Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Enhancing the Performance of Asphalt Mixtures Containing High RAP Content with the Use of Different WMA Technologies

Project No. 19BLSU01

Lead University: Louisiana State University

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16. Abstract

The production of Warm-mix asphalt mixtures in conjunction with reclaimed asphalt pavement (RAP) has received considerable interest in recent years for economic and environmental reasons. The primary objective of this project is to enhance the performance of asphalt mixtures containing RAP in Region 6 using different WMA technologies. In this project, the effect of utilizing 0%, 25%, and 35% RAP contents on the performance of different WMA mixtures against rutting, moisture damage, and fatigue cracking are evaluated. The effects of the WMA technologies on the rutting performance of the asphalt mixtures and recovered binders were investigated using loaded wheel tracker (LWT) and multiple stress creep recovery (MSCR), respectively. Further, the influences of these technologies on the cracking performance of the asphalt mixtures and recovered binders were evaluated using Semi-Circular Bending (SCB) and linear amplitude sweep (LAS) test, respectively. Based on the results, WMA mixtures containing no RAP have a lower value of the J_{nr} compared to the HMA control mixture. This is an indication of the better performance of the WMA mixtures against the permanent deformation. Moreover, findings from the LWT test completely agree with the results from the MSCR test. On the other hand, the fracture resistance is found to be enhanced with the incorporation of a higher percentage of RAP and WMA technologies. Overall fracture resistance performance of WMA-RAP mixtures is observed to be better compared to HMA-RAP mixtures. Moreover, the results of the LAS test show that the incorporation of RAP materials and WMA technologies is associated with improved fatigue life of the WMA-RAP mixtures.

17. Key Words
Warm-Mix asphalt, Reclaimed asphalt pavement (RAP), Hot-mix asphalt (HMA), rutting, moisture damage, fatigue cracking

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m	square meters	10.764	square feet	ft^2
m	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m	cubic meters	35.314	cubic feet	ft^3
m	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Official
Advera®	Foaming technology
AMPT	Asphalt Mixture Performance Tester
ANOVA	Analysis of Variance
ArDOT	Arkansas Department of Transportation
ASTM	American Society for Testing and Materials
BBR	Bending Beam Rheometer
DOT	Department of Transportation
DSR	Dynamic Shear Rheometer
E^*	Dynamic Modules
FHWA	Federal Highway Administration
FT	Fisher–Tropsch
ESAL	Equivalent Single Axle Load
Evotherm®	Chemical additive
G_{mb}	Bulk Specific Gravity of the Mixture
G_{mm}	Maximum Specific Gravity of the Mixture
G^*	Complex Modulus
HMA	Hot-Mix Asphalt
J_c	Critical strain energy release rate
JMF	Job Mix Formula
LAS	Linear Amplitude Sweep
LaDOTD	Louisiana Department of Transportation and Development
LTOA	Long-Term Oven Aging
LWT	Loaded Wheel Tracker
MSCR	Multiple Stress Creep and Recovery
NAPA	National Asphalt Pavement Association
NMAS	Nominal Maximum Aggregate Size
NMDOT	New Mexico Department of Transportation

ODOT	Oklahoma Department of Transportation
RAP	Reclaimed Asphalt Pavement
RTFO	Rolling Thin Film Oven
Sasobit®	Organic additive
SCB	Semi-Circular Bending
SD	Standard Deviation
SGC	Superpave Gyratory Compactor
STOA	Short-Term Oven Aging
Superpave	Superior Performing Asphalt Pavement
TxDOT	Texas Department of Transportation
WMA	Warm-Mix Asphalt

EXECUTIVE SUMMARY

The term Warm-Mix Asphalt (WMA) refers to various technologies that allow reducing mixing and compaction temperatures of asphalt mixtures without negatively affecting their performance against common major distress types. WMA technologies include foaming process, chemical additives, and organic (wax) additives. Application of WMA technologies was found to reduce production and construction costs, extend construction season, improve field compaction, and enhance working conditions by reducing exposure to fuel emissions, fumes, and odors.

In this research project, an in-depth literature review has been conducted to summarize previous studies and research projects on the advantages of using WMA additives/technologies in asphalt mixtures, and the performance of WMA mixtures with RAP materials against rutting, moisture damage, and cracking. Moreover, the current specifications used in the south-central states (i.e., Arkansas, Louisiana, New Mexico, Oklahoma, and Texas) on the use of RAP and WMA technologies are discussed (Task1). In this study, three WMA additives/technologies were evaluated in the laboratory by testing asphalt mixtures and extracted & recovered binders. To this end, Sasobit® (organic), Evotherm® (chemical), and Advera® (foaming) were used to prepare different asphalt mixtures with a RAP content higher than the allowable RAP percentage in the State of Louisiana. The Louisiana Department of Transportation and Development (LaDOTD) allows only 20-25% of RAP in asphalt mixtures used for the wearing course with a nominal maximum aggregate size (NMAS) of 0.5 in. (12.5 mm) and 0.75 in. (19 mm). The produced asphalt mixtures in this study contain 0%, 25%, and 35% RAP contents to investigate the effect of using these WMA technologies on the performance of mixtures with high RAP content (Task 2). The prepared mixtures have been short- and long-term oven-aged (STOA and LTOA) and were tested against permanent deformation and moisture damage using the Loaded Wheel Tracker (LWT) test at high temperature (Task 3), and against cracking using the Semi-Circular Bending (SCB) test at intermediate temperature (Task 4). Furthermore, the rheological properties of the extracted and recovered binders from the prepared mixtures were evaluated in the laboratory using Dynamic Shear Rheometer (DSR) and correlated to the mixtures testing results. The results of these laboratory tests compared to those of a control Hot-Mix Asphalt (HMA) and WMA mixture to evaluate the effects of using WMA additives on the mixture performance (Task 5).

The primary objective of this study is to enhance the performance of asphalt mixtures containing high RAP content in Region 6 using different WMA technologies. In this project, the effect of utilizing high RAP content on the performance of different WMA mixtures against rutting, moisture damage, and fatigue cracking was evaluated.

This study concludes that extracted and recovered binders coming from WMA mixtures containing RAP have a lower value of the J_{nr} compared to the HMA control mixture. This is an indication of the better performance of combining WMA technologies and RAP materials against the permanent deformation. Moreover, findings from the LWT test agreed with the results from the MSCR test and the rutting resistance of the asphalt mixtures has an increasing rate by applying more percentages of RAP materials in both WMA and HMA mixtures. The fracture resistance is found to be enhanced with the incorporation of RAP and WMA technologies. Such a trend in the present research work may be attributed to the softening effect of the rejuvenator, WMA additives, and the lower performing temperature. Overall fracture resistance performance of WMA-RAP mixtures is observed to be better compared to HMA-RAP mixtures. Moreover, the results of the LAS test show that the incorporation of RAP materials and WMA technologies is associated with improved fatigue life of the WMA-RAP mixtures. The better performances of mixtures containing RAP against cracking, which is in contradiction to what would be expected from high RAP mixtures, can come from WMA additives.

1. INTRODUCTION

The use of the reclaimed asphalt pavement (RAP) in asphalt mixtures is economically and environmentally beneficial compared to the conventional asphalt mixtures without RAP. The economic benefits of using RAP include a reduction in the use of virgin aggregates and transportation costs, whereas the environmental benefits include lower consumption of non-renewable resources (aggregates), and reduction in gas emission otherwise required to produce virgin aggregates.

For asphalt mixtures containing the higher value of RAP, the incorporation of the aged binder from the RAP and long-term exposure to air and sunlight during service life can increase stiffness and brittleness of the asphalt mixtures (*1*). Therefore, asphalt mixtures with high RAP contents are susceptible to the development of intermediate- and low-temperature cracking (*2*,*3*). Low-temperature cracking or thermal cracking is one of the most prevalent asphalt pavement distresses which can result in performance problems of the pavement structures. On the other hand, it has been proved in another study that the increment in stiffness with the addition of RAP will negatively impact the fatigue and low-temperature cracking properties of asphalt mixtures (*2*,*4*). Significant efforts have been made to control and decrease the negative impacts of the addition of RAP to asphalt mixtures. Warm-mix asphalt (WMA) technologies have been widely used in the United States (US) and worldwide to reduce production and construction costs, extend construction season, improve field compaction, and enhance working conditions without affecting in-service performance (*5*,*6*,*7*). One of the most important benefits of using WMA technologies is allowing more utilization of RAP if recycling agents or rejuvenators are appropriately used to enhance the level of blending between RAP and virgin asphalt binders (*8*). WMA technologies also reduce viscosity at a lower temperature for better compaction of mixtures with recycled materials, decrease the aging rate by lowering the production and construction temperatures. In the case of WMA mixtures, the results showed that decreasing the production temperatures would result in decreasing the binder aging. Thus, high proportions of RAP could be used in WMA mixtures (*9*).

The most common types of WMA technologies are classified based on the type of additives used as a foaming, organic or wax additives, and chemical additives. The primary objective of this research project is to evaluate the performance of asphalt mixtures containing RAP content higher than the allowable in Louisiana by using different WMA technologies. In this research project, three WMA technologies: Sasobit® (organic), Evotherm® (chemical), and Advera® (foaming) are used to prepare different asphalt mixtures with high contents of RAP. The Louisiana Department of Transportation and Development (LaDOTD) allows only 20 to 25% of RAP in asphalt mixtures of the wearing course with a nominal maximum aggregate size (NMAS) of 0.5 in. (12.5 mm) and 0.75 in. (19 mm), respectively (*10*). This research is aimed to investigate the effect of using these WMA technologies on the performance of 0.5 in. NMAS mixtures with 0%, 25%, and 35% RAP contents. The prepared mixtures were short- and long-term oven aged to be tested against permanent deformation and moisture damage using the Loaded Wheel Tracker (LWT) test at a high temperature, and against cracking using the Semi-Circular Bending (SCB) test at an intermediate temperature. Besides, the rheological properties of the extracted and recovered binders from the prepared mixtures were evaluated using Dynamic Shear Rheometer (DSR) and compared to the mixtures testing results. The results of these laboratory tests were also compared to those of a control HMA mixture – with and without RAP – to evaluate the impact of using WMA additives, and with a WMA mixture that has no RAP.

2. OBJECTIVES

The primary objective of this study is to enhance the performance of asphalt mixtures containing high RAP content mainly in Louisiana and using different WMA technologies. In this project, the effect of utilizing high RAP content on the performance of different WMA mixtures against rutting, moisture damage, and fatigue cracking is evaluated. To achieve the primary objective of this project, two phases are included: Technical Phase and Implementation Phase. Technical Phase includes six tasks as follows:

- Conduct an in-depth literature review;
- Preparation of asphalt mixtures for testing;
- Evaluation of rutting and moisture damage resistance of short-term aged asphalt mixtures using Loaded Wheel Tracker (LWT) test at high temperature;
- Evaluation of cracking resistance for long-term aged asphalt mixtures using the Semi-Circular Bending (SCB) test at an intermediate temperature;
- Evaluation of the rheological properties of the extracted and recovered binders from the produced mixtures using Dynamic Shear Rheometer (DSR); and
- Preparation and submission of the final report of the project.

The Implementation Phase includes:

- Technology Transfer (T2) activities
- Education and Workforce Development activities; and
- Outreach Activities.

