Optimizing the Effective Use of RAP in Local Roadways by Using Recycling Agents

A thesis presented to

the faculty of

the Russ College of Engineering and Technology of Ohio University

In partial fulfillment

of the requirements for the degree

Master of Science

Amro Abu Shama

August 2018

This thesis titled

Optimizing the Effective Use of RAP in Local Roadways by Using Recycling Agents

by

AMRO ABU SHAMA

has been approved for

the Department of Civil Engineering

and the Russ College of Engineering and Technology by

Munir Nazzal

Associate Professor of Civil Engineering

Dennis Irwin

Dean, Russ College of Engineering and Technology

ABSTRACT

ABU SHAMA, AMRO, M.S., August 2018, Civil Engineering

Optimizing the Effective Use of RAP in Local Roadways by Using Recycling Agents

Director of Thesis: Munir Nazzal

This study evaluates the effect of using recycling agents (RA) on the performance of asphalt mixtures containing high reclaimed asphalt pavement (RAP) content and compare it to that of using softer asphalt binder. Asphalt mixes with three different RAP contents, namely, 30%, 40%, and 50% RAP that include a recycling agent or soft asphalt binder were designed and tested. Three different recycling agents were used (Sylvaroad, Hydrolene and Soybean oils). Different tests were used to evaluate the fatigue cracking, low-temperature cracking, moisture damage susceptibility and rutting of asphalt. In addition, cost analyses were performed to examine the cost effectiveness of using recycling agents in high RAP mixes.

The results of this study showed that the use of softer asphalt PG 64-28 binder was not effective when more than 30% RAP was used in the asphalt mix. Sylvaroad-RA and Hydrolene-RA were efficient in improving the fatigue cracking resistance in mixes with up to 50% RAP. However, the Soybean-RA with 40% and 50% RAP had much lower fatigue cracking resistance compared to the mixes with the other RAs. Although Soybean-RA had the lowest Indirect Tensile Strength (ITS) values and highest rut depth, all mixes had acceptable resistance to moisture damage and rutting.

The results of the cost analysis indicated that a 50% RAP mix with Hydrolene can reduce the cost of asphalt mix cost by 26% as compared to the currently used RAP mixes.

In addition, the 50% RAP mix with Sylvaroad is 13% cheaper than the RAP mixes currently being used.

DEDICATION

To my parents

Mohammad Abu Shamma and Narmen Abu Shamma

ACKNOWLEDGMENTS

Foremost, I would like to express my sincere gratitude to my advisor, Dr. Munir Nazzal for the continuous support of my masters' study and research. His constant assistance and encouragement have been a great inspiration throughout my thesis.

Besides my advisor, I would like to thank Dr. Sang Soo Kim for his endless help, valuable comments and feedback. My acknowledgment also goes to the rest of the committee members, Dr. Bhaven Naik and Marcel Bischoff.

Special thanks to my fellow PhD student, Arkan Obaid who stood beside me and shared his experience throughout my research.

I would like to thank Ohio Department of Transportation (ODOT), Ohio's Research Initiative for Locals (ORIL), and the Federal Highway Administration (FHWA) for sponsoring this study; Dr. Ala Abbas of the Department of Civil Engineering at the University of Akron for providing access to his lab and equipment; Shelly and Sand Company for providing all the materials for this research.

I would like to express my appreciations to my fellow graduate students for their support and friendship. Finally, I am very thankful to my family for their endless love and support.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1: INTRODUCTION

1.1 Background

In the 1970s, the prices of the oil around the world have increased and that led the cost of the crude oil used in Hot Mix Asphalt (HMA) to increase as well (Copeland, 2011). Since then, the Reclaimed Asphalt Pavement (RAP) has been used to substitute the virgin aggregate materials and asphalt binder in asphalt mixtures so that the cost is reduced. Moreover, the refining process of these virgin materials as well as the transportation result in producing energy, which influences the environment according to the National Center for Asphalt Technology (NCAT) report 12-05 by (Tran et al, 2012). According to the Federal Highway Administration (FHWA), any usage of RAP above the 25% of RAP by weight in the mix is considered to be a high content RAP mixture. However, FHWA allowed the state agencies to use up to 30% RAP in mix design of HMA beginning of 2011, but the average RAP usage in (HMA) is still between 10% and 20% in most of the states (Copeland, 2011). Recently, some state agencies have started using high content of RAP in HMA mixtures.

In spite of the advantages that RAP has, using high RAP content (> 30%) may cause premature distress such as fatigue cracking. That might happen because of the stiff aged binder contained in RAP, which makes the mixture very stiff, less workable and challenging during compaction (Im et al, 2014; Mogawer et al, 2012; Moghaddam and Baaj, 2016). In order to overcome this problem, recycling agents (RAs) or softer virgin binder grade are usually used. The RAs are differently defined by researchers, the recent definition explains them as the diffusible additives that are capable of restoring the original properties (the mechanical and chemical) of the aged RAP binder without affecting the long-term aging performance of the pavement (Apostolidis et al., 2017). In addition, rejuvenating agents aim to restore the asphaltene/maltene ratio that was lost during construction (Im et al., 2014). Recycling agents are classified into either organic base oils such as waste vegetable oils, waste cooking oil or Sylvaroad or petroleum base oils like paraffinic, aromatic and naphthenic oils.

The softer virgin binders are only able to reduce the stiffness of the oxidized RAP binder but that can still cause cracking issues in the pavement as their ability to diffuse cannot be controlled (lack of diffusion). Thus, the recycling agents are more advantageous than the softer asphalt binders and that is due to their inexpensive storage. They can easily and precisely be added to the mixture, they can directly dose on RAP and often they are not costly (Zaumanis, Mallick & Frank, 2014).

The aim of this research is to study the effects of using three different recycling agents (RA) with three different high RAP contents on the performance of flexible pavement such as fatigue and low temperature cracking, moisture susceptibility damage and the rutting of asphalt.

1.2 Objectives

The objective of this study is to evaluate and compare the performance of asphalt mixtures containing high RAP content and recycling agents (RA) with the conventional asphalt mixture and high RAP content mixtures with no rejuvenating agents. The specific goals of this project were to:

- Evaluate the effects of using various RAs in high RAP content mixtures on the fatigue cracking, low temperature cracking, moisture susceptibility damage and rutting.
- Compare the results of the high RAP content mixtures including RA with the conventional mixture and mixtures with high RAP percentages with no RA.
- Conduct a cost comparison of HMA mixtures including high RAP contents only with HMA mixtures including high RAP and RA.

1.3 Thesis Outline

This thesis is divided into five chapters. First chapter provides an introduction about the work that has been done on this project along with the main objectives of this thesis. Literature review on relevant work is presented in chapter two. It includes the use of the recycling materials such as RAP and the recycling agents RA in Hot Mix Asphalt (HMA) and their effects on the performance of flexible pavement. The methodologies that have been used to evaluate the performance of high RAP-RA mixes is described is chapter three. Chapter four offers the test results and the analysis of the data as well as a statistical analysis of the obtained results. Finally, conclusions and recommendations are summarized in chapter five.

CHAPTER 2: LITERATURE REVIEW

This chapter provides a review of studies that have been done on using softening additives such as RAs in asphalt mixes that include reclaimed asphalt pavement (RAP). The types of RAs and the effect of each type on flexible pavement behaviors will also be discussed in this chapter as well as the general working mechanism for them and finally, how to obtain the optimum RA dosage within a specific asphalt RAP mix.

2.1 Reclaimed Asphalt Pavement (RAP)

The use of reclaimed asphalt pavement has recently increased due to its relatively inexpensive cost and the increasing cost of the raw constituents derived from the crude oil. As this refining process for the asphalt binders produces emissions consequently, utilizing RAP in hot mix asphalt (HMA) mixes helps in saving the energy which, results from those productions. Moreover, using RAP in HMA mixes is able to sustain the performance of pavement to almost the same as those mixes that do not include recycling material or RAP (Huang et al., 2015). However, because of the high stiffness of asphalt binder in RAP, using a high percentage of RAP (more than 25%) can create early distresses in pavement such as fatigue cracking, low temperature cracking and moisture damage. Therefore, recycling agents (RA’s) can be used so that the properties of the stiff binder in RAP can be restored to its original properties (Moghaddam & Baaj, 2016).

2.2 Recycling Agents (RAs)

Researchers have resorted to the use of softer asphalt binder in HMA mixes containing more than 20% RAP in order to soften RAP binder. Although softer binders have been utilized by some transportation agencies in RAP mixes, the use of the recycling agents might be more beneficial when using high RAP contents since those additives have not only the ability to soften the aged RAP binder, but also to restore its physical and chemical properties (Zaumanis et al., 2014; Xiaokong et al., 2014).

RAs have been similarly defined by different researcher. In 2014, Im et al defined RAs as additives that substitute the lost components during construction and service like maltenes within the oxidized RAP binder and try to soften that binder so that it can back to its original properties. In order to revert the aged RAP binder origin, natural products are used in asphalt RAP mixes so that it can restore RAP binder mechanical features to almost the virgin binder ones (Martin et al., 2015). According to a paper Apostolidis et al., 2017, RAs were demonstrated as a diffusible materials that are able to reinstate the aged binder in RAP to its original properties without affecting the performance on the long term. Therefore, in line with these definitions RAs can be considered as the helping materials that can be used with a high RAP asphalt mixes to restore the original properties of the aged binder in RAP.

2.2.1 The Chemistry and Benefits of Recycling Agents

Other solutions besides recycling agents which have been used in asphalt mixes are the softer binders. Although some agencies recommend using softeners or softer virgin binders as a solution for high aged RAP used in asphalt mixtures, the mixture will still be stiff without adding recycling agents and that will still cause performance problems such as cracking. Both, the recycling and the softer binders are able to reduce the stiffness of the aged asphalt binder. However, the main difference between them is that the recycling agents not only reduce the stiffness of the aged binder but also retrieve the mechanical characteristics of that aged binder (Martin et al., 2015) as well as the phase angle of the high RAP Binder Ratio (RBR) mixtures (Mercado et al., 2018). In other words, softening agents like flux and lube oil aim to lower the aged asphalt binder's viscosity whereas the rejuvenating agents contains lubricating oil that is able to reclaim the rheological properties of RAP binder (Al-Qadi et al., 2007). The binder chemistry was also discussed through the NCHRP report by (Martin et al., 2015). It is related to the polarity and the micelles created of the oxidative binder. So, the micelles are splitting up by the recycling agent while the softening agents lowers the molecular weight of the oils added to the mix.

The benefits of using the rejuvenators/recycling agents (RA) in asphalt mixes includes the ease and the capability of being added to the recycled binder at the exact required dosage, and the ability to be added directly to RAP instead of the fresh binder since RAs usually do not need to be heated up before mixing. Furthermore, the cost and the storage of such materials is low (Zaumanis, Mallick, & Frank, 2015). Overall, RAs are more advantageous than softening agents as they provide better recovery of the aged binder properties, enhancing the embrittlement of the aged asphalt.

2.2.2 Types and Characteristic of Recycling Agents

In the past decade, different kinds of RAs have been industrialized based on the material and process used to manufacture them, and these RAs can be categorized into two main groups; petroleum and organic type (Apostolidis et al., 2017). Based on Martin et al., 2015 and Tran et al., 2012, Table 2.1 shows the common commercial types of the RA under these two main categories. RAs obtained from petroleum sources are the results of purifying and adjustment process for crude oil. Examples of petroleum RAs are, paraffinic oils, aromatic and naphthenic. Whilst, the organic RA type as mentioned in paper published by (Apostolidis et al., 2017) can basically be obtained from human consumption, fatty acids or food manufacture. Aromatic oil is the most common type available as of petroleum nature. Based on a study conducted by (Ali, Nolan, & Bennert, 2016) the paraffinic oils were the most ones that restored the properties of the aged asphalt binder at both the high and low temperatures whereas the aromatic oils showed lower values at low temperature. On the other hand, (Zaumanis, Mallick, & Frank, 2015) in their study show that the results of using vegetable oils like the fatty acids have improved the asphalt binder performance to the level of fresh binder. Table 2.2 provides the cost, dosage, and other characteristics for the different types of petroleum and organic RAs collected from different sources. It is clear that the organic RAs requires smaller dose as compared to petroleum RAs to cause a similar effect on aged asphalt binder. Moreover, organic RAs are in general less expensive than petroleum RAs.

Table 2.1: Description of Different Types of RAs (Martin et al., 2015; Tran et al., 2012).

Category	Type	Recycling Agent Example	Description
Petroleum	Paraffinic Oils	Waste Engine Oil (WEO) Waste Engine Oil Bottom (WEOB) and Hydrolene SP125	Refined used lubricating oils. Consist of straight or branched chains of hydrogen and carbon atoms containing at least 18% of aromatics
	Aromatic Extracts	Hydrolene and Cyclogen L	Refined crude oil products with polar aromatic oil components
	Naphthenic Oils	SonneWarmix RJ™ and Ergon HyPrene	Engineered hydrocarbons for asphalt modification
Organic	Triglycerides & Fatty Acids	Waste Vegetable Oil (WV Oil) and Waste Vegetable Grease (WV Grease)	Derived from vegetable oils
	Tall Oils	Sylvaroad™ RP1000 and Hydrogreen (formerly BITUTECH RAP)	Paper industry by-products Same chemical family as liquid antistrip agents and emulsifiers

Table 2.2: Description of Different types of RAs

RA	[a]Max dose (%)	[a]Min dose (%)	[a]Category	[a]Refined or waste	[a]Polarity	[b&c]Cost per ton of material
Paraffinic Oils	25.0	16.0	Petroleum	Waste	Slight	$418
Aromatic Extracts	27.8	11.5	Petroleum	Refined	Very	$1200
Nathenic Oils	18.4	9.1	Petroleum	Refined	Very	$1427
Triglycerides & Fatty Acids (WV Oil)	16.4	7.4	Organic	Waste	Non	$600
Triglycerides & Fatty Acids (WV grease)	16.4	8.1	Organic	Waste	Mild	$664
Hydrogreen Tall Oils	18.8	9.4	Organic	Refined	Mild	$1445
Sylvaroad	18.8	8.0	Organic	Refined	Mild	$2161

a: (Zaumanis M. , Mallick, Poulikakos, & Frank , 2014)
b: (Tan, Taylor & Willis, 2012), c: (Veeraragavan et al., 2017)

2.2.3 The Effect of Using Recycling Agents

Several laboratory studies have been conducted during the past few years to evaluate the effects of the different types of RAs on the mechanical properties and performance of mixes with RAP. Table 2.3 presents a summary of the results of these studies. In general, all of the paraffinic oils resulted in higher rutting susceptibility (Ali, 2016; Mogawer, 2015; Purdy, 2017; Zaumanis, 2014). In addition, all of them except the Hydrolene SP125 did not improve the fatigue cracking resistance of mixes with high RAP content (>40% RAP) (Ali, 2016; Mogawer, 2015; Zaumanis, 2014). In general, the paraffinic oils improved the low temperature cracking properties of RAP mixes as well as the moisture susceptibility (Ali, 2016; Mogawer, 2015; Purdy, 2017; Zaumanis, 2014).

Aromatic extracts and oils improved the resistance of high RAP mixes to fatigue and thermal cracking as well as to moisture damage. In addition, it slightly increased the rutting of high RAP mixes but still within the acceptable rutting limit (Ali, 2016; Mogawer, 2015; Tran, 2012; Zaumanis, 2014).

Naphthenic oils increased the rutting but improved RAP mixture's resistance to thermal cracking and the moisture damage too. In addition, they had slight improvement to fatigue cracking resistance (Ali, 2016; Booshehrian, 2013).

Triglycerides and fatty acids recycling agents decreased the moisture and rutting susceptibility of RAP mixes. They improved the fatigue and thermal cracking resistance; particularly when used in mixes with 50% RAP (Ali, 2016; Veeraragarvan, 2017; Zaumanis, 2014).

Hydrogreen as part of tall oils-RA reduced the resistance to low-temperature cracking and slightly increased rutting of RAP mixes. However, it improved resistance to moisture damage and fatigue cracking (Ali, 2016; Veeraragarvan, 2017; Zaumanis, 2014). Veeraragavan et al. (2017) reported that Sylvaroad (Tall oil products) improved thermal and fatigue cracking resistance of mixes with 50% RAP, but they did not evaluate the effect of this RA on moisture sensitivity or rutting of RAP mixes.

Another type of RA that has been recently investigated by (Im S. Karaki P., Zhou F., 2016) along with Texas DOT is the Evoflex. Contractors have used it accompanied by Evotherm M1 (a warm mix asphalt additive) in asphalt mixes containing recycled materials like RAP and Recycled Asphalt Shingles (RAS). Despite of the limited studies on this kind of recycling agents, the study by Texas DOT assessed the effects of Evofelx on the rutting and fatigue cracking performance when used with 10% RAP and 5% RAS. From that study, Evoflex improved the fatigue cracking resistance but increased the rutting of RAP/RAS mix. Rutting and fatigue cracking resistance were improved when Hydrogreen was used as RA in the same study.

