



CHARACTERIZING RECYCLED ASPHALT MIXES USING IDEAL CT AND CREEP COMPLIANCE

FINAL REPORT



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CHARACTERIZING RECYCLED ASPHALT MIXES USING IDEAL CT AND CREEP COMPLIANCE

FINAL PROJECT REPORT

Report No. INE/AIDC 25.04

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Appendix

Impact of RAP Material on Cracking Resistance of Alaskan Asphalt Mixes

Final Report

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**In cooperation with the Alaska Department of Transportation and Public
Facilities**

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²
*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)				

TABLE OF CONTENTS

Disclaimer.....	i
Technical Report Documentation Page	ii
SI* (Modern Metric) Conversion Factors.....	iii
List of Figures	vi
List of Tables	vii
Abstract.....	1
CHAPTER 1. Introduction	2
1.1. Overview	2
1.2. Study Objectives	2
1.3. Best Practices for RAP USE.....	3
1.4. Performance of RAP Asphalt Mixtures	4
1.4.1. Binder Characterization.....	5
CHAPTER 2. Rejuvenators	6
2.1. Introduction	6
CHAPTER 3. IDEAL Cracking Test for Asphalt Mix Design, Control and Quality Assurance	8
3.1. Background	8
3.2. CT _{index} Review.....	8
3.3. Normalized Air Voids Adjustment.....	9
CHAPTER 4. IDEAL-CT Testing	10
4.1. Testing.....	10
4.2. Discussion of the Data.....	12
CHAPTER 5. Creep Compliance	15
5.1. Background	15
5.2. Testing and Analysis.....	16
5.2.1. PG52-28 Test Results	16
5.3. PG52-40 Test Results	17
CHAPTER 6. Discussion of Findings	20
6.1. Comparison of PG52-28 and PG52-40 with No RAP	20
6.2. Performance of Recycled Asphalt Pavement Mixes	20
6.3. Rejuvenators	22
CHAPTER 7. Conclusions and Recommendations	23
7.1. Conclusions	23

7.2. Recommendations	24
CHAPTER 8. References	25
APPENDIX A.....	A
APPENDIX B	00
APPENDIX C	TT

LIST OF FIGURES

Figure 4-1: Testing equipment and sample report produced.....	11
Figure 4-2: Inclusion of RAP tends to increase the CTindex for both grades of asphalt below 35% RAP	13
Figure 4-3: Inclusion of the rejuvenators tend to reduce the CTindex for PG52-28 when compared to RAP mixes without rejuvenators.	14
Figure 5-1 Comparison PG52-28 and PG58-40 at -10oC and -20oC	16
Figure 5-2 Summary of Creep Compliance at 100 seconds for various percentages of RAP at three temperatures.....	17
Figure 5-3 Comparison of PG52-40 at No RAP, 25, 35, and 50% RAP.....	18
Figure 5-4 Comparison of Creep Compliance of PG52-28 at 0oC, -10oC, and -20oC	18
Figure 5-5 PG52-40 Creep Compliance at 100 Seconds Sorted by RAP Content.	19
Figure 6-1 Estimated new binder required for a total binder content of 5.2 % and a RAP binder content of 5.0%.	21

LIST OF TABLES

Table 2-1 Families of Rejuvenators; Source, Performance, Cost and Environmental Impact	6
Table 4-1: IDEAL-CT Test Matrix	10
Table 4-2: Summary of IDEAL CT Test Data	11

ABSTRACT

This study provides insights into the performance of Recycled Asphalt Pavement (RAP) in Alaskan asphalt mixes. The findings highlight the potential benefits and challenges associated with incorporating RAP into asphalt mixtures, particularly in cold climates. The research demonstrates that while RAP can enhance the high-temperature performance of asphalt mixes by improving stiffness and resistance to deformation, it also poses a risk of increased cracking at low temperatures. The maximum recommended RAP content was identified as 25%, balancing performance and durability. The use of rejuvenators showed mixed results, indicating the need for specific mix designs for each combination of RAP and rejuvenator. The Creep Compliance test results further emphasized the importance of careful mix design, as higher RAP content increased stiffness but also the risk of cracking. The study also found that the binder PG 52-40 provided better resistance to cracking compared to PG 52-28. The use of RAP in Alaskan asphalt mixes requires careful consideration of mix design and testing to ensure suitability for specific climate and traffic conditions. Further research on rejuvenators and the development of predictive models for RAP content in asphalt mixes are recommended to optimize the performance and durability of these mixtures.

CHAPTER 1. INTRODUCTION

1.1. Overview

Recycled Asphalt Pavement (RAP) is a material used in the reconstruction and rehabilitation of highways globally. It minimizes the need for new materials and reduces costs, energy consumption, and emissions. Approximately 80 to 100% of asphalt can be recycled through full depth recycling, which can replace virgin asphalt concrete in surface and asphalt treated base courses, and serve as a surface course for driveways and parking lots. According to NAPA SR-229 (Fort, Jean-Paul 2024), several factors limit the use of RAP:

- Reduced service life due to raveling and cracking
- Variation in binder content, gradation, and aggregate specific gravity
- Interaction between RAP and modified asphalts
- Plant limitations
- Availability of RAP
- Specifications

States permit between 15% and 20% RAP for surface courses. Among the 43 states and two Canadian provinces surveyed, the median maximum asphalt content was 20%. Forty states allow a maximum of 10% RAP in the surface course, 31 states allow up to 19% and two states allow up to 29%. No states allow higher RAP content in the surface course although three states allow greater than 30% in the intermediate layer (Copeland 2011).

Most states impose restrictions on the amount of RAP used in mix types and layers. According to a survey conducted by the Ohio Department of Transportation, most respondents indicated that there are no special requirements for high RAP mixtures beyond standard mix design procedures. Approximately half of the respondents noted that they have experimented with or routinely use high RAP mixes (Copeland 2011). Alaska reported that it did not use high RAP mixes.

The National Center for Asphalt Technology (NCAT) completed a study comparing mixes containing 30% RAP with virgin mixes using data from the Long-Term Pavement Performance (LTPP) program. The study analyzed rutting, fatigue cracking, longitudinal cracking, transverse cracking, block cracking, and raveling from 18 projects across North America. These projects were in service for periods ranging from 6 to 17 years. The analysis indicated that performance was statistically similar except for fatigue, longitudinal cracking, and transverse cracking, where the virgin sections performed slightly better (National Center for Asphalt Technology 2009).

1.2. Study Objectives

The objective of this study was to investigate the impact of RAP and rejuvenators on the cracking performance of Alaskan HMA materials containing RAP and develop a method to estimate RAP content for a given mix containing RAP material. This work complements the previous ADOT&PF study titled *Characterization of Alaskan HMA Containing RAP Materials* (Liu et al. 2016).

Issues related to construction and performance associated with higher RAP content can be addressed through mix design and material selection. The use of additives, such as rejuvenating agents, has been shown to be effective in improving cracking resistance based on several NCHRP studies.

Following discussions between the research team and ADOT&PF personnel, variables in the experimental matrix include: one RAP source from the Northern Region, two regional asphalt binders (PG 52-28 from the Northern Region and PG 52-40E from the Central Region), three RAP contents (0%, 15%, and 25% RAP), and two types of rejuvenators recommended by local industry. It is important to investigate if the use of rejuvenators can allow higher percentages of RAP in Alaskan mixtures while maintaining the required level of low-temperature performance.

Type II-B mixes without RAP are used as references.

This report includes a description of the research methods and approach for this project, the test procedures and results, the project's findings, and suggestions for further study. Recommendations for the use of RAP and rejuvenators in new design projects are also provided. Based on the analysis of the Ideal-CT test results, the team will make recommendations regarding the incorporation of the Ideal-CT test into the mix design procedures for RAP. The equipment cost is approximately \$10,000, which can also be used for the Marshall Mix Design.

1.3. Best Practices for RAP USE

There is a minimal difference between designing virgin mixes and those incorporating RAP (Reclaimed Asphalt Pavement). However, when utilizing RAP, the following factors should be considered (Copeland 2011):

- The characterization and impact of the RAP on the properties of the blended binder. This will guide the determination of appropriate blending ratios.
- Developing practices to minimize variability in the RAP source.
- The QC process requires additional effort.

The quality and uniformity of the RAP significantly influence the overall quality and uniformity of the final mix. RAP stockpiles often consist of material from multiple sources, which should ideally be blended to ensure a uniform product. Despite thorough blending being impractical, it does not imply that the owner has no control. The percentage of RAP from unmanaged sources can be limited. When higher percentages are incorporated into the mix, the owner can require the contractor to use a known source of RAP.

Additionally, the contractor may be required to process the RAP through screening, crushing, and/or fractionating. Performance testing, composition analysis, and variability assessments may also be necessary. Fractionating RAP, similar to multi-pile aggregate management, is an effective method for controlling variability in the recycled asphalt mix. Fractionated RAP is divided into three stockpiles: coarse, fine, and oversized.

As with aggregate, RAP stockpiles should be managed in a way that minimizes segregation and promotes drainage. Finally, adjusting the grade of virgin asphalt or using rejuvenators may be necessary to achieve the required performance.

1.4. Performance of RAP Asphalt Mixtures

The performance of RAP asphalt mixtures has been extensively studied to ensure they meet the necessary standards for durability and longevity (Copeland 2011).

- **Crack Resistance:** RAP mixtures must demonstrate resilience against various types of cracks, including thermal and fatigue cracking. Studies have shown that with proper mix design, RAP mixtures can achieve comparable or superior cracking resistance to virgin asphalt mixtures.
- **Rut Resistance:** Rutting is a common issue in asphalt pavements. RAP mixtures, when properly designed, offer adequate resistance to rutting, ensuring the pavement remains smooth and functional over time.
- **Moisture Susceptibility:** The ability of RAP mixtures to withstand moisture-induced damage is critical. Evaluations indicate that, with correct binder selection and mix composition, RAP asphalt mixtures exhibit strong moisture resistance.
- **Structural Integrity:** The overall structural performance of RAP mixtures is assessed through load-bearing tests and long-term observations. Well-designed RAP mixtures have been shown to maintain structural integrity comparable to traditional asphalt.

Good performance with RAP mixes requires careful mix design and testing to ensure the suitability of the mix for the climate and anticipated traffic. As noted earlier, mixes with high RAP content require increased effort to ensure performance. This includes selection of the right virgin binder, performance testing to validate the suitability of the mix, and adequate quality controls.

Several studies have examined how different levels of RAP content affect the characteristics of recycled asphalt mixtures. These studies reinforce that RAP contents of 15% or lower have little impact on the mix properties, that is, the properties are similar to those of the virgin mix. Higher RAP contents tend to result in stiffer mixes. Creep compliance curves and dynamic modulus showed similar trends (Liu 2016).

The binder selected should consider local climatic conditions. In colder regions, a softer binder may help mitigate thermal cracking, while in warmer areas, a stiffer binder can enhance rut resistance.

Liu et al. (2016) investigated the properties of Alaskan hot-mix asphalt (HMA) containing reclaimed asphalt pavement (RAP) material. The study evaluated three asphalt binders commonly used in Alaska—PG 52-28, PG 52-40, and PG 58-34—and 11 HMA mixtures with up to 35% RAP. Various engineering properties of binders and mixtures were examined, such as stiffness, stress, strain, and dynamic modulus. Binder cracking temperatures were also determined using specialized software and tests. The goal of the research was to enhance the understanding and performance of HMA materials in cold climates.

The research found that incorporating RAP into Alaskan HMA can improve certain properties of the mixtures. Specifically, the inclusion of RAP increased stiffness and resistance to deformation at high temperatures, though it also raised the risk of cracking at low temperatures. The findings suggest the importance of balancing RAP content to optimize performance in Alaska's climate conditions.

Key findings include:

High-Temperature Performance: The inclusion of RAP improved stiffness and resistance to deformation at high temperatures, as measured by parameters like complex modulus (G^*) and phase angle (δ).

Low-Temperature Cracking: RAP increased the risk of cracking at low temperatures, determined through binder cracking temperatures using Thermal Stress Analysis Routine (TSAR) software.

The study emphasizes the need to balance RAP content to optimize performance for Alaska's extreme climate conditions. The creep compliance results indicated that mixtures containing RAP exhibited higher stiffness compared to virgin mixtures. This increased stiffness can enhance resistance to permanent deformation under sustained loads, which benefits high-temperature performance. However, the higher stiffness also indicated a reduced ability to relax stresses, potentially increasing the risk of cracking in cold climates. The findings highlight the necessity of carefully balancing RAP content to achieve both durability and flexibility in Alaskan hot-mix asphalt.

1.4.1. Binder Characterization

The appendix provides comprehensive testing for characterizing Alaskan virgin and RAP binders for this study, including evaluations of their viscoelastic behavior, rutting potential, and thermal cracking resistance (Lui 2024). The results indicate that incorporating RAP did not significantly affect binder performance at high temperatures, but the low-temperature performance was compromised as RAP content increased. The study found that while the neat binder performed well, the binders with higher RAP contents showed increased stiffness and reduced flexibility.

The performance grading of the binders was determined according to AASHTO standards, revealing that the neat binder is rated PG 64-40, while the 100% RAP binder received a rating of PG 82-16. The BBR test results indicated that as RAP content increased, the low-temperature cracking resistance decreased, with critical temperatures rising from -40 °C for neat binder to -30 °C for 25% RAP.

The master curves suggest the binder modulus increases as the aging and RAP content increase. Binder extracted from RAP mixtures containing 25% RAP indicates that at lower mixtures may have similar performance in the early life of the pavement. However, it is not clear as to the long-term performance.

MSCR data suggests that any mixture containing RAP will not be a major concern relating to rutting resistance.

Liu, et. al. (2016) developed a predictive model was developed to estimate RAP content based on rheological test results. This model can be applied in practical scenarios to back calculate the RAP content in loose mixtures, facilitating better quality assurance practices in asphalt pavement construction. The model is based on the high PG grading, the non-recoverable creep compliance (derived from the MSCR test, the stiffness modulus and the critical temperature. The details of the model are provided in the Appendix.

While incorporating RAP can be beneficial, careful consideration must be given to the percentage used to avoid compromising low-temperature performance. A RAP mix containing 25% RAP

In summary, the study provides valuable insights into the performance of asphalt binders with RAP, emphasizing the need for a balanced approach to maximize the benefits of RAP while ensuring the durability of asphalt pavements in Alaskan conditions.

CHAPTER 2. REJUVENATORS

2.1. Introduction

Rejuvenators were introduced in the 1970s to restore the properties of aged asphalt binders, making them more flexible and less brittle. This practice gained prominence during the Arab Oil Embargo of 1973, which led to increased asphalt binder prices and encouraged the development of recycling technologies.

Rejuvenators are classified into two categories: softening agents and rejuvenating agents. Softening agents decrease the viscosity of the aged binder, while rejuvenating agents restore the balance between maltenes and asphaltenes that has been disrupted by the aging process. Oxidation causes the maltenes in the asphalt cement to convert to asphaltenes, resulting in pavement that is dry, brittle, and hard. By restoring this balance, rejuvenating agents enhance the ductile, cohesive, and adhesive properties of the recycled binder. Rejuvenators are an effective means of mitigating the effects of aging in RAP binders.

There are three main types of rejuvenators:

- Petroleum-Based
- Bio-Based
- Chemical

Table 2-1 provides an overview of these families.

Table 2-1 Families of Rejuvenators; Source, Performance, Cost and Environmental Impact

Rejuvenator	Source	Performance	Cost	Environmental Impact
Petroleum-based	Fossil Fuels	Restores viscosity, ductility, durability and resistance to cracking	Often more widely available and consistent in quality	Higher carbon footprint compared to other options
Bio-Based	Plant bases such as vegetable oils	Effective in softening aged binders, improving flexibility, and reducing brittleness.	Cost-effective, but availability and production scale influence pricing	Lower carbon footprint compared to petroleum-based options.
Chemical Based	Engineered additives including polymers and surfactants	Improve properties like moisture resistance, flexibility, and (Verified Market Reports 2025) cohesion between aged and new binders.	More expensive due to specialized formulations	Varies depending on composition

Despite extensive research, consensus on rejuvenation mechanisms is limited. It is known that rejuvenators soften aged asphalt binder by targeting asphaltenes. The variety of rejuvenators and unclear mechanisms hinder specification acceptance (Bhatt 2025).

Determining the correct amount of rejuvenator for RAP is challenging: too much causes rutting; too little fails to restore properties. Proper blending ensures rejuvenator penetration into the RAP binder. Ideally, rejuvenator and virgin binder blend with RAP binder, but improper application leads to coating without blending (black rock).

The Asphalt Institute recommends using a recycled asphalt blending chart to determine the optimal mix of RAP and virgin binder for desired performance. Most designs assume complete blending, but partial blending can soften the virgin binder and cause rutting. Diffusion blending and mechanical stirring are essential.

While lab studies show improved RAP performance with rejuvenators, field studies yield mixed results due to differences in rejuvenators, mixing, and laydown methods. Field studies typically last 2 years or less, so long-term performance is not well documented (Bhatt 2025).

In summary, rejuvenators have potential, but further research is needed to optimize performance and establish standards. Long-term studies are crucial to assess RAP with rejuvenators.

CHAPTER 3. IDEAL CRACKING TEST FOR ASPHALT MIX DESIGN, CONTROL AND QUALITY ASSURANCE

3.1. Background

The Ideal Cracking Test (IDEAL-CT) evaluates the cracking resistance of asphalt mixtures in balanced mix designs (Zhoum 2017). It is particularly useful for assessing recycled asphalt mixes, determining if they retain resistance to fatigue, reflective, and thermal cracking. The IDEAL-CT ensures that higher recycled content does not lead to brittle mixes, maintaining the durability of the asphalt.

3.2. CT_{index} Review

A strong correlation has been observed between the Texas Overlay test, the Illinois Flexibility Index test, and the IDEAL-CT. The IDEAL-CT is easier to perform and exhibits a lower Coefficient of Variation compared to the other tests. Correlations with field tests, including the Federal Highway Administration (FHWA) Long Term Pavement Performance SPS 10 warm mix test results, the FHWA Accelerated Loading Facility, numerous in-service pavements in Texas, and the NCAT test track, have demonstrated strong relationships (Zhoum 2017).

The IDEAL-CT evaluates cracking resistance through the Cracking Tolerance Index, a parameter based on fracture mechanics. This index considers failure energy, post-peak slope of the load-displacement curve, and deformation tolerance at 75% of the peak load (ASTM 2019). IDEAL-CT values greater than 80 indicate good cracking resistance, values between 50 and 80 suggest moderate cracking resistance, and values below 50 predict premature cracking. Factors influencing IDEAL-CT values include asphalt mix composition, binder type and content, aggregate gradation, RAP content, environmental conditions, traffic loading, pavement structure, and compaction techniques. While states like Texas, Oklahoma, and Alabama focus on high temperature and heavy-truck traffic, northern states such as Maine and Minnesota are more concerned with cold temperature cracking. Consequently, states with colder winter temperatures tend to set higher values than more temperate states. However, specific values related to average temperature ranges have not been explicitly defined (Zhou 2019).

NCAT Report 23-02 evaluated six IDEAL-CT testing devices for compliance with ASTM D8225-19 and compared their results. A total of 328 tests were conducted on 280 specimens, with seven test results discarded as outliers. Previous work indicated that two machines were considered equivalent if "the entire 90% confidence interval for the difference estimate between two devices was less than 20% of the average CT_{index}" (Moore 2023). Data processing employed manufacturer-provided software without correction. All but two testing apparatus met the requirements of ASTM D8225-19. The Humboldt 5125 and Cox & Sons 9500 exhibited inconsistent data sampling frequencies and deformation rates. Nevertheless, the study concluded that all devices, except Device #5, provided equivalent results. Consequently, Humboldt, Instron Inc., and Pine modified their equipment to improve performance (Moore 2023).

Readers are directed to NCHRP IDEA Project 195 and ASTM D8225-19 for detailed information related to the test.

3.3. Normalized Air Voids Adjustment

ASTM D8225 is sensitive to the void content and dimensions of asphalt concrete specimens. The test requires a thickness of 62 ± 1 mm and air voids content of $7 \pm 0.5\%$. While laboratory specimens easily meet these dimensions, achieving the correct air voids content is challenging (Montanez, 2023).

Montanez et al. developed correction factors for sample diameter and air void variation to calibrate field samples. They noted that significant differences between corrected field cores and lab specimens suggest a need for new CT-index criteria.

- The TC Model accurately predicted thermal cracking levels.
- Fundamental mixture properties determined by IDT testing did not predict thermal cracking.
- Creep compliance and temperature shift factors correlated well with thermal cracking development at five MnRoad cells.

CHAPTER 4. IDEAL-CT TESTING

4.1. Testing

Conducting the IDEAL-CT testing on this project addresses the notion that the CT_{index} could be used as a specification to ensure RAP mixes would perform well in Alaska's cold climate. This would provide input regarding the amount of RAP that can be used in the mix. In addition, it allowed the efficacy of rejuvenating agents in RAP mixes. The test matrix, as shown in Table 4-1, was developed to answer those question.

Table 4-1: IDEAL-CT Test Matrix

PG Grade	%RAP	Rejuvenator	PG Grade	%RAP	Rejuvenator
PG 52 - 28	0	N/A	PG 52 -40	0	N/A
		N/A			N/A
	25	None		25	None
		RO			RO
		DS			DS
	35	None		35	None
		RO			RO
		DS			DS
	50	None		50	None
		RO			RO
		DS			DS

As noted earlier, increasing RAP content tends to reduce rutting due to plastic deformation. However, once the RAP content exceeds 25%, fatigue and thermal cracking tends to increase. Thermal cracking is a primary concern in Alaska.

Samples were prepared with an asphalt content 5% by weight and a target voids of 7% as required by the test method. The 5% asphalt content was based on an existing mix design for the aggregate source. Screening the plus 1-inch RAP significantly improved the uniformity of the voids. However, it was very difficult to maintain $7\% \pm 0.5\%$ when adding RAP. The mix was prepared at $7\% \pm 1\%$ using the correction factor developed by Montanez et al. for the voids applied This improved the coefficient of variation.

Rejuvenators were added to the binder at 3 % of the weight of the RAP as specified by the supplier.

Testing was performed on the InstronTek Smart Loader using the software provided by InstronTek. The Smart Loader proved to be easy to use. The software provided ingested the data produced by the Smart Loader and produced a report which included the input data, intermediate computations and the CT_{index} . Figures 4-1a and 4-1b show the Smart Loader and the resulting report. Table 4-2 provides a summary of the test data.



Ideal CT Cracking Tolerance Index	
Project ID:	Specimen ID: 52-28-15C1
Date / Time: 11/11/2016 13:13	Stability (Peak Load): 7.3 kN
Specimen Diameter: 150.0 mm	CT Strength: 515.4 kPa
Specimen Thickness: 82.0 mm	Peak Displacement: 3.3 mm
Starting Load: 0.01 kN	Flow (0.254 mm units): 14.9
Stopping Load: 0.10 kN	Work of Failure: 48.7 Joules
Max Specific Gravity: 2.46	Strain Energy to Peak: 17.98 Joules
% AC: 4.7	Failure Energy: 4916.2 Joules/m²
% AC: 1.0	Temperature: 25 °C
Preparation Method:	Aging Condition:
Medium Type: 4.0	Average Speed: 49.8 mm/min
Displacement at 25%: 4.7 mm	IDEAL CT Index: 124.1
Post-Peak Slope (25%): 1798.77 N/mm	
Project ID:	Specimen ID: 52-28-15C2
Date / Time: 11/11/2016 13:16	Stability (Peak Load): 8.2 kN
Specimen Diameter: 150.0 mm	CT Strength: 560.0 kPa
Specimen Thickness: 82.0 mm	Peak Displacement: 3.7 mm
Starting Load: 0.01 kN	Flow (0.254 mm units): 14.4
Stopping Load: 0.10 kN	Work of Failure: 44.8 Joules
Max Specific Gravity: 2.46	Strain Energy to Peak: 19.27 Joules
% AC: 4.5	Failure Energy: 5066.8 Joules/m²
% AC: 6.0	Temperature: 25 °C
Preparation Method:	Aging Condition:
Medium Type: 4.0	Average Speed: 49.3 mm/min
Displacement at 25%: 4.9 mm	IDEAL CT Index: 107.1
Post-Peak Slope (25%): 1381.305 N/mm	
Project ID:	Specimen ID: 52-28-15C3
Date / Time: 11/11/2016 13:19	Stability (Peak Load): 7.3 kN
Specimen Diameter: 150.0 mm	CT Strength: 498.8 kPa
Specimen Thickness: 82.0 mm	Peak Displacement: 3.3 mm
Starting Load: 0.01 kN	Flow (0.254 mm units): 14.0
Stopping Load: 0.10 kN	Work of Failure: 48.1 Joules
Max Specific Gravity: 2.46	Strain Energy to Peak: 18.30 Joules
% AC: 4.5	Failure Energy: 4902.2 Joules/m²
% AC: 1.0	Temperature: 25 °C
Preparation Method:	Aging Condition:
Medium Type: 4.0	Average Speed: 49.3 mm/min
Displacement at 25%: 4.9 mm	IDEAL CT Index: 105.0
Post-Peak Slope (25%): 1242.004 N/mm	
Technician: _____ Signature: _____	
IscanPDF Inc. Total Label Access V 2.0.0 www.iscanpdf.com	

Figure 4-1: Testing equipment and sample report produced.

Table 4-2: Summary of IDEAL CT Test Data

Asphalt Grade	% RAP	Average Voids	Rejuvenator	Computed CT _{index}	Corrected Ct _{index}	COV
PG52-28	0	7.1	none	118.8	110.7	7
	25	7	None	137.6	139.3	27.7
	35	7.2	None	170.1	160.1	9.6
	50	7.2	None	129.5	125.4	34.6
PG52-28	25	6.4	DS	91.4	70.9	37.3
	35	7.2	DS	120.2	113.7	17.3
	50	7.3	DS	147	144.7	16.4
PG52-28	25	6.4	RO	104.5	82.8	27.7
	35	7.1	RO	105	96.8	39.9
	50	7.1	RO	105.7	95.8	10.4
PG52-40	0	7	None	175.6	161	30.6
	25	6.8	None	216.4	193.6	13.2
	35	7	None	214.7	193.6	8.1
	50	7	None	175.6	161	30.6
PG52-40	25	6.8	DS	107.2	110.3	24.5
	35	7.5	DS	157.8	159.7	12.7
	50	7	DS	140.3	128.1	16.4

Asphalt Grade	% RAP	Average Voids	Rejuvenator	Computed CT _{index}	Corrected Ct _{index}	COV
PG52- 40	25	6.5	RO	102.2	81.3	34
	35	7.3	RO	155.3	161.2	16.4
	50	6.6	RO	161.3	133.2	22

4.2. Discussion of the Data

Figure 4-2 shows that PG52-40 increases the CT_{index} compared to PG52-28. A higher CT_{index} indicates greater resistance to cracking, suggesting that PG52-40 provides a more crack-resistant mix. The figure also shows the CT_{index} increasing with RAP content up to 35%, then decreasing. Initially, this seems contrary to the idea that more RAP increases cracking potential. There are four potential causes.

