Research on High-RAP Mixtures with Rejuvenator-Field Implementation

FINAL REPORT

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16. Abstract

The use of Rejuvenating Agents (RAs), as Recycled Asphalt Pavement (RAP) modifiers, has been increasing over the past years. However, the field performance of asphalt mixtures containing high-RAP materials and modified with RAs has raised some concerns regarding the long-term performance of RAs. This study evaluated the laboratory and field performance of high-RAP mixtures with and without bio-oil RA. Three sets of plant-produced specimens were collected: 1) laboratory-compacted; 2) field-compacted and cored after paving; and 3) field-compacted and cored after one and two years. The Hamburg Wheel Tracking (HWT) test was used to evaluate the specimens' resistance to rutting and moisture damage. The Semi-Circular Bending (SCB) fracture test was performed to examine the specimens' resistance to cracking. The results showed that using the bio-oil RA resulted in an increase in cracking resistance and a decrease in rutting and moisture damage resistance of the RAP-blended mixtures compacted in the laboratory. However, after one and two years of exposure to the environmental conditions and traffic loads, the effect of RA on moisture and rutting susceptibility of the mixtures reduced. The cracking resistance of specimens, estimated by Flexibility Index (FI) and Cracking Resistance Index (CRI), and Tukey's Honestly Significant Difference (HSD) test results implied that the bio-oil RA used in this study could not provide long-term improvement for the RAP-blended mixtures in the laboratory-aging and field-aging conditions. The field performance observations showed that the use of the bio-oil RA in the second layer might have indirectly resulted in more cracks (fatigue and thermal) and ruts in the surface layer.

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Table of Contents

List of Figures

List of Tables

Glossary

AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
CRI	Cracking Resistance Index
DOT	Department of Transportation
ESAL	Equivalent Single Axle Load
FAM	Fine Aggregate Mixture
FC0	Field Compacted 0-year Sample
FC1	Field Compacted 1-year Sample
FC2	Field Compacted 2-year Sample
FCR0	Field Compacted 0-year Sample with Rejuvenating agent
FCR1	Field Compacted 1-year Sample with Rejuvenating agent
FCR2	Field Compacted 2-year Sample with Rejuvenating agent
FI	Flexibility Index
G_f	Fracture Energy
HSD	Honestly Significant Difference
HWT	Hamburg Wheel Tracking
I-FIT	Illinois Flexibility Index Test
IRI	International Roughness Index
LC	Lab Compacted Sample
LCLT	Lab Compacted Long-term Aged Sample
LCLTR	Lab Compacted Long-term Aged Sample with Rejuvenating Agent
LCR	Lab Compacted Sample with Rejuvenating Agent
MTD	Mean Texture Depth
NCAT	National Center for Asphalt Technology
NDOT	Nebraska Department of Transportation
OT	Overlay Test
PG	Performance Grading
P_{max}	Peak Load
RA	Rejuvenating Agent
RAP	Reclaimed Asphalt Pavement
RAS	Recycled Asphalt Shingles
RD	Rut Depth
SCB	Semi-Circular Bending
SIP	Strip Inflection Point
TSR	Tensile Strength Ratio

Chapter 1 Introduction

The use of reclaimed asphalt pavement (RAP) in asphalt mixtures has gained considerable attention in recent years due to its economic benefits and environmental advantages. The use of RAP in new asphalt pavement reduces the cost of materials and the impact associated with extraction, transportation, and processing of conventional asphalt materials. In the United States, there are different guidelines for the use of RAP in asphalt mixtures; the state of Nebraska allows the use of 40% -55% of RAP in asphalt mixture. Although there are benefits to a higher percentage of RAP in asphalt mixtures, there are concerns predominantly related to higher stiffness and partial coating of the binder with aggregates. Higher stiffness results in poor workability and eventually leads to improper compaction in the pavement layers, leading to premature failure of asphalt pavement (Mogawer et al., 2012).

To address this concern, chemical additives, so-called rejuvenating agents (RAs), can be introduced to RAP-blended asphalt mixtures to improve their engineering properties by recovering the properties of the aged asphalt binder in RAP materials. The basic function of an RA is to restore the balance in the chemical composition of an aged binder that was altered during the service life of the pavement (Tran, Taylor, and Willis, 2012; Haghshenas et al., 2022). A survey of the literature shows that in comparison to unmodified high-RAP mixtures, the addition of RAs to RAP-blended mixtures improves the cracking resistance of these mixtures while increasing the susceptibility to rutting (Karlsson and Isacsson, 2006; Ozer et al., 2016; I. L. Al-Qadi, Qazi, and Carpenter, 2012; Xie et al., 2017; West et al., 2009; Nabizadeh et al., 2017; Nsengiyumva et al., 2020). There is no general agreement in the literature on the effect of RAs on the resistance of high-RAP asphalt mixtures to moisture damage. It should be noted that the term of rejuvenating agent (RA) in this study refers to recycling agent which can be either a rejuvenator or a softening agent. Since rejuvenating agent has been used in pervious phases of this study, and to avoid any confusion for readers, this term (i.e., rejuvenating agent) is used here as well.

There are many studies that have evaluated the performance of laboratory-produced asphalt mixtures containing RAP with and without RAs (Kaseer et al. 2020; Zaumanis and Mallick, 2015; Haghshenas et al., 2018). However, the field performance of the mixtures was not examined in those studies. A few studies have compared and correlated the laboratory and field performance of RAP-blended mixtures with and without RAs (Xie et al., 2017; R. West et al., 2009). For instance, Tran et al. (Tran, Taylor, and Willis, 2012) used a tall oil RA to enhance the performance of a 40%-RAP mixture to the level of the control mixture. They reported that in comparison to a control mixture with 30% RAP, the use of the RA in the 40%-RAP mixture resulted in statistically similar resistance to intermediate- and low-temperature cracking. Furthermore, a field survey of the test sections ten months after construction showed reflective cracking on the surface of the pavement built with RAP-blended mixtures treated with the RA. In another study, Jahangiri et al. focused on using RAP and Recycled Asphalt Shingles (RAS) with additives including RA (EvoFlex®), warm mix additive, anti-stripping agent, and baghouse fines; the study investigated eighteen pavements of dense-grade asphalt mixtures in Missouri (Jahangiri et al., 2019). The significant finding from the study was the detection of brittle behavior of the asphalt mixture in most of the sections. Six pavement sections performed well in the disk-shaped compaction test; the probable reasons were the selection of a softer binder grade and the use of low recycling content.

Although a few studies have attempted to fill the knowledge gap in understanding the field performance of asphalt mixtures containing a high percentage of RAP materials and RAs, more field and laboratory data are still needed; a better understanding of the complex behavior of these mixtures is important to the development of more effective recycling practices.

1.1 Research Objectives and Scope

The primary goal of this research is to evaluate the recycling practice that has recently been implemented in Nebraska. This study has two specific objectives:

- To evaluate the variability, properties, and performance of plant-produced and field-implemented mixtures containing high-RAP materials with and without RA.
- To compare the field performance characteristics of high-RAP asphalt mixtures with and without RA by monitoring their performance over time.

To this end, two mixtures, a high-RAP mixture with and without RA, were studied in three different scenarios: 1) laboratory-compacted, 2) field-compacted and cored after construction, and 3) field-compacted and cored one and two years after construction. These specimens were tested for susceptibility to cracking, rutting, and moisture. The semi-circular bending (SCB) fracture test and the Hamburg Wheel Tracking (HWT) test were used to evaluate the performance of the mixtures and correlate their performance under different scenarios.

1.2 Organization of the Report

This report contains six chapters. Chapter 1 is an overall introduction to the project, including the research objectives and scope. Chapter 2 is a summary of phase I and phase II of this research study and literature review on the field performance of pavements due to the addition of RAs. Chapter 3 describes the materials and specimen fabrication procedures for two tests: the SCB test, and the HWT test. Chapter 4 provides and interprets the results of the tests used to understand the cracking and rutting performance of the specimens as well as their moisture damage resistance. Chapter 5 reports field performance observations, focusing on four different distresses including International Roughness Index (IRI), Rut Depth (RD), fatigue, and thermal cracking. Chapter 6 summarizes the major findings of the project and makes recommendations for future research.

Chapter 2 Background

The use of reclaimed asphalt pavement (RAP) materials has been increasing quite rapidly over the past few decades, and many Departments of Transportation (DOTs) have been consistently interested in increasing the amount of RAP in their asphalt mixtures. Currently, Nebraska DOT allows RAP materials in some plant mixtures for asphalt pavements up to about 50%. The major motivation for the utilizing of high-RAP content mixes for the pavement is due to the advantage of lowering the use of expensive virgin aggregates and binders, recycling of construction materials, and environmental preservation. The use of high-RAP mixture is typically incorporated with RA to improve mixture properties. This inherently induces various complexities such as: (1) the interaction of the aged RAP materials with the virgin materials and their influence on the overall performance of the asphalt mixture, and (2) the interaction of the RA with the aged RAP and virgin binder. Another important factor that affects the performance of the high-RAP pavements in the field is the methods and technologies adopted by the plants or manufacturers producing mixtures. Although many studies have investigated the influence of RAs on the laboratory performance of high-RAP mixtures, the laboratory-level investigation is not sufficient to address how production parameters affect the blending of RAs, RAP, and virgin materials, and eventually, their influence on the field performance of the RA treated high-RAP asphalt mixtures.