Table 2.3: Summary of Previous Laboratory Studies on the Effect of RAs on RAP Mixes Performance

RA Type	RA Name	Resistance to: Rutting	Resistance to: Thermal Cracking	Resistance to: Moisture Damage	Resistance to: Fatigue Cracking	Reference
Paraffinic oil	Waste Engine Oil (WEO)	Increased rutting susceptibility but still passed and was lower than virgin mix	Improved but still was worse than virgin mixture	Improved	Reduced	Ali et.al, 2015; Mogawer et al.,2015; Zaumanis et al,2014
	Waste Engine Oil Bottom (WEOB)	Increased rutting susceptibility but still passed and was lower than virgin mix	Improved but still was worse than virgin mix	Improved	Reduced (both tensile strength and fracture energy)	Ali et.al, 2015; Mogawer et al.,2015; Zaumanis et al,2014
	Holly Frontier Hydrolene SP125	Increased rutting susceptibility but still passed and was lower than virgin mix	Improved and was better than virgin mix	Improved	Improved	Ali et.al, 2015; Mogawer et al.,2015; Zaumanis et al,2014
	Valero VP 165	Increased rutting resistance based on binder testing	Decreased, but still was within the range	Improved	Reduced	Purdy et al., 2017
Aromatic Extracts	Hydrolene	Slightly increased rutting but has the least rutting depth among all RAs	Improved properties and was better than virgin mix	Improved	Improved the fatigue cracking resistance, but was worse than virgin mix	Zaumanis et al,2014
	Cyclogen L	Increased the rutting of 50% RAP mix but still rutting was acceptable	Improved for 50% RAP mix	Improved	Improved for 50% RAP mix	Ali et.al, 2015; Mogawer et al.,2015;Tran et al,2014
Naphthenic Oils	SonneWarmix RJ™	Rut depth increased	Improved and was better than virgin mix	Improved	Slightly improved, but was worse than virgin mix	Ali et.al, 2015; Booshehrian et al., 2013
Triglycerides & Fatty Acids	Waste Vegetable Oil (WV Oil)	Has the second highest rutting depth, rutting susceptibility increased	Improved and was similar to the virgin mix	Reduced resistance	Improved significantly when more than 11% used	Booshehrian et al., 2013; Zaumanis et al., 2014
	Waste Vegetable Grease (WV Grease)	Has the highest rutting depth passes, significantly increased rutting susceptibility	Improved but still was worse than virgin mix	No effect	Slight improvement	Booshehrian et al., 2013; Zaumanis et al., 2014
	Evoflex	Increased rutting	Not reported	Not reported	Improved	Im et al., 2016
Tall Oils	Sylvaroad	Not reported	Improved	Not reported	Improved	Veeraragavan et al., 2017
	Hydrogreen	Increased rutting susceptibility but still passed and was lower than virgin mix	Reduced (worst)	Improved	Improved	Ali et al., 2015; Im et al., 2016; Zaumanis et al., 2014

2.2.4 Mechanism of Recycling Agents

The RA follow two processes of mechanism, which are the dispersion of the RA within the recycled mixtures and the diffusion of the RA into the aged asphalt (RAP) (Tan et al., 2012).

The first process "Dispersion" is produced through physical processes. This process is a function of time as it depends on the mixing mechanism at the plants that ensures even spreading of the RA. In this process, the fresh binder and the mixture will be covered with the recycling agent homogenously. However, sometimes the aged RAP binder absorbs hydrocarbon-type liquid before achieving the required dispersion. (Martin et al., 2015). The second process is called the diffusion process, which has been summarized into four steps according to Carpenter & Wolosick, (1980). First step is that the aggregate coated with asphalt will be encircled by the RA. Then, the RA begins softening the aged RAP binder by penetrating into the aggregate and forming a layer with little stickiness. At that point, the diffusion process remains until the viscosity of the outer layer is greater than that of the inner layer. Finally, after time, all RAP binder will be able to reach stability. The diffusion is also affected by the method of adding the RA to the recycled materials (Martin et al., 2015), the most efficient method is by adding the RA to the recycled materials before mixing them with the virgin materials, but this method is hard to apply in the asphalt plant and much costly so, usually the RA is blended with the virgin binder before combined with the recycled materials and the virgin aggregate (Tran et al., 2012). As mentioned in article by (Moghaddam & Baaj, 2016), several other factors affect the rate of diffusion such as the size and shape of the molecules and the temperature. The most influential factor in this process used in this study was the temperature. Increasing the mixing and compaction temperatures can speed up the degree of diffusion so, the higher the temperature, the better the diffusion will be (Tran et al., 2012).

According to Zaumanis et al., 2015, incomplete diffusion process will lead to pavement distresses. If the diffusion is not completed before opening the roadway to traffic then, the outer layer of the binder film will have the highest RA dosage and that can cause early rutting in pavement life. In addition, part of the aged binder will last as a “black rock” when the RA does not fully diffuse into it and that might risk the pavement to have cracking failure.

2.2.5 Optimum Dosage of Recycling Agent

The required dosage of RA has to be controlled for each RAP asphalt mix since the amount of recycling agent added to the mix affects the process of restoring the aged RAP binder properties. Small amounts of RAs are commonly used and suggested by the companies. Nonetheless, other factors like the source of aggregate and binder can extend the amount to be large (Martin et al., 2015).

The performance of flexible pavement is critical; it is directly affected by the RA dose. Thus, the aged RAP binder will promptly be affected by any extra amount of RA. That extra amount could be harmful to the performance particularly to rutting as well as to the overall cost. Therefore, PG grade of the aged binder is the most crucial part to be considered when dealing with recycling agents (Martin et al., 2015).

Several RA dosage selection methods were explored by researchers. The first one was recommended by (NCHRP 09-58) by (Martin et al., 2016). This method involves preparing three asphalt binder blends; one with no RA, one with high RA dosage, and one with low RA dosage. This method depends mainly on laboratory measurements in order to obtain the continuous high performance grades (PGH) through the rolling thin film oven (RTFO) aged by the dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests and to find the continuous low performance grade (PGL) by using the pressure aging vessel (PAV) aged to get the stiffness ($S < 300$ MPa) and the minimum change rate in stiffness ($m \geq 0.300$). The procedure of obtaining the optimum RA dosage is a) plot the RTFO and the Original for the PGH and the S-curve and m-curve for the PGL versus the RA dosage. b) Construct the regression equations for the colder PGH curve and warmer PGL curve. c) Use a preliminary RA dosage to start with and in 0.5% increments to hit the target continuous PGL. d) Use the obtained PGL value to check the PGH value by substituting in the colder regression equation. e) Increase or decrease the RA dosage to meet the target binder PGL.

Another method was suggested by Anderson et al., 2011, where the thermal cracking is lessened to a $\Delta T_c = -5$ºC after 40 hour PAV aging. However, this minimization of ΔT_c is costly as that significantly causes an increment in RA dosage,

Recently, the NCHRP project 09-58 extended their first suggested method by adding extra asphalt content to the mixture so that the durability and the cracking resistance are improved and the rutting susceptibility is prevented. Likewise, the RA dosage is added to the blend with a specific portion without affecting the rutting.

In 2014, Zaumanis et al. conducted a laboratory study to determine the optimum dose of different types of RA, which included: aromatic extract, waste engine oil, waste vegetable oil, organic oil, waste vegetable grease and distilled tall oil. Based on their study, they recommended using Equations 1 and 2 to determine the RA dose to ensure adequate low temperature cracking resistance and fatigue cracking resistance, respectively, and setting the minimum dose as the higher value obtained from these equations. In addition, they recommended using Equation 3 to determine maximum RA dose to ensure sufficient rutting resistance. The optimum dose should be selected to be between the computed maximum and minimum RA dose value.

$$\text{Max dosage\%} = \frac{(\text{high PGtarget} - \text{high PGRAP}) \times (-\%\text{trial})}{(\text{high PGRAP} - \text{high PGtrial})} \quad (1)$$

$$\text{Min dosage}_{\text{low PG}}\ \% = \frac{(\text{low PGtarget} - \text{low PGRAP}) \times (-\%\text{trial})}{(\text{low PGRAP} - \text{low PGtrial})} \quad (2)$$

$$\text{Min dosage}_{\text{intermed PG}}\ \% = \frac{(5000 - \text{Intermed PGRAP}) \times (-\%\text{trial})}{(\text{Intermed PGRAP} - \text{Intermed PGtrial})} \quad (3)$$

Where;

$\%_{trial}$ is the RA dosage for trial blend (%).

high PG_{target} is the specified high PG temperature (°C).

high PG_{RAP} is RAP high PG temperature (°C).

high PG_{trial} is the high PG temperature for trial blend (°C).

And the same notations for low and intermediate PG.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter explains the materials and the equipment that have been used in this thesis work to produce different samples of HMA mixtures that include recycled asphalt pavement (RAP) and recycling agents (RA). Moreover, in this chapter the design of asphalt mixes, the process of specimen preparation, and the asphalt specimen testing will be presented. The potential distresses of asphalt in Ohio were tested based on four different tests which are the Semi-Circular Bend test (SCB) for fatigue cracking at intermediate temperature, the Asphalt Concrete Cracking Device (ACCD) test for low temperature cracking, the Indirect Tensile Strength (ITS) test for moisture susceptibility and the Asphalt Pavement Analyzer (APA) test for rutting prediction. All tests were implemented according to American Association of State Highway and Transportation officials (AASHTO) and Ohio Department of Transportation (ODOT) standard specifications.

3.2 Aggregates

The Shelly Company, an ODOT approved supplier was the provider of the aggregate for this study, two types of aggregates were obtained from Shelly Materials in Columbus, OH. The first one is the siliceous limestone with its two types; the manufactured sand and the #8 gradation sand. The second type is the natural sand. All the aggregates were sieved using the mechanical sifter and the retained amount on each sieve sizes between 3/8’’ and 0.075” (#200) and the pan was collected in containers after being dried in the oven over night. The gradation of the aggregate was obtained from ODOT and a small adjustment on #8 crushed limestone had been made to achieve the 12.5 mm NMAS curve. Table 3.1 below shows the aggregate gradation blends for all mixes in this project.

Figure 3.1 demonstrates the 0.45 power chart (12.5 mm NMAS) for all mixes with RAP-Shelly-2017 PileA.

Table 3.1: Aggregate Gradation Blends for all mixes

Sieve	Control	20%RAP	30%RAP	40%RAP	50%RAP
2" (50.8)	100.0	100	100.0	100.0	100.0
1-1/2" (38.1)	100.0	100	100.0	100.0	100.0
1" (25.4)	100.0	100	100.0	100.0	100.0
3/4" (19)	100.0	100	100.0	100.0	100.0
1/2" (12.7)	100.0	100	100.0	100.0	100.0
3/8" (9.5)	94.5	92.0	91.2	91.1	91.2
#4 (4.75)	56.1	55.6	54.8	54.7	54.5
#8 (2.36)	38.0	37.5	37.2	37.6	37.3
#16 (1.18)	26.0	26.6	26.9	27.6	27.9
#30 (0.6)	16.2	16.9	17.4	18.1	18.2
#50 (0.3)	9.1	10.0	10.6	11.2	11.1
#100 (0.15)	5.6	6.4	6.8	7.3	7.7
#200 (0.075)	3.6	4.2	4.6	5.0	5.4

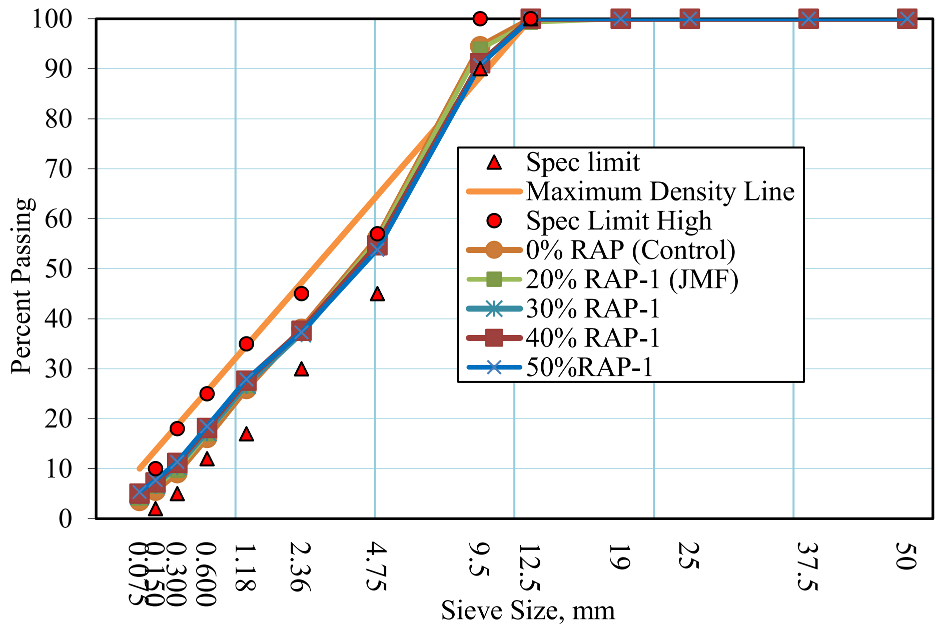

Figure 3.1. Gradations of RAP-RA mixes evaluated in this study

3.3 Recycled Asphalt Pavement (RAP)

All RAP for this project was provided by the Shelly Company from seven different resurfacing projects in Ohio (Shelly 2017 Pile RAP-A). RAP binder was extracted and recovered in accordance with AASHTO T164 and AASHTO R59. Based on AASHTO M320, the performance grade of each extracted RAP binder was determined. The solvent used to extract the binder from RAP was toluene. The continuous high and low temperature grades for the selected Shelly RAP binder was 93.1°C and -14.3°C, respectively.

All RAP obtained was moist. Thus, all RAP needed to be dried out before being used. RAP was manually sieved on ½'' and split to make sure of the consistency of RAP portion in the blend. Then, the split RAP was left in the air to dry out for 24 hours and then put in the oven for 3 hours at 110 $\overset{o}{C}$. Four percentages of RAP were used in this project, 20%, 30%, 40% and 50% and mixed with the virgin materials according to the job mix formula (JMF) for an asphalt mixture with RAP and in accordance with Item 441 in ODOT specifications.

3.4 Asphalt Binder

In this project, the asphalt binder of PG 64-22 was used for the control virgin mixture as well as for all RAP-RA mixtures. The PG 64-22 is commonly used in the State of Ohio in surface course mixes on local roads for median traffic volumes. A softer binder of PG 64-28 (PPA modified) was also used in this research for the 30%, 40% and 50% RAP mixes. Both binders were obtained from the Shelly Company in Columbus attached with the appropriate mixing and compaction temperatures. All binders were tested according to AASHTO M320. Table 3.2 shows the continuous and performance grade obtained for each binder.

Table 3.2: Performance and Continuous Grade of the Considered Binders

Binder	Continuous Performance Grade	Performance Grade
PG 64-28	CG 64.9-30.6	PG 64-28
PG 64-22	CG 66.7-22.0	PG 64-22

3.5 Recycling Agents (RA)

Three different types of recycling agents were selected for evaluation in this work. They were categorized into two main groups, the first one is the organic group and it has two kinds which are a tall oil (Sylvaroad™ RP1000, hereinafter referred to as Sylvaroad) and a vegetable oil (Soybean). The second group is petroleum base and only one RA of this group was used, which is the aromatic oil (Hydrolene® H90T hereinafter referred to as Hyrolene). The Holly Frontier Company was the provider for the Hydrolene and Soybean oils, KRATON was the supplier of the Sylvaroad oil. Table 3.3 below shows the properties of each RA. Each type of the RAs was heated in the oven at 60ºC for 20 minutes just before mixing. Fifteen minutes right after putting the RA in the oven, the required amount of RA dosage blended with the required amount of asphalt binder and the blend was stirred for one minute before placing it back in the oven for another 5 minutes at the mixing temperature to complete the 20 minutes heating process.

Table 3.3: Properies of recycling agents used in this study.

RA / Property	Sylvaroad	Hydrolene	Soybean
Viscosity (cm^2/s)	1.008 at 20 °C	0.162 at 100 °C	0.582-0.622
Specific Gravity	Not Available	0.98	0.916-0.922
Engineered or Generic	Generic	Generic	Generic
Petroleum or Organic	Organic	Petroleum	Organic
Price per pound (USD)	1.5	0.2705	0.32
Source	KRATON	HollyFrontier LLC	HollyFrontier LLC

3.6 Hot Mix Asphalt Mixtures

In this project, fourteen different surface asphalt mixes were designed. Three of them with 30% RAP, 40% RAP and 50% RAP mixes were designed with asphalt binder of PG 64-28 and no RA. The Control (no RAP), 20% RAP mix and the rest of nine (RAP-RA) mixes with three different kinds of RAs were designed with PG 64-22 asphalt binder.

The gradation of the aggregate for all mixes were maintained closely to the job mix formula (JMF) by modifying the amount of virgin aggregate in the mix. For each mix, the manufacture sand to natural sand ratios was also adjusted to be close to each other to make sure that the effects of sand angularity is eliminated. Four aggregate blends have been used for all mixes with ½ inch (12.5-mm) nominal maximum aggregate size (NMS) which are, the crushed #8 limestone, manufactured sand limestone, natural sand and RAP blends. For each RAP percentage - each blend contribution percentage was determined to achieve the gradation according to ODOT Item 401.04 Method 2. All the fourteen mixes that were prepared are listed below.

- Control Mix (0% RAP) with asphalt binder PG 64-22.
- 20% RAP with asphalt binder PG 64-28 and 0% recycling agent (RA).
- 30% RAP with asphalt binder PG 64-28 and 0% RA.
- 40% RAP with asphalt binder PG 64-28 and 0% RA.
- 50% RAP with asphalt binder PG 64-28 and 0% RA.
- 30% RAP with asphalt binder PG 64-22 and 8% Sylvaroad™ RP1000 Oil.
- 40% RAP with asphalt binder PG 64-22 and 8% Sylvaroad™ RP1000 Oil.
- 50% RAP with asphalt binder PG 64-22 and 8% Sylvaroad™ RP1000 Oil.
- 30% RAP with asphalt binder PG 64-22 and 10% Hydrolene® H90T Oil.
- 40% RAP with asphalt binder PG 64-22 and 10% Hydrolene® H90T Oil.
- 50% RAP with asphalt binder PG 64-22 and 10% Hydrolene® H90T Oil.
- 30% RAP with asphalt binder PG 64-22 and 9.5% Soybean Oil.
- 40% RAP with asphalt binder PG 64-22 and 9.5% Soybean Oil.

- 50% RAP with asphalt binder PG 64-22 and 9.5% Soybean Oil.

3.6.1 Aggregate Preparation

As it was mentioned earlier, the aggregates were oven heated overnight and then sieved using the mechanical sifter. Thereafter, sieve analysis was conducted based on the achieved gradation according to ODOT specifications and batches were prepared following the percentage of each blend. Different aggregate blends were used for the Control, 20% RAP, 30% RAP, 40% RAP and 50% RAP mixtures and are summarized in Table 3.4.

Table 3.4: Aggregate blends proportions for each mixture type

Aggregate / Surface Mixtures	Aggregate Proportions for (12.5 mm) NMAS			
	Crushed LS #8	Natural Sand	Manufactured Sand	RAP
Control	55.0%	21.0%	24.0%	0.0%
20% RAP	47.0%	16.0%	17.0%	20.0%
30% RAP	43.0%	13.0%	14.0%	30.0%
40% RAP	38.0%	10.5%	11.5%	40.0%
50% RAP	34.0%	7.5%	8.5%	50.0%

LS=Limestone
NS=Natural Sand
MN= Manufactured Sand

3.6.2 Optimum Asphalt Content

The NCHRP 752 team recommended an equation (1) to determine the performance grade of the virgin binder. According to that equation, a PG 64-22 binder was used with the Control, 20% RAP as well as the 30% RAP, 40% RAP and 50% RAP with different RA. On the other hand, the 30% RAP, 40% RAP and 50% RAP with no RA was prepared using PG 64-28 asphalt binder.

$$T_{C(virgin)} = \frac{T_{C(need)} - (RBR \times T_{C(RAP\ binder)})}{1 - RBR} \qquad (1)$$

where $T_{c(virgin)}$ is the critical temperature (high or low) of the virgin asphalt binder, $T_{c(needed)}$ is the critical temperature (high or low) needed for the climate and pavement layer, and RBR is RAP to Binder Ratio, which is the ratio of RAP binder in the mixture divided by the mixture's total binder content, and $T_{c(RAP\ Binder)}$ is the critical temperature (high or low) of RAP binder.

