.6 and 8.3 percent by weight of reclaimed binder) and R7 (at 11.3 percent by weight of reclaimed binder) with 25 percent RAP resulted in a cost reduction of 19.4, 18.5, and 18.7 percent respectively. However, the use of R6 and R7 at 25 percent RAP resulted in reduced cracking performance compared to mixtures with 25 percent RAP without rejuvenators (IDEAL-CT_{Index} of 59). The IDEAL-CT_{Index} values for mixtures prepared with 25 percent RAP and 6.6 and 8.3 percent of R6 and 11.3 percent of R7 were 43, 56, and 54, respectively.
- The use of softer binder grade (i.e., PG 64-34) at 25 percent RAP didn't impact the cracking performance (IDEAL-CT_{Index} of 59) compared to mixtures with 25 percent and PG 70-28 (IDEAL-CT_{Index} of 60). Meanwhile, the cost increased by 6.4 percent as compared to the control mix (i.e., 0 percent) and 36 percent as compared to mixtures with PG 70-28.
- The use of 50 percent RAP resulted in a cost reduction of 43 percent compared to the control mix (0 percent RAP); however, this was associated with reduced cracking resistance (IDEAL-CT_{Index} of 90 for the control mixture compared to IDEAL-CT_{Index} of 59 for mixtures with 37 percent RAP).
- The use of R6 at a lower dose of 6.6 percent and a higher dose of 8.3 percent resulted in cost reduction of 38.2 and 38.0 percent compared to the control mixture without RAP or rejuvenators. However, this was associated with reduced cracking resistance (i.e., IDEAL-CT_{Index} of 36 and 44 for the lower and higher doses of R6, respectively compared to IDEAL-CT_{Index} of 90 for the control mixture). Similarly, mixtures prepared with 50 percent RAP and rejuvenator R7 showed 37.6 percent reduction in the total cost but with reduced IDEAL-CT_{Index} of 33 compared to the control mixture of 90. These results showed that the use of both R6 and R7 were not effective at 50 percent RAP.
- The use of 70 percent RAP provided the maximum cost reduction of 60.9 percent; however, the cracking performance decreased from good (IDEAL-CT_{Index} of 90 for the control mixture) to poor (IDEAL-CT_{Index} of 24). The use of R6 at two doses (6.6 and 8.3 percent), and R7 at 70 percent RAP reduced the cost by 55.1, 46.0, and 45.4 percent, respectively. Meanwhile, the IDEAL-CT_{Index} values for mixtures prepared with R6 and R7 at 70 percent RAP were much lower compared to the control mixture without RAP but were slightly higher compared to mixtures with 70 percent RAP. The use of 6.6 percent of R6 improved the cracking performance from poor for mixture with 70 percent RAP (IDEAL-CT_{Index} of 24) to good (IDEAL-CT_{Index} of 39).

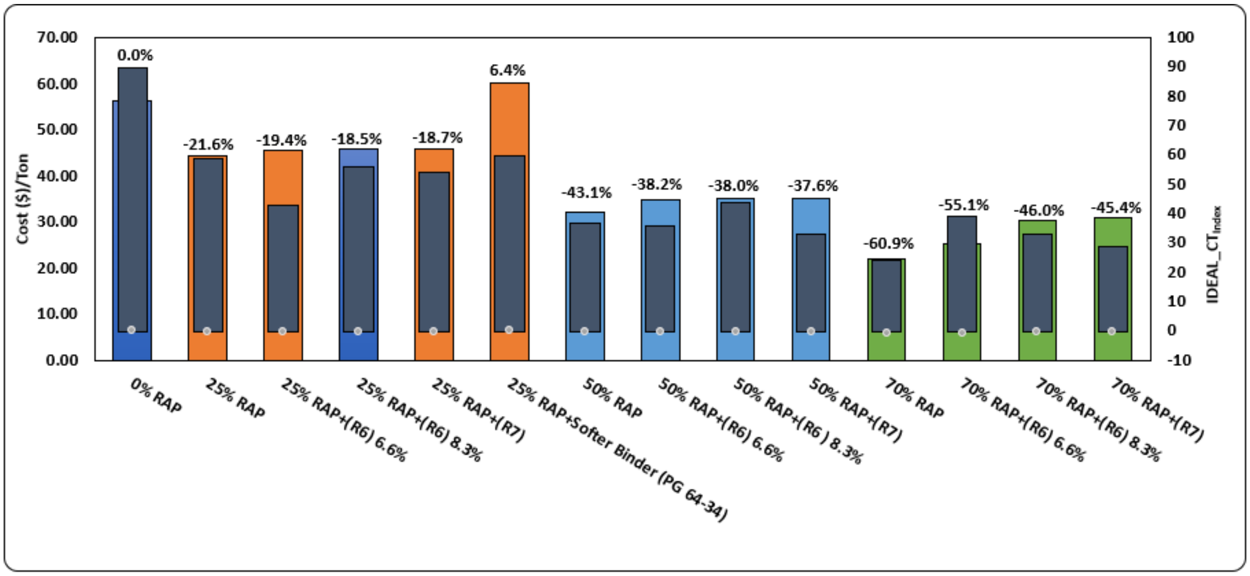


Figure 71. Cost Comparison of Mixtures with RAP No. 4 and Rejuvenators

Table 19. RAP No. 4 Cost Analysis Summary

Mix Type	Cost ($/ton)	Cost Difference ($/ton)	Performance, IDEAL-CT_{Index}
0% RAP	57	0	90
25% RAP	44	-13	59
25% RAP+ (R6) 6.6%	45.54	-11	43
25% RAP+ (R6) 8.3%	46	-11	56
25% RAP+ (R7)	46	-11	54
25% RAP+ Softer Binder (PG 64-34)	60	3	60
50% RAP	32	-25	37
50% RAP+ (R6) 6.6%	35	-22	36
50% RAP+ (R6) 8.3%	35	-22	44
50% RAP+ (R7)	35	-22	33
70% RAP	22	-35	24
70% RAP+ (R6) 6.6%	25.37	-32	39
70% RAP+ (R6) 8.3%	31	-26	33
70% RAP+ (R7)	31	-26	29

7. Conclusions and Recommendations

The researchers examined the performance of asphalt mixtures with different percentages of RAP. In addition, they evaluated the use of rejuvenators to improve the performance of asphalt mixtures through a balanced mix design approach that produces asphalt mixtures with sufficient resistance to cracking and rutting. The researchers prepared and tested mixtures prepared with different sources of RAP (i.e., RAP No. 1, RAP No. 2, RAP No. 3, and RAP No. 4) as well as different RAP contents (e.g., 0, 25, 50, 70 percent RAP). Seven unique commercially available rejuvenators (i.e., R1 though R7) were acquired and included in the testing program. These rejuvenators were tall oil, aromatic extract, bio-based forestry, engineered product, triglycerides and fatty acids product, bio-based oil, petroleum-based oil for R1 through R7, respectively. Asphalt mixtures prepared employing different doses of each rejuvenator were examined as discussed in Chapter 3. Furthermore, the researchers prepared and tested asphalt mixtures at different binder contents (i.e., optimum binder content [OBC] and OBC+0.5 percent) and binder grades (e.g., PG 58-28, PG58-34, PG, PG 64-28, PG 64-34, and PG 70-28).

Also, the researchers prepared Plant-Mixed Laboratory-Compacted (PMLC) test specimens obtained from new ITD paving projects. Loose asphalt mixtures from 23 projects were obtained and tested to evaluate the cracking and rutting performance of asphalt mixtures currently produced and used in the state. These projects were distributed across the six districts of the state (District 1 to District 6). The mixtures included different mix designs, binder grades, percent of RAP content, and percent of RAP binder replacement as discussed in detail in Chapter 3. The researchers evaluated the performance of the test mixtures based on the performance thresholds developed in RP 261 and the ones proposed in the respective standards and literature.

The researcher conducted several laboratory tests to evaluate the cracking and rutting performance of asphalt mixtures examined in this study. The cracking tests included the Indirect Tensile (IDT) Strength Test in accordance with ASTM D8225 to evaluate the intermediate cracking resistance. In addition, the researchers evaluated the low temperature cracking performance of selected mixtures by measuring the creep compliance and strength of the test mixtures at low temperature in accordance with AASHTO T 322. In addition, the researchers examined the rutting performance of the test mixtures in accordance with AASHTO T 324. The main findings from this study are summarized below.

Evaluation of the Performance of Asphalt Mixtures Prepared with RAP and Rejuvenators

- The cracking resistance decreased with the increase of RAP content. Both IDEAL-CT_{Index} and $Weibull_{CRI}$ decreased with the increase of RAP content which demonstrates reduced cracking resistance. Meanwhile, the $IDT_{Strength}$ increased with the increase of RAP content which demonstrates that the mixtures become stiffer with the addition of RAP.
- The use of rejuvenators in mixtures with low RAP content (e.g., 25 percent), especially for mixtures with good cracking performance, didn't improve the cracking resistance (i.e., did not

increase IDEAL-CT_{Index}). In fact, it was observed that the addition of some rejuvenators (i.e., R4 and R6) could be detrimental to the cracking resistance at low RAP content for mixtures with good cracking resistance at low RAP content.

- Mixtures prepared with 70 percent RAP had statistically significant lower IDEAL-CT_{Index} values compared to the ones without RAP (0 percent RAP) irrespective of the binder grade.
- The favorable effect of rejuvenators in asphalt mixtures is observed in mixtures with higher RAP content (e.g., 70 percent) for different RAP sources evaluated in this study. In some cases (e.g., RAP No. 2 and RAP No. 3), it was possible to produce mixtures prepared with 70 percent RAP and rejuvenators that provided comparable cracking performance to the mixture without RAP.
- The use of rejuvenator R1 (tall oil) and rejuvenator R5 (waste vegetable oil) with mixtures with high RAP contents provided the best performance compared to other rejuvenators examined in this study, and these mixtures had comparable cracking performance to the virgin mix (i.e., 0 percent RAP).
- The binder PG did not affect the IDEAL-CT_{Index} for mixtures without RAP (0 percent RAP) and those prepared with 70 percent RAP. However, the $IDT_{Strength}$ for mixtures prepared with PG 64-28 and PG 70-28 was higher compared to the ones for PG 58-34 for the mixtures without RAP. The results of $IDT_{Strength}$ were comparable for mixtures of different binder PG at higher RAP content (70 percent RAP) which demonstrates stiffer mixtures. Also, the rejuvenator R1 provided better results with softer binders, likely due to better compatibility between that product and the binder used.
- The rejuvenator R4 (engineered product) at a higher dose improved the cracking performance of mixtures with RAP; however, these mixtures failed the rutting criteria prematurely (i.e., the mixtures were over softened). These results demonstrated the importance of following a balanced mix design (BMD) approach to satisfy both cracking and rutting criteria.
- Depending on the RAP source and aging conditions, rejuvenators could improve the cracking performance significantly.
- Increasing the binder content was found to increase the cracking resistance for some mixtures with or without RAP. This further emphasizes the effectiveness of following BMD approach.
- The use of rejuvenators R1 and R5 could slightly increase the rut depth compared to the control mixtures (i.e., 70 percent RAP); however, such increase is not statistically significant. All mixtures prepared with these rejuvenators passed the rutting criteria.
- All mixtures with and without rejuvenators prepared with RAP No. 4 provided good rutting resistance and there was no sign of moisture damage or stripping and the rut depth for all mixture was under 4 mm. Meanwhile, the use of RAP in the mixtures tends to decrease the rut depth.
- The use of rejuvenator R1 (tall oil) and rejuvenator R5 (waste vegetable oil) provided higher creep compliance compared to the virgin mixture (0 percent RAP) and control mixture (70 percent RAP) which demonstrated improved cracking resistance at a low temperature.
- Some rejuvenators (e.g., R1 and R5) were highly effective in improving cracking performance of asphalt mixtures with higher RAP content, which offers significant environmental and economic benefits. Furthermore, these rejuvenators enhanced the thermal cracking performance.

- There was a good agreement between the results of $IDT_{Strength}$ (measured at -10 °C) and that of the creep compliance test. The results further demonstrated the favorable impact of rejuvenators on improving the performance of asphalt mixtures with high RAP content at low temperature.

Evaluation of Cracking and Rutting Performance of Plant Mixtures

- The researchers examined the cracking and rutting performance of 23 loose mixtures collected from new paving projects. These loose mixtures were collected from different districts in Idaho and have different properties.
- Most of the field mixes (18 out of 23) exceeded the proposed IDEAL-CT_{Index} threshold of 73.7 which indicates that these mixtures are expected to exhibit good cracking resistance in the field. Four projects were within the moderate cracking performance range, while only one project had an IDEAL-CT_{Index} less than the minimum proposed threshold of 26.4 which demonstrates poor cracking resistance.
- Based on the cracking performance results of IDEAL-CT_{Index} and $Weibull_{CRI}$ and the corresponding thresholds proposed in RP 261, there is no concern with the expected cracking performance of most asphalt mixtures currently produced in Idaho.
- The results demonstrated that IDEAL-CT_{index}, $Weibull_{CRI}$, N_{Flex}, CRI, and FI had direct strong correlations (r > 0.90). Also, the results showed that both $IDT_{Strength}$ and $IDT_{Modulus}$ had an inverse correlation with most indicators (i.e., that IDEAL-CT_{index}, $Weibull_{CRI}$, N_{Flex}, CRI, and FI), except between each other.
- The Pearson correlation results demonstrated that $Weibull_{CRI}$ and IDEAL-CT_{Index} had a strong correlation (r = 0.964); however, $Weibull_{CRI}$ had lower variability in the test results (average COV = 6.6 percent) compared to IDEAL-CT_{index} (average COV = 18.8 percent) which is consistent with the results of ITD RP 280 (Kassem et al. 2021).
- The HWTT rut depth for the field mixes ranged from 1.12 mm to 4.41 mm after 20,000 passes. Therefore, all the mixtures had a rut depth way below the maximum threshold of 12.5 mm after 20,000 passes.
- The HWTT results further demonstrated that there was no sign of moisture damage. Most of the examined projects had anti-strip agents of 0.5 percent except Project No. 1 and No. 13 where 0.75 percent was used.
- Based on the HWTT results, there is no concern on the rutting performance of asphalt mixtures currently produced in Idaho which is consistent with the findings of RP 261 and RP 280.

Economic Benefits of Incorporating RAP and Rejuvenators in Asphalt Mixtures

- The researchers conducted cost analysis to assess economic savings associated with using rejuvenators with high RAP content in asphalt mixtures without compromising the performance (i.e., cracking and rutting resistance).
- At 25 percent RAP, increasing the binder content was more effective than using rejuvenators in terms of cracking performance and associated cost reduction. This leads to cost savings as well as producing mixtures with comparable or improved performance.
- At 50 percent RAP, the use of rejuvenator R1 (tall oil) was the most cost-effective alternative to improve performance as compared to the other rejuvenators including R2 (waste vegetable oil)

or increasing the binder content. In addition, R1 provided comparable cracking performance to that of the virgin mixture.

- At a higher percentage of RAP (e.g., 70 percent), the use of rejuvenators (especially R1) was very effective in improving the cracking resistance with associated cost savings.

Recommendations and Implementation

The results of this study demonstrated that the use of rejuvenators in asphalt mixtures with RAP is beneficial and could offer environmental benefits and cost savings. However, it is more cost effective to incorporate rejuvenators in mixtures with high RAP content (e.g., 50 or 70 percent). The cracking performance of mixtures with certain rejuvenators and high RAP content could be comparable to that of the virgin mixture (0 percent RAP) with additional cost savings. At a low RAP content, increasing the binder content could be more effective in improving the cracking resistance and reducing the cost of asphalt mixtures as compared to that of the virgin mixtures. In addition, the use of rejuvenators R1 (tall oil) and R2 (waste vegetable oil) were found effective in improving the cracking resistance and providing cost savings compared to other rejuvenators. Furthermore, different doses of rejuvenators should be evaluated at the mixture level to select the optimum dose based on cracking performance.

Based on the cracking and rutting assessment of 23 PMLC projects, it is recommended to implement the performance thresholds for cracking and rutting proposed in RP 261 and further evaluated in RP 280 and this study (RP 292) in assessing the performance of asphalt mixtures produced in the state as well as designing new mixtures using a BMD approach. The results of this study clearly demonstrate the importance of implementing a BMD approach to optimize the design of asphalt mixtures prepared with RAP and rejuvenators to provide adequate performance in terms of cracking and rutting resistance. Furthermore, the balanced mix design should be supplemented by conducting a cost-benefit analysis to compare different alternatives that provide acceptable performance.

It is recommended to construct trial sections in the field. These sections should be constructed using asphalt mixtures designed based on a BMD approach. The performance thresholds proposed in RP 261 and evaluated in this study can be adopted to ensure adequate resistance to cracking, rutting as well as moisture damage. The asphalt mixtures used in these sections should be prepared with RAP and rejuvenators. The performance of these sections should be monitored overtime to evaluate the need to revise or adjust the performance thresholds proposed for the BMD approach. In addition, field cores should be extracted and tested in the laboratory to examine the correlation between laboratory tests and field performance.

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Appendix A. RAP Properties

Design Specifications: Blend 1 / 75 Gyrations @ N Design PG 64-28 (58-34 Adjusted Binder)

Gyratory Compactor: Model # AFG2AS, Serial # 8436

#		Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	**5.3**	--
2	Percent Asphalt by Weight of Aggregate	5.64	--
3	Virgin Asphalt by Weight of Mix	4.08	--
4	Virgin Asphalt by Weight of Aggregate	4.32	--
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	15.6	14 min
7	Compacted Unit Weight Gmb, pcf	2.366 147.3	--
8	Theoretical Maximum Density Gmm, pcf	**2.465 153.4**	--
9	Percent Effective Asphalt Content (Pbe)	5.04	--
10	Percent Absorbed Asphalt (Pba)	0.32	--
11	Specific Gravity of Binder (Gb)	**1.028**	--
12	Percent Gmm @ N Initial (7 Gyrations)	86.8	≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.3	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.1	0.6-1.4
16	Percent Passing #200 Sieve	5.6	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	74	65-75
18	Laboratory Mixing Temperature for Design (°F)	320	316-324
19	Laboratory Compaction Temperature for Design (°F)	**299**	295-303
20	Laboratory Sample Weight for Volumetric Testing (g)	**4720**	--
21	Ignition Oven (NCAT) Correction Factor @ 538 °F	**0.30**	--
22	*Los Angeles Abrasion (LAR) (%)	24	30 max
23	*Idaho Degradation Δ % -200	3.5	5.0 max
24	Sand Equivalent	66	40 min
25	*Fracture Face Count (%)	98/96	75/60
26	Fine Aggregate Angularity (%)	47.2	40 min
27	*Flat and Elongated Particles in Coarse Aggregates (%)	0.3	10 max
	Recycled Asphalt Pavement (RAP) Properties		
28	Percentage of Asphalt in RAP (Wt. of Mix)	4.20	
29	Percentage of RAP by Total Weight of Aggregate	30	--
30	Percent of RAP Binder by Weight of Total Binder	24	30 max
31	RAP Contribution by Mix	1.26	--
32	RAP Contribution by Aggregate	1.32	
33	RAP NCAT Correction Factor	0.36	--

***Composite blend including RAP**

Figure A.1: RAP No. 1

Project Name: **US-26, MP 271.83 to MP 284.2; US-26, Puzzle to MP 283**

Project Number: **A020(590)** Project Key Number: **20590**

Asphalt Mix Type:	**19 mm SP3 (Design ESALs, 1<10)**	Mix Producer:	
JMF Identification:	**20036-19mmSP3-R30**	Specified Oil:	**PG 58-34**
Binder Supplier:	**Idaho Asphalt Supply**	Adjusted Oil:	**PG 58-34**
Anti-Strip:	**Morlife 5000**	Agg. Source Number:	**Bu-26s**

Job Mix Formula Targets and Volumetric Data

Target Oil Content:	**5.0**	RAP Percent By Binder:	**30**	JMF G_{mb} Specimen Weight:	**4675**
Virgin Oil Added by Mix:	**3.5**	RAP Oil Contribution:	**1.5**	JMF Ncat Correction Factor:	**0.40**
Virgin Oil Added by Agg:	**3.7**	Compaction Temp. Range:	**288-302 °F**	Lab Compaction Temp (F°):	**292**
Percent Anti-Strip:	**0.75**	Mixing Temp. Range:	**315-329 °F**	Binder Specific Gravity (G_b):	**1.0293**

Aggregate, RAP and Binder Specific Gravities

Combined Gsb:	**2.585**	Effective Specific Gravity (G_{se}):	**2.624**	D6 RAP Bulk Specific Gravity:	**2.589**
Fine Aggregate Gsb:	**2.562**	Fine SSD Specific Gravity:	**2.606**	IF RAP Bulk Specific Gravity:	**2.605**
Coarse Aggregate Gsb:	**2.594**	Coarse SSD Specific Gravity:	**2.621**	Fine Apparent Specific Gravity (G_{sa}):	**2.679**
Fine Agg. % Absorption	**1.6**	Coarse Agg. % Absorbtion:	**1.1**	Coarse Apparent Specific Gravity (G_{sa}):	**2.667**
		IF RAP Correction Factor:	**0.08**	D6 RAP Correction Factor:	**0.07**

Job Mix Formula Target Volumetric Properties

	Design	Spec.		Design	Spec.
Maximum Theoretical Specific Gravity (G_{mm}):	**2.435**	--	Bulk Specific Gravity (G_{mb}):	**2.338**	--
Percent Air Voids (P_a):	**4.0**	2.5-5.0	Voids In Mineral Aggregate (VMA):	**14.1**	13.0 min
Voids Filled with Asphalt (VFA):	**72**	65-75	Dust Proportion (DP):	**1.2**	0.6-1.4
Absorbed Apshalt (P_{ba}):	**0.59**	--	Effective Asphalt Content (P_{be}):	**4.44**	--
Density Percent G_{mm} @ Nini:	**97.6**	≤ 89.0	Density Percent G_{mm} @ Ndes:	**96**	96.0
Density Percent G_{mm} @ Nmax:	**97.3**	≤ 98.0	Average Rut Depth @15,000 Passes	**5.2**	10.0 max
Uncompacted Void Content of Fine Aggregate:	**51**	40 min	Sand Equivalent:	**60**	40 min
Fracture Face Coarse Aggregate (1 Face/2 Face):	**98/98**	75/60	Flat and Elongated Particles:	**0**	10 max
			Average IDEAL-CT Cracking Index:	**123**	80 min

JMF Target Aggregate, Breakdown, Proportions

Blend Percentages:	A-Pile:	**12.0**	B-Pile:	**21.0**	C-Pile:	**37.0**	IF RAP:	**20.0**	D6 RAP:	**10.0**