2.1 Summary of Phase I and Phase II of this study

When using high-RAP in asphalt mixtures, the key factors to be considered include but are not limited to: (i) the use of right RAs based on their chemical properties, (ii) the use of an optimal dosage and blending method of the selected RA to satisfy desired mixture and pavement performance. Performance indicators such as rutting, cracking, and moisture susceptibility are some of the important distresses that need to be evaluated in the laboratory. For six years, the research team has conducted NDOT-sponsored research projects on high-RAP mixtures treated with RAs. The research was conducted in two phases, and in both, 65% RAP was applied to a typical Nebraska asphalt mixture. Three different RAs: petroleum-tech based, green-tech based, and agriculture-tech based materials, were used, this ensured variability in the chemical properties of the RAs. The research project evaluated various mechanical and chemical properties of asphalt mixtures, fine aggregate matrix (FAM) mixtures, and binders modified by the RAs. Test results in different length scales (i.e., asphalt mixture, FAM, and binder) demonstrated that the RAs made high-RAP mixtures are more compliant (ductile), which decreased stiffness and improved the fatigue resistance of high-RAP materials. Also, the recommended practices of different RAs were sought by further investigating the properties and performance of mixtures/materials at different treatments (i.e., blending dosages and curing methods) of RAs.

After determining the optimal dosages, a series of laboratory testing on mixtures treated with the RAs were undertaken to evaluate two primary mixture-level characteristics, such as cracking and rutting. The mixture testing results confirmed the observations from the binder level in that RAs softened RAP-blended asphalt mixtures and improved their cracking resistance. Several RA blending methods were also evaluated, and it was concluded that they did not significantly affect the testing outcomes. This implied that after mixing RAP with RA, curing was not necessary. Furthermore, it was also found that blending RA into a virgin binder before mixing with virgin aggregates and RAP minimally affected the testing results as well, as shown in Figure 2-1. From the asphalt mixture testing, it was concluded that homogenous mixing of RA into RAP was the most important factor in achieving consistent performance from asphalt mixtures with high-RAP content. As illustrated in Figure 2-2, research findings from phases I and II imply potential implementation of the high-RAP projects in Nebraska with proper use of RAs.

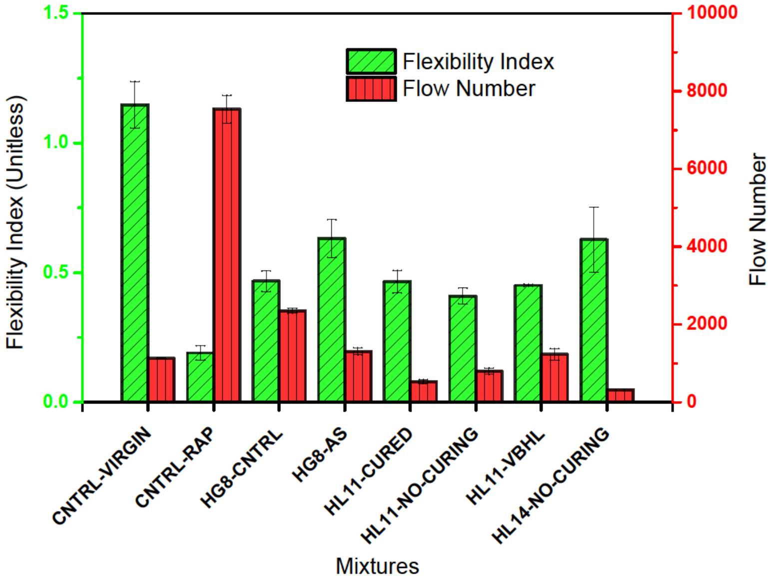


Figure 2-1. Mixture test results from Phase II (Haghshenas et al. 2019).

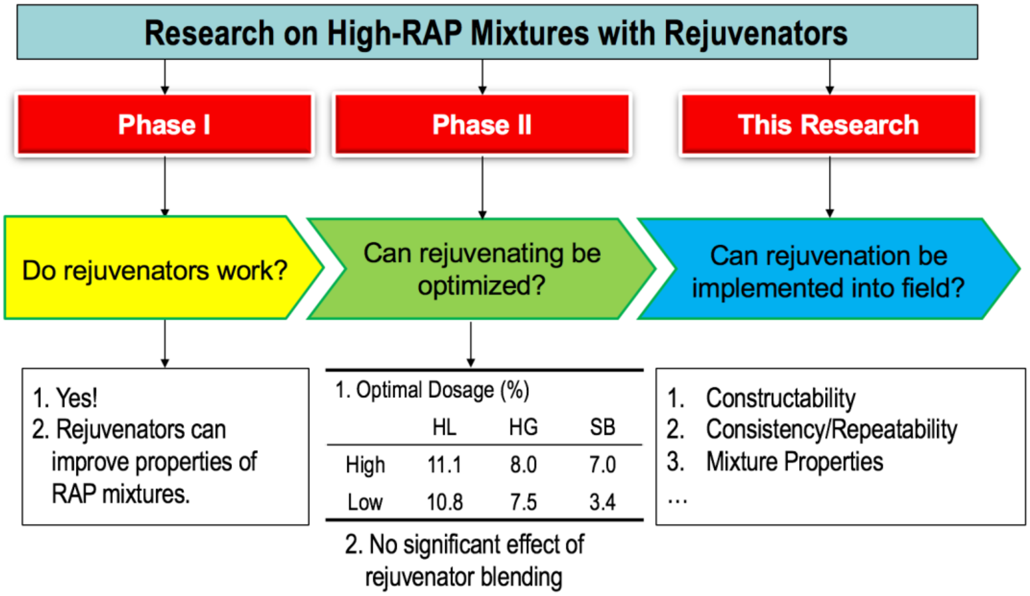


Figure 2-2. Research needs from previous efforts (Phases I and II) (Haghshenas et al. 2016 and 2019).

2.2 Summary of National Center for Asphalt Technology (NCAT) Projects

One of the studies associated with the performance of RAs on the pavement structure was performed by National Center for Asphalt Technology (NCAT) (West et al. 2021). The research focused on using a bio-oil RA (Delta S) to enhance the performance of RAP-blended asphalt mixtures. Delta S was utilized in an asphalt mixture containing 20% RAP, 5% RAS, and a performance grade (PG 67-22) virgin binder, and the resultant mixture was placed on the surface of test section N7. Also, a control test track section referred to N1 was laid using a mixture with 20% RAP and a PG 67-22 virgin binder for the field performance comparison and the cracking group experiment. The test track sections have been trafficked since 2015. The information of the N1 and N7 test sections is presented in Table 2-1.

Table 2-1. The information of N1 and N7 test sections.

Description	**Properties**
Compaction Effort	80 gyrations
Base and Binder Asphalt Layer	High Polymer Modified Asphalt Mixture
Thickness of Asphalt Layer	15.2 cm (6 in.)
Thickness of Base layer and Type	15.2 cm (6 in.) crushed, granite
Subgrade Type	A-4 (AASHTO Classification)
Surface layer PG Grading	PG 67-22

The field performance of both sections, N1 and N7, were monitored at each research cycle of 2015 and 2018. Different observations were made based on cracking, rutting, International Roughness Index (IRI), and Mean Texture Depth (MTD). The changes observed between these distresses in 2018 research cycle concerning ESALs are presented in Table 2-2.

Table 2-2. Field observation in 2015 and 2018 research cycles.

Distresses	Year	Section N1	Section N7
Cracking (% of the lane area)	2016	0.20% @6.2 million ESALs	0.10% @6.2 million ESALs
	2017	21.30% @9.7 million ESALs	10.20% @9.7 million ESALs
	2018	11.5% @ 16.6 million ESALs	NR
	2019	NR	22.9% @ 8.9 million ESALs
	2020	37.4% @ 16.9 million ESALs	33.1% @ 13.3 million ESALs (before rejuvenator spray)
			53.4% @ 14.2 million ESALs (after rejuvenator spray)
	2021	45.8% @ 16.9 million ESALs	NR
Rutting	2017	Good	Good
	2021	Good	Good
IRI	2017	Good	Good
	2021	Good	Good

NR: Not Reported

Table 2-2 shows that the cracking performance of the section (N7) was initially good when the RA was utilized. However, with the application of Delta S spray, more surface cracks were observed in the section with RA at lesser ESALs (Table 2-2). The spraying of RA provided a softening effect to distressed asphalt, and the failure related to cracking was accelerated. On the other hand, both sections provided good ride quality and rutting performances during the research cycles.

In addition, the study also correlated the field performance results with the laboratory test results, including Texas Overlay Test (Texas-OT), NCAT Overlay Test (NCAT-OT), and Illinois Flexibility Index Test (I-FIT). The Texas-OT and I-FIT tests showed that the cracking resistance of field and laboratory specimens is statistically similar. In contrast, the NCAT-OT test presented statistically different results between field and laboratory specimens in two sections. They concluded that the reaction time of aged binder and RA could significantly affect the field performance of high-RAP mixtures. Also, it was recommended that the long-term performance of RA modified mixtures needs to be monitored in the field carefully.

Xie et al. (2017) also correlated the field and laboratory performance of asphalt mixtures with RAP and RAS modified with various RAs. Three different mixtures were examined in this study, including 1) control mixture with 20 % of RAP materials, 2) mixtures consisting of 25 % RAP and 5% RAS treated by fatty acid derivatives, and 3) mixtures consisting of 25 % RAP and 5% RAS treated by bio-oil produced through fast pyrolysis of pine trees. The control mixtures were prepared at the typical hot mix asphalt production temperature; 149 ˚C. While the mixtures with RAs were prepared at 129 ˚C, which is considered as a typical warm mix asphalt production temperature.