The laboratory samples were prepared using the Marshall Mix design method according to AASHTO T 245 "Resistance to Plastic Flow of Bituminous Mixtures Using the Marshall Apparatus" in order to determine the optimum asphalt content for the different considered mixes. Each sample should attain the volumetric criteria of 3.5% air void target. The dimensions of each sample are 100-mm diameter and 63.5-mm height and four samples were prepared for every asphalt content percentage, a total of eight samples for each mix. A total of five mixtures were designed. Figure 3.2 shows the Marshall Device setup used in this project. Table 3.5 summarizes the resulted properties of the mix design for the designed mixtures.

Figure 3.2 Marshall Compactor used in this study

Table 3.5: Tested Mixture Properties

Mix	% RAP	Virgin Binder type	Optimum Virgin AC%	RBR	Gmm
Control	0	PG 64-22	6.3	0	2.429
20% RAP-1	20	PG 64-22	5.3	16%	2.428
30% RAP-1	30	PG 64-28	4.8	25%	2.440
40% RAP-1	40	PG 64-28	4.3	33%	2.448
50% RAP-1	50	PG 64-28	3.8	41%	2.455
30% RAP-1 -Hydrolene RA	30	PG 64-22	4.8	25%	2.439
40% RAP-1 -Hydrolene RA	40	PG 64-22	4.3	33%	2.439
50% RAP-1 -Hydrolene RA	50	PG 64-22	3.8	41%	2.435
30% RAP-1 -Sylvaroad RA	30	PG 64-22	4.8	25%	2.440
40% RAP-1 -Sylvaroad RA	40	PG 64-22	4.3	33%	2.447
50% RAP-1 -Sylvaroad RA	50	PG 64-22	3.8	41%	2.444
30% RAP-1 -Soybean RA	30	PG 64-22	4.8	25%	2.437
40% RAP-1 -Soybean RA	40	PG 64-22	4.3	33%	2.441
50% RAP-1 -Soybean RA	50	PG 64-22	3.8	41%	2.439

Two different trial asphalt content proportions for every mix were chosen so that the optimum asphalt content falls between these two percentages. The asphalt binder was heated at mixing temperature of 154 ºC for three hours before mixing. Also, the necessary amount of blended aggregate was put in the oven at the same mixing temperature the night before while the specified amount of RAP were placed in the oven, but two hours before mixing. Thereafter, the asphalt binder, the blended aggregate and RAP were carefully mixed using the Humboldt bucket mixer and made sure that all the aggregate particles were thoroughly coated with asphalt binder. Then, the hot mix asphalt mixture was placed again in the oven for the short term aging at the compaction temperature, which is 142 ºC. After two hours of aging, the samples were compacted using Marshall Device with 50 blows on each side of the sample as required in the specification of this method for roads with medium traffic volume.

RAP mixtures with no RA s were only considered in the designing process of different mixtures, and according to AASHTO T-209, and AASHTO T-166, the "Theoretical Maximum Specific Gravity of HMA Mixtures (G_{mm})" and the "Bulk Specific Gravity of Compacted Asphalt Mixtures (G_{mb})", respectively, were calculated for all mixtures. From that point, the air voids were also calculated for the two asphalt contents percentages of each mix.

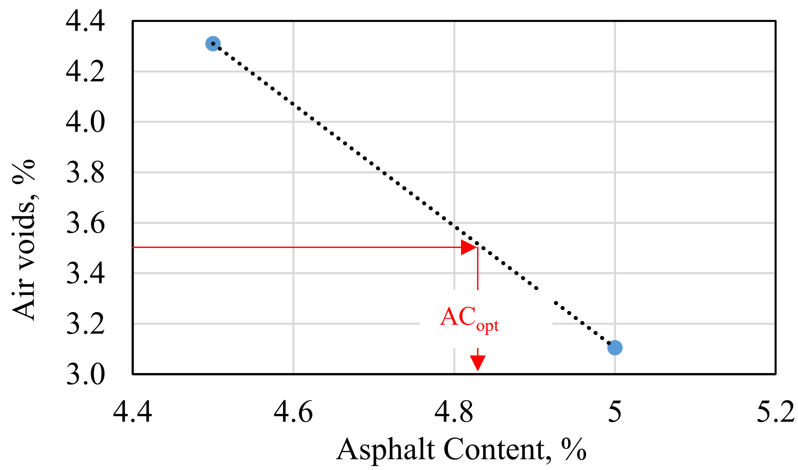

Figure 3.3 Air voids % vs asphalt content%

Figure 3.3 above is an illustration of how the optimum asphalt contents are obtained. From the graph, by determining the average air voids corresponding to each asphalt content chosen for design, the optimum asphalt content corresponding to the target 3.5% air voids can be determined. The same procedure was followed for the rest of the mixes and the results of the used optimum asphalt content in the project are summarized in Table 3.5.

3.6.3 Optimum Recycling Agent Dosage

Three methods have been utilized to determine the optimum RA dosage. The first recommended one was constructed via the "National Cooperative Highway Research Program (NCHRP 09-58)" by (Martin et al., 2016). This method depends on the characteristics of the binder blends with different RA dosages to restore the continuous grading temperatures for PG graded asphalt binder according to ASTM D7643-16. In this project two different dosages of RA have been used. The second method depends on a maximum ΔT_c edge of -5°C after the long-term aging, this method is costly as the recycling agents dosage will increase. Recently, the NCHRP project 09-58 research team published a paper that recommended a new method for dosage selection method. This method follows the same suggested procedure, but it requires extra asphalt content to be added to the mixture in order to prevent rutting and to enhance the durability and cracking resistance. In the same way, the RA dosage is added to the blend to improve the low temperature cracking without affecting the rutting.

Using the first recommended method, the binder blends characteristics were tested at the University of Akron using the dynamic shear rheometer (DSR). The G*/sinδ from Rolling Thin Film Oven (RTFO) aged samples and G*/sinδ from (original) unaged samples of the binder blends were obtained so that the continuous high-temperature grading temperature (PGH) can be found. Furthermore, in order to find the continuous low-temperature grading temperature (PGL), another two binder blends properties were tested using the Bending Beam Rheometer test (BBR) on Pressure Aging Vessel (PAV) aged binder blends samples. In this test, the properties have to have a stiffness of ($S < 300$ MPa) and a minimum rate of change in stiffness of (slope, $m \geq 0.30$).

Once the PGH and PGL are calculated, the PGH from the DSR tests on RTFO aged and unaged samples and the PGL from the S-controlled and m-controlled values are plotted versus the RA dosage. Now, the colder regression equation of the PGH and the warmer regression equation of the PGL are created. Hereafter, and for each RA, a preliminary RA dosage is selected and through increasing or decreasing the dosage by 0.5%, the RA dosage that restore the target binder was calculated using the colder PGH regression line. Then, to validate that the PGL of the selected RA dosage meets the target binder PGL, it was calculated using the warmer PGL regression line. Eventually, the RA dosage was selected according to that. For more illustration of the procedure, Figure 3.4 was constructed.

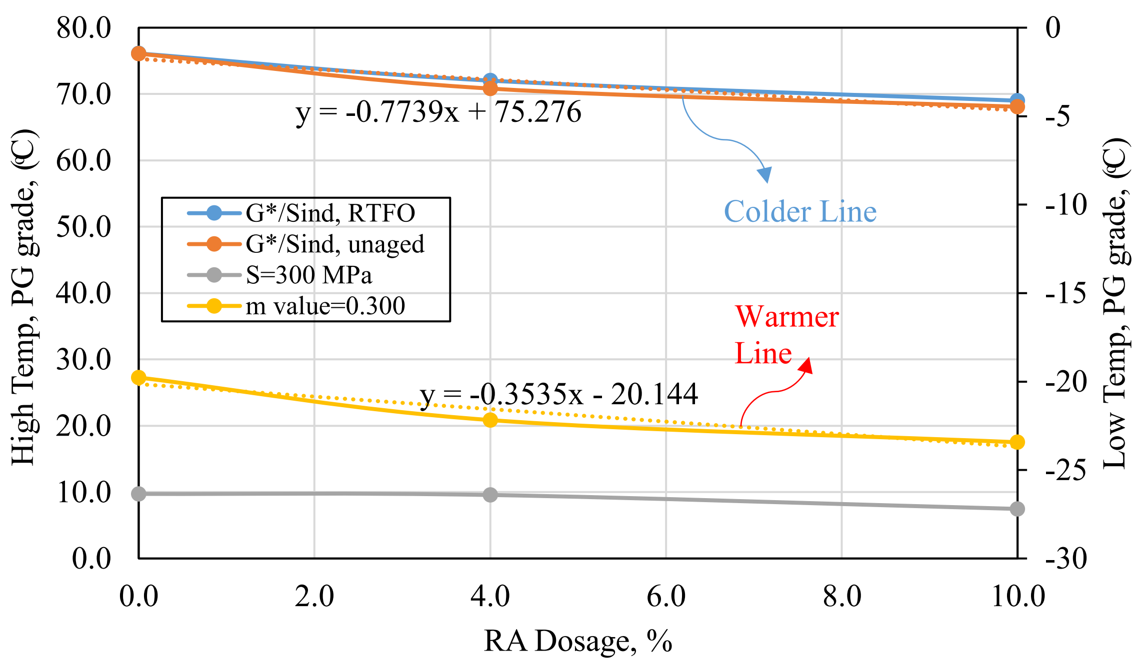

Figure 3.4 RA dosage selection method

3.7 Sample Preparation

As mentioned in section 3.6.1, aggregates were put in the oven overnight at 150ºC to dry out of moisture, then sieved by the mechanical sieve shaker, and then collected in containers according to their sieve size. Later, batches between 8000 g to 11000 g were prepared based on the weight in the job mix formula (JMF). The aggregate batch was usually placed in the oven the night before the mixing day at the mixing temperature of 154 ºC. All mixing equipment and tools as well as the asphalt mixing bucket were heated at the mixing temperature for three hours before mixing. The asphalt binder was also set in the oven at the same temperature three hours prior to the mixing procedure while the recycled material (RAP) were placed just two hours before the mixing begins. The preparation of the RA is already explained in section 3.5 where it heats at 60 ºC in the chamber for 15 minutes, blended with the required heated virgin asphalt binder, and placed back inside the oven for extra 5 minutes. At this point, the beater was attached to the Humboldt bucket mixer, and the aggregate batch was poured inside the bucket along with amount of RAP needed. Both were mixed for a few seconds before adding the asphalt binder blend to the crater formed in the middle. Directly, the bucket was placed in the mixer and the mixing process was continued until all the aggregates were thoroughly coated with the asphalt binder blend. The mixture was poured on clean pan and was set in the oven for four hours for the short-term aging process at the compaction temperature of 142 ºC. To secure a uniform aging of the mixture, it was stirred two to three times over the aging time. About an hour before compaction, the mixture was split into different specified weight samples depending on the type of the samples needed; SCB, ACCD or ITS samples. Lastly, the samples were compacted using the Superpave Gyratory Compactor and left for cooling down so that the air voids of 7.0 ± 0.5% of each sample can be obtained.

The SCB prepared samples needed to be trimmed, cut, and prepared for testing using the sawing machine as shown in Figure 3.5 (a). Every SCB compacted sample is cut into four semi-circular specimens, where two of them drive for long-term aging process and the other two left as short-term aged. In the middle of each short-term aged semi-circle specimen, a notch of 15-mm was made as captured in Figure 3.5 (b). For the ACCD samples, they were cut into two halves and each half was cored in the middle with 60-mm hole using the coring device in Figure 3.6 (a). Similarly, a notch of 22.5-mm was made on the side surface of each short-term aged specimen as depicted in Figure 3.6 (b) and one of the specimens was considered for the long-term aging.

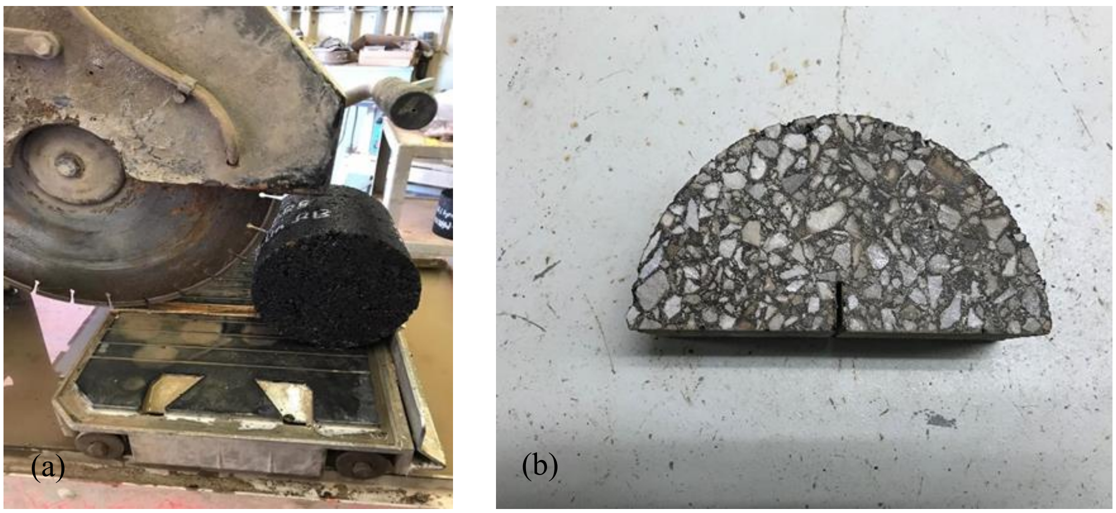

Figure 3.5. (a) Sawing Machine (b) Short-term aged semi-circle Specimen

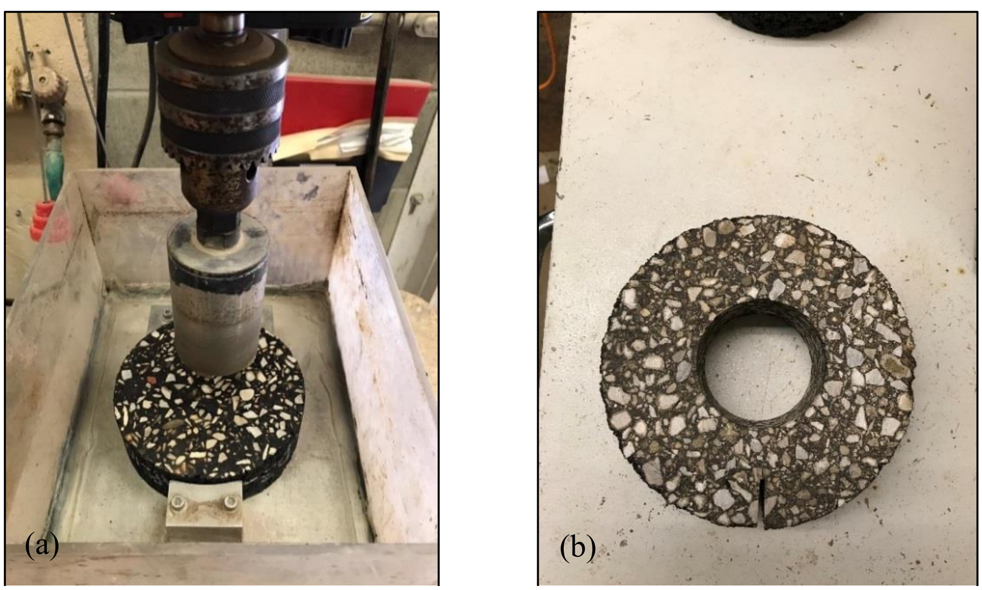

Figure 3.6. (a) ACCD coring device (b) Short-term aged ACCD specimen

For every mixture, six semi-circle specimens of SCB and three half of ACCD specimens drove to the environmental aging chamber for five-days aging process at 85ºC. After the aging is finished, all the specimens were kept at room temperature until next day and then they were notched as their instances of the short-term aged specimens. Next day, testing practice of all the specimens (short and long term aged) begins. The specimens for permanent deformation (Rutting) were prepared, tested and analyzed at the University of Akron using the APA test device. Typically, the specimens compacted to have 150-mm diameter and 75-mm height. The target air void has to be 7.0 ± 0.5 %.

3.8 Mixture Testing of Asphalt Specimens

In assessing the performance of the considered mixtures, different tests were conducted to check the resistance of the prepared mixtures to fatigue cracking, moisture damage, low- temperature cracking and rutting.

3.8.1 Semi-Circular Bend (SCB) test

The Illinios SCB Test method AASHTO TP 124-16 “Determining the Fracture Potential of Asphalt Mixtures Using Semi-circular Bend Geometry (SCB) at Intermediate Temperatures” was used to examine the performance of asphalt to fatigue cracking at intermediate temperature of 25ºC. Three samples of 150-mm diameter and 150-mm height were prepared using the Gyratory Compactor. Then, each sample was cut into two halves and trimmed using the cutting jig shown in Figure 3.5(a). Each half was cut into two semi-circular slices with target 7.0 ± 0.5 percent air voids. After that, a notch of 15 ± 1 mm depth and 1.5 ± 1.5 mm width was made in the middle of each specimen Figure 3.5(b). The three samples result in 12 semi-circular specimens, 6 of them were conditioned for a long-term aging of 5 days at 85ºC in an environmental chamber. The rest of the specimens were directly tested the next day, but after placing them inside environmental chamber at 25ºC for at least three hours. Both the long-term aged and the short-term aged specimens were tested using the InstroTek® Auto SCB machine as captured in Figure 3.7.

Figure 3.7. InstroTek ® Auto SCB machine.