Job Mix Formula Aggregate Gradations & Stockpile Averages

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
JMF Specifications:		100	90-100	90 max		28-58					2.0-10.0
JMF Target Gradation:	**100**	**99**	**85**	**73**	**48**	**32**	**23**	**17**	**12**	**8.0**	**5.2**
Ncat C.F. Gradation:	**100.0**	**98.3**	**84.4**	**72.7**	**49.2**	**30.7**	**23.2**	**16.9**	**11.9**	**7.2**	**4.2**
Agg. Correction Factor:	**0.0**	**0.7**	**0.6**	**0.3**	**-1.2**	**1.3**	**-0.2**	**0.1**	**0.1**	**0.8**	**1.0**
A-Pile	**100**	**91**	**21**	**5**	**2**	**1**	**1**	**1**	**1**	**1**	**0.6**
B-Pile	**100**	**100**	**80**	**45**	**5**	**2**	**2**	**1**	**1**	**1**	**0.7**
Breakdown:	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**90.0**
C-Pile:	**100**	**100**	**100**	**100**	**80**	**53**	**35**	**24**	**16**	**10**	**7.3**
IF Category 1 RAP:	**100**	**100**	**96**	**88**	**62**	**43**	**33**	**28**	**22**	**14**	**7.6**
D6 Category 1 RAP:	**100**	**100**	**90**	**78**	**51**	**36**	**28**	**22**	**17**	**12**	**7.6**

Figure A.2: RAP No. 2

Design Specifications: Blend 4 / 75 Gyrations @ N Design PG 70-28 (64-34 Adjusted Binder)

Gyratory Compactor: Model # AFG2AS, Serial # 8732

		Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	5.1	--
2	Percent Asphalt by Weight of Aggregate	5.4	--
3	Virgin Asphalt by Weight of Mix	3.62	--
4	Virgin Asphalt by Weight of Aggregate	3.83	--
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	14.7	14 min
7	Compacted Unit Weight Gmb, pcf	2.485 154.7	--
8	Theoretical Maximum Density Gmm, pcf	2.589 161.2	--
9	Percent Effective Asphalt Content (Pbe)	4.44	--
10	Percent Absorbed Asphalt (Pba)	0.69	--
11	Specific Gravity of Binder (Gb)	1.030	--
12	Percent Gmm @ N Initial (7 Gyrations)	86.4	≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.6	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.3	0.6-1.5
16	Percent Passing #200 Sieve	5.8	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	73	65-75
18	Laboratory Mixing Temperature for Design (°F)	328	321-329
19	Laboratory Compaction Temperature for Design (°F)	305	299-308
20	Laboratory Sample Weight for Volumetric Testing (g)	4950	--
21	Ignition Oven (NCAT) Correction Factor @ 482 °F	1.05	--
22	*Los Angeles Abrasion (LAR) (%)	20	30 max
23	*Idaho Degredation Δ % -200	2.6	5.0 max
24	Sand Equivalent	68	40 min
25	*Fracture Face Count (%)	99/93	75/60
26	Fine Aggregate Angularity (%)	48.0	40 min
27	*Flat and Elongated Particles in Coarse Aggregates (%)	3.1	10 Max
	Recycled Asphalt Pavement (RAP) Properties		
28	Percentage of Asphalt in RAP (Wt. of Mix)	4.34	--
29	Percentage of RAP by Total Weight of Aggregate	34	--
30	Percent of RAP Binder by Weight of Total Binder	29	30 Max
31	RAP Contribution by Mix	1.48	--
32	RAP Contribution by Aggregate	1.54	--
33	RAP NCAT Correction Factor	1.73	--

*Composite blend including RAP

Figure A.3: RAP No. 3

Table A.1: RAP No. 4

True RAP Grade:	PG 82-16
Available Asphalt Content (RAP):	5.3%

Sieve Size	% Passing
1”	100
¾”	100
½”	94
3/8”	83
No. 4	57
No. 8	42
No. 16	33
No. 30	25
No. 50	17
No. 100	11
No. 200	7.2

Appendix B. Rejuvenator Dose using Blending Charts

Table B.1: Binder Blend Critical Temperatures (˚C)

Testing	Property (units)	RAP	R6 (5%)	R6 (8%)	R7 (8%)	R7 (12%)
Org. High	G*/sinδ (1 kPa)	85.3	81.9	74.2	78.7	70.7
RTFO High	G*/sinδ (2.2 kPa)	89.0	84.1	81.2	81.2	75.6
PAV BBR	BBR, Stiffness (300 MPa)	-24.5	-31.2	-34.7	-36.2	-40.7
PAV BBR	BBR, m-value (0.3)	-16.2	-24.5	-31.7	-17.3	-20.0
True Grade		PG 85.3-16.2	PG 81.9-24.5	PG 74.2-31.7	PG 78.7-17.3	PG 70.7-20
PG Grade (M320)		PG 82-16	PG 76-22	PG 70-28	PG 76-16	PG 70-16

Table B.2: Calculated Dose

DSR/BBR property	PG 70-28 value	RA type	RA dose (%)
Stiffness (BBR)	245	R6	**3.6**
Stiffness (BBR)	245	R7	**-1.3**
m-value (BBR)	0.32	R6	**8.3**
m-value (BBR)	0.32	R7	**31.6**
G*/sin(δ)	1.36	R6	**8.3**
G*/sin(δ)	1.36	R7	**11.3**
Log [G*/sin(δ)]	0.13354	R6	**8.5**
Log [G*/sin(δ)]	0.13354	R7	**11.0**
m-value (#2)	0.3 (standard minimum)	R6	**6.6**
m-value (#2)	0.3 (standard minimum)	R7	**23.6**

Appendix C. LMLC Mix Design Summary

Design Specifications: Blend 1 / 75 Gyrations @ N Design PG 64-28 (58-34 Adjusted Binder)

Gyratory Compactor: Model # AFG2AS, Serial # 8436

		Job Mix Formula		Spec
1	Percent Asphalt by Weight of Total Mix	5.3		--
2	Percent Asphalt by Weight of Aggregate	5.64		--
3	Virgin Asphalt by Weight of Mix	4.08		--
4	Virgin Asphalt by Weight of Aggregate	4.32		--
5	Percent Air Voids (Pa)	4.0		4.0
6	Voids in Mineral Aggregate (VMA)	15.6		14 min
7	Compacted Unit Weight Gmb, pcf	2.366	147.3	--
8	Theoretical Maximum Density Gmm, pcf	2.465	153.4	--
9	Percent Effective Asphalt Content (Pbe)	5.04		--
10	Percent Absorbed Asphalt (Pba)	0.32		--
11	Specific Gravity of Binder (Gb)	1.028		--
12	Percent Gmm @ N Initial (7 Gyrations)	86.8		≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0		96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.3		≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.1		0.6-1.4
16	Percent Passing #200 Sieve	5.6		2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	74		65-75
18	Laboratory Mixing Temperature for Design (°F)	320		316-324
19	Laboratory Compaction Temperature for Design (°F)	299		295-303
20	Laboratory Sample Weight for Volumetric Testing (g)	4720		--
21	Ignition Oven (NCAT) Correction Factor @ 538 °F	0.30		--
22	*Los Angeles Abrasion (LAR) (%)	24		30 max
23	*Idaho Degradation Δ % -200	3.5		5.0 max
24	Sand Equivalent	66		40 min
25	*Fracture Face Count (%)	98/96		75/60
26	Fine Aggregate Angularity (%)	47.2		40 min
27	*Flat and Elongated Particles in Coarse Aggregates (%)	0.3		10 max
	Recycled Asphalt Pavement (RAP) Properties			
28	Percentage of Asphalt in RAP (Wt. of Mix)	4.20		
29	Percentage of RAP by Total Weight of Aggregate	30		--
30	Percent of RAP Binder by Weight of Total Binder	24		30 max
31	RAP Contribution by Mix	1.26		--
32	RAP Contribution by Aggregate	1.32		
33	RAP NCAT Correction Factor	0.36		--

*Composite blend including RAP

Figure C.1: Mix Design of LMLC with RAP No. 1

Asphalt Mix Type:	12.50 mm SP3 (Design ESALs 1<10)	Mix Producer:	KRC
JMF Identification:	21030	Specified Oil:	PG 58-28
Binder Supplier:	Idaho Asphalt	Adjusted Oil:	NR
Anti-Strip:	Morelife 5000	Agg. Source Number:	NP169c

Job Mix Formula Targets and Volumetric Data

Target Oil Content:	5.8	RAP Percent By Binder:	17.5	JMF G_{mb} Specimen Weight:	4650
Virgin Oil Added by Mix:	4.8	RAP Oil Contribution:	1.02	JMF Ncat Correction Factor:	0.73
Virgin Oil Added by Agg:	5.1	Compaction Temp. Range:	272-281	Lab Compaction Temp (F°):	275
Percent Anti-Strip:	0.05	Mixing Temp. Range:	293-305	RAP Correction Factor:	0.53

Aggregate, RAP and Binder Specific Gravities

Combined G_{sb}:	2.591	Effective Specific Gravity (G_{se}):	2.657	RAP Bulk Specific Gravity:	2.685
Fine Aggregate G_{sb}:	2.559	Fine SSD Specific Gravity:	2.615	Fine Apparent Specific Gravity (G_{sa}):	2.711
Coarse Coarse G_{sb}:	2.581	Coarse SSD Specific Gravity:	2.629	Coarse Apparent Specific Gravity (G_{sa}):	2.710
Fine Agg.% Absorbtion:	2.223	Coarse Agg. % Absorbtion:	1.80	Binder Specific Gravity (G_b):	1.0317

Job Mix Formula Target Volumetric Properties

	Design	Spec.		Design	Spec.
Maximum Theoretical Specific Gravity (G_{mm}):	2.433	–	Bulk Specific Gravity (G_{mb}):	2.335	–
Percent Air Voids (Pa):	4.0	2.5-5.0	Voids in Mineral Aggregate (Vma):	15.1	14.0 min
Voids Filled with Asphalt (VFA)	74	65-75	Dust Proportion (DP):	1.2	0.6-1.4
Absorbed Apshalt (P_{ba}):	1.0	–	Effective Asphalt Content (P_{be}):	4.9	–
Density Percent Gmm @ Nini:	86.9	≤ 89.0	Uncompacted Void Content of Fine Aggregate:	51.0	40.0
Density Percent Gmm @ Ndes:	96.0	96	Sand Equivalent (SE):	57	40
Density Percent Gmm @ Nmax:	97.5	≤ 98.0	Flat and Elongated Particles:	0	10
Fracture Face Coarse Aggregate (1Face/2Face):	100/100	75/60	Rut Depth @ 15,000 Passes (Average):	NR	≤ 10.0 mm
			IDEAL-CT Cracking Index (Average):	NR	80

JMF Target Aggregate, Breakdown, Proportions

Blend Percentages:	B-Pile	40.0	C-Pile	40.0	RAP	20.0

Job Mix Formula Aggregate Gradations & Stockpile Averages

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
JMF Specifications:	–	100	90-100	90 max	–	28-58	–	–	–	–	2.0-10.0
JMF Target Gradation:	100	100	90	79	55	38	25	18	13	9	6.1
Ncat C.F. Gradation:	100	100	92	79	55	38	25	18	13	10	6.5
Agg. Correction Factor:	0.0	0.0	2.2	-0.1	-0.1	-0.3	-0.2	-0.2	0.0	0.6	0.4
B-Pile	100	100	79	54	12	2	1	1	1	1	0.6
C-Pile	100	100	100	100	93	70	46	32	22	15	10.7
RAP	100	100	94	86	64	46	33	24	17	12	8.0
0											

Figure C.2: Mix Design of LMLC with RAP No. 2

Design Specifications: Blend 4 / 75 Gyrations @ N Design PG 70-28 (64-34 Adjusted Binder)

Gyratory Compactor: Model # AFG2AS, Serial # 8732

		Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	**5.1**	--
2	Percent Asphalt by Weight of Aggregate	5.4	--
3	Virgin Asphalt by Weight of Mix	3.62	--
4	Virgin Asphalt by Weight of Aggregate	3.83	--
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	14.7	14 min
7	Compacted Unit Weight Gmb, pcf	2.485 154.7	--
8	Theoretical Maximum Density Gmm, pcf	**2.589 161.2**	--
9	Percent Effective Asphalt Content (Pbe)	4.44	--
10	Percent Absorbed Asphalt (Pba)	0.69	--
11	Specific Gravity of Binder (Gb)	**1.030**	--
12	Percent Gmm @ N Initial (7 Gyrations)	86.4	≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.6	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.3	0.6-1.5
16	Percent Passing #200 Sieve	5.8	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	73	65-75
18	Laboratory Mixing Temperature for Design (°F)	328	321-329
19	Laboratory Compaction Temperature for Design (°F)	**305**	299-308
20	Laboratory Sample Weight for Volumetric Testing (g)	**4950**	--
21	Ignition Oven (NCAT) Correction Factor @ 482 °F	**1.05**	--
22	*Los Angeles Abrasion (LAR) (%)	**20**	30 max
23	*Idaho Degredation Δ % -200	**2.6**	5.0 max
24	Sand Equivalent	68	40 min
25	*Fracture Face Count (%)	99/93	75/60
26	Fine Aggregate Angularity (%)	48.0	40 min
27	*Flat and Elongated Particles in Coarse Aggregates (%)	3.1	10 Max
	Recycled Asphalt Pavement (RAP) Properties		
28	Percentage of Asphalt in RAP (Wt. of Mix)	4.34	--
29	Percentage of RAP by Total Weight of Aggregate	34	--
30	Percent of RAP Binder by Weight of Total Binder	29	30 Max
31	RAP Contribution by Mix	1.48	--
32	RAP Contribution by Aggregate	1.54	--
33	RAP NCAT Correction Factor	1.73	--

***Composite blend including RAP**

Figure C.3: Mix Design of LMLC with RAP No. 3

Table C.1: Mix Design of LMLC with RAP No. 4

Sieve Size	1 inch	¾ inch	½ inch	3/8 inch	No.4	No.8	No.16	No.30	No.50	No.100	No.200
Virgin % Passing	100	100	94	76	50	37	24	18	14	10	5.3
RAP4 % Passing	100	100	94	83	57	42	33	25	17	11	7.2
25% RAP % Passing	100	100	94	76	50	37	24	18	14	10	5.3
50% RAP % Passing	100	100	94	76	50	37	24	18	14	10	5.3
70% RAP % Passing	100	100	94	76	50	37	24	18	14	10	5.3
Control Points		100	90			28					2.0
Control Points		100	100	90		58					10.0
Restricted Zone						39.1	25.6	19.1	15.5		
Restricted Zone						39.1	31.6	23.1	15.5		

Mix Property	Job Mix Formula	Spec.
Percent Asphalt by Weight of Total Mix	**5.3**	-
Percent Asphalt by Weight of Aggregate	5.3	-
Percent Air Voids (Pa)	4.1	4.0
Voids in Mineral Aggregate (VMA)	14.7	14 min
Compacted Unit Weight Gmb, pcf	2.307	-
Theoretical Maximum Density Gmm, pcf	2.406	-
Percent Effective Asphalt Content (Pbe)	4.7	-
Percent Absorbed Asphalt (Pba)	0.54	-
Specific Gravity of Binder (Gb)	1.0331	-
Percent Gmm @ N Initial (7 gyrations)	86.7	≤ 89.0
Percent Gmm @ N Design (75 gyrations)	95.9	96.0
Percent Gmm @ N Maximum (115 gyrations)	96.8	≤ 98.0
Dust to Asphalt Ratio (DP)	1.1	0.8-1.2
Percent Passing #200 Sieve	5.0	3.0-6.0
Voids Filled with Asphalt (VFA)	72.1	-
Laboratory Mixing Temperature for Design (F̊)	336	327-337
Laboratory Compaction Temperature for Design (F̊)	314	306-316
Laboratory Sample Weight for Volumetric Testing (g)	4741	-
Ignition Oven (NCAT) Correction Factor @ 538 F̊	0.37	-
Los Angeles Abrasion (LAR) (%)	29	40 max
Sand Equivalent	64	45 min
Fracture Face Count (%)	98	75 min (2 Face)
Fine Aggregate Angularity (%)	46.1	45.0 min
Flat and Elongated Particles in Coarse Aggregates (%)	0	20 max (3:1)
Coarse Clay Lumps and Friable Particles	0	0.3 max
Fine Clay Lumps and Friable Particles	0	0.3 max
Percent Natural Sand	0	15 max
Coarse Sodium Sulfate Soundness	1.1	12 max

Figure C.4: Mix Design of LMLC with RAP No. 4

Appendix D. PMLC Mix Design Summary

Project Name: **US-26, MP 271.83 to MP 284.2; US-26, Puzzle to MP 283**

Project Number: **A020(590)** Project Key Number: **20590**

Asphalt Mix Type:	19 mm SP3 (Design ESALs, 1<10)	Mix Producer:	
JMF Identification:	20036-19mmSP3-R30	Specified Oil:	PG 58-34
Binder Supplier:	Idaho Asphalt Supply	Adjusted Oil:	PG 58-34
Anti-Strip:	Morlife 5000	Agg. Source Number:	Bu-26s

Job Mix Formula Targets and Volumetric Data

Target Oil Content:	5.0	RAP Percent By Binder:	30	JMF G_{mb} Specimen Weight:	4675
Virgin Oil Added by Mix:	3.5	RAP Oil Contribution:	1.5	JMF Ncat Correction Factor:	0.40
Virgin Oil Added by Agg:	3.7	Compaction Temp. Range:	288-302 °F	Lab Compaction Temp (F°):	292
Percent Anti-Strip:	0.75	Mixing Temp. Range:	315-329 °F	Binder Specific Gravity (G_b):	1.0293

Aggregate, RAP and Binder Specific Gravities

Combined Gsb:	2.585	Effective Specific Gravity (G_{se}):	2.624	D6 RAP Bulk Specific Gravity:	2.589
Fine Aggregate Gsb:	2.562	Fine SSD Specific Gravity:	2.606	IF RAP Bulk Specific Gravity:	2.605
Coarse Aggregate Gsb:	2.594	Coarse SSD Specific Gravity:	2.621	Fine Apparent Specific Gravity (G_{sa}):	2.679
Fine Agg. % Absorption	1.6	Coarse Agg. % Absorbtion:	1.1	Coarse Apparent Specific Gravity (G_{sa}):	2.667
		IF RAP Correction Factor:	0.08	D6 RAP Correction Factor:	0.07

Job Mix Formula Target Volumetric Properties

	Design	Spec.		Design	Spec.
Maximum Theoretical Specific Gravity (G_{mm}):	2.435	--	Bulk Specific Gravity (G_{mb}):	2.338	--
Percent Air Voids (P_a):	4.0	2.5-5.0	Voids In Mineral Aggregate (VMA):	14.1	13.0 min
Voids Filled with Asphalt (VFA):	72	65-75	Dust Proportion (DP):	1.2	0.6-1.4
Absorbed Apshalt (P_{ba}):	0.59	--	Effective Asphalt Content (P_{be}):	4.44	--
Density Percent G_{mm} @ Nini:	97.6	≤ 89.0	Density Percent G_{mm} @ Ndes:	96	96.0
Density Percent G_{mm} @ Nmax:	97.3	≤ 98.0	Average Rut Depth @15,000 Passes	5.2	10.0 max
Uncompacted Void Content of Fine Aggregate:	51	40 min	Sand Equivalent:	60	40 min
Fracture Face Coarse Aggregate (1 Face/2 Face):	98/98	75/60	Flat and Elongated Particles:	0	10 max
			Average IDEAL-CT Cracking Index:	123	80 min

JMF Target Aggregate, Breakdown, Proportions

Blend Percentages:	A-Pile:	12.0	B-Pile:	21.0	C-Pile:	37.0	IF RAP:	20.0	D6 RAP:	10.0

Job Mix Formula Aggregate Gradations & Stockpile Averages

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
JMF Specifications:		100	90-100	90 max		28-58					2.0-10.0
JMF Target Gradation:	100	99	85	73	48	32	23	17	12	8.0	5.2
Ncat C.F. Gradation:	100.0	98.3	84.4	72.7	49.2	30.7	23.2	16.9	11.9	7.2	4.2
Agg. Correction Factor:	0.0	0.7	0.6	0.3	-1.2	1.3	-0.2	0.1	0.1	0.8	1.0
A-Pile	100	91	21	5	2	1	1	1	1	1	0.6
B-Pile	100	100	80	45	5	2	2	1	1	1	0.7
Breakdown:	100	100	100	100	100	100	100	100	100	100	90.0
C-Pile:	100	100	100	100	80	53	35	24	16	10	7.3
IF Category 1 RAP:	100	100	96	88	62	43	33	28	22	14	7.6
D6 Category 1 RAP:	100	100	90	78	51	36	28	22	17	12	7.6

Figure D.1: Job Mix Formula for Project No. 1

Key Number	Project Number	Project Name	District
19863	A019 (863)	SH-75, Old US-93 to Richfield	4

Identification Number (Program/Task/Phase/Sample#)	Contract Item Number	Testing Laboratory Name & Location	Mix Design No.
Superpave HMA 3/8" SP3 / P-174880	405-435A	ITD Central Laboratory	A520-0221

Send Reports To(Resident Engineer's Name)	Sampled By	WAQTC Number	Date Sampled	Date Lab Received	Date Lab Tested
Doug Yearsley	D. Kilmer	22046	6/10/2020	6/10/2020	6/11/2020

Asphalt Binder Supplier	Asphalt Binder Grade	Sp. Gr. of Binder (from Mix Design)	JMF Intended Binder, % (by Wt of Mix)	Source Number
Idaho Asphalt Supply	PG 70-28	1.031	6.2	Ln-84s

Sample Location (Sta./offset, truck, plant, lab, etc.)	Mix Design Lab & Location	SPMDT	P.E. in Responsible Charge of Design
Lab Prepared	All West, Meridian	Dan Kilmer	Adrian Mascorro, P.E.