- Asphalt demand
- Activation of RAP binder
- Stiffness of the blended binder
- There is uncoated aggregate that is not accounted for.

When the combined asphalt content exceeds the designed asphalt content, the crack both the CT_{index} and the creep compliance are expected to increase.

Any deviation from the anticipated percentage of RAP binder that is activated during the blending process. It is unlikely that 100% of the RAP binder will be activated. If the percentage of the RAP binder that is activated is less than the anticipated activation, the stiffness increases. Conversely, if it is greater than anticipated, the stiffness will decrease.

Determining the binder stiffness of the blended binder requires expensive, time-consuming testing. As a result, these tests are generally not performed. Instead, the designer will either rely on experience or test the RAP mix. If the blended binder is stiffer than expected, the stiffness will increase.

Finally, if there is uncoated aggregate that is not accounted for, the mix will be stiffer than expected.

In this case, we can expect the percentage RAP binder to remain constant, and the uncoated aggregate was observed to be near zero. So only an excess of binder and the stiffness of the RAP binder are at play. It appears that the amount of blended binder controls until the RAP content exceeds 35%. At that point the stiffness of the RAP binder appears to overwhelm the excess asphalt. Estimation of excess asphalt will be discussed in Chapter 6.

Literature consistently indicates that RAP improves rut resistance. Liu et al. confirmed that Alaskan RAP mixes show increased rut resistance with higher RAP content (Liu et al. 2016). Thus, it's unlikely that excess asphalt from black rock significantly raises rutting potential.

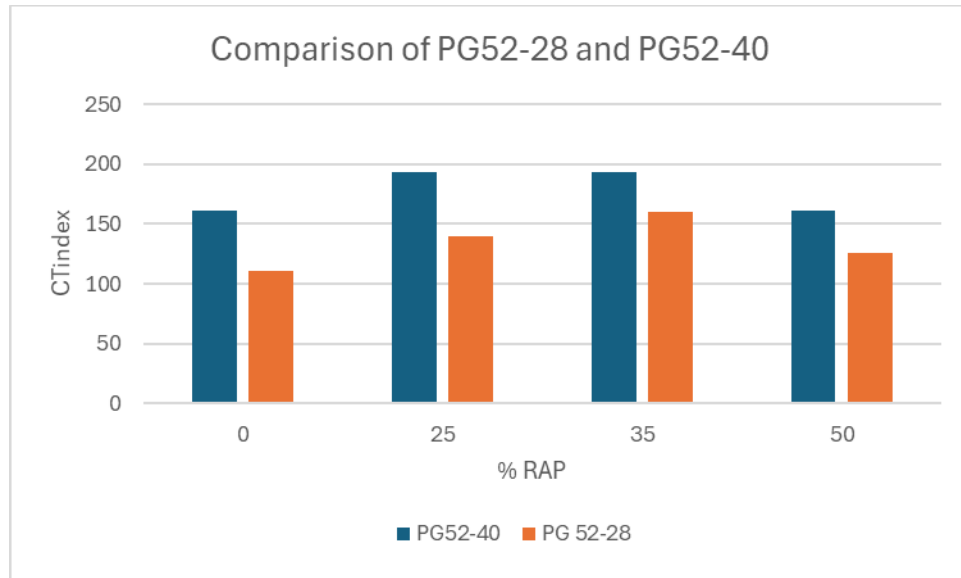


Figure 4-2: Inclusion of RAP tends to increase the CTIndex for both grades of asphalt below 35% RAP

The impact of adding rejuvenators proved to be ambiguous. Generally, both rejuvenators appeared to have a more significant effect on the PG52-40 asphalt mixture. Both rejuvenators seemed to decrease the CT_{index} for mixtures by 25% and 35% RAP, while having minimal effect on the 50% RAP mixture.

This outcome was contrary to expectations, which predicted that the rejuvenators would enhance the CTIndex. A plausible explanation is that the rejuvenator facilitated the blending of virgin asphalt with the aged asphalt coating the aggregate, thereby increasing the asphalt demand and consequently decreasing the CTIndex. This raises the question of whether a specific mix design should be developed for each combination of RAP and rejuvenator. As noted earlier, the literature supports this concept.

Many states use a minimum CTIndex value of 80, while some northern states require higher values. The appropriate value for cold regions remains unclear. Data suggests that PG52-28 can achieve a CT_{index} of 100, while PG52-40 can reach 150, indicating that PG52-40 provides a more crack-resistant mix. Additionally, RAP mixes with virgin PG52-40 are more crack-resistant with or without rejuvenators.

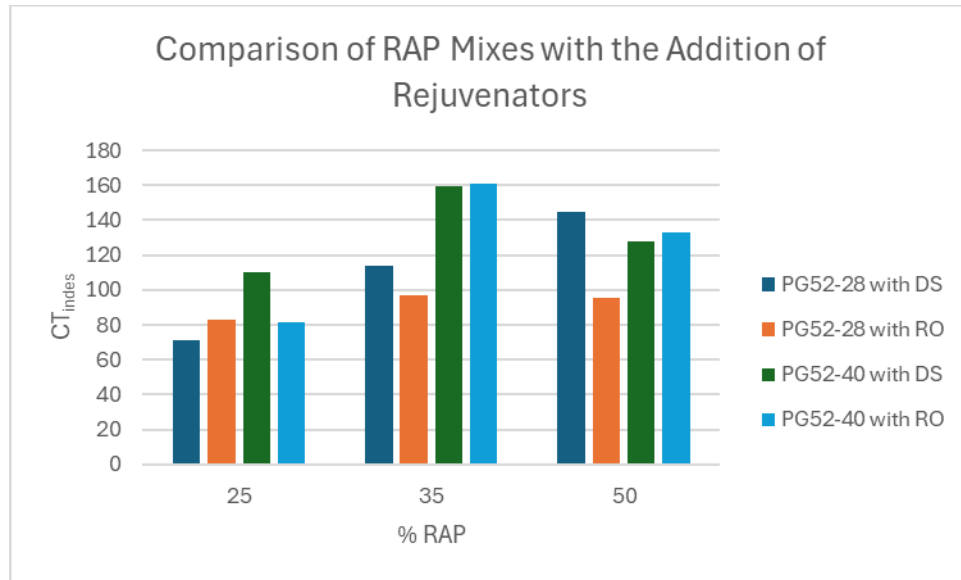


Figure 4-3: Inclusion of the rejuvenators tend to reduce the CTindex for PG52-28 when compared to RAP mixes without rejuvenators.

CHAPTER 5. CREEP COMPLIANCE

5.1. Background

The Creep Compliance test, AASHTO T 322-07 (2020), evaluates the time-dependent behavior of asphalt under sustained loading at various temperatures. The objective is to assess the ability of the asphalt mix to resist permanent deformation in pavements. This test is crucial for optimizing asphalt mixtures to enhance pavement longevity and performance. Creep compliance provides valuable insights into long-term deformation and viscoelastic properties, making it useful for several purposes:

Rutting Resistance: Creep compliance evaluates an asphalt mix's ability to resist permanent deformation, particularly under high temperatures and heavy traffic loads (Law PCS 2001).

Thermal Cracking Analysis: In cold climates, asphalt can develop cracks due to thermal stress. Creep compliance testing predicts how well asphalt can relax these stresses before cracking occurs (Law PCS 2001).

Material Selection and Mix Design: Engineers utilize creep compliance data to optimize asphalt mixtures, ensuring a balance of stiffness and flexibility appropriate for different environmental and traffic conditions (Law PCS 2001).

Long-Term Pavement Performance: By incorporating creep compliance into pavement models, designers can predict road behavior over time, leading to improved maintenance strategies and longer-lasting infrastructure (Law PCS 2001).

Creep compliance is used to predict thermal cracking in asphalt pavements in cold regions. This is done using three methods.

Stress Relaxation Analysis: Asphalt contracts as temperatures drop, generating internal stresses. Creep compliance quantifies the material's ability to relax these stresses over time, reducing the likelihood of cracking.

Fracture Mechanics Integration: Many thermal cracking models incorporate creep compliance to estimate the material's resistance to fracture under low-temperature conditions. The **AASHTO T322 test** is commonly used to measure creep compliance for this purpose (Jeong 2005).

Time-Temperature Superposition: Engineers use creep compliance master curves to predict how asphalt behaves at different temperatures. This assessment helps determine cracking susceptibility across seasonal variations (Jeong 2005).

Research at the University of Minnesota integrated creep compliance into the MEPDG models to predict thermal cracking by comparing measured and predicted fracture energy. This indicated how creep compliance influences crack formation (Marasteanu 2009).

MnRoad employed the Superpave IDT test to assess thermal cracking in asphalt pavements, demonstrating strong agreement between predicted and observed cracking patterns. This study validated the effectiveness of creep compliance in forecasting pavement performance (Waldhoff 1999).

5.2. Testing and Analysis

Samples for creep compliance were prepared according to AASHTO T 322-07 (2020). The samples were compacted using a Pine Gyratory Compactor with 5% virgin asphalt, targeting 7% air voids. This method aligns with the specimen preparation for the IDEAL CT. Asphalt grades PG52-28 and PG52-40 were tested. For the RAP, PG52-28 was used as the virgin asphalt, with material larger than $\frac{3}{4}$ inch removed. Creep compliance tests were conducted with RAP contents of 0%, 25%, 35%, and 50%. Testing temperatures for PG52-28 were 0°C, -10°C, and -20°C, while PG52-40 was tested at -10°C, -20°C, and -30°C, in accordance with AASHTO T 322-07 (2020). The testing was performed using the COX & Sons load frame and environmental chamber.

The asphalt content of 3.9 % of dry aggregate was used based on DOT&PF practices.

Analysis was conducted using the LTSTRESS Excel spreadsheet developed by Don Christensen of Advanced Asphalt Technologies, LLC. Due to the large volume of graphs, they are compiled in Appendix A for convenience.

A comparison of creep compliance between PG52-28 and PG52-40 indicates that PG52-40 exhibits higher creep compliance, which is consistent with expectations (Refer to Figure 5-1). This finding aligns with the CTindex results (Refer to Figure 4-2), validating that both tests indicate PG52-40 is more resistant to cracking than PG52-28.

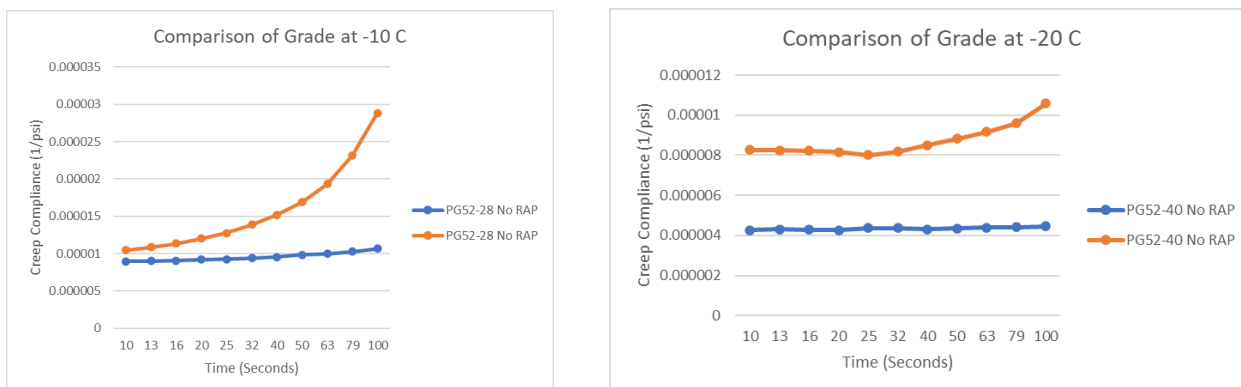


Figure 5-1 Comparison PG52-28 and PG58-40 at -10oC and -20oC

5.2.1. PG52-28 Test Results

Figure 5-2 shows that creep compliance for PG52-28 increases with temperature regardless of RAP content. The -30°C data at 35% RAP seems flawed and should be disregarded. Generally, higher RAP content should decrease creep compliance, but anomalies were noted: at 0°C and -10°C, 50% RAP showed higher compliance than 35% RAP and No RAP, respectively. At -20°C, 50% RAP exceeded No RAP compliance, while 35% RAP was lower. These trends align with the CTindex.

The unexpected results might be due to the black rock coating reducing asphalt demand and aged asphalt in voids hardening the mixture. Current methods cannot quantify these effects. Figure 5-2 confirm this phenomenon, showing increased stiffness with 35% RAP and decreased stiffness at 50% RAP, possibly due to higher overall asphalt content and the increasing impact of the aged binder.

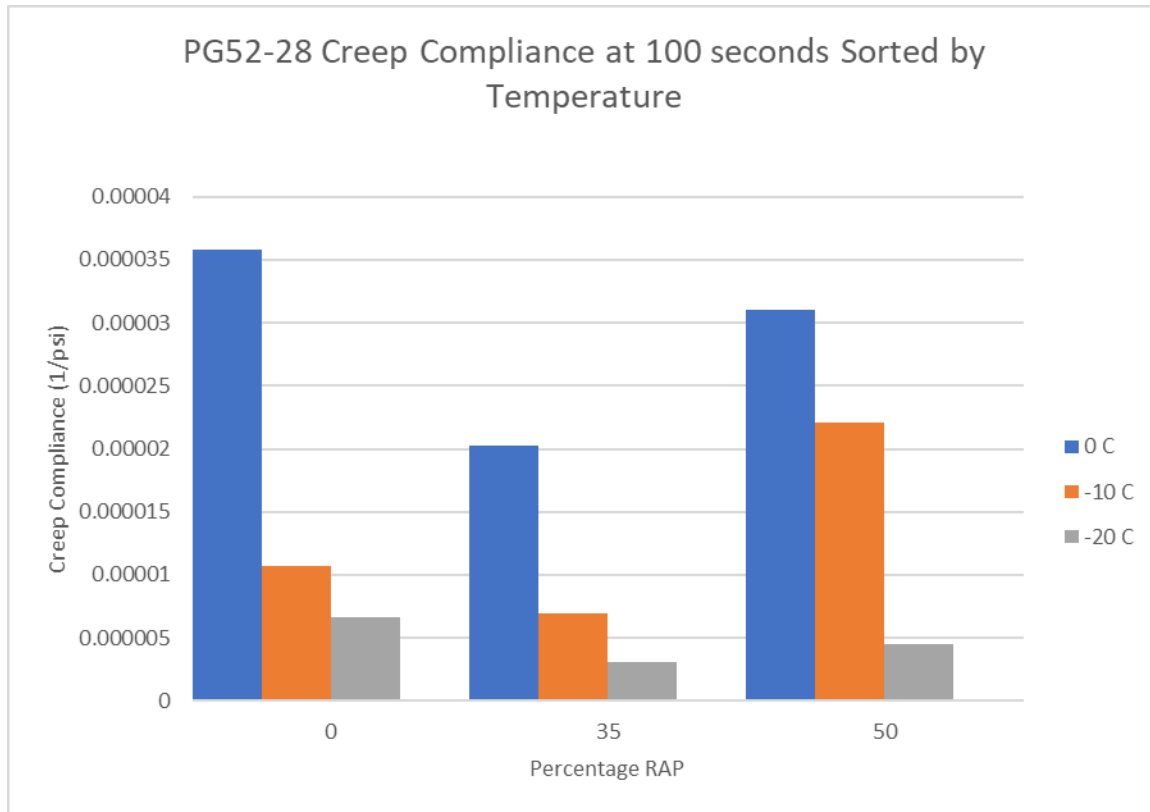


Figure 5-2 Summary of Creep Compliance at 100 seconds for various percentages of RAP at three temperatures.

5.3. PG52-40 Test Results

Figures 5-3 and 5-4 show the results of the creep compliance for PG52-40 and sorted by percent RAP (Figure 5-3) and by temperature (Figure 5-4). Figure 5-3 shows that the creep compliance at 0°C has the highest creep compliance. The difference between creep compliance at -20°C and -30°C for when no RAP is incorporated into the mix. However, when the creep compliance curves are sorted by % RAP, the relationships are unexpected. The differences between the curves are much smaller than for the PG52-28 but the order becomes unpredictable.

Again, plotting the creep compliance at 100 seconds provides some clarity. The mix is optimized for a RAP content of 25%. The creep compliance is higher at 0°C for all RAP contents which is counter to what is considered normal. However, at lower temperatures mixes containing higher than 25% RAP show a lower creep compliance. This is likely due to the interaction between the asphalt content, RAP binder activation and the effects of the aged binder. This interaction will be discussed later.

As shown in Figures 5-5, the addition of the two rejuvenators tested resulted in a decrease in the CT_{index} .

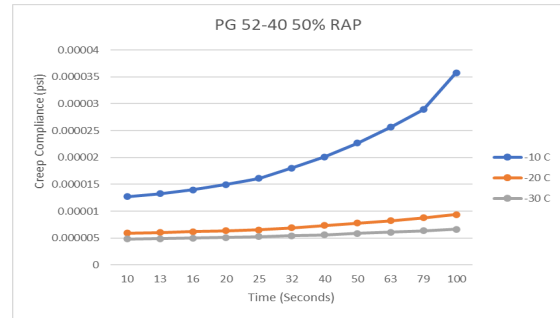
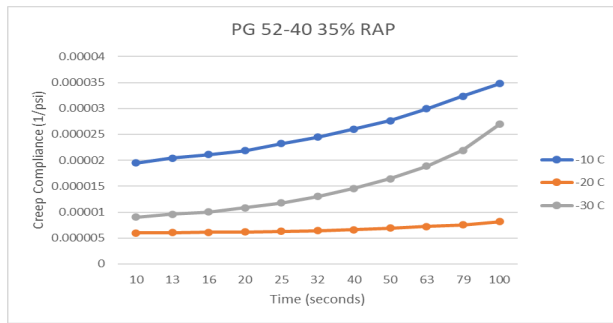
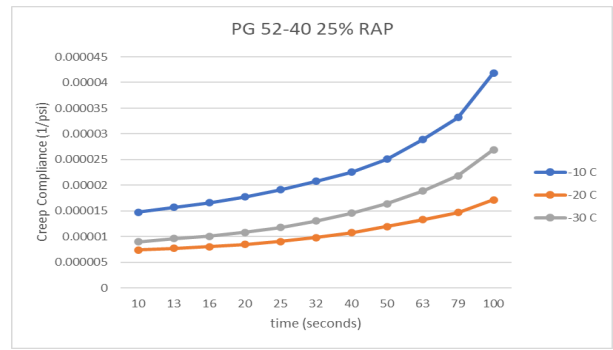
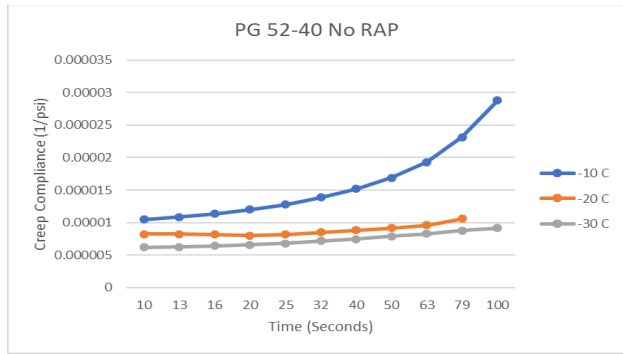


Figure 5-3 Comparison of PG52-40 with No RAP, 25, 35, and 50% RAP

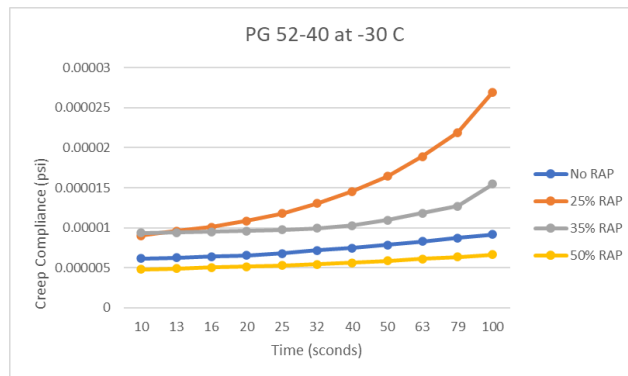
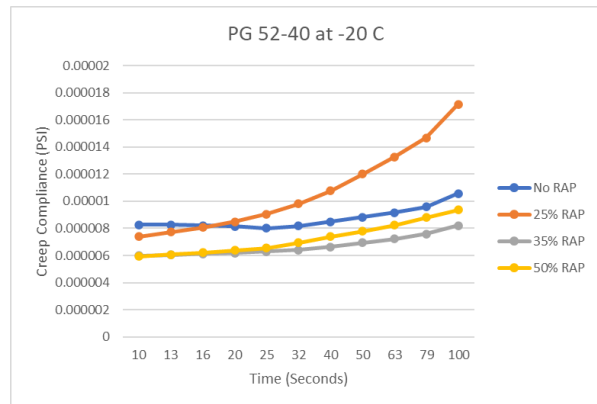
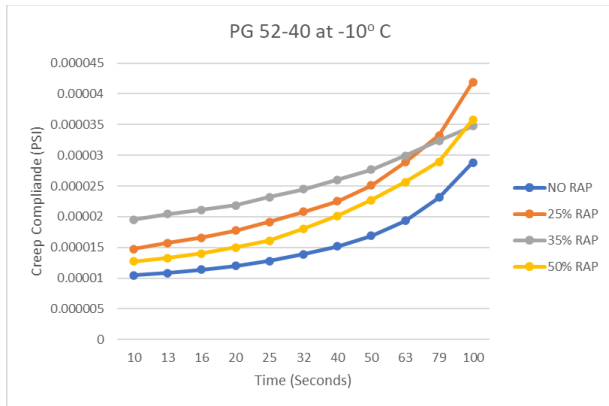


Figure 5-4 Comparison of Creep Compliance of PG52-28 at 0oC, -10oC, and -20oC

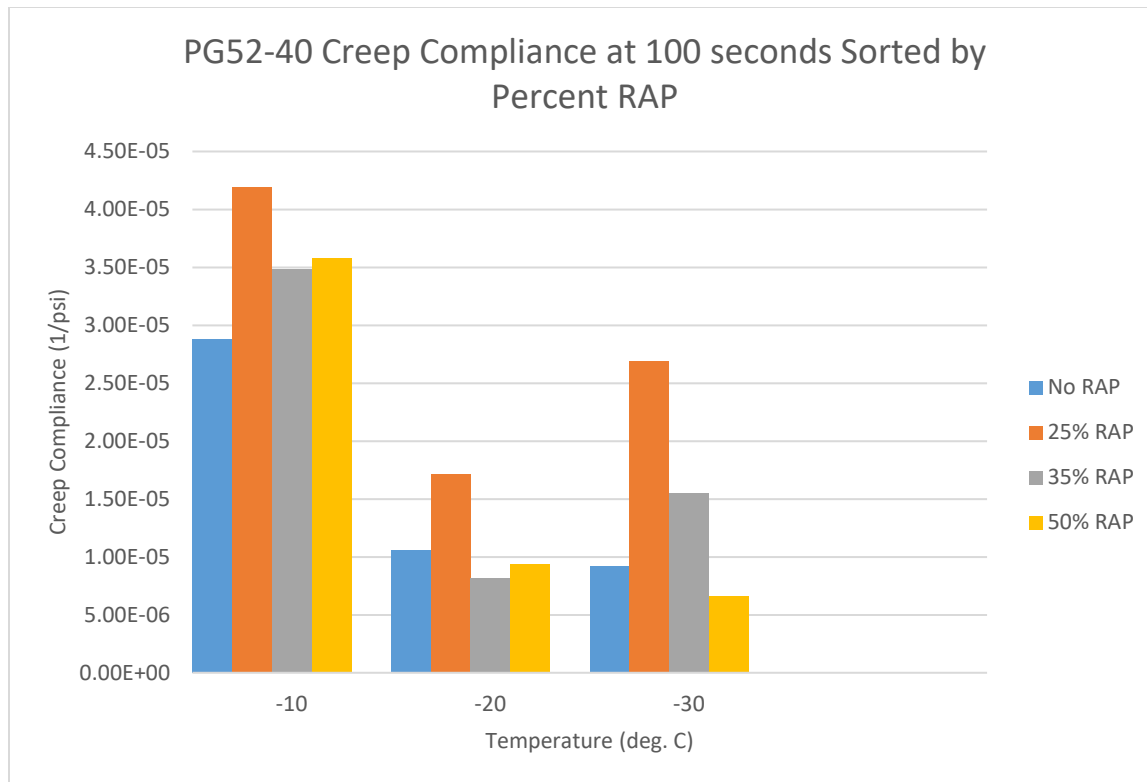


Figure 5-5 PG52-40 Creep Compliance at 100 Seconds Sorted by RAP Content.

CHAPTER 6. DISCUSSION OF FINDINGS

This study investigates how RAP content affects recycled asphalt's thermal cracking. Liu (2016) found that higher RAP content increases mix stiffness, as indicated by creep compliance and dynamic modulus tests. This finding aligns with other research. Both CTindex and Creep Compliance tests measure asphalt mixture stiffness to predict crack resistance, where lower values suggest stiffer mixes and lower crack resistance.

The IDEAL CT test is effective for predicting crack resistance at a single temperature and is quick to run, making it suitable for mix design processes. In contrast, the creep compliance test can predict crack resistance at cold temperatures but is complex and data-intensive, making it more appropriate for detailed analyses rather than routine use.