The samples were loaded with 10 kN load at a constant rate of 50 mm/min to failure. During the loading, the vertical deformations of the specimen were recorded. This test considers two parameters, which are the Fracture Energy (FE) and the Flexibility Index (FI). The fracture energy is an indication of the resistance to fatigue cracking and can be computed through equation (1). The flexibility index (FI) is calculated based on the fracture energy through equation (2), the FI detects the brittleness of the asphalt mixture to early cracking. These two equations depends on the load-displacement curve Figure 3.9 resulted from the test for each specimen (Al-Qadi et al. 2015). Nazzal et al., (2017) suggested normalizing the Fracture Energy based on the maximum strength mixture because (FE) is a function of peak load and displacement. Accordingly, the normalized fracture energy value (NFE) was used to inspect the fatigue cracking resistance (equation 3). Figure 3.8 shows how the crack propagated within the SCB specimen after loading.

Figure 3.8. Aged SCB specimen after loading

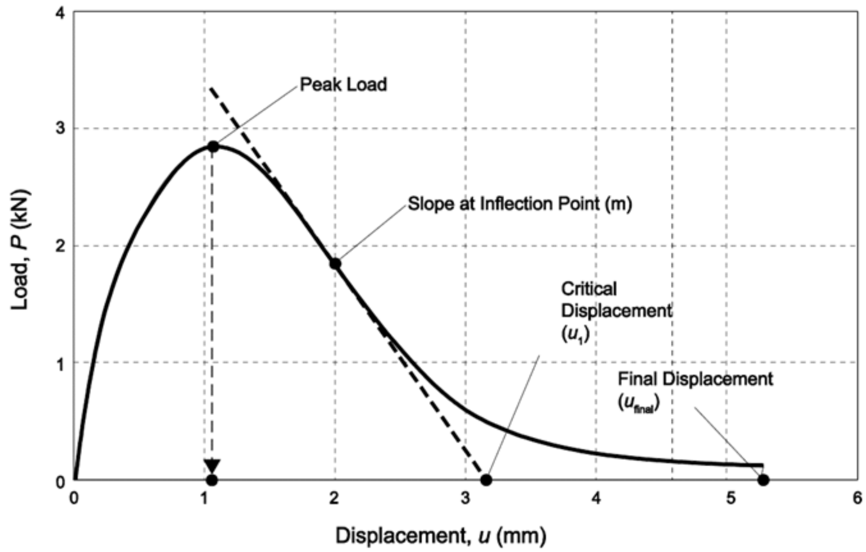

Figure 3.9. Plot of Load vs. Displacement Obtained from Illinois SCB Test (Al Qadi et al., 2015).

$$G_F = \frac{W_f}{Area_{lig}} \text{ x } 10^6 \quad (1)$$

Where:
G_f= fracture energy (Joules/m^2).
W_f= work of fracture (joules).
$Area_{lij}$= ligament area (mm^2).

$$FI = \frac{G_F}{|m|} \text{ x } A \quad (2)$$

Where;
$|m|$ = absolute value of post-peak load slope m (kN/mm).
A= unit conversion (0.01).

$$NFE = \frac{FE}{Strength} \quad (3)$$

NFE= Normalized Fracture Energy.

3.8.2 Indirect Tensile Strength (ITS)

According to AASHTO T283 test procedure modified based on the State of Ohio specifications, eight samples of each mixture were prepared with 100-mm diameter and 63.5-mm height to attain 7.0 ± 0.5 % air voids. The specimens were divided into two subsets, one for dry ITS conditioning and the other for wet ITS conditioning such that both groups have almost the same average air voids. Each sample of the four wet specimens were covered with at least 1 in of water above the specimen surface and partially saturated in water container so that the saturation is between 70%-80% after subjected to a vacuum pressure of 2.9 psi (20 kPa) for two to three minutes. The degree of saturation was calculated based on the equation (3) below.

$$S=\frac{100J'}{Va} \tag{3}$$

Where:

S= Degree of Saturation (%).
J'= B'-A where:
J'= volume of absorbed water (cm^3).
B'= Weight of saturated surface dry (SSD) specimen (g).
A= Dry weight of the specimen (g).
V_a= Volume of air voids.

If the degree of saturation was less than 0.70, the process of saturation should be repeated until the required saturation degree is achieved. If it was above 0.80, then the specimen could not be used and must be wasted. Once the saturation degree attained, the specimens wrapped with stretch plastic wrap and stored in two zip-lock plastic bags containing 10 ml of water. Then, the plastic bags were put inside the chamber at 0ºF (18ºC) for (16-18 hours) after lessening the amount of air inside the bags. Usually, after 17 hours of freezing, the specimens were taken out of the plastic wraps and bags and placed inside water bath at 140ºF (60ºC) for 24 hours of thawing cycle, check Figure 3.10. After that and 2 hours before testing, the specimens were placed in water bath at 77ºF (25ºC).

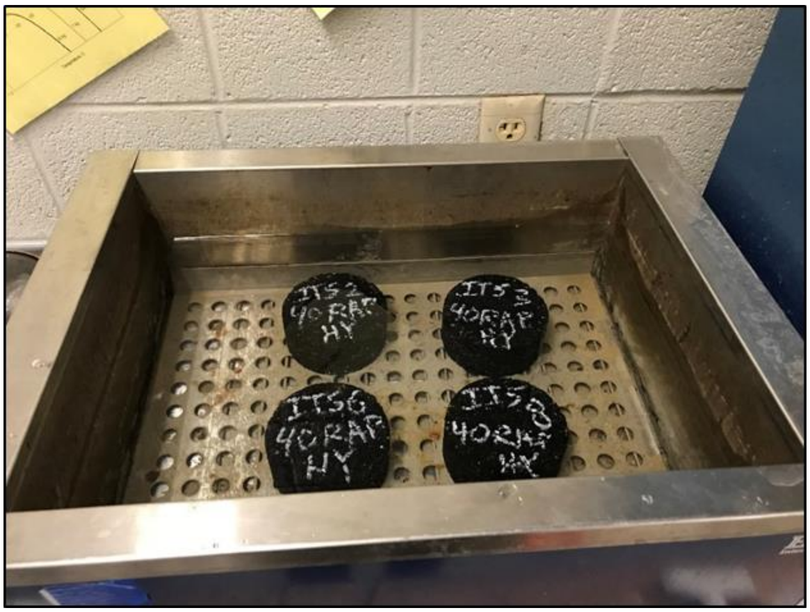

Figure 3.10. ITS samples soaked in water for conditioning.

Afterwards, specimen by specimen was tested using the InstroTek® Auto SCB machine. The specimen was placed on its side between two steel bearing plates specified for the 4 in diameter ITS samples Figure 3.11(a). A load of (25 kN) was applied to the specimen at 50-mm/minute constant loading rate until the failure happened Figure 3.11(b). During the loading process, two LVDT seniors were attached to the specimen on both sides to measure the horizontal displacement occurred and another vertical LVDT sensor to measure the vertical displacement. The maximum load is recorded and the stress peak was calculated for each wet specimen according to AASHTO T 283 equation (4) and the average of all the peak stresses of the wet samples indicates the (wet ITS). Similarly, the dry ITS samples were tested after placing them in the chamber at 77ºF (25ºC) for a minimum of 3 hours and the peak stresses were also calculated and the average values designates the (dry ITS). Finally, for each mixture the Tensile Strength Ratio (TSR) was calculated as the ratio of the average wet ITS to the average dry ITS (equation (5)).

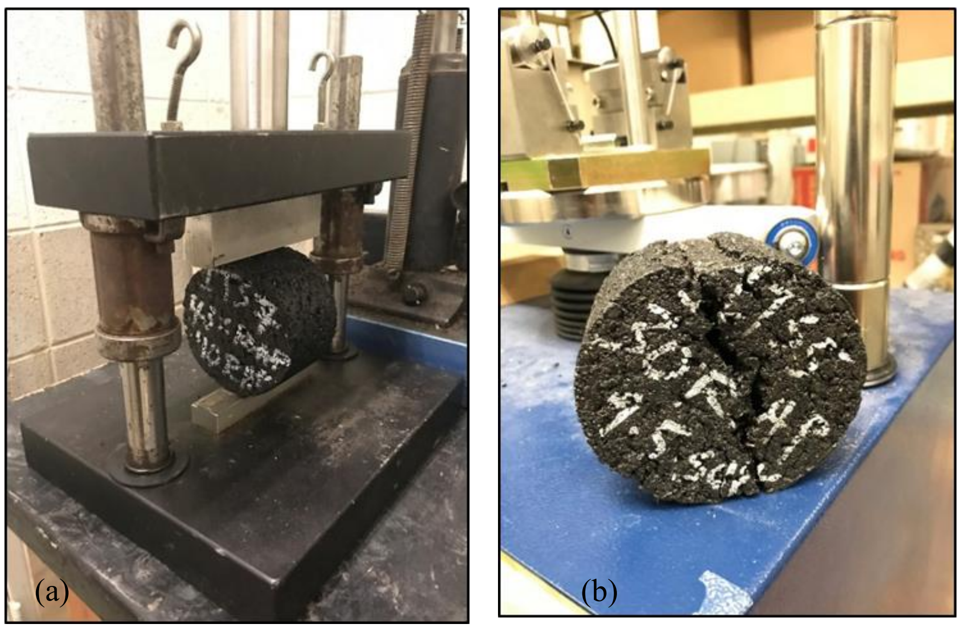

Figure 3.11. (a) ITS sample setup (b) ITS sample after failure.

$$S_t = \frac{2P}{\pi t D} \tag{4}$$

Where:
S_t= tensile strength, psi.
P= maximum load, lbs.
t= specimen thinckness, in.
D= specimen diameter, in.

$$\text{Tensile Strength Ratio (TSR)} = \frac{Average\ Wet\ ITS}{Average\ Dry\ ITS} \tag{5}$$

The TSR value is an indication of the resistance of the asphalt to moisture damage. Whenever the ratio of the TSR is high, the asphalt mixture resistance to moisture damage is low.

3.8.3 Asphalt Concrete Cracking Device (ACCD)

The ACCD device was used to test the behavior of asphalt specimens to resist the low temperature cracking. The asphalt specimens were grouped into short-term and long-term aged sets. Each group is of three samples which were, tested separately, the sample dimension is 150-mm in diameter and 50-60-mm thickness. A hole of 60-mm diameter was cored in the middle of the sample (Figure 3.6a) and a notch depth of 22.5-mm was created at the outer surface of the specimen. Figure 3.6b shows the final shape of an ACCD specimen. s

To simulate the real life aging in the field, three of the samples were placed in the chamber for long-term aging process for 5 days at 85ºC. The specimens and the ACCD rings were placed inside an environmental chamber at 60ºC for one hour and then the specimens were smoothly slipped around the rings Figure 3.12 (a). The notch was aligned with the strain gauge locator on top of the rings so that it can record the temperature and the strain that are changing within the specimen. Metal straps were placed around the specimens to hold the samples with the rings and this assembly was conditioned in the chamber at 10ºC for another hour. After that, the straps were removed and the test starts. The chamber temperature starts cooling down until it reaches -65ºC at a cooling rate of 10ºC/hr. The ACCD cracking temperature is recognized as the temperature where the strain is 80% of the maximum strain-temperature slope and at this point where the crack is originated (Figure 3.12 (b)).

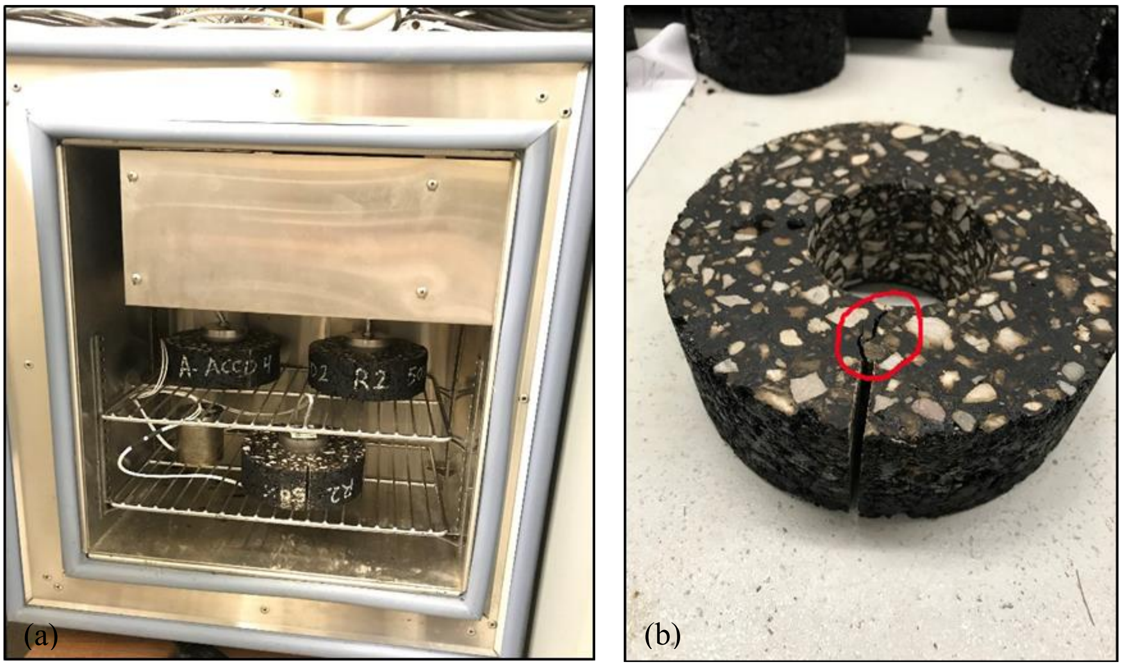

Figure 3.12. (a) ACCD test Setup (b) Aged ACCD specimen after testing.

3.8.4 Asphalt Pavement Analyzer (APA)

According to AASHTO TP-63—06 "Standard method of test for determining the rutting susceptibility of HMA using the Asphalt Pavement Analyzer (APA)" and based on the ODOT Supplement 1057 specification, the asphalt pavement analyzer (APA) was used in this project to determine the average rut depths of asphalt samples. It mimics the real asphalt rutting caused by the vehicle's wheels at a speed of approximately 23.5 inch/sec (60 cm/sec) over a rubber hose with a pressure of 100 psi (689.5 kPa) to 120 psi (827.4 kPa). This pressure is the effect of high tire pressure. Six specimens were prepared for each mixture with a dimension of 150 mm diameter and 75 ± 2 mm thickness using the Gyratory

Compactor machine. Each sample must attain a 7.0 ± 0.5 % target air voids. Then, all the specimens were heated before loading for a minimum of 12 hours at the testing temperature. The APA device measures the deformation at different number of wheel cycles and the total rutting was calculated as the difference between the rut depth at the final reading cycle (8000 cycle) and at the initial reading cycle (5 cycles). Finally, the average rut depths of the six specimens were recorded. Figure 3.13 is an illustration of the APA samples after testing.

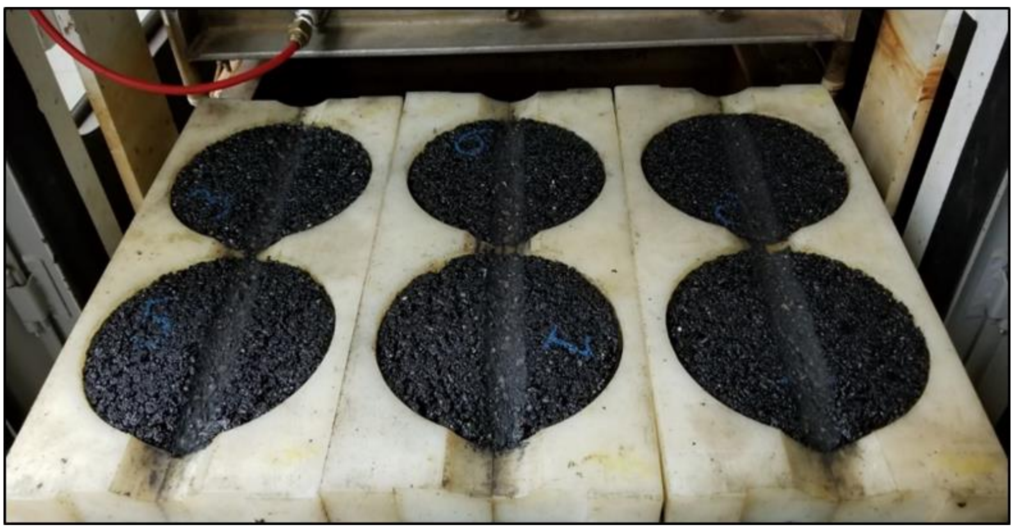

Figure 3.13. Samples of APA test after repeated wheel loading

3.8.5 Material Costs

The prices of the materials used to prepare the mixes were obtained from the supplier of each product and are presented in Table 3.6 . Based on prices, cost analysis was performed to determine the cost of each prepared mix and is presented in the following chapter.

Table 3.6: Cost of asphalt binder and recycling agent used, spring 2018

Material	Price ($/ton)
PG 64-22	$345.83
PG 64-28	$455.83
Sylvaraod RP1000	$3,000.00
Hydrolene ®H90T	$541.00
Soybean	$640.00

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Recycling Agent Dosage Selection

The optimum dosage of the recycling agent for each recycling agent was determined based on the selection method explained in section 3.6.3, and the results of each selection are presented in Figure 4.1 through Figure 4.3.

The concept behind the figures as presented by (Martin et al. 2016) through the NCHRP project 09-58, is to select an optimum dosage for a specific RA so that it meets the continuous temperature performance grading (PG) of the target asphalt binder, which in this project is a PG 67.7-22.2.

Three recycled blends were prepared with virgin asphalt binder of PG 64-22. One with no RA (Control blend), and the other two blends one with low and another with high RA dosages based on the maximum and minimum manufactured doses provided by the manufacture. RAP percentage used in preparing the blends was 40% and then the results of these blends were estimated to the other RAP percentages the (30% and 50%) Afterwards, laboratory measurements were conducted to obtain the PGH by using the Dynamic Shear Rheometer (DSR) on RTFO original (unaged) and aged blends, and the PGL by using the Bending Beam Rheometer test (BBR) conducted on the Pressure Aging Vessel (PAV) aged samples as stated in AASHTO M 320.

The RA dosages were selected based on the regression line of the PGH and PGL. A 0.5% increments in RA dosage are maintained to meet the PGH of the target binder of 67.7°C. The PGL was then computed based on the warmer PGL equation for each RA and compared to the target binder of 22.2°C. Table 4.1 illustrates the selected dosage for different RAs.