3. LITERATURE REVIEW

3.1. The use of reclaimed asphalt pavement (RAP) materials in new asphalt mixtures

The use of reclaimed asphalt pavement (RAP) has gained increasing popularity as an environmentally friendly and cost-effective approach in asphalt mixture design. The economic benefits of using RAP include a reduction in the use of virgin aggregates and transportation costs whereas the environmental benefits include lower consumption of non-renewable resources (e.g., aggregates), and reduction in gas emission otherwise required to produce virgin asphalt mixtures.

According to the most recent National Asphalt Pavement Association (NAPA) survey on recycled materials, the average percentage of RAP used in asphalt mixtures has increased from 15.6% in 2009 to 21.1% in 2018 (*11*). A study by Al-Qadi et al. (*12*) showed an increase in RAP usage by many state agencies between 2007 and 2009. At the time, the recommended maximum limit of using RAP in the mixture was used to be 25%, however, many agencies used only 20%. Through the years this limit has reached 100% RAP at times, however, a consensus has not been reached by agencies regarding the maximum limit of RAP that can be added to virgin mixture without compromising the performance of asphalt pavements (*13*). An experimental study by Valdés et al. (*14*) showed that by proper handling of RAP stockpiles, a high rate of RAP could be added to asphalt mixtures. Contrary to its economic and environmental benefits, the introduction of aged binders from RAP into virgin asphalt mixtures increases the stiffness and reduces the relaxation capability of the asphalt pavements (*15*). Due to this, mixtures with high RAP content exhibit higher susceptibility to intermediate and low temperature cracking (*4*,*5*,*6*). Test results from the dynamic modulus test have shown an increment in stiffness with an increase in RAP content (*17*). The increment in stiffness caused by the addition of 25% of RAP as compared to virgin mixtures was quantified and was found to be equivalent to an increment in stiffness for a bump in one level of PG binder grade (*18*). A study by Boriack et al. (*19*) showed an increment in stiffness up to 400% for mixtures containing 100% RAP as compared to virgin mixtures. Due to such increment in stiffness, the addition of RAP is associated with improvement in rutting resistance (*10*,*3*). A study West et al. (*21*) simulated actual heavy traffic loading suggested that mixtures up to 50% RAP content exhibited an enhanced rutting resistance. A study by Magawer et al. (*22*) evaluated different percentages of RAP contents ranging from 0 to 40 % and different binder performance grades (PG 52-34, PG 58-28, PG 64-28) and showed the positive impact of the addition of RAP into the mixtures on rutting performance. Moreover, the results of a study by Moghadas et al. (*23*) showed 60% of RAP improved rutting resistance of asphalt mixture by increasing the viscosity of the mixture.

On the other hand, the increment in stiffness with the addition of RAP has shown to impact the fatigue and low-temperature cracking resistance of asphalt mixtures negatively (*4*,*14*). To address the negative impact of the addition of RAP on asphalt mixture performance, different studies have been undertaken. As part of this effort, the field performance of the asphalt mixtures containing a high percentage of RAP was evaluated using the Long-Term Pavement Performance (LTPP) data (*24*). A comparison was made between the performance of RAP and virgin asphalt overlays showed that the use of RAP slightly increased the risk of fatigue cracking and weakened pavement structure, while it increased the rutting resistance. A study by McDaniel et al. (*16*) indicated a reduction in low-temperature cracking resistance property with the addition of RAP. Studies on moisture susceptibility showed the pre-existing coating of the aggregate in the RAP reduces stripping from happening. The findings from different studies support this hypothesis that an increase in RAP content results in better moisture resistance (*15*,*3*,*16*). A study by West et al. (*27*) compared the performance of virgin and recycled mixtures using data from LTPP based on data from 18 states and concluded equivalent performance as virgin mixtures could be attained for mixtures containing up to 30% RAP by making a certain adjustment to the mixture. It could be concluded that the rutting performance of asphalt mixtures has improved using RAP, while the fatigue and thermal performance has been inconsistent. Thermal resistance is typically lowered because of the stiffer nature of the recycled mixtures (*18*).

Several studies have been conducted to counter-effect the negative impacts of the RAP on fatigue cracking resistance of the asphalt mixtures. A study by Haghshenas et al. (*28*) investigated the effects of three types of rejuvenators on fatigue performance when they are added to aged asphalt materials. The dosage level of rejuvenators was selected from binder PG testing by considering binders PG recovery. Based on the Semi-Circular Bending (SCB) fracture test results, asphalt mixtures treated with rejuvenators showed improved fracture resistance compared to unrejuvenated mixtures. Moreover, another study by Kaseer et al. (*29*) focused on the stiffness characterization of recycled asphalt mixtures containing a recycle agent (RA). The test results indicated that the softening effect of RA was diminished with the aging level of high recycled materials, and recycled mixtures with a softer and virgin binder and higher value of RA showed acceptable stiffness and relaxation properties after short- and long-term oven-aging (STOA and LTOA). To investigate the effects of rejuvenation additives on the rutting and cracking resistance of RAP mixtures, laboratory testing was conducted in a study by Kodippily et al. (*30*) on 11 RAP mixtures that were produced with RAP proportions of 15% and 30% and different types of rejuvenating agents. Based on the results, the fatigue performance of rejuvenated 30% of RAP mixtures was similar to the 15% RAP mixtures without any rejuvenating agents. Explaining how using rejuvenating agents can allow the use of higher RAP quantities without compromising the mixture performance (*30*).

According to the literature, the following methods and approaches are commonly implemented to counter-effect the negative impact of RAP on cracking resistance of asphalt mixtures:

- Limiting the usage of RAP in the mixtures;
- Using a softer binder than it is required for virgin mixtures;
- Introducing rejuvenators to asphalt mixtures;
- Attaining a lower density during construction; and
- Introducing WMA technology to asphalt mixtures.

In this study, different WMA technologies and one type of rejuvenator were used to evaluate their effect on the performance of prepared mixtures against rutting and cracking resistance.

3.2. WMA technologies and performance

Since its first introduction in 2004, the Warm-mix asphalt (WMA) technology has been widely used in the United States. The WMA mixtures have been used worldwide to save energy and reduce emissions throughout the production process without decreasing the in-service performance (*6*). Figure 1 shows the cumulative number of publications on WMA technologies and their use over the years from January 2000 to October 2019. Based on the plot, there is rapid progress in the number of publications in the last ten years.

A research effort was conducted by Bennert et al. (*31*) to show the higher workability of mixtures with WMA additives compared to conventional hot-mix asphalt (HMA) mixtures. This is beneficial due to its positive impact on global warming, air pollution, as well as fuel efficiency. Rughooputh et al. (*32*) concluded that the incorporation of WMA into mixtures containing up to 25% RAP will provide a better working environment in tropical weather by a reduction in fumes. A study by Mohammad et al. (*33*) utilized various WMA technologies to evaluate the laboratory performance of WMA and compared the expending cost of WMA and emission data to HMA mixtures. The results showed that there is a similar performance between WMA and HMA whereas there is a significant reduction in air pollution and cost. Moreover, based on the results from previous studies on the different WMA technologies and their effects on the performance of WMA binders and mixtures, WMA technologies can decrease environmental pollution, production cost, and energy usage, and improve the workability and compatibility of asphalt mixtures (*34*). Some studies also showed that there is no significant difference between the volumetric properties of the WMA and the corresponding HMA mixtures.

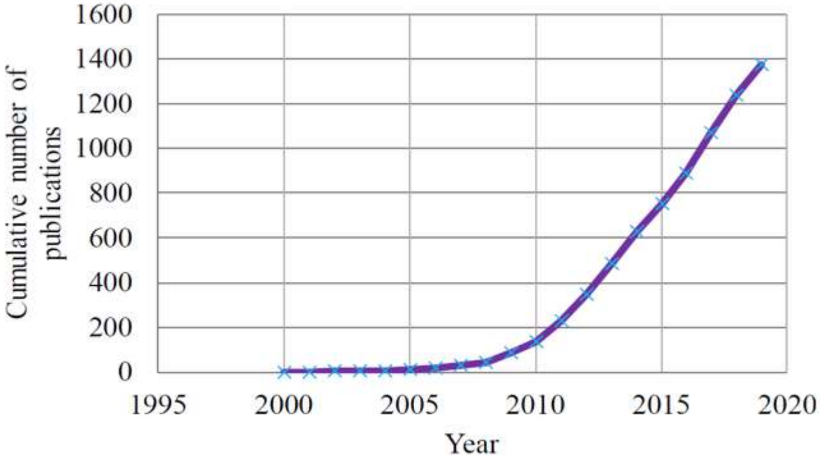

Figure 1. The cumulative number of publications on WMA over years (*34*).

3.2.1. Warm-mix asphalt (WMA) technologies

WMA technologies or additives can be categorized into three main categories of foaming technologies, chemical additives, and organic or wax additives (*6*). Several factors should be considered to select the most suitable technology and its optimized value for pavement projects. WMA technologies by changing the binder rheological properties such as viscosity allow reducing the mixing and compaction temperatures of the asphalt mixtures. Jamshidi et al. (*35*) described three non-dimensional factors to characterize the changes in viscosity, rutting factor, and fatigue parameter to examine different WMA additives. In the following sections, a summary of studies that have been conducted based on the different types of WMA technologies in the asphalt industry is presented.

Organic Additives:

The addition of organic additives like organic wax to the binder or asphalt mixture could result in reducing the viscosity of the binder. Organic wax can act as a modifier and allows the aggregate to move more freely in the binder. Also, it decreases the viscosity of the binder which reduces the mixing temperature compared to the conventional mixing temperature used for HMAs. It can be stated that using organic additives allows a mixing temperature reduction of 20–30°C (*14*,*9*). When the asphalt binder cools, the additive forms a lattice structure of microscopic particles which can result in increasing the binder stiffness and its resistance to deformation (*36*). Sasobit® shown in Figure 2(a) is one of the most common commercial organic additives, which is produced from natural gas using the so-called Fisher–Tropsch (FT) process (*14*,*15*). Sasobit could be added to the HMA mixture directly as a pill during the mixing process, or it could be blended with a hot binder then added to the hot aggregates. Sasobit could be blended with the hot binder manually or mechanically, however, there is no need for a high-sheer mixer. The melting temperature of the Sasobit is 216°F (102°C), so it is completely soluble in the asphalt binder at temperatures higher than 248°F (120°C) (*38*). It is recommended to use Sasobit at the rate of 0.8 to 4 percent by weight of the binder (*6*).

(a) **(b)** **(c)**

Figure 2. WMA technologies selected for this project: (a) Sasobit (organic), (b) Evotherm (chemical), and (c) Advera (foaming).

Chemical Additives:

Different types of chemical additives have been introduced and discussed in the literature review. Evotherm® shown in Figure 2(b) is one of the most typical chemical WMA additives that is used to enhance the coating rate of the aggregate particle by binder. Evotherm is a dark liquid chemical additive including surfactants that reduce the surface tension between a solid and a liquid or two liquids (*33*). Evotherm is designed to allow a lower temperature for producing asphalt mixtures. Interacting between hot aggregates and Evotherm during the production process causes the water in the emulsion to be evaporated and the binder covers the hot aggregates properly (*6*). Findings from a study by Dai Lu et al. (*39*) showed mixing and compaction temperature reduction of asphalt mixtures about 20–30°C. It can be added directly to the heated binder just before mixing with aggregate, or it can be added to the preheated asphalt binder and be kept in storage. Recommended dosage can be different for unmodified binders and modified binders. It is recommended to use 0.30 to 0.75 percent by weight of the total binder for polymer-modified binders, and it could be added directly to the heated binder at 244°F (118°C) for polymer-modified binders before the mixing.