6.1. Comparison of PG52-28 and PG52-40 with No RAP

Both test methods indicate that PG52-40 has greater resistance to cracking. The creep compliance shows PG52-40 performs better in cold temperatures. Between -10 and -20°C, the change in creep compliance for PG52-28 is 6.2E-6, while for PG52-40, it is 1.82E-5, indicating PG52-40 is much less temperature sensitive.

Liu et al. (2016) reported the critical temperature for a Northern Region PG 52-28 mix to be -23.3 and a PG52-40 mix to be 41.9. These results confirm PG52-40 is a good choice in the colder regions of the state.

6.2. Performance of Recycled Asphalt Pavement Mixes

Conventional wisdom suggests that the inclusion of Reclaimed Asphalt Pavement (RAP) results in a stiffer mix with reduced tolerance to low temperature cracking. However, the findings of this study contradict that assumption. As illustrated in Figure 4-2, the integration of 35% RAP into a PG52-28 mix slightly increases the CT_{index}, indicating that these mixes will likely exhibit crack resistance properties similar to those of virgin mixes.

In contrast, Figure 5-2 predicts a decrease in creep compliance with the addition of 35% RAP. Notably, at a 50% RAP content, there is an observed increase in creep compliance over 35% RAP, although it remains lower than a mix without RAP. This trend holds true for 0 and -10 C. However, at -20 C the trend is shows the highest creep compliance is for the no RAP case and minimum for the 50% RAP as expected.

The performance of the PG52-40 mix varies. According to Figure 4-2, the CTindex increases with RAP content up to 35%, but decreases at 50% RAP, yet remains comparable to the mix without RAP. Figure 5-5 indicates that the optimal RAP content is 25%, beyond which the creep compliance significantly drops. Liu et al. (2016) found that the critical temperature for RAP contents up to 35% did not significantly differ from the no RAP mix for both PG52-28 and PG52-40.

The reasons behind the behavior of RAP mixes are not entirely clear, likely due to the total asphalt demand and the interaction between virgin asphalt cement and recycled asphalt cement. The Department of Transportation & Public Facilities (DOT&PF) practice involves adding 3.9% virgin asphalt

cement based on dry aggregate, including RAP. If virgin asphalt mix requires 5.2 % asphalt, a RAP mix based on the same mix design can be expected to have 5.2% asphalt content. However, not all of the RAP binder contributes to the performance of the mix. For example, if the aged binder coating the RAP aggregate (black rock) is simply coated by the virgin binder, the RAP coating is not actively contributing to the performance of the mix. However, the RAP binder in the void's blends with it. For dense graded mixes, typically 60-70%. This binder will likely be activated during the mixing process. Only the portion of the RAP binder that has been activated can be considered as part of the total asphalt content. The percentage of new binder can be estimated using the following equation.

$$P_{new} = P_{total} - A \left(\frac{\%RAP \times P_{RAP}}{100} \right) \quad \text{EQ 1}$$

Where

P_{new} = the percentage of new asphalt binder

P_{total} = the total binder required

A = the decimal portion of the aged asphalt binder activated. Typically between 60 and 100%.

%RAP = the percentage of RAP incorporated into the mix

P_{RAP} = the percentage of binder in the RAP

Figure 6-1 shows the new binder required for a total binder of 5.2% and 5.0% binder contained in the RAP at varying RAP content and percentage of the RAP binder activated.

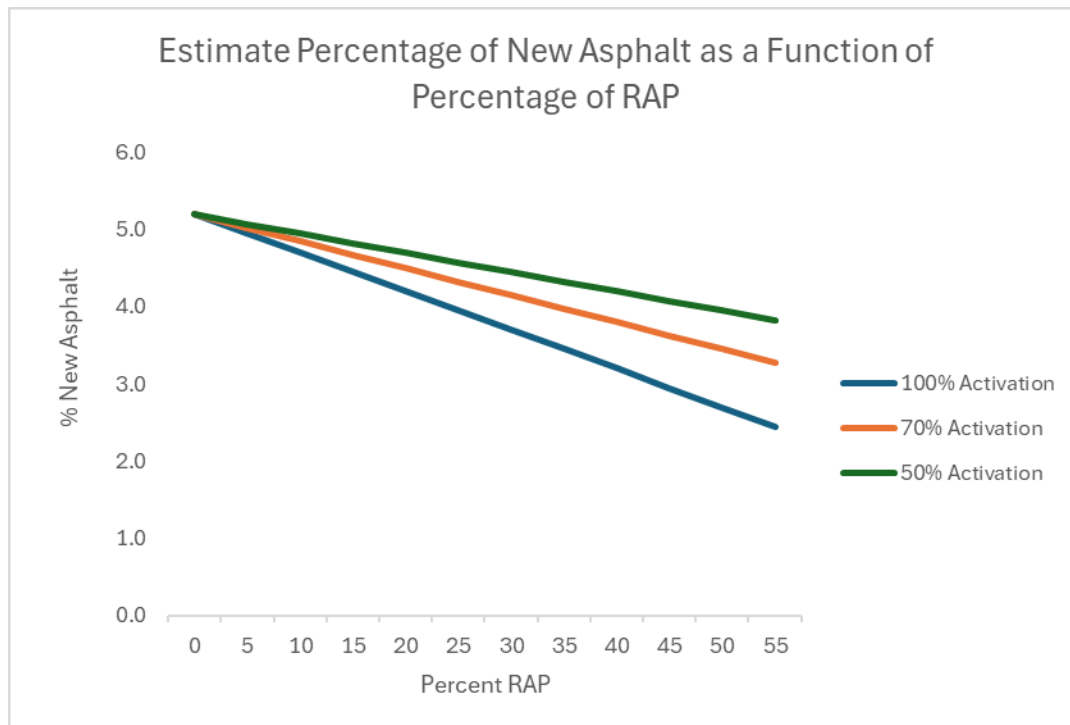


Figure 6-1 Estimated new binder required for a total binder content of 5.2 % and a RAP binder content of 5.0%.

Note that as the binder content increases, the new binder content decreases. However, as the RAP binder activated decreases, the new binder required increases. Thus, if the new binder is kept at a constant as was the case in this study, the test results will capture the impact of deviation from the optimum total desirable binder content. Thus, if the total active binder content is too low, a low crack resistance can be expected. If the total active binder is too high, we can expect to see a higher crack resistance. Note that the deviation in binder content will also affect rutting and fatigue characteristics.

This example demonstrates the impact of varying RAP content once the virgin asphalt content is set. For a mix design with 5.2% total asphalt content, using 20% RAP with 100% binder activation establishes new asphalt required to 4.2%. At 25% RAP, new asphalt drops to 4.0%, leaving a 0.2% surplus, increasing CTindex and creep compliance. Assuming only 70% binder activation in the voids, 20% RAP results in a new asphalt binder demand of 4.5%, creating a 0.3% deficit, which lowers CTindex and creep compliance.

Liu et al. (2016) and Liu et al. (2024) found that higher RAP content increases mix stiffness, as indicated by creep compliance and dynamic modulus tests. This finding aligns with other research. Both CTindex and Creep Compliance tests measure asphalt mixture stiffness to predict crack resistance, where lower values suggest stiffer mixes and lower crack resistance. This is consistent with Equation 1.

The IDEAL CT test is effective for predicting crack resistance at a single temperature and is quick to run, making it suitable for mix design processes. In contrast, the creep compliance test can predict crack resistance at cold temperatures but is complex and data-intensive, making it more appropriate for detailed analyses rather than routine use.

6.3. Rejuvenators

Two rejuvenators were used, noted as DS and RO, in this study. The amount added followed the supplier's recommendations and was mixed with virgin asphalt cement. Both rejuvenators were added to the mix at a rate of 3% by weight of RAP, the amount suggested by the supplier.

DS reverses the effects of oxidation. The supplier claims the binder is softened for workability but later stiffens for durability. Tests data suggests that 50% RAP that has been treated with DS shows performance similar to virgin asphalt.

Information related to RO is not readily available.

Some literature suggests adding rejuvenators directly to RAP to react with aged asphalt before blending with virgin asphalt, though this increases costs. Notably, the chosen rejuvenators were more effective with RAP plus PG52-40 binder.

The exact cause of the rejuvenator performance in CTindex is unclear, as Bhatt (2025) noted that rejuvenator performance is highly variable. Finding the right type and amount requires significant effort. The two products did not perform as expected, but a comprehensive testing program might have identified the correct application rate or a product that improves RAP mix performance.

Rejuvenators may impact the asphalt demand by altering the percentage of RAP binder activated especially if they soften the aged asphalt. The impact can be estimated using Equation 1. The percentage of the activated asphalt binder will take additional work.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

It is widely believed that the inclusion of Reclaimed Asphalt Pavement (RAP) results in asphalt concrete that is stiffer and less crack-resistant compared to those made with virgin asphalt cement. However, data from this effort, Liu et al. (2016) and other studies (Law PCS 2001) indicate that RAP mixes can be equivalent to or superior to virgin mixes in resisting rutting. Data from this study includes the binder characterization, however, Liu et al. (2024) suggests that even though up to 25% RAP can produce a mix with similar properties as virgin mix, this does not guarantee the RAP mix will be crack resistant throughout its life. As Bhatt (2005) points out, there are few studies that track the performance of recycled asphalt pavement for more than two years.

The creep compliance and IDEAL-CT tests predict crack resistance but show different trends due to their differing methodologies. Creep compliance measures the mix's relaxation rate under constant stress at cold temperatures, while IDEAL-CT assesses specimen failure rate under increasing load at room temperature. Despite suggesting higher resistance with higher values, creep compliance is complex and impractical for routine mix design. On the other hand, IDEAL-CT is practical for mix-design protocols, with a recommended minimum CTindex of 80, and potentially higher minimums in colder climates, such as 100 for Alaska.

At this point, neither the IDEAL CT nor the creep compliance can estimate the percentage of RAP in the mix. As noted in the discussion related to Equation 1, the impact of increasing the test results can be due to the impact on the asphalt demand as the RAP changes and/or due to the percentage of the RAP binder being activated. However, the use of Equation 1 can help determine which of the two are at play.

Data derived from both the creep compliance and the IDEAL-CT tests indicate an increased likelihood of cracking potential above 25% RAP, consistent with the findings of Liu et al. (2016) and Liu (2024). Alaska's mix design procedures set virgin asphalt at 3.9%, assuming 15% RAP, which is the maximum allowed. However, test results suggest this may not be suitable for all RAP contents. This approach was adopted for this project. It is probable that a full mix design for each RAP content will yield different results.

The rejuvenators in this study significantly reduced the CTindex. However, optimizing the virgin asphalt and rejuvenator content or modifying the introduction method could improve performance.

The use of a constant 3.9% virgin asphalt in RAP is questionable since as shown in Figure 6-1, the percentage of virgin asphalt is a function of the total asphalt required, the percentage of the RAP asphalt activated. The variability in the test results for RAP contents above 25% are likely influenced by this practice. Further, it is likely that this constant was developed for 15 -25 % RAP and subsequently applied universally.

In summary, the use of RAP will generally improve the rutting resistance of the mix. In most cases, up to 25% RAP in the mix will likely not increase low temperature cracking in the short term, but there is a possibility the long-term cracking resistance may be affected.

The results of both rejuvenators provided for this project resulted in a significant decrease in the CT_{index}. The reasons are unclear since the rejuvenators were expected to reduce the hardness of the RAP binder

and/or increase the activation of the RAB binder. The determination of the causes for the decrease in CTindex would require an effort outside the scope of this project. As discussed by Bhatt (2005) the selection of and the dosage of rejuvenators requires considerable effort using a battery of tests to achieve the desired results. Even then the field performance is not guaranteed.

7.2. Recommendations

Based on the conclusions of this study and those developed by Liu (2016) the following recommendations are suggested.

- Using the IDEAL CT test method in mix design helps ensure RAP matches or improves mix performance. This should be added to existing mix design protocols. While most states use a value of 80 as a minimum, a minimum value of 100 is suggested for PG52-28 and 140 for PG52-40. Additional testing will be required to confirm these values.
- Equation 1 may be used to estimate the virgin asphalt binder added to the RAP mix. The resulting mix should be validated through testing, including the IDEAL CT.
- The predictive equations provided by (Lui et al. 2024) provide potentially provide a means of estimating the quantity of RAP in a mix. Using that data, a variance of Equation 1 can be developed. It may also be possible to develop equations that combine the impacts of RAP content, percentage of RAP binder activated, blended binder stiffness and uncoated aggregate into a single equation.
- Develop mix design protocols for anticipated RAP contents to meet or exceed the performance of mixes without RAP, limiting the maximum RAP content to 25% until protocols are proven.
- Implement controls for consistent RAP content. Consider fractionating the RAP pile into course and fine stockpiles to improve control of the mix. As shown in Figure 6-1, variance in the asphalt demand will have an impact on the crack resistance of the mix.
- Rejuvenators require considerable care and cannot be assumed to be helpful in improving the performance of a RAP mix. Consequently, they should not be used without proper testing and evaluation. These processes are outlined in Bhatt (2005)

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APPENDIX A

Impact of RAP Material on Cracking Resistance of Alaskan Asphalt Mixes

Final Report

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DISCLAIMER

This report presents the perspectives and understandings of the author, who bears responsibility for the factual content and the accuracy of the data included. Moreover, this report should not be considered as an official standard, specification, or regulation.

Appendix: TABLE of CONTENTS

DISCLAIMER.....	B
ABSTRACT.....	F
CHAPTER 1.0 INTRODUCTION	G
1.1 Problem Statement.....	G
1.2 Background	G
1.3 Objectives	H
1.4 Research Methodology.....	H
CHAPTER 2.0 EXPERIMENTAL DETAILS	J
2.1 Loose Mixture Fabrication	J
2.2 Extraction of Asphalt Binder	K
2.3 Recovery of Asphalt Binder	L
2.4 Binder Characterization	M
2.4.1 Bending Beam Rheometer Test.....	N
2.4.2 Dynamic Shear Rheometer Tests	P
2.4.2.1 Frequency Sweep Test	P
2.4.2.2 Master Curve Construction	R
2.4.2.3 Multi Stress Creep Recovery Test	S
CHAPTER 3.0 DATA RESULTS AND ANALYSIS	U
3.1 Characterization of the Binder Linear Viscoelastic Properties	U
3.1.1 Complex Modulus Master Curve.....	U
3.1.2 Critical Parameters Derived from Linear Viscoelastic (LVE) Properties	X
3.2 Permanent Deformation Resistance	Z
3.3 Thermal Cracking Resistance	DD
3.4 Performance Grading	GG
3.5 RAP Content Prediction	HH
3.5.1 Predictive Model Development	HH
3.5.2 Step-by-Step Procedure to Backcalculate RAP Content.....	KK
CHAPTER 4.0 CONCLUSIONS AND RECOMMENDATIONS	LL
REFERENCES	MM

LIST OF FIGURES

Figure 2.1. 25% RAP loose mixture.	J
Figure 2.2. Empty and filled bowl of extraction.	K
Figure 2.3. Extractor machine.	L
Figure 2.3. Separator centrifuge for aggregate fines.	M
Figure 2.4. Rotary evaporator.	M
Figure 2.6. RTFO machine.	O
Figure 2.7. PAV machine and degassing process.	O
Figure 2.8. BBR test procedure.	P
Figure 2.9. DSR machine and different specimens.	Q
Figure 2.10. Components of complex modulus.	R
Figure 3.1. Master Curves of original binders at 25 °C.	U
Figure 3.2. Master Curves of original binders at reference temperature of 25 °C.	V
Figure 3.3. Master curves of short-term aged binders at reference temperature of 25 °C.	W
Figure 3.4. Master Curves of long-term aged binders at reference temperature of 25 °C.	X
Figure 3.5. Crossover frequency-rheological index black space.	Y
Figure 3.6. Black Space diagram with Glover-Rowe damage zonas.	Z
Figure 3.7. Recovery percent at 100 Pa.	AA
Figure 3.8. Recovery percent at 3200 Pa.	AA
Figure 3.9. J_{nr} at 100 Pa.	BB
Figure 3.10. J_{nr} at 3200 Pa.	CC
Figure 3.11. J_{nr} diff of all specimens.	CC
Figure 3.12. Stiffness modulus (MPa) of all specimens.	FF
Figure 3.13. m-values of all specimens.	FF
Figure 3.14. Comparison of critical temperatures determined by m-value and Stiffness with the corresponding ΔT_c	GG
Figure 3.15. High PG grading fitting line.	II
Figure 3.16. J_{nr} diff fitting line after short-term aging.	II
Figure 3.17. Stiffness modulus fitting line.	JJ
Figure 3.18. Critical temperature fitting line.	JJ

LIST OF TABLES

Table 2.1. Testing Plan	N
Table 3.1. Summary of the MSCR Test.....	DD
Table 3.2. Stiffness modulus (MPa) of all specimens.....	EE
Table 3.3. m-values of all specimens	EE
Table 3.4. Summary of Performance Grading of the Tested Binders	HH
Table 3.5. Summary of predictive models	KK

ABSTRACT

This research evaluates the impact of Reclaimed Asphalt Pavement (RAP) on binder performance. An Alaskan PG 52E-40 binder along with the binder extracted and recovered from mixtures containing 25% RAP and 100% RAP were systematically examined with a series of rheological tests. The tests included the frequency sweep test with Dynamic Shear Rheometer (DSR), the high-temperature Multiple Stress Creep Recovery (MSCR) test, and the low-temperature Bending Beam Rheometer (BBR) test. Multiple parameters derived from the testing results, such as the Glover-Rowe parameter, the ΔT_c parameter, and the non-recoverable creep compliance (J_{nr}), were applied to evaluate the binders' cracking and rutting resistance at different temperatures and aging levels. The testing results suggested that incorporating RAP did not dramatically affect the binder performance at high and intermediate temperatures; however, according to the BBR tests, the critical low-temperature cracking temperatures increased from -40 °C for the neat PG 52E-40 binder to -30 °C with the binder with 25% RAP. As the BBR test only evaluate binder performance within the linear viscoelastic range, further cracking tests at low temperatures were recommended to confirm the findings. A predictive model to estimate the RAP content in a given mixture was also developed in this study. A step-by-step procedure was provided, and the method can be applied to backcalculate the RAP content in a loose mixture sample during quality assurance.

CHAPTER 1.0 INTRODUCTION

1.1 Problem Statement

State highway agencies acknowledge the environmental and economic advantages of incorporating Reclaimed Asphalt Pavement (RAP) into asphalt mixes. In Alaska, the current statewide Hot Mix Asphalt (HMA) highway specification permits up to 15% RAP in the road pavement wearing course and 25% RAP in the binder or base course layer(s). Though these percentages are considerably lower compared to those allowed in other states, compromised fatigue and low temperature performances were reported when the RAP content was higher. Research is needed to develop a method to determine the maximum allowable amount of RAP that can be incorporated in Alaskan asphalt mixes without degrading their key cold temperature performance. A better understanding of recycled binder availability and its impact on performance will support the greater use of RAP material and minimize the risk of premature failure.

1.2 Background

The global yearly production of asphalt mix for paving exceeds one billion tons. As flexible pavements require large amounts of aggregates and asphalt binders, there's an incentive to use alternative materials for sustainable pavement construction (Behnood 2019). RAP stands as a widely adopted practice in the United States, holding the top rank among recycled materials used in pavement construction (Hansen et al. 2013, Zhang et al. 2019). Incorporating RAP not only utilizes waste material effectively but also reduces the need for new, virgin material, resulting in significant cost savings. Additionally, the usage of RAP decreased reliance on virgin material contributes to a reduced environmental footprint and energy savings (Feih et al. 2011, Farooq et al. 2017).

Between 2011 and 2021, the collective production of hot and warm mix asphalts in the USA and Europe amounted to nearly 390 and 290 million tons, respectively, with a noteworthy portion of this volume being attributed to the incorporation of RAP (A.E.A.P. 2021). Between 2009 and 2016, the total amount of RAP used in HMA and Warm Mix Asphalt (WMA) in the United States increased from 56 million tons to 76.9 million tons, representing substantial growth. During this period, the national average percentage of RAP in asphalt mixtures also steadily rose from 15.6% to 20.5%, resulting annual savings of over \$2 billion (Hansen et al. 2015, Zhang et al. 2019). Moreover, in the United States, the annual production of RAP through resurfacing and widening has reached an estimated 100 million tons, with hot recycling of RAP being the predominant asphalt recycling method worldwide (Williams et al. 2020, Liu et al. 2021).

It becomes evident that understanding the properties of asphalt binders is crucial in pavement research. To conduct tests on these properties, particularly in pavement applications, which include degree of blending (Xing et al. 2023) and assessments of rutting, fatigue, and thermal cracking resistance (Mollamohammadi et al. 2023), it is necessary to extract the binder from the aggregate mix. This extraction is pivotal for analysis and to ensure that the asphalt binder is suitable for various pavement applications (Huet 1988).

Integrating RAP into new asphalt mixtures leads to changes in the mixture's characteristics. Key elements influencing the performance of RAP mixtures include: the nature of the mixture; the consistency of the mix containing RAP; the uniformity of the RAP itself; the methods used for incorporating RAP; the percentages of RAP included; and the type and application of rejuvenating agents

(Antunes et al. 2019). The amount of RAP content is particularly significant as it directly impacts the mixture's durability, environmental benefits, and cost-effectiveness, making its optimal determination a crucial aspect of asphalt mixture design.

A critical research gap exists in the development of a methodology to establish the maximum allowable RAP content without compromising their low-temperature performance. While state highway agencies in Alaska acknowledge the environmental and economic advantages of RAP use, the current RAP content restrictions in their specifications are notably more conservative than those in other states due to reported issues with fatigue and low-temperature performance as RAP content increases. Addressing this knowledge gap is essential for optimizing the utilization of RAP in Alaskan road construction, ensuring pavement durability and sustainability. Additionally, exploring the potential of rejuvenating agents to enhance cracking resistance and investigating their ability to facilitate the use of higher RAP percentages in Alaskan mixtures while maintaining the required low-temperature performance can advance the understanding and practical integration of RAP in the state's highway construction practices.

This report is organized into distinct sections, commencing with the background segment. Following the background section, the methodology portion delineates the research approach, encompassing data collection methods, procedures, and any experimental arrangements. Subsequent to the methodology section, the results section offers the study's discoveries and results, often represented through data, visuals, and analysis. Lastly, the discussion section critically interprets these findings, delves into their consequences, and imparts insights into the research's significance, constraints, and potential avenues for future research.

1.3 Objectives

The objective of this study is to investigate the impact of RAP and rejuvenators on cracking performance of Alaskan HMA materials containing RAP and develop a method to estimate RAP content for a given mix containing RAP material.

1.4 Research Methodology

The following tasks were conducted to achieve the objective of this study:

Materials Collection: A testing plan with different binders and mixtures with RAP was formulated. The target binder and other components were acquired with the assistance of Alaska Department of Transportation and Public Facilities (ADOT&PF).

Characterization of Asphalt Binder with RAP: A series of recovered binder tests were conducted under this task to investigate impact of RAP on performance of Alaskan HMA materials containing RAP, as detailed in Chapter 2. The tests included the frequency sweep test with Dynamic Shear Rheometer (DSR), the high-temperature Multiple Stress Creep Recovery (MSCR) test, and the low-temperature Bending Beam Rheometer (BBR) test.

Data Processing and Analyses: Laboratory data were processed and analyzed, and statistical analysis was conducted to investigate the effects of RAP and rejuvenators on cracking resistance of Alaskan asphalt mixes.

Draft of Final Report and Recommendations: As presented in this document, the report included the experimental details, test procedures and results, and findings. Recommendations for the use of RAP and rejuvenators were provided.

CHAPTER 2.0 EXPERIMENTAL DETAILS

This chapter details the experimental procedures of virgin PG 52E-40 binder and its RAP derivation i.e., 25% RAP-recovered binder and 100% RAP-recovered binder. The fabrication of the mixtures adheres to the Job Mix Formula (JMF), followed by an aging process. The extraction process for the asphalt binder from these mixtures involves the use of Trichloroethylene (TCE), focusing on separating the binder for subsequent analysis. The subsequent recovery of the asphalt binder is carried out to ensure its purity and suitability for testing and practical applications. Various tests are conducted to characterize these binders, assessing their behavior under different conditions. These tests include the DSR for evaluating high-temperature properties, the BBR for low-temperature performance, and additional aging simulation tests like the Rolling Thin-Film Oven (RTFO) and Pressure Aging Vessel (PAV) aging conditioning.

2.1 Loose Mixture Fabrication

The laboratory-engineered mixtures with 25% of RAP content were fabricated in adherence to the JMF. Each aggregate gradation was measured and subjected to a 165°C oven for a duration of 2 hours. Similarly, the asphalt binder underwent a 2-hour heating process at 165°C to attain the required workability. The RAP followed a heating procedure, first at 65°C for 24 hours and then in a separate oven at 110°C for an additional 1 hour, aligning with standard RAP processing guidelines. The three pivotal components—aggregate, binder, and RAP—were blended using a commercial-grade mixer. Subsequently, the resulting loose asphalt mix underwent an extended 4-hour period in the oven at 135°C to emulate short-term aging. Following the aging process, the loose mix was evenly spread on the sheath for further evaluation and analysis (Figure 2.1).



Figure 2.1. 25% RAP loose mixture.

2.2 Extraction of Asphalt Binder

The first phase of the extraction procedure commences by loading a metal pan or bowl with a blend of materials, which could be either a composite mixture or RAP. Within the context of this specific investigation, the binders from the 25% RAP mixture and 100% RAP were examined (see Figure 2.2). Subsequently, TCE is introduced to the mixtures, ensuring complete filling of the bowl (see Figure 2.3). Following the introduction of TCE, a 60 ± 5 -minute waiting period was used to allow the TCE to effectively dissolve the binder within the RAP.

Once the waiting period elapses, the centrifuge extractor is initiated, gradually escalating to a maximum speed of 3600 rpm until all solutions are completely emptied from the centrifuge bowl. The process is then repeated for a second cycle, involving the use of approximately 1000 ml of TCE, refilling the centrifuge bowl. The extractor is restarted with the same speed and procedural steps, ensuring the thorough extraction of the asphalt binder from the mixture or RAP. This procedure, including the waiting time, TCE addition, and centrifuge operation, is related to achieving comprehensive asphalt binder extraction for subsequent testing and analysis.