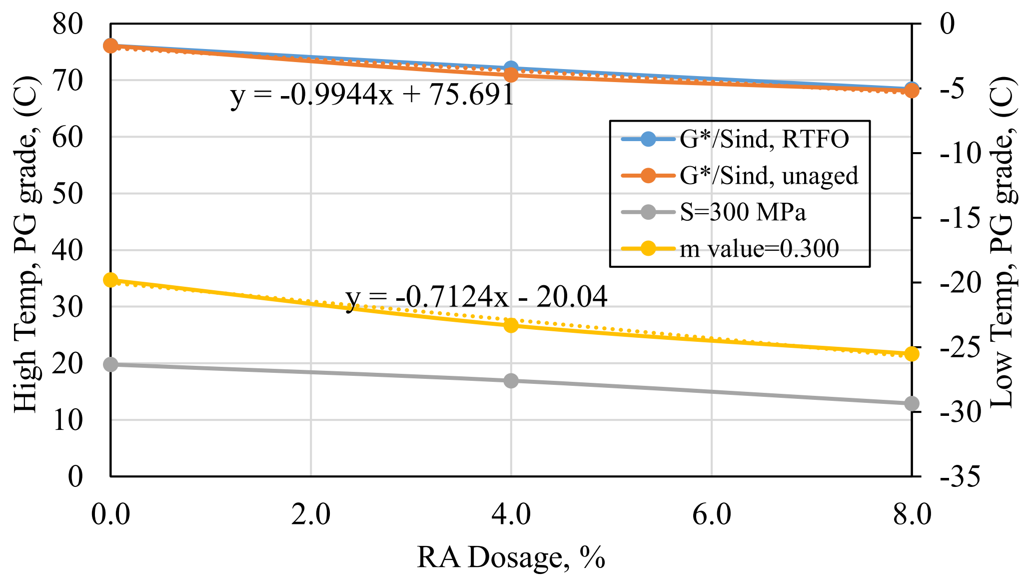

Figure 4.1. RA dosage selection of Sylvaroad-RA blend with PG64-22 with 40% RAP

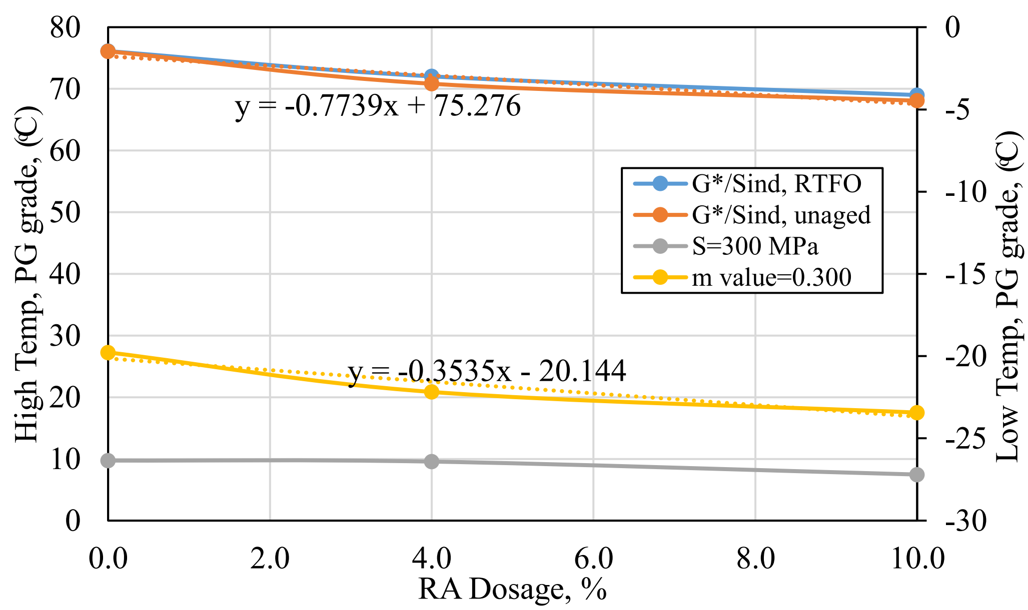

Figure 4.2. RA dosage selection of Hydrolene-RA blend with PG64-22 with 40% RAP

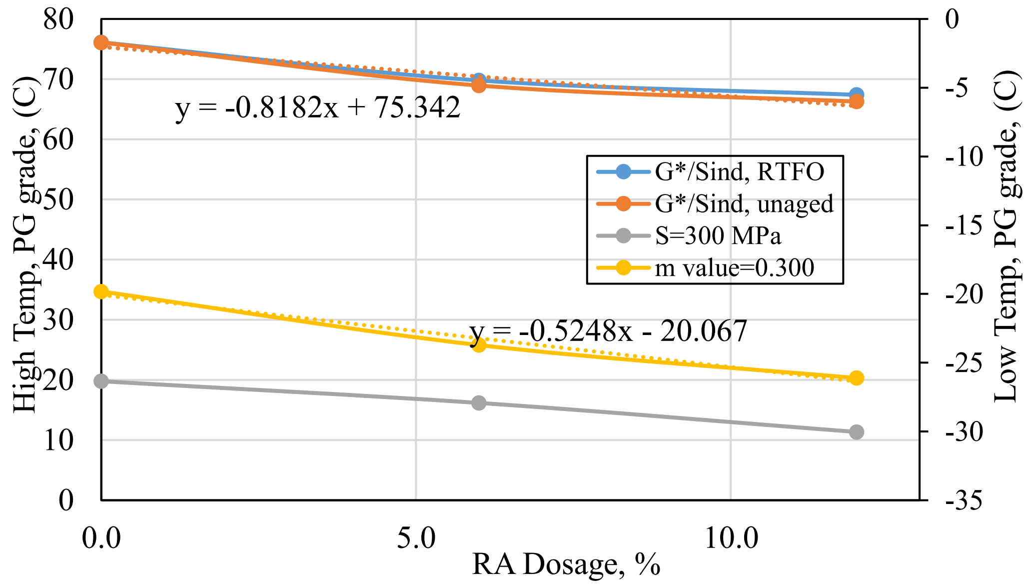

Figure 4.3. RA dosage selection of Soybean-RA blend with PG64-22 with 40% RAP

Table 4.1: Selected RA dosages

RA	Selected RA Dosage	PGL	PGH
Sylvaroad	8.00%	-25.7	67.7
Hydrolene	10.00%	-23.7	67.5
Soybean	9.50%	-25.1	67.6

4.2 Results of Mixture Testing

The results of the performance tests on the prepared asphalt specimens are discussed in this section. The fatigue cracking of asphalt at intermediate temperature was assessed by the Semi-Circular Bend (SCB) test, the moisture susceptibility to damage was evaluated through the modified Lottman test, both the SCB and the Lottman were tested using the Instrotek© Auto SCB machine. In addition, the specimens were tested against low temperature cracking via the Asphalt Concrete Cracking Device (ACCD) while the Asphalt Pavement Analyzer (APA) was utilized to test the resistance of asphalt specimens to rutting. The Control mix, the 20% RAP with no RA as well as all RAP-RA mixes were prepared using asphalt binder of PG 64-22 while the 30% RAP, 40% RAP and 50% RAP mixes with no RA were prepared with asphalt binder of PG 64-28.

4.2.1 Fatigue Cracking at Intermediate Temperature

Figure 4.4 through Figure 4.9 present the average fracture energy (FE), normalized fracture energy (NFE) and the flexibility index (FI) for the short-term and long-term aged samples of each mix with the corresponding standard deviations. It can be observed that the values of the (FE) (NFE) and the (FI), for the short-term aged specimens were higher than the long-term aged ones. The short-term aged values over the long-term aged values were computed and plotted in figures 4.10, 4.11, and 4.12 to see the difference between the different RAs on Fatigue cracking.

For all mixes with RA and PG 64-22 binder and for mixes with softer binder PG 64-28 and no RA, the NFE values decreased as RAP content increased. This means that using softer binder PG 64-28 was not effective in maintaining the fatigue cracking resistance of the mixes with RA and PG 64-22 binder when 30% RAP or more was used.

It can be noticed from Figure 4.7 that all the aged RAP-RA mixes produced higher energy of fracture than the one produced by the Control mix except for the 50% RAP-Soybean mix which shows a slight reduction in fracture energy compared to the Control and the 20% RAP mixes, which means that the crack needed less energy to propagate through the asphalt specimen. Figure 4.8 shows how the data are normalized based on the average strength of each mix. The higher the value the better the cracking resistance. Clearly, the Sylvaroad and Hydrolene RAs showed much higher NFE than the Soybean

RA and RAP mixes with softer PG 64-28 binder. Accordingly, using Sylvaroad and Hydrolene RAs might be more effective in improving the fatigue cracking resistance.

Figure 4.9 shows the averaged Flexibility Index (FI) of aged samples in every mix. The FI is an indication of the asphalt mix cracking, the higher the FI the better the cracking resistance. For the 30% and 40% RAP-Sylvaroad and for the 40% RAP-Hydrolene, the FI values were slightly higher than the FI of the control mix, which means that these mixes are less brittle and has a greater resistance to cracking. In addition, the 50% RAP mixes with Sylvaroad and Hydrolene had similar FI to the 20% RAP mix. In general, RAP mixes with Hydrolene RA had slightly higher FI than those with Sylvaroad RA. To conclude, it can be seen from Figure 4.9 that the FI aged values of the Soybean mixes with different RAP percentages are significantly less than those with Sylvaroad and Hydrolene mixes, which means that adding the Soybaen RA to RAP mixes did not considerably improve the brittleness of the mixes. Figure 4.10 represents the Short-term aged over Long-term aged ratios of fracture energy of each mix. It can be noticed from this figure that Soybean mixes values were slightly greater than other RA mixes as well as RAP mixes except for the 40% RAP-Hydrolene and 50% RAP mix. Also, as the RAP content increased the ratios increased. In Figure 4.11, it is obvious that for the flexibility index effect, the ratios of short-term aged over the long-term aged for the Soybean-RA were way bigger than the ratios for Sylvaroad and Hydrolene. It was also noticed that Soybean ratios were bigger than ratios of mixes with no RA, but asphalt PG 64-28 binder and RAP. This suggests that the Soybean resulted in softening the aged RAP binder rather than restoring its properties. Moreover, this indicates a deterioration had happen upon aging. In Figure 4.12, as the RAP content increased the deterioration upon aging increased. Soybean mixes had the highest ratio among other mixes. However, the 50% RAP mix ratio with PG 64-28 and no RA was bigger than the 50% RAP-Soybean ratio which means that using softer binder of PG 64-28 had more significant deterioration than the Soybean-RA mix upon aging.

Comparing the results to previous studies presented by Veeraragarvan (2017) and Zaumanis (2014), both, Sylvaroad and Hydrolene results were compatible with these literature results as both improved the fatigue cracking resistance.