The mixtures were tested to evaluate moisture susceptibility, rutting resistance, and cracking resistance. Based on the tensile strength ratio (TSR), it was observed that the TSR of the control mixtures were higher than the TSR of the mixtures modified by RAs, indicating that the addition of RAs to the mixtures may result in a decrease in moisture damage resistance. However, the control mixture exhibited more rutting compared to both mixtures modified with RAs. The cracking resistance of the mixtures was characterized using the Louisiana SCB test, Overlay Test (OT), and Illinois Flexibility Index Test (I-FIT). It was reported that the control mixture had a higher resistance to crack, regardless of testing methods.

In addition to the laboratory performance testing, early field performances after two years were monitored. The field performance observations indicated that all of the pavement sections had a good ride quality and rutting performances, less than Federal Highway Administration

(FHWA) thresholds; 2.7 mm/m of IRI and 10 mm of rut depth, irrespective of the mixture utilized. There was no negative effect of RAs reported in the case of IRI and rutting. In terms of field cracking performance, the control section showed higher resistance to cracking, and the sections built with mixtures modified by RAs were more prone to crack. This study suggested that the dosages of RAs need to be carefully selected based on the percentage of RAP utilized.

Chapter 3 Site Location, Materials Selection, and Specimens Fabrication

This chapter describes the materials and the specimen fabrication procedures used in this study. In addition, the location of the test sections, data from the cored and the laboratory-compacted specimens are presented.

3.1 Site Location and Pavement Sections

The control and test sections were built in September 2019. The sections were located at highway NE-21 in Nebraska and monitored for two years. Figure 3-1 shows the location of the pavement sections and the schematic diagram for the location of the test stretch.

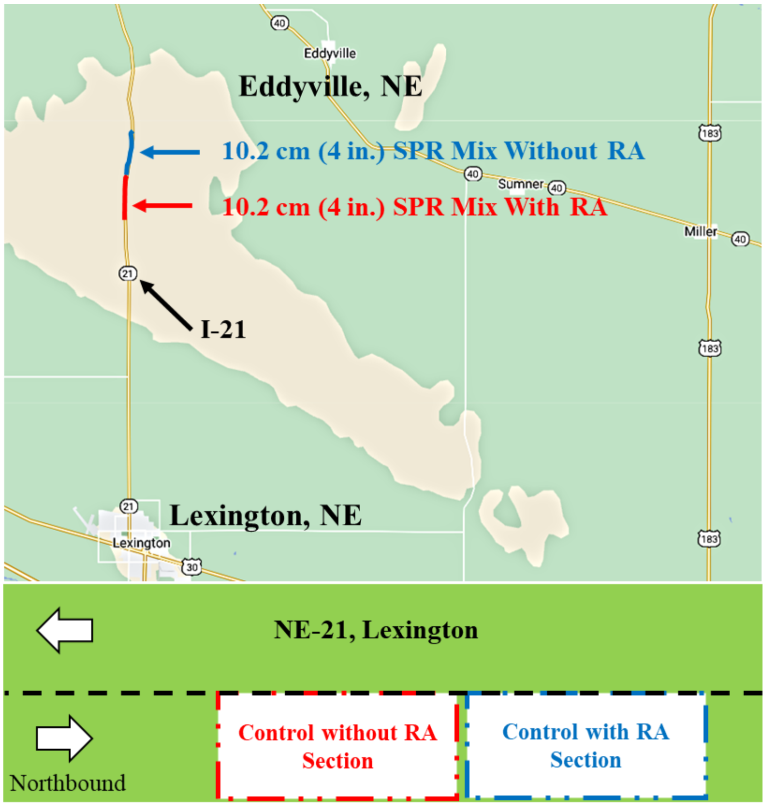


Figure 3-1. Location of test sections.

Figure 3-2 illustrates the detail of pavement structural layers of the sections. The control and test sections were composed of a typical asphalt mixture surface, asphalt mixture base, subbase, and subgrade layer. The only difference between the control section and the test section was the incorporation of an RA in the asphalt mixture base of the test section.

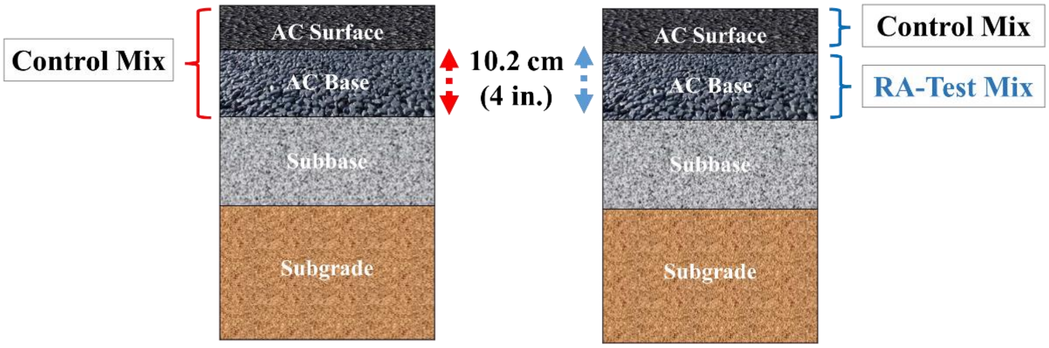
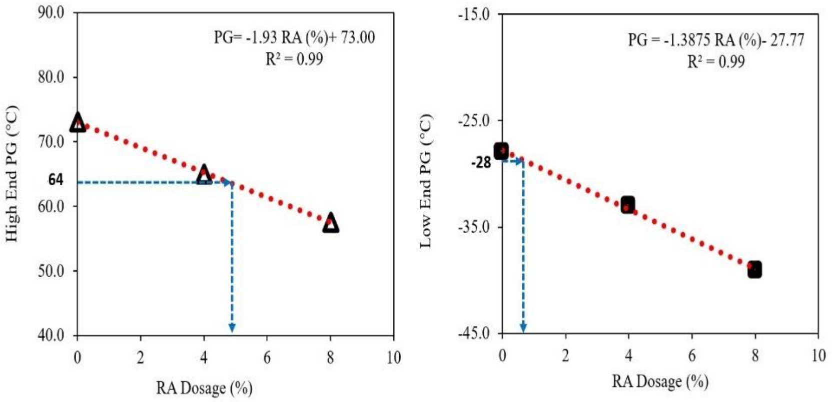


Figure 3-2. Pavement structural layers of the control and test sections.

3.2 Materials

3.2.1 RA

A bio-based oil RA was used in this study to investigate the influence of this chemical modifier on the laboratory and field performance of high-RAP mixtures. In order to find the optimum dosage range of RA, Superpave Performance Grading (PG) approach was utilized. Figure 3-3 (a) demonstrates that the high-temperature PG controls the maximum allowable dosage of RA, while the low-temperature PG limits the minimum required dosage (Figure 3-3 (b)). The dosage range of RA was determined using the data presented in Figure 3-3 by recovering the PG of the control binder (50% virgin binder + 50% RAP binder) to the desired PG, i.e., 64-28. Figure 3-3 shows that the dosage range required to achieve PG 64-28 is between 0.2 % and 4.7 % based on the total weight of the binder and 1.6% was selected to be added to the asphalt mixtures.



(a) (b)

Figure 3-3. PG test results of binders: (a) high end, (b) low end.

3.2.2 Aggregates

This study used the traditional SPR mixtures containing 50% RAP. The blend of virgin aggregates was composed of 38% limestone, 5% 3A gravel, and 5% 2A gravel. Figure 3-4 shows the gradation of the blend of RAP and virgin materials, with the maximum and minimum limits for the state of Nebraska. Table 3-1 summarizes the percent of aggregates and aggregate gradation of the mixtures.

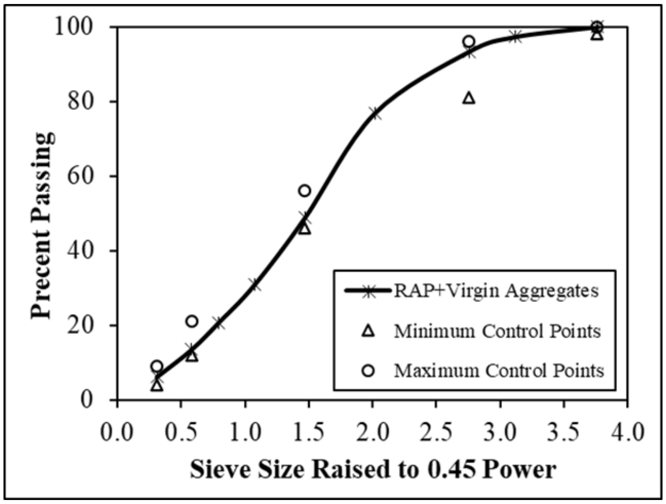


Figure 3-4. Gradation of RAP and virgin mixture.

Table 3-1. Gradation of RAP and virgin materials.

Material	Weight (%)	Sieve Analysis								
		19.0	12.5	9.50	4.75	2.36	1.18	600	300	75
		3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#200
3A Gravel	38	100	100.0	100.0	93.0	63.3	40.1	25.7	15.1	5.7
2A Gravel	5	100	93.5	87.8	64.1	29.8	13.1	6.3	1.8	0.3
5/8 Limestone	5	100	81.6	44.2	6.6	4.9	4.4	4.0	3.6	3.0
RAP	52	100	97.2	93.6	72.8	44.3	28.5	20.1	14.4	7.4

3.2.3 Asphalt Binders

A PG 58V-34 was selected as a virgin binder. The optimum content of the binder was determined based on the available amount of binder in the RAP. Table 3-2 presents the target binder utilization in the mix design and production.