Foaming Technologies:

Foaming technology could be divided into two main groups. In the first group, water is added to the mixing process using specific equipment to generate foaming. In the second group, a finely crushed synthetic zeolite (a crystalline hydrated aluminum silicate), which contains about 20% of water trapped in its structure is introduced to the mixing process (*7*,*10*). Advera® shown in Figure 2(c) is one of the famous foaming additives and after adding it to the binder, there will be a sudden decrease in the temperature as a part of the energy is used to vaporize the moisture (*13*,*6*). The released steam is encapsulated by the binder and it will result in a temporary volume expansion of the binder and reduction in the binder viscosity at the same time (*7*,*14*). Advera is one of the Zeolites foaming technologies in a powder shape that makes it easier to produce a laboratory WMA mixture. It is recommended to add around 5% by the weight of the binder (*6*). By adding Advera to the mixture at the same time as the binder, a very fine water spray is created. This release of water creates a volume expansion of the binder that results in asphalt foam and allows increased workability and aggregate coating at lower temperatures (*9*). Zeolite technologies can reach a reduction in mixing and compacting temperatures around 86°F (30°C). It is recommended to avoid adding Advera to the binder before mixing because it might result in evaporating the internal moisture before it is needed (*43*).

3.2.2. WMA mixtures performance

WMA mixtures require lower mixing and compaction temperatures, approximately 212°F to 285°F (100°C to 140°C), as compared to HMAs, approximately 295°F to 330°F (145°C to 165°C) subsequently lowering the aging that takes place during production and placement (*44*). This is because the required viscosity for mixing and compaction can be attained by applying a minimum heat. Therefore, it is expected to see less rutting resistance for WMA mixtures compared to HMA due to the less aging condition used in their preparation process (*45*). Based on the results of the previous studies, Sasobit has been widely used as an organic additive to increase the rutting resistance of WMA mixtures, while Advera and Rediset (chemical additives) have been found to reduce the rutting resistance of the WMA mixtures (*35*,*5*). This is because Sasobit includes a lot of wax crystals, which are harder than other additives. Based on the findings from a study by Mohd Hasan et al. (*46*), it has been found that Advera demonstrates better fatigue life compared to the other WMA technologies. It is recommended to use a soft binder with the WMA mixtures containing Sasobit to improve the fatigue life of mixtures (*47*).

In terms of environmental benefits, the lower mixing and compaction temperature provides an 18 to 30% reduction in energy consumption compared to the conventional HMA (47,48,49). Moreover, the economic benefits of the use of WMA technologies regarding fuel usage include up to a 20-25% decrease in fuel consumption (*6*,*50*). Based on the findings from previous studies, depending on the technology, about 10 to 30% of cost reduction has been reported in the lifecycles cost assessment of WMA technologies (*47*,*51*).

Asphalt pavement's resistance to moisture damage may decrease over the service life due to the reduced adhesion between the binder and the aggregate. Moisture susceptibility of WMA mixtures could be affected by various factors such as the type, gradation, and moisture content of the aggregates, the type and source of the binder, and the binder aggregate adhesion (*53*). In a study by Wen et al. (*37*) the long-term field performance of the WMA and HMA pavements in the term of moisture resistance was compared, and no moisture damage or raveling was observed for the selected projects in the field. However, based on the Hamburg Wheel-Tracking (HWT) test results, mixtures without an antistripping agent exhibited stripping inflection points (SIPs). Therefore, it is recommended to use an antistripping agent in both HMA and WMA mixtures. Moreover, it has been found that the reduction in mixing and compaction temperatures may cause adhesion failure due to some moisture that might still exist in the aggregates (*38*).

Low temperature cracking resistance of wax modified asphalt binders were studied using the Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR)(*54*). Based on the results, a minor negative effect of wax modification has been observed at low temperatures. In a recent study by Luo et al. (*55*) the effect of a new WMA additive, Siligate, on low-temperature performance of asphalt binders has been compared with Sasobit and Evotherm. The results showed that the addition of Siligate, can significantly decrease the critical cracking temperature of asphalt binders, which are not achievable with the use of the other two additives. In another study by Xu et al. (*56*), thermal stress and ductile resistance of the asphalt binders mixed with Sasobit and ET-3100, as two different types of warm mix additives, have been evaluated. The results indicate that the addition of Sasobit increased the thermal stress of the bitumen, and with increasing the rate of the Sasobit its low-temperature critical cracking temperature increases linearly while the effect of ET-3100 is not significant. Also, the ductile resistance of asphalt binders containing Sasobit decreased as the blending amount increased.

Lee and Kim (*5*) summarized the benefits of WMA mixtures as follows:

- Reduced consumption of fuel to heat the aggregates;
- Less aging of the asphalt binder during production and placement of the asphalt mixture;
- Reduced mixing and compaction temperature leading to lower emission of heat;
- Allow incorporation of a higher percentage of RAP; and
- Allow achievement of higher compaction density.

In this study, all common WMA technologies were used, and the performance of the produced WMA mixtures have been compared using these three common technologies. The WMA technologies used in this research project are Sasobit® (organic), Evotherm® (chemical), and Advera® (foaming).

3.3. WMA mixtures containing high RAP content

As it has been mentioned in previous sections, the use of RAP in new asphalt mixtures has gained increasing popularity in recent years, however, a consensus has not been reached by agencies regarding the maximum limit of RAP that can be added to the new asphalt mixtures. Therefore, there is a strong need to evaluate the performance of the asphalt mixtures containing RAP content higher than the allowable RAP percentage in the state. At the time, the maximum allowable content specified by the Louisiana Department of Transportation and Development is 20-25% for the wearing course of the new asphalt mixtures. Binder aging is one of the main concerns of producing asphalt mixtures at high temperatures. Therefore, it is not recommended to use high proportions of RAP in conventional HMA production since RAP binders are aged already. However, in the case of WMA production, the results showed that decreasing the production temperatures would result in decreasing the binder aging. Thus, high proportions of RAP could be used in WMA (*57*). A concern associated with the use of RAP is the blending of the virgin and RAP binders during asphalt mix production, storage, and placement. In the asphalt mixtures containing RAP, the assumption is that the blending level between RAP binder and virgin binder is 100% and the aged binder in the RAP is totally effective (*18*). However, it is hard to get a 100% blending degree of absorbed binder portion in RAP and virgin binder in the blending process (*58*). Based on the rheological properties of asphalt binder measured with a dynamic shear rheometer (DSR) in a study by He et al. (*59*), a full blending of the age-hardened binder and the new binder was achieved during HMA mixing and construction, while only partial blending was observed during WMA production and construction. The phenomenon of the blending of the virgin binder with a binder from RAP is an ongoing issue that has not been fully investigated yet. It is recommended to use a softer binder when using a high percentage of RAP. However, findings from previous studies show that the use of asphalt rejuvenator agents allows the incorporation of more reclaimed material than using a softer binder (*23*,*24*).

3.3.1. WMA-RAP mixtures performance

Different types and dosages of WMA additives show different effects on the rutting and cracking performance of WMA mixtures. Zhao et al. (*45*) found that foaming technology presented lower rutting resistance than corresponding HMA mixtures regardless of RAP content. For mixtures with a high RAP content, different researchers have shown the benefits of WMA additives. The addition of these components has been found to improve the cracking resistance of asphalt mixtures. A study by NCAT (*61*) and a study by Vargas et al. (*62*) shown mixtures with 50% RAP content produced at a warm mixing temperature exhibited a good rutting and cracking resistance. A study by Zaumanis et al. (*36*) concluded that the lowered viscosity due to the use of WMA could enable agencies to incorporate more RAP into their mixtures. A study by Faheem et al. (*63*) evaluated the volumetric limits of the asphalt mixtures by changing different factors as RAP content, mixing/compaction temperatures, WMA type, and other factors. Comparing 15 and 30 percent of the RAP showed that 15% of RAP WMA mixes could meet volumetric limits. However, at 30% RAP, a hot production temperature is required to achieve the same level of compaction.

A study by Mogawer et al. (*22*) showed that for asphalt rubber gap-graded mixtures that contain RAP up to 40%, the cracking resistance was significantly improved when WMA is introduced. Another study by Magawer et al. (*64*) also showed that the addition of WMA improved the reflective cracking performance of asphalt mixtures. Sol-Sánchez et al. (*65*) used the three main technologies (i.e., chemical additives, organic additives, and the foaming process) for producing WMA to compare the fatigue-cracking life of the WMA and HMA. The results revealed that there is similar resistance to fatigue cracking and there is no significant difference between various types of technologies. Additionally, the results of a literature review on the use of different WMA technologies illustrated the fact that the fatigue resistance of WMA mixtures containing RAP could be improved with organic additives while it could be decreased in the presence of chemical additives and foaming technology (*34*).

Further, Zhao et al. (*45*) assessed the rutting resistance, moisture susceptibility, and fatigue resistance of WMA mixtures containing a range of 0% up to 50% RAP based on the laboratory performance tests. The results revealed that WMA mixtures with higher percentages of RAP presented higher resistance to rutting, better resistance to moisture damage, and better fatigue cracking. Another study by Fakhri et al. (*66*) found the improving impact of glass fiber and RAP percentage on the performance of the WMA mixture by observing the results that come from the KN Toosi University of technology Wheel track test. Zhu et al. (*67*) studied rutting and fatigue performance of WMA mastic containing a high percentage of artificial RAP binders (i.e., 50%). In this study, two types of WMA additives with the filler/asphalt ratio ranging from 0.0 to 1.5 was used. It was found that depending on the WMA additives, the high-temperature performance of the asphalt mixtures could be different, and the effect of mineral fillers and WMA additives on the fatigue resistance of asphalt mastic also is highly dependent on the load mode.

A study by Alsalihi et al. (*63*) showed that for WMA mixtures with high RAP content (i.e., 15% and 30%), lower production temperature, and RAP source have a significant effect on the workability and stability of the mixture. A study by Wang et al. (*68*) analyzed the performance of mixtures with a high percentage of artificial RAP binders (up to 70%) and WMA additives. The test results exhibited that artificial RAP content and WMA additive type affected the performance of recycled binders. It should be noted that an artificial RAP binder refers to the RAP binder that is artificially obtained through RTFO and PAV aging rather than the RAP binder extracted from milled materials. Further, another study by Zhou et al. has been conducted to understand whether WMA additives can counter the negative impact of adding 50% RAP to asphalt mixtures. Also, SBR latex was used as a modified additive. SBR latex is a milk-white liquid at a normal temperature, and it is usually used to improve the performance of the conventional asphalt mixtures (*69*). It can be seen from the test results that high RAP-WMA mixtures have potential problems of fatigue cracking. While the addition of SBR latex can improve fatigue cracking performance of high RAP-WMA mixtures without sacrificing the rutting performance of mixtures (*70*). A study by Doyle and Howard (*71*) showed that 50% of RAP in WMA mixtures might be suitable for use in surface layers. However, another study by Mogawer et al. (*72*) showed that WMA with RAP contents up to approximately 50% RAP provided an acceptable laboratory performance. Case studies from Germany, Netherlands, and South Africa have reported up to 50% RAP content in mixtures (*42*,*55*). Dinis-Almeida et al. (*74*) conducted a study to evaluate the performance of several WMA mixtures containing 100% of RAP and different emulsion content. The test results show that WMA containing a high percentage of RAP could be used in road pavements instead of conventional HMA. Moreover, the results of another study by Monu et al. (*75*) showed that incorporation of WMA in dense bituminous macadam (DBM) mixtures containing 35% RAP could ensure the longevity of the mixtures even in the worst conditions of moisture.