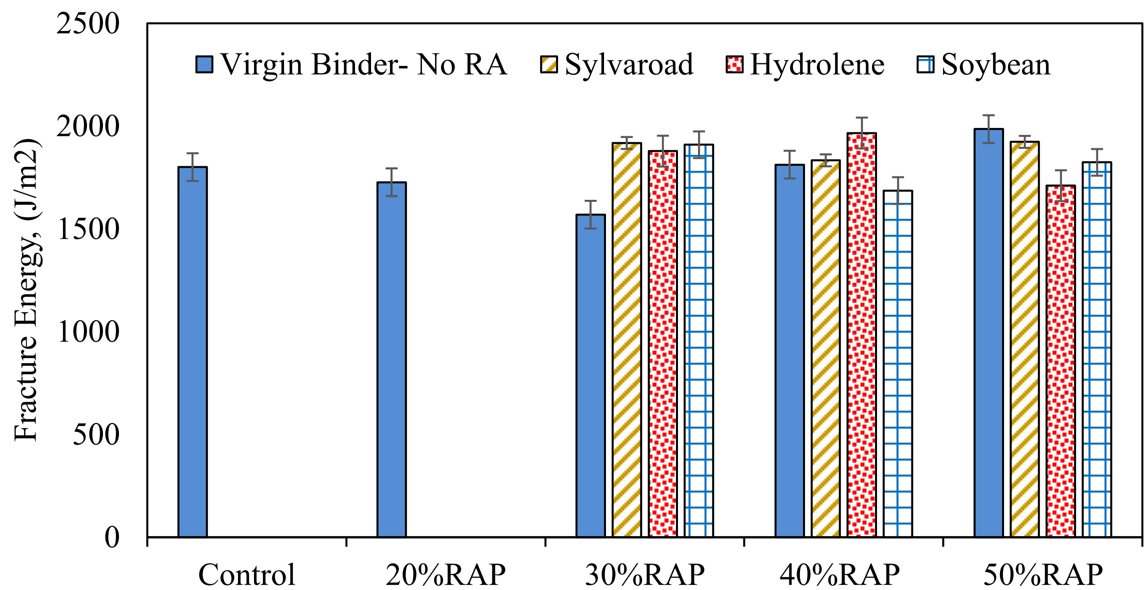

Figure 4.4. Fracture Energy (FE) for short-term aged RAP-RA mixes

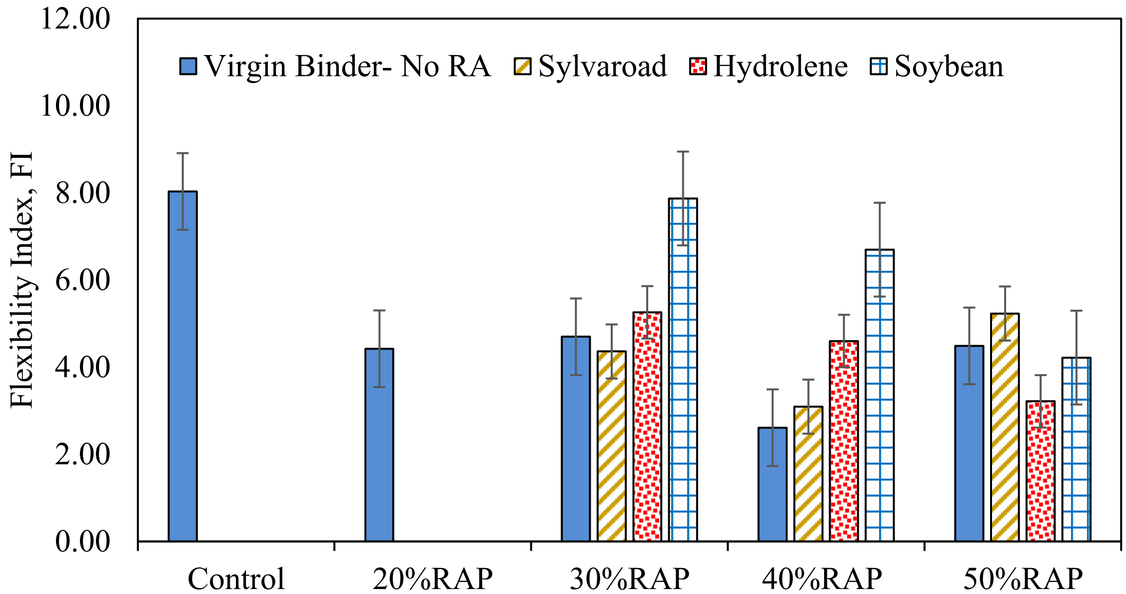

Figure 4.5. Flexibility Index (FI) for short-term aged RAP-RA mixes

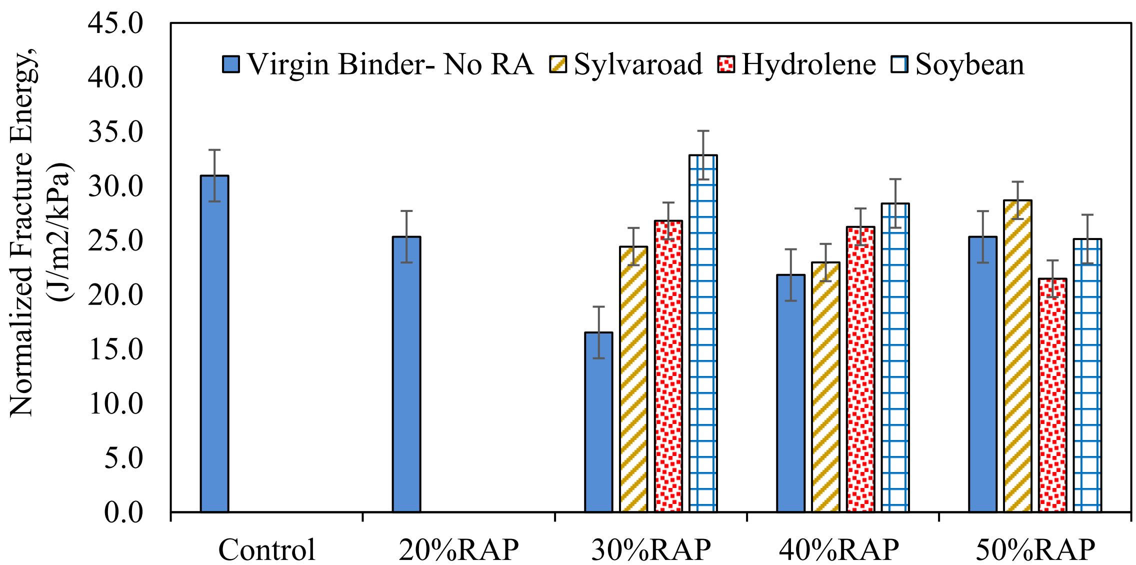

Figure 4.6. Normalized Fracture Energy (NFE) for short-term aged RAP-RA mixes

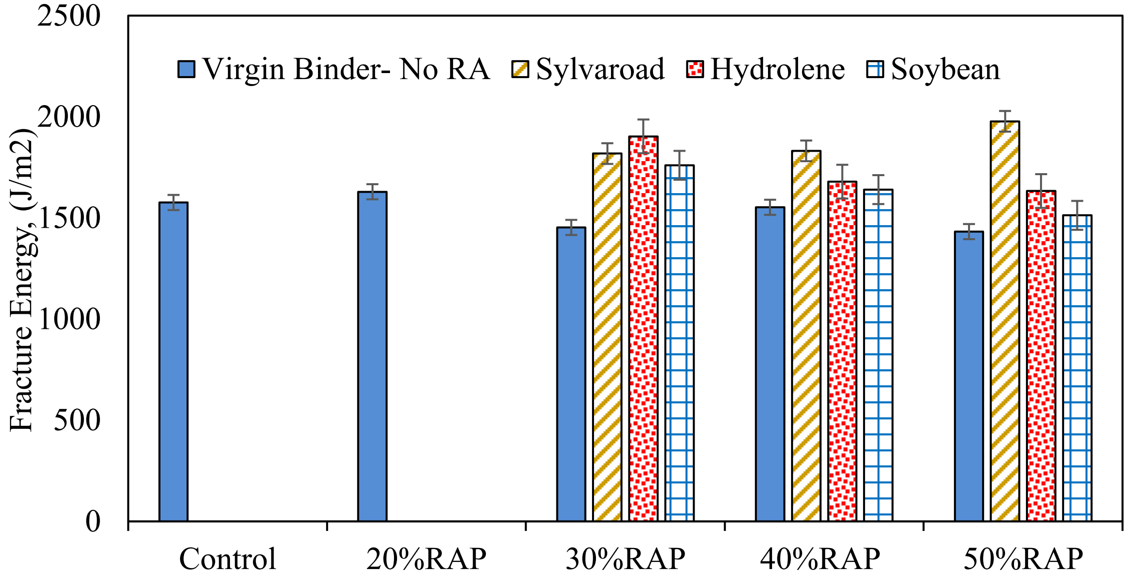

Figure 4.7. Fracture Energy (FE) for long-term aged RAP-RA mixes

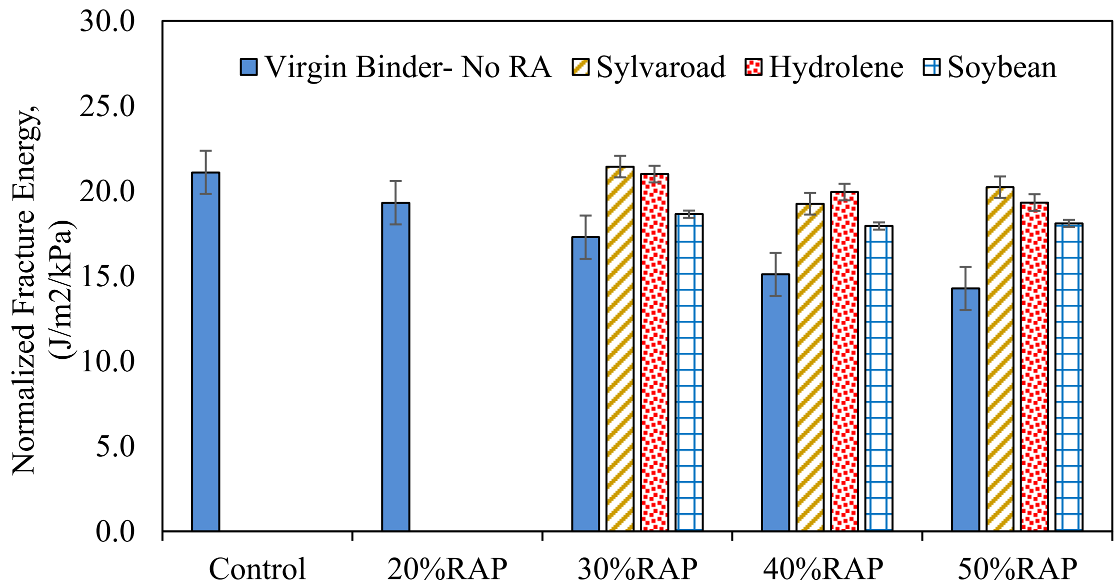

Figure 4.8. Normalized Fracture Energy (NFE) for long-term aged RAP-RA mixes

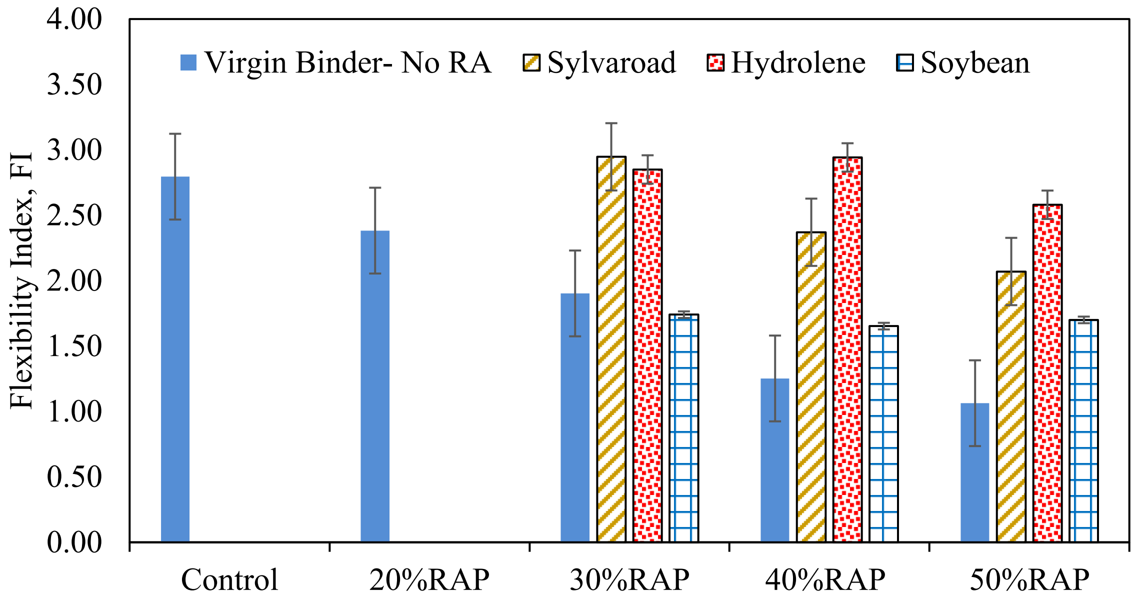

Figure 4.9. Flexibility Index (FI) for long-term aged RAP-RA mixes

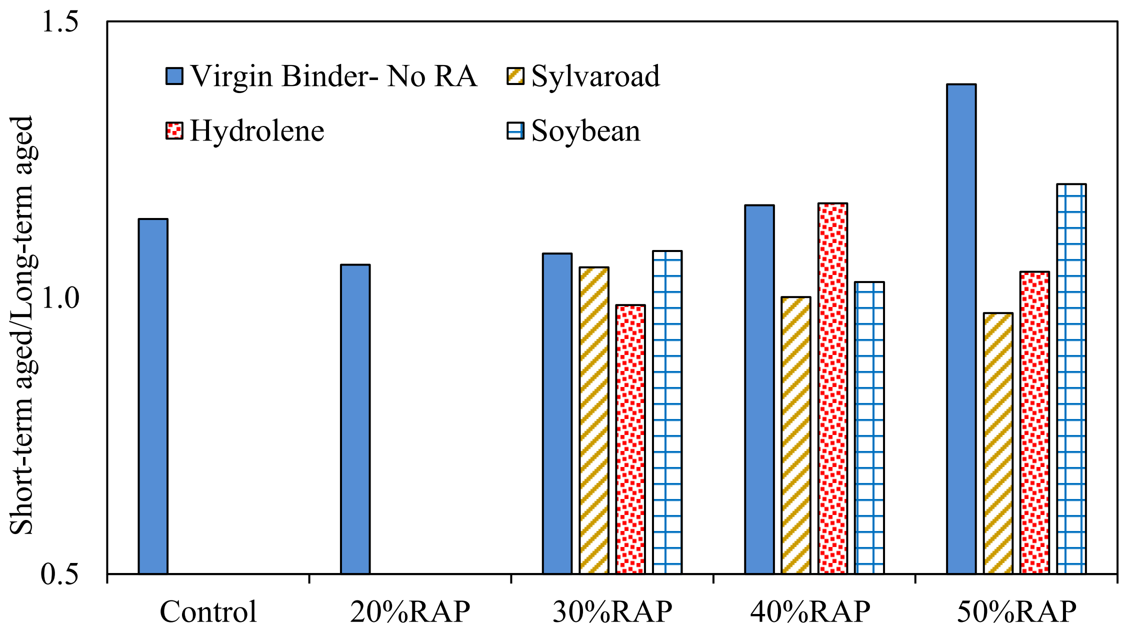

Figure 4.10. Short-term aged/long-term aged ratio of fracture energy

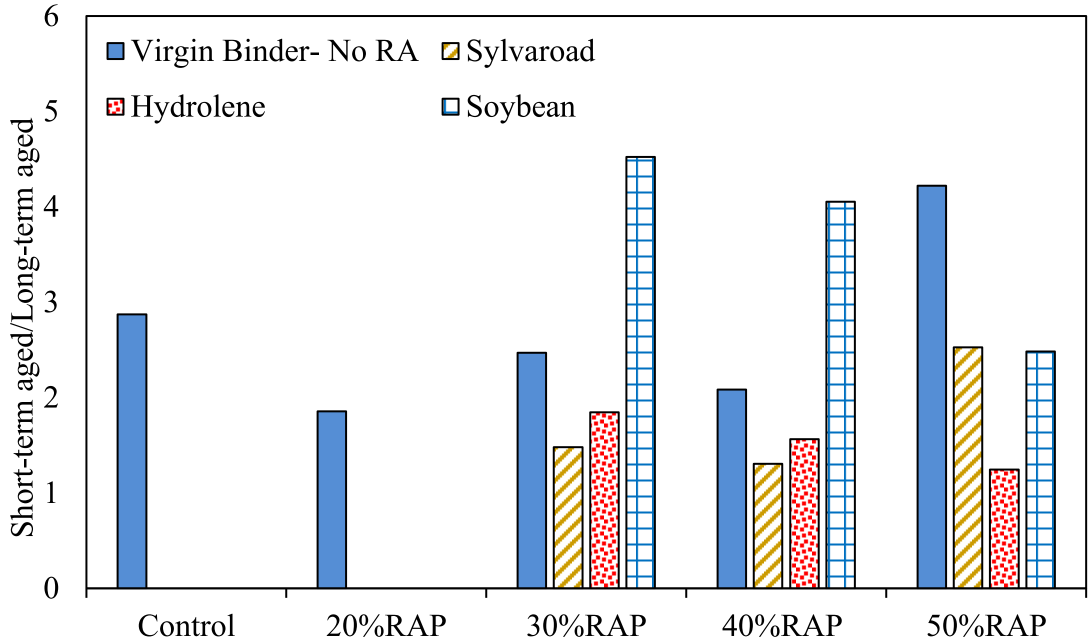

Figure 4.11. Short-term aged/long-term aged ratio of flexibility index

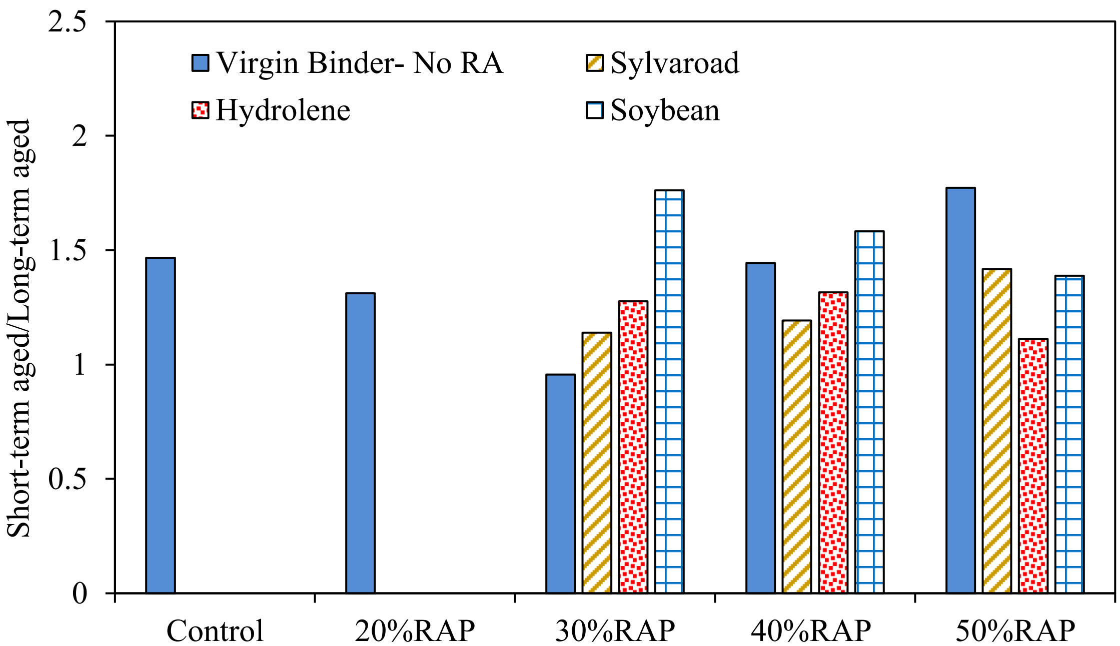

Figure 4.12. Short-term aged/long-term aged ratio of normalized fracture energy

4.2.2 Moisture Susceptibility

The modified Lottman test as recommended by the Superpave mix design standard was used to evaluate the moisture susceptibility damage of high content reclaimed asphalt pavement with RA. The Indirect Tensile Strength (ITS) of dry and wet samples of all mixes were demonstrated in Figure 4.13 and Figure 4.14, respectively. The test results were obtained and the Tensile Strength Ratio (TSR) of all dry and wet specimens were calculated and plotted in one graph as shown in Figure 4.15. It can be perceived from Figure 4.13 that RA mixes of 30%, 40% and 50% RAP with Sylvaroad and Hydrolene RAs have higher ITS values compared to the ITS values of the control mix. The higher ITS values mean that these RA mixes are able to endure great strain before failure. Furthermore, the ITS values of the Soybean mixes had lower ITS with 30% and 50% RAP compared to the control mix. This may indicate that the soybean RA has significantly softened the binder in RAP mixes. That means that the Soybean RA is more likely to be a softening agent than a recycling agent. Figure 4.14 presents the wet ITS values and their behavior was pretty much similar to the dry ITS samples.

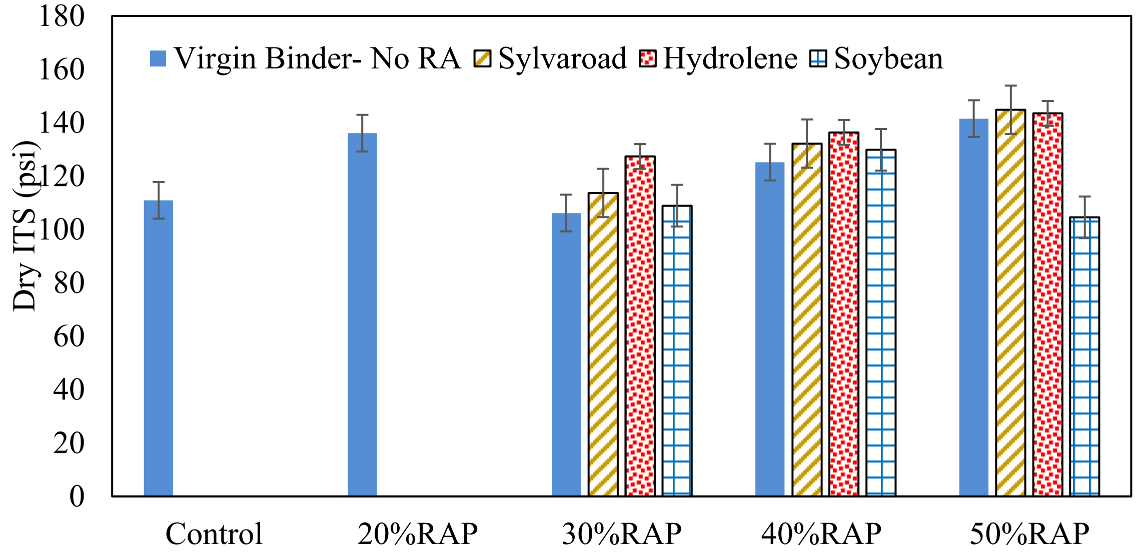

Figure 4.13. ITS values of dry samples of RAP-RA mixes

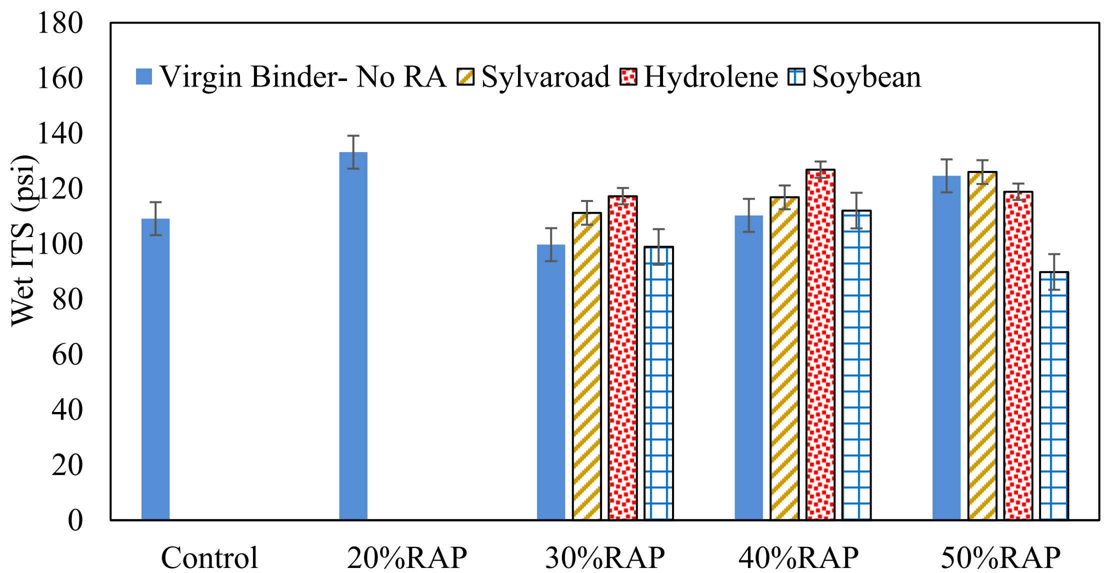

Figure 4.14. ITS values of wet samples of RAP-RA mixes

The TSR values were calculated by dividing the average wet ITS over the average dry ITS values and Figure 4.15 indicates that all the values obtained from all mixes are above the standard TSR value of 0.80, which means that all mixtures are able to resist the moisture susceptibility damage according to the minimum acceptable TSR value specified by ODOT. In comparison to the Control mix, it is clear that none of the mixes exceeded the TSR value of the control mix and that is because of the higher ITS values of the dry RAP mixes. Comparing the results with literature, moisture damage was improved in both the literature and this study. Although the moisture damage effect of Sylvaroad was not reported in the literature, but overall, tall oil improved the moisture damage resistance according to (Ali, 2016; Veeraragarvan, 2017; Zaumanis, 2014) which is consistent with the results of this study.