Table 3-2. Asphalt binder information in mix design and production.

Description	**Mix Design Target (%)**	**Production Target (%)**
Virgin Binder	2.1	2.2
Binder in RAP	6.0	6.3
Binder Replacement	59.5	59.5
Binder from RAP	3.1	3.1

Note: % of RAP by total weight of aggregates is 52 and 50 in mix design and production target, respectively.

3.3 Field-Cored and Laboratory Specimens

The control and test sections were constructed using the SPR mixtures with and without bio-oil RA, respectively. Several cored specimens were collected from the field on the day after each test section was constructed, as shown in Figure 3-5(a). The construction lanes remained closed until the cores were acquired. The cores, with a diameter of 150 mm, were taken from the selected areas and then cut at the lift and bottom lines, as shown in Figure 3-5(b). A total of 60 cores were taken for each of the two sections: 10 cores were taken one day after construction, 10 cores one year after construction, and 10 cores two years after construction.

(a) (b)

Figure 3-5. Field core specimens.

The plant produced SPR mixtures were collected from same project and used to prepare laboratory specimens. The loose mixtures were reheated in an oven for around 2 hours at 135 ˚C until the mixtures were workable. Also, to simulate the field condition for about ten years, the long-term aging protocol developed at the National Center for Asphalt Technology (NCAT) was utilized in which the loose mixtures collected from the asphalt plant were reheated and kept in an oven for 8 hours at 135 ˚C (Chen et al., 2018). The mixtures were compacted using a gyratory compactor, and the target air void was 7%. Overall, ten types of specimens were prepared for this study. Table 3-3. summarizes the characteristics of the specimens prepared and tested in this study.

Table 3-3. Characteristics of the specimens.

Specimens ID	**Compaction**	**Cored**	**Rejuvenating Agent (RA)**
FC0	Field	After Paving (0 Year)	No
FCR0	Field	After Paving (0 Year)	Yes
FC1	Field	After 1 Year	No
FCR1	Field	After 1 Year	Yes
FC2	Field	After 2 Years	No
FCR2	Field	After 2 Years	Yes
LC	Laboratory	-	No
LCR	Laboratory	-	Yes
LCLT*	Laboratory	-	No
LCLTR*	Laboratory	-	Yes

* LCLT and LCLTR are laboratory long-term aged of LC and LCR, respectively.

3.4 Specimen Fabrication

3.4.1 SCB Test Specimen

From a gyratory-compacted specimen of 170 mm height and 150 mm diameter, a 10-mm portion was removed from both the top and the bottom because of non-uniform air voids at those locations. It should be noted that the target air void was 7 percent ± 0.5 percent. Then, the resultant specimens were sliced and halved to be used as SCB test specimens with a thickness of 50 mm and a diameter of 150 mm. Fracture tests were performed on the test specimens after making a notch of 15 mm depth and 2.5 mm width. Figure 3-6 shows the specimen production process and SCB test configuration.

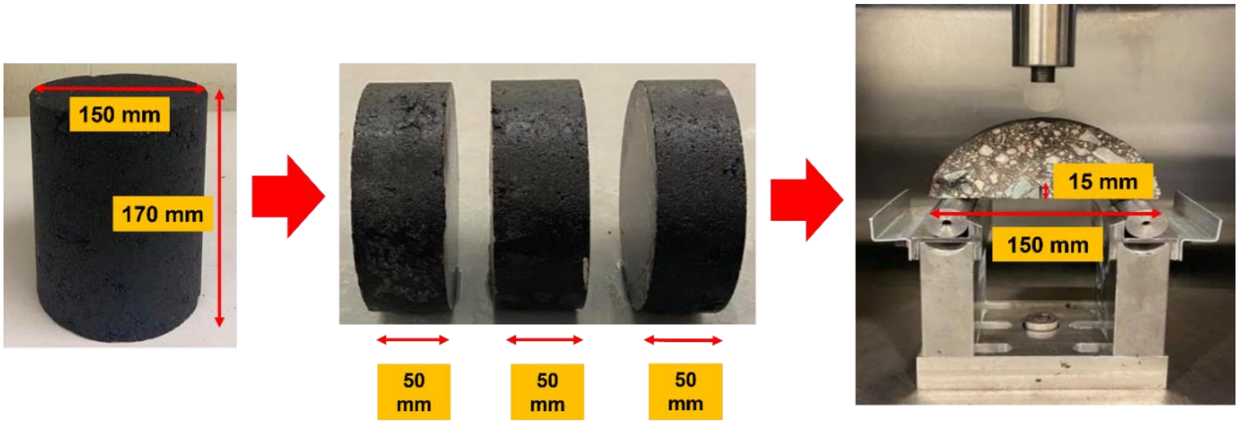
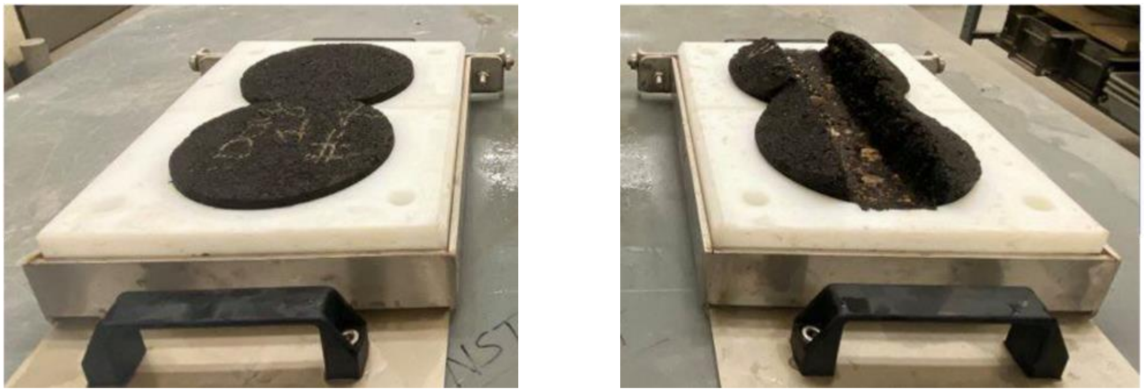


Figure 3-6. Specimen fabrication, slicing, and test setup.

3.4.2 *HWT Test Specimen*

The specimens with 62 mm height and target air void of 7 percent ± 0.5 percent were obtained from the Superpave gyratory compactor. The necessary cuttings were followed based on (AASHTO, 2017). Similarly, field-cored specimens were cut into the desired height and geometry before testing. Figure 3-7 shows specimens were placed inside the testing tray before and after testing.



(a) (b)

Figure 3-7. HWT test specimens (a) before testing, and (b) after testing.

Chapter 4 Laboratory Tests and Data Analysis

In this study, the SCB and the HWT test were used to investigate the laboratory performance of asphalt mixtures and their field performance after paving, one year and two years using cores taken from pavement sections. The SCB test was performed to assess the mid-temperature cracking performance of the specimens. The HWT test was conducted to characterize the permanent deformation (rutting) and moisture susceptibility of the specimens. Figure 4-1 shows the experimental plan developed for this study.

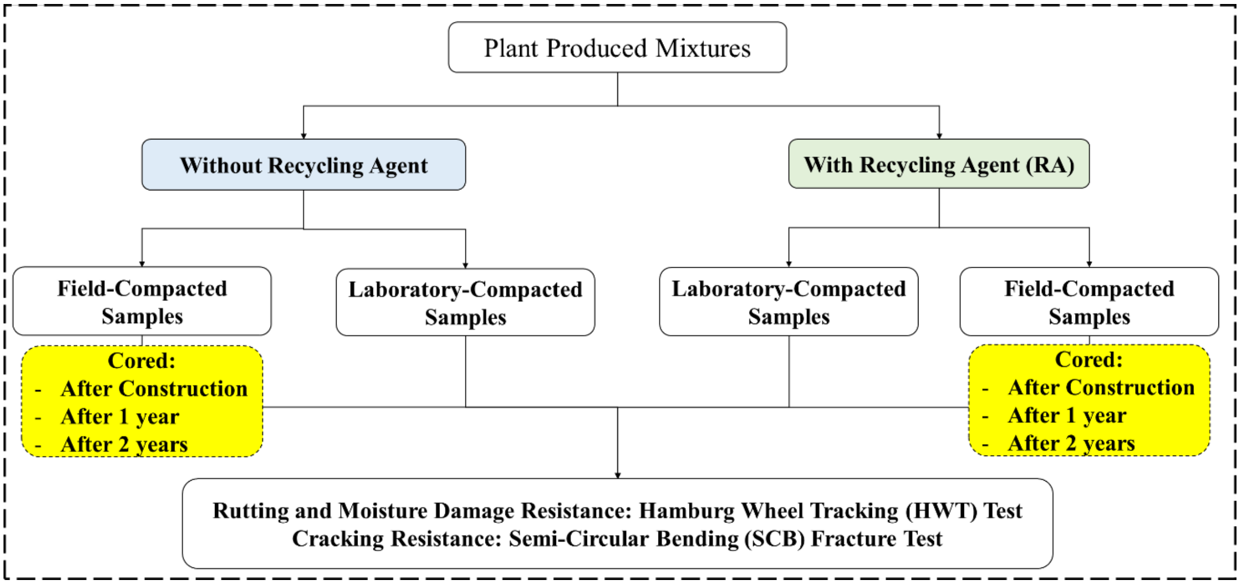


Figure 4-1. Experiment plan.