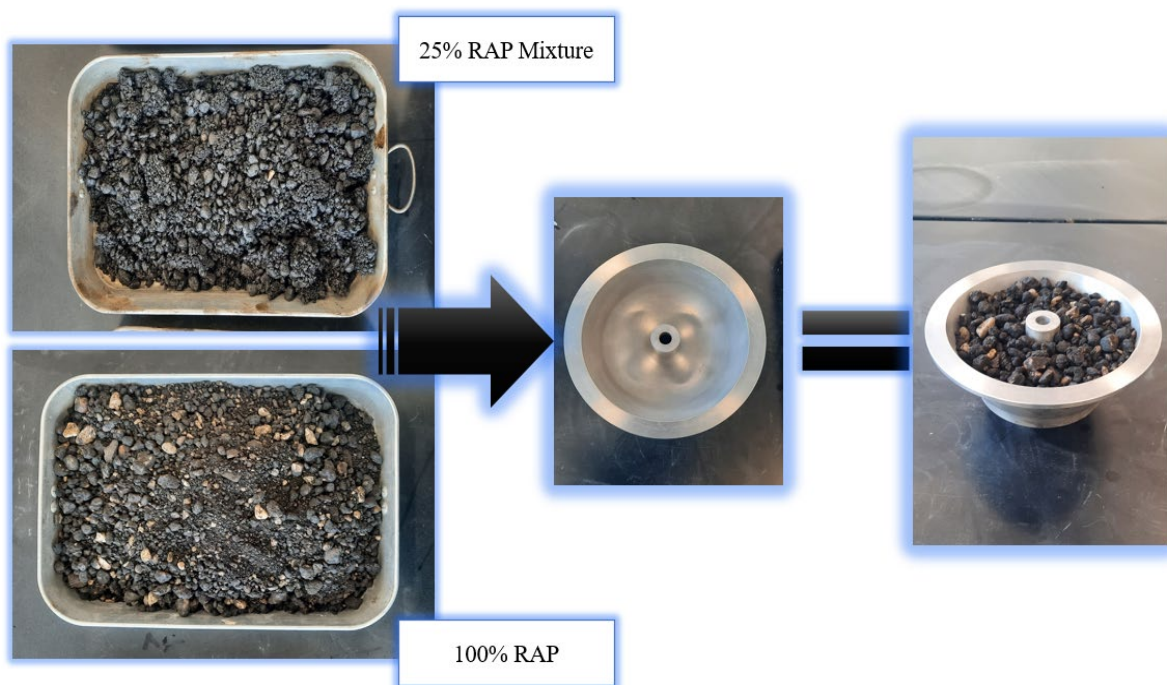


Figure 2.2. Empty and filled bowl of extraction.

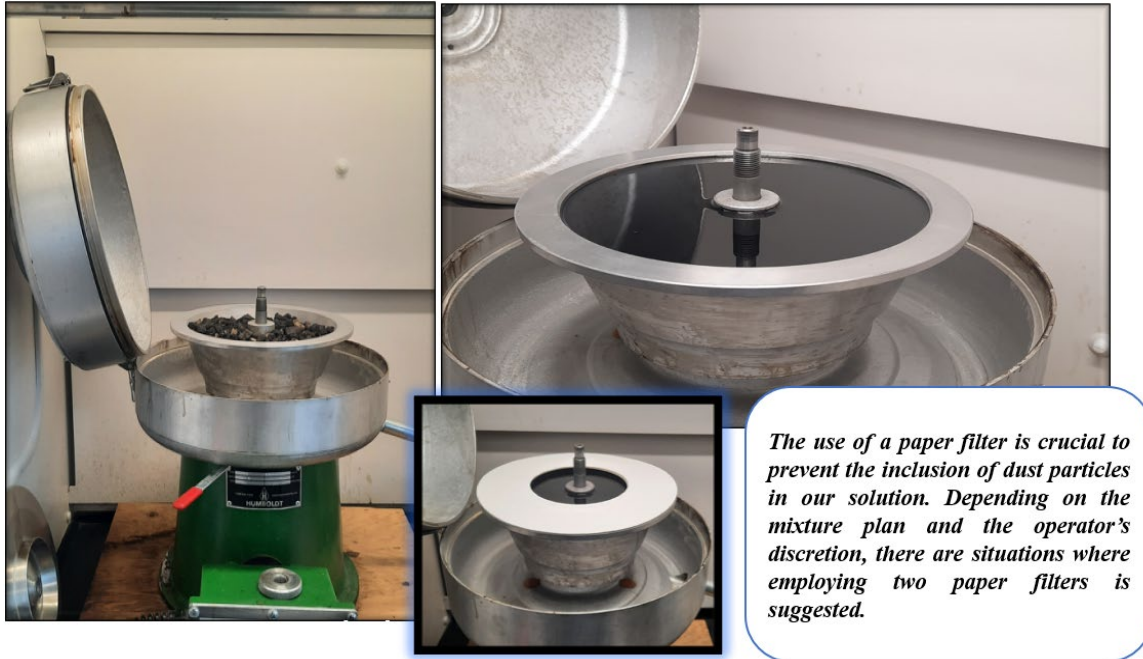


Figure 2.3. Extractor machine.

2.3 Recovery of Asphalt Binder

Following the extraction phase, the recovered asphalt binder undergoes additional processing for purification and concentration. Employing filters has the potential to minimize dust to zero; however, in cases of elevated dust levels, the concentrated asphalt binder solution undergoes centrifugation to separate out aggregate fines (Figure 2.4). Subsequently, the resultant solution undergoes a conclusive distillation process to eradicate any lingering traces of the solvent. This distillation process involves gradually increasing the temperature in a rotary evaporator, controlling vacuum levels, and carefully transferring the solution to ensure no foaming or back pressure (Figure 2.5).

The distilled asphalt binder is collected, and the procedure concludes with transferring the recovered binder into Teflon bottles for further centrifugation. After this centrifugation step, the asphalt solution is transferred to a clean rotational evaporating flask for a final distillation to remove any remaining solvent. The purified and recovered asphalt binder is then ready for immediate use in testing or can be reheated for further applications, adhering to specified temperature ranges and safety measures throughout the entire process.

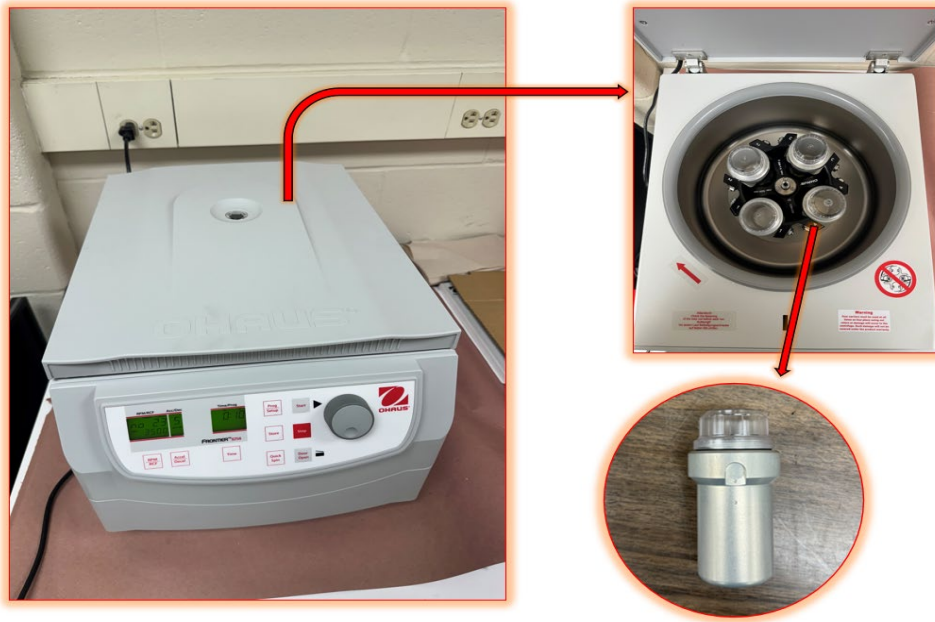


Figure 2.3. Separator centrifuge for aggregate fines.

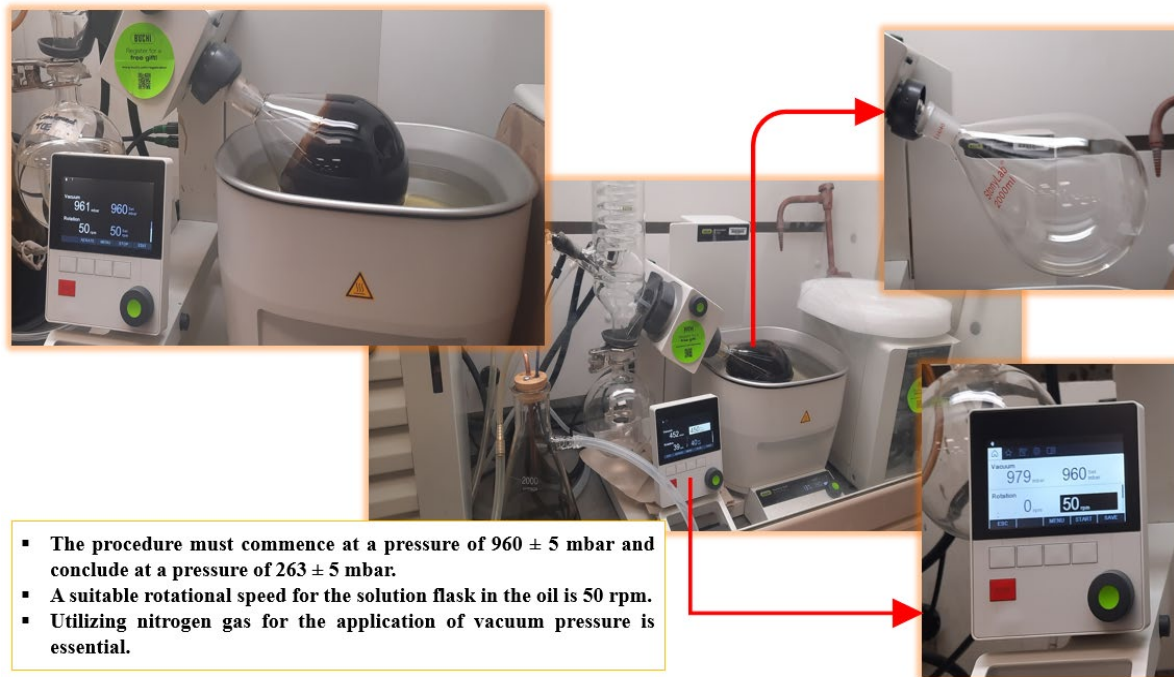


Figure 2.4. Rotary evaporator.

2.4 Binder Characterization

Table 2.1 offers a detailed summary of the binder-testing plan, developed through collaborative discussions with engineers from ADOT&PF. The assessment of these binders was conducted through a comprehensive and multifaceted methodology. Initially, the DSR played a role in examining the high-temperature characteristics of the binders. The analysis included an assessment of their viscoelastic

behavior, the establishment of a master curve, and the evaluation of rutting potential utilizing the MSCR method. Furthermore, to appraise the binders' performance under low-temperature conditions, the study incorporated the BBR test. By combining both high and low-temperature evaluations, the study aimed to present a view of the binders' performance spectrum.

Table 2.1. Testing Plan

Test	Properties	Parameters	Aging	Standard	Equipment
Frequency Sweep	Viscoelastic Behavior	Master curve (G^* and δ); Black space diagram; Glover-Rowe Parameter; R-value	Unaged/STA/LTA	AASHTO T 315 DSR	
DSR	Rutting	Rutting parameter ($G^*/\sin\delta$)	STA	AASHTO T 315 DSR	
MSCR	Rutting	J_{nr} ; Percent recovery (R%)	STA	AASHTO T 350 DSR	
BBR	Thermal Cracking	S; m-value; Delta Tc	LTA	AASHTO T 313 BBR	

2.4.1 Bending Beam Rheometer Test

Following AASHTO T 313 specifications, the BBR test, as illustrated in Figure 2.8, was employed to assess the stiffness characteristics of three type of asphalt binders, i.e., the neat PG 52E-40 binder, 25% RAP-recovered binder and 100% RAP-recovered binder. The BBR test involves subjecting a small beam of the binder to a constant creep load, and subsequently measuring the resulting deflection. To examine aging conditions, specimens were created for each binder. All specimens underwent aging via the RTFO (Figure 2.6) and PAV (Figure 2.7) methods. Four temperatures were selected, aligning with the anticipated lowest pavement service temperatures. For each temperature, three sample beams were prepared and appropriately aged through their respective methods. Application of simple beam theory enables the calculation of creep stiffness (S) and the creep rate (m-value), representing the rate of stiffness change over time. The testing standard outlined in AASHTO M 320 specifies that the measured S value at 60 seconds must be below 300 MPa, and the m-value at this loading time should be a minimum of 0.3 for compliance with binder requirements.

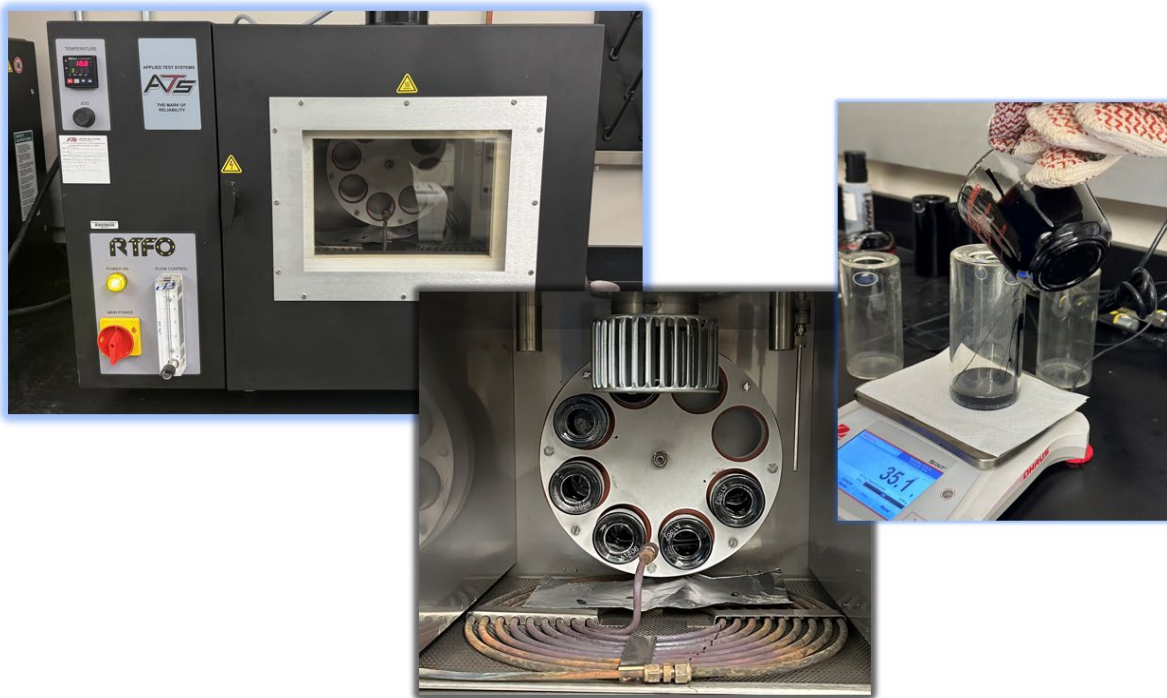


Figure 2.6. RTFO machine.

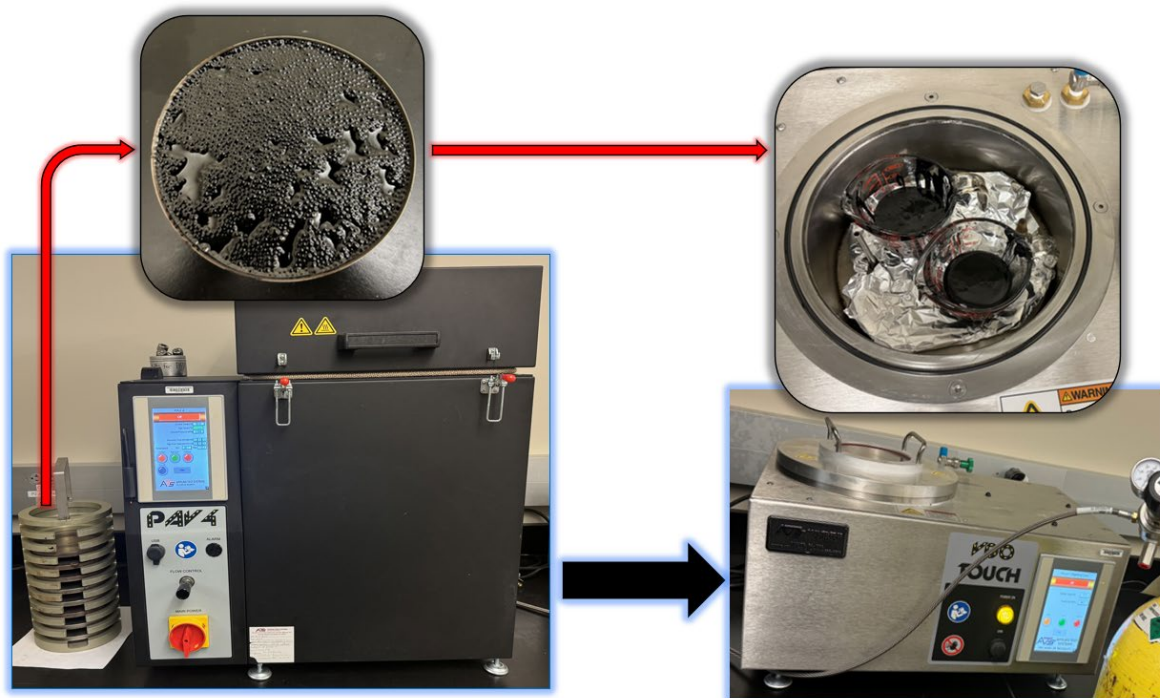


Figure 2.7. PAV machine and degassing process.

In the BBR test, the ΔT_c parameter has been developed to evaluate the low-temperature cracking potential of asphalt binders. It represents the difference between the critical cracking temperature and the binder's continuous grade temperature, calculated from the stiffness and m-value data obtained in the BBR test.



Figure 2.8. BBR test procedure.

2.4.2 Dynamic Shear Rheometer Tests

The DSR test, conducted in accordance with ASTM D7643 and AASHTO T 315 standards (Figure 2.9), was employed to assess the rheological behaviors of three asphalt binders—PG 52E-40, 25% RAP-recovered binder, and 100% RAP-recovered binder. During the DSR test, a thin film of the binder specimen was positioned between two plates of the DSR device. The lower plate remained fixed, while torque was applied to the upper plate at a frequency of 10 radians per second. The resultant torque and shearing strain, measured by the DSR test, contributed to the computation of complex modulus (G^*) and phase angle (δ). The binder master curve for G^* and δ was developed, capturing values at various high with a reference temperature of 25°C.

2.4.2.1 Frequency Sweep Test

In the analysis of the asphalt binders, a set of specimens was subjected to DSR testing for each binder under investigation. Within this set, three specimens were specifically designated as constituents of the virgin binder group, representing the baseline characteristics of the binders in their pristine state. Concurrently, the remaining three specimens from each binder category underwent a short-term or long-term aging process. In this study, for the base PG 52E-44 binder and the binder extracted from 100% RAP, the aging process was conducted using the regular RTFO and PAV procedures since both

binders are considered as virgin material. As for the binder extracted from loose mixtures with 25% RAP, since the binder has gone through the mixing and short-term oven aging process, the extracted binder was considered as short-term aged, and only PAV conditioning was applied if long-term aging is needed.

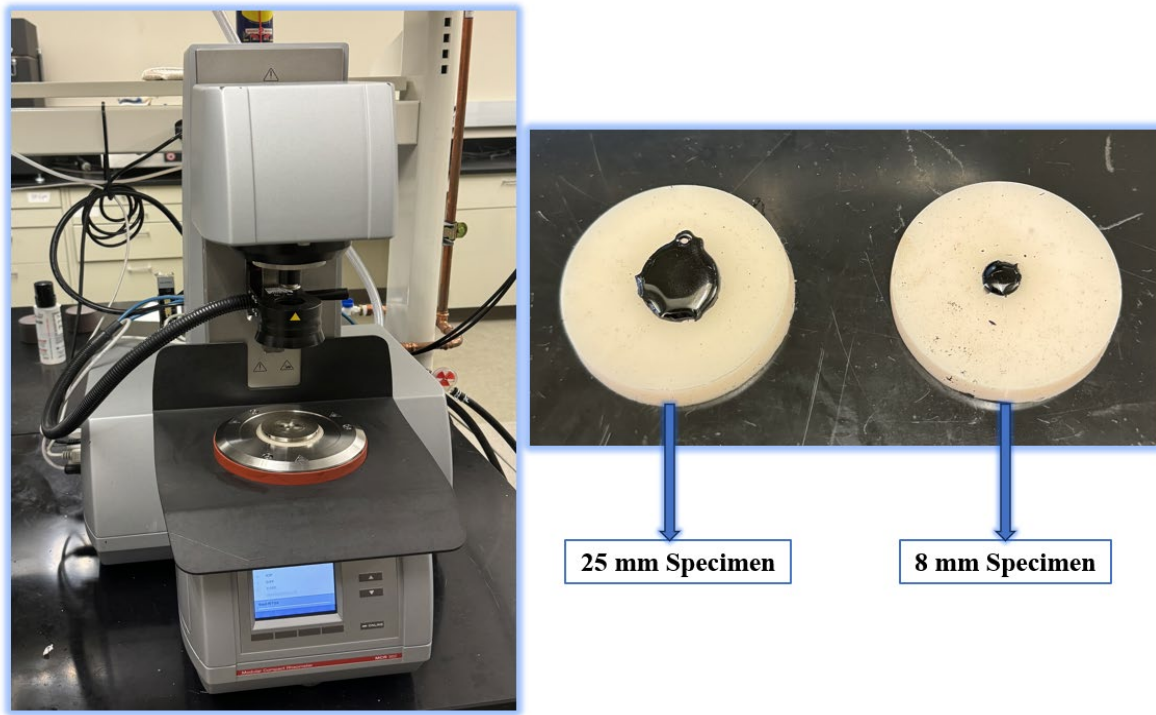


Figure 2.9. DSR machine and different specimens.

In the PG system, the DSR test addresses asphalt's viscoelastic behavior. It characterizes how asphalt behaves at medium to high temperatures. The DSR test determines complex modulus (G^*) and phase angle (δ), where G^* includes both the elastic (G') and viscous (G'') components. The phase angle δ represents the viscoelastic nature of asphalt. If δ is close to 0° , it signifies predominantly elastic behavior while if δ is close to 90° , it indicates predominantly viscous behavior. For asphalt, δ typically falls within the range of 0 - 90° , illustrating its viscoelastic properties (Figure 2.10). The obtained complex modulus and phase angle are also used to determine the performance grade of the tested binders.

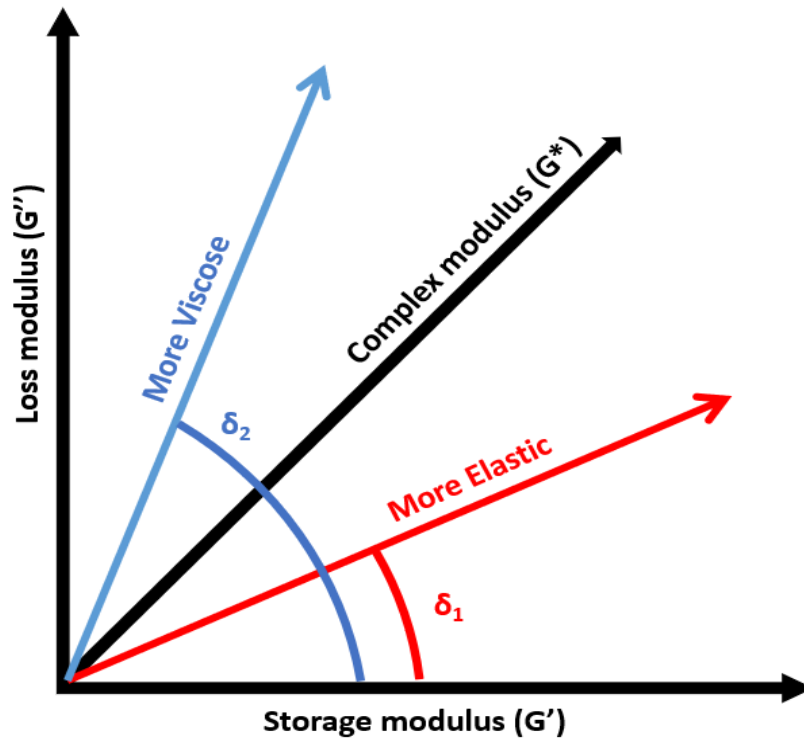


Figure 2.10. Components of complex modulus.

2.4.2.2 Master Curve Construction

The asphalt binder master curve serves as a fundamental tool, establishing a correlation between binder stiffness and reduced frequency across varying temperatures and frequencies. This relationship allows for the prediction of viscoelastic properties over a broad frequency range and the anticipation of such properties at any temperature. The construction of a master curve involves measuring the complex modulus of an asphalt binder at numerous temperatures and frequencies. Subsequently, the data is fitted into the Christensen-Anderson model (CAM). This methodology facilitates the prediction of viscoelastic properties and is particularly valuable in evaluating asphalt mixtures that incorporate recycled materials, where a blend of aged and virgin binders may be present.

The Christensen-Anderson model emerges as a valuable tool due to the specific physical significance of its master curve parameters. The cross-over frequency (ω_c) signifies the overall hardness of the binder, with decreasing values indicating increased hardness. The rheological index (R) serves as an indicator of rheological type, reflecting the transition from elastic behavior to steady-state flow. A higher R -value suggests a more gradual transition, indicative of rubbery/leathery behavior rather than brittleness.

To measure the complex shear modulus (G^*) of the binders, a frequency sweep was conducted at multiple temperatures using the DSR. The test involved collecting eighteen G^* values at each temperature, spanning a frequency sweep from 100 to 0.1 rad/s. Different DSR head geometries (8mm and 25mm) were employed based on the temperature range. For temperatures ranging from 10°C to 30°C degrees, the 8mm plate was utilized while the 25mm plate was used at temperatures from 34°C to 70°C degrees.