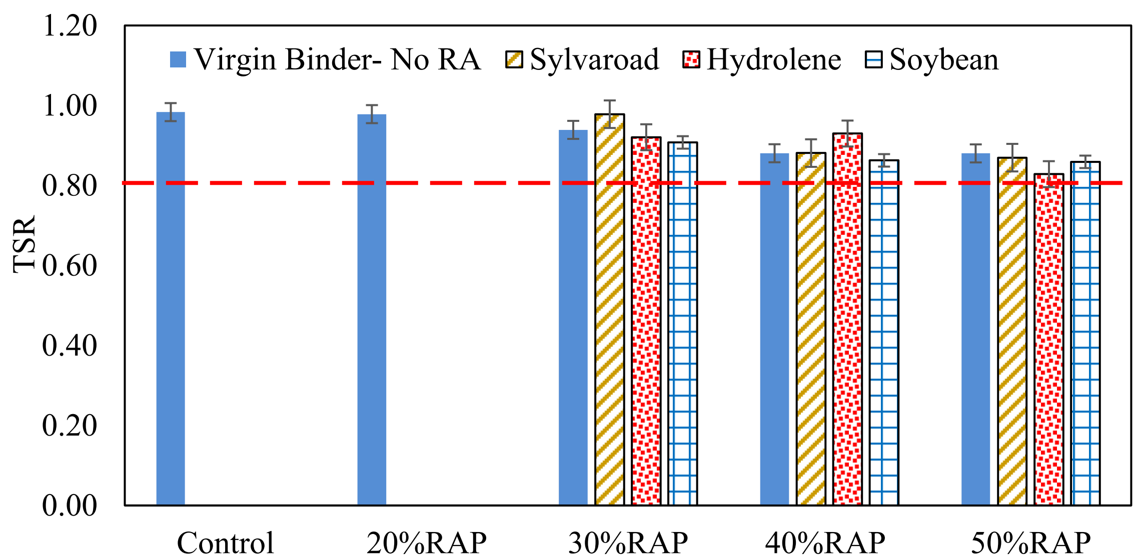

Figure 4.15. TSR values of RAP-RA mixes

4.2.3 Low Temperature Cracking

Figure 4.16 illustrates the cracking temperature of the averaged short-term aged specimen with different RAP and RA percentages. Clearly, all the mixes cracked at colder temperatures as compared to their counterparts of the long-term aged samples. The long-term aged ACCD results are considered in Figure 4.17. All RAP mixes with RA had similar cracking temperature to the control mix, but they had slightly warmer temperature than the mixes with softer PG 64-28 binder. Mixes with softer PG 64-28 binder were effective in maintaining the cracking temperature as they cracked at colder temperature. It can be concluded that using a suitable low temperature grading for the binder could be a solution to achieve the adequate low-temperature cracking resistance of RAP mixes. Figure 4.18 shows the short-term aged over the long-term aged ratios of the low temperature cracking. The greater the ratio, the higher the softening effect. The ratios for the Soybean that are related to the 40% and 50% RAP mixes showed higher values compared to other RAs which confirms that Soybean had more significant softening effect than other RAs.

The results of the Sylvaroad and Hydrolene are matching the results from the literature where all improved the low-temperature cracking resistance (Veeraragarvan, 2017; Zaumanis, 2014).

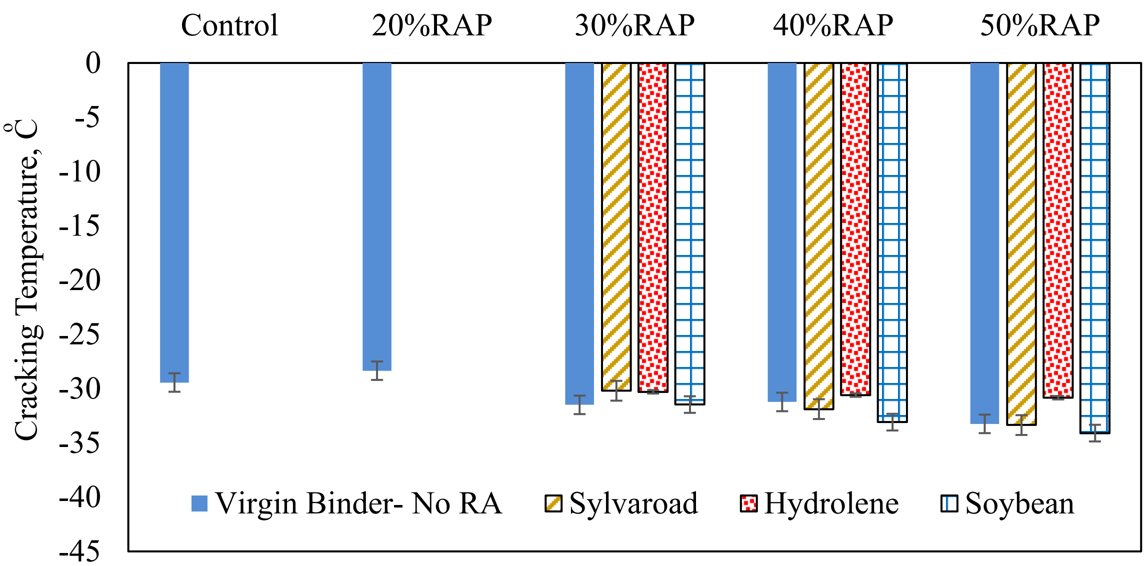

Figure 4.16. ACCD cracking temperature of short-term aged samples

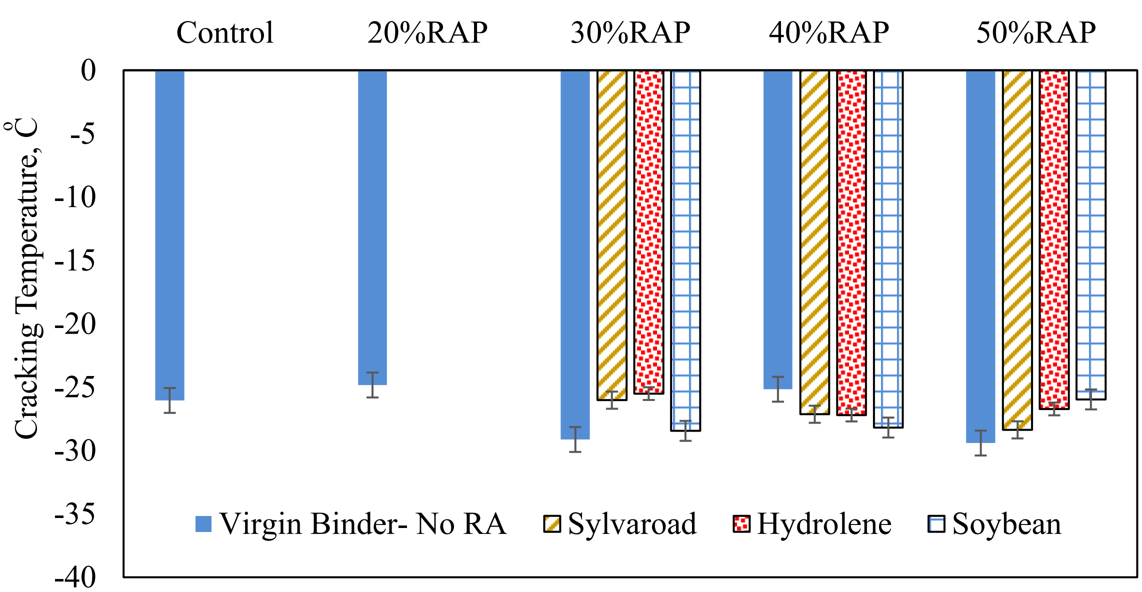

Figure 4.17. ACCD cracking temperature of long-term aged samples

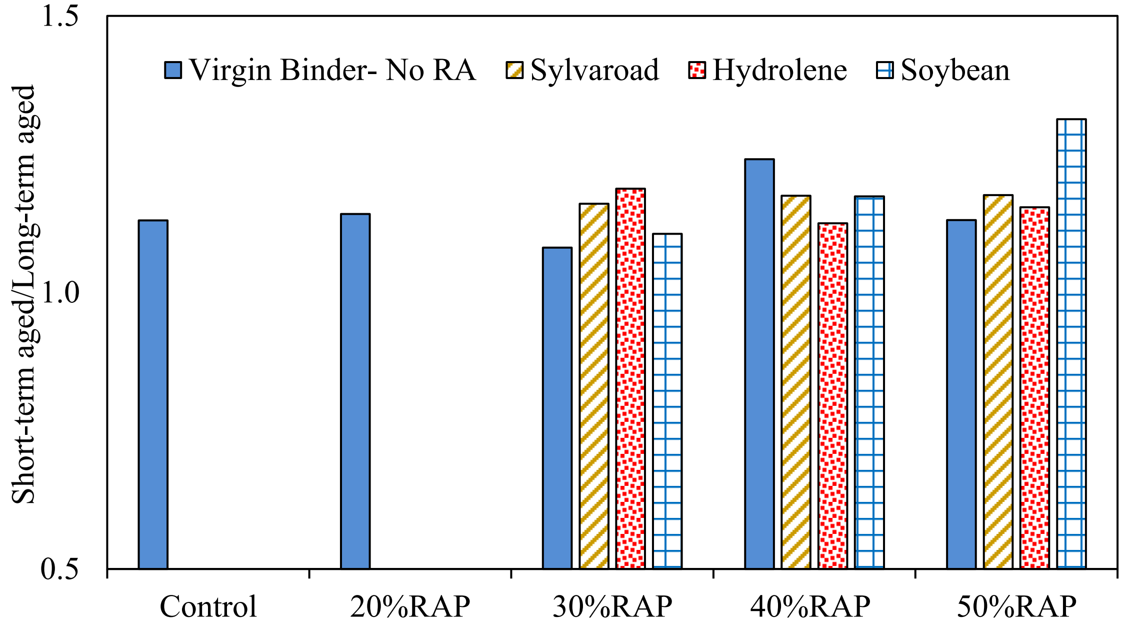

Figure 4.18. Short-term aged/long-term aged ratio of cracking temperature

4.2.4 Permanent Deformation (Rutting)

All RA mixes in Figure 4.19 indicate a higher rutting depth than the rutting depth of the control mix; particularly the 30% RAP mixes. However, the Soybean mixes showed the highest rutting depths among the other RA mixes. This means that the Soybean RA considerably softened the binder in RAP mixes so, it can be considered as a softening agent rather than a recycling agent. Although using the softer PG 64-28 binder with 50% RAP mix resulted in lower rutting than the control mix, increasing RAP content will decrease the rutting occurred as resulted in 30% RAP and 40% RAP mixes. All mixes were within the 5-mm rut depth limit, which is a very good standard rut depth required by ODOT on roadways with medium traffic. Thus, all obtained APA values were acceptable. Comparing the Hydrolene results with the results from previous studies, both showed an increase in rut depth. The rutting results of the Sylvaroad was not previously reported in

(Veeraragarvan, 2017) study, but overall results of tall oils based on Ali (2016) and Zaumanis (2014) increased the rutting and that is compatible with the results of this study.

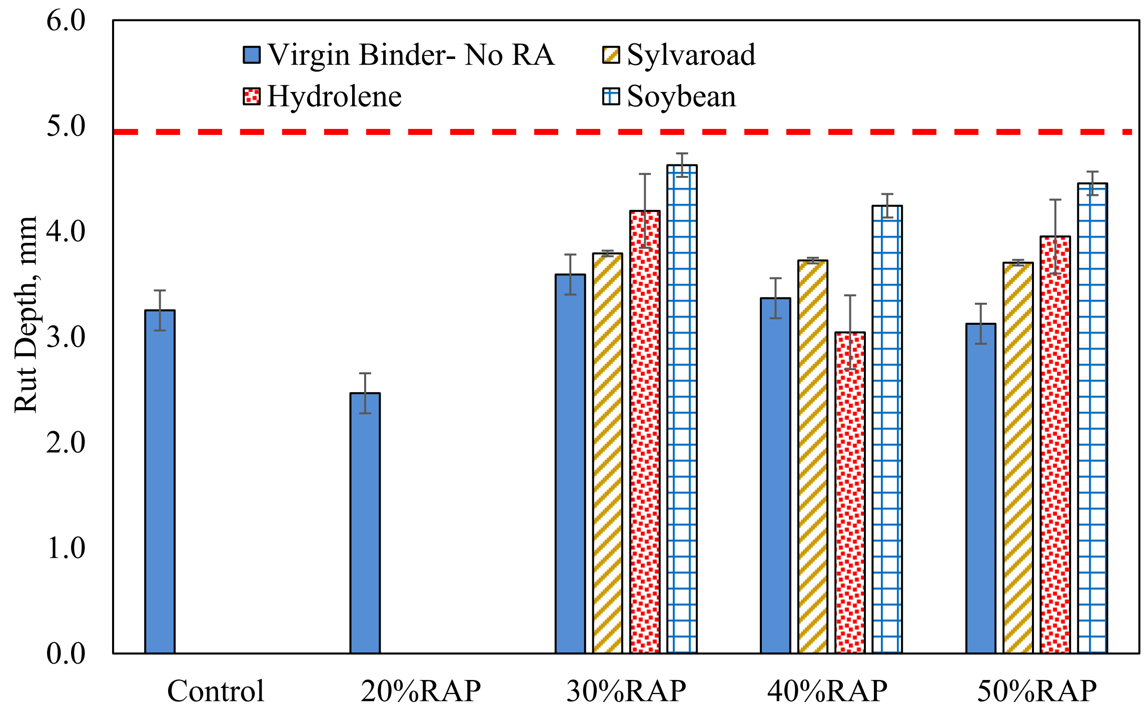

Figure 4.19. APA test results for RAP-RA mixes

4.3 Statistical Analysis

The analysis of Variance (ANOVA) was conducted to evaluate the effect of using recycling agents (RA) with HMA mixtures including high RAP contents on the performance of asphalt pavement. The analysis was performed to see the effect on the aged SCB, dry ITS, aged ACCD and the APA values. The Post ANOVA Least Square Means (LSM) analyses were run to compare the effect of each RA and different RAP content separately. SAS software (SAS Institute Inc., 2004) was used to run the statistical analysis at 95% level of confidence (LOC).

The null hypothesis assumes equal means to all groups of RAP and RA type. It depends on the F-value and p-value from SAS. The null hypothesis will be rejected if p-value is less than 0.05 % significant level. That means at least there is one value of the tested mixtures that is different than the other. F-value in ANOVA does not tell which mixture is different so, SAS software is able to run Post ANOVA LSM to perform pairwise comparison between different means. Tukey-Kramer test was used to run the LSM. In Kramer test, the means are ordered from highest to lowest giving the highest mean the letter A, the lower B and so on. When the same letter is given to more than one group that means there is no significant difference between these groups means. If a group was assigned two letters that means this group mean is very close to the means of the other groups that have these letters.

The independent t-test was also conducted to determine whether there is a statistically significant difference between the RA-type mixtures and the control and the RA-type mixtures and the 20% RAP mix.

4.3.1 Statistical Analysis for Aged SCB test.

Tables 4.2 through 4.7 show the results of ANOVA, Post ANOVA LSM and t-test analysis performed on the aged SCB values for different RAP contents with different RA.

Table 4.2 shows the effect of using different RAP contents and RA types on Flexibility Index (FI). The results show that RAP and the RA type had a significant effect on the flexibility index (FI) as the significant level (α) is less than 0.05. However, the interaction between RAP and the RA type was not significant. Table 4.3 presents the Tukey Kramer's test and the effect of RA type on the FI of the aged SCB samples. Clearly, the

Sylvaroad-RA was statistically similar to the Hydrolene-RA as both carried the letter A, and the Softer Binder (SB) had the lowest FI value and was statistically different from the other RA types. Table 4.4 presents the values of the independent t-test. Almost all the RA-types with the control mix and the RA-type with the 20% RAP mix had no statistically significant difference in their means as the values were greater than 0.05 significant level except for the Soybean-RA type group and the Control mix, which had a significant difference between their means as the values where less than the significant level ($\alpha < 0.05$).

Similarly, the normalized fracture energy (NFE) results show that RAP and RA type had a significant effect on NFE while the interaction between them had no significant effect on the NFE Table 4.5 Moreover, the Sylvaroad-RA and Hydrolene-RA had no significant difference between their means and using softer binder (SB) resulted in statistically different mean as compared to the other RA-types (Table 4.6). In comparing the means of the NFE of the RA-type mixes with the Control mix and RA-type mixes with the 20% RAP mix, it was noted that all the t-test values the RA-type mixes were greater than the significant level of 0.05, which mean there is no significant difference between their means. In Table 4.7, only the 40% RAP-Soybean mix had statistically significant mean difference compared to the Control mix mean.

Table 4.2: ANOVA results of FI for aged SCB samples.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
RAP content	2	33	3.47	0.0428
RA type	3	33	14.98	<.0001
RAP*type	6	33	0.5	0.8033

Num DF: numerator degree of freedom
Den DF: dominator degree of freedom

Table 4.3: Post ANOVA results of FI for aged SCB samples.

Obs	RA type	Estimate	Standard Error	Letter Group
1	S	20.6717	0.5778	A
2	H	20.3219	0.4476	A
3	Soy	18.4081	0.4883	B
4	SB	16.1246	0.4735	C

S: Sylvaroad-RA
H: Hydrolene-RA
Soy: Soybean-RA
SB: Soft Binder (PG 64-28)

Table 4.4: Independent T-test results of FI for aged SCB samples.

T-test	Control-mix	20%RAP-mix-mix
30%RAP- Sylvaroad	0.899	0.714
40%RAP- Sylvaroad	0.634	0.811
50%RAP Sylvaroad	0.069	0.419
T-test	Control-mix	20%RAP-mix
30%RAP- Hydrolene	0.836	0.852
40%RAP- Hydrolene	0.855	0.707
50%RAP- Hydrolene	0.258	0.882
T-test	Control-mix	20%RAP-mix
30%RAP- Soybean	0.020	0.312
40%RAP- Soybean	0.013	0.213
50%RAP- Soybean	0.015	0.232

Table 4.5: ANOVA results of NFE for aged SCB samples.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
RAP content	2	33	4.77	0.0151
RA type	3	33	18.21	<.0001
RAP*type	6	33	0.72	0.6347

Table 4.6: Post ANOVA results of NFE for aged SCB samples

Obs	RA type	Estimate	Standard Error	Letter Group
1	S	20.6717	0.5778	A
2	H	20.3219	0.4476	A
3	Soy	18.4081	0.4883	B
4	SB	16.1246	0.4735	C

Table 4.7: Independent T-test results of NFE for aged SCB samples.