ESALs	Nom. Max. Size Aggregate	Primary Control Sieve	Percent Passing Primary Control Sieve	Class of Mix
1 <10 (75 Gyrations)	3/8"	No. 8	47 %	SP3

Combined Aggregate Bulk SPG G_{sb} from ITD 0802 2.548

Test Results

Gradation Anayisis
FOP for AASHTO T 30

Sieve Size (mm)	(in.)	Lab No. 209MX--0088	Lab No.	Lab No.	Avg.	JMF
(50)	2	100			100	100
(37.5)	1/1/2	100			100	100
(25)	1	100			100	100
(19)	3/4	100			100	100
(12.5)	1/2	100			100	100
(9.5)	3/8	95			95	94
(4.75)	No. 4	70			70	70
(2.36)	No. 8	46			46	46
(1.18)	No. 16	31			31	32
(0.600)	No. 30	23			23	23
(0.300)	No. 50	17			17	17
(0.150)	No. 100	12			12	11
(0.075)	No. 200	7.2			7.2	6.4
Avg. Sample Height, mm		115.4				

Asphalt Binder Content (By Weight of Mix)
FOP for AASHTO T 308

	Lab No. 209MX--0088	Lab No.	Lab No.	Average
Total Asphalt Binder Content	6.59			
NCAT Correction Factor	0.42			
Moisture % (-)	0.03			
Act. Asph. Binder Content %	6.14			6.1

Compaction Temperature, °F 304

FOP for AASHTO T 312 / AASHTO M 323

				Average
Lab Air Voids % at N_{Design}	3.6			3.6
G_{mb} (compacted mixture)	2.307			2.307
G_{mm} (max spec gravity)	2.392			2.392
VMA, %	15.0			15.0
VFA, %	76			76
Dust Proportion (DP)	1.4			1.4
G_{se} - Effective Sp. Gravity	2.619			
P_{be} - Eff. Binder Content, %	5.12			
P_{ba} - Binder Absorbed, %	1.09			

FOP for AASHTO T 209 result within 0.020 of JMF? Gmm from JMF= 2.389 Gmm from Sample Tested= 2.392 **Yes**
FOP for AASHTO T 166 result within 0.020 of JMF? Gmb from JMF= 2.293 Gmb from Sample Tested= 2.307 **Yes**

ASTM D1075 & AASHTO T 167

Sample #

84 % @ 0.50 % MORLIFE 5000

FAIL

AASHTO T 340

Sample # n/a

Rutting Depth, mm	n/a	Maximum Allowable Rut Depth
Left Sample	n/a	
Center Sample	n/a	0.2 in. (5 mm)
Right Sample	n/a	n/a

Mix Design Volumetrics Confirmation: [X] **Pass** [ ] **Fail**

Remarks

APA became inoperable prior to test. Retaining pucks for information only testing.

Tested By	WAQTC Number
Dan Henscheid/Jaime Conley/ Shelby Alvarado/ Heather Miley	24083/24080/24079/24047

Date Mailed	Laboratory Manager's Signature
6/16/2020	Chad W. Clawson Digitally signed by Chad W. Clawson — Chad Clawson, P.E.

Figure D.2: Job Mix Formula for Project No. 2

Class:	**12.5mm SP-3 PG 70-28**
Project:	**US-93, 200 South**

Proposed Job Mix Formula

Laboratory Values	Target			Spec.
Total Asphalt by Weight of Mix % (Pb)	5.6			
Total Aspalt by Weight of Aggregate	5.98			
Air Voids % (Va)	4.0			3.0-5.0
Voids in Mineral Aggregate (VMA)	14.7			14.3
Voids Filled with Asphalt (VFA)	73			65-75
Bulk Specific Gravity (Gmb)	2.304			
Unit Weight lb./cuft.	143.4			
Theo Max Spec Gravity (Gmm)	2.401			
Theo Max Spec Gravity lb./cuft.	149.5			
Effective Specific Gravity of Blend (Gse)	2.608			
Effect of Water on Compressive Strength *(AllWest)*	95			85 min
Ninitial (7 Gyrations)	86.4			≤ 89.0
Ndesign SP-5 (75 Gyrations)	96.0			= 96.0
Nmax (115 Gyrations)	97.6			≤ 98.0
NCAT Asphalt Correction Factor	0.23			
Dust to Asphalt	1.1			
Laboratory Mixing Temperature(deg in F)	320			
Laboratory Compaction Temperature(deg in F)	300			
Plant Mixing Temperature(deg in F)**	316	-	324	
Field Compaction Temperature(deg in F)**	295	-	303	
Superpave Design Sample Wt. in grams	4580			

**Field mixing and compaction may be adjusted +/- 25 degrees per Viscosity Graph*

Aggregate Gradation Data

Sieve Size		Ln-80c B 23.0%	Cs-201 C 16.0%	Ln-80c WC 25.5%	Md-101c Sand 5.0%	RAP 30.0%	Break down 0.5%	JMF Blended Gradation
1" / 25mm		100	100	100	100	100	100	100
3/4" / 19mm		100	100	100	100	100	100	100
1/2" / 12.5mm		88	100	100	100	95	100	96
3/8" / 9.5mm		46	100	100	100	86	100	83
No. 4 / 4.75mm		2	85	75	100	62	100	57
No. 8 / 2.36mm		2	58	43	85	45	100	39
No.16 / 1.18mm		1	41	26	66	34	100	27
No. 30 / 600um		1	30	16	54	26	100	20
No. 50 / 300um		1	22	9	20	20	100	14
No. 100 / 150um		1	15	4	4	14	100	9
No. 200 / 75um		0.7	9.9	1.4	1.4	9.5	90.0	5.5

** Aggregate breakdown will be controlled by the Hot Plant dust control system.*

Figure D.3: Job Mix Formula for Project No. 3

ASPHALT CONCRETE JOB MIX FORMULA

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Project: Big Wood River Bridge Replacement
Paving Contractor: Valley Paving
Asphalt Supplier: Idaho Asphalt
Anti-Strip Agent: 0.5% Morelife 5000
Aggregate Sources: BE 106c
Design Specification: ITD

Date: 7/18/2016
Class of Mixture: SP-3
Specified Grade of Asphalt: PG 64-34
Prepared by: LLC
Gyratory Compactor: Pine AFGC125X

	AASHTO	JMF	Requirements
1. Asphalt by Weight of Total Mix, %	R 35	5.8%	
2. Asphalt by Weight of Aggregates, %		6.1%	
3. Asphalt by Weight of Total Mix (Added), %		5.0%	
4. Asphalt by Weight of Aggregates (Added), %		5.2%	
5. Air Voids (Va), %	T 269	4.0%	3.0-5.0
6. Voids in Mineral Aggregate (VMA), %	R 35	15.0%	13.3 min
7. Bulk Specific Gravity @ Ndes (Gmb)	T 166	2.296	142.9 pcf
8. Theoretical Maximum Specific Gravity (Gmm)	T 209	2.391	148.8 pcf
9. Relative Density %Gmm @ Nini (7 Gyrations)	R 35	87.4	≤ 89.0
10. Relative Density %Gmm @ Nmax (115 Gyrations)	R 35	97.2	≤ 98.0
11. Voids Filled w/ Asphalt (VFA), %	R 35	73.3%	65-75
12. Film thickness, microns		1	
13. Absorbed Asphalt (Pba) by Weight of Aggregate, %	R 35	0.90%	
14. Effective Asphalt Content (Pbe) by Total Wt of Mixture, %	R 35	4.9%	
15. Specific Gravity of Asphalt		1.026	
16. Laboratory Mixing Temp, °C/°F		318-333	
17. Laboratory Compaction Temp, °C/°F		288-304	
18. Recommended Plant Mixing Temp, °F		325	
19. Compaction Temp Range, °F		296	
20. NCAT Ignition Oven Correlation Factor @ 538° C	T 308	0.17	
21. Dust to Asphalt Ratio	R 35	1.2	0.6-1.2
22. Immersion Compression Retained Strength, %	T 165	85%	85% min
23. Gyratory Gmb specimen weight, grams		4500	
24. Combined Bulk Dry Specific Gravity of Aggregate (Gsb)	T 85 / IT 144	2.545	

AGGREGATE STOCKPILE GRADATION

		A-Pile	B-Pile	C-Pile	RAP	0	Blended Gradation	Mix Design Tolerances
		15%	18%	50%	17%	0%		
25.0 mm (1")		100%	100%	100%	100%	0%	100%	100
19.0 mm (3/4")		99%	100%	100%	100%	0%	100%	100
12.5 mm (1/2")		12%	95%	100%	96%	0%	85%	79-91
9.5 mm (3/8")		2%	61%	100%	88%	0%	76%	70-82
4.75 mm (No.4)		1%	2%	87%	66%	0%	55%	49-61
2.36 mm (No.8)		1%	1%	55%	46%	0%	36%	31-41
1.18 mm (No.16)		1%	1%	36%	34%	0%	24%	19-29
600 um (No.30)		1%	1%	26%	25%	0%	18%	13-23
300 um (No.50)		1%	1%	18%	19%	0%	13%	9-17
150 um (No.100)		1%	1%	13%	14%	0%	9%	5-13
75 um (No.200)		0.2%	0.1%	8.3%	9.5%	0.0%	5.8%	3.8-7.8

Figure D.4: Job Mix Formula for Project No. 4

Class:	**12.5mm SP-2 PG 58-28**
Project:	**SH-27, Poleline INT Improvement**

Proposed Job Mix Formula

Laboratory Values	Target			Spec.
Total Asphalt by Weight of Mix % (Pb)	5.7			
Total Aspalt by Weight of Aggregate	6.01			
Air Voids % (Va)	4.0			3.0 - 5.0
Voids in Mineral Aggregate (VMA)	14.9			14.3
Voids Filled with Asphalt (VFA)	73			65 - 78
Bulk Specific Gravity (Gmb)	2.304			
Unit Weight lb./cuft.	143.4			
Theo Max Spec Gravity (Gmm)	2.401			
Theo Max Spec Gravity lb./cuft.	149.5			
Effective Specific Gravity of Blend (Gse)	2.610			
IDEAL-CT_{Index}	93			≥ 80
Rut Depth @ 15,000 Passes	1.8mm			≤ 10.0 mm
Stripping Passes	NA			15,000
Ninitial (6 Gyrations)	86.3			≤ 60.5
Ndesign SP-5 (50 Gyrations)	96.0			= 96.0
Nmax (75 Gyrations)	97.6			≤ 98.0
NCAT Asphalt Correction Factor	0.05			
Dust to Asphalt	1.2			0.6 - 1.4
Laboratory Mixing Temperature(deg in F)	300			
Laboratory Compaction Temperature(deg in F)	280			
Plant Mixing Temperature(deg in F)**	316	-	303	
Field Compaction Temperature(deg in F)**	275	-	283	
Superpave Design Sample Wt. in grams	4580			

**Field mixing and compaction may be adjusted +/- 25 degrees per Viscosity Graph*

Aggregate Gradation Data

Sieve Size		Ln-80c B 34.0%	Cs-201 C 13.0%	Ln-80c WC 12.0%	Md-101c Sand 5.0%	RAP 35.0%	Break down 1.0%	JMF Blended Gradation
1" / 25mm		100	100	100	100	100	100	100
3/4" / 19mm		100	100	100	100	100	100	100
1/2" / 12.5mm		88	100	100	100	95	100	94
3/8" / 9.5mm		46	100	100	100	86	100	77
No. 4 / 4.75mm		2	78	75	100	62	100	48
No. 8 / 2.36mm		2	52	43	85	45	100	34
No.16 / 1.18mm		1	37	26	66	34	100	24
No. 30 / 600um		1	28	16	54	26	100	19
No. 50 / 300um		1	22	9	20	20	100	13
No. 100 / 150um		1	15	4	4	14	100	9
No. 200 / 75um		0.7	10.2	1.4	1.4	9.5	90.0	6.0

** Aggregate breakdown will be controlled by the Hot Plant dust control system.*

Figure D.5: Job Mix Formula for Project No. 5

ASPHALT CONCRETE JOB MIX FORMULA

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Project: Big Wood River Bridge Replacement
Paving Contractor:
Asphalt Supplier: Idaho Asphalt
Anti-Strip Agent: 0.5% Morelife 5000
Aggregate Sources: BE 106c
Design Specification: ITD

Date: 7/18/2016
Class of Mixture: SP-3
Specified Grade of Asphalt: PG 64-34
Prepared by: LLC
Gyratory Compactor: Pine AFGC125X

	AASHTO	JMF	Requirements
1. Asphalt by Weight of Total Mix, %	R 35	**5.8%**	
2. Asphalt by Weight of Aggregates, %		6.1%	
3. Asphalt by Weight of Total Mix (Added), %		5.0%	
4. Asphalt by Weight of Aggregates (Added), %		5.2%	
5. Air Voids (Va), %	T 269	4.0%	3.0-5.0
6. Voids in Mineral Aggregate (VMA), %	R 35	15.0%	13.3 min
7. Bulk Specific Gravity @ Ndes (Gmb)	T 166	2.296	142.9 pcf
8. Theoretical Maximum Specific Gravity (Gmm)	T 209	**2.391**	148.8 pcf
9. Relative Density %Gmm @ Nini (7 Gyrations)	R 35	87.4	≤ 89.0
10. Relative Density %Gmm @ Nmax (115 Gyrations)	R 35	97.2	≤ 98.0
11. Voids Filled w/ Asphalt (VFA), %	R 35	73.3%	65-75
12. Film thickness, microns		1	
13. Absorbed Asphalt (Pba) by Weight of Aggregate, %	R 35	0.90%	
14. Effective Asphalt Content (Pbe) by Total Wt of Mixture, %	R 35	4.9%	
15. Specific Gravity of Asphalt		**1.026**	
16. Laboratory Mixing Temp, °C/°F		318-333	
17. Laboratory Compaction Temp, °C/°F		288-304	
18. Recommended Plant Mixing Temp, °F		325	
19. Compaction Temp Range, °F		296	
20. NCAT Ignition Oven Correlation Factor @ 538° C	T 308	**0.17**	
21. Dust to Asphalt Ratio	R 35	1.2	0.6-1.2
22. Immersion Compression Retained Strength, %	T 165	85%	85% min
23. Gyratory Gmb specimen weight, grams		4500	
24. Combined Bulk Dry Specific Gravity of Aggregate (Gsb)	T 85 / IT 144	**2.545**	

AGGREGATE STOCKPILE GRADATION

		A-Pile	B-Pile	C-Pile	RAP	0	Blended Gradation	Mix Design Tolerances
		15%	18%	50%	17%	0%		
25.0 mm (1")		100%	100%	100%	100%	0%	**100%**	100
19.0 mm (3/4")		99%	100%	100%	100%	0%	**100%**	100
12.5 mm (1/2")		12%	95%	100%	96%	0%	**85%**	79-91
9.5 mm (3/8")		2%	61%	100%	88%	0%	**76%**	70-82
4.75 mm (No.4)		1%	2%	87%	66%	0%	**55%**	49-61
2.36 mm (No.8)		1%	1%	55%	46%	0%	**36%**	31-41
1.18 mm (No.16)		1%	1%	36%	34%	0%	**24%**	19-29
600 um (No.30)		1%	1%	26%	25%	0%	**18%**	13-23
300 um (No.50)		1%	1%	18%	19%	0%	**13%**	9-17
150 um (No.100)		1%	1%	13%	14%	0%	**9%**	5-13
75 um (No.200)		0.2%	0.1%	8.3%	9.5%	0.0%	**5.8%**	3.8-7.8

Figure D.6: Job Mix Formula for Project No. 6

Class: 12.5mm SP-3 PG 70-28
Project: US-93, 200 South

Proposed Job Mix Formula

Laboratory Values	Target			Spec.
Total Asphalt by Weight of Mix % (Pb)	5.6			
Total Aspalt by Weight of Aggregate	5.98			
Air Voids % (Va)	4.0			3.0-5.0
Voids in Mineral Aggregate (VMA)	14.7			14.3
Voids Filled with Asphalt (VFA)	73			65-75
Bulk Specific Gravity (Gmb)	2.304			
Unit Weight lb./cuft.	143.4			
Theo Max Spec Gravity (Gmm)	2.401			
Theo Max Spec Gravity lb./cuft.	149.5			
Effective Specific Gravity of Blend (Gse)	2.608			
Effect of Water on Compressive Strength *(AllWest)*	95			85 min
Ninitial (7 Gyrations)	86.4			≤ 89.0
Ndesign SP-5 (75 Gyrations)	96.0			= 96.0
Nmax (115 Gyrations)	97.6			≤ 98.0
NCAT Asphalt Correction Factor	0.23			
Dust to Asphalt	1.1			
Laboratory Mixing Temperature(deg in F)	320			
Laboratory Compaction Temperature(deg in F)	300			
Plant Mixing Temperature(deg in F)**	316	-	324	
Field Compaction Temperature(deg in F)**	295	-	303	
Superpave Design Sample Wt. in grams	4580			

**Field mixing and compaction may be adjusted +/- 25 degrees per Viscosity Graph*

Aggregate Gradation Data

Sieve Size		Ln-80c B 23.0%	Cs-201 C 16.0%	Ln-80c WC 25.5%	Md-101c Sand 5.0%	RAP 30.0%	Break down 0.5%	JMF Blended Gradation
1" / 25mm		100	100	100	100	100	100	100
3/4" / 19mm		100	100	100	100	100	100	100
1/2" / 12.5mm		88	100	100	100	95	100	96
3/8" / 9.5mm		46	100	100	100	86	100	83
No. 4 / 4.75mm		2	85	75	100	62	100	57
No. 8 / 2.36mm		2	58	43	85	45	100	39
No.16 / 1.18mm		1	41	26	66	34	100	27
No. 30 / 600um		1	30	16	54	26	100	20
No. 50 / 300um		1	22	9	20	20	100	14
No. 100 / 150um		1	15	4	4	14	100	9
No. 200 / 75um		0.7	9.9	1.4	1.4	9.5	90.0	5.5

** Aggregate breakdown will be controlled by the Hot Plant dust control system.*

Figure D.7: Job Mix Formula for Project No. 7

Design Specifications: Blend 1 / 75 Gyrations @ N Design PG 64-34

Gyratory Compactor: Model # AFG2AS
Serial # 8436

#		Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	**5.4**	--
2	Percent Asphalt by Weight of Aggregate	5.71	--
3	Percent Air Voids (Pa)	4.0	4.0
4	Voids in Mineral Aggregate (VMA)	14.7	14 min
5	Compacted Unit Weight Gmb, pcf	2.313 144.0	--
6	Theoretical Maximum Density Gmm, pcf	**2.410 150.0**	--
7	Percent Effective Asphalt Content (Pbe)	4.74	--
8	Percent Absorbed Asphalt (Pba)	0.70	--
9	Specific Gravity of Binder (Gb)	**1.026**	--
10	Percent Gmm @ N Initial (7 Gyrations)	87.2	≤ 89.0
11	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
12	Percent Gmm @ N Max (115 Gyrations)	97.6	≤ 98.0
13	Dust to Asphalt Ratio (DP)	1.3	0.6-1.4
14	Percent Passing #200 Sieve	6.0	2.0-10.0
15	Voids Filled w/ Asphalt (VFA)	73	65-75
16	Laboratory Mixing Temperature for Design (°F)	311	307-315
17	Laboratory Compaction Temperature for Design (°F)	**290**	286-294
18	Laboratory Sample Weight for Volumetric Testing (g)	**4590**	--
19	Ignition Oven (NCAT) Correction Factor @ 538 °F	**0.37**	--
20	Sand Equivalent	64	40 min
21	Fracture Face Count (%)	99/97	75/60
22	Fine Aggregate Angularity (%)	46.3	40 min
23	Flat and Elongated Particles in Coarse Aggregates (%)	0.0	10 max

Figure D.8: Job Mix Formula for Project No. 8

Design Specifications: Blend 1 / 75 Gyrations @ N Design PG 64-34 (58-34 Adjusted Binder)

Gyratory Compactor: Model # AFG2AS, Serial # 8436

		Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	5.5	–
2	Percent Asphalt by Weight of Aggregate	5.79	–
3	Virgin Asphalt by Weight of Mix	4.36	–
4	Virgin Asphalt by Weight of Aggregate	4.61	–
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	15.1	14 min
7	Compacted Unit Weight Gmb, pcf	2.397 149.2	–
8	Theoretical Maximum Density Gmm, pcf	2.497 155.4	–
9	Percent Effective Asphalt Content (Pbe)	4.75	–
10	Percent Absorbed Asphalt (Pba)	0.76	–
11	Specific Gravity of Binder (Gb)	1.027	–
12	Percent Gmm @ N Initial (7 Gyrations)	86.3	≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.2	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.3	0.6-1.5
16	Percent Passing #200 Sieve	6.3	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	74	65-75
18	Laboratory Mixing Temperature for Design (°F)	312	308-316
19	Laboratory Compaction Temperature for Design (°F)	290	286-294
20	Laboratory Sample Weight for Volumetric Testing (g)	4775	–
21	Ignition Oven (NCAT) Correction Factor @ 538 °F	0.77	–
22	Sand Equivalent	69	40 min
23	Fracture Face Count (%)	100/100	75/60
24	Fine Aggregate Angularity (%)	48.4	40 min
25	Flat and Elongated Particles in Coarse Aggregates (%)	0.9	10 Max
	Recycled Asphalt Pavement (RAP) Properties		
26	Percentage of Asphalt in RAP (Wt. of Mix)	5.57	–
27	Percentage of RAP by Total Weight of Aggregate	20	–
28	Percent of RAP Binder by Weight of Total Binder	20	30 max
29	RAP Contribution by Mix	1.11	–
30	RAP Contribution by Aggregate	1.18	–
31	RAP NCAT Correction Factor	1.09	–

Figure D.9: Job Mix Formula for Project No. 9

Design Specifications: Blend 3 / 75 Gyrations @ N Design PG 64-28 (58-34 Adjusted Binder)

Gyratory Compactor: Model # AFG2AS, Serial # 8732

		Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	**5.7**	--
2	Percent Asphalt by Weight of Aggregate	6.1	--
3	Virgin Asphalt by Weight of Mix	4.30	--
4	Virgin Asphalt by Weight of Aggregate	4.58	--
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	15.0	14 min
7	Compacted Unit Weight Gmb, pcf	2.391 148.8	--
8	Theoretical Maximum Density Gmm, pcf	**2.491 155.1**	--
9	Percent Effective Asphalt Content (Pbe)	4.73	--
10	Percent Absorbed Asphalt (Pba)	1.06	--
11	Specific Gravity of Binder (Gb)	**1.030**	--
12	Percent Gmm @ N Initial (7 Gyrations)	86.6	≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.4	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.4	0.6-1.5
16	Percent Passing #200 Sieve	6.4	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	73	65-75
18	Laboratory Mixing Temperature for Design (°F)	324	316-324
19	Laboratory Compaction Temperature for Design (°F)	**302**	294-303
20	Laboratory Sample Weight for Volumetric Testing (g)	**4750**	--
21	Ignition Oven (NCAT) Correction Factor @ 482 °F	**1.51**	--
22	*Los Angeles Abrasion (LAR) (%)	**20**	30 max
23	*Idaho Degredation Δ % -200	**4.3**	5.0 max
24	Sand Equivalent	61	40 min
25	*Fracture Face Count (%)	99/98	75/60
26	Fine Aggregate Angularity (%)	47.4	40 min
27	*Flat and Elongated Particles in Coarse Aggregates (%)	4.8	10 Max
	Recycled Asphalt Pavement (RAP) Properties		
28	**Percentage of Asphalt in RAP (Wt. of Mix)	4.75	--
29	Percentage of RAP by Total Weight of Aggregate	30	--
30	Percent of RAP Binder by Weight of Total Binder	25	17 Max
31	RAP Contribution by Mix	1.43	--
32	RAP Contribution by Aggregate	1.50	--
33	RAP NCAT Correction Factor	1.82	--