The Glover-Rowe (G-R) parameter was based on low-temperature ductility test stress states (King et al. 2012). This parameter, further validated through its application in analyzing early-life cracking, proved effective in explaining early durability issues (Rowe et al. 2014). Originally applied to non-load-associated cracking in airport pavements, the G-R parameter also demonstrated its efficacy in assessing damage in RAP-modified mixtures. Calculated as Equation 2.1 and derived from $|G^*|$ and δ measurements at 15°C and 0.005 rad/sec, it's plotted on black space diagrams to indicate cracking risk. G-R values of 180 kPa and 600 kPa correspond to warning and limit levels for cracking, respectively (Rowe 2012).

$$G - R \text{ Parameter} = \frac{|G^*|(\cos\delta)^2}{\sin\delta} \quad (\text{Eq. 2.1})$$

2.4.2.3 Multi Stress Creep Recovery Test

The MSCR test was employed to assess the high-temperature properties of the asphalt binders. This test is designed to reflect rutting performance. The MSCR test involved applying a 1-second creep load to the asphalt binder sample, followed by a 9-second recovery period. The first 20 cycles of creep and recovery were executed under a shear load of 0.1 kPa (with the initial 10 cycles serving as binder conditioning). Subsequently, a shear load of 3.2 kPa was applied to the same specimen for an additional 10 cycles. The temperature for the MSCR test on an asphalt binder is determined based on the binder's Performance Grade (PG) system, which classifies binders according to their performance in specific temperature ranges to prevent rutting and thermal cracking. The test temperature, typically focused on the high-temperature grade, reflects the maximum pavement design temperature at which the binder can resist deformation. This temperature is chosen considering the specific climatic conditions of the area where the pavement will be used, ensuring the binder is evaluated under realistic service conditions. Regional climate data and expected traffic loads further refine the selection, ensuring the asphalt binder is tested at a temperature that mirrors its operational environment, optimizing pavement durability and performance. In this study due to the fact that we are using modified binder, the test performed in different temperature for finding the performance of our binder in different climate condition.

The MSCR examination was carried out using the DSR device. The highest operational temperature for the control asphalt binder PG 52E-40 was 52°C. To assess binder performance under varied temperatures, the experiment was also conducted at 46°C. Three replicates for each binder type have been experimented with. Specimen dimensions were set at a diameter of 25 mm and a thickness of 1 mm. For recovered binder of 100% RAP, The MSCR test was conducted at temperatures of 70°C, 76°C, 82°C and 88°C, and the test was performed at 46°C, 52°C, 58°C and 64°C for recovered binder of 25% RAP. The MSCR test characterizes the recovery and non-recovery properties of the asphalt binder under shear creep load, specifically the percent recovery ($R\%$) and non-recoverable creep compliance (J_{nr}). J_{nr} quantifies the binder's tendency to undergo permanent deformation under applied stress, with lower J_{nr} values indicating superior resistance to rutting, a critical property for ensuring long-term pavement durability under traffic loads. Percent Recovery ($R\%$), on the other hand, assesses the binder's ability to return to its original shape after the stress is removed, effectively measuring its elastic characteristics. A higher Percent Recovery signifies a better elastic response, which contributes to the pavement's ability to withstand repetitive traffic loading without permanent deformation. These parameters could be measured as follows:

$$J_{nr \text{ 0.1 or 3.2}} = \frac{\text{Sum } J_{nr}(\text{0.1 or 3.2}) \text{ of 10 cycle}}{10}$$

(Eq. 2.2)

$$R^{\%}_{\text{0.1 or 3.2}} = \frac{\text{Sum } R^{\%}(\text{0.1 or 3.2}) \text{ of 10 cycle}}{10}$$

(Eq. 2.3)

which J_{nr} is non-recoverable creep compliance and R denotes recovery percent at different stresses (0.1 and 3.2 kPa).

CHAPTER 3.0 DATA RESULTS AND ANALYSIS

In this study, the binders with different RAP contents were systematically evaluated in terms of their viscoelastic properties, resistance to permanent deformation, and susceptibility to low-temperature cracking. The binders were also tested at different aging conditions. To achieve the short-term aging, the neat binder and the binder extracted from 100% RAP were conditioned with the RTFO. For the binder with 25% RAP, the loose asphalt mixtures were first fabricated and short-termed-aged in the oven, and then the binder was extracted and recovered. Based on the results of the rheological tests, a predictive model to estimate the RAP content in a given mixture was developed, and a step-by-step procedure for the evaluation was also provided.

3.1 Characterization of the Binder Linear Viscoelastic Properties

3.1.1 Complex Modulus Master Curve

The complex modulus master curves were constructed using the frequency sweep testing results at multiple temperatures. The CAM model was applied, and the model coefficients were determined through regression analyses during the master curve development. Figures 3.1 to 3.4 present the complex modulus master curve for different binders. It can be observed that for the same binder, as the aging level increases, the modulus of the binders increases. While the 100% RAP binder has higher modulus at the same reduced frequency than the other two binders at all aging levels, the binder with 25% RAP and the neat binder had similar modulus after the short-term aging conditioning and exhibiting higher modulus after the PAV long-term aging conditioning. The results indicate that the impact of using 25% RAP may be insignificant at the beginning of their service life but may emerge in the long term.

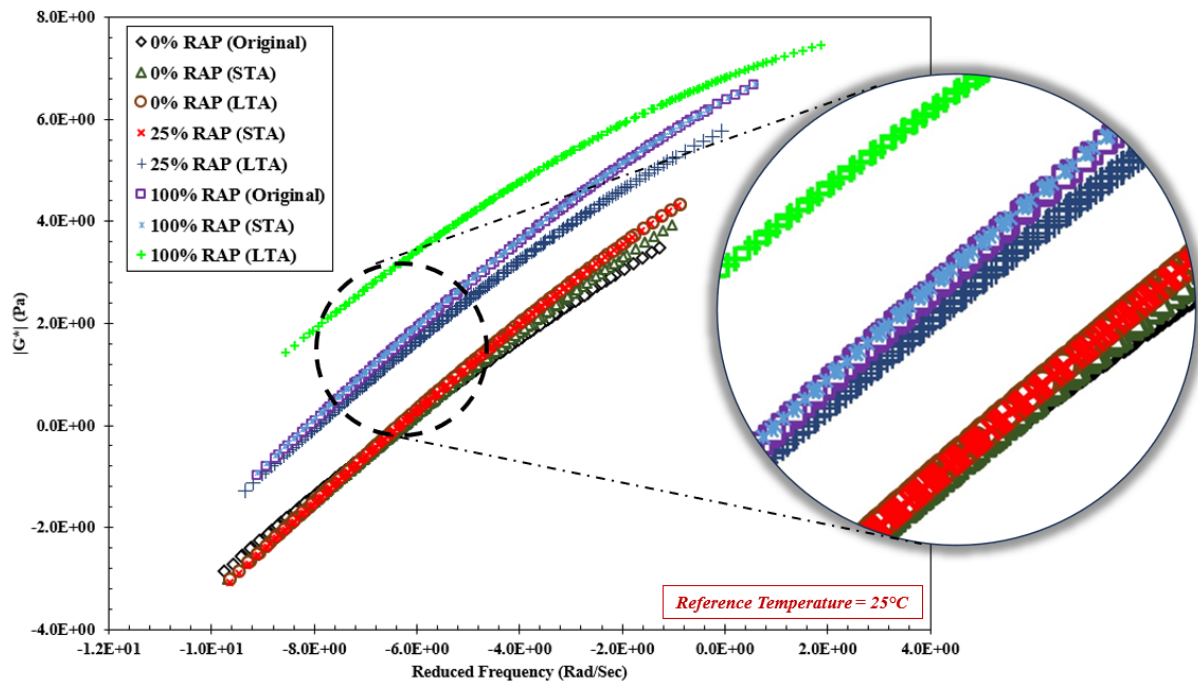


Figure 3.1. Master Curves of original binders at 25 °C.

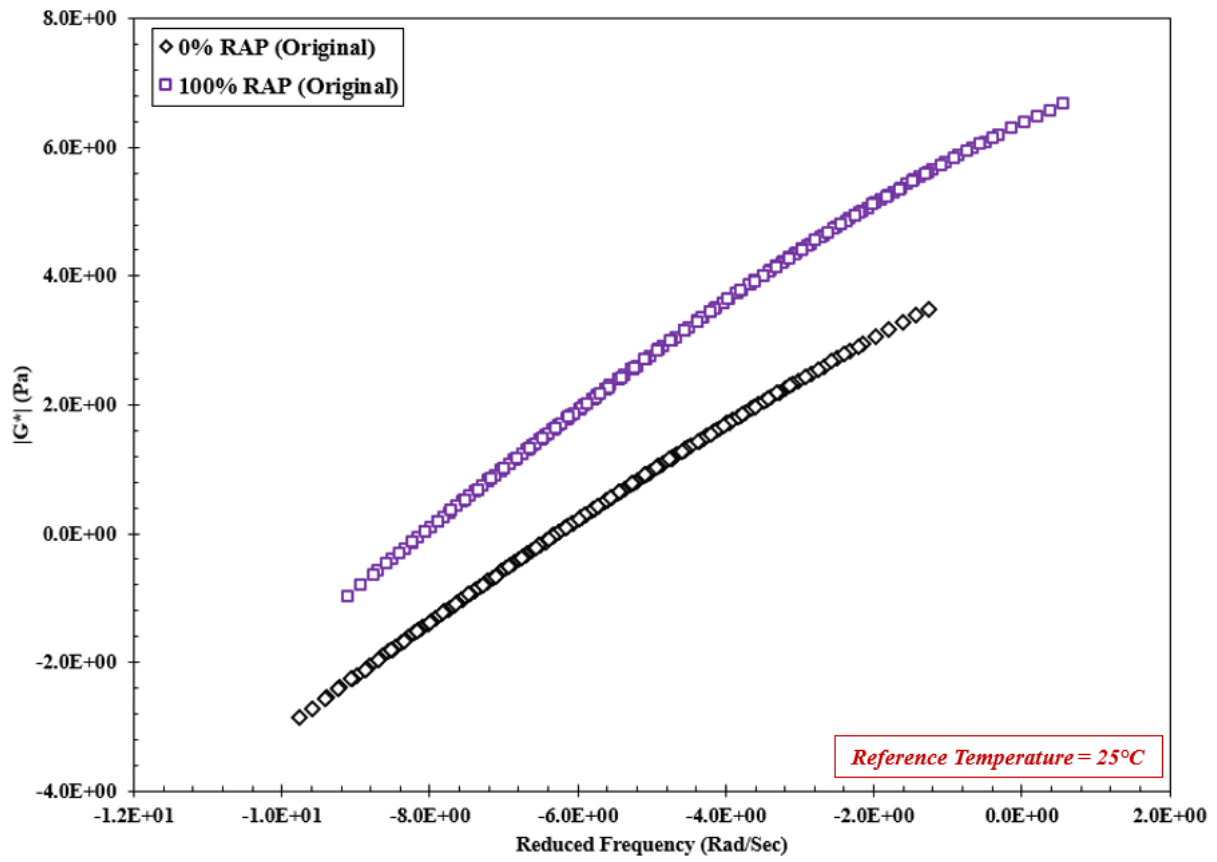


Figure 3.2. Master Curves of original binders at reference temperature of 25 °C.

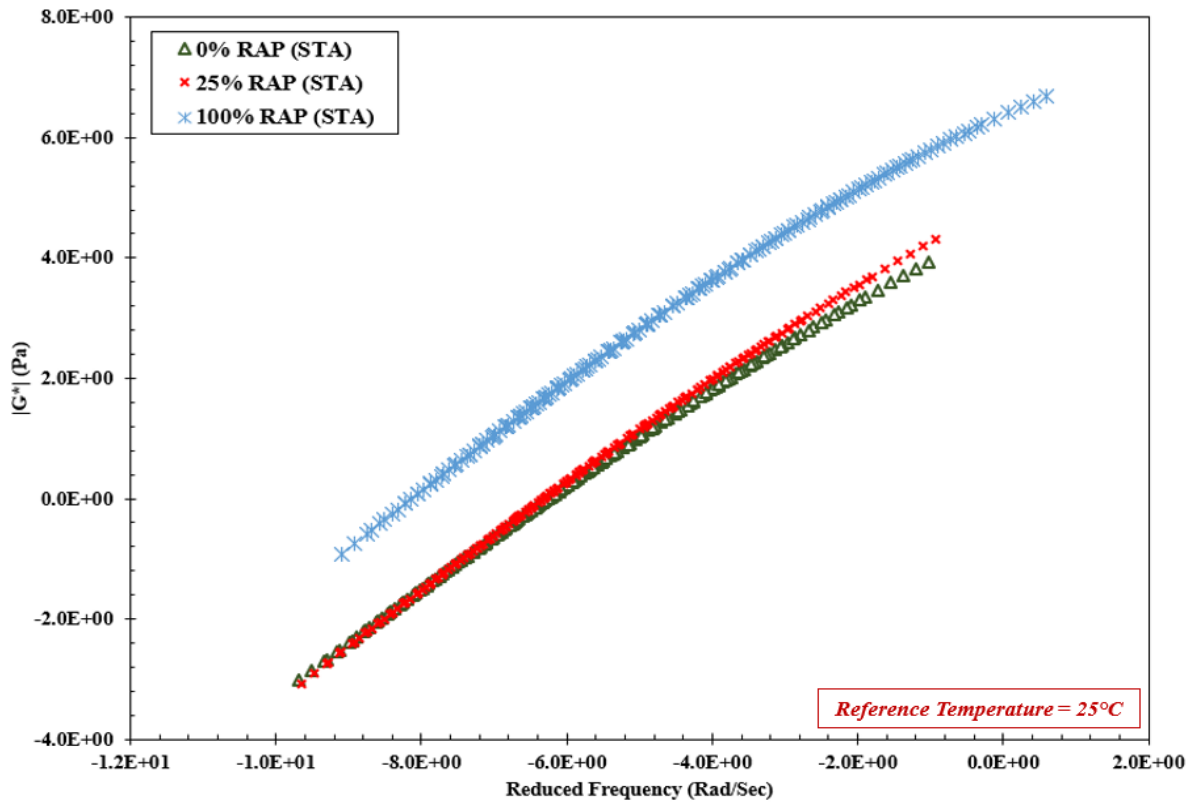


Figure 3.3. Master curves of short-term aged binders at reference temperature of 25 °C

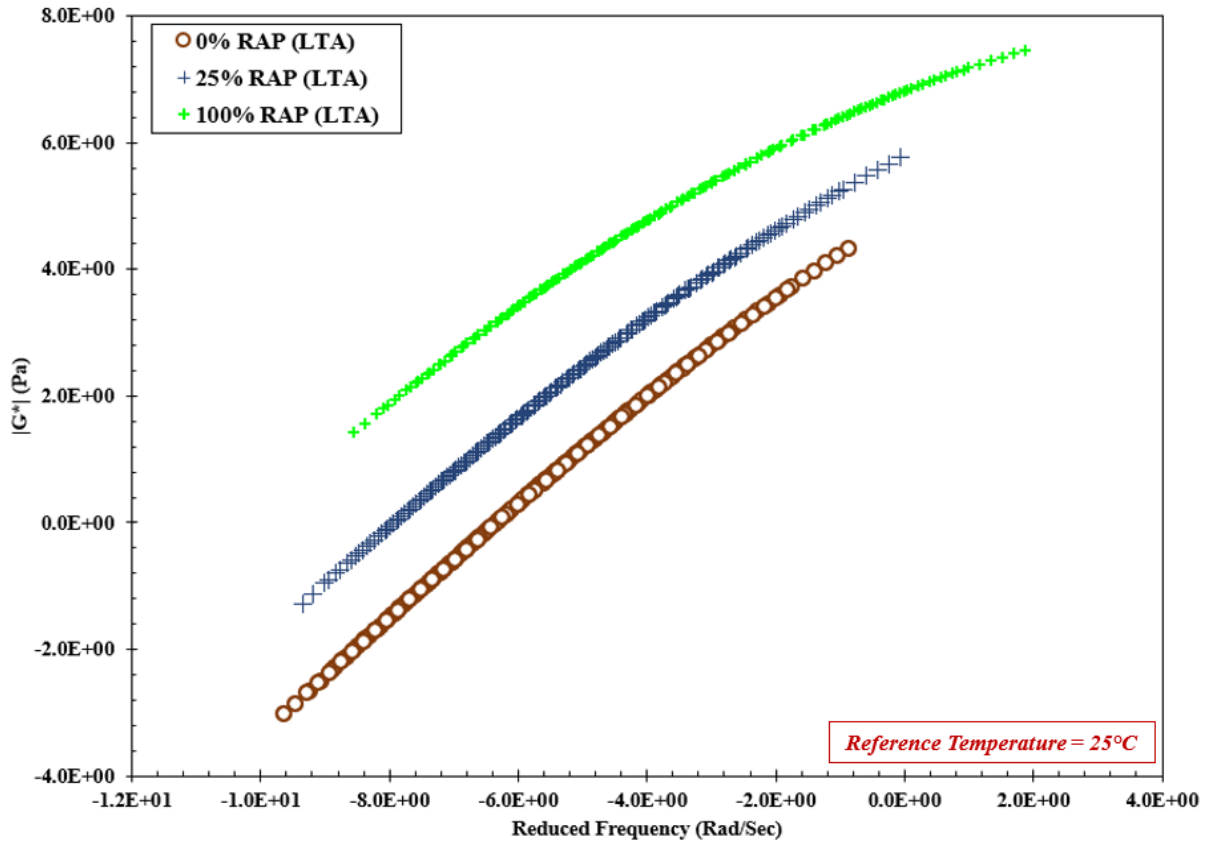


Figure 3.4. Master Curves of long-term aged binders at reference temperature of 25 °C.

3.1.2 Critical Parameters Derived from Linear Viscoelastic (LVE) Properties

The frequency sweep test characterizes the linear viscoelastic properties of the binders. Other than the complex master curve, several critical parameters can be calculated from the LVE properties to evaluate binder performance, including the crossover frequency, the rheological index, and the Glover-Rowe (G-R) parameter. The crossover frequency, ω_c , is identified as the frequency at which the storage modulus (G') equals the loss modulus (G'') at a given temperature. The parameter indicates the overall hardness of the binders. As the crossover frequency decreases, the hardness of binder increases. On the other hand, the rheological index, R , is considered as an indicator for type of the material rheological behavior, i.e., viscous (fluid-like) or elastic (solid-like). The rheological index is defined as the difference between the log of the glassy modulus and the log of the dynamic modulus at the crossover frequency. With increasing of R , more gradual transition from elastic behavior to steady-state flow will be expected. In other words, the behavior of the asphalt at intermediate temperatures will be more rubbery/leathery and less brittle. In general, R values are higher for aged (oxidized) asphalt binders. The crossover frequency-rheological index black space is often used to assess the asphalt binder's resistance to cracking. For typical binders, the crossover frequency may decrease, and the rheological index may increase as aging time progresses. Also asphalt binders more susceptible to cracking tend to fall in the bottom-right corner of this black space (Romero et al. 2013, Mensching et al. 2016).

Figure 3.5 presents the testing results of in the crossover frequency-rheological index black space. The results show that as the aging level increases, the position of the 100% RAP binder moves towards the

right bottom corner of the back space. However, for the neat PG 52E-40 binder, while the crossover frequency is much higher than that of the RAP binder, the binder exhibits a different trend with aging. The irregular trend can be attributed to the low phase angle, δ , values of polymer modified binder. Research related to using such LVE properties evaluating cracking resistance of modified binder is continuing in the asphalt binder field.

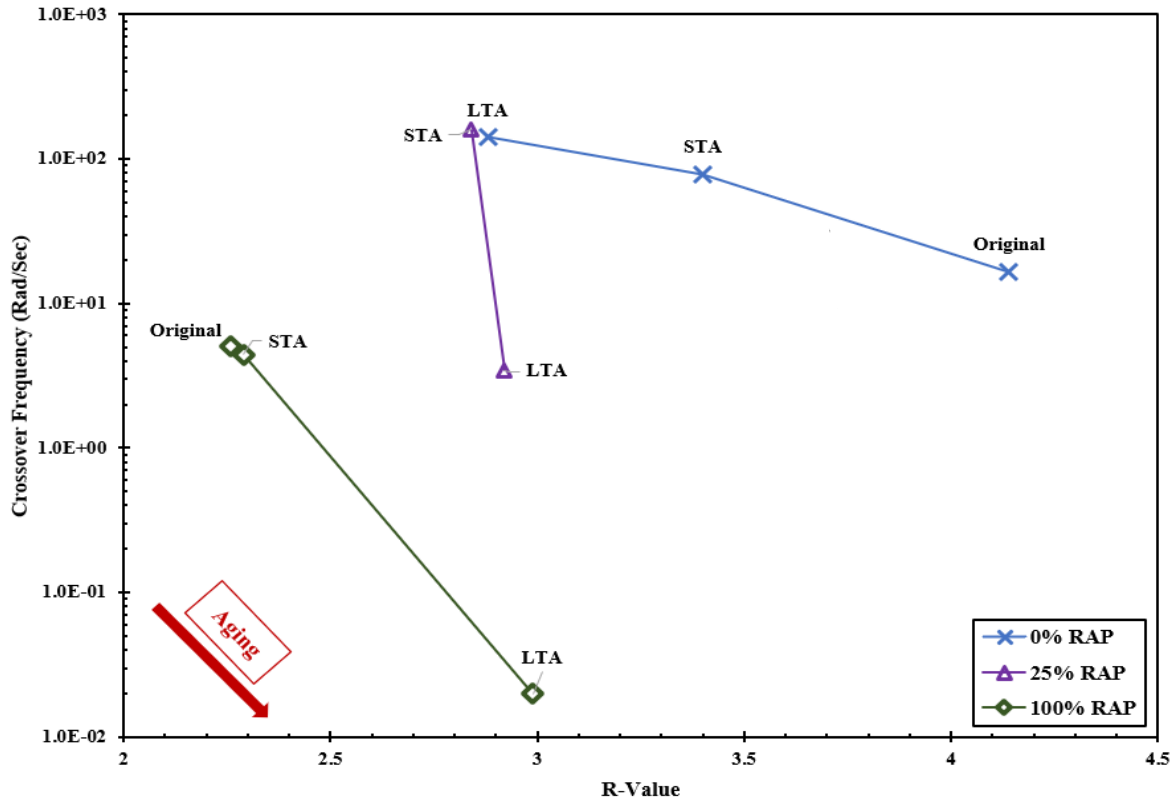


Figure 3.5. Crossover frequency-rheological index black space.

The black space diagram with Glover-Rowe damage zone is presented in Figure 3.6. As the aging level increases, the rheological characteristics move from the lower right towards the upper left on the black space diagram, indicating a trend towards higher risk of cracking due to aging. Among all binders, the only binder that reaches the damage zone is 100% RAP after LTA conditioning. It can also be observed that at the same aging level, the binder approaches the damage zone as the RAP content increases. According to G-R parameter analysis results, PG 52E-40 binder with 25% RAP can be safely applied even after long-term aging.

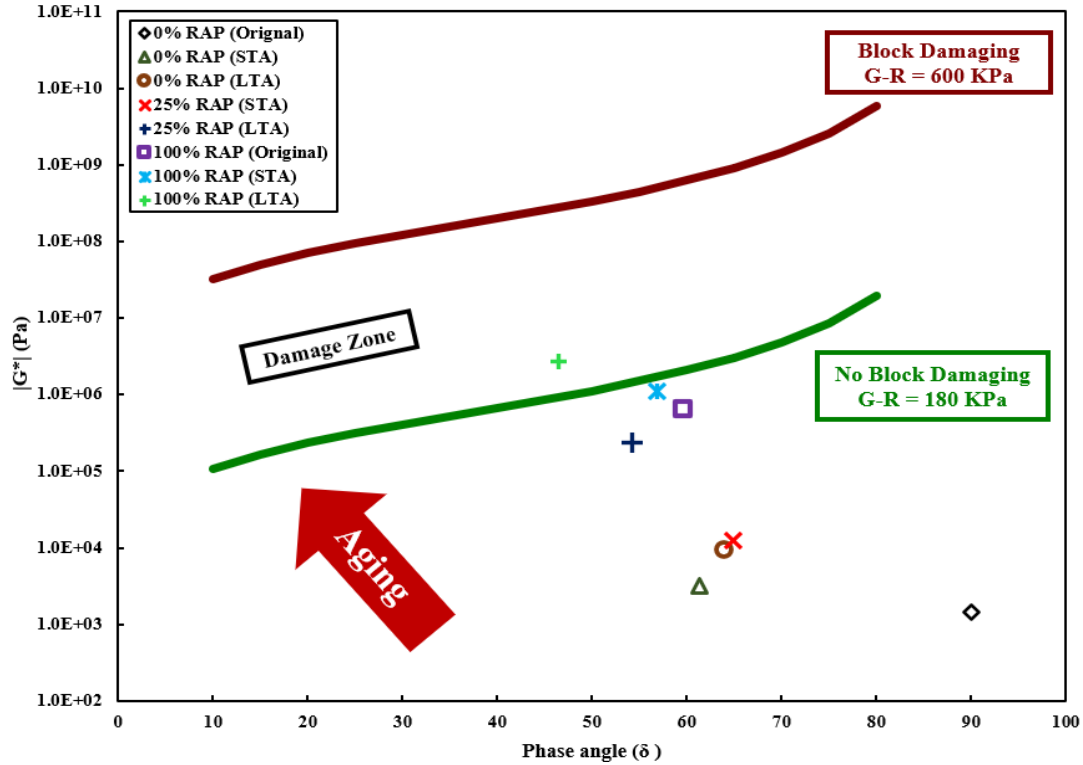


Figure 3.6. Black Space diagram with Glover-Rowe damage zonas.

3.2 Permanent Deformation Resistance

The MSCR test provides parameters for evaluating the rutting resistance of asphalt binders at high temperatures. The non-recoverable creep compliance (J_{nr}) quantifies the irreversible deformation under different stress levels while the removal Recovery percent ($R\%$) signifies the binder's ability to rebound. Additionally, the J_{nr} diff parameter reveals binder's sensitivity to stress amplitudes.

Figures 3.7 and 3.8 present the recovery percentages of binders under load levels of 0.1 kPa and 3.2 kPa after short-term age conditioning, respectively, at multiple temperatures. The testing results indicate that the neat binder has the highest recovery level at the two stress levels and not sensitive to temperatures compared to the two binders containing RAP components. For those two binders, the recovery percentage decreases dramatically as temperature increases. The superior recovery rate of the neat binder can be due to the impact of polymer modification.