A study by Doyle and Howard (*71*) showed that WMA technology could be used with high RAP content (i.e., 25% and 50%) to produce mixtures that are more resistant to moisture damage. A study by Solaimanian et al. (*76*) showed that the measurement of Tensile Strength Ratio (TSR) indicated RAP mixtures with WMA showed less susceptibility to moisture. On the other hand, the study of Guo et al. (*78*) showed that WMA mixtures without RAP exhibited better moisture and low temperature cracking resistance. A recent study by Goli et al. (*79*) evaluated the effect of moisture on the performance of the WMA-RAP mixture in all service temperatures using experimental methods including Resilient Modulus, Indirect Tensile Strength (ITS), Indirect Tensile (IDT) fatigue failure, Semi-Circular Bending (SCB), and Dynamic Creep tests. Results showed that even though WMA mixtures containing RAP have hydrophilic and moisture-sensitive aggregates, they have an acceptable performance against the effect of moisture. An investigation has been conducted to evaluate the performance of the WMA open-graded (OG) mixtures containing 15% RAP in the case of adhesion properties and durability. The results showed that although mixtures have good compatibility and satisfying mechanical acceptance requirements, significant water susceptibility has been observed for the OG-WMA mixtures (*80*).

3.3.2. WMA-RAP mixtures with rejuvenators

In general, softening agents are used to reducing modulus or viscosity of the asphalt binders, while rejuvenators are used to reverses the impact of aging on asphalt performance, properties, and durability (*81*). Results of a study by Gue et al. (*78*) showed that the use of rejuvenator in asphalt mixtures can increase the upper limit of RAP content, however, the use of too much rejuvenator excessively softened the aged asphalt binder and can decrease the rutting performance of the asphalt mixtures. Xuan Dai Lu et al. (*82*) investigated the possibility of adding rejuvenator to produce high-performing WMA mixtures containing high amounts of RAP materials. The results showed that adding rejuvenator directly into the RAP significantly improved the moisture resistance of WMA mixtures containing more than 50% of RAP. Fatigue cracking and rutting resistance of WMA mixture with a high amount of RAP (up to 70%) were evaluated by Xuan Dai Lu et al. (*83*). The results showed that increasing RAP would result in improved rutting performance, while fatigue resistance will increase only by adding rejuvenator to the mixture. Further, the results of a study by Yousefi et al. (*84*) showed that rejuvenators can be applied in WMA and HMA mixtures to mitigate the negative effects associated with the incorporation of RAP into asphalt mixtures. Another laboratory-based study by Farooq and Mir (*85*) evaluated the mechanical properties of the WMA mixtures by adding different percentages of the rejuvenator. The results showed that using a rejuvenator allows accommodating up to 60% RAP in the WMA mixtures. An experimental study by Mirhosseini et al. (*86*) investigates the use of high percentages of RAP (i.e., up to 90%) in WMA using bio-oil rejuvenator. Results indicated that the effect of adding 90% of RAP in the mix design is balanced by introducing both the rejuvenator in the blend and the WMA additive. Test results demonstrated higher fatigue life and improvement in moisture resistance of WMA mixtures containing 90% RAP and bio-oil rejuvenator. Another study by Song et al. (*87*) also showed that WMA technology and the use of rejuvenator would improve the performance of the pavements containing up to 50% of RAP.

In this study, one type of rejuvenator at various percentages by the total weight of binder depending on the percentage of RAP has been used.

3.4. The use of RAP materials and WMA mixtures in the South-Central states

Results of research by Kentucky Transportation Center and the University of Kentucky (*88*) indicated that WMA technologies are being used in all of the southeastern states, and all of the states have made modifications in standard specifications and special requirements to permit the use of WMA. In this part of the study, the specifications for the RAP and WMA technologies use in the south-central states (i.e., Arkansas, Louisiana, New Mexico, Oklahoma, and Texas) are reviewed and discussed.

3.4.1. Current regional specifications on the use of RAP materials

There are sections in the specifications of the south-central states discussing the use of RAP in asphalt mixtures, however, they vary in requirements and detailed information. Table 1 lists the sections that are discussing the use of RAP in different specifications. The specifications of each south-central state mention that there are allowable percentages of RAP that can be used in asphalt mixtures. Table 2 shows the maximum percentage of the RAP content in asphalt mixtures as per DOTs specifications.

By reviewing the Arkansas DOT specifications (*89*), it is mentioned that up to 30% RAP can be used in new asphalt mixtures. However, there are no particular procedures for the addition of RAP to asphalt mixtures mentioned in the Arkansas specification. According to the Arkansas specification, an approved softening agent may have to be used in mixtures containing RAP in addition to virgin materials.

The requirements and check processes for RAP stockpiles differ between the south-central states. According to the Arkansas specification, temperature viscosity curves must be submitted if any binder besides PG 64-22 and more than 15% RAP is used in the mixture. Moreover, Arkansas specifications state that the design of asphalt mixtures containing RAP must follow the guidelines for all virgin mixtures, and the size of RAP aggregates should be lower than is 3 in. (75 mm).

Table 1. The Sections that are Discussing the Use of RAP in Different Specifications.

South-Central States	Specifications	Sections
New Mexico	Standard Specifications for Highway and Bridge Construction (2019)	412.1, 412.3.2.3, 413.1, 413.3.1.1, 413.3.1.2, 413.3.1.7, 413.3.2.3, 413.3.2.8, 413.3.2.9, 417.2.3, 423.2.1, 423.2.2.1.2, 423.2.2.4, and 902.2.1.6
Oklahoma	Oklahoma Department of Transportation Commission (2009)	411.03 (A), and 708.04 (C)
Louisiana	Louisiana Standard Specifications for Roads and Bridges (2016)	501.02.7, 502.02.3.2, 502.03.1, 503.02.2, 503.03.4, and 503.03.5
Texas	Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges (2014)	320.2.1.1.2, 340.2.1, 340.2.1.1.1, 340.2.1.3, 340.2.7, 340.2.7.1, 340.2.7.2, 340.2.8, 341.2.1, 341.2.1.1.1, 341.2.1.3, 341.2.7, 341.2.7.1, 341.2.7.2, 342.2.1, 342.2.1.1.1, 342.2.6, 342.2.6.1, 342.2.6.2, 344.2.1, 344.2.1.1.1, 344.2.1.3, 344.2.7, 344.2.7.1, 344.2.7.2, 344.2.8, 346.2.1, 346.2.1.1.1, 346.2.1.3, 346.2.7, 346.2.7.1, and 346.2.7.2
Arkansas	Arkansas State Highway and Transportation Department: Standard Specifications for Highway Construction (2014 Edition)	416

Table 2. Maximum Percentage of the RAP Content in Asphalt Mixtures as per Specifications.

South-Central States	Maximum RAP, %	Considerations
New Mexico	35	The binder grade should change
	15	Without changing the binder grade
Oklahoma	25	PG 64-22
	15	PG 70-28
	15	PG 76-28
Louisiana	20	Maximum aggregate size should be 12.5 mm and 19 mm
Texas	20	Fractionated RAP
	10	Unfractionated RAP
Arkansas	30	-

New Mexico's DOT specifications (*90*) state that no more than 35% RAP (by weight) can be used in HMA mixtures, and up to 15% (by weight) can be used without changing the binder grade. There is no specific procedure for the addition of RAP to asphalt mixtures mentioned in New Mexico specifications. However, New Mexico specifications state that the Contractor must perform process control testing on the RAP and check for "deleterious materials" so that it can be included in the mixture. It states that an asphalt rejuvenating agent may have to be used to revive the properties of the RAP binder. Moreover, it states that 100% of RAP aggregate must pass through a 1-1/2-inch sieve to be used in asphalt mixtures. However, the top size may be reduced to 1/2 inch or stockpiles may be split into three to adjust the consistency of the mixture.

Oklahoma's DOT specifications (*91*) mention that up to 25% RAP can be used if it is not in the surface layer and meets the requirements for the binder grade being used. There is no explicit procedure for the addition of RAP to asphalt in Oklahoma's specifications. However, it is mentioned that the insoluble residue content must be measured to adjust the proportion of natural sand and gravel in the RAP materials. Moreover, Oklahoma specifications state that asphalt mixtures with reclaimed materials should not be exposed to the burner flame or high-temperature combustion gas. It also states that when RAP is used in a Superpave mixture, 100% of the course stockpile must pass through a 1-1/2-inch sieve and 100% of the fine stockpile must pass through a 5/8-inch, 1/2-inch, or 3/8-inch sieve.

According to Louisiana DOTD specifications (*10*), the maximum percentage of RAP allowed in a wearing course mixture is 20% when the maximum aggregate size is 1/2-inch and 3/4-inch. Louisiana specifications also state that RAP must be added to the dryer in a location in a manner that does not expose it directly to the flame. The method of addition of RAP to the dryer should be followed according to the recommendation made by the manufacturer. Louisiana specifications are silent about the check processes for RAP stockpiles and the guidelines for the design of asphalt mixtures containing RAP. However, it mentions that the maximum size for RAP aggregate is 1 inch (25.4 mm).

Texas DOT specifications (*92*) state that the maximum allowable amount of RAP material in asphalt mixtures is 20% fractionated RAP or 10% unfractionated RAP. There is no specific procedure for the addition of RAP to asphalt mixtures mentioned in Texas specifications. However, the Texas specifications state that RAP that is polluted with objectionable materials, has a decantation value over 5%, or a Plasticity Index (PI) over 8 must not be used unless it was recovered through extraction or ignition. Texas specifications also state that Contractor-owned and Department-owned RAP materials must not be combined in unfractionated RAP stockpiles, but fractionated stockpiles of Contractor-owned RAP materials can be replaced with an equal amount of Department-owned RAP. Furthermore, Texas specifications state that both the course and fine stockpiles of fractionated RAP must only be comprised of a material that passes a 3/8-inch or ½-inch screen unless otherwise approved and that sand may be added to increase workability. Texas specifications also offered the most comprehensible information concerning the use of RAP in asphalt mixtures compared to the specifications of the other south-central states.

3.4.2. Current regional specifications on the use of WMA mixtures

There are sections in some of the specifications of the south-central state concerning the use of WMA technologies in the production of asphalt. Table 3 lists the sections in the specifications of the south-central states that mention or discuss WMA technologies and additives.

There are no sections in Arkansas specifications that mention discussing the use of WMA technologies in the production of asphalt mixtures. Therefore, there is an absence of information discussing specific WMA technologies, the production process, mix design, and mixing and compaction temperatures of WMA-mixtures in the state of Arkansas.

Table 3. The Sections that are Discussing the Use of WMA in Different Specifications.