***Composite blend including RAP**

Figure D.10: Job Mix Formula for Project No. 10

Class: 12.5mm SP-3 PG 70-28
Project: SH-55 Snake River Bridge Marsing, SH-55

Proposed Job Mix Formula

Laboratory Values	Target			Spec.
Total Asphalt by Weight of Mix % (Pb)	5.3			
Total Aspalt by Weight of Aggregate	5.63			
Air Voids % (Va)	4.0			3.0-5.0
Voids in Mineral Aggregate (VMA)	14.4			14.0
Voids Filled with Asphalt (VFA)	72			65-75
Bulk Specific Gravity (Gmb)	2.320			
Unit Weight lb./cuft.	144.4			
Theo Max Spec Gravity (Gmm)	2.418			
Theo Max Spec Gravity lb./cuft.	150.5			
Effective Specific Gravity of Blend (Gse)	2.616			
Effect of Water on Compressive Strength *(AllWest)*	89			85 min
Ninitial (7 Gyrations)	88.9			≤ 89.0
Ndesign SP-3 (75 Gyrations)	96.0			= 96.0
Nmax (115 Gyrations)	97.8			≤ 98.0
NCAT Asphalt Correction Factor	0.23			
Dust to Asphalt	1.2			0.6 - 1.2
Laboratory Mixing Temperature(deg in F)	320			
Laboratory Compaction Temperature(deg in F)	300			
Plant Mixing Temperature(deg in F)**	316	-	324	
Field Compaction Temperature(deg in F)**	295	-	303	
Superpave Design Sample Wt. in grams	4615			

**Field mixing and compaction may be adjusted +/- 25 degrees per Viscosity Graph*

Aggregate Gradation Data

Sieve Size	1/2" Chips 15.0%	#4 Chips 12.0%	C Pile 27.0%	Washed C Pile 4.0%	C-33 Sand 10.0%	RAP 31.0%	Break Down 1.0%	JMF Blended Gradation
1" / 25mm	100	100	100	100	100	100	100	100
3/4" / 19mm	100	100	100	100	100	100	100	100
1/2" / 12 5mm	74	100	100	100	100	94	100	94
3/8" / 9 5mm	16	79	100	100	100	86	100	81
No 4 / 4 75mm	2	4	81	75	98	65	100	57
No. 8 / 2 36mm	2	2	58	46	87	50	100	43
No.16 / 1 18mm	1	2	42	28	78	40	100	34
No. 30 / 600um	1	2	29	16	56	30	100	25
No. 50 / 300um	1	1	20	7	15	18	100	14
No 100 / 150um	1	1	12	3	2	12	100	9
No. 200 / 75um	0.8	0.9	7.8	1.7	0.7	7.5	90.0	5.7

** Aggregate breakdown will be controlled by the Hot Plant dust control system*

Figure D.11: Job Mix Formula for Project No. 11

Class:	12.5mm SP-3 PG 64-34
Project:	SH-55, MP91 to Smith's Ferry

Proposed Job Mix Formula

Laboratory Values	Target			Spec.
Total Asphalt by Weight of Mix % (Pb)	5.3			
Total Aspalt by Weight of Aggregate	5.64			
Air Voids % (Va)	4.0			3.0-5.0
Voids in Mineral Aggregate (VMA)	14.3			14.0
Voids Filled with Asphalt (VFA)	72			65-75
Bulk Specific Gravity (Gmb)	2.320			
Unit Weight lb./cuft.	144.4			
Theo Max Spec Gravity (Gmm)	2.417			
Theo Max Spec Gravity lb./cuft.	150.5			
Effective Specific Gravity of Blend (Gse)	2.616			
Effect of Water on Compressive Strength *(AllWest)*	91			85 min
Ninitial (7 Gyrations)	88.8			≤ 89.0
Ndesign SP-3 (75 Gyrations)	96.0			= 96.0
Nmax (115 Gyrations)	97.7			≤ 98.0
NCAT Asphalt Correction Factor	0.25			
Dust to Asphalt	1.2			0.6 - 1.2
Laboratory Mixing Temperature(deg in F)	305			
Laboratory Compaction Temperature(deg in F)	285			
Plant Mixing Temperature(deg in F)**	302	-	310	
Field Compaction Temperature(deg in F)**	281	-	289	
Superpave Design Sample Wt. in grams	4615			

**Field mixing and compaction may be adjusted +/- 25 degrees per Viscosity Graph*

Aggregate Gradation Data

Sieve Size	1/2" Chips 14.0%	#4 Chips 15.0%	C Pile 22.0%	Washed C Pile 8.0%	C-33 Sand 9.0%	RAP 31.0%	Break Down 1.0%	JMF Blended Gradation
1" / 25mm	100	100	100	100	100	100	100	100
3/4" / 19mm	100	100	100	100	100	100	100	100
1/2" / 12.5mm	74	100	100	100	100	94	100	95
3/8" / 9.5mm	16	79	100	100	100	86	100	81
No. 4 / 4.75mm	2	4	81	75	98	65	100	55
No. 8 / 2.36mm	2	2	58	46	87	50	100	41
No.16 / 1.18mm	1	2	42	28	78	40	100	32
No. 30 / 600um	1	2	29	16	56	30	100	23
No. 50 / 300um	1	1	20	7	15	18	100	13
No. 100 / 150um	1	1	12	3	2	12	100	8
No. 200 / 75um	0.8	0.9	7.8	1.7	0.7	7.5	90.0	5.4

** Aggregate breakdown will be controlled by the Hot Plant dust control system.*

Figure D.12: Job Mix Formula for Project No. 12

Project Name: FY 20 D6 Ballast Stabilization
Project Number: A019(812)
Project Key Number: 19812

Asphalt Mix Type:	12.5mm SP5 (Design ESALs, ≥ 10)	Mix Producer:	Knife River
JMF Identification:	20030-ITD-12.5mmSP5-R27	Specified Oil:	PG 64-34
Binder Supplier:	Idaho Asphalt Supply	Adjusted Oil:	PG 58-34
Anti-Strip:	Morlife 5000	Agg. Source Number:	CI-56s

Job Mix Formula Targets and Volumetric Data

Target Oil Content:	4.9	RAP Category:	Cat 1	JMF G_{mb} Specimen Weight:	4725 g
Virgin Oil Added:	3.5	RAP Oil Contribution:	1.4	JMF Ncat Correction Factor:	0.07
Percent Anti-Strip:	0.75	Compaction Temp. Range:	291-306	Lab Compaction Temp (F°):	300
RAP Percent By Binder:	29	Mixing Temp. Range:	320-333	RAP Correction Factor:	0.07

Aggregate, RAP and Binder Specific Gravities

Combined G_{sb}:	2.619	Effective Specific Gravity (G_{se}):	2.647	RAP Bulk Specific Gravity:	2.617
Fine Aggregate G_{sb}:	2.616	Fine SSD Specific Gravity:	2.636	Fine Apparent Specific Gravity (G_{sa}):	2.670
Coarse Agg. Coarse G_{sb}:	2.625	Coarse SSD Specific Gravity:	2.639	Coarse Apparent Specific Gravity (G_{sa}):	2.665
Fine Agg.% Absorbtion:	0.8	Coarse Aggregate % Absorbtion:	0.6	Binder Specific Gravity (G_b):	1.0287

Job Mix Formula Target Volumetric Properties

	Design	Spec.		Design	Spec.
Maximum Theoretical Specific Gravity (G_{mm}):	2.458	--	Bulk Specific Gravity (G_{mb}):	2.360	--
Percent Air Voids (P_a):	4.0	3.0-5.0	Voids In Mineral Aggregate (VMA):	14.3	14.0 min
Voids Filled with Asphalt (VFA):	72	65-75	Dust Proportion (DP):	0.9	0.8-1.6
Absorbed Apshalt (P_{ba}):	0.42	--	Effective Asphalt Content (P_{be}):	4.50	--
Density Percent G_{mm} @ Nini:	87.8	≤ 89.0	Density Percent G_{mm} @ Ndes:	96	96.0
Density Percent G_{mm} @ Nmax:	97.3	≤ 98.0	Immersion Comp. Retained Strength:	90	85 min
Uncompacted Void Content of Fine Aggregate:	52	45 min	Sand Equivalent:	74	45 min
Fracture Face Coarse Aggregate (1 Face/2 Face):	100/99	98/98	Flat and Elongated Particles:	0	10 max

JMF Target Aggregate, Breakdown, Proportions

Blend Percentages:	CI-56s	28	BD	0.0	CI-56s	44.0	RAP:	28.0

Job Mix Formula Aggregate Gradations & Stockpile Averages

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
JMF Specifications:		100	90-100	90 max		28-58					2.0-10.0
JMF Target Gradation:	100	100	92	80	54	36	25	19	13	8	4.0
Ncat C.F. Gradation:	100.0	100.0	90.9	80.2	55.5	36.8	26.1	18.8	13.2	7.6	4.1
Agg. Correction Factor:	0.0	0.0	1.1	-0.2	-1.5	-0.8	-1.1	0.2	-0.2	0.4	-0.1
B-Pile Average:	100	100	84	53	4	1	1	1	1	1	0.3
C-Pile Avg.:	100	100	100	100	88	59	40	28	19	11	6.5
Category 1 RAP Avg.:	100	100	88	77	51	36	27	22	17	11	5.8

Figure D.13: Job Mix Formula for Project No. 13

Design Specifications: Blend 1 / 75 Gyrations @ N Design PG 64-28 (58-34 Adjusted Binder)

Gyratory Compactor: Model # AFG2AS, Serial # 8436

#		Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	5.3	–
2	Percent Asphalt by Weight of Aggregate	5.6	–
3	Virgin Asphalt by Weight of Mix	3.72	–
4	Virgin Asphalt by Weight of Aggregate	3.96	–
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	~~14.5~~ 14.8	14 min
7	Compacted Unit Weight Gmb, pcf	2.331 145.1	–
8	Theoretical Maximum Density Gmm, pcf	2.428 151.1	–
9	Percent Effective Asphalt Content (Pbe)	~~4.65~~ 4.76	–
10	Percent Absorbed Asphalt (Pba)	~~0.71~~ 0.57	–
11	Specific Gravity of Binder (Gb)	1.029	–
12	Percent Gmm @ N Initial (7 Gyrations)	86.8	≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.2	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.2	0.8-1.6
16	Percent Passing #200 Sieve	5.6	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	~~72~~ 73	65-75
18	Laboratory Mixing Temperature for Design (°F)	322	317-326
19	Laboratory Compaction Temperature for Design (°F)	299	295-303
20	Laboratory Sample Weight for Volumetric Testing (g)	4,680	–
21	(L5-134) Ignition Oven (NCAT) Correction Factor @ 538 °F	0.33	–
22	*Los Angeles Abrasion (LAR) (%)	27	30 max
23	*Idaho Degradation Δ % -200	4.3	5.0 max
24	Sand Equivalent	66	40 min
25	*Fracture Face Count (%)	99/97	75/60
26	Fine Aggregate Angularity (%)	46.7	40 min
27	*Flat and Elongated Particles in Coarse Aggregates (%)	0.0	10 max
	Recycled Asphalt Pavement (RAP) Properties		
28	Percentage of Asphalt in Yard RAP (Wt. of Mix)	3.78	–
29	Percentage of Asphalt in Coarse RAP (Wt. of Mix)	2.67	–
30	Percentage of RAP by Total Wt of Aggregate (Yard RAP)	32	–
31	Percentage of RAP by Total Wt of Aggregate (Coarse RAP)	14	–
32	Percent of RAP Binder by Weight of Total Binder	30	30 max
33	RAP Contribution by Mix	1.58	–
34	RAP Contribution by Aggregate	1.64	–
35	RAP NCAT Correction Factor (Combined)	0.40	–

*Composite blend including RAP

Figure D.14: Job Mix Formula for Project No. 14

Design Specifications: Blend 3 / 75 Gyrations @ N Design (PG 64-28) Binder Bump PG 58-34

Gyratory Compactor: Model # AFG2AS, Serial # 8732

#		Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	**5.2**	--
2	Percent Asphalt by Weight of Aggregate	5.5	--
3	Virgin Asphalt by Weight of Mix	3.88	--
4	Virgin Asphalt by Weight of Aggregate	4.11	--
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	14.3	14 Min
7	Compacted Unit Weight Gmb, pcf	2.497 155.4	--
8	Theoretical Maximum Density Gmm, pcf	**2.602 162.0**	--
9	Percent Effective Asphalt Content (Pbe)	4.2	--
10	Percent Absorbed Asphalt (Pba)	1.03	--
11	Specific Gravity of Binder (Gb)	**1.031**	--
12	Percent Gmm @ N Initial (7 Gyrations)	87.3	≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.3	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.4	0.8-1.6
16	Percent Passing #200 Sieve	6.0	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	72	65-75
18	Laboratory Mixing Temperature for Design (°F)	324	316-324
19	Laboratory Compaction Temperature for Design (°F)	**298**	295-303
20	Laboratory Sample Weight for Volumetric Testing (g)	**4950**	--
21	Ignition Oven (NCAT) Correction Factor @ 482 °F	**1.36**	--
22	Sand Equivalent	74	40 min
23	Fracture Face Count (%)	100/99	75/60
24	Fine Aggregate Angularity (%)	49.5	40 min
25	Flat and Elongated Particles in Coarse Aggregates (%)	5.5	10 Max
	Recycled Asphalt Pavement (RAP) Properties		
26	Percentage of Asphalt in RAP (Wt. of Mix)	4.4	--
27	Percentage of RAP by Total Weight of Aggregate	30	--
28	Percent of RAP Binder by Weight of Total Binder	25.4	30 Max
29	RAP Contribution by Mix	1.32	--
30	RAP Contribution by Aggregate	1.38	--
31	RAP NCAT Correction Factor	1.33	--

Figure D.15: Job Mix Formula for Project No. 15

Design Specifications: Blend 3 / 75 Gyrations @ N Design PG 64-28

Gyratory Compactor:	Model # AFG2AS Serial # 8732	Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	**5.6**	--
2	Percent Asphalt by Weight of Aggregate	5.9	--
3	Virgin Asphalt by Weight of Mix	5.10	--
4	Virgin Asphalt by Weight of Aggregate	5.40	--
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	15.0	14 min
7	Compacted Unit Weight Gmb, pcf	2.453 152.7	--
8	Theoretical Maximum Density Gmm, pcf	**2.555 159.0**	--
9	Percent Effective Asphalt Content (Pbe)	4.66	--
10	Percent Absorbed Asphalt (Pba)	0.95	--
11	Specific Gravity of Binder (Gb)	**1.034**	--
12	Percent Gmm @ N Initial (7 Gyrations)	86.3	≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.4	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.4	0.6-1.5
16	Percent Passing #200 Sieve	6.5	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	73	65-75
18	Laboratory Mixing Temperature for Design (°F)	325	317-327
19	Laboratory Compaction Temperature for Design (°F)	**304**	295-306
20	Laboratory Sample Weight for Volumetric Testing (g)	**4825**	--
21	Ignition Oven (NCAT) Correction Factor @ 538 °F	**0.59**	--
22	*Los Angeles Abrasion (LAR) (%)	**17**	30 max
23	*Idaho Degredation Δ % -200	**4.1**	5.0 max
24	Sand Equivalent	65	40 min
25	*Fracture Face Count (%)	100/100	75/60
26	Fine Aggregate Angularity (%)	46.3	40 min
27	*Flat and Elongated Particles in Coarse Aggregates (%)	1.6	10 Max
	Recycled Asphalt Pavement (RAP) Properties		
28	**Percentage of Asphalt in RAP (Wt. of Mix)	4.64	--
29	Percentage of RAP by Total Weight of Aggregate	10	--
30	Percent of RAP Binder by Weight of Total Binder	8	17 Max
31	RAP Contribution by Mix	0.46	--
32	RAP Contribution by Aggregate	0.49	--
33	RAP NCAT Correction Factor	1.67	--

***Composite blend including RAP**

** ITD determined RAP AC used for design as requested by ITD

Figure D.16: Job Mix Formula for Project No. 16

September 29, 2020

RE: ½" SP-5 HMA C-JMF

Project: I-84 Jerome IC to Twin IC
Key: 20559 & 20596

Mr.

is planning to provide ½" SP-5 hot mix per JMF A520-0304 from our hot plant located south of the Con Paulos Dealer off I-84 exit 168. The JMF will be altered to target the following C-JMF during production. We anticipate a potential need to adjust the Gmm and Gse again after we get results for our first day's production.

Asphalt Content target: 5.2% by weight of mix (before AAO adjustment).

Gmm: 2.442
Gse: 2.632

Gradation Targets:

¾"	100%
½"	93%
3/8"	80%
#4	52%
#8	34%
#16	23%
#30	17%
#50	12%
#100	9%
#200	5.3%

Please call or email me with any questions , or cell phone

Thank you,

Figure D.17: Job Mix Formula for Project No. 17

Design Specifications: Blend 1 / 100 Gyrations @ N Design PG 70-28			
Gyratory Compactor:	Model # AFG2AS Serial # 8436	**Job Mix Formula**	**Spec**
1	Percent Asphalt by Weight of Total Mix	**5.7**	--
2	Percent Asphalt by Weight of Aggregate	6.09	--
3	Virgin Asphalt by Weight of Mix	4.78	--
4	Virgin Asphalt by Weight of Aggregate	5.08	--
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	13.5	13 min
7	Compacted Unit Weight Gmb, pcf	2.206 137.3	--
8	Theoretical Maximum Density Gmm, pcf	**2.298 143.0**	--
9	Percent Effective Asphalt Content (Pbe)	4.44	--
10	Percent Absorbed Asphalt (Pba)	1.38	--
11	Specific Gravity of Binder (Gb)	**1.031**	--
12	Percent Gmm @ N Initial (8 Gyrations)	86.6	≤ 89.0
13	Percent Gmm @ N Design (100 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (160 Gyrations)	97.2	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.3	0.8-1.6
16	Percent Passing #200 Sieve	5.6	2.0-8.0
17	Voids Filled w/ Asphalt (VFA)	70	65-75
18	Laboratory Mixing Temperature for Design (°F)	330	324-338
19	Laboratory Compaction Temperature for Design (°F)	**304**	297-311
20	Laboratory Sample Weight for Volumetric Testing (g)	**4340**	--
21	Ignition Oven (NCAT) Correction Factor @ 538 °F	**0.27**	--
22	Sand Equivalent	47	45 min
23	Fracture Face Count (%)	100/100	98/98
24	Fine Aggregate Angularity (%)	45.6	45 min
25	Flat and Elongated Particles in Coarse Aggregates (%)	0.0	10 Max
Recycled Asphalt Pavement (RAP) Properties			
26	Percentage of Asphalt in RAP (Wt. of Mix)	5.07	--
27	Percentage of RAP by Total Weight of Aggregate	19	--
28	Percent of RAP Binder by Weight of Total Binder	17	17 max
29	RAP Contribution by Mix	0.96	--
30	RAP Contribution by Aggregate	1.01	--
31	RAP NCAT Correction Factor	0.51	--

Figure D.18: Job Mix Formula for Project No. 18

Class: SP3 19mm (3/4")
Project: A020(051)
Key: 20051

PROPOSED JOB MIX FORMULA

Laboratory Gyratory Values	Min	Target	Max	Spec.
Total Asphalt by Weight of Mix % (Pb)		5.00		
Virgin Asphalt by Weight of Mix Hot Plant		3.64		
Rap Binder Replacement 27.2%		1.36		
Air Voids % (Va)		4.0		4.0
Voids in Mineral Aggregate (VMA)		13.3		13.0 Min
Voids Filled with Asphalt (VFA)		73.0%		65-75
Dust Ratio(PCS 35% passing #8 / 0.8%-1.6%,MS2)		1.18		0.6-1.4
Bulk Specific Gravity (Gmb)		2.368		
Unit Weight lb./cuft.		147.4		
Theo Max Spec Gravity (Gmm)		2.466		
Theo Max Spec Gravity lb./cuft.		153.5		
% Gmm @ Nini(7 gyrations)		85.6%		89% Max
% Gmm @ Ndes(75 gyrations)		95.9%		96% Max
% Gmm @ Nmax(115 gyrations)		97.0%		98% Max
Effective Specific Gravity of Blend (Gse)		2.661		
Specific Gravity of Aggregate (Gsb provided by ITD)		2.595		
Ideal CT, Cracking Test		93.1		80 index value
Hamburg Wheel Track T324		20816		15000
Fine Aggregate Angularity		46%		40% Min
NCAT Asphalt Correction Factor(538 deg C)		-0.44		
Sand Equivalency (SE)		67%		40% Min
Flat and Elongation		1%		10% Max
Percent Fracture 1 Face		97%		75% Min
Percent Fracture 2 Face		96%		60% Min
Laboratory Mixing Temperature(deg in F)		320 deg		
Laboratory Compaction Temperature(deg in F)		295 deg		
Plant Mixing Temperature(deg in F)	315 d eg		3329 deg	
Field Compaction Temperature(deg in F)	288 deg		302 deg	
Super pave Design Sample Wt. in grams		4650		

Figure D.19: Job Mix Formula for Project No. 19

Key Number	Project Number	Project Name	District
19373	A019(373)	US-95, Whitebird GradeRehab	2

Identification Number (Program/Task/Phase/Sample#)	Contract Item Number	Testing Laboratory Name & Location	Mix Design No.
E163590	405-435A	ITD Central Laboratory	19020

Send Reports To(Resident Engineer's Name)	Sampled By	WAQTC Number	Date Sampled	Date Lab Received	Date Lab Tested
Curtis Arnzen	Greg Mitchell	49376	6/17/2019	6/17/2019	6/18/2019

Asphalt Binder Supplier	Asphalt Binder Grade	Sp. Gr. of Binder (from Mix Design)	JMF Intended Binder, % (by Wt of Mix)	Source Number
Idaho Asphalt Supply	PG 70-28	1.032	5.9	ID-256c

Sample Location (Sta./offset, truck, plant, lab, etc.)	Mix Design Lab & Location	SPMDT	P.E. in Responsible Charge of Design
Lab Produced	Boise Id	Greg Mitchell	Gary thompson

ESALs	Nom. Max. Size Aggregate	Primary Control Sieve	Percent Passing Primary Control Sieve	Class of Mix
1 <10 (75 Gyrations)	1/2"	No. 8	39 %	SP3

Combined Aggregate Bulk SPG G_{sb} from ITD 0802 2.703

Test Results

Gradation Anaylsis
FOP for AASHTO T 30

Sieve Size (mm)	(in.)	Lab No. 190MX 0061	Lab No.	Lab No.	Avg.	JMF
(50)	2	100				100
(37.5)	1/1/2	100				100
(25)	1	100				100
(19)	3/4	100				100
(12.5)	1/2	92				92
(9.5)	3/8	80				81
(4.75)	No. 4	57				58
(2.36)	No. 8	37				38
(1.18)	No. 16	24				25
(0.600)	No. 30	15				17
(0.300)	No. 50	11				12
(0.150)	No. 100	8				9
(0.075)	No. 200	6.6				6.7

Avg. Sample Height, mm: 114.4

Asphalt Binder Content (By Weight of Mix)
FOP for AASHTO T 308

	Lab No. 190MX 0061	Lab No.	Lab No.	Average
Total Asphalt Binder Content	6.25			
NCAT Correction Factor	0.55			
Moisture % (-)	-0.02			
Act. Asph. Binder Content %	5.72			

Compaction Temperature, °F
#VALUE!