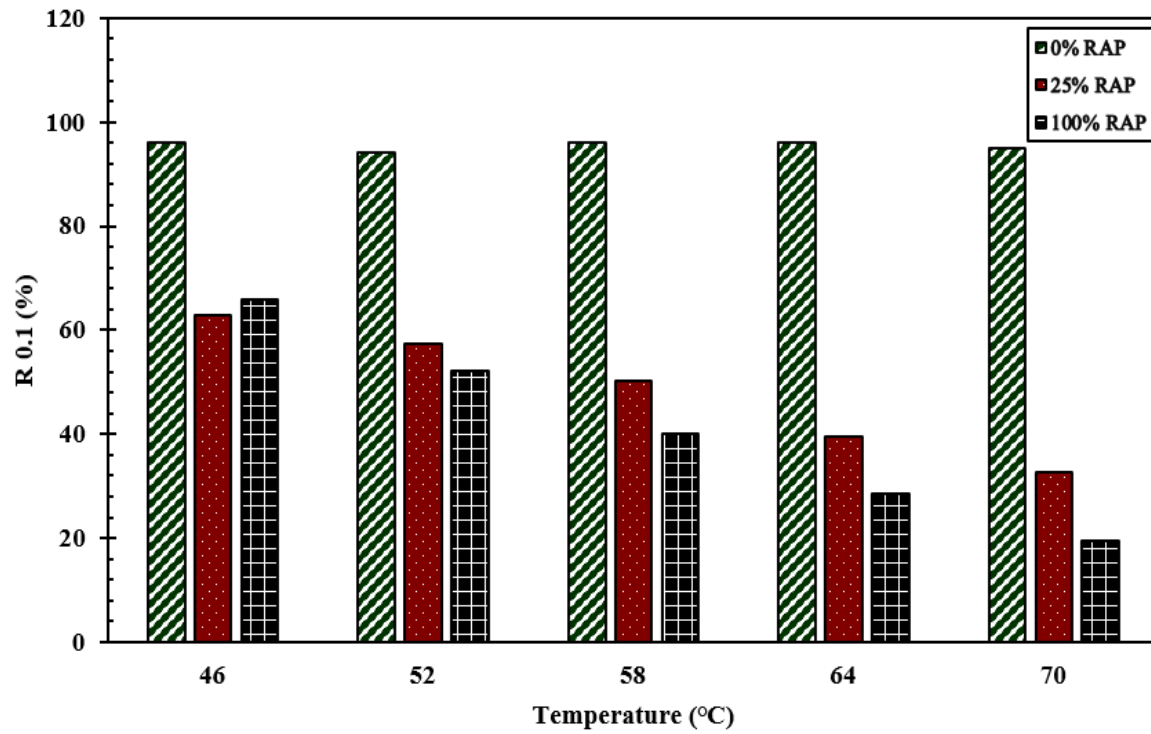


Figure 3.7. Recovery percent at 100 Pa

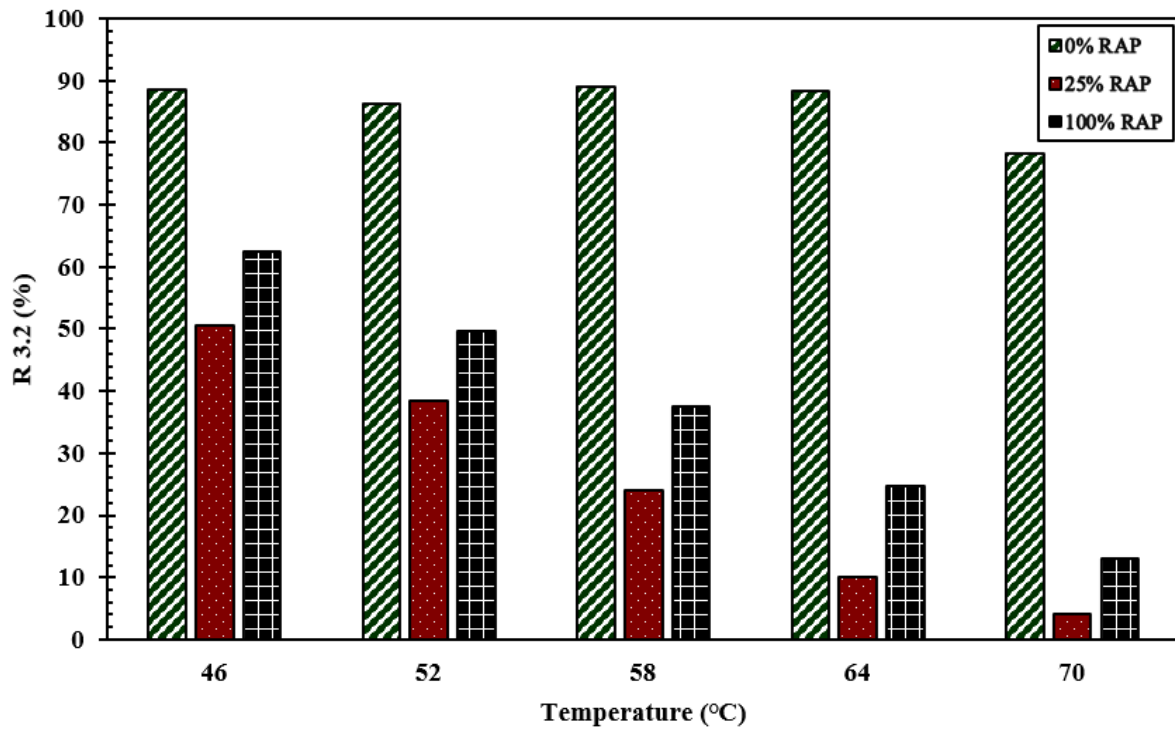


Figure 3.8. Recovery percent at 3200 Pa.

As presented in Figures 3.9 and 3.10, the non-recoverable creep compliance at low stresses for both neat binder and 100% RAP remains almost constant; however, for 25% RAP, an increase in temperature

significantly impacts the binder's resistance to permanent deformation. It is reasonable to believe the different J_{nr} values of the 25% RAP binder can be attributed to its short-term aging conditioning method.

Figure 3.11 presents the difference between non-recoverable creep compliance (J_{nr} diff) at low and high stresses. Among the three types of binders, the neat binder has the highest stress level sensitivity, and the 100% RAP binder has the lowest. The results indicate that the addition of RAP can mitigate the binder's stress sensitivity to some extent.

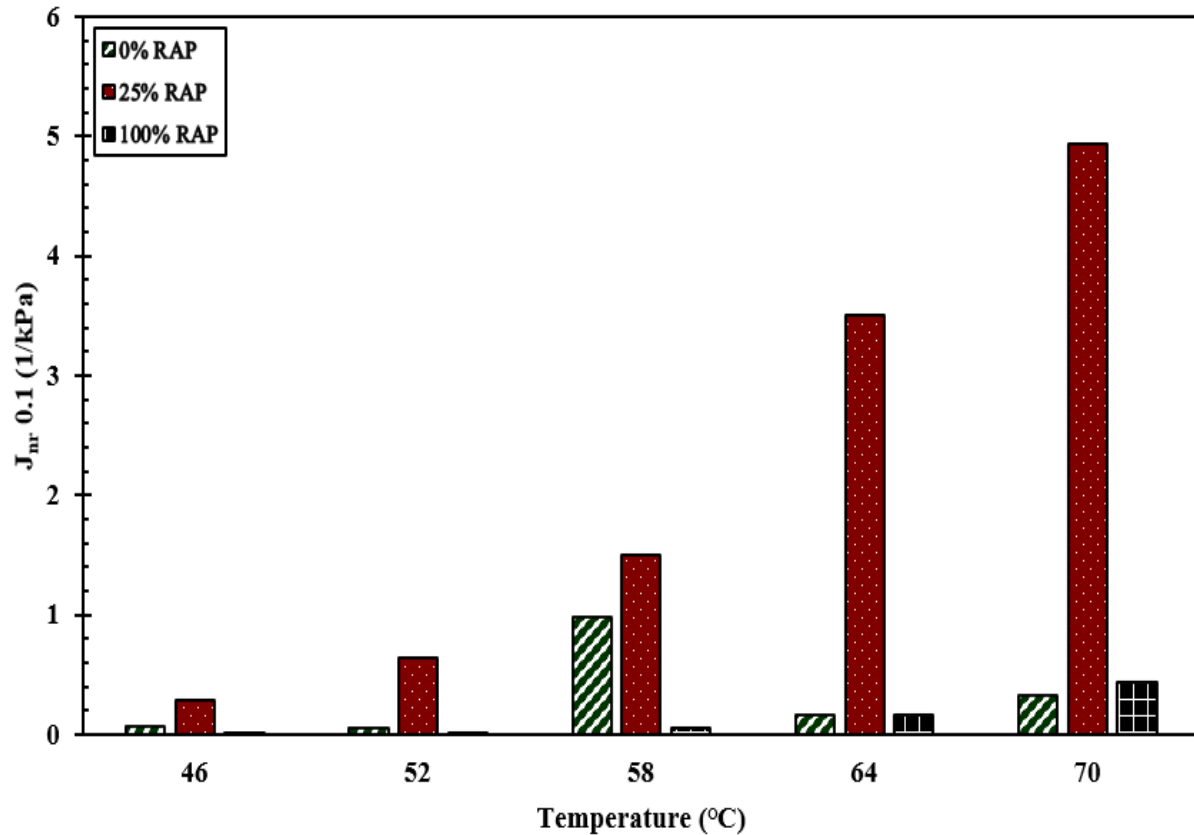


Figure 3.9. J_{nr} at 100 Pa.

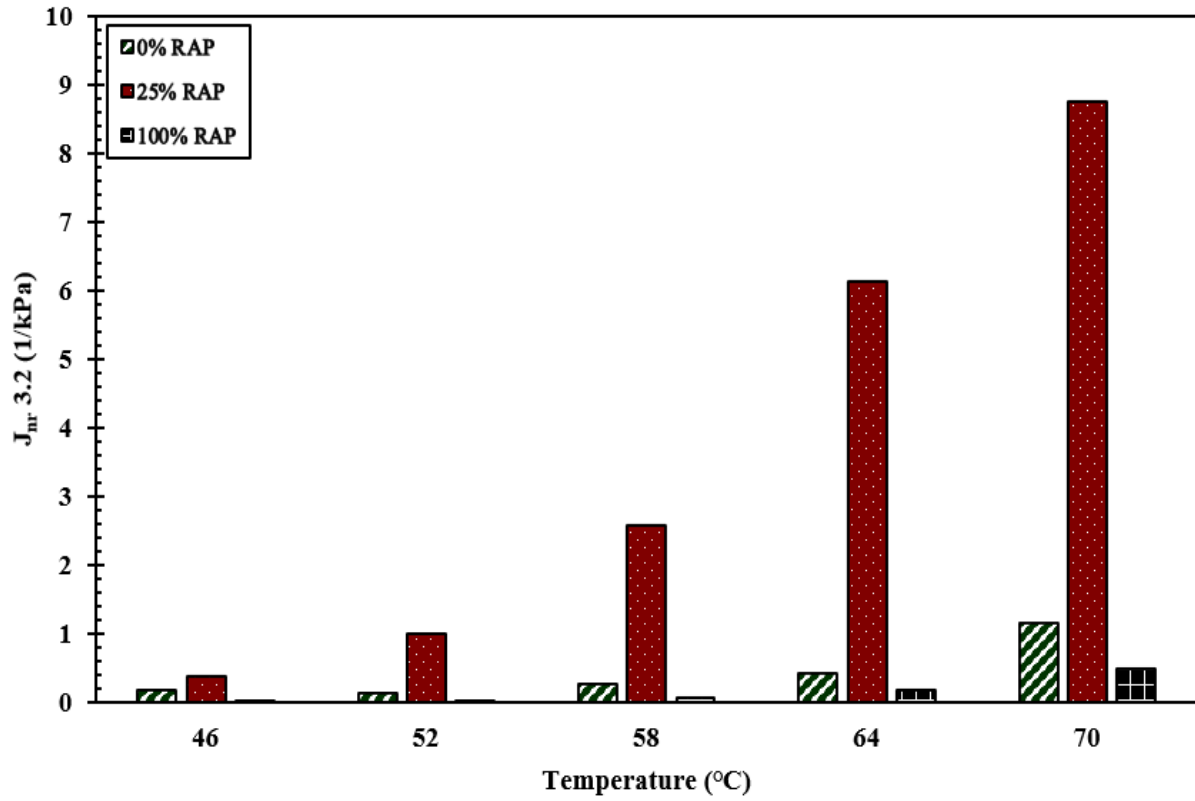


Figure 3.10. J_{nr} at 3200 Pa.

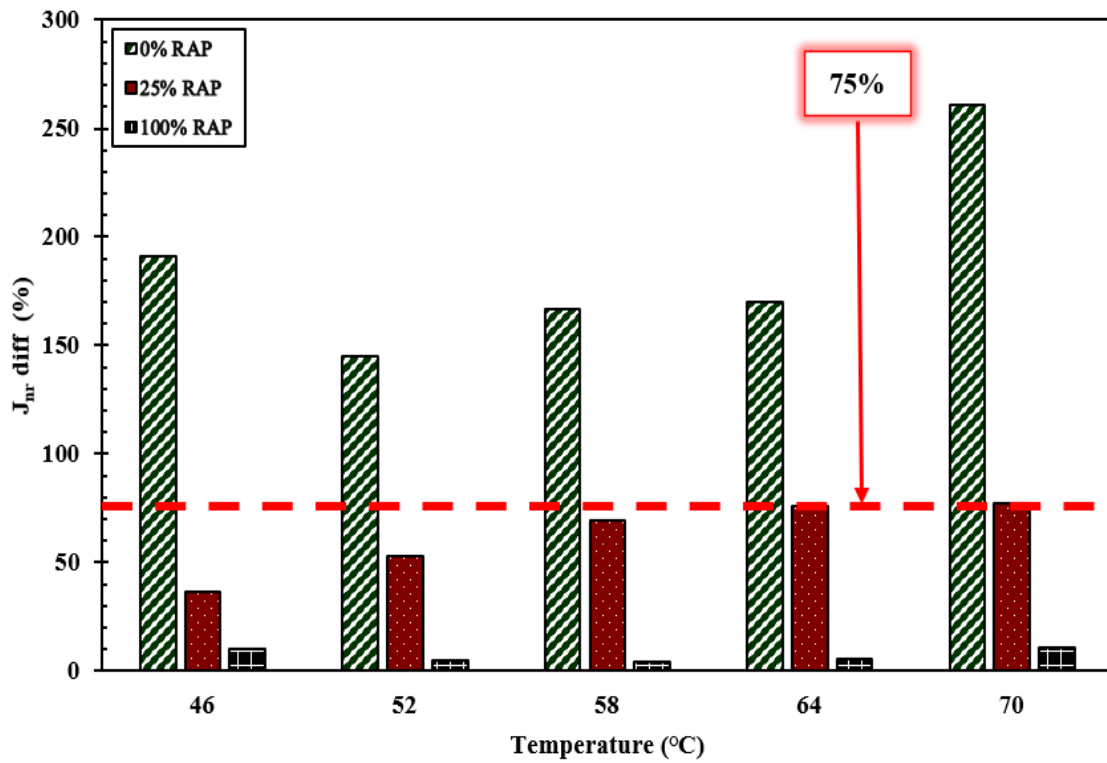


Figure 3.11. J_{nr} diff of all specimens.

Table 3.1 presents the summary of the MSCR test. As observed, binders with 0%, 25%, and 100% RAP fail at 70°C, 64°C, and 88°C, respectively. Additionally, the table includes the testing results for 100% RAP at 76°C, 82°C, and 88°C.

Table 3.1. Summary of the MSCR Test

Binder	T (°C)	R 0.1 (%)	R 3.2 (%)	R diff (%)	J _{nr} 0.1 (1/kPa)	J _{nr} 3.2 (1/kPa)	J _{nr} diff (%)	F/P	ESAL
0%RAP	46	96.06	88.59	7.22	0.07	0.18	190.89	Pass	E
	52	94.11	86.31	8.18	0.05	0.13	144.77	Pass	E
	58	95.96	88.96	7.3	0.98	0.26	166.6	Pass	E
	64	96.17	88.23	8.26	0.15	0.42	170.07	Pass	E
	70	94.89	78.29	17.49	0.31	1.15	260.87	Failed	-
25%RAP	46	62.98	50.61	19.59	0.28	0.38	36.67	Pass	E
	52	57.27	38.46	32.62	0.64	0.99	53.1	Pass	V
	58	50.19	24.13	52.77	1.5	2.58	69.26	Pass	S
	64	39.53	10	74.24	3.5	6.13	75.99	Failed	-
	70	32.66	4.22	87.09	4.94	8.75	77.24	Failed	-
100%RAP	46	65.82	62.55	4.97	0.004	0.0044	10.09	Pass	E
	52	52.25	49.66	4.97	0.0159	0.0168	5.13	Pass	E
	58	40.18	37.54	6.57	0.053	0.0552	4.23	Pass	E
	64	28.41	24.72	12.97	0.15	0.16	5.36	Pass	E
	70	19.44	13.05	32.71	0.43	0.48	10.55	Pass	E
	76	12.3	4.29	65	1.11	1.28	15.54	Pass	H
	82	6.46	0.4	94.6	2.74	3.34	20.22	Pass	S
	88	3.29	0	100	6.29	7.74	21.55	Failed	-

3.3 Thermal Cracking Resistance

The BBR test evaluates asphalt binder performance in low-temperature environments after long term aging. Key findings of this test include stiffness modulus components (S_m) and the m-value, which is the slope in the stiffness modulus's logarithmic representation at 60 seconds. These factors indicate the binder's resistance to cracking and deformation. A lower stiffness modulus indicates a better low-temperature crack resistance, and a higher m-value signifies an improved deformation resistance. The stiffness modulus and m-values are presented in Tables 3.2 and 3.3, and their trends can be observed in Figures 3.12 and 3.13. The testing temperatures for each binder was determined according to the standards, and the low-temperature properties of the three binders can be directly compared at -24 °C, which was the common testing temperature among the three binders. With increasing the RAP percentage, stiffness modulus (cracking susceptibility) increases while m-value (flexibility) decreases. The results suggest that as the RAP content increase, the low-temperature cracking resistance decreases.

The critical temperatures calculated from the *S* and *m*-values are presented in Figure 3.14. The BBR testing results indicate that the critical temperature for the binder from 25% RAP mixture is increased to -30 °C while for the neat PG 52E-40 binder, the critical temperature is -40 °C. The elevation of the critical low temperatures may raise some concerns given the climate in Alaska. However, since the BBR test only applies loads within the linear viscoelastic range, low-temperature cracking tests with damage induced is recommended for further verification.

Table 3.2. Stiffness modulus (MPa) of all specimens

Temperature (°C)	-6	-12	-18	-24	-30	-36
Binder						
0%RAP	-	-	-	104.3	276.08	519.36
25%RAP	23.444	51.581	102.94	205.22	-	-
100%RAP	126.28	226.25	413.62	690.23	-	-

Table 3.3. *m*-values of all specimens

Temperature (°C)	-6	-12	-18	-24	-30	-36
Binder						
0%RAP	-	-	-	0.37	0.31	0.26
25%RAP	0.367	0.362	0.321	0.274	-	-
100%RAP	0.301	0.252	0.248	0.183	-	-

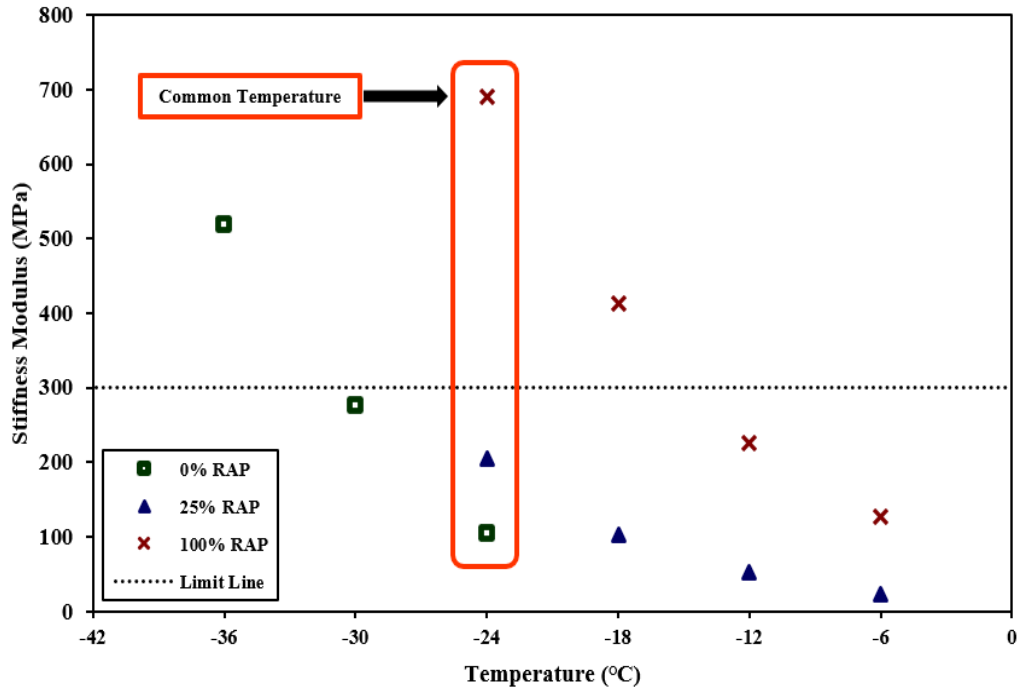


Figure 3.12. Stiffness modulus (MPa) of all specimens

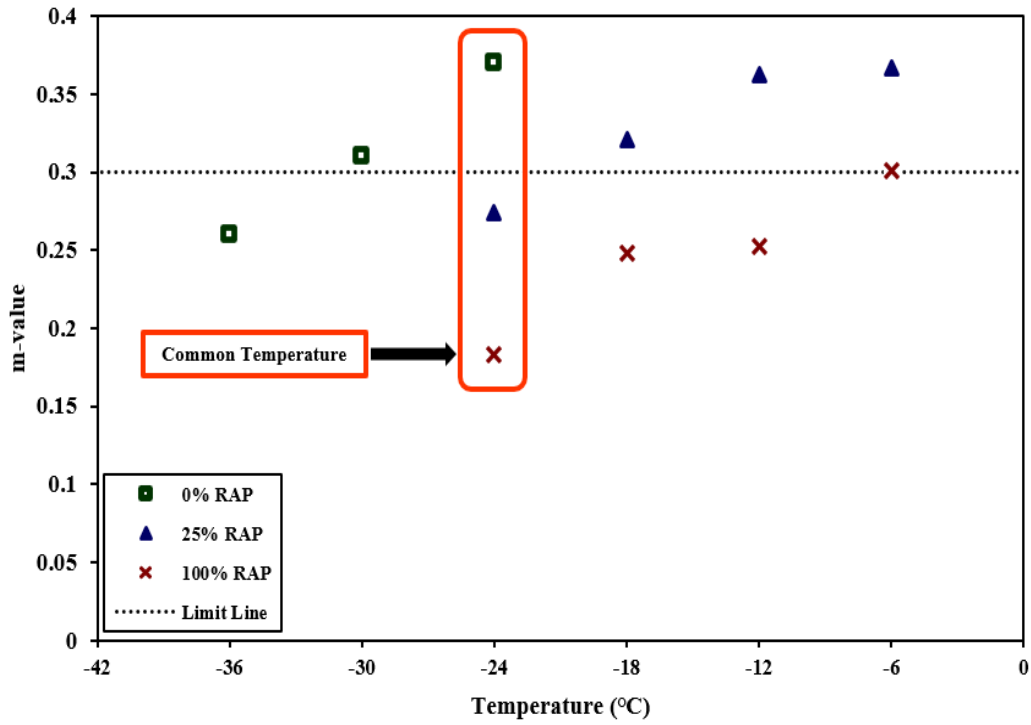


Figure 3.13. m-values of all specimens

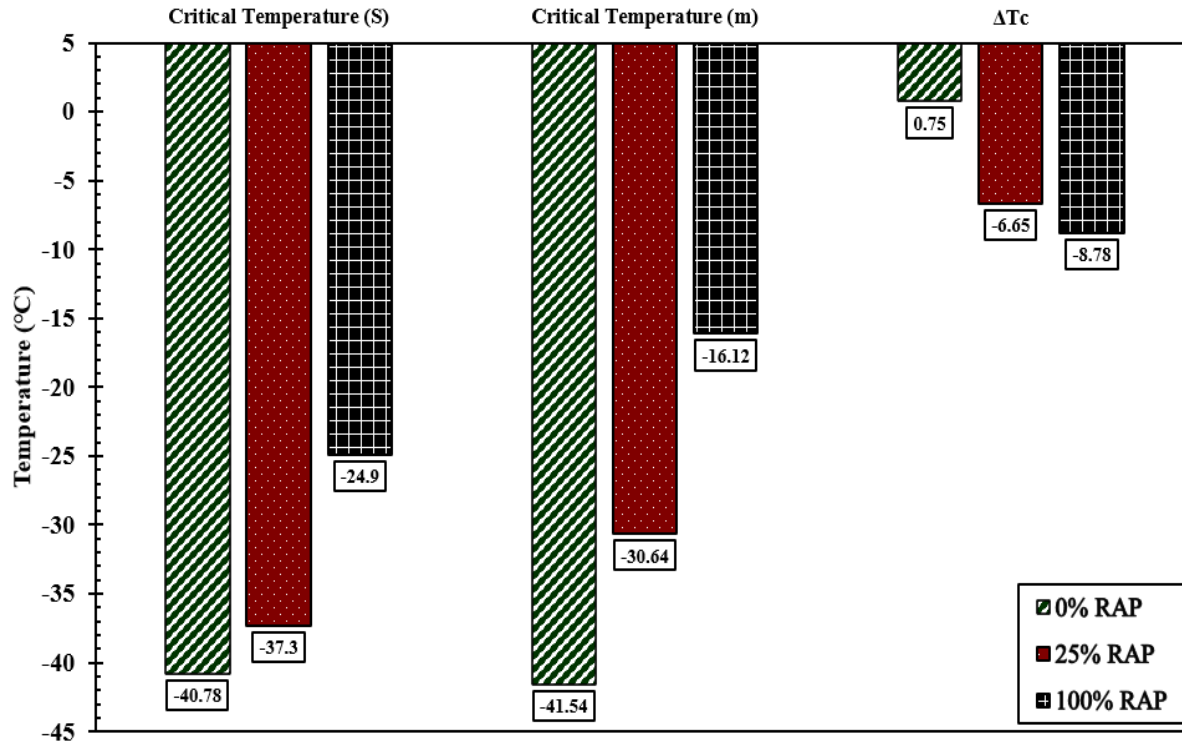


Figure 3.14. Comparison of critical temperatures determined by m-value and Stiffness with the corresponding ΔT_c .