4.1 SCB Test and Results

The SCB test has been widely used to estimate the cracking resistance of asphalt mixtures. Researchers in the field of pavement engineering have been actively working to enhance the testing protocols of the SCB test. The protocols developed by Mohammad et al. (Mohammad, Wu, and Aglan, 2004) and Al-Qadi et al. (Al-Qadi et al., 2015) are two renowned forms of the SCB testing protocols that are highly accepted and being used by various DOTs in the U.S. The major differences between these two protocols are that the former considers fracture energy as the governing criteria to characterize the fracture properties of an asphalt mixture, while the latter considers a post-peak slope along with fracture energy to characterize the fracture properties of an asphalt mixture.

In this study, AASHTO TP 124-16 testing protocol was followed for the SCB testing. Before testing, specimens were placed inside an environment chamber of a universal testing machine to achieve an equilibrium temperature of 25° C. Then, the test specimen was placed in the loading frame of a three-point bending configuration. A monotonic loading of 50 mm/min displacement was applied on the top of the specimen. A data acquisition device connected to the computer system recorded the loading (reaction force) and the displacement during testing. The load and displacement relationships were used to measure the cracking performance of different specimens.

Parameters such as stress intensity factor (K), fracture energy (G_f), fracture toughness (K_{ic}), critical energy rate (J_c), J integral, Flexibility Index (FI), and Cracking Resistance Index (CRI) can be measured from a typical SCB test result shown in Figure 4-2. Each of these developed parameters is significant in characterizing the fracture behavior of asphalt mixtures. The FI and the CRI are used in this study to evaluate the fracture behavior of the asphalt mixtures.

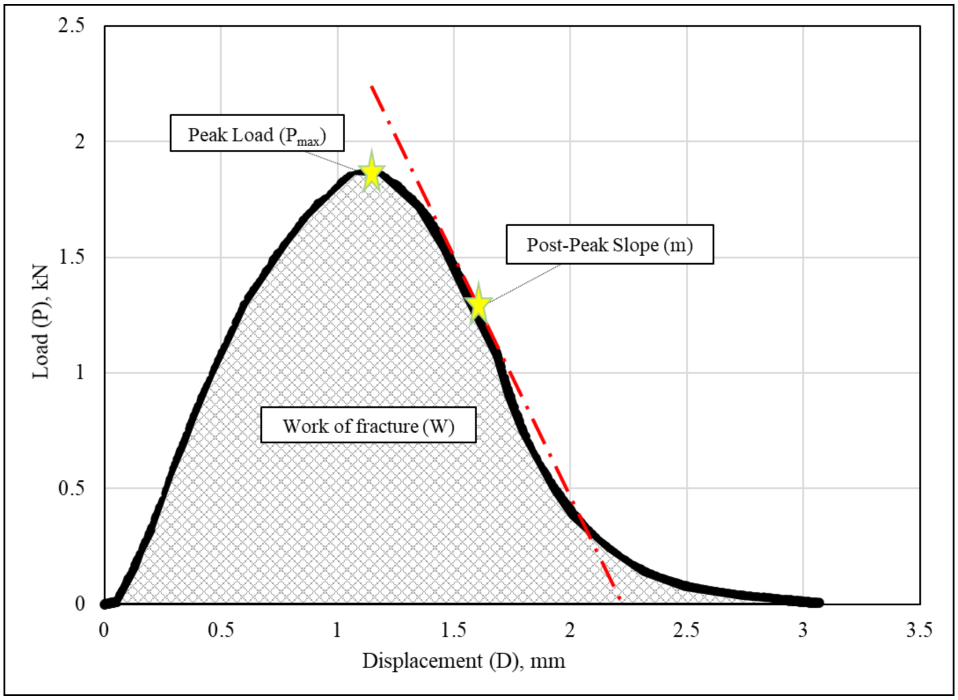


Figure 4-2. Typical SCB test result.

Fracture energy is one of the important properties of a material and measures the resistance of the material against fracture. It also reflects the energy required to form a new fracture surface. Fracture energy can be derived from the load-displacement relationship obtained from SCB testing results and is measured by dividing the work of fracture by the ligament area. Mathematically, fracture energy G_f is calculated using Equation 1:

$$G_f = \frac{W}{A_{lig}} \qquad \text{Equation 1}$$

where W is the fracture work (i.e., the area below the load-displacement curve), and A_{lig} is the ligament area.

The FI is an indicator for the cracking resistance of asphalt mixtures and was developed by Al-Qadi et al. (2015). They found that fracture energy alone could not differentiate asphalt materials, and both strength and ductility needed to be considered for cracking resistance characterization. In SCB test, the peak load defines the strength of the material, and the maximum displacement observed at the end of the test is ductility. If a material has a higher peak load, it may not show a higher ductility. Therefore, the FI was proposed and shown to have a good correlation with the speed of crack growth. The FI can be calculated using Equation 2:

$$FI = A\frac{G_f}{|m|} \qquad \text{Equation 2}$$

where G_f, |m|, and A are the fracture energy (J/m^2), the absolute value of the post-peak slope, and the unit conversion factor, respectively.

Zhu et al. (2017) calculated fracture strength using peak load (P_{max}), which was normalized based on G_f. Then, the CRI is proposed as an alternative SCB cracking-test parameter, defined as the ratio of total G_f to P_{max} as follows:

$$CRI = \frac{G_f}{P_{max}} \qquad \text{Equation 3}$$

where G_f is the fracture energy (J/m^2), and P_{max} is the peak load (kN).

As discussed earlier, apart from the fracture energy, the FI correlates well with the field performance and the cracking of an asphalt specimen. Figure 4-3 shows that the laboratory-compacted specimens with RA (LCR) had a higher FI than that of without RA (LC), showing an active role of the bio-oil RA in the performance enhancement of the RAP-blended asphalt mixtures. The long-term performance of mixtures was also evaluated through NCAT long-term laboratory aging protocol. Figure 4-3 shows that LCLT and LCLTR specimens had lower FI values than LC and LCR, respectively, as expected. Furthermore, a 67% and 80 % drop was observed in the FI of LCLT and LCLTR with respect to LC and LCR specimens, respectively, which indicates that the mixtures with bio-oil were more susceptible to crack.

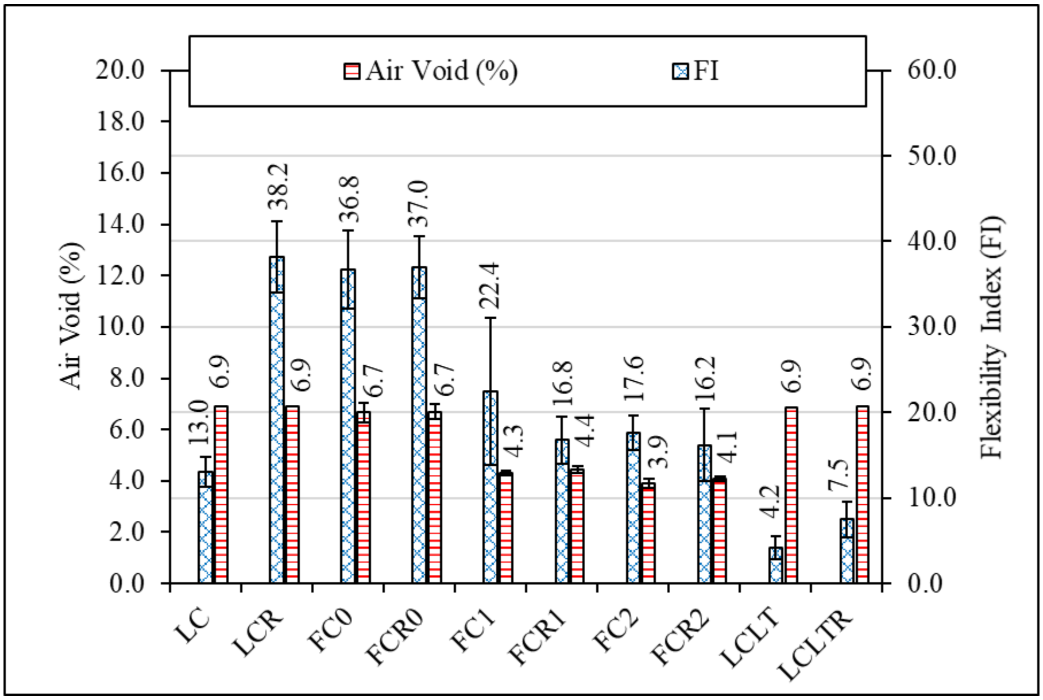


Figure 4-3. FI of specimens.

As can be seen in Figure 4-3, the effect of the bio-based oil RA in softening of the RAP materials was not noticeable in the field-compacted specimens (FC0 and FCR0) compared to laboratory-compacted specimens (LC and LCR). The FI values of the field-compacted specimens cored after one and two years (FC1, FCR1, FC2, and FCR2) were lower than the FI of FC0 and FCR0 specimens, which indicates that these specimens were more prone to crack as they were exposed to environmental conditions and traffic loads for a longer time. It is worth mentioning that the field-compacted mixtures with RA had the highest rate of loss of FI compared to that of without RA after one year, which could be related to the bio-based RA introduced to the mixtures. Haghshenas et al. reported that the use of bio-oil RAs might accelerate the aging process of asphalt binders and mixtures since these RAs contain high oxygen content and some chemical functional groups susceptible to aging and moisture (Haghshenas et al., 2020). This finding was further confirmed by Fakhri and Ahmadi, 2017, Yang et al., 2014, and Haghshenas et al., 2021. The FI of both field-compacted mixtures slightly decreased in the second year as the aging rate slows as aging progresses.