FOP for AASHTO T 312 / AASHTO M 323

	Lab No. 190MX 0061	Lab No.	Lab No.	Average
Lab Air Voids % at N_{Design}	4.4			
G_{mb} (compacted mixture)	2.422			
G_{mm} (max spec gravity)	2.532			
VMA, %	15.5			
VFA, %	72			
Dust Proportion (DP)	1.4			
G_{se} - Effective Sp. Gravity	2.777			
P_{be} - Eff. Binder Content, %	4.76			
P_{ba} - Binder Absorbed, %	1.02			

FOP for AASHTO T 209 result within 0.020 of JMF?	Gmm from JMF=	2.518	Gmm from Sample Tested=	2.532	Pass
FOP for AASHTO T 166 result within 0.020 of JMF?	Gmb from JMF=	2.417	Gmb from Sample Tested=	2.422	Pass

ASTM D1075 & AASHTO T 167

Sample # 61

100 % @ 0.05 % MORLIFE 5000

PASS

AASHTO T 340

Sample # 61

Rutting Depth, mm	2.2
Left Sample	2.274
Center Sample	1.998
Right Sample	2.278

Maximum Allowable Rut Depth
0.2 in. (5 mm)
PASS

Remarks

Figure D.20: Job Mix Formula for Project No. 20

ASPHALT CONCRETE JOB MIX FORMULA

Page 5

Project:
Paving Contractor: V
Asphalt Supplier:
Anti-Strip Agent: 0.5% Morelife 5000
Aggregate Sources: BE 106c
Design Specification: ITD

Date: 7/18/2016
Class of Mixture: SP-3
Specified Grade of Asphalt: PG 64-34
Prepared by: LLC
Gyratory Compactor: Pine AFGC125X

	AASHTO	JMF	Requirements
1. Asphalt by Weight of Total Mix, %	R 35	5.8%	
2. Asphalt by Weight of Aggregates, %		6.1%	
3. Asphalt by Weight of Total Mix (Added), %		5.0%	
4. Asphalt by Weight of Aggregates (Added), %		5.2%	
5. Air Voids (Va), %	T 269	4.0%	3.0-5.0
6. Voids in Mineral Aggregate (VMA), %	R 35	15.0%	13.3 min
7. Bulk Specific Gravity @ Ndes (Gmb)	T 166	2.296	142.9 pcf
8. Theoretical Maximum Specific Gravity (Gmm)	T 209	2.391	148.8 pcf
9. Relative Density %Gmm @ Nini (7 Gyrations)	R 35	87.4	≤ 89.0
10. Relative Density %Gmm @ Nmax (115 Gyrations)	R 35	97.2	≤ 98.0
11. Voids Filled w/ Asphalt (VFA), %	R 35	73.3%	65-75
12. Film thickness, microns		1	
13. Absorbed Asphalt (Pba) by Weight of Aggregate, %	R 35	0.90%	
14. Effective Asphalt Content (Pbe) by Total Wt of Mixture, %	R 35	4.9%	
15. Specific Gravity of Asphalt		1.026	
16. Laboratory Mixing Temp, °C/°F		318-333	
17. Laboratory Compaction Temp, °C/°F		288-304	
18. Recommended Plant Mixing Temp, °F		325	
19. Compaction Temp Range, °F		296	
20. NCAT Ignition Oven Correlation Factor @ 538° C	T 308	0.17	
21. Dust to Asphalt Ratio	R 35	1.2	0.6-1.2
22. Immersion Compression Retained Strength, %	T 165	85%	85% min
23. Gyratory Gmb specimen weight, grams		4500	
24. Combined Bulk Dry Specific Gravity of Aggregate (Gsb)	T 85 / IT 144	2.545	

Figure D.21: Job Mix Formula for Project No. 21

Key Number	Project Number	Project Name	District
20051	A020(051)	US-30, Caribou Co. to Georgetown Bear Lake Co, ID	5

Send Reports To (Resident Engineer's Name)	Contract Item Number	Class of Mix	ESALs	Nominal Max Agg Size	PCS	Passing PCS
Eric Staats	405-435A	SP3	1 < 10 (75 Gyrations)	3/4"	No. 4	47 %

C-JMF Number	C-JMF Target P_b	Aggregate Source Number	Contractor Producing Mix	Designed by
231043	4.8	BL70	Idaho Materials and Construction	HK Contractors

Virgin Binder Grade	Anti-strip Additive	Listed on QPL	Asphalt Binder Supplier	% Anti-Strip Additive	% Binder Replacement
PG 58-34	Moorelife 5000	Yes	Idaho Asphalt Supply	0.5	22.0

FOP for AASHTO T168 Sampling Bituminous Paving Mixtures — Sample ID Number: SB/P175550-A-CE/A#659

Test Number	Date Sampled	Time Sampled	Sample Temperature	Sampling Method	Sample Location (Sta./offset, truck, plant, lab, etc.)
A#659	10/21/2020	2:30 PM	293 °F	Other (Must Specify in Remarks)	MP 413.3, 6.5' LT of CL

Sampled By	WAQTC Number	Sampler's Employer	Quantity Represented	Lift Thickness
S. Borchert	23511	MTI	1408 Tons	0.2'

FOP for AASHTO R47 Reducing Samples of Hot Mix Asphalt (HMA) to Testing Size (Initial Reduction of Sample)

Qualified Lab No.	Testing Laboratory Location	Initial Reduction Method	Split Retained for Dispute	Split ID Number
LQ 5014	Pocatello, ID	Quartering Method (Full Quartering)	Yes	A#659

Initial Reduction Performed By	WAQTC Number	Technician's Employer	Date Reduced	Time Reduced	Sample Temperature
B. French	23554	MTI	10/22/2020	2:00 AM	285 °F

FOP for AASHTO T 209 Theoretical Max Specific Gravity (Bowl Method)

T209 Sample Reduction Method	Date Reduced	Time Reduced	Sample Temperature
Quartering Method (By Apex)	10/22/2020		°F

Final Reduction for T209 Performed By	WAQTC Number
B. French	23554

$$G_{mm} = \frac{A}{A - C}$$

	Increment 1	Increment 2	
Mass of Bowl *(Required)*	2705.8	2707.4	
Mass of Bowl and Sample	5228.8	5230.1	
Mass of Dry Sample in Air (A)	2523.0	2522.7	0.3
Agitation Method	Mechanical		
Water Bath Temperature	77.5 °F	77.6 °F	
Submerged Weight of Bowl and Sample	3207.1	3208.2	
Submerged Weight of Bowl	1706.9	1707.6	
Submerged Weight of Sample (C)	1500.2	1500.6	0.4
G_{mm} (Maximum Specific Gravity)	2.467	2.468	0.0
Average G_{mm}	2.467		
Range 0.001 (Within d2s precision?)	YES		

FOP for AASHTO T 312 SuperPave Gyratory Compactor

T312 Sample Reduction Method	Date Reduced	Time Reduced	Sample Temperature
Quartering Method (By Apex)	10/22/2020		°F

Final Reduction for T312 Performed By	WAQTC Number
B. French	23554

Gyratory Compactor Brand	Model Number	Serial Number
PINE	AFG1A	2243

	Specimen 1	Specimen 2	Design Mass
Mass of Sample	4652.3	4652.5	4650.0
Temp. of Sample When Placed in Mold	295 °F	295 °F	
Time Compaction Begins	3:10 AM	3:29 AM	Spec Limits
Sample Height (mm)	116.0	115.7	115±5

FOP for AASHTO T 166 Bulk Specific Gravity of Compacted Mix (Method A)

$$G_{mb} = \frac{A}{B - C}$$

	Specimen 1	Specimen 2	
Surface Temperature	°F	°F	
Water Bath Temperature	78 °F	77.9 °F	
Mass of Puck Dry (A)	4640.7	4638.8	1.9
Submerged Weight of Puck in Water (C)	2684.4	2678.7	
Wt. of Puck SSD (B)	4668.9	4663.3	
G_{mb} (Bulk Specific Gravity)	2.338	2.337	
Average G_{mb}	2.338		
Range 0.001 (Within d2s precision?)	YES		

Summary of Mix Properties

Property	Sample 1A	Sample 1B	Combined	LSL	USL
G_{sa}					
G_{se}	2.6479	2.6495	2.649		
G_{sb}	2.599	2.599	2.599		
G_{mm}	2.4668	2.4682	2.467		
G_{mb}	2.3385	2.3374	2.338		
Abs_{t166}	1.4210	1.2345	1.328		
G_b	1.0293	1.0293	1.0293		
P_b	4.669	4.669	4.67	4.50	5.10
P_{ba}	0.731	0.755	0.74		
P_{be}	3.972	3.949	3.96		
P_s	95.3	95.3	95.3		
SA	19.6	19.6	19.6		
AFT	10.37	10.31	10.34		
P_a	5.201	5.298	5.25	3.0	5.0
VMA	14.225	14.264	14.24	13.0	100
VFA	63.440	62.860	63.1	65.0	75.0
P200	3.819	3.819	3.8	3.2	6.2
DP	0.962	0.967	0.96	0.6	1.4