T-test	Control-mix	20%RAP-mix-mix
30%RAP- Sylvaroad	0.862	0.329
40%RAP- Sylvaroad	0.796	0.728
50%RAP Sylvaroad	0.552	0.572
T-test	Control-mix	20%RAP-mix-mix
30%RAP- Hydrolene	0.744	0.256
40%RAP- Hydrolene	0.349	0.646
50%RAP- Hydrolene	0.218	0.995
T-test	Control-mix	20%RAP-mix-mix
30%RAP- Soybean	0.094	0.643
40%RAP- Soybean	0.047	0.360
50%RAP- Soybean	0.095	0.621

4.3.2 Statistical Analysis for Dry ITS test

ANOVA test results on dry (unconditioned) ITS samples are presented in Table 4.8. The results showed that RAP and RA-type effects as well as their interaction significantly affected the dry ITS values. Following ANOVA test is the LSM test which is presented in Table 4.9. The Soybean-RA samples had significantly lower ITS values and the other two RA-types (Hydrolene and Sylvaroad) had significantly similar ITS values. From Table 4.10, the 30% RAP-Sylvaraod, 30% RAP-Soybean, 40% RAP-Soybean and 50% RAP-Soybean mixes showed a significant difference in their means as compared to the mean of the Control Mix (α <0.05). Furthermore, the 30% RAP-Sylvaroad, 30% RAP-Soybean and 50% RAP-Soybean had a significant mean difference as compared to the 20% RAP mix.

Table 4.8: ANOVA results of dry ITS samples.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
RAP content	2	28	18.64	<.0001
RA type	3	28	10.16	0.0001
RAP*type	6	28	4.9	0.0015

Table 4.9: Post ANOVA results of dry ITS samples.

Obs	RA type	Estimate	Standard Error	Letter Group
1	H	135.75	2.806	A
2	S	130.25	2.8615	AB
3	SB	122.98	3.3201	BC
4	Soy	114.45	2.9429	C

Table 4.10: Independent T-test results of dry ITS samples.

T-test	Control-mix	20%RAP-mix-mix
30%RAP- Sylvaroad	0.537	0.014
40%RAP- Sylvaroad	0.010	0.444
50%RAP Sylvaroad	0.008	0.342
T-test	Control-mix	20%RAP-mix-mix
30%RAP- Hydrolene	0.016	0.153
40%RAP- Hydrolene	0.003	0.543
50%RAP- Hydrolene	0.001	0.215
T-test	Control-mix	20%RAP-mix-mix
30%RAP- Soybean	0.634	0.009
40%RAP- Soybean	0.054	0.331
50%RAP- Soybean	0.306	0.006

4.3.3 Statistical Analysis for Aged ACCD test

ANOVA test showed that RAP had no significant effect on aged ACCD values as p-value was greater than 0.05 level of confidence (LOC). On the other hand, RA-type had a statistically significant impact on the aged ACCD samples and that resulted in a significant impact when RA-type interacted with RAP with a confidence level less than 0.05 (Table 4.11). Kramer's test in Table 4.12 showed that the softer binder (SB) group had the lowest average cracking temperature. Both the Hydrolene-RA and Sylvaroad-RA had very similar average cracking temperature as both carried the letter A while the Soybean-RA had a very close average cracking temperature to both groups carrying letters A and B. Table 4.13 shows that the 50% RAP-Sylvaroad and the 30% RAP-Soybean had a significant mean difference as compared to the control mix. On the other hand, the 30% RAP-Sylvaroad, 40% RAP-Sylvaroad and the 50%RAP-Soybean had no significant mean difference with the 20% RAP mix mean.

Table 4.11: ANOVA results of aged ACCD samples.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
RAP content	2	26	0.32	0.7266
RA type	3	26	4.83	0.0084
RAP*type	6	26	2.91	0.0262

Table 4.12: Post ANOVA results of aged ACCD samples.

Obs	RA type	Estimate	Standard Error	Letter Group
1	H	-26.643	0.3948	A
2	S	-27.129	0.3604	A
3	Soy	-27.299	0.3948	AB
4	SB	-28.661	0.3948	B

Table 4.13: Independent T-test results of aged ACCD samples.

T-test	Control-mix	20%RAP-mix-mix
30%RAP- Sylvaroad	0.752	0.057
40%RAP- Sylvaroad	0.345	0.327
50%RAP Sylvaroad	0.016	0.006
T-test	Control-mix	20%RAP-mix-mix
30%RAP- Hydrolene	0.646	0.104
40%RAP- Hydrolene	0.052	0.010
50%RAP- Hydrolene	0.151	0.028
T-test	Control-mix	20%RAP-mix-mix
30%RAP- Soybean	0.016	0.005
40%RAP- Soybean	0.056	0.031
50%RAP- Soybean	0.983	0.393

4.3.4 Statistical Analysis for APA test

In Table 4.14, RAP and the RA-type significantly affected the average rutting values since p-value was less than 0.05. However, the interaction was statistically not significant to the APA values. Post ANOVA presented for the APA values presented in Table 4.15. The Hydrolene-RA and the Sylvaroad-RA shares the same letter B, which means both mixes had very comparable average rut depth and using soft binder (SB) resulted in lower rut depth compared to the other recycling agent mixes. All the t-test results in Table 4.16 showed that all the RA-type mixes had a significant difference in their means compared to the control mix and the 20% RAP mix. However, the 40% RAP- Hydrolene was the only mix that did not show statistically significant difference in the mean compared to the control mix as (α <0.05).

Table 4.14: ANOVA results of APA samples.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
RAP content	2	46	7.16	0.002
RA type	3	46	30.4	<.0001
RAP*type	6	46	2.18	0.0625

Table 4.15: Post ANOVA results of APA samples.

Obs	RA type	Estimate	Standard Error	Letter Group
1	Soy	4.4439	0.07801	A
2	H	3.8309	0.08663	B
3	S	3.74	0.1103	B
4	SB	3.36	0.08546	C

Table 4.16: Independent T-test results of APA samples.

T-test	Control-mix	20%RAP-mix-mix
30%RAP- Sylvaroad	0.132	0.008
40%RAP- Sylvaroad	0.070	0.001
50%RAP Sylvaroad	0.073	0.000
T-test	Control-mix	20%RAP-mix-mix
30%RAP- Hydrolene	0.007	0.000
40%RAP- Hydrolene	0.843	0.012
50%RAP- Hydrolene	0.000	0.000
T-test	Control-mix	20%RAP-mix-mix
30%RAP- Soybean	0.000	0.000
40%RAP- Soybean	0.000	0.000
50%RAP- Soybean	0.000	0.000

4.4 Cost Comparison

Based on the prices presented in Table 3.6, cost analysis was conducted to determine the cost of the control and RAP mixes with recycling agents and PG 64-28 and PG 64-22 binders and the results are presented in Figure 4.20. Clearly, the cost of the asphalt mixture decreased as RAP content increased. However, that depends on the type of RA used. Apparently, Hydrolene with 30%, 40% and 50% RAP was the least costly oil additive among the other two recycling agents, and it is a quite close to the Soybean oil. Table 4.17 and Table 4.18 show the initial percent savings in costs among the different RAP percentages compared to the cost per ton of the control virgin mix and the 20% RAP mix, respectively. It is noted that all of them can save at least 17% of the cost per ton comparted to the virgin mix and the Hydrolene shows the highest savings among the other two recycling agents and can reduce the cost by 39% when 50% RAP is used.

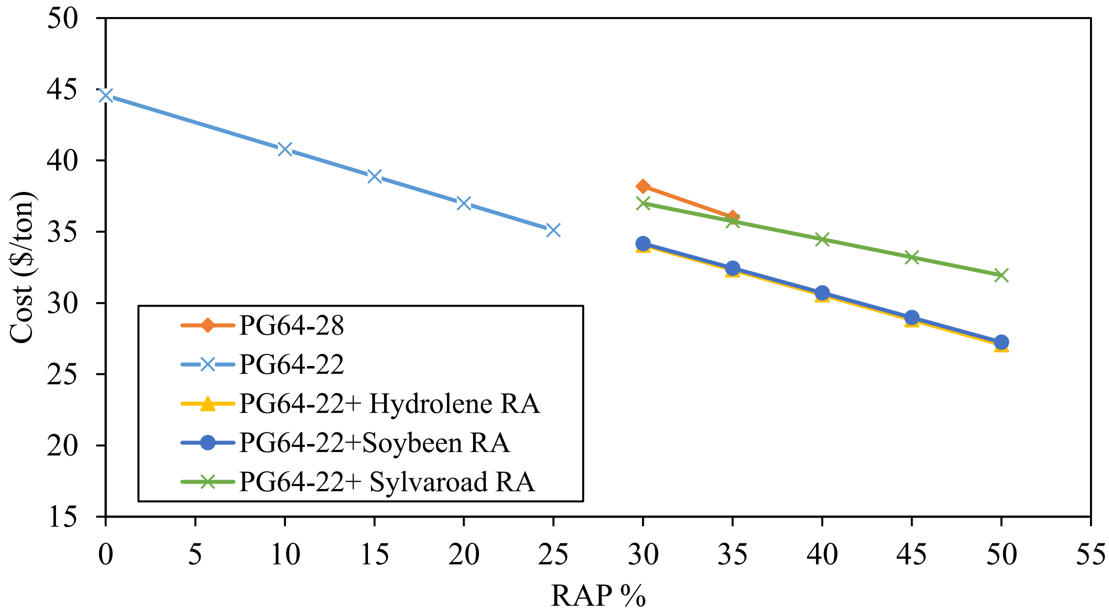

Figure 4.20. Cost of RAP mixes with different recycling agents

Table 4.17: Cost benefits ratio for RAP mixes with recycling agents to a virgin mix.

RAP %	Sylvaroad	Hydrolene	Soybean
30%	17.00%	23.60%	23.30%
40%	22.70%	31.40%	31.10%
50%	28.30%	39.30%	38.90%

Table 4.18: Cost benefits ratio for RAP mixes with recycling agents to a 20% RAP mix.

RAP%	Sylvaroad	Hydrolene	Soybean
30%	0.00%	7.90%	7.60%
40%	10.20%	22.10%	21.70%
50%	13.70%	26.80%	26.40%

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

The main purpose of this study was to evaluate the effects of using different recycling agents (RA) in hot mix asphalt mixtures that include high RAP contents. In addition, comparing the results and the costs of these mixes with the conventional (virgin) mixture and the 20% RAP mix with no RA. Also, statistical analysis was conducted to differentiate the most effective recycling agent.

The main findings of this study are provided in the following sections and conclusions were made based on the obtained results.

5.1 Conclusion

5.1.1 Resistance to Fatigue Cracking

- Using softer binder of PG 64-28 with more than 30% RAP content was not effective in resisting the fatigue cracking RAP mix.
- Using Sylvaroad-RA and Hydrolene-RA might be more effective in improving fatigue cracking resistance than using the softer PG 64-28 binder with high RAP content as their NFE values were much higher than other mixes.
- The Hydrolene-RA had the highest flexibility index (FI) among other RA-mixes.
- Adding Soybean-RA did not considerably improve the brittleness of the mix.
- ANOVA test showed that both the FI and the NFE were significantly affected by the RA type.

5.1.2 Resistance to Moisture Susceptibility Damage

- Mixes of Sylvaroad-RA and Hydrolene-RA had higher ITS values than the conventional virgin mix values when more than 30% RAP content was used. This means that these mixes are able to sustain more strain before failure.
- Adding Soybean-RA to the 30% RAP and 50% RAP softened RAP binder as of the resulted low ITS values.
- Soybean-RA acts more as a softening agent rather than a recycling agent.
- Based on the ODOT specifications, all mixes were able to resist moisture damage with tensile strength ratio (TSR) of less than 80% for each mix.
- The dry ITS values were significantly affected by the type of RA used and RAP content.

5.1.3 Resistance to Low-Temperature Cracking

- Using softer binder PG 64-28 had a warmer cracking temperature than other RA mixes.
- The results of the ACCD test suggests that using the appropriate low-temperature performance grade can help in ensuring satisfactory low-temperature cracking resistance of RAP mixes.
- Hydrolene RA and Sylvaroad RA had significantly improved the cracking resistance of mixes with up to 50%.
- ANOVA test results showed that RAP had no effect on cracking temperature, however, the RA-type had a statistically significant effect on cracking temperature and the so did the interaction between RAP and the RA-type.

5.1.4 Resistance to Permanent Deformation (Rutting)

- Rut depth increased as RAP content increased.
- Soybean-RA had the highest rut depth among the other RAs mixes, which means that it is close to be a softening agent rather than a recycling agent.
- The rut depth of all mixes were within the 5-mm rut depth required by ODOT on medium traffic roadways.
- Based in ANOVA results, RAP, RA-type and the interaction between both significantly affected the asphalt rutting.

5.1.5 Cost Analysis

- Cost analyses showed that 50% RAP mix with Hydrolene RA can be 26% less expensive than RAP mixes currently being used.
- Cost analyses showed that 50% RAP mix with Sylvaroad RA can be 13% less expensive than RAP mixes currently being used.

5.2 Recommendations

- Construct a field testing program to validate the performance of the designed laboratory mixes with 30%, 40% and 50% RAP with two or more different recycling agents.
- More experiments should be implemented on Soybean to more investigate if it is a softening agent or a recycling agent.
- Use different RAP materials with different recycling agents to see if they behave as the ones used for this study.

REFERENCES

Ali, A. W., Mehta, Y. A., Nolan, A., Purdy, C., & Bennert, T. (2016). Investigation of the impacts of aging and RAP percentages on effectiveness of asphalt binder rejuvenators. Construction and Building Materials, 110, 211-217.

Al-Qadi, I. L., Elseifi, M., & Carpenter, S. H. (2007). Reclaimed asphalt pavement—a literature review.

Al-Qadi, I. L., Ozer, H., Lambros, J., El Khatib, A., Singhvi, P., Khan, T., & Doll, B. (2015). Testing protocols to ensure performance of high asphalt binder replacement mixes using RAP and RAS. Illinois Center for Transportation/Illinois Department of Transportation.

Apostolidis, P., Liu, X., Kasbergen, C., & Scarpas, A. T. (2017). Synthesis of Asphalt Binder Aging and the State of the Art of Antiaging Technologies. Transportation Research Record: Journal of the Transportation Research Board, (2633), 147-153.

Arámbula-Mercado, E., Kaseer, F., Martin, A. E., Yin, F., & Cucalon, L. G. (2018). Evaluation of recycling agent dosage selection and incorporation methods for asphalt mixtures with high RAP and RAS contents. Construction and Building Materials, 158, 432-442.

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

Copeland, A. (2011). Reclaimed asphalt pavement in asphalt mixtures: State of the practice (No. FHWA-HRT-11-021).

Huang, S. C., Grimes, W., & Qin, Q. (2015). Rejuvenator for enhancing RAP applications and improving materials compatibility: fundamental properties of asphalts and modified asphalt III: FP 16. Technical White Paper, Western Institute March.

Hydrolene H90T. (n.d.). Retrieved from https://www.hollyfrontierlsp.com/asphalt-rejuvenator/.

Im, S., Karki, P., & Zhou, F. (2016). Development of new mix design method for asphalt mixtures containing RAP and rejuvenators. Construction and Building Materials, 115, 727-734.

Im, S., Zhou, F., Lee, R., & Scullion, T. (2014). Impacts of rejuvenators on performance and engineering properties of asphalt mixtures containing recycled materials. Construction and Building Materials, 53, 596-603.

Martin, A. E., Zhou, Z., Arambula, E., Park, E., Chowdhury, A., Kaseer, F., & Glover, C. (2015). The effects of recycling agents on asphalt mixtures with high RAS and RAP binder ratios. National Cooperative Highway Research Program Phase I Interim Report, NCHRP, 958.

Mogawer, W. S., Booshehrian, A., Vahidi, S., & Austerman, A. J. (2013). Evaluating the effect of rejuvenators on the degree of blending and performance of high RAP, RAS, and RAP/RAS mixtures. Road Materials and Pavement Design, 14(sup2), 193-213.

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

Mogawer—SiavashVahidi, A. B. W. S. Evaluating the Effect of Rejuvenators on the Degree of Blending and Performance of High RAP, RAS, RAP/RAS Mixtures.

Moghaddam, T. B., & Baaj, H. (2016). The use of rejuvenating agents in production of recycled hot mix asphalt: A systematic review. Construction and Building Materials, 114, 805-816.

Purdy, C., Rizvi, H., Mehta, Y., Nolan, A., & Ali, A. (2017). Methodology to determine optimum rejuvenator dosage for 50 percent high-rap mixture (No. 17-04683).

Sylvaroad RP1000 Performance Additive. (n.d.). Retrieved from http://kraton.com/products/sylvaroad.php

Tran, N. H., Taylor, A., & Willis, R. (2012). Effect of rejuvenator on performance properties of HMA mixtures with high RAP and RAS contents. NCAT Report, 12-05.

Veeraragavan, R. K., Mallick, R. B., Tao, M., Zaumanis, M., Frank, R., & Bradbury, R. L. (2017). *Laboratory Comparison of Rejuvenated 50 Percent Reclaimed Asphalt Pavement and Hot-Mix Asphalt with Conventional 20 Percent RAP Mix* (No. 17-04140).

West, R. C., Willis, J. R., & Marasteanu, M. O. (2013). Improved mix design, evaluation, and materials management practices for hot mix asphalt with high reclaimed asphalt pavement content (Vol. 752). Transportation Research Board.

Yu, X., Zaumanis, M., Dos Santos, S., & Poulikakos, L. D. (2014). Rheological, microscopic, and chemical characterization of the rejuvenating effect on asphalt binders. Fuel, 135, 162-171.

Zaumanis, M., Mallick, R. B., & Frank, R. (2015). Evaluation of different recycling agents for restoring aged asphalt binder and performance of 100% recycled asphalt. Materials and Structures, 48(8), 2475-2488.

Zaumanis, M., Mallick, R. B., Poulikakos, L., & Frank, R. (2014). Influence of six rejuvenators on the performance properties of Reclaimed Asphalt Pavement (RAP) binder and 100% recycled asphalt mixtures. Construction and Building Materials, 71, 538-550.