To investigate the sensitivity of FI, an Analysis of Variance (ANOVA) at a 95 % confidence level and Tukey's honestly significant difference (HSD) test were performed. The ANOVA table for FI is shown in Table 4-1. Since the p-value is less than the α-level (i.e., 0.05), the null hypothesis was rejected, meaning that there was at least one mixture significantly different from other mixtures in terms of their FI values. As a result, Tukey's HSD can be conducted. The Tukey's HSD test has been used by many researchers to identify differences in asphalt mixtures performances (West et al., 2021, West et al. 2018, Xie et al. 2017, Faruk et al. 2014). In Tukey's HSD, the mixtures that shared the same grouping letter, their average FIs were not statistically different. As can be seen in Table 4-2, the LC and LCR specimens were statistically different, while there was not a statically significant difference between FC0 and FCR0 specimens. The FC1, FCR1, FC2, and FCR2 had the same grouping letter (i.e., B), meaning that the FI of these specimens was not statistically different. In other words, both RAP-blended mixtures with and without bio-oil RA, aged in the field conditions, showed similar cracking performance after one and two years. However, a longer field performance monitoring can provide a better insight into the performance of these mixtures. Table 4-2 shows that the LCLTR and LCLT fell in the same grouping letter (i.e., D) for FI while they were statistically different before aging occurs as LC and LCR had different grouping letters. The FI and Tukey's HSD test results imply that the bio-oil RA used in this study could not provide long-term improvement for the RAP-blended mixtures in the laboratory and field aging conditions.

Table 4-1. ANOVA: Single factor about FI.

Source of Variation	Sums of Squares (SS)	Degree of Freedom (df)	Mean Squares (MS)	F	P-value	F crit
Between Groups	8385	9	931.66	51.95	<0.001	2.073351
Within Groups	896.8	50	17.94			
Total	9281.7	59				

Table 4-2. Summary of Tukey grouping (α=0.05) for FI.

Specimens ID	**Mean**	**Grouping**			
LC	13.0		B	C	D
LCR	38.2	A			
FC0	36.8	A			
FCR0	37.0	A			
FC1	22.4		B		
FCR1	16.8		B	C	
FC2	17.6		B	C	
FCR2	16.2		B	C	
LCLT	4.2				D
LCLTR	7.5			C	D

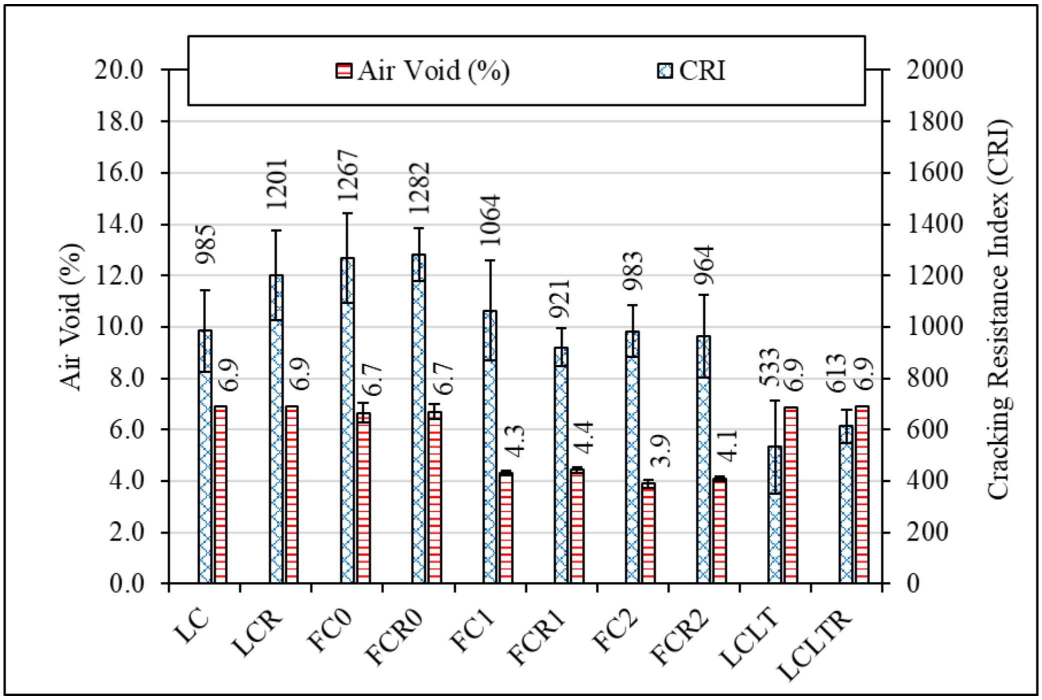


Figure 4-4. CRI of specimens.

The CRI shows a similar cracking performance as represented by the FI. Figure 4-4 presents that the CRI value of LCR was higher than LC. The primary reason for the increase in the

CRI was due to the softening effect of the bio-oil RA. However, this softening effect was not perceptible in the field-compacted specimens cored after paving; FC0 and FCR0. As expected, there was a reduction in the CRI of field-compacted mixtures with and without bio-oil RA, cored after one year, which could be related to environmental conditions and traffic loads. The ANOVA table for CRI is shown in Table 4-3. Although the cracking resistance of mixtures with RA was reversed in the second year (higher CRI for FCR2 than FCR1), the Tukey's HSD test results summarized in Table 4-4 show that these mixtures were not statistically different as they had a same grouping letter (i.e., C). The results presented in Figure 4-4 and Table 4-4 confirmed the findings based on FI; there is a concern regarding the long-term performance of RAP-blended asphalt mixtures modified by bio-oil RA.

Table 4-3. ANOVA: single factor about CRI.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3415365	9	379485	16.01	<0.001	2.073351
Within Groups	1185495	50	23710			
Total	4600859	59				

Table 4-4. Summary of Tukey grouping (α=0.05) for CRI.

Specimens ID	**Mean**	**Grouping**			
LC	985		B	C	
LCR	1201	A	B	C	
FC0	1267	A	B		
FCR0	1282	A			
FC1	1064	A	B	C	
FCR1	921			C	
FC2	964			C	
FCR2	983		B	C	
LCLT	533				D
LCLTR	613				D

On the other hand, Barry (Barry, 2016) and Haslett's (Haslett, 2018) correlated air void content and cracking indices such as CRI, G_f, FI, and P_{max} of high-RAP asphalt mixtures. They reported that the air void content is directly related to the cracking indices, a decrease in the air void content of specimens due to traffic loads leads to a decrease in cracking resistance of specimens. As can be seen in Figure 4-3 and Figure 4-4, about 2.4% reduction in air void content between field-cored specimens after paving and one year resulted in a decrease in both cracking indices utilized in this study (i.e., FI and CRI).

4.2 HWT Test and Results

The HWT test is used to characterize the rutting and moisture damage resistance of an asphalt mixture in laboratory. The HWT test was performed per AASHTO T 324 procedure (AASHTO, 2017) at 50° C under a water bath. A wheel passed over the specimen's surface at a 52 mm/min rate, and the resulting deformation was recorded by the transducers attached to the machine. The testing device had the provision to stop at 12.5 mm of rutting or 20,000 passes of the wheel, whichever occurs first. However, in this study, 20,000 passes were selected as the stopping criteria to record the full depth rutting. Rutting is a direct measurement of the deformation depth over the surface of the specimen. The stripping inflection point (SIP) is defined as the number of wheel passes obtained at the intersection of the creep slope and the stripping slope and can be used as an indicator for estimating moisture susceptibility of an asphalt specimen a higher SIP number indicates better moisture damage resistance. Figure 4-5 shows a typical HWT test output. It should be noted that the ANOVA and Tukey's HSD test was not performed on HWT results due to the limited numbers of specimens tested for each mixture.

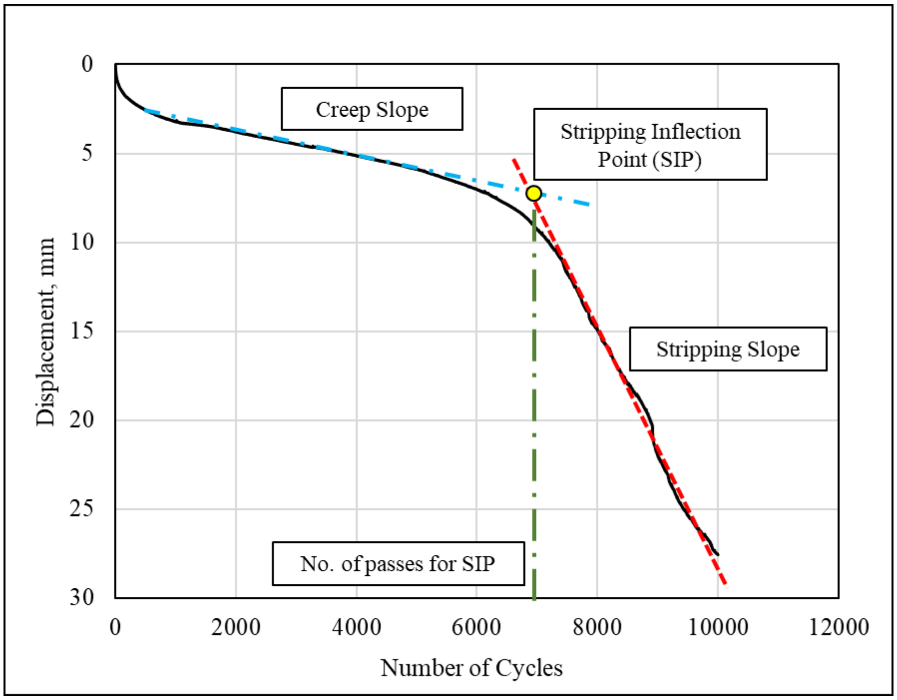


Figure 4-5. Typical HWT test output.