South-Central States	Specifications	Sections
New Mexico	Standard Specifications for Highway and Bridge Construction (2019)	424, 902.2.1.3, 902.2.1.7
Oklahoma	Oklahoma Department of Transportation Commission (2009)	None
Louisiana	Louisiana Standard Specifications for Roads and Bridges (2016)	502.02.2.5, 502.03, 502.06, 503.05.2, 503.05.3, 503.05.3.1, 503.05.3.2

South-Central States	Specifications	Sections
Texas	Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges (2014)	340.2.6.2, 340.2.8:Table 5, 340.4.4.2, 341.2.6.2, 341.2.8:Table 5, 341.4.3.3, 341.4.4.2, 341.4.2.1.8, 341.4.5.2, 342.2.5.4, 342.4.3.3, 342.4.4.2, 342.4.4.2.1.9, 342.4.5.2, 344.2.6.2, 344.2.8, 344.4.3.3, 344.4.4.2, 344.4.4.2.1.8, 344.4.5.2, 346.2.6.3, 346.4.3.3, 346.4.4.2, 346.4.4.2.1.8, 346.4.5.2
Arkansas	Arkansas State Highway and Transportation Department: Standard Specifications for Highway Construction (2014 Edition)	None

According to the New Mexico specifications, WMA may be manufactured by one or a combination of many technologies such as foaming technology, mineral additives, or chemical additives, all of which lower the production temperature. However, no section is discussing the production process of WMA-mixtures in New Mexico specifications. New Mexico specifications contained the most detailed description of the design of WMA-mixtures, stating that WMA-mixtures must contain a minimum of 1% hydrated lime, anhydrite-based material, or Portland cement. Moreover, the lubricating anti-strip should be approved by the DOT, and the HMA should be tested using 6-inch diameter specimens compacted, endure one freeze-thaw cycle, have a visual estimation of interior surface moisture damage on a scale of one to five (five being the most damage) and have a tensile stress ratio of at least 85%. Furthermore, New Mexico specifications state that it is recommended to mix and compact at the maximum allowable temperatures for the mix design according to the WMA Additive or Technology Supplier and the Asphalt Binder Supplier and should be between 215°F and 275°F.

As previously demonstrated in Table 3, there is no section in Oklahoma specifications that mention or discuss the use of WMA technologies in asphalt production. For this reason, there is no information provided on the specific WMA technologies, production process, mix design, or mixing and compaction temperature of WMA-mixtures in Oklahoma.

There is no section in Louisiana specifications that discuss the use of specific WMA technologies and therefore do not recommend any technology over another. It also does not discuss the production process of WMA-mixtures in Louisiana. However, Louisiana specifications do state that all WMA-mixtures must be aged for two hours. Moreover, WMA may be used instead of HMA if it is produced at a minimum temperature of 275°F.

According to Texas specifications, WMA mixtures may be produced using any approved WMA additives or processes from the DOT's Material Producer List (MPL). However, no section recommends the use of one WMA technology over another. Texas specifications state that the burners may have to be adjusted when producing WMA-mixtures to ensure complete combustion so that there is no residue from the burner fuel in the mixture. No section in Texas specifications discusses the mix design of WMA-mixtures but, it does state that WMA-mixtures must be mixed at a temperature between 215 and 275°F.

3.4.3. Current regional specifications on the use of WMA mixtures containing RAP

Few south-central states have sections in their specifications discussing the use of WMA containing RAP in the production of asphalt mixtures. In the sections that do mention the use of RAP in WMA-mixtures, there are very few details provided. Table 4 shows the sections in different specifications that mention or discuss the incorporation of RAP in WMA-mixtures.

Table 4. The Sections that are Discussing the Use of WMA in Different Specifications.

South-Central States	Specifications	Sections
New Mexico	Standard Specifications for Highway and Bridge Construction (2019)	424.2.7
Oklahoma	Oklahoma Department of Transportation Commission (2009)	None
Louisiana	Louisiana Standard Specifications for Roads and Bridges (2016)	None
Texas	Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges (2014)	340.2.8
Arkansas	Arkansas State Highway and Transportation Department: Standard Specifications for Highway Construction (2014 Edition)	None

As demonstrated in Table 4, there are no sections in Arkansas specifications that discuss the use of RAP in WMA-mixtures. Therefore, there is no information about the production process or mix design of WMA-mixtures containing RAP. New Mexico specifications state that the same guidelines for HMA-mixtures apply to WMA-mixtures. However, there is no section in New Mexico specifications that discuss the production process or mix design of WMA-mixtures containing RAP.

Besides, there is no section in Oklahoma specifications that mention or discuss the incorporation of RAP into WMA-mixtures. For this reason, there is no information on the production process or mix design of WMA containing RAP in Oklahoma specifications. Louisiana specifications do not contain any section that discusses the incorporation of RAP in WMA-mixtures. Thus, there is no information about the production process or mix design of WMA-mixtures that include RAP materials.

Texas specifications provide the most details about WMA-mixtures containing RAP, stating that the maximum ratio of recycled binder to the total amount of binder in the mixture is 30%. However, Texas specifications do not provide any information on the production process or mix design of WMA-mixtures that include RAP.

4. METHODOLOGY

In this research project, twelve Superpave asphalt mixtures utilizing an NMAS of 0.5 in. (12.5 mm) were designed, produced in the laboratory, and evaluated in accordance with AASHTO R 35 (*93*), AASHTO M 323 (*94*), and Section 502 of the 2016 Louisiana Standard Specifications for Roads and Bridges (*10*). The job mix formula is designed with a 65 number of gyrations and all mixtures contain the same PG 76-22 binder and Limestone aggregate. In this project, asphalt mixtures with 0%, 25%, and 35% RAP were included to determine if WMA additives could enhance the performance of mixtures with high RAP content. One HMA mixture was classified as a control mixture containing no RAP no recycling agents. Description of materials, the procedure for preparing the asphalt mixtures, and basic information about RAP material, testing descriptions, and procedures are presenting in the following subsections.

4.1. Materials

According to the Superpave mix design procedure, it is recommended to contain at least three different virgin aggregate stockpiles. For this study, three Limestone aggregate stockpiles; #89, #11, and #78 were collected from Vulcan Materials Company from their Grand Rivers Quarry located in Lafayette, Louisiana. The RAP materials were collected as Fine and Coarse RAP materials from Diamond B in Louisiana (binder content of 4.7% and 3.1%, respectively). The detailed properties of these stockpiles and the RAP materials are shown in Appendix A. Table 5 illustrates the aggregate gradation for the three different stockpiles and two RAP materials that have been used in this work. All virgin and RAP aggregates were sieved, and materials retained on the 3/4”, 1/2”, 3/8”, No. 4 sieves, and passing No. 4 sieve were stored in separate buckets for batching. Aggregate materials passing No. 4 sieve of #11 stockpile were sieved again, and materials retained on No. 8, 16, 30, 50, 100, and 200 sieves, and passing No. 200 sieve were stored in separate buckets for better batching. The required aggregate blend gradations can be batched directly from individual-sized fractions for the desired HMA and WMA mix designs. It is an essential consideration of keeping the collected materials away from any source of contamination. The blended mixtures should pass control points and prevent the restricted zone.

Table 5. Aggregate gradation and % passing for three different stockpiles and two different RAP sources.

Sieve Size	#89 Stockpile	#11 Stockpile	#78 Stockpile	Fine RAP	Coarse RAP
25.0mm - 1"	100.0	100.0	100.0	100.00	100.0
19.0mm - 3/4"	100.0	100.0	100.0	100.0	97.6
12.5mm - 1/2"	100.0	100.0	93.0	99.7	76.7
9.5mm - 3/8"	95.1	100.0	50.1	96.2	51.1
4.75mm - No. 4	34.6	92.0	3.5	70.5	31.4
2.36mm - No. 8	8.6	63.0	1.2	50.0	22.2
1.18mm - No. 16	4.0	39.0	1.0	38.3	17.6
0.600mm - No. 30	3.0	25.0	1.0	30.9	14.6
0.300mm - No. 50	2.6	17.0	1.0	20.4	10.2
0.150mm - No. 100	2.3	13.0	0.9	12.1	6.0
0.075mm - No. 200	1.4	10.0	0.8	8.7	3.7

At the time, the Louisiana Department of Transportation and Development (LaDOTD) allows only 20 to 25% of RAP for asphalt mixtures used for wearing course with the NMAS of 0.5 in (12.5 mm). The mixtures produced in this study contained 25% and 35% RAP to investigate the effect of using these WMA technologies on the performance of mixtures with high RAP content. Once the RAP aggregate gradation has been determined, it has been blended with the virgin aggregate to meet the overall mixture gradation requirements.

The asphalt binder used in this study was Styrene-Butadiene-Styrene (SBS)-modified PG 76-22 binder and was collected from Marathon Petroleum refinery in Garyville, Louisiana. The properties of this binder are summarized in Appendix A.

4.1.1. Warm-Mix Asphalt Technologies

This study covered all common WMA technologies and compared the performance of the produced WMA mixtures using these three common technologies. The WMA technologies used in this research project are Sasobit® (organic), Evotherm® (chemical), and Advera® (foaming). The findings from previous studies show that these technologies are the most common technologies to improve the performance of the Warm-Mix asphalt mixtures against typical distress types.

Organic Additives: In this research study, Sasobit was added to the hot PG 76-22 binder at 120°C at the rate of 4% by the total weight of the binder. A mechanical shear mixer with a normal paddle (high-shear mixing is not needed) has been used to completely blend the Sasobit with the hot binder. The blended binder can meet the target mixing temperature without any delay, or it can be kept in the storage to be used later, the Sasobit in the blended binder stays homogeneous for weeks.

Chemical Additives: The dosages and the procedure for adding the Evotherm are based on the recommendations from the additive producer. In this research project, Evotherm was added to the heated binder at 248°F (120°C), using a mechanical shear mixer with a normal paddle, at the rate of 0.5% by the weight of the PG 76-22 binder.

Foaming Additives: In this study, Advera has been added to the hot binder at the rate of 5% by weight of the binder just before mixing with aggregates. The production was conducted at 284°F (140°C) with the proper coating of the aggregates.

4.1.2. Asphalt Rejuvenator Agent

The recycling agent selected in this study was incorporated into the asphalt mixtures at various percentages by the total weight of binder depending on the percentage of RAP. The rate of recycling agent added was based on the supplier recommendation. Also, it is recommended to use low-shear blending for a few minutes into the heated virgin asphalt binder to have a homogenous blend. More information about the used rejuvenator can be found in Appendix B.

4.2. Mix Designs

As discussed earlier, three types of WMA technologies were selected to be used in the asphalt mixtures produced in the laboratory for this study. The experimental design of this project including variables is summarized in Table 6. Table 7 summarizes details of the asphalt mixtures, including the mixture code designations used in the report.

Table 6. Project experimental design.

Variable	Description
NMAS	0.5 in. (12.5 mm)
RAP Source	Single source (Fine and Coarse RAP)
Asphalt Binder	Polymer-modified binder: PG 76-22

Asphalt Binder Content	Optimum asphalt binder content[1]
RAP % (by weight of the aggregate blend)	0%, 25%, 35%
WMA Additives (dosages by wt% of total binder)	None[2] (0%), Sasobit (3%), Evotherm (0.6%), and Advera (5%)
Asphalt rejuvenator (dosages by wt% of total binder)	Mixtures with 25% RAP (1.6%), Mixtures with 35% RAP (2.5%)

[1] Determined at N_{design}

[2] This mixture will be prepared as HMA

Table 7. Details of the asphalt mixtures of this study.