Figure D.22: Job Mix Formula for Project No. 22

Appendix E. Additional Figures of Chapter 4

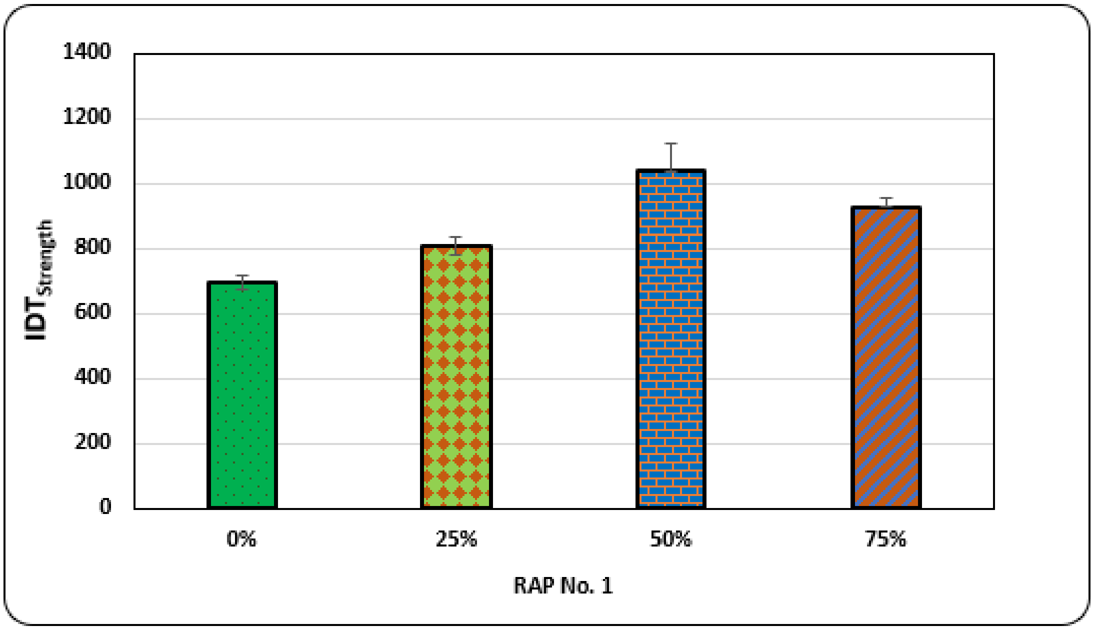

Figure E.1: Effect of RAP Content of RAP No. 1 on $IDT_{Strength}$

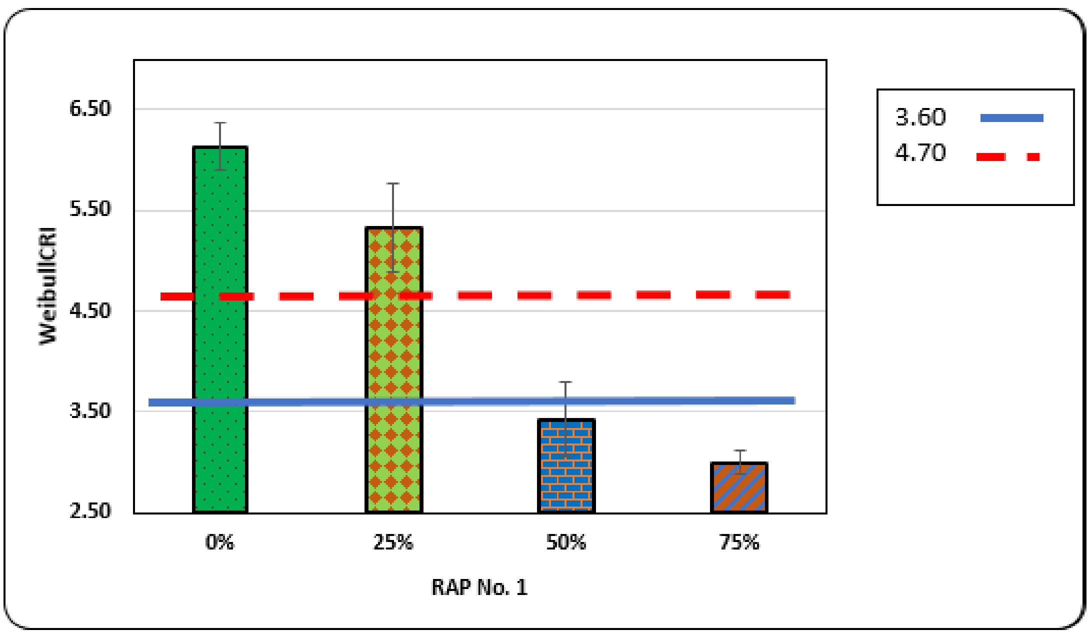

Figure E.2: Effect of RAP Content of RAP No. 1 on WeibullCRI

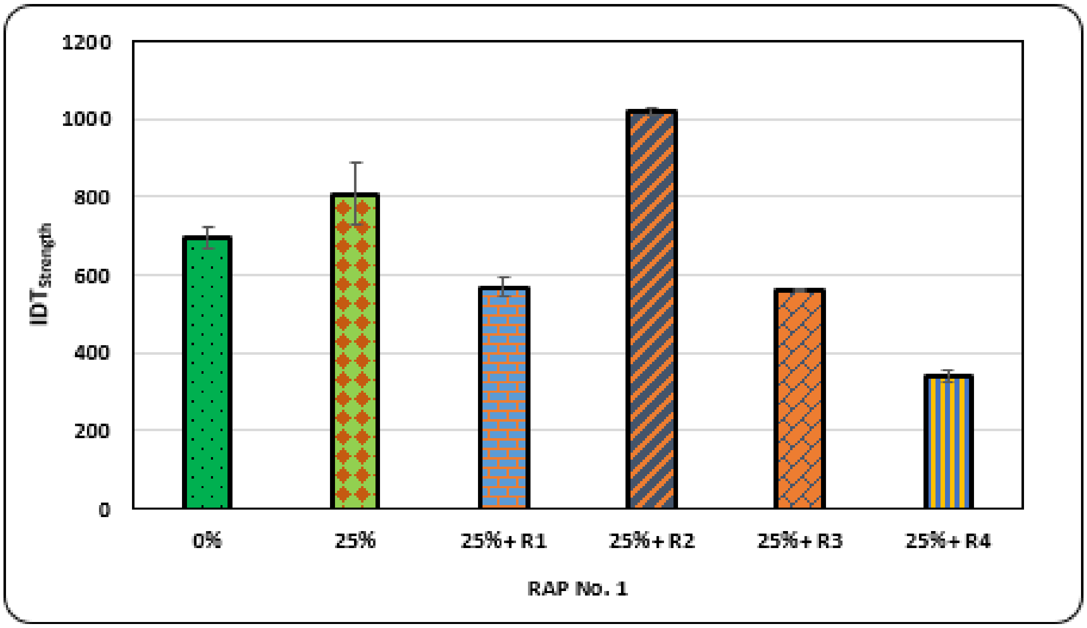

Figure E.3: Effect of Rejuvenator Type at 25% RAP No. 1 on $IDT_{Strength}$

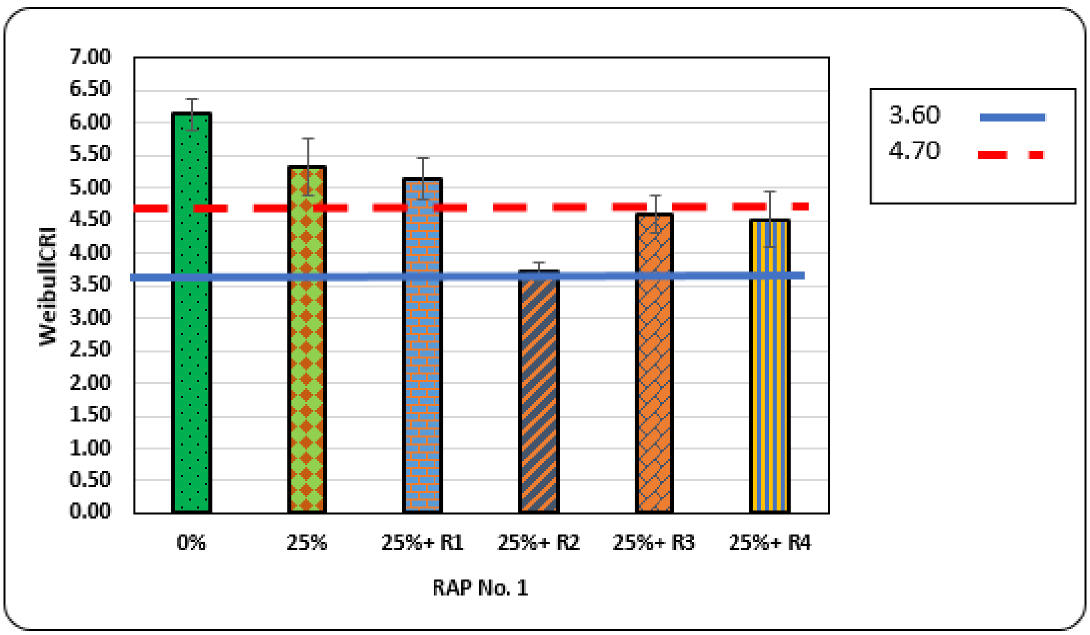

Figure E.4: Effect of Rejuvenator Type at 25% RAP No. 1 on WeibullCRI

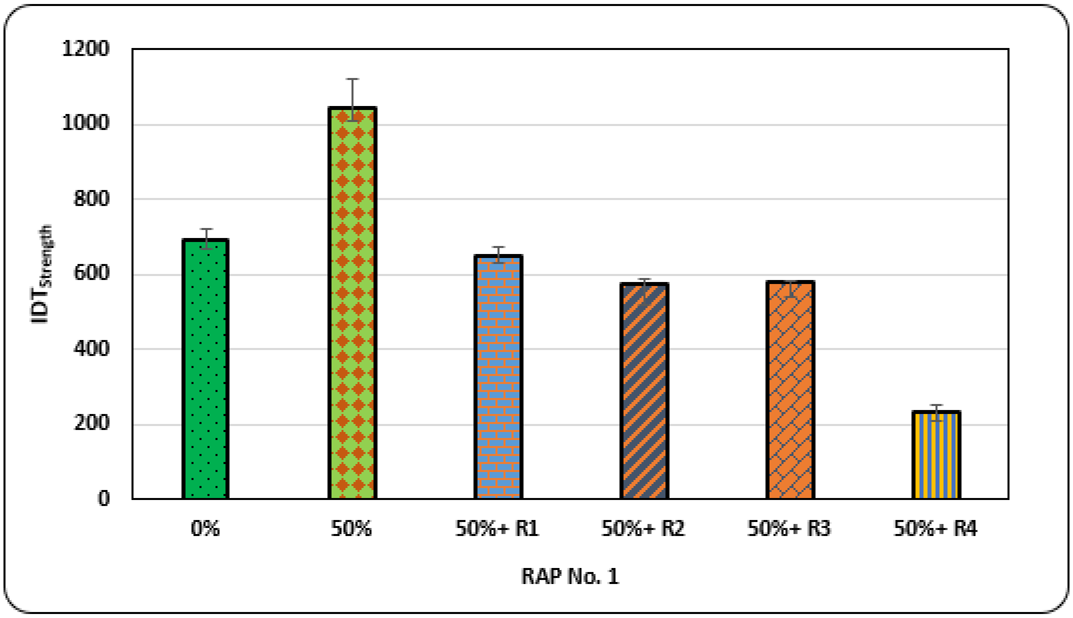

Figure E.5: Effect of Rejuvenator Type at 50% RAP No. 1 on $IDT_{Strength}$

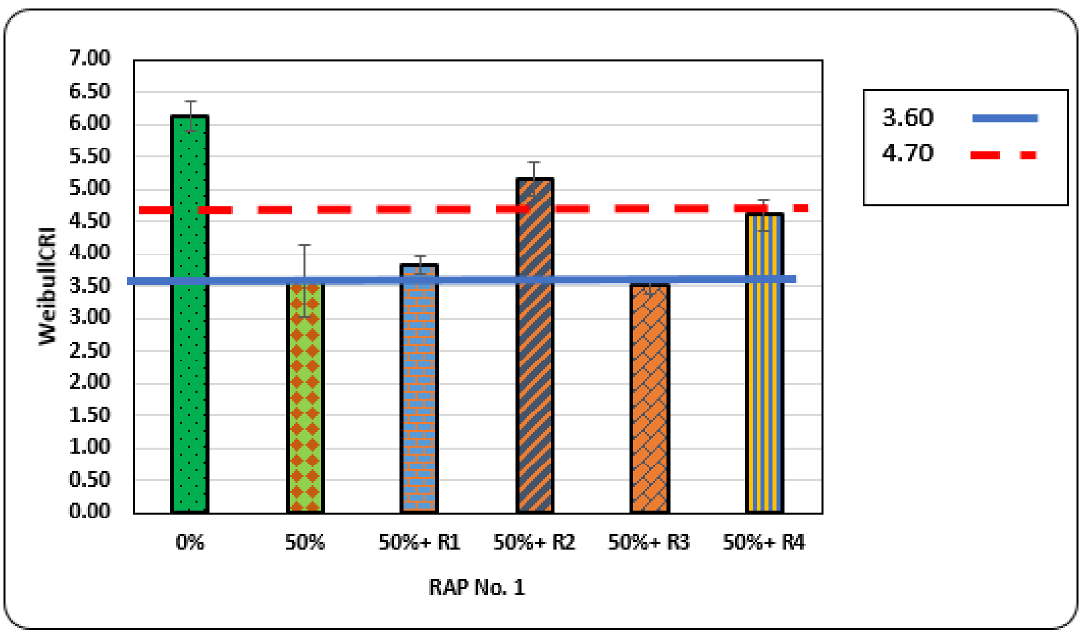

Figure E.6: Effect of Rejuvenator Type at 50% RAP No. 1 on WeibullCRI

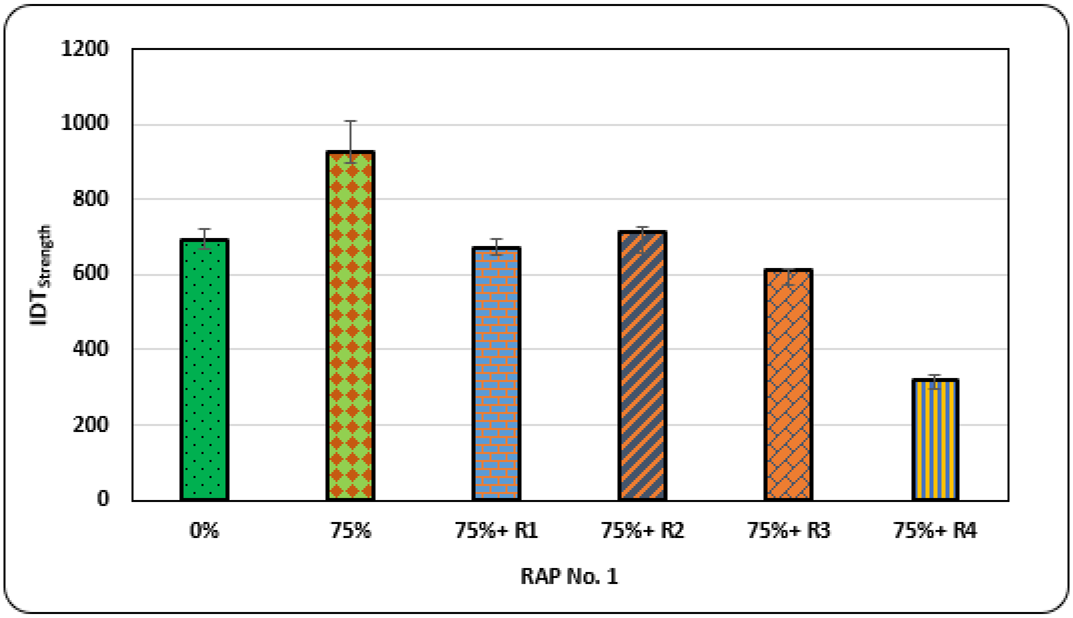

Figure E.7: Effect of Rejuvenator Type at 75% RAP No. 1 on $IDT_{Strength}$

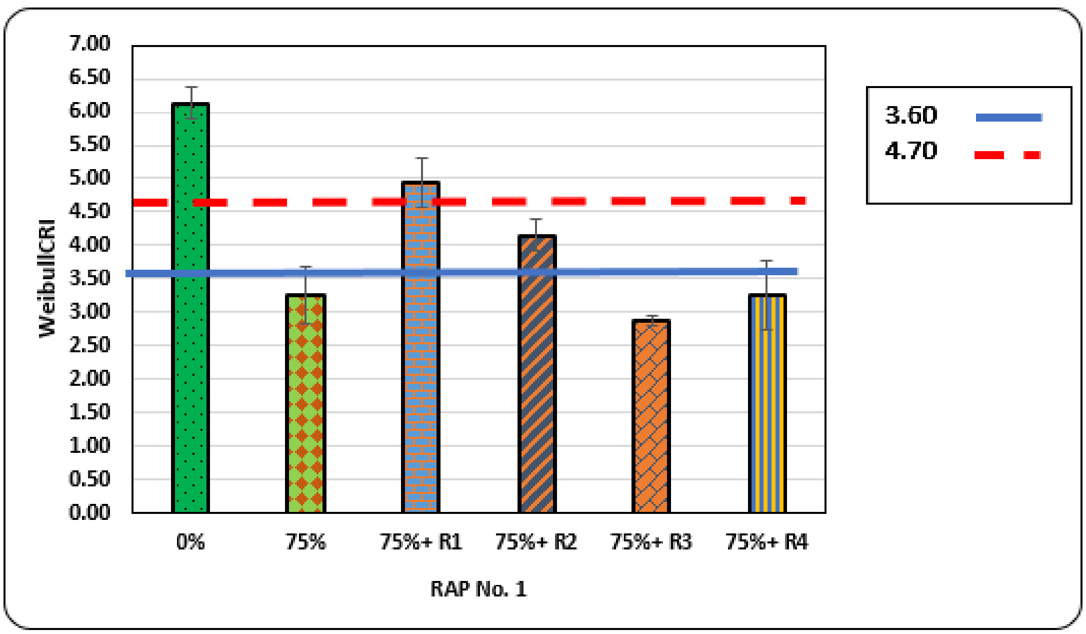

Figure E.8: Effect of Rejuvenator Type at 75% RAP No. 1 on WeibullCRI

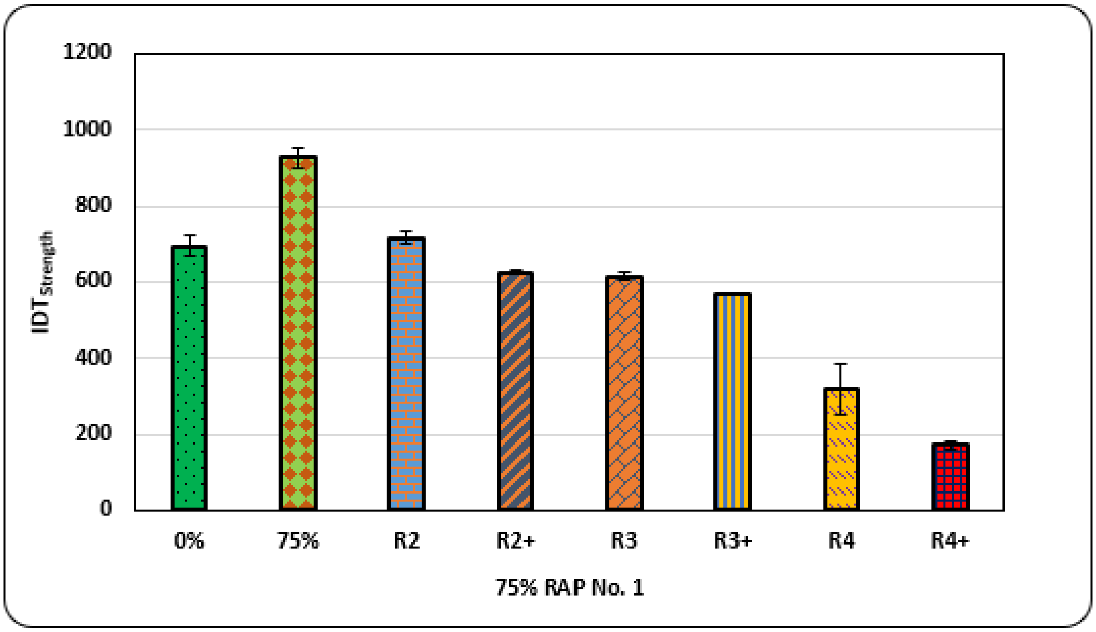

Figure E.9: Effect of Rejuvenator dose at 75% RAP No. 1 on $IDT_{Strength}$

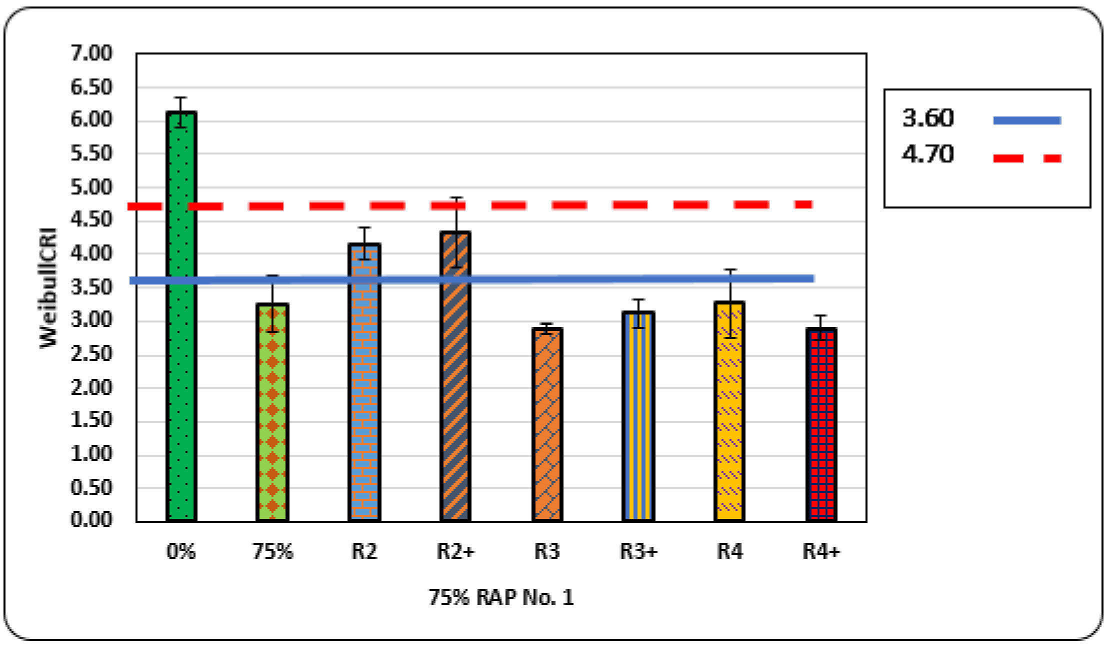

Figure E.10: Effect of Rejuvenator Type at 75% RAP No. 1 on WeibullCRI

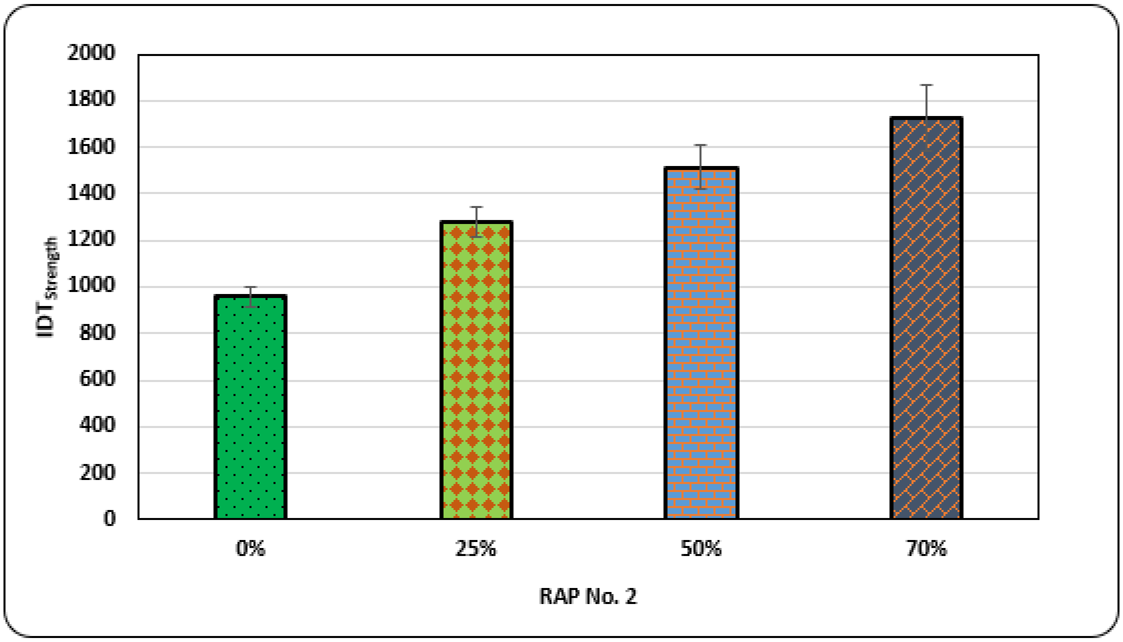

Figure E.11: Effect of RAP Content of RAP No. 2 on IDT$_{Strength}$

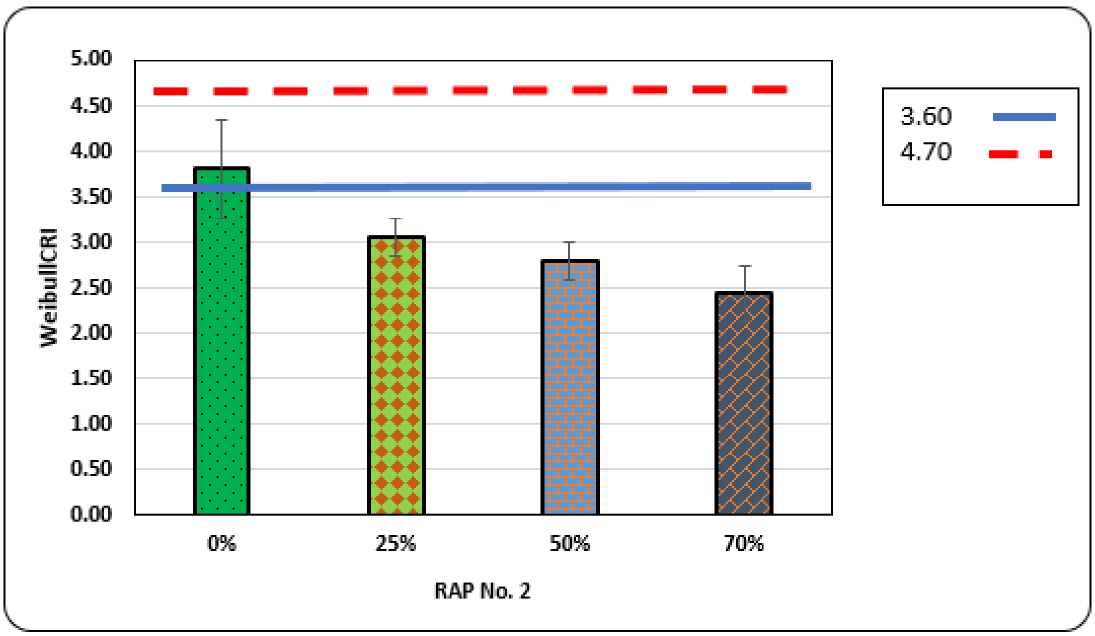

Figure E.12: Effect of RAP Content of RAP No. 2 on WeibullCRI

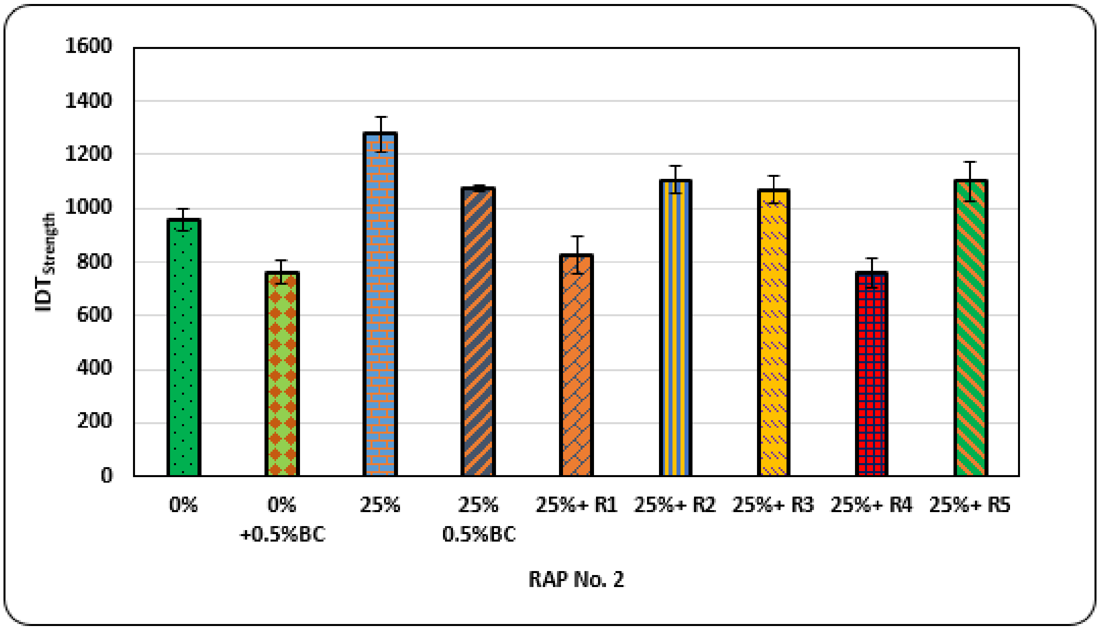

Figure E.13: Effect of Rejuvenator Type at 25% RAP No. 2 on $IDT_{Strength}$