4.2.1 Rutting

Figure 4-6 shows the rutting performance of different specimens using the 12.5-mm criterion as suggested by researchers (Yin et al., 2020; Azari, 2014*)*. A higher number of passes to meet the 12.5-mm criterion indicates a better rut resistance of a specimen, while a lower number of passes shows a specimen more susceptible to permanent deformation (rutting). The results show that the addition of RA softened the LC specimen as the number of passes decreased from 15,200 to 12,000 passes for LCR, while this trend reversed for field-compacted samples cored after paving (FC0 and FCR0). This softer behavior of FC0 compared to FCR0 could be related to the field compaction practices and plant production variabilities. The field-compacted specimens cored after one year (FC1 and FCR1) and two years (FC2 and FCR2) showed notably less rutting compared to the cored specimens after paving (FC0 and FCR0), which may be due to the aging that occurred in the field conditions. Moreover, one of the predominant factors which affect the rutting resistance of specimens is air void content (Roy, Veeraragavan, and Krishnan 2013). Figure 4-6 shows about a 2.4% reduction in the air void content of FC1 and FCR1 with respect to those after paving, while the air void content slightly changed in the second year. The reduction in the air void content resulted in an increase in the rutting resistance of the specimens, as can be seen in Figure 4-6. Other researchers reported the same findings regarding the effect of air void content on the rutting resistance of specimens (Tran, Turner, and Shambley 2016).

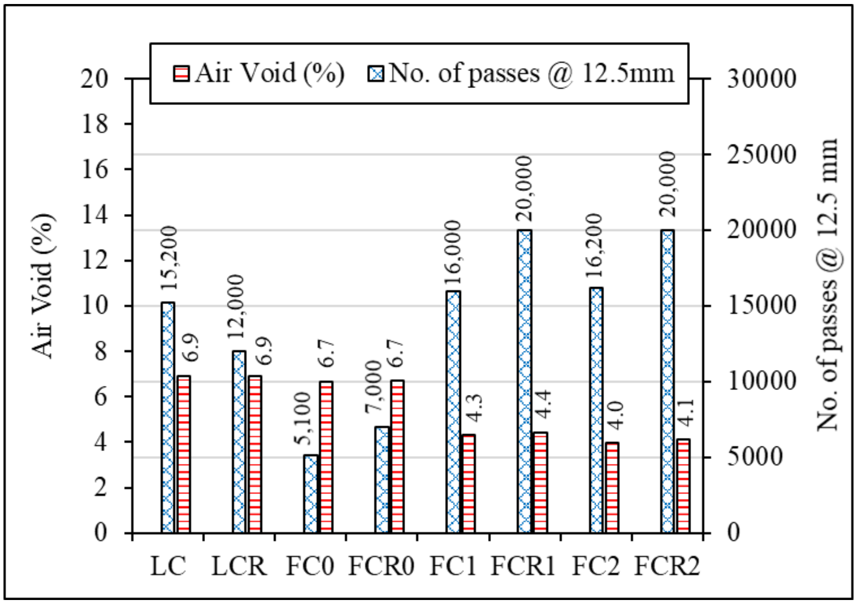


Figure 4-6. Summary of HWT test results of specimens.

The higher numbers of passes to 12.5 mm rut depth observed in the field-compacted specimens with RA (FCR1 and FCR2) compared to those of without RA (FC1 and FC2) could be considered as evidence for a faster degradation rate of high-RAP asphalt mixtures modified with bio-oil RA which resulted in stiffer specimens. It should be noted that other factors such as RA dosage, good RAP homogeneity, good distribution of RA and its diffusion into the RAP binder, and good blending of all the materials (Zaumanis, Cavalli, and Poulikakos, 2020) can also affect the overall performance of asphalt mixtures containing RAP materials treated with RA, including rutting performance, and these factors need to be further evaluated.

4.2.2 Moisture Susceptibility

In order to quantify the moisture susceptibility of specimens, the SIP was estimated from the HWT test results shown in Figure 4-5. In fact, the SIP is the point in the HWT test results where moisture dominates the high-temperature cracking with the partial and total segregation of the aggregates (Rafiq et al. 2020). The SIP of all specimens is presented in Figure 4-7. It is observed that the LCR had lower SIP than the LC, which means the specimens with bio-oil RA are more susceptible to moisture. Although the SIP of FCR0 specimens is lower than the SIP of FC0, the difference between SIPs is not significant. The results indicate that RAP-blended mixtures modified with bio-oil RA are susceptible to moisture in the initial stage regardless of compaction practices, i.e., laboratory and field. This agrees well with the results of studies conducted by Haghshenas et al. and Dong et al. in the binder and mixture level, respectively (Haghshenas et al. 2020, 2021; Dong et al. 2020). However, as aging progresses, the moisture damage resistance of RAP-blended mixtures with bio-oil RA improved; the SIP of FCR1 and FCR2 is higher than FCR0. Therefore, using a bio-oil RA might not be suitable where moisture damage is a concern.

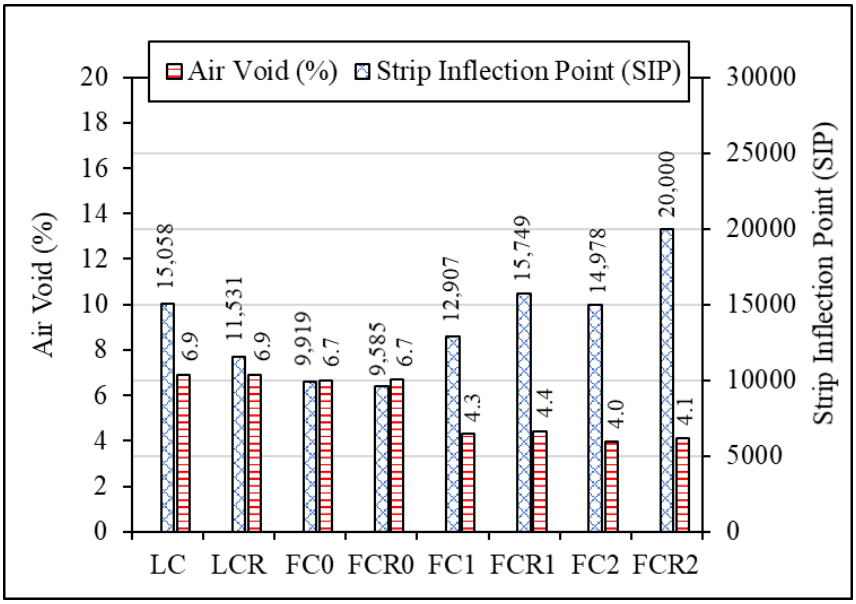


Figure 4-7. SIP of specimens.

Chapter 5 Field Performance Observations

A pavement surface is evaluated and rated based on the prevailing distresses in the pavement structure. There are various distresses occurring in a pavement structure due to the traffic loads and environmental conditions. Cracking and rutting are two forms of distress that have important roles in determining pavement performance and need to be carefully characterized. These distresses can be estimated through the International Roughness Index (IRI), Rut Depth (RD), cracking index amount, and the number of thermal cracking occurrences per mile. Table 5-1 summarizes federal rating scale for pavement conditions reported in Nebraska Transportation Asset Management Plan guidelines (NDOT, 2019). The "Good," "Fair," and "Poor" conditions are attributed to the pavement conditions based on the above-mentioned distresses.

Table 5-1. Federal rating scale for pavement conditions (NDOT, 2019).

Rating	Good	Fair	Poor
IRI (mm/m)	<1.50	1.50-2.68	>2.68
Cracking Percent (%)	<5	5-20	>20
Rutting (mm)	<5	5-10	>10

The pavement sections shown in Figure 3-1 were monitored for two years, and the necessary data were collected before paving (2019), one year after paving (2020), and two years after paving (2021). Although there were some correlations between the field performances and laboratory test results, it is worth noting that the high-RAP mixtures with and without RA were used in the second layer of each section, while the observed distresses were for the first (surface) layer.

5.1 IRI

The IRI is a measure of the longitudinal road profile based on accumulated roughness. Most departments of transportation report the annual IRI performance of pavement sections, and they have their own criteria for interpreting the pavement performance. Typically, the acceptable IRI thresholds for all road classifications range from 1.50 mm/m to 2.68 mm/m (Arhin et al., 2015). A pavement section with an IRI less than 1.50 is considered as a "Good" section, where a smaller number of deformations are presented per mile of the pavement section.

Figure 5-1 shows the IRI observations for the pavement sections with and without RA. A higher IRI indicates more irregularities and roughness in the road surface. It is worth mentioning that a similar IRI was observed in both pavement sections before the re-construction in 2019. The IRI of the pavement section with and without RA was same one year after construction. Although the IRI of pavement section with RA is slightly less than that of without RA, just how much of a role the RA plays in the IRI of the section needs further investigation.