Mix Code	Mix Type	Binder Grade	NMAS, mm	RAP, %	WMA Technologies
H0R	HMA	PG 76-22	12.5	0	-
H25R	HMA-RAP	PG 76-22	12.5	25	-
H35R	HMA-RAP	PG 76-22	12.5	35	-
WA0R	WMA	PG 76-22	12.5	0	Advera
WE0R	WMA	PG 76-22	12.5	0	Evotherm
WS0R	WMA	PG 76-22	12.5	0	Sasobit
WA25R	WMA-RAP	PG 76-22	12.5	25	Advera
WE25R	WMA-RAP	PG 76-22	12.5	25	Evotherm
WS25R	WMA-RAP	PG 76-22	12.5	25	Sasobit
WA35R	WMA-RAP	PG 76-22	12.5	35	Advera
WE35R	WMA-RAP	PG 76-22	12.5	35	Evotherm
WS35R	WMA-RAP	PG 76-22	12.5	35	Sasobit

The design aggregate gradation was developed for mixtures with 0%, 25%, and 35% RAP. Figure 3 shows the blend gradation only for the three basic HMA mixtures since their companion WMA mixtures had the same aggregate blends. The mix design procedure (*94*) was performed to determine the optimum binder content for the aggregate blend gradation of each mixture.

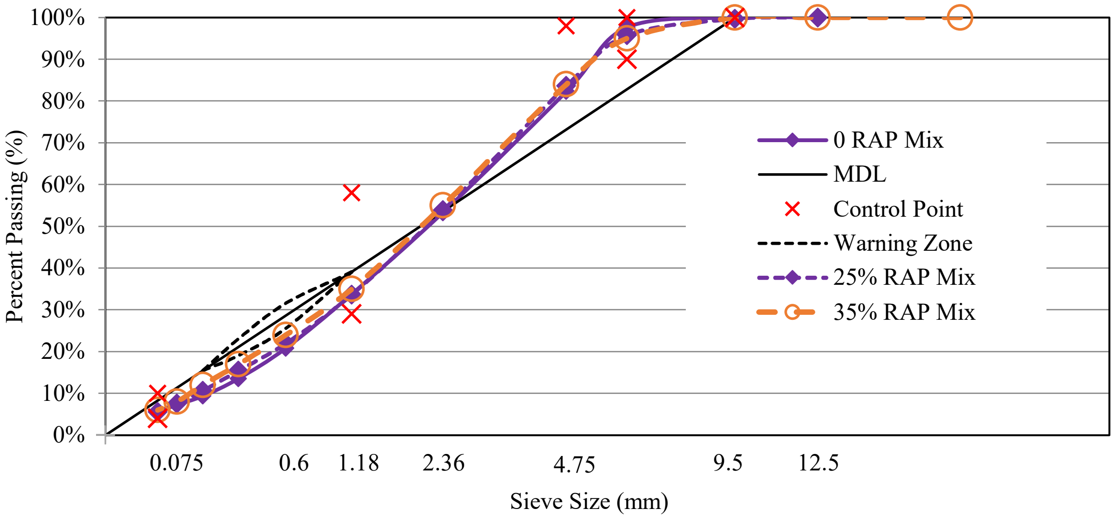

Figure 3. Blend gradation for the 0%,25% and 35% RAP mixtures.

To prepare the twelve different mixtures of this research work, three different mixture blending methods were used depending on the temperature and presence of the RAP in the mixture composition.

HMA Mixtures without RAP: After the determination of each aggregate batch weight, aggregates were weighed and placed in a flat pan. A series of steps that have been followed to prepare mixtures after batching are summarized as follows:

- The virgin aggregates were placed in an oven at 325°F (163°C) for at least 3 hours before the mixing.
- Binder and all mixing tools were placed in the oven at 325°F (163°C) approximately 1 hour before mixing.
- After all the components reach the temperature of 325°F (163°C), the heated aggregate was placed in the heated mixing bucket and placed on the balance. After that, the required amount of binder was added to the aggregate. The mixing started immediately.
- Mixing continued until the asphalt binder was uniformly distributed over the aggregate particles and ensured that the binder coats the aggregate particles.
- After mixing, the mixture was spread in a pan and short-term oven-aged for 2 hours at 275°F (135°C)(*95*).
- After that, the compacted cylindrical specimens were prepared using the Superpave gyratory compactor (SGC) shown in Figure 4 to the specified dimensions for each particular test procedure.
- Finally, the volumetric properties and densification criteria were determined (*12*,*11*).

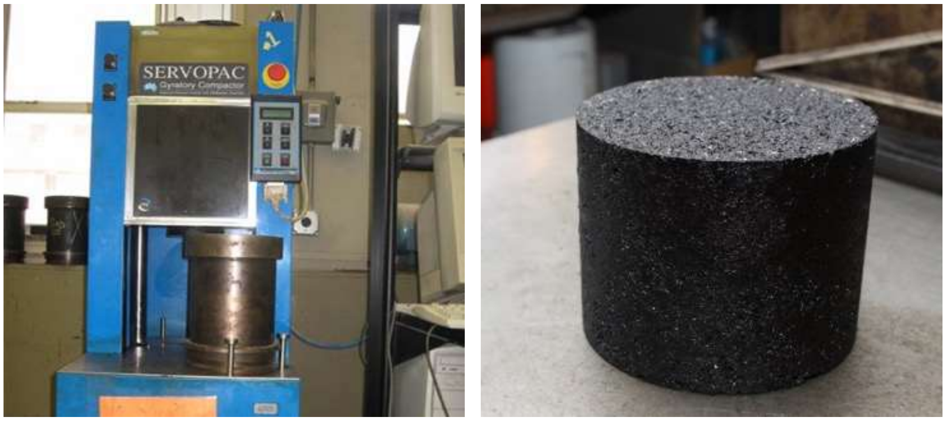

Figure 4. (a) Superpave gyratory compactor, and (b) compacted sample.

HMA Mixtures Containing RAP: After the determination of aggregate composite blend, virgin aggregates and RAP were weighed and placed in two different flat pans. Based on the conducted literature review, blending between the virgin binder and binder from RAP is an ongoing issue. In this study, the mixing procedure is based on a study by Cooper et al. (*96*) that ensures 100% of the available recycle binder is utilized within the asphalt mixture. Mixture blending and compacting steps are described below:

- 5% of moisture content was added to RAP.
- Virgin aggregates were superheated to 383°F (195°C) (minimum) for 3 hours.
- Heated mixing tools to 325°F (163°C).

- Moisture laden RAP was placed on the bottom of the heated mixing bucket and the superheated virgin aggregates placed on top of the RAP.
- Superheated virgin aggregates and RAP were mixed together resulting in steaming.
- Mixing was continued until steam seized.
- Blended aggregates and RAP were placed into 325°F (163°C) oven till the blended aggregates reached the suitable temperature for mixing with asphalt cement.
- Heated asphalt cement and blended aggregates were mixed together in a heated mixing bucket.
- After mixing, the mixture was spread in a pan and short-term oven-aged for 2 hours at 275°F (135°C) (*95*).
- After that, the compacted cylindrical specimens were prepared using the Superpave gyratory compactor (SGC) shown in Figure 4 to the specified dimensions for each particular test procedure.
- Finally, the volumetric properties and densification criteria were determined (*12*,*11*).

WMA Mixture without RAP: The main difference between WMA and HMA mixtures preparation is temperature and three types of WMA technologies that have been added to the binder before the mixing. Mixing and compaction temperatures are the same for all three technologies. Steps for mixture producing and compacting are summarized below:

- The aggregates were placed in an oven at 284°F (140°C) at least 3 hours before the mixing.
- Binder and all the mixing tools were placed in the oven at 284°F (140°C) approximately 1 hour before the mixing.
- After all the components reached a temperature of 284°F (140°C), the heated aggregates were placed in the mixing bucket and placed on the balance. After that, the required amount of binder was added to the aggregates. The mixing started immediately.
- Mixing continued until the asphalt binder was uniformly distributed over the aggregates particles and ensured that the binder coats the aggregate particles.
- After mixing, the mixture was spread in a pan and short-term oven-aged for 2 hours at 257°F (125°C) (*95*).
- After that, the compacted cylindrical specimens were prepared using the Superpave gyratory compactor (SGC) shown in Figure 4 to the specified dimensions for each particular test procedure.
- Finally, the volumetric properties and densification criteria were determined (*12*,*11*).

WMA Mixture Containing RAP: The procedure is completely the same with HMA mixtures contain RAP, the only difference is preparation and compaction temperature and three types of WMA technologies that have been added to the binder before the mixing. The steps are summarized as follows:

- 5% of moisture content was added to RAP.
- Virgin aggregates were superheated to 383°F (195°C) (minimum) for 3 hours.
- Heated mixing tools to 284°F (140°C).
- Moisture laden RAP was placed on the bottom of the heated mixing bucket and the superheated virgin aggregates were placed on top of the RAP.
- Superheated virgin aggregates and RAP were mixed together resulting in steaming.
- Mixing continued until steam seized.

- Blended aggregates and RAP were placed into 284°F (140°C) oven till the blended aggregates reached the suitable temperature for mixing with asphalt cement.
- Heated asphalt cement and blended aggregates were mixed together in a heated mixing bucket.
- After mixing, the mixture was spread in a pan and short-term oven-aged for 2 hours at 257°F (125°C) (*95*).
- After that, the compacted cylindrical specimens were prepared using the Superpave gyratory compactor (SGC) shown in Figure 4 to the specified dimensions for each test procedure.
- Finally, the volumetric properties and densification criteria were determined (*12*,*11*).

The volumetric properties of the mixture are determined for the design binder content. The results show that the design binder value satisfied the criteria in accordance with Louisiana Standard Specifications for Roads and Bridges (*10*). According to Table 502-6, for 0.5 in. (12.5 mm) NMAS asphalt concrete mixtures, the air voids (AV%) should be in the range of 2.5% to 4.5%, voids in mineral aggregate (VMA) should be higher than 13.5%, and voids filled with asphalt (VFA) should be between 69% to 80%. The mix design details for mixtures are presented in trough Table 8 to Table 10.

Table 8. Job mix formula for 0% RAP mixtures.

Mix Code		H0R	WA0R	WE0R	WS0R
Mix Type		12.5 mm HMA	12.5 mm WMA		
Aggregate Blend		15 % #89LS[1] 51% #11LS 34% #78LS 0% F. RAP 0% C. RAP	15 % #89LS 51% #11LS 34% #78LS 0% F. RAP 0% C. RAP		
Binder type		PG 76-22	PG 76-22		
Design volumetric properties	G_{mm}, N_d[2]	2.472	2.478	2.468	2.469
	%AC	5.5	5.5	5.5	5.5
	%Voids	3.2	4.0	3.5	2.8
	%VMA	13.8	14.3	14.2	13.6
	%VFA	77.0	71.9	75.1	79.2
Gradation, (%passing)	25.0mm - 1"	100	100		
	19.0mm - 3/4"	100	100		
	12.5mm - 1/2"	98	98		
	9.5mm - 3/8"	82	82		
	4.75mm - No. 4	53	53		
	2.36mm - No. 8	34	34		
	1.18mm - No. 16	21	21		
	0.600mm - No. 30	14	14		
	0.300mm - No. 50	9	9		
	0.150mm - No. 100	7	7		
	0.075mm - No. 200	6	6		

[1] LS: Limestone

[2] Nd: design number of gyrations

Table 9. Job mix formula for 25% RAP mixtures.