The ΔT_c parameter can also be computed from the BBR testing results as presented in Figure 3.14. This parameter reflects the brittleness of the asphalt binder at low temperatures. The assessment of an asphalt binder is based on the sign of ΔT_c : a positive ΔT_c suggests that stiffness modulus influences the binder's performance while a negative ΔT_c indicates a dominance of the m-value. For the neat binder (0% RAP) the ΔT_c is positive and for 25% RAP and 100% RAP, this value is negative, which indicates neat binder's performance is governed by stiffness modulus while for 25 and 100% RAP this governing is influenced by m-value.

A binder with a low negative ΔT_c value (or a high absolute value below zero) at a specific low-temperature grade suggests inadequate stress-relief capacity.

3.4 Performance Grading

In this study, performance grade of the binders was also determined as per the AASTHO M 320 and M 332 specifications, respectively, and the results are presented in Table 3.4. According to the M 320 standard, the tradition PG of the neat binder is PG 64-40. In contrast, the 100% RAP binder has grades of PG 82-16.

Combining outcomes from the MSCR test presented in Table 3.1 with AASHTO M 332 standards, the PGs with traffic levels were also determined and presented in Table 3.4. This system accounts for both high-temperature performance and low-temperature cracking resistance while also considering the binder's suitability under varying traffic load conditions. The neat binder receives a PG classification of 64E-40, signifying its appropriateness for extreme traffic loads by demonstrating resilience against deformation

at elevated temperatures and capacity to endure low-temperature cracking to -40°C. For binders incorporating 25% RAP, the grades are specified as PG 58S-X (PG 52V-X, or PG 46E-34) based on MSCR test results, indicating their adaptability to standard traffic conditions, very high-temperature performance, or extreme traffic loads, respectively. The binder's low PG could not be determined since the unaged status could not be obtained since the binder had to experience the heating process during mixing. Meanwhile, the 100% RAP binder is classified as PG 82S-6 (PG 76H-6, or PG 70E-6) in line with MSCR results, illustrating a marked improvement in resistance to high-temperature deformation across a spectrum from standard to extreme traffic conditions and changing the low-temperature cracking threshold to -6°C. Table 3.4 also presents the continuous high PGs of the binders.

Table 3.4. Summary of Performance Grading of the Tested Binders

Binder	AASHTO M320	AASHTO M332	Continuous
	PG Grade	PG Grade	High PG
0% RAP	64-40	64E-40	57.35
25% RAP	-	58S-X	60.73
100% RAP	82-16	82S-16	80.93

3.5 RAP Content Prediction

3.5.1 Predictive Model Development

Building on the prior analyses, a predictive model to estimate RAP content for a given mixture was developed in this study. The model was constructed based on a series of trendlines from the testing data, including the continuous high PG, the J_{nr} diff from the MSCR test, the complex modulus, and the critical temperatures from the low-temperature BBR test for binders with different RAP contents. The selected testing results cover the binder linear viscoelastic properties as well as the performance at low and high temperatures.

Figure 3.15 presents the change of continuous high PG as the RAP content increases in the binder. As presented in the figure, an exponential function can be applied to fit the trendline, and the R-square of the regression is over 0.99. It is assumed that the change of the continuous high PG of the binder will increase as the RAP content increases following an exponential function. To estimate the RAP content for a given mixture, it is suggested that a loose mixture with the same original components be fabricated first with known a RAP content (this study used 25% to be consistent with the mix design), and binder from the loose mixture as well as binder from 100% RAP be extracted and recovered. Then, the rheological tests can be performed on the neat binder and the extracted binders, and the testing results can be used to fit the coefficients of the exponential model. After the model coefficients are obtained, the binder from the given mixture can also be extracted and tested. Based on the reported testing results, the RAP content can be backcalculated. The predictive model can be further validated by using more datapoints and tests on different binders and RAP.

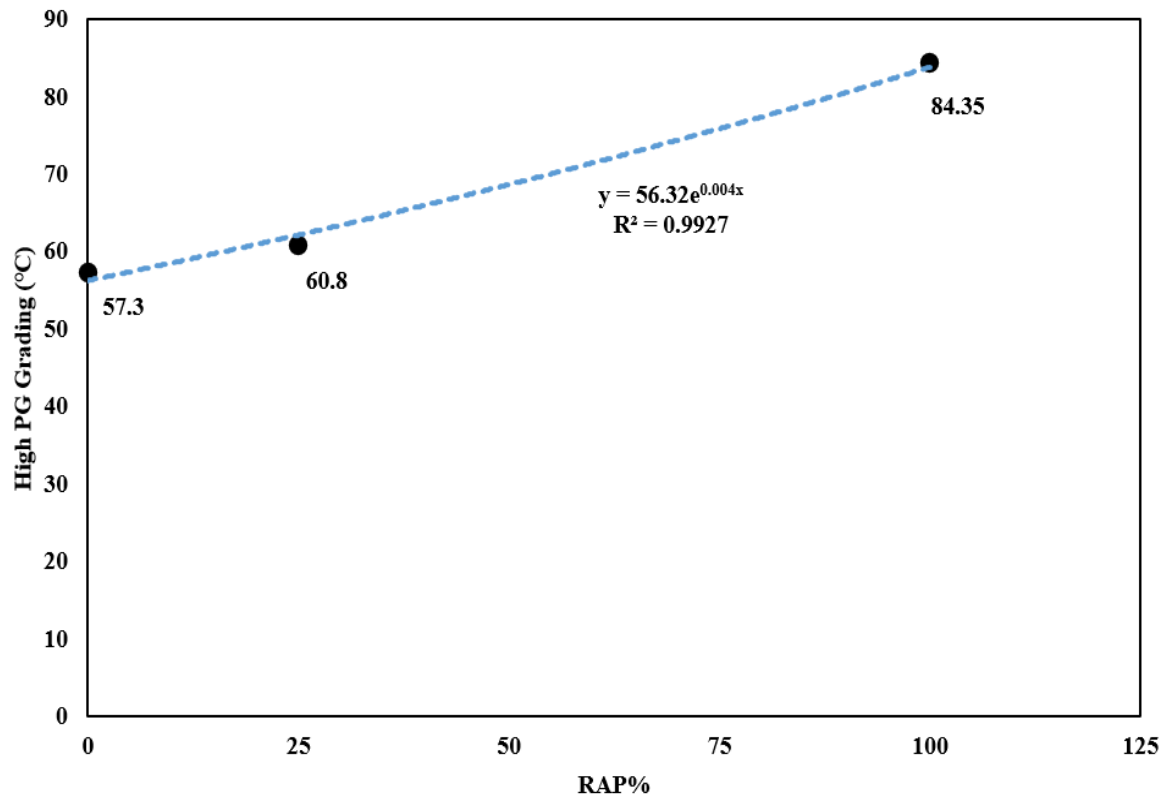


Figure 3.15. High PG grading fitting line.

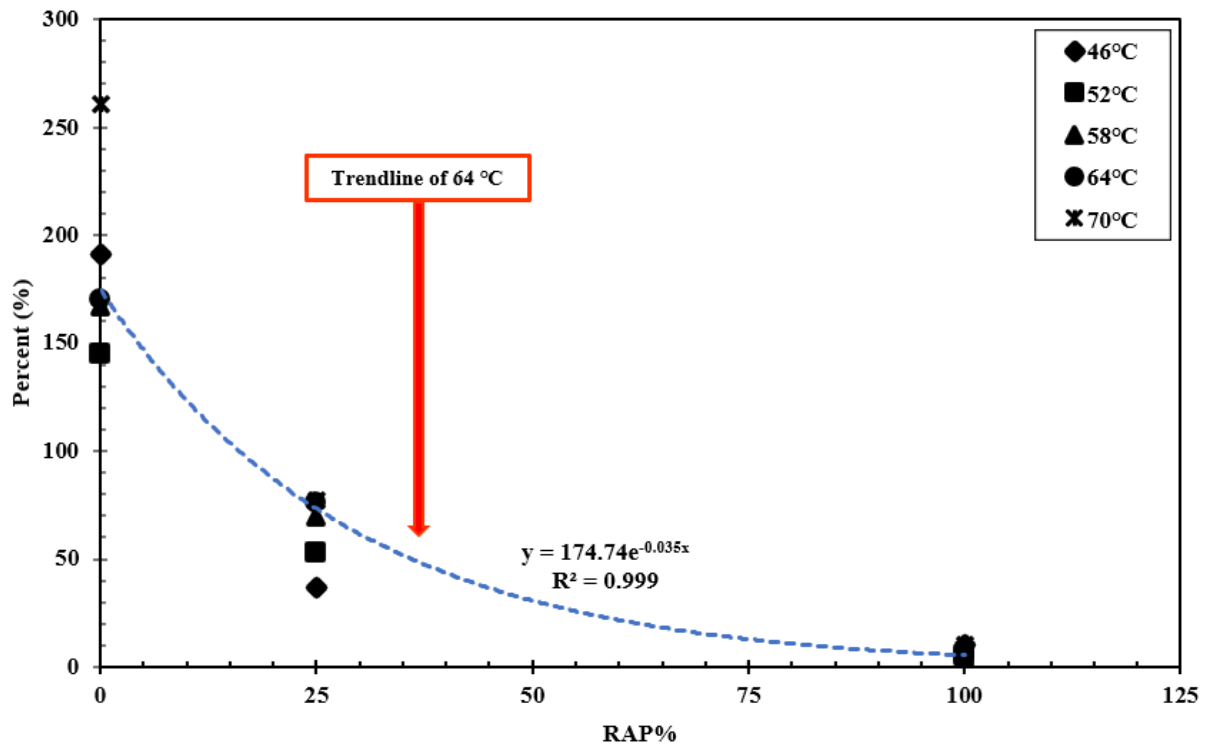


Figure 3.16. J_{nr} diff fitting line after short-term aging.

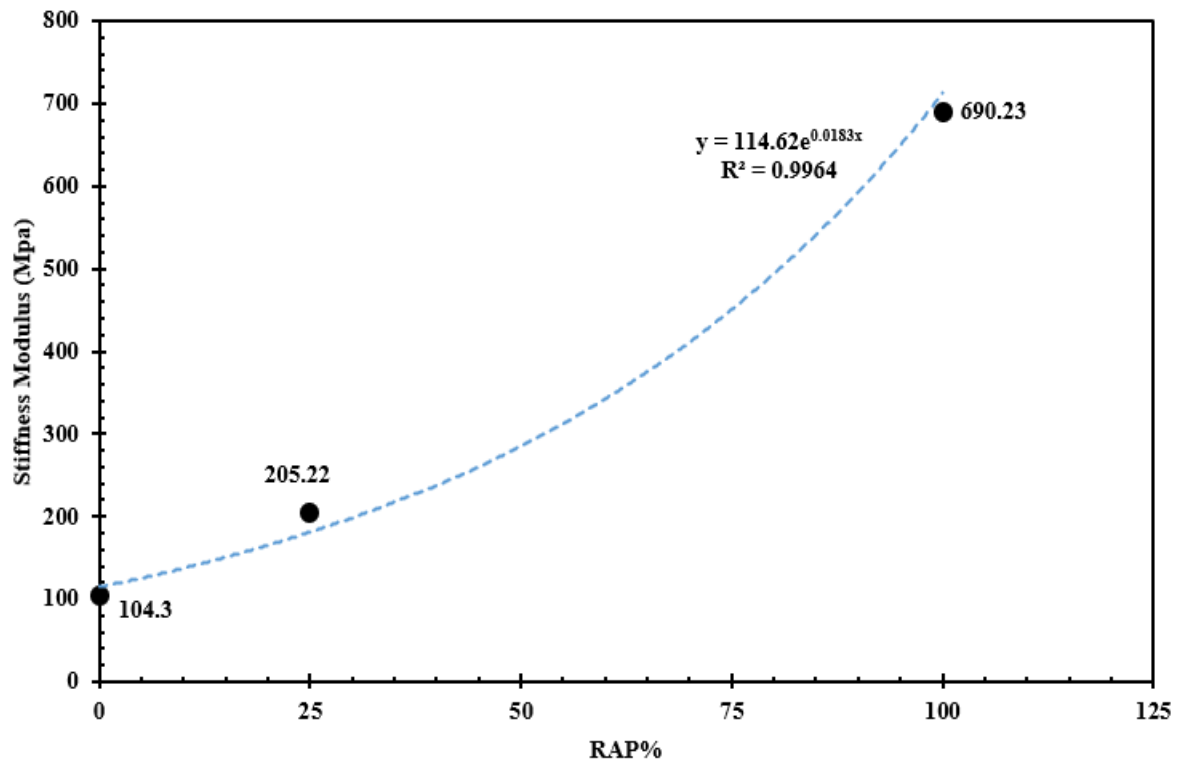


Figure 3.17. Stiffness modulus fitting line.

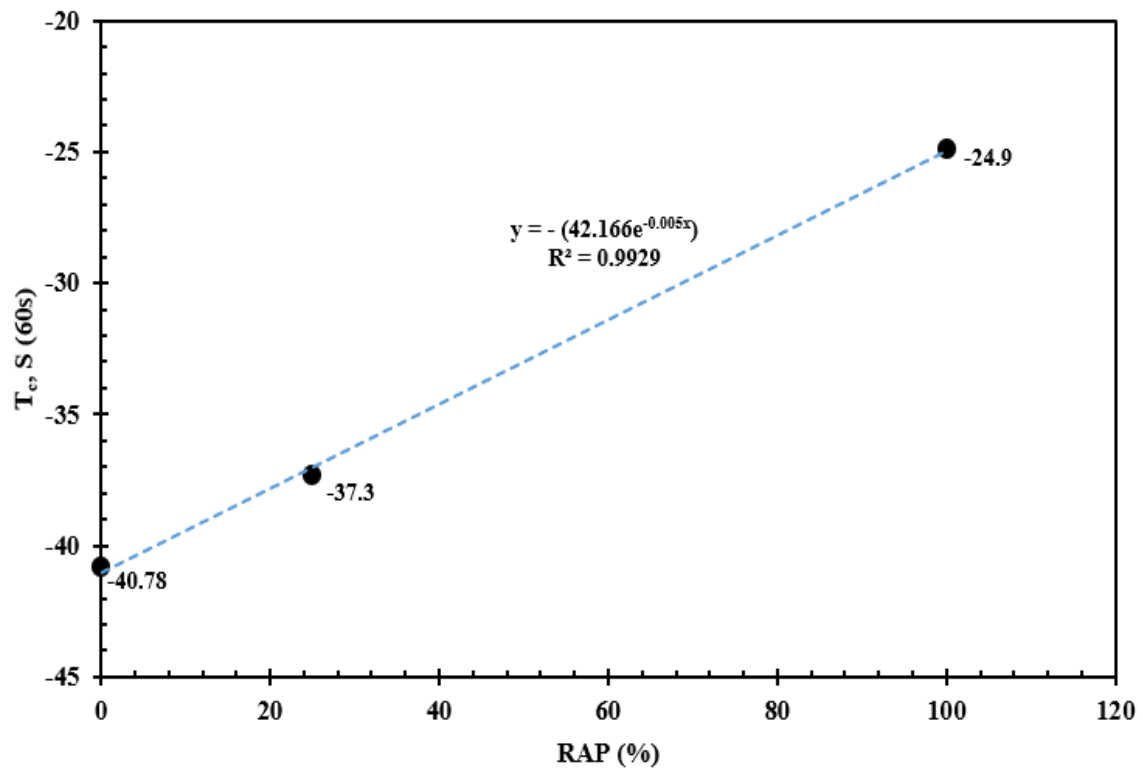


Figure 3.18. Critical temperature fitting line.

Figure 3.16 presents the trends of the J_{nr} diff change from the MSCR tests as a function of RAP content. The fitting line with the data at 64 °C using an exponential function is also presented in the figure. The temperature 64 °C is selected since is the high PG of the virgin binder. It indicates that the RAP content of a given mixture can also be calculated based on the J_{nr} diff parameter using the same procedure as presented above. Similarly, the regression models have also been developed using the stiffness modulus and the critical temperatures obtained from the low-temperature BBR tests with different RAP contents (Figure 3.17 and 3.18). The equations obtained in this study are summarized in Table 3.5.

Table 3.5. Summary of predictive models

Test	Model
DSR	High PG Grading = $56.32e^{0.004 \text{ RAP } \%}$
MSCR	$J_{nr} \text{ diff} = 174.74e^{-0.035 \text{ RAP } \%}$
BBR	Modulus Stiffness = $114.62e^{0.0183 \text{ RAP } \%}$
BBR	Critical Cracking Temperature = $-(42.166e^{-0.005 \text{ RAP } \%})$

3.5.2 Step-by-Step Procedure to Backcalculate RAP Content

To further illustrate the method to estimate the RAP content in a given mixture, a preliminary step-by-step procedure is developed and presented in this section.

- **Material Preparation.** Acquire the component materials and fabricate loose mixtures with one or multiple defined RAP contents. Extract and recover the binders from the loose mixtures as well as from the RAP material.
- **Performance Testing.** Conduct the rheological tests, including the frequency sweep test, the MSCR test, and the BBR test with binders conditioned to their required aging levels.
- **Regression Equation Development.** Extract the parameters from the testing data, including the continuous high PG, the J_{nr} diff from the MSCR test, and the stiffness and the critical temperatures from the BBR test. Perform regression analysis using exponential functions and determine the model coefficients for each key parameter.
- **Performance Evaluation on the Target Mixture.** Extract and recover the binder from the target mixture and perform the same tests on the recovered binder.
- **RAP Content Estimation.** Apply the regression equations obtained from Step 3 to backcalculate the RAP content of the target mixture using the results from Step 4. One RAP content will be reported from each equation. The RAP content of the target mixture roughly falls into the reported range.

CHAPTER 4.0 CONCLUSIONS AND RECOMMENDATIONS

This study investigated the impact of the incorporation of RAP on the performance of asphalt binder. A series of rheological tests were conducted on the neat Alaskan PG 52E-40 binder and the extracted and recovered binders from mixtures containing 25% RAP and 100% RAP. Based on the testing results, a method was also developed to estimate the RAP content for a given asphalt mixture, which can be practical in quality assurance. The following conclusions have been developed from the investigation.

According to the master curves constructed based on the frequency sweep test results, the binder modulus increases as the aging level and the RAP content increase. The results also show that the neat binder and the binder extracted from mixtures with 25% RAP have similar modulus after short-aging conditioning. It indicates that the incorporating RAP with relatively low dosage may not affect the performance in the early service time but may impact the long-term performance.

The analysis using the Glover-Rowe parameter suggests that as the aging level and the RAP content increase, the susceptibility to cracking increases. However, except the long-term aged 100% RAP binder, all other tested binders are below the limit for cracking damage, including the binder with 25% RAP after long-term aging.

The percentage recovery parameter from the MSCR tests suggest that the neat binder without RAP exhibits the highest recovery rate, and the non-recoverable compliance (J_{nr}) of both the neat binder and the 100% RAP binder are low, indicating incorporating RAP would not raise major concern in rutting resistance.

BBR test results indicated that the neat binder (52E-40) had a critical low temperature of -40 °C based on stiffness and m-value criteria. As the RAP content increases, the low-temperature cracking resistance decreases. The tests suggest that the critical low temperatures for the binders extracted from mixture with 25% RAP and 100% RAP are -30 °C and -16°C, respectively.

A predictive model for estimating RAP content in a mixture has also been developed in the study, and a step-by-step procedure to backcalculate the RAP content for a given mixture. The preliminary model can be easily used during quality assurance. The model coefficients are needed to be calibrated once, and backcalculation can be efficiently conducted for a new mixture sample.

For future studies, it is recommended that the developed model be validated with more data points from different RAP contents and binder types.

The BBR tests only assessed the binder low-temperature cracking resistance within the linear viscoelastic range. To further verify the findings in this study, it is recommended that low-temperature cracking tests be conducted on Alaskan binders with different RAP contents.

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APPENDIX B

IDEAL CT DATA Summary

Mix Type	Test Temp.C	Binder PG	RAP%	TotBinder Rejuv	Compaction Cnt, %	Gmm %	Air Voids%	Displacement Rate (mm/min)	Tensile Strength(KPa)	Displacement L75 (mm)	Post-Peak slope, S, m75 , N/m	Fracture/Failure Energy, Gf, (J/m2)	Work of Failure, Wf, (Joules)	Cracking Tolerance Index, CTIndex	Cracking Tolerance Index, CTIndex	Corrected for Voids
II-B	25	52-40	35	0	5.0	93.0	2.488	7.0	49.5	490.2	5.8	0.97	5236.1	48.7	207.6	230.7
II-B	25	52-40	35	0	5.0	92.8	2.488	7.2	49.3	423.6	7.4	1.05	4881.0	45.4	227.4	240.1
II-B	25	52-40	35	0	5.0	93.2	2.488	6.8	49.6	444.5	6.9	1.07	4881.2	45.4	209.0	244.4
II-B							Average	7.0	49.5	452.8	6.7	1.0	4999.4	46.5	214.7	238.4
II-B							StDev	0.2	0.1	27.8	0.7	0.0	167.3	1.6	9.0	5.7
II-B							COV	2.3	0.2	6.1	9.8	4.2	3.3	3.4	4.2	2.4
II-B	25	52-40	25	0	5.0	93.5	2.484	6.5	49.5	440.3	6.4	0.9	5002.9	46.5	235.7	297.5
II-B	25	52-40	25	0	5.0	93.4	2.484	6.6	49.5	439.1	6.3	0.93	4874.3	45.3	219.4	270.0
II-B	25	52-40	25	0	5.0	93	2.484	7.0	49.6	443	6.3	0.86	5015.7	46.7	245.2	272.5
II-B	25	52-40	25	0	5.0	92.9	2.488	7.1	49.3	460.3	5.8	1.11	4698.8	43.7	165.4	179.2
							Average	6.9	49.5	445.7	6.2	1.0	4897.9	45.6	216.4	254.8
							StDev	0.2	0.1	8.6	0.2	0.1	127.6	1.2	30.9	45.0
							COV	3.1	0.2	1.9	3.8	10.1	2.6	2.6	14.3	0.0
II-B	25	52-40	15	0	5.0	92.7	2.490	7.3	49.7	392.3	10.2	0.77	4686.5	43.6	415.3	427.5
II-B	25	52-40	15	0	5.0	93.4	2.490	6.6	49.7	349.0	11.3	0.62	4623.4	43.0	566.8	697.5
II-B	25	52-40	15	0	5.0	92.6	2.490	7.4	49.6	331.5	7.0	0.58	4376.8	40.7	355.7	356.9
							Average	7.1	49.7	357.6	9.5	0.7	4562.2	42.4	445.9	494.0
							StDev	0.4	0.0	25.6	1.8	0.1	133.6	1.2	88.9	146.8
							COV	5.0	0.1	7.1	19.2	12.5	2.9	2.9	19.9	29.7
II-B	25	52-28	0	0	5.0	93	2.489	7.0	48.3	435.2	5.73	1.29	4300.7	40.0	126.7	140.8
II-B	25	52-28	0	0	5.0	93.1	2.489	6.9	48.4	418.6	5.53	1.26	2889.3	36.2	114.1	130.1
II-B	25	52-28	0	0	5.0	92.5	2.489	7.5	49.4	740.4	5.6	2252621	6991.1	65.0	115.5	113.0
							Average	7.1	48.7	531.4	5.6	750874.5	4727.0	47.1	118.8	127.9
							StDev	0.3	0.5	147.9	0.1	1061895.1	1701.5	12.8	5.6	11.5
							COV	3.7	1.0	27.8	1.5	141.4	36.0	27.1	4.7	9.0
II-B	25	52-28	15	0	5.0	93.3	2.486	6.7	49.6	515.4	5.7	1.4	4910.2	45.7	134.0	160.7
II-B	25	52-28	15	0	5.0	93.5	2.486	6.5	49.5	560	5.9	1.40	5896.6	54.9	167.1	210.9
II-B	25	52-28	15	0	5.0	93.5	2.486	6.5	49.3	499.9	5.6	1.24	4959.2	46.1	150.2	189.6
							Average	6.6	49.5	525.1	5.7	1.3	5255.3	48.9	150.4	187.1
							StDev	0.1	0.1	25.5	0.1	0.1	453.9	4.2	13.5	20.6
							COV	1.4	0.3	4.9	2.2	5.6	8.6	8.7	9.0	11.0
II-B	25	52-28	25	0	5.0	92.6	2.48	7.4	49.1	549.3	6	1.49	5630.2	52.4	151.8	152.3
II-B	25	52-28	25	0	5.0	93.5	2.48	6.5	49.2	557	6.2	1.67	5722.8	53.2	142.7	180.1
II-B	25	52-28	25	0	5.0	93.3	2.48	6.7	49.5	667.5	6.3	1.69632	7489.3	69.7	184.2	221.0
							Average	7.0	49.3	591.3	6.2	1.6	6280.8	58.4	159.6	184.5
							StDev	0.5	0.2	54.0	0.1	0.1	855.4	8.0	17.8	28.2
							COV	6.5	0.3	9.1	2.0	5.6	13.6	13.7	11.2	15.3
II-B	25	52-28	35	0	5.0	92.7	2.473	7.3	49.2	551.8	6.6	1.56	3011.4	55.9	170.9	175.9
II-B	25	52-28	35	0	5.0	92.8	2.473	7.2	49.4	500.1	6.4	1.28	5515.2	51.3	185.0	195.4
II-B	25	52-28	35	0	5.0	93.0	2.473	7.0	49.1	559.3	6.5	1.63	5843.6	54.3	154.5	171.7
							Average	7.2	49.2	537.1	6.5	1.5	4790.1	53.8	170.1	181.0
							StDev	0.1	0.1	26.3	0.1	0.2	1264.8	1.9	12.5	10.3
							COV	1.7	0.2	4.9	1.3	10.1	26.4	3.5	7.3	5.7