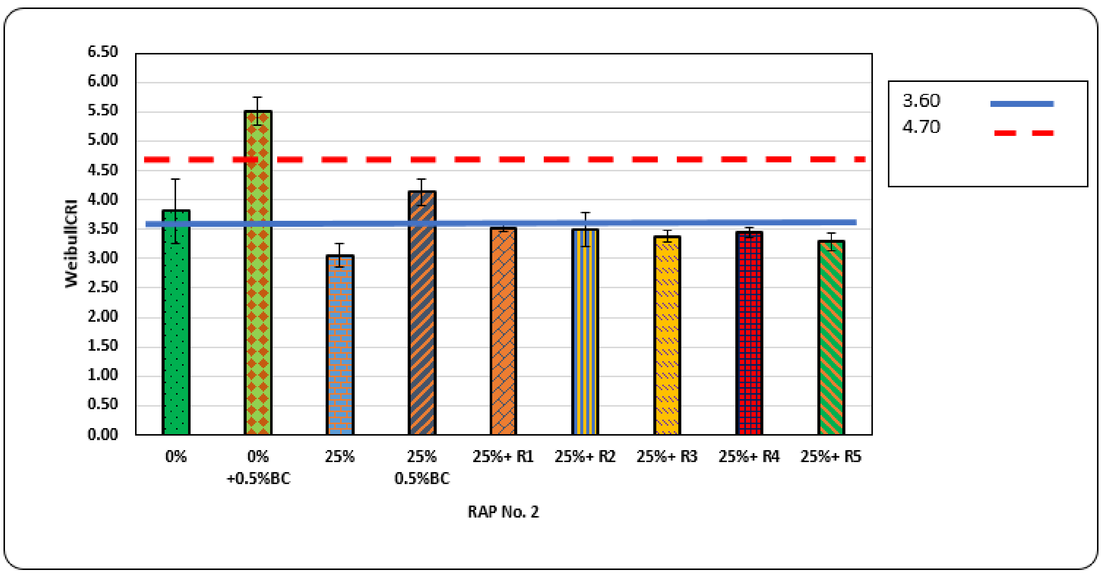

Figure E.14: Effect of Rejuvenator Type at 25% RAP No. 2 on WeibullCRI

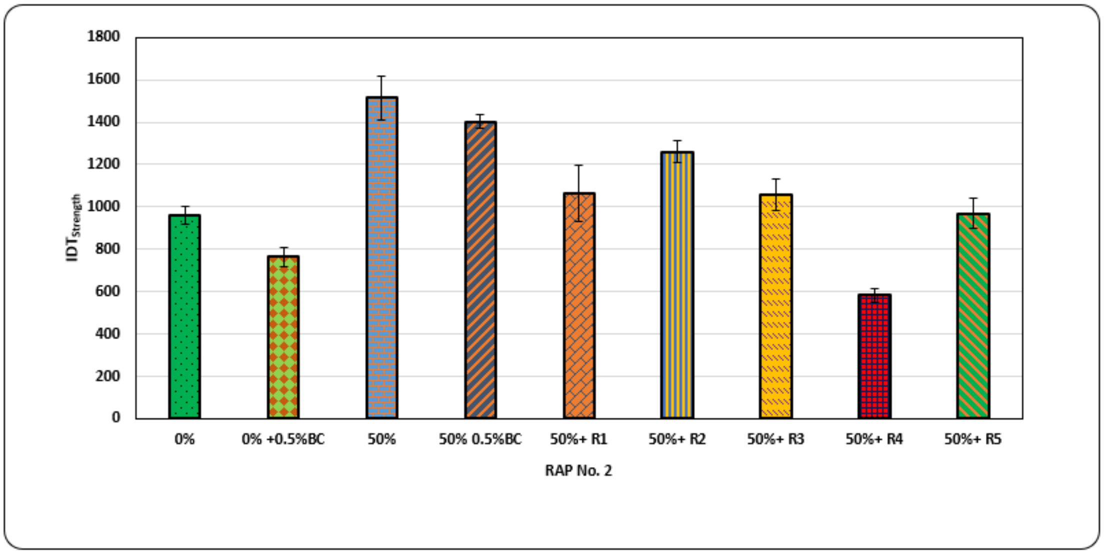

Figure E.15: Effect of Rejuvenator Type at 50% RAP No. 2 on $IDT_{Strength}$

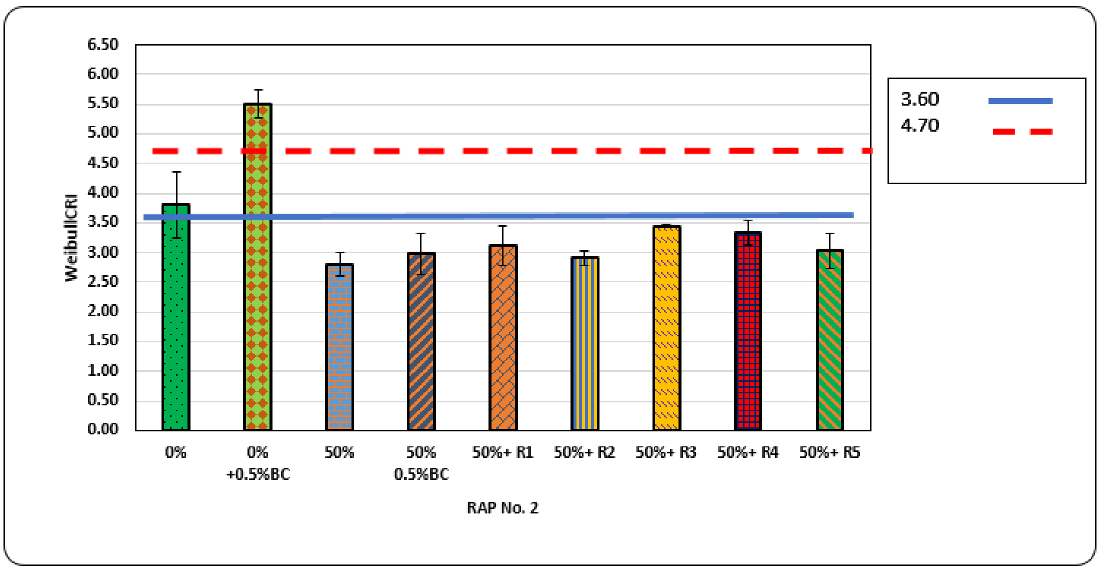

Figure E.16: Effect of Rejuvenator Type at 50% RAP No. 2 on WeibullCRI

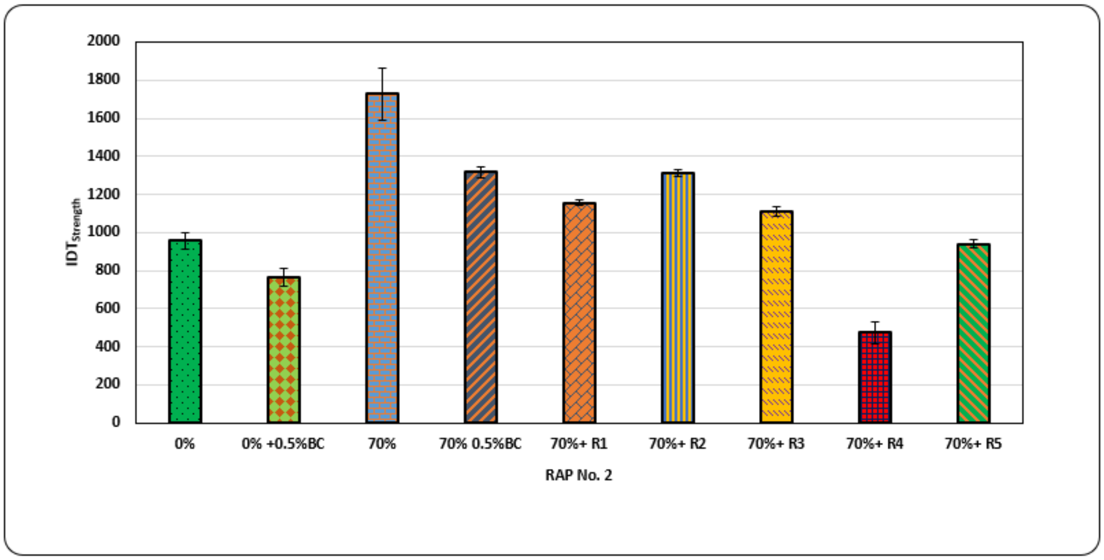

Figure E.17: Effect of Rejuvenator Type at 70% RAP No. 2 on $IDT_{Strength}$

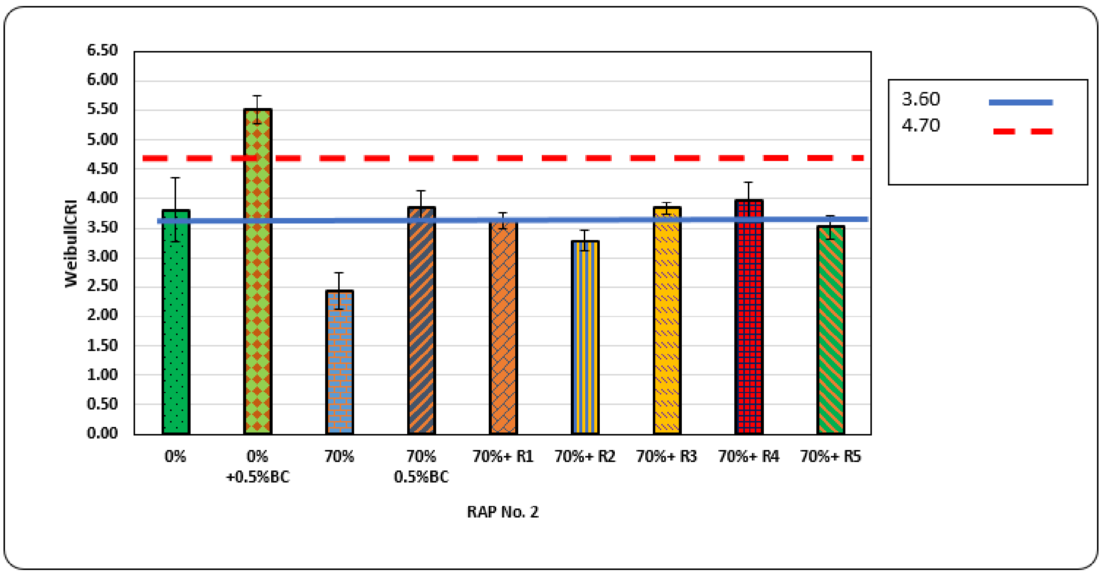

Figure E.18: Effect of Rejuvenator Type at 70% RAP No. 2 on WeibullCRI

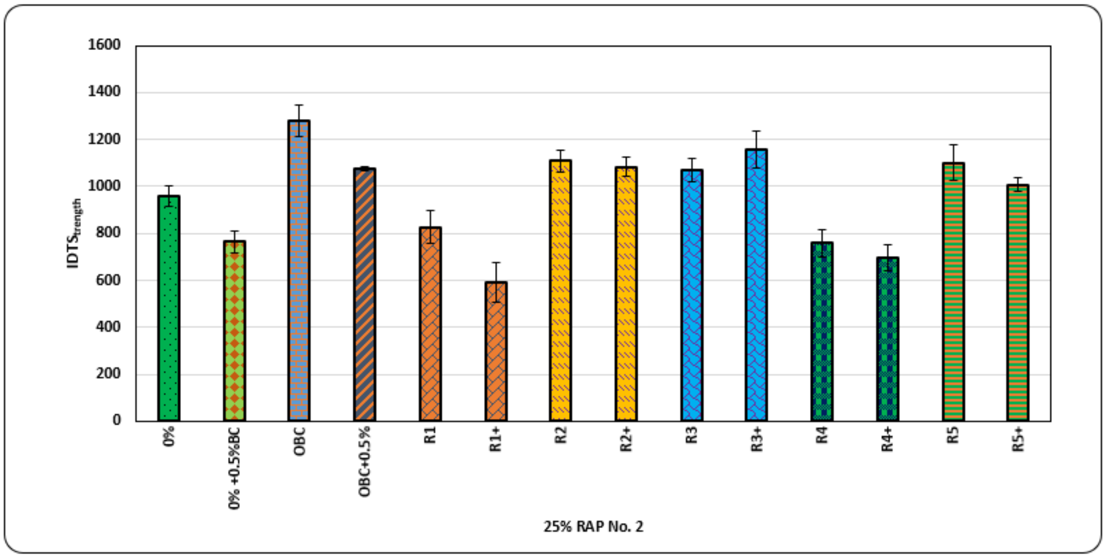

Figure E.19: Effect of Rejuvenator Dose at 25% RAP No. 2 on $IDT_{Strength}$

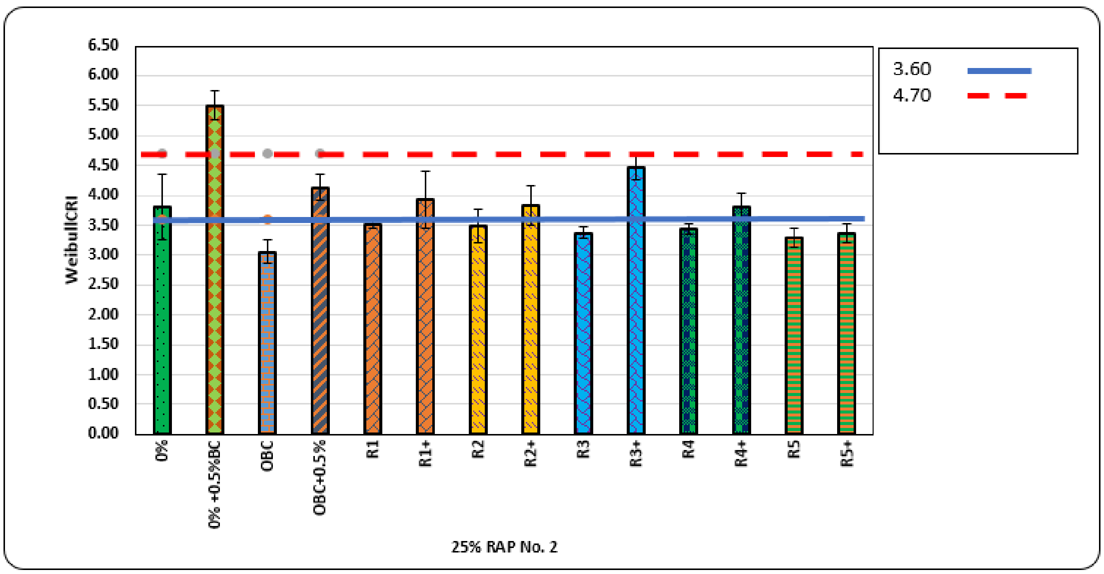

Figure E.20: Effect of Rejuvenator Dose at 25% RAP No. 2 on WeibullCRI

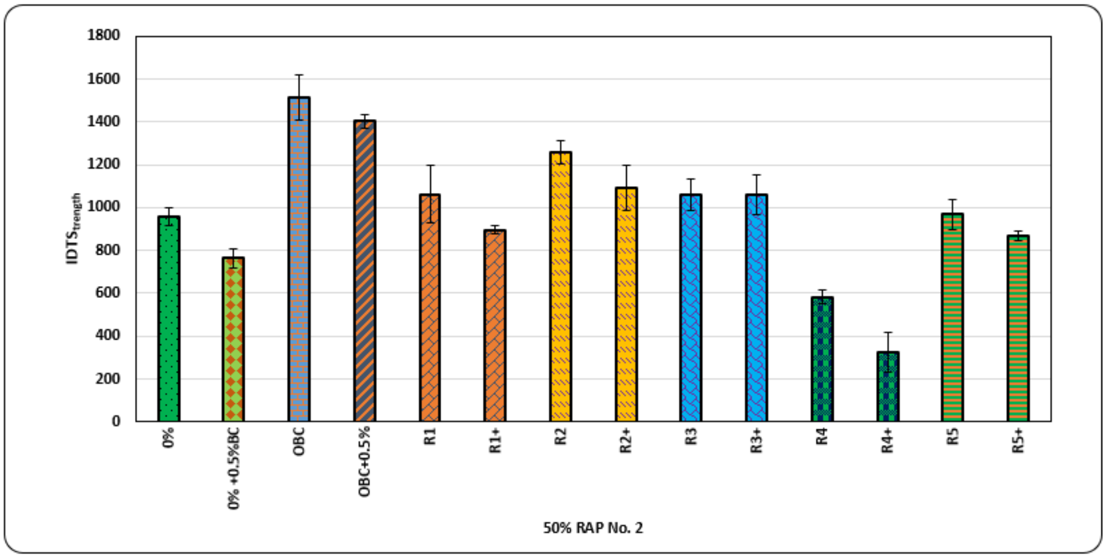

Figure E.21: Effect of Rejuvenator Dose at 50% RAP No. 2 on $IDT_{Strength}$

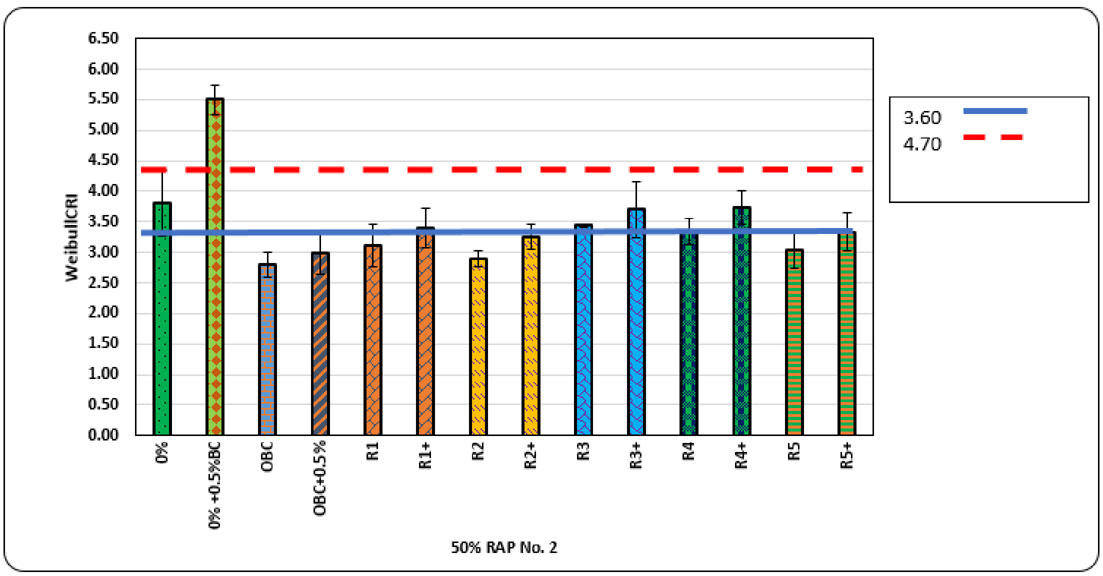

Figure E.22: Effect of Rejuvenator Dose at 50% RAP No. 2 on WeibullCRI

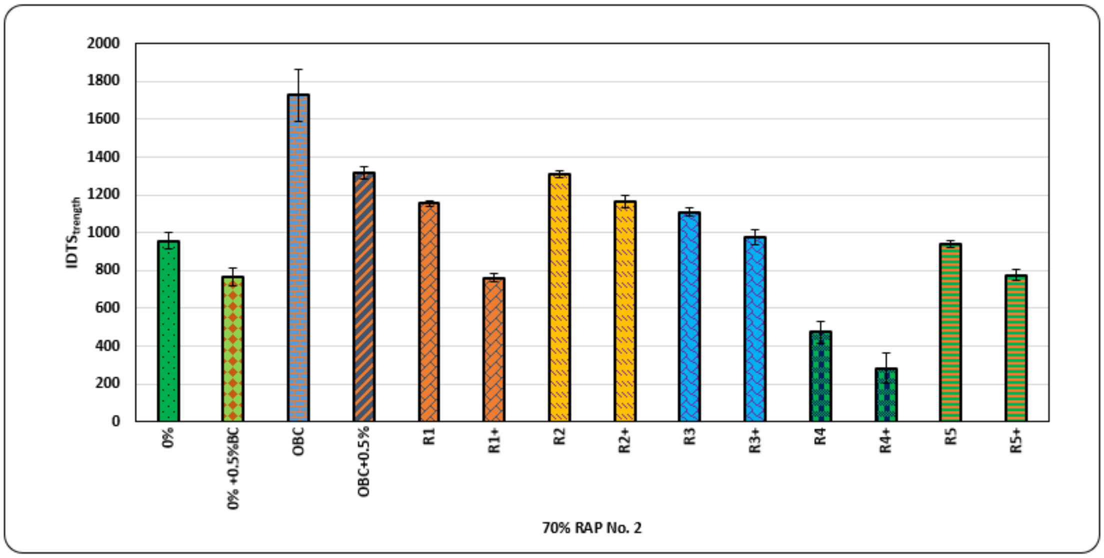

Figure E.23: Effect of Rejuvenator Dose at 70% RAP No. 2 on IDT$_{Strength}$

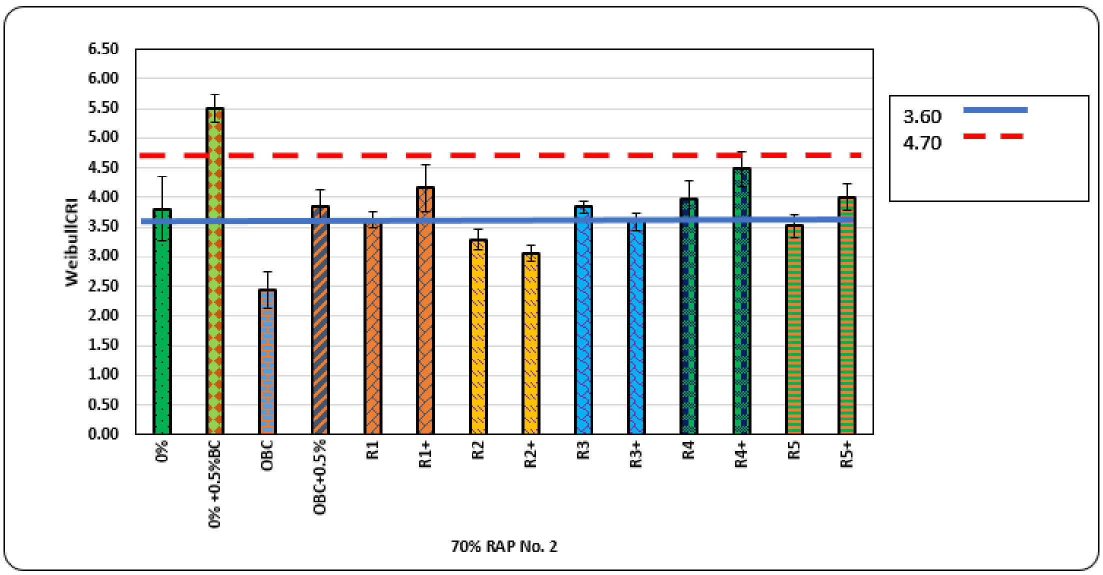

Figure E.24: Effect of Rejuvenator Dose at 70% RAP No. 2 on WeibullCRI

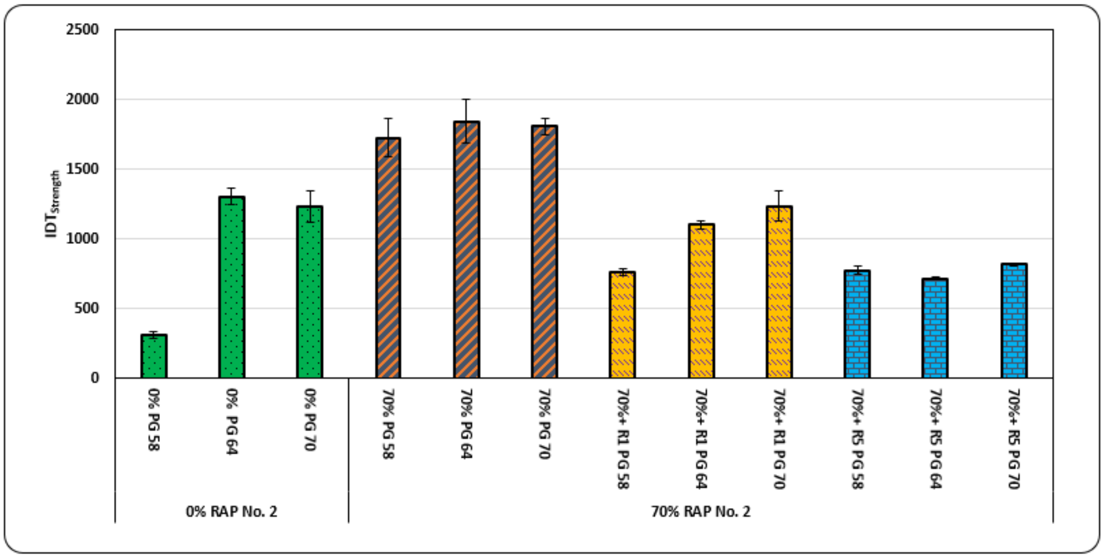

Figure E.25: Effect of Rejuvenators on Different Binder Grade at 70% RAP No. 2 on $IDT_{Strength}$

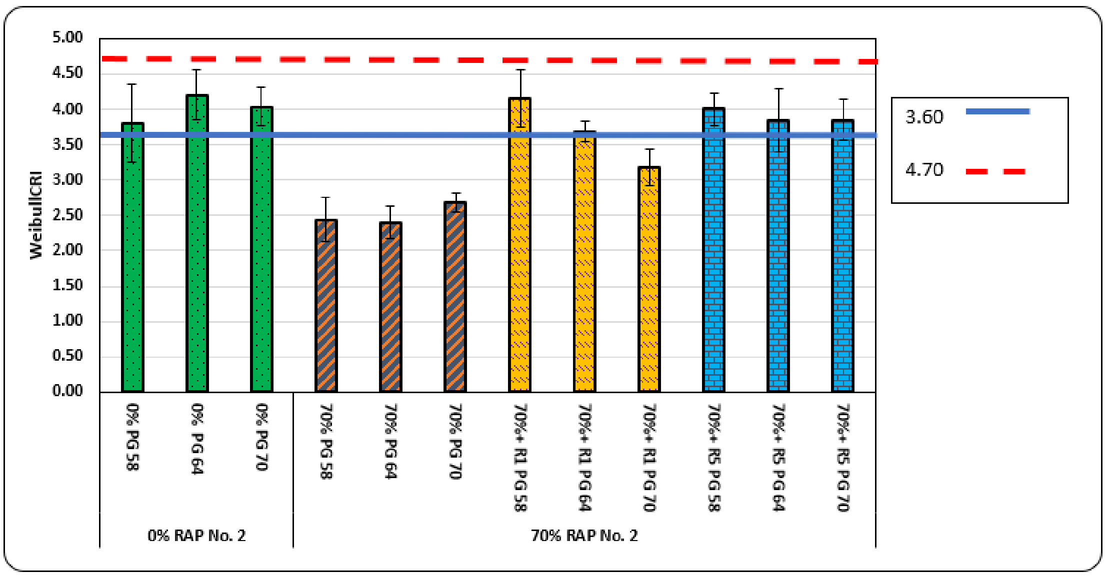

Figure E.26: Effect of Rejuvenators on Different Binder Grade at 70% RAP No. 2 on WeibullCRI