Mix code		H25R	WA25R	WE25R	WS25R
Mix type		12.5 mm HMA-RAP	12.5 mm WMA-RAP		
Aggregate Blend		22 % #89LS 36% #11LS 17% #78LS 12% F. RAP 13% C. RAP	22 % #89LS 36% #11LS 17% #78LS 12% F. RAP 13% C. RAP		
Binder type		PG 76-22	PG 76-22		
Design volumetric properties	G_{mm}, N_d	2.465	2.463	2.461	2.451
	%AC	5.0	5.0	5.0	5.0
	% air voids	3.6	3.6	2.9	2.9
	%VMA	14.0	14.0	13.5	13.8
	%VFA	74.1	74.2	78.4	79.2
Gradation, (%passing)	25.0mm - 1"	100	100		
	19.0mm - 3/4"	100	100		
	12.5mm - 1/2"	96	96		
	9.5mm - 3/8"	84	84		
	4.75mm - No. 4	54	54		
	2.36mm - No. 8	34	34		
	1.18mm - No. 16	22	22		
	0.600mm - No. 30	15	15		
	0.300mm - No. 50	11	11		
	0.150mm - No. 100	8	8		
	0.075mm - No. 200	6	6		

Table 10. Job mix formula for 35% RAP mixtures.

Mix code		H35R	WA35R	WE35R	WS35R
Mix type		12.5 mm HMA-RAP	12.5 mm WMA-RAP		
Aggregate Blend		% #89LS % #11LS % #78LS % F. RAP % C. RAP	% #89LS % #11LS % #78LS % F. RAP % C. RAP		
Binder type		PG 76-22	PG 76-22		
Design volumetric properties	G_{mm}, N_d	2.451	2.450	2.448	2.440
	%AC	4.5	4.5	4.5	4.5
	%Voids	2.9	3.0	2.9	2.7
	%VMA	13.6	13.6	14.0	13.8
	%VFA	78.4	74.8	75.1	78.3
Gradation, (%passing)	25.0mm - 1"	100.0%	100.0%		
	19.0mm - 3/4"	99.6%	99.6%		
	12.5mm - 1/2"	95.5%	95.5%		
	9.5mm - 3/8"	84.0%	84.0%		
	4.75mm - No. 4	55.3%	55.3%		
	2.36mm - No. 8	35.3%	35.3%		
	1.18mm - No. 16	23.7%	23.7%		
	0.600mm - No. 30	17.1%	17.1%		
	0.300mm - No. 50	11.7%	11.7%		
	0.150mm - No. 100	8.0%	8.0%		
	0.075mm - No. 200	5.9%	5.9%		

4.3. Asphalt Binder Performance Tests

It is important to recognize the rheological properties of the asphalt binder and know that these properties affect the performance of the asphalt mixtures. In this project, the asphalt binders were extracted and recovered from the short-term aged loose mixtures using the methods commonly used in Louisiana. The auto extraction method has been conducted according to ASTM D8159-18 (*97*) followed by a recovery process using the Abson method in accordance with ASTM D1856-09 (*98*). Trichloroethylene (TCE) has been used as the solvent agent to extract the binder from the loose mixtures.

It is essential to test the extracted asphalt binders and make sure that binder rheology could meet the specified criteria to minimize pavement distresses due to change in binder rheology because of aging. In this study, the following binder tests have been conducted using the Kinexus Ultra+ Dynamic Shear Rheometer (DSR) shown in Figure 5. The objective was to characterize the performance of the virgin and the extracted and recovered binders at high temperature (permanent deformation), intermediate temperature (fatigue) cracking, and low temperature (thermal) cracking.

Figure 5. Kinexus Ultra+ Dynamic Shear Rheometer (DSR) used in this study.

4.3.1. Linear domain rheological evaluation using DSR

The Superpave parameters (G*.sinδ, and G*/sinδ), and PG grades were determined using AASHTO M320 (*99*) standard specifications to evaluate the impacts of the WMA technologies and aged binder on the rheological properties of the asphalt binder. The rheological properties of the extracted and recovered binders were measured in the linear domain using the DSR according to AASHTO T315 (*100*), after standard short-term aging using Rolling Thin Film Oven (RTFO) as per AASHTO T240 (*101*), and long-term aging using Pressure Aging Vessel (PAV) as per AASHTO R28 (*102*).

The G*/sinδ is a rutting parameter, where G* is the complex modulus, and δ is the phase angle. According to the Superpave specification, the testing temperature for PG 76-22 is 76°C for the RTFO aged binders. The G*/sinδ must be at least 1.00 kPa for the virgin asphalt binder and a minimum of 2.20 kPa after the short-term aging. The G*.sinδ is also used in the Superpave asphalt specification to determine the fatigue cracking resistance of the asphalt pavements. The extracted and recovered binders have been aged under both short-term and long-term aging conditions (RTFO and PAV) to simulate the behavior of the asphalt pavements during their service life. A value of $G^*.\sin\delta$ greater than 5,000 kPa indicates that the asphalt binder is prone to fatigue cracking.

4.3.2. Multiple Stress Creep and Recovery (MSCR) test

MSCR test is conducted according to AASHTO T350 (*103*) standard method, and it was used to evaluate binder upper PG-temperature considering both climate and traffic levels according to AASHTO M332 (*104*) standard specifications. This test was introduced to characterize the binder rutting resistance at high temperatures. Findings from previous studies (*105*) show that the MSCR test parameters correlate well with mixture rutting performance as measured by accelerated pavement testing.

In this study, the MSCR test was run on the extracted and recovered binders after short-term aging (RTFO) to simulate the rutting that occurs at the beginning of the pavement service life. DSR 25-mm parallel plate geometry with a 1-mm gap was used to test the samples at two different stress levels; 0.1 and 3.2 kPa. The test protocol applies a creep load of 1-second duration followed by 9-second recovery at zero loads. The non-recoverable creep compliance, J_{nr} is considered as an alternative for current $G^*/\sin\delta$, and ε_r is the percent recovery for each cycle. Equations 1 and 2 were used to calculate percent recovery and non-recoverable creep compliance for each cycle at different stress levels.

$$\varepsilon_r = \left[\frac{\text{recoverable strain}}{\text{peak strain}}\right] \times 100 \qquad [1]$$

$$J_{nr} = \frac{\text{non−recovare} \quad \text{strain}}{\text{shear stress}} \qquad [2]$$

where:
ε_r = Percent recovery for each cycle; and
J_{nr} = The non-recoverable creep compliance for each cycle.

J_{nr} is a test specification parameter indicator of resistance of a binder to permanent deformation under repeated load. It is the ratio of the residual strain left in the specimen under the repeated load to the amount of applied shear stress. The lower value of the J_{nr} shows the better resistance of the asphalt binder to the permanent deformation.

4.3.3. Linear Amplitude Sweep (LAS) Test

The test is conducted in accordance with AASHTO TP101-14 (*106*) and the purpose of the test is to evaluate an asphalt binder's ability to resist fatigue damage under cyclic loading by increasing the strain amplitudes to accelerate damage. The rate of damage accumulation is used to indicate fatigue performance. The virgin asphalt binders were both short-term aged (RTFO) and long-term aged (PAV) in accordance with AASHTO T240 (*107*) and AASHTO R28 (*108*), respectively. The extracted and recovered asphalt binders from the asphalt mixtures were considered short-term aged since the asphalt mixtures were short-term aged during mixing. The extracted and recovered binders were long-term aged in accordance with AASHTO R28 (*108*). After aging, the asphalt binders were LAS tested and the greater the number of cycles to failure indicates a better asphalt binder's resistance to fatigue damage.

4.3.4. Four-mm Plates on a DSR as an alternative to the Bending Beam Rheometer (BBR) test

4mm-diameter parallel plate DSR is used in this test to measure binder rheological properties at sub-zero temperatures instead of Bending Beam Rheometer (BBR) to save time and conserve samples. It was used to determine an essential rheological index: Delta Tc (ΔTc), which is the difference between the critical temperature based on stiffness limit Tc(S) and the critical temperature based on relaxation rate Tc(m). The ΔTc has been shown to correlate with cracking in the field. Values below -5°C difference are assumed to be prone to significant low-temperature cracking and are likely to get accepted as possible limits.

4.4. Asphalt Mixture Performance Tests

Laboratory mechanistic tests and material characterization tests were conducted to evaluate the performance of the conventional HMA and WMA mixtures and the mixtures containing a high percentage of RAP content. All the twelve mixtures characterizations have been evaluated and analyzed to determine the effects of the WMA technologies and high RAP content in the terms of intermediate-temperature (fatigue cracking) and high-temperature (permanent deformation and moisture damage). Table 11 presents each laboratory test factorial conducted in this study.

Table 11. Asphalt mixtures performance tests were conducted in this study.

Tests	Standards	Purpose	Specimen details
SCB-Louisiana	ASTM D8044	Fatigue Cracking Resistance	Φ 150 mm x 57 mm
Loaded Wheel Tracker (LWT)	AASHTO T 324	Rutting Susceptibility and Moisture Resistance	Φ 150 mm x 60 mm

4.4.1. Loaded Wheel Tracking (LWT)

Permanent deformation (also known as rutting) is one of the major distresses in asphalt pavements due to its inability to resist the traffic loading. In this study, the ability of the twelve asphalt mixtures to resist permanent deformation and their moisture resistance has been evaluated in accordance with AASHTO T324-17 (*109*). In this test, the prepared mixtures will be short-term oven-aged as per AASHTO R30 (*95*) before compaction using the SGC to 60 ± 1 mm and 7 ± 1% air voids for LWT testing. For each mixture, four SGC specimens were prepared and tested (a pair for each LWT test). Samples were conditioned in a 122ºF (50ºC) water bath for 30 minutes before running the test for 20,000 passes (52 passes/min), per AASHTO T324 (*109*) standard procedure. The 50ºC temperature was selected as per Table 502-6 "Asphalt Concrete General Criteria" in LaDOTD specification (*10*). The Hamburg Double Wheel Tracker was used in this study (Figure 6). Specimens are subjected to a steel wheel weighing 703 N (158 pounds), which repeatedly roll across its surface. The test completion time is predicated upon test specimens being subjected to a maximum of 20,000 passes or attainment of 6 mm deformation, whichever is reached first following Table 502-6 of LaDOTD specification (*10*).

The rut depth data is recorded during the test by Linear Variable Differential Transformers (LVDTs) at the side of the steel wheel. Figure 7 represents a typical LWT test output. The rut depth is recorded to the nearest 0.01 mm. The average of the middle 7 rut measurements (points 3 to 9) in the center of the two samples is calculated and used as the rut depth at each recorded pass. The average rut depth versus passes curve is then plotted and fitted to a 6-degree polynomial model following the modified Iowa DOT approach to determine the number of passes at maximum impression (rut depth), maximum impression, creep slope (CS), stripping slop (SS), and stripping inflection point (SIP) for each mixture.