Mix Type	Test Temp.C	Binder PG	TotBinder			Compaction Cnt, %	Gmm %	Air Voids%	Displacement Rate (mm/min)	Tensile Strength(KPa)	Displacement L75 (mm)	Post-Peak slope, S, [m75], N/m	Fracture/Failure Energy, Gf, (J/m2)	Work of Failure, Wf, (Joules)	Cracking	
			RAP%	Rejuv	%										Tolerance Index, CTIndex	Tolerance Index, CTIndex Corrected for Voids
II-B	25	52-40	15	0	5.0	93.8	2.49	6.2	49.7	256.5	5.3	0.62	2522.2	23.5	142.5	194.2
II-B	25	52-40	15	0	5.0	92.9	2.49	7.1	49.6	282.3	5.6	0.66	2834.8	26.4	161.1	174.5
II-B	25	52-40	15	0	5.0	93.6	2.49	6.4	49.5	278.8	5.6	0.68	2864.7	26.7	157.1	203.4
							Average	6.6	49.6	272.5	5.5	0.7	2740.6	25.5	153.6	190.7
							StDev	0.4	0.1	11.4	0.1	0.0	154.9	1.4	8.0	12.1
							COV	5.9	0.2	4.2	2.6	3.8	5.7	5.7	5.2	6.3
II-B	25	52-40	25	0	5.0	93.8	2.484	6.2	49.5	173.5	6.6	0.31	2013.1	18.7	283.1	385.8
II-B	25	52-40	25	0	5.0	92.9	2.484	7.1	49.7	118.2	8.5	0.21	1637.2	15.2	433.4	469.5
II-B	25	52-40	25	0	5.0	93.6	2.484	6.4	49.6	188.7	36.2	0.38	2058.9	19.1	222.9	288.6
							Average	6.6	49.6	160.1	17.1	0.3	1903.1	17.7	313.1	381.3
							StDev	0.4	0.1	30.3	13.5	0.1	188.9	1.8	88.5	73.9
							COV	5.9	0.2	18.9	79.1	23.3	9.9	9.9	28.3	19.4
II-B	25	52-40	25	DS	5.0	93.6	2.49	6.4	49.7	256.5	5.3	0.62	2522.2	23.5	142.5	184.5
II-B	25	52-40	25	DS	5.0	93.1	2.49	6.9	49.5	282.3	5.6	0.65	2834.8	26.4	161.1	183.6
II-B	25	52-40	25	DS	5.0	92.9	2.49	7.1	49.6	278.8	5.6	0.68	2864.7	26.7	157.1	170.2
							Average	6.8	49.6	272.5	5.5	0.7	2740.6	25.5	153.6	126.3
							StDev	0.3	0.1	11.4	0.1	0.0	154.9	1.4	8.0	67.5
							COV	4.3	0.2	4.2	2.6	3.8	5.7	5.7	5.2	53.4
II-B	25	52-28	50	0	5.0	92.6	2.467	7.4	49.2	765.5	6.1	2274922	7981.6	74.2	143.0	143.5
II-B	25	52-28	50	0	5.0	92.6	2.467	7.4	49.5	678.7	6.9	1996331	7319.3	68.1	168.5	169.1
II-B	25	52-28	50	0	5.0	93.2	2.467	6.8	49.4	802.9	5.3	3114477	6744.2	62.7	76.9	89.9
							Average	7.2	49.4	749.0	6.1		7348.4	68.3	129.5	134.2
							StDev	0.3	0.1	52.0	0.7		505.6	4.7	38.6	33.0
							COV	3.9	0.3	8.5	12.8	23.6	8.4	0.3	36.5	24.6
II-B	25	52-40	50	0	5.0	92.6	2.473	7.4	49.4	579.3	5.3	2006713	5228.2	48.6	91.9	92.2
II-B	25	52-40	50	0	5.0	92.9	2.473	7.1	49.3	674.7	4.9	2312335	5558	51.7	78.1	84.6
II-B	25	52-40	50	0	5.0	93.6	2.473	6.4	49.2	515	5.1	1776633	4532.9	42.2	86.2	111.6
							Average	7.0	49.3	589.7	5.1		5106.4	47.5	85.4	96.1
							StDev	0.5	0.1	80.4	0.2		427.3	4.0	5.7	11.4
							COV	7.4	0.2	13.6	3.2		8.4	8.3	6.6	11.8
II-B	25	52-28	25	1.5	5.0	93.7	2.480	6.3	49.3	740.1	5.6	1997570	7198.5	66.9	135.6	180.1
II-B	25	52-28	25	1.5	5.0	93.8	2.480	6.2	49.1	840.3	5.1	3328172	6994.5	65	72.0	98.1
II-B	25	52-28	25	1.5	5.0	93.6	2.480	6.4	49.2	718.4	5.4	2336296	6376.2	59.3	98.0	126.9
II-B	25	52-28	25	1.5	5.0	93.4	2.480	6.6	49.6	828.9	5.6	2751943	7650.8	71.2	103.1	126.9
II-B	25	52-28	25	1.5	5.0	93.1	2.480	6.9	49.7	763.6	5.4	2296234	7202.8	67	113.8	129.7
							Average	6.5	49.4	778.3	5.4		7084.6	65.9	104.5	132.3
							StDev	0.2	0.2	48.3	10.1		414.1	3.9	20.8	26.5
							COV	3.8	0.5	6.2	186.4		5.8	5.9	19.9	20.1
II-B	25	52-28	25	1.5	5.0	93.5	2.480	6.5	49.8	658.9	4.9	1996289	5706	53.1	93.9	118.5
II-B	25	52-28	25	1.5	5.0	93.8	2.480	6.2	49.5	673.3	5	2326034	5362.2	49.9	76.6	104.4
II-B	25	52-28	25	1.5	5.0	93.5	2.480	6.5	49.5	681	5.3	2094973	6105.3	56.8	103.7	130.9
							Average	6.4	49.6	671.1	5.1		5724.5	53.3	91.4	117.9
							StDev	0.1	0.1	9.2	0.2		303.7	2.8	11.2	47.2
							COV	2.2	0.3	1.4	3.4		5.3	5.3	12.3	40.0

Mix Type	Test Temp.C	Binder PG	RAP%	TotBinder Rejuv	Compaction Cnt, %	Gmm %	Air Voids%	Displacement Rate (mm/min)	Tensile Strength(KPa)	Displacement L75 (mm)	Post-Peak slope, S, m75 , N/m	Fracture/Failure Energy, Gf, (J/m2)	Work of Failure, Wf, (Joules)	Cracking Tolerance Index, CTIndex	Cracking Tolerance Index, CTIndex Corrected for Voids
II-B	25	52-40	25	1.5	5.0	93.1	2.484	6.9	49.3	557.9	5.5	1931283	5163.4	48	112.2
II-B	25	52-40	25	1.5	5.0	93.4	2.484	6.6	49.3	513.7	5.4	1480791	4969.7	46.2	149.4
II-B	25	52-40	25	1.5	5.0	94.1	2.484	5.9	49.3	594.7	5	1941287	5084.8	47.3	127.5
							Average	6.5	49.3	555.4	5.3		5072.6	47.2	129.7
							StDev	0.4	0.0	33.1	0.2		79.5	0.7	43.9
							COV	6.5	0.0	6.0	4.1		1.6	1.6	33.8
II-B	25	52-40	25	1.5	5.0	93.6	2.484	6.4	49.2	518.7	5.2	1682097	4610.7	42.9	123.0
II-B	25	52-40	25	1.5	5.0	93.1	2.484	6.9	49.4	463	5.8	1330423	4687.2	43.6	156.6
II-B	25	52-40	25	1.5	5.0	92.9	2.484	7.1	49.4	499.1	5.8	1265113	4823.4	44.9	160.9
							Average	6.8	49.3	493.6	5.6		4707.1	43.8	146.8
							StDev	0.3	0.1	23.1	0.3		88.0	0.8	16.9
							COV	4.3	0.2	4.7	5.1		1.9	0.0	11.5
II-B	25	52-28	35	1.5	5.0	92.7	2.473	7.3	49.2	854.7	6.1	2723657	8485.4	78.9	129.9
II-B	25	52-28	35	1.5	5.0	92.9	2.473	7.1	49.5	789.4	6.3	2338725	8025	74.6	154.9
II-B	25	52-28	35	1.5	5.0	92.8	2.473	7.2	49.6	769.7	6.1	3198975	7172.8	66.7	96.4
							Average	7.2	49.4	804.6	6.2		7894.4	73.4	127.1
							StDev	0.1	0.2	36.3	0.1		543.8	5.1	24.0
							COV	1.1	0.3	4.5	1.5		6.9	6.9	18.9
II-B	25	52-28	35	1.5	5.0	92.8	2.473	7.2	49.6	809.6	5.4	2553166	7661.8	71.3	113.7
II-B	25	52-28	35	1.5	5.0	92.4	2.473	7.6	49.3	723.6	5.4	2747847	6420.6	59.7	80.4
II-B	25	52-28	35	1.5	5.0	93.4	2.473	6.6	49.6	766.8	5.8	2252941	7207.3	67	151.2
							Average	7.1	49.5	766.7	5.5		7096.6	66.0	115.1
							StDev	0.4	0.1	35.1	0.2		512.7	4.8	51.1
							COV	5.8	0.3	4.6	3.4		7.2	7.3	44.4
II-B	25	52-40	35	1.5	5.0	92.7	2.488	7.3	49.4	506.9	5.8	1323695	5111.1	47.5	154.7
II-B	25	52-40	35	1.5	5.0	92.4	2.488	7.6	49.5	550.9	6.2	1327048	5989.7	55.7	176.5
II-B	25	52-40	35	1.5	5.0	92.4	2.488	7.6	49.3	490.7	6.2	1392277	4969.6	46.2	140.6
II-B	25	52-40	35	1.5	5.0	92.7	2.488	7.3	49.7	526.5	5.7	1312566	5131.5	47.7	152.8
							Average	7.5	49.5	518.8	6.0		5300.5	49.3	156.1
							StDev	0.2	0.1	22.5	0.2		402.8	3.8	13.0
							COV	2.0	0.3	4.3	3.8		7.6	7.6	8.3
II-B	25	52-40	35	1.5	5.0	92.2	2.488	7.8	49.5	551.9	6.1	1377184	6068.9	56.4	161.2
II-B	25	52-40	35	1.5	5.0	92.7	2.488	7.3	49.5	523	6.3	1310413	5587.8	52	183.9
II-B	25	52-40	35	1.5	5.0	92.2	2.488	7.8	49.6	490.5	5.7	1348699	4838.8	45	122.8
II-B	25	52-40	35	1.5	5.0	92.7	2.488	7.3	49.5	518	5.7	1453767	4944	46	133.1
							Average	7.6	49.5	520.9	6.0		5359.9	49.9	150.2
							StDev	0.3	0.0	21.8	0.3		499.8	4.6	24.0
							COV	3.3	0.1	4.2	4.4		9.3	9.3	16.0

Cracking Tolerance Index, CTIndex																	Cracking Tolerance Index, CTIndex Corrected for Voids
Mix Type	Test Temp.C	Binder PG	RAP%	Rejuv	TotBinder Cnt, %	Compaction %	Gmm	Air Voids%	Displacement Rate (mm/min)	Tensile Strength(KPa)	Displacement L75 (mm)	Post-Peak slope, S, [m75], N/m	Fracture/Failure Energy, Gf, (J/m2)	Work of Failure, Wf, (Joules)	Cracking Tolerance Index, CTIndex	Cracking Tolerance Index, CTIndex Corrected for Voids	
II-B	25	52-28	50	1.5	5.0	92.9	2.467	7.1	49.4	794.3	6.3	2128860	8677.3	80.7	172.4	186.8	
II-B	25	52-28	50	1.5	5.0	92.2	2.467	7.8	49.7	684.3	6.4	2052977	7188.2	66.9	148.3	134.4	
II-B	25	52-28	50	1.5	5.0	92.9	2.467	7.1	49.3	763.8	5.7	2306564	7301.9	67.9	120.4	130.4	
							Average	7.3	49.5	747.5	6.1		7722.5	71.8	147.0	150.5	
							StDev	0.3	0.2	46.4	0.3		676.8	6.3	21.2	25.7	
							COV	4.5	0.3	6.2	5.0		8.8	8.7	14.5	17.1	
II-B	25	52-28	50	1.5	5.0	92.7	2.467	7.3	49.6	883.1	5.6	3295186	7922.9	73.7	89.6	92.2	
II-B	25	52-28	50	1.5	5.0	93.3	2.467	6.7	49.5	899.4	6.2	2805280	8951.2	83.2	131.7	158.0	
II-B	25	52-28	50	1.5	5.0	92.8	2.467	7.2	49.6	887.5	5.6	3087652	7986.1	74.3	95.8	101.2	
							Average	7.1	49.6	890.0	5.8		8286.7	77.1	105.7	117.1	
							StDev	0.3	0.0	6.9	0.3		470.6	4.3	18.6	29.1	
							COV	3.7	0.1	0.8	4.9		5.7	5.6	17.6	24.9	
II-B	25	52-40	50	1.5	5.0	93.1	2.473	6.9	49.6	564.1	5.8	1710736	5496	51.1	123.6	140.9	
II-B	25	52-40	50	1.5	5.0	92.7	2.473	7.3	49.5	464.9	6.4	1334263	5054.4	47	161.8	166.6	
II-B	25	52-40	50	1.5	5.0	93.1	2.473	6.9	49.5	548.8	5.9	1567522	5389.1	50.1	135.4	154.3	
							Average	7.0	49.5	525.9	6.0		5313.2	49.4	140.3	153.9	
							StDev	0.2	0.0	43.6	0.3		188.1	1.7	16.0	10.5	
							COV	2.7	0.1	8.3	4.4		3.5	3.5	11.4	6.8	
II-B	25	52-40	50	1.5	5.0	93.2	2.473	6.8	49.5	544.7	6.6	1439837	5903.9	54.9	180.8	211.4	
II-B	25	52-40	50	1.5	5.0	93.1	2.473	6.9	49.5	588.5	6	1427200	6192.4	57.6	174.7	199.1	
II-B	25	52-40	50	1.5	5.0	93.9	2.473	6.1	49.8	593.9	5.9	1829322	5981.2	55.6	128.3	179.4	
							Average	6.6	49.6	575.7	6.2		6025.8	56.0	161.3	196.6	
							StDev	0.4	0.1	22.0	0.3		121.9	1.1	23.4	13.2	
							COV	5.4	0.3	3.8	5.0		2.0	2.0	14.5	6.7	
II-B	25	52-40	0	0	5.0	92.9	2.492	7.1	49.7	387.6	6.1	731295	4517.5	42	250.0	270.8	
II-B	25	52-40	0	0	5.0	92.6	2.492	7.4	49.5	371.2	5.8	892879	3781.9	35.2	163.2	163.8	
II-B	25	52-40	0	0	5.0	93	2.492	7.0	49.7	399.2	5.9	915450	4106.2	38.2	176.4	196.0	
II-B	25	52-40	0	0	5.0	93.4	2.492	6.6	49.4	380.6	5.3	1081308	3443.2	32	112.8	138.8	
							Average	7.0	49.6	384.7	5.8		3962.2	36.9	175.6	192.4	
							StDev	0.3	0.1	10.2	0.3		397.2	3.7	49.1	49.6	
							COV	4.1	0.3	2.7	5.1		10.0	10.0	27.9	25.8	

APPENDIX C

INDIRECT TENSION TEST RAW DATA SUMMARY CREEP COMPLIANCE, M-VALUE, AND POISSON'S RATIO									
Temp., F:	-20			-10			0		
Loading Time s	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$
10	4.25E-06	0.03	0.50	8.97E-06	0.01	0.50	1.94E-05	0.05	0.50
13	4.31E-06	0.03	0.50	9.00E-06	0.02	0.50	2.03E-05	0.09	0.50
16	4.28E-06	0.02	0.50	9.06E-06	0.04	0.50	2.08E-05	0.13	0.50
20	4.26E-06	0.02	0.50	9.19E-06	0.05	0.50	2.14E-05	0.16	0.50
25	4.36E-06	0.02	0.50	9.26E-06	0.06	0.50	2.22E-05	0.19	0.50
32	4.37E-06	0.02	0.50	9.41E-06	0.07	0.50	2.29E-05	0.23	0.50
40	4.31E-06	0.01	0.50	9.55E-06	0.08	0.50	2.35E-05	0.26	0.50
50	4.34E-06	0.01	0.50	9.80E-06	0.10	0.50	2.51E-05	0.30	0.50
63	4.38E-06	0.01	0.50	9.99E-06	0.11	0.50	2.72E-05	0.33	0.50
79	4.41E-06	0.00	0.50	1.03E-05	0.12	0.50	3.00E-05	0.37	0.50
100	4.46E-06	0.00	0.50	1.07E-05	0.13	0.50	3.58E-05	0.40	0.50

Figure 2: PG52-28 No RAP Data

INDIRECT TENSION TEST RAW DATA SUMMARY CREEP COMPLIANCE, M-VALUE, AND POISSON'S RATIO									
Temp., F:	-20			-10			0		
Loading Time s	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$
10	2.44E-06	0.05	0.50	1.26E-05	-0.13	0.50	9.38E-06	0.23	0.50
13	2.49E-06	0.06	0.50	1.20E-05	-0.16	0.50	9.94E-06	0.25	0.50
16	2.50E-06	0.07	0.50	1.16E-05	-0.18	0.50	1.05E-05	0.27	0.50
20	2.56E-06	0.08	0.50	1.12E-05	-0.21	0.50	1.12E-05	0.29	0.50
25	2.61E-06	0.10	0.50	1.06E-05	-0.23	0.50	1.19E-05	0.32	0.50
32	2.67E-06	0.11	0.50	1.00E-05	-0.26	0.50	1.30E-05	0.34	0.50
40	2.76E-06	0.12	0.50	9.39E-06	-0.29	0.50	1.41E-05	0.36	0.50
50	2.81E-06	0.13	0.50	8.71E-06	-0.32	0.50	1.54E-05	0.39	0.50
63	2.91E-06	0.15	0.50	8.11E-06	-0.34	0.50	1.68E-05	0.41	0.50
79	3.01E-06	0.16	0.50	7.53E-06	-0.37	0.50	1.85E-05	0.43	0.50
100	3.07E-06	0.17	0.50	6.96E-06	-0.40	0.50	2.02E-05	0.46	0.50

Figure 3: PG52-28 35% RAP Data

INDIRECT TENSION TEST RAW DATA SUMMARY									
CREEP COMPLIANCE, M-VALUE, AND POISSON'S RATIO									
Temp., F:	-20			-10			0		
Loading Time s	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$
10	4.68E-06	0.09	0.50	9.82E-06	0.36	0.50	1.27E-05	0.22	0.50
13	4.81E-06	0.11	0.50	1.06E-05	0.36	0.50	1.35E-05	0.26	0.50
16	4.93E-06	0.12	0.50	1.14E-05	0.37	0.50	1.44E-05	0.29	0.50
20	5.07E-06	0.13	0.50	1.26E-05	0.37	0.50	1.54E-05	0.32	0.50
25	5.24E-06	0.15	0.50	1.37E-05	0.37	0.50	1.66E-05	0.36	0.50
32	5.43E-06	0.16	0.50	1.50E-05	0.37	0.50	1.82E-05	0.39	0.50
40	5.65E-06	0.18	0.50	1.63E-05	0.37	0.50	1.99E-05	0.43	0.50
50	5.87E-06	0.19	0.50	1.76E-05	0.37	0.50	2.20E-05	0.46	0.50
63	6.15E-06	0.20	0.50	1.93E-05	0.37	0.50	2.46E-05	0.49	0.50
79	6.44E-06	0.21	0.50	2.10E-05	0.37	0.50	2.75E-05	0.53	0.50
100	6.69E-06	0.23	0.50	2.21E-05	0.37	0.50	3.10E-05	0.56	0.50

Figure 4: PG52-28 50% RAP Data

INDIRECT TENSION TEST RAW DATA SUMMARY									
CREEP COMPLIANCE, M-VALUE, AND POISSON'S RATIO									
Temp., F:	-30			-20			-10		
Loading Time s	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$
10	6.18E-06	0.08	0.50	8.27E-06	-0.11	0.50	1.05E-05	0.06	0.50
13	6.25E-06	0.10	0.50	8.25E-06	-0.07	0.50	1.08E-05	0.14	0.50
16	6.40E-06	0.12	0.50	8.22E-06	-0.03	0.50	1.14E-05	0.21	0.50
20	6.56E-06	0.14	0.50	8.15E-06	0.01	0.50	1.20E-05	0.28	0.50
25	6.82E-06	0.16	0.50	8.01E-06	0.05	0.50	1.28E-05	0.35	0.50
32	7.18E-06	0.18	0.50	8.18E-06	0.09	0.50	1.39E-05	0.43	0.50
40	7.47E-06	0.20	0.50	8.49E-06	0.13	0.50	1.52E-05	0.49	0.50
50	7.87E-06	0.22	0.50	8.82E-06	0.17	0.50	1.69E-05	0.56	0.50
63	8.27E-06	0.24	0.50	9.16E-06	0.22	0.50	1.93E-05	0.64	0.50
79	8.75E-06	0.26	0.50	9.59E-06	0.26	0.50	2.32E-05	0.71	0.50
100	9.18E-06	0.28	0.50	1.06E-05	0.30	0.50	2.88E-05	0.78	0.50

Figure 5: PG52-40 No RAP Data

INDIRECT TENSION TEST RAW DATA SUMMARY CREEP COMPLIANCE, M-VALUE, AND POISSON'S RATIO									
Temp., F:	-30			-20			-10		
Loading Time s	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$
10	9.01E-06	0.17	0.50	7.38E-06	0.13	0.50	1.47E-05	0.17	0.50
13	9.62E-06	0.24	0.50	7.73E-06	0.18	0.50	1.57E-05	0.23	0.50
16	1.01E-05	0.29	0.50	8.07E-06	0.22	0.50	1.66E-05	0.27	0.50
20	1.09E-05	0.34	0.50	8.49E-06	0.27	0.50	1.78E-05	0.32	0.50
25	1.18E-05	0.40	0.50	9.06E-06	0.31	0.50	1.91E-05	0.37	0.50
32	1.30E-05	0.46	0.50	9.81E-06	0.36	0.50	2.08E-05	0.42	0.50
40	1.46E-05	0.52	0.50	1.08E-05	0.40	0.50	2.25E-05	0.47	0.50
50	1.64E-05	0.57	0.50	1.20E-05	0.45	0.50	2.51E-05	0.52	0.50
63	1.89E-05	0.63	0.50	1.33E-05	0.49	0.50	2.89E-05	0.57	0.50
79	2.19E-05	0.69	0.50	1.47E-05	0.53	0.50	3.32E-05	0.62	0.50
100	2.69E-05	0.74	0.50	1.72E-05	0.58	0.50	4.19E-05	0.67	0.50

Figure 6: PG52-40 25% RAP Data

INDIRECT TENSION TEST RAW DATA SUMMARY CREEP COMPLIANCE, M-VALUE, AND POISSON'S RATIO									
Temp., F:	-10			-20			-30		
Loading Time s	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$
10	1.95E-05	0.13	0.50	5.98E-06	-0.01	0.46	9.36E-06	-0.07	0.46
13	2.04E-05	0.16	0.50	6.05E-06	0.02	0.46	9.43E-06	-0.02	0.46
16	2.11E-05	0.18	0.50	6.13E-06	0.04	0.46	9.49E-06	0.03	0.46
20	2.19E-05	0.21	0.50	6.19E-06	0.07	0.46	9.59E-06	0.08	0.46
25	2.32E-05	0.23	0.50	6.30E-06	0.10	0.46	9.74E-06	0.12	0.46
32	2.45E-05	0.26	0.50	6.40E-06	0.13	0.46	9.94E-06	0.17	0.46
40	2.60E-05	0.28	0.50	6.64E-06	0.16	0.46	1.03E-05	0.22	0.46
50	2.77E-05	0.31	0.50	6.93E-06	0.19	0.46	1.10E-05	0.27	0.46
63	2.99E-05	0.33	0.50	7.23E-06	0.22	0.46	1.18E-05	0.32	0.46
79	3.24E-05	0.36	0.50	7.58E-06	0.24	0.46	1.27E-05	0.37	0.46
100	3.48E-05	0.39	0.50	8.20E-06	0.27	0.46	1.54E-05	0.42	0.46

Figure 7: PG52-40 35% RAP Data

INDIRECT TENSION TEST RAW DATA SUMMARY									
CREEP COMPLIANCE, M-VALUE, AND POISSON'S RATIO									
Temp., F:	-30			-20			-10		
Loading	Creep			Creep			Creep		
Time	Comp.	m(t)	$\mu(t)$	Comp.	m(t)	$\mu(t)$	Comp.	m(t)	$\mu(t)$
s	1/psi			1/psi			1/psi		
10	4.82E-06	0.07	0.50	5.92E-06	0.07	0.44	1.27E-05	0.18	0.44
13	4.92E-06	0.08	0.50	6.07E-06	0.10	0.44	1.33E-05	0.23	0.44
16	5.03E-06	0.10	0.50	6.22E-06	0.12	0.44	1.40E-05	0.28	0.44
20	5.13E-06	0.11	0.50	6.37E-06	0.15	0.44	1.50E-05	0.32	0.44
25	5.29E-06	0.13	0.50	6.55E-06	0.18	0.44	1.61E-05	0.37	0.44
32	5.45E-06	0.14	0.50	6.94E-06	0.21	0.44	1.80E-05	0.43	0.44
40	5.62E-06	0.16	0.50	7.38E-06	0.24	0.44	2.01E-05	0.47	0.44
50	5.87E-06	0.17	0.50	7.77E-06	0.26	0.44	2.27E-05	0.52	0.44
63	6.11E-06	0.19	0.50	8.25E-06	0.29	0.44	2.56E-05	0.57	0.44
79	6.37E-06	0.20	0.50	8.80E-06	0.32	0.44	2.89E-05	0.62	0.44
100	6.65E-06	0.22	0.50	9.36E-06	0.35	0.44	3.58E-05	0.67	0.44

Figure 8: PG52-40 50% RAP Data