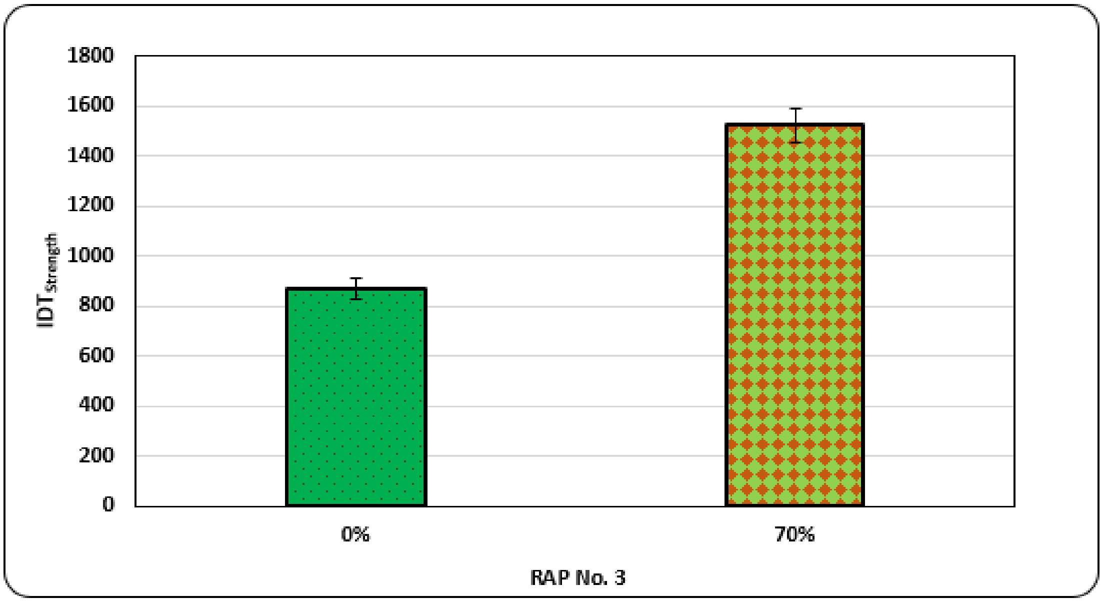

Figure E.27: Effect of RAP Content of RAP No. 3 on $IDT_{Strength}$

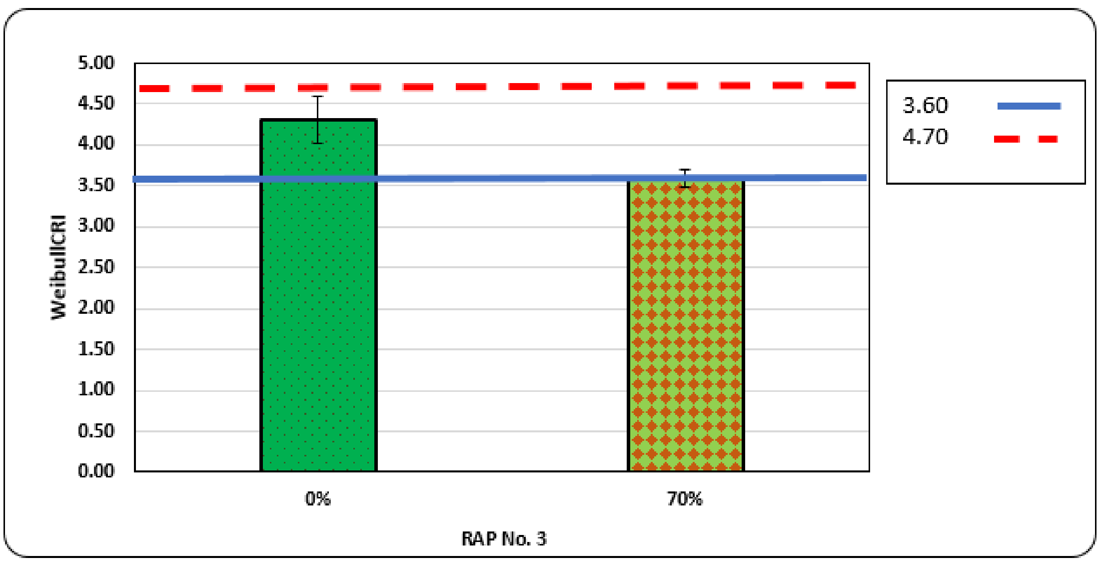

Figure E.28: Effect of RAP Content of RAP No. 3 on WeibullCRI

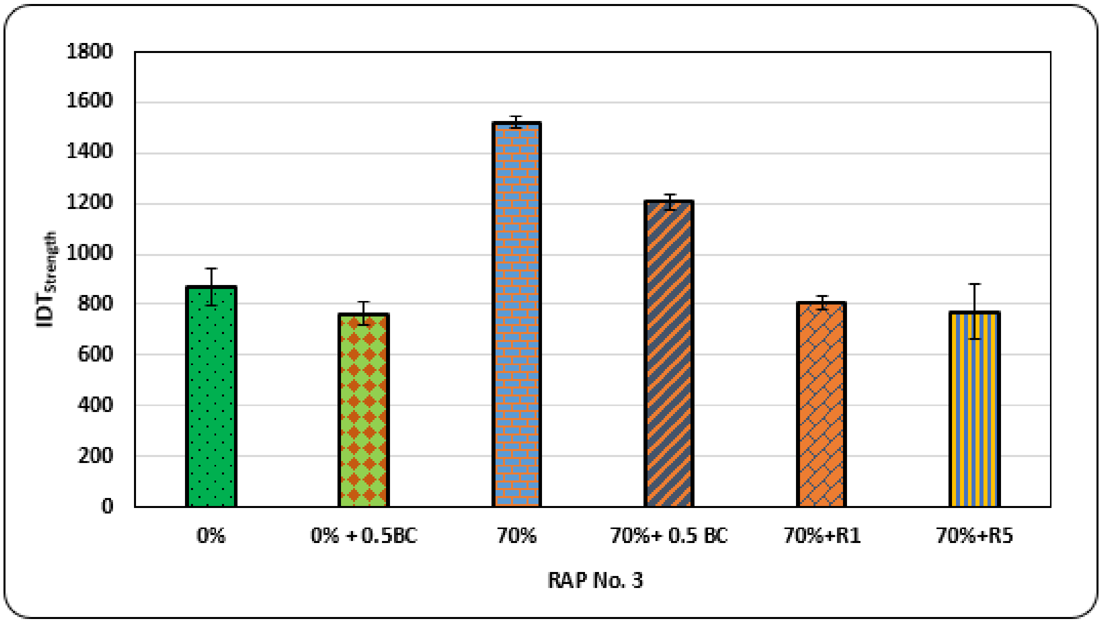

Figure E.29: Effect of Rejuvenator Type at 70% RAP No. 3 on $IDT_{Strength}$

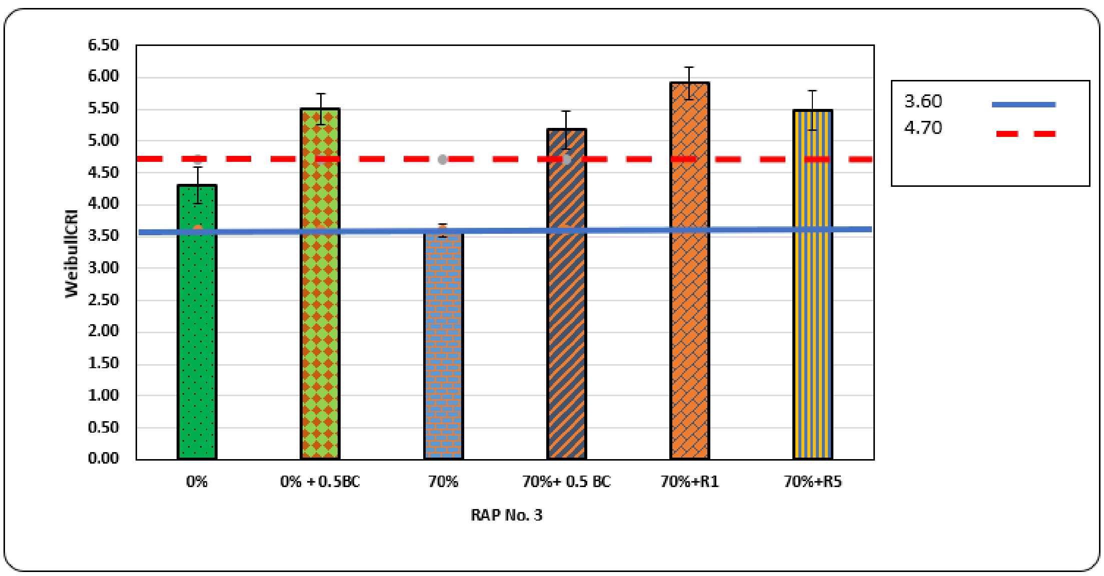

Figure E.30: Effect of Rejuvenator Type at 70% RAP No. 3 on WeibullCRI

Appendix F. Cost Analysis Detail

Mix type		Control 0%		IDEAL-CT_{index}	Control 0% +0.5BC		IDEAL-CT_{index}	25% RAP		IDEAL-CT_{index}	25% RAP + 0.5 BC		IDEAL-CT_{index}	25% RAP + R1		IDEAL-CT_{index}	25% RAP + R5		IDEAL-CT_{index}
Material	Unit Cost $/Ton	Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $	
Virgin Aggregate	$ 13.5	0.94	$12.72		0.94	$11.92		0.71	$ 9.54		0.70	$ 9.49		0.71	$ 9.54		0.71	$ 9.54	
RAP Aggregate	$ 6.5	-	-		-	-		0.25	$ 1.62		0.25	$ 1.61		0.25	$ 1.62		0.25	$ 1.62	
RAP Binder		-	-		-	-		-	-		-	-		-	-		-	-	
Binder Content		0.06	-		0.06	-		0.04	-		0.05	-		0.04	-		0.04	-	
PG 58-28	$ 750	0.06	$43.50		6.3%↑	$47.25		5.80	$33.06		6.3↑	$36.86		5.80	$33.06		5.80	$33.06	
PG 58-34	$ 875		$50.75			$55.13			$38.57			$43.00			$38.57			$40.00	
PG 64-28	$ 800		$46.40			$50.40			$35.26			$39.31			$35.26			$35.26	
PG 70-28	$ 825		$47.85			$51.98			$36.37			$40.54			$36.37			$36.37	
Tall Oil	$ 4,450	-	-		-	-		-	-		-	-		0.004	$18.07		-	-	
Waste Vegetable Oil	$ 3,800	-	-		-	-		-	-		-	-		-	-		0.002	$ 8.46	
Total Cost $	PG 58-28	-	-		-	-		-	-		-	-		-	-		-	-	
	PG 58-34	-	$ 63	39	-	$ 67	102	-	$ 50	20	-	$ 54	46	-	$ 68	52	-	$ 60	26
	PG 64-28	-	-		-	-		-	-		-	-	-	-	-		-	-	
	PG 70-28	-	-		-	-		-	-		-	-	-	-	-		-	-	

Mix type		Control 0%		IDEAL-CT_{index}	Control 0% +0.5BC		IDEAL-CT_{index}	50% RAP		IDEAL-CT_{index}	50% RAP + 0.5 BC		IDEAL-CT_{index}	50% RAP + R1		IDEAL-CT_{index}	50% RAP + R5		IDEAL-CT_{index}
Material	Unit Cost $/Ton	Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $	
Virgin Aggregate	$ 13.5	0.94	$12.72		0.94	$11.92		0.47	$ 6.36		0.47	$ 6.32		0.47	$ 6.36		0.47	$ 6.36	
RAP Aggregate	$ 6.5	-	-		-	-		0.50	$ 3.24		0.50	$ 3.22		0.50	$ 3.24		0.50	$ 3.24	
RAP Binder		-	-		-	-		-	-		-	-		-	-		-	-	
Binder Content		0.06	-		0.06	-		0.03	-		0.04	-		0.03	-		0.03	-	
PG 58-28	$ 750	0.06	$43.50		6.3%↑	$47.25		5.80	$23.06		6.3↑	$26.93		5.80	$23.06		5.80	$23.06	
PG 58-34	$ 875		$50.75			$55.13			$26.90			$31.42			$26.90			$26.90	
PG 64-28	$ 800		$46.40			$50.40			$24.59			$28.73			$24.59			$24.59	
PG 70-28	$ 825		$47.85			$51.98			$25.36			$29.63			$25.36			$25.36	
Tall Oil	$ 4,450	-	-		-	-		-	-		-	-		0.004	$18.07		-	-	
Waste Vegetable Oil	$ 3,800	-	-		-	-		-	-		-	-		-	-		0.004	$16.57	
Total Cost $	PG 58-28	-	-		-	-		-	-		-	-		-	-		-	-	
	PG 58-34	-	$ 63	39	-	$ 67	102	-	$ 36	14	-	$ 41	18	-	$ 55	33	-	$ 53	25
	PG 64-28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	PG 70-28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Mix type		Control 0%		IDEAL-CT_{index}	Control 0% +0.5BC		IDEAL-CT_{index}	70% RAP		IDEAL-CT_{index}	70% RAP + 0.5 BC		IDEAL-CT_{index}	70% RAP + R1		IDEAL-CT_{index}	70% RAP + R5		IDEAL-CT_{index}
Material	Unit Cost $/Ton	Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $	
Virgin Aggregate	$ 13.5	0.94	$12.72		0.94	$11.92		0.28	$ 3.82		0.28	$ 3.79		0.28	$ 3.82		0.28	$ 3.82	
RAP Aggregate	$ 6.5	-	-		-	-		0.70	$ 4.53		0.69	$ 4.51		0.70	$ 4.53		0.70	$ 4.53	
RAP Binder		-	-		-	-		-	-		-	-					-	-	
Binder Content		0.06	-		0.06	-		0.02	-		0.04	-		0.02			0.02	-	
PG 58-28	$ 750	0.06	$43.50		6.3%↑	$47.25		5.80	$15.23		6.3↑	$28.35		5.80	$15.23		5.80	$15.23	
PG 58-34	$ 875		$50.75			$55.13			$17.76			$33.08			$17.76			$17.76	
PG 64-28	$ 800		$46.40			$50.40			$16.24			$30.24			$16.24			$16.24	
PG 70-28	$ 825		$47.85			$51.98			$16.75			$31.19			$16.75			$16.75	
Tall Oil	$ 4,450	-	-		-	-		-	-		-	-		0.004	$18.07		-	-	
Waste Vegetable Oil	$ 3,800	-	-		-	-		-	-		-	-					0.004	$16.57	
Total Cost $	PG 58-28	-	-		-	-		-	-		-	-		-	-		-	-	
	PG 58-34	-	$ 63	39	-	$ 67	102	-	$ 26	14	-	$ 41	30	-	$ 44	40	-	$ 43	39
	PG 64-28	-	$ 59	46	-	-		-	$ 25	10	-	-		-	$ 43	31	-	$ 41	41
	PG 70-28	-	$ 61	40	-	-		-	$ 25	14	-	-		-	$ 43	21	-	$ 42	40

Figure F1. Detailed Cost Estimate of Mixtures with RAP No. 2 and Rejuvenators

Mix type		Control 0%		IDEAL-CT_{Index}	Control 0% +0.5BC		IDEAL-CT_{Index}	70% RAP		IDEAL-CT_{Index}	70% RAP + 0.5 BC		IDEAL-CT_{Index}	70% RAP + R1		IDEAL-CT_{Index}	70% RAP + R5		IDEAL-CT_{Index}
Material	Unit Cost $/Ton	Quantity (Ton)	Cost $ /ton		Quantity (Ton)	Cost $ /ton		Quantity (Ton)	Cost $ /ton		Quantity (Ton)	Cost $ /ton		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $ /ton	
Virgin Aggregate	$ 13.5	0.94	$12.72		0.94	$ 12.65		0.28	$ 3.82		0.28	$ 3.79		0.28	$ 3.82		0.28	$ 3.82	
RAP Aggregate	$ 6.5	-	-		-	-		0.69	$ 4.48		0.69	$ 4.46		0.69	$ 4.48		0.69	$ 4.48	
RAP Binder		-	-		-	-		-	-		-	-		-	-		-	-	
Binder Content		0.06	-		0.06	-		0.03	-		0.03	-		0.03	-		0.03	-	
PG 58-28	$ 750	5.8%	$43.50		6.3%↑	$ 47.25		5.80	$ 20.88		6.3↑	$ 24.57		5.80	$ 20.88		5.80	$ 20.88	
PG 58-34	$ 875		$50.75			$ 55.13			$ 24.36			$ 28.67			$ 24.36			$ 24.36	
PG 64-28	$ 800		$46.40			$ 50.40			$ 22.27			$ 26.21			$ 22.27			$ 22.27	
PG 70-28	$ 825		$47.85			$ 51.98			$ 22.97			$ 27.03			$ 22.97			$ 22.97	
Tall Oil	$ 4,450	-	-		-	-		-	-		-	-		0.004	$ 18.07		-	-	
Waste Vegetable Oil	$ 3,800	-	-		-	-		-	-		-	-		-	-		0.005	$ 18.34	
Total Cost $	PG 58-28	-	$ 56	49	-	$ 60	102	-	$ 29	23	-	$ 33	72	-	$ 47	118	-	$ 48	92
	PG 58-34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	PG 64-28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	PG 70-28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure F2. Detailed Cost Estimate of Mixtures with RAP No. 3 and Rejuvenators

Mix type		Control 0%		IDEAL-CT_{index}	25% RAP		IDEAL-CT_{index}	25% RAP+ (R6) 6.6%		IDEAL-CT_{index}	25% RAP+ (R6) 8.3%		IDEAL-CT_{index}	25% RAP+ (R7)		IDEAL-CT_{index}	25% RAP+ Softer Binder (PG 64-34)		IDEAL-CT_{index}
Material	Unit Cost $/ton	Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $	
Virgin Aggregate	$ 13.5	0.95	$ 12.78		0.72	$ 9.72		0.72	$ 9.72		0.72	$ 9.72		0.72	$ 9.72		0.71	$ 9.58	
RAP Aggregate	$ 6.5	-	-		0.24	$ 1.56		0.24	$ 1.56		0.24	$ 1.56		0.24	$ 1.56		0.237	$ 1.54	
RAP Binder	-	-	-		-	-		-	-		-	-		-	-		-	-	
Binder Content	-	-	-		-	-		-	-		-	-		-	-		-	-	
PG 70-28	$ 825	0.05	$ 43.72		0.04	$ 33.00		0.04	$ 32.50		0.04	$ 32.34		0.04	$ 32.01		-	-	
PG 64-34	$ 925	-	-		-	-		-	-		-	-		-	-		0.053	$ 49.02	
Bio-Based Oil	$ 2,200	-	-		-	-		0.0008	$ 1.76		0.0011	$ 2.42		-	-		-	-	
Petroluem-Based Oil	$ 1,900	-	-		-	-		-	-		-	-		0.0014	$ 2.66		-	-	
Total Cost $	PG 70-28	-	$ 57	90	-	$ 44	59	-	$ 45.54	43	-	$ 46	56	-	$ 46	54	-	-	
	PG 64-34	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	$ 60	60

Mix type		Control 0%		IDEAL-CT_{index}	50% RAP		IDEAL-CT_{index}	50% RAP+ (R6) 6.6%		IDEAL-CT_{index}	50% RAP+ (R6) 8.3%		IDEAL-CT_{index}	50% RAP+ (R7)		IDEAL-CT_{index}
Material	Unit Cost $/ton	Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $	
Virgin Aggregate	$ 13.5	0.95	$ 12.78		0.49	$ 6.56		0.49	$ 6.56		0.49	$ 6.56		0.49	$ 6.56	
RAP Aggregate	$ 6.5	-	-		0.49	$ 3.16		0.49	$ 3.16		0.49	$ 3.16		0.49	$ 3.16	
RAP Binder	-	-	-		-	-		-	-		-	-		-	-	
Binder Content	-	-	-		-	-		-	-		-	-		-	-	
PG 70-28	$ 825	0.05	$ 43.72		0.03	$ 22.44		0.03	$ 21.45		0.03	$ 20.71		0.02	$ 20.05	
PG 64-34	$ 925	-	-		-	-		-	-		-	-		-	-	
Bio-Based Oil	$ 2,200	-	-		-	-		0.0017	$ 3.74		0.0021	$ 4.62		-	-	
Petroluem-Based Oil	$ 1,900	-	-		-	-		-	-		-	-		0.0029	$ 5.51	
Total Cost $	PG 70-28	-	$ 57	90	-	$ 32	37	-	$ 35	36	-	$ 35	44	-	$ 35	33
	PG 64-34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Mix type		Control 0%		IDEAL-CT_{index}	70% RAP		IDEAL-CT_{index}	70% RAP+ (R6) 6.6%		IDEAL-CT_{index}	70% RAP+ (R6) 8.3%		IDEAL-CT_{index}	70% RAP+ (R7)		IDEAL-CT_{index}
Material	Unit Cost $/ton	Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $		Quantity (Ton)	Cost $	
Virgin Aggregate	$ 13.5	0.95	$ 12.78		0.29	$ 3.98		0.295	$ 3.98		0.295	$ 3.98		0.295	$ 3.98	
RAP Aggregate	$ 6.5	-	-		0.69	$ 4.47		0.688	$ 4.47		0.688	$ 4.47		0.688	$ 4.47	
RAP Binder	-	-	-		-	-		-	-		-	-		-	-	
Binder Content	-	-	-		-	-		-	-		-	-		-	-	
PG 70-28	$ 825	0.05	$ 43.72		0.02	$ 13.61		0.01	$ 11.63		0.01	$ 8.66		0.01	$ 6.85	
PG 64-34	$ 925	-	-		-	-		-	-		-	-		-	-	
Bio-Based Oil	$ 2,200	-	-		-	-		0.0024	$ 5.28		0.006	$ 13.42		-	-	
Petroluem-Based Oil	$ 1,900	-	-		-	-		-	-		-	-		0.008	$ 15.58	
Total Cost $	PG 70-28	-	$ 57	90	-	$ 22	24	-	$ 25.37	39	-	$ 31	33	-	$ 31	29
	PG 64-34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure F3. Detailed Cost Estimate of Mixtures with RAP No. 4 and Rejuvenators