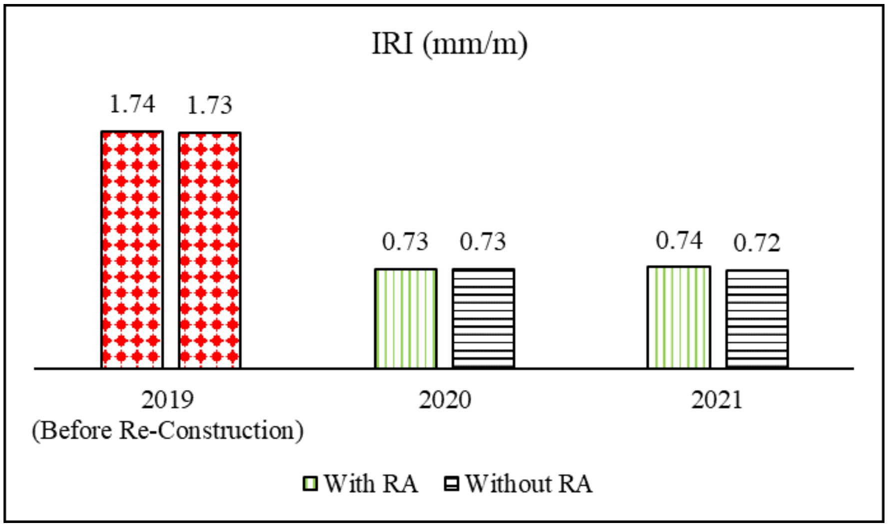


Figure 5-1. Field measurements of IRI for pavement sections.

5.2 RD

Rutting is another important parameter used to evaluate the performance of pavement sections based on the depth of the depression on the wheel path. Rutting is a characteristic feature of relatively softer pavement mixtures; higher rutting indicates poor serviceability of the pavement section. The rutting performance of the sections with and without RA is shown in Figure 5-2. Compared to the pavement section without RA, the RD in the pavement section with RA was higher after one year; the difference in RD was half as much after two years. The softening effect of RA could be considered as a major cause of this difference.

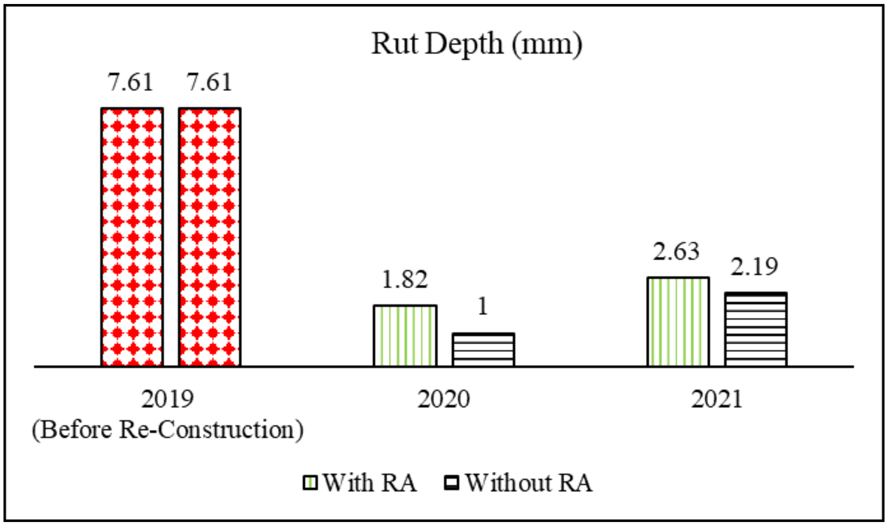
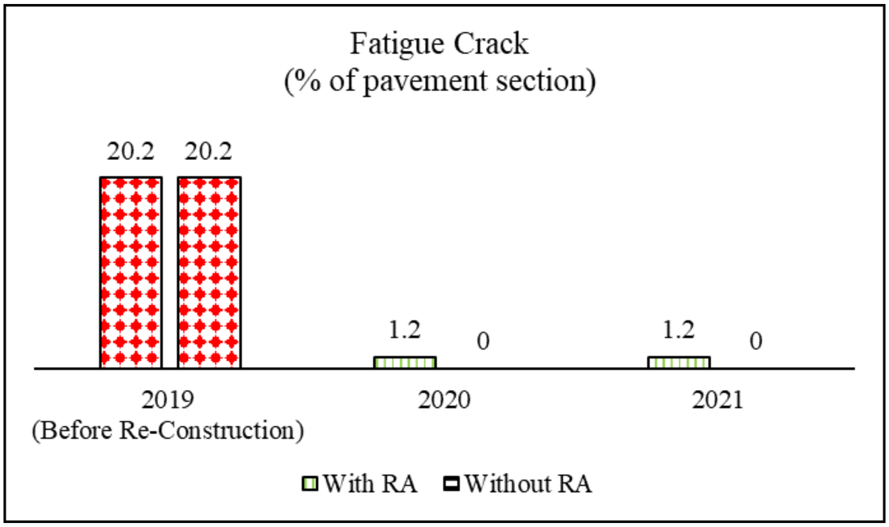


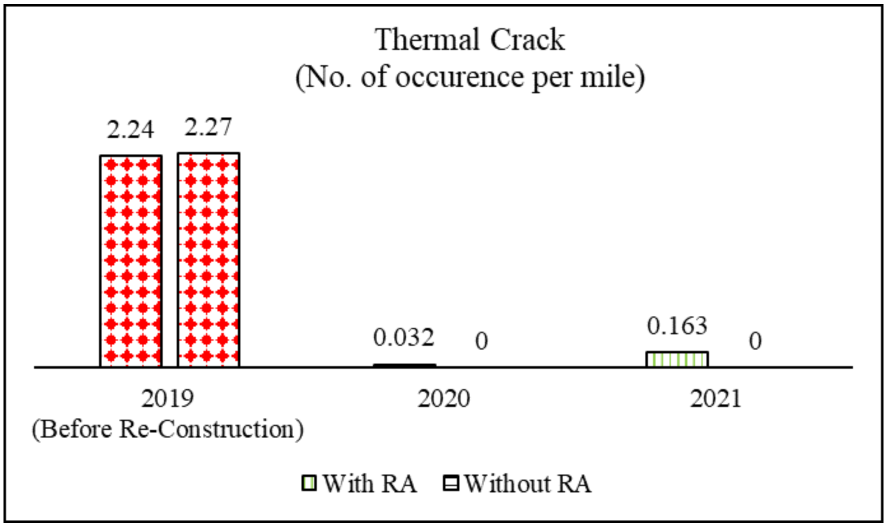
Figure 5-2. Field measurements of rutting for pavement sections.

5.3 Fatigue and Thermal Cracking

A continuous wheel load leads to fatigue cracking while thermal cracking is initiated and developed by temperature changes. Figure 5-3 shows the fatigue and thermal cracks were developed in the pavement section with RA one year and two years after re-construction in 2019; a greater number of thermal cracks were observed, and this number increased in the second year. However, there was no fatigue and thermal crack in the pavement section without RA for two years. It should be noted that the sections need to be continuously monitored to better understand the inter-layer and the RA effects on overall performance of pavement.



(a)



(b)

Figure 5-3. Field measurements of crack: (a) fatigue and (b) thermal for pavement sections.

Chapter 6 Conclusions and Future Work

This study evaluated the laboratory- and field-performances of high-RAP mixtures with and without bio-oil RA. The cracking resistance of mixtures was characterized using Semi-Circular Bending (SCB) fracture test and rutting and moisture damage resistance of mixtures were evaluated using Hamburg Wheel Tracking (HWT) test. The following conclusions can be drawn based on the results and findings:

- The use of the bio-oil RA resulted in an increase in cracking resistance of the RAP-blended mixtures compacted in the laboratory; however, this improvement was not noticeable in the field-compacted specimens cored after paving. Both RAP-blended mixtures with and without bio-oil RA, aged in the laboratory and field conditions, showed similar cracking performance which implied that the bio-oil RA used in this study could not provide long-term improvement for the RAP-blended mixtures.
- The specimens with bio-oil RA cored after re-construction exhibited less rutting than the specimens without RA which might be due to field compaction practices and plant production variabilities. On the other hand, the specimens with RA cored after one year and two years showed a higher number of passes to meet 12.5 mm rut depth (better rutting resistance). This could be related to the aging susceptibility of bio-oil RA and a reduction in the air void content.
- The SIP was utilized to evaluate the moisture damage resistance of specimens. It was found that the laboratory and field-compacted specimens with the bio-oil RA were more susceptible to moisture. However, the moisture susceptibility of the specimens cored one year after paving decreased; similar findings on the reduction of moisture susceptibility can be reported for the specimens tested after two years.
- The field performance observations showed that the use of the bio-oil RA in the second layer might have indirectly resulted in more cracks (fatigue and thermal) and ruts in the surface layer. These observations might require further forensic analysis through longer field performance monitoring since any conclusions based on two years' field data could be inconclusive.

Future Work

This study focused on the field and laboratory performance of the asphalt mixtures containing a high percentage of RAP materials with and without bio-oil RA. Although different performances were observed from different mixtures, a limited number of field cores were taken from each section, and the sections were monitored for just two years. It is recommended that the sections are monitored for a longer time. In addition, only one type of RA was used in this study, and the use of different RAs may result in different performance observations. Furthermore, the effect of other additives such as antioxidants and anti-stripping agents on the performance of asphalt binders and mixtures modified by RAs needs to be evaluated in future research since these additives may address some concerns regarding durability and long-term performance of rejuvenated asphaltic materials. Also, setting guidelines to characterize the performance of an asphalt mixture based on rutting or cracking would be recommended to understand the field and laboratory performance of asphalt mixtures in different scenarios.

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