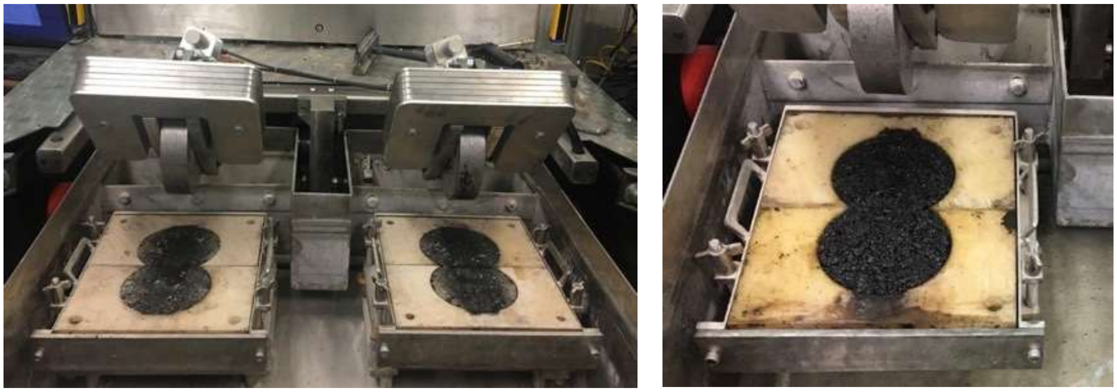

Figure 6. Hamburg Double Wheel Tracking Device.

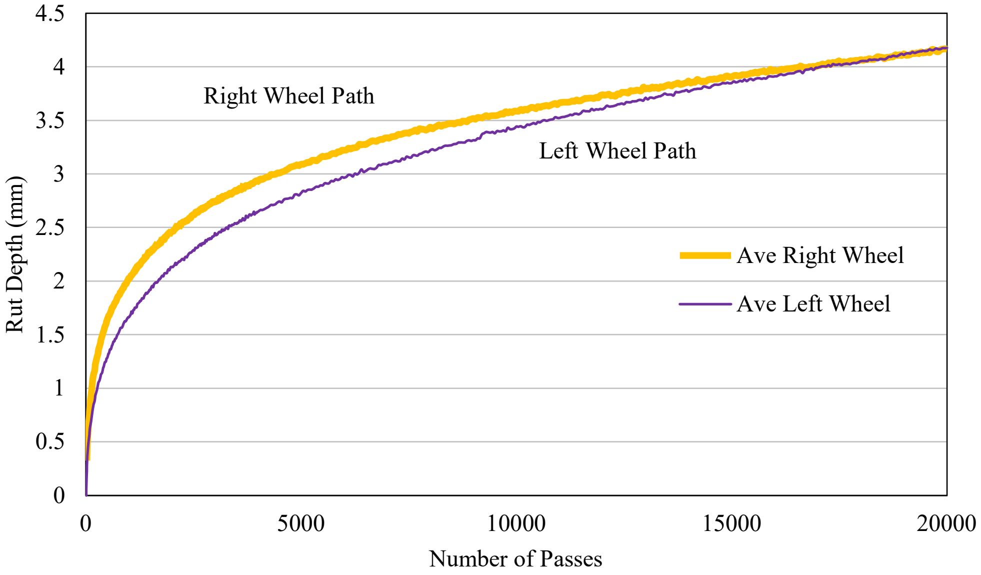

Figure 7. Typical LWT test output (rut depth vs. the number of passes).

4.4.2. Semi-Circular Bending (SCB) test

SCB test is one of the most important tests to evaluate the cracking resistance of the lab-produced asphalt pavement mixtures at intermediate temperatures. In this research work, the Louisiana SCB test was conducted according to the ASTM D8044 (*110*) and the results are evaluated.

Louisiana SCB test: The test has been conducted in accordance with ASTM D8044. The STOA mixtures will be SGC compacted to a height of 57 mm and 150 mm diameter, and 7.0 ± 0.5% air voids before LTOA. After that, the STOA semi-circular specimens will be LTOA for 120 h ± 0.5 hr at a temperature of 85 ± 3°C before testing. The LTOA cylindrical samples will then be cut along the diameter resulting in two semi-circular specimens. For this test, three sets of samples with three different notch depths (25.4, 31.8, and 38.1 mm) are required. Each set includes four semi-circular specimens, resulting in 12 semi-circular notched specimens. Using a three-point bending set-up (Figure 8), semi-circular samples will be loaded monotonically with a loading rate of 0.5 mm/min. The test is performed at 25 ± 0.3°C. The critical strain energy release rate, also called the critical value of J-integral (J_c), have been used to describe the mixture's resistance to fracture:

$$J_c = -\left(\frac{1}{b}\right)\frac{dU}{da} \qquad [3]$$

where:
J_c = critical strain energy release rate (kJ/m^2);
b = sample thickness (mm);
a = notch depth (mm);
U = strain energy to failure (N.mm); and
dU/da = change of strain energy with notch depth.

The load and deformation should be recorded continuously. The area under the loading portion of the load-deflection curves, up to the maximum load, will be measured for each notch depth, represents the strain energy to failure, U. The average values of U then will be plotted versus the different notch depths to compute a regression line slope, which gives the value of (dU/da). The J_c is computed by dividing dU/da value by the specimen thickness. According to Louisiana specifications (*10*), a J_c value of 0.6 kJ/m^2 is recommended for adequate cracking performance.

Figure 8. Set-up of Louisiana Semi-Circular Bending (SCB) test.

5. ANALYSIS AND FINDINGS

5.1. Asphalt Binder Test Results

It is important to recognize the rheological properties of the asphalt binders to assure that the binder rheology will meet the specified requirements to decrease binder related pavement distresses. Asphalt binder tests have been conducted to characterize low-temperature, intermediate-temperature, and high-temperature performance of the extracted and recovered asphalt binders. The binders were extracted and recovered from asphalt loose mixtures after short-term conditioning according to AASHTO R30 (*95*). The auto extraction method has been conducted according to ASTM D8159-18 (*97*) followed by a recovery process using the Abson method in accordance with ASTM D1856-09 (*98*) using trichloroethylene (TCE) as the solvent agent.

5.1.1. MSCR test results

For the MSCR test, three replicates from each extracted and recovered binder were tested. Based on the results in Table 12, all the mixtures containing RAP, at both stress levels have a lower value of the J_{nr} compare to mixtures without RAP that confirms the hardening effect of the binder that comes from RAP. Based on Figure 9 and Figure 10 all the WMA mixtures containing no RAP have a lower value of the J_{nr} compare to the HMA control mixture. This is an indication of the better performance of the WMA mixtures against the permanent deformation, specifically, it is more highlighted in the WS0R mixture with a 36% reduction in J_{nr} compare to the H0R mixture. However, it could not have been observed for all WMA mixtures containing 25% RAP. It might show that the addition of the rejuvenator can encounter the hardening impacts that come from using aged binders in mixtures with high RAP content. However, based on the test results even in WMA mixtures containing RAP, the WS25R mixture at the two stress levels has the lower value of the J_{nr} and is more resistant to permanent deformation compared to the H25R mixture.

The ε_r is the measure of the amount of recoverable strain relative to the amount of peak stress. It can be concluded that the higher the percent recovery, ε_r, the more resistant to rutting the binder will be. The results for ε_r in Table 12 confirm the better performance of the WMA mixtures. Decreasing the mixing and compacting temperature and use of the WMA technologies, both helped to make a softened binder with a higher value of the recoverable strain.

It is shown that WS0R and WS25R mixtures have the lower and higher value of the J_{nr} and ε_r, which indicate the better performance of the Sasobit between all the mixtures and the three different WMA technologies at both stress levels.

Table 12. MSCR test results of the extracted and recovered binder from the twelve mixtures.

Binder	$J_{nr\ 0.1}$ (kPa^{-1})	$J_{nr\ 3.2}$ (kPa^{-1})	%J_{nrdiff}	% Recoverable strain 0.1 kPa	% Recoverable strain 3.2 kPa
H0R	0.49	0.82	65.73	56.67	35.00
WA0R	0.46	0.79	71.77	60.43	38.97
WE0R	0.35	0.46	61.57	55.60	37.23
WS0R	0.24	0.53	118.97	68.90	44.83
H25R	0.37	0.57	55.97	53.57	34.83
WA25R	0.36	0.62	74.4	55.60	34.35
WE25R	0.32	0.67	56.7	55.00	37.80
WS25R	0.23	0.43	83.6	62.33	41.47

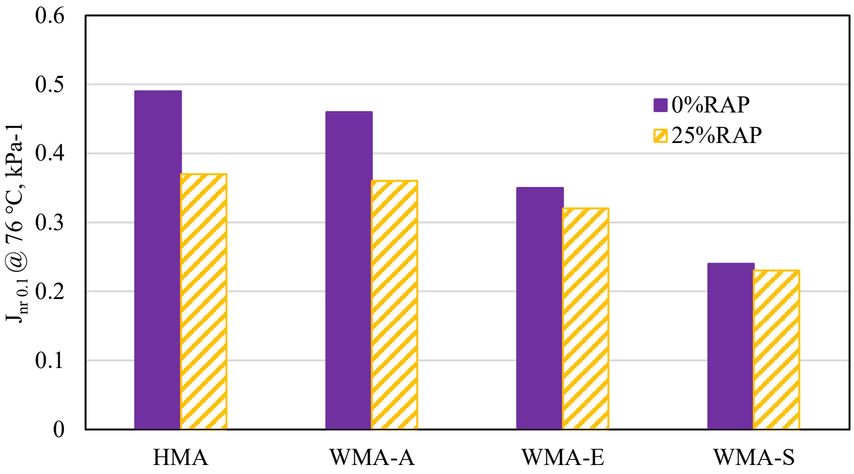

Figure 9. MSCR $J_{nr0.1}$ kPa @ 76°C vs. mixture type.

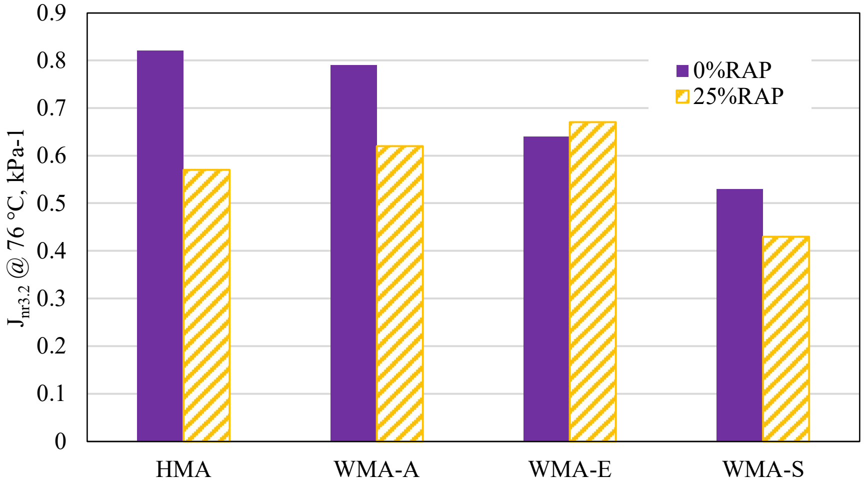

Figure 10. MSCR $J_{nr3.2}$ kPa @ 76°C vs. mixture type.

Analysis of Variance or ANOVA test was used to check the statistical difference of MSCR test results between different extracted and recovered asphalt binders. JMP Pro15 software was used to perform ANOVA on the rheological data. Eight groups of datasets corresponding to the eight types of extracted and recovered binders with three replicates totaling a dataset of 24 data points were statistically tested. A significance level of 0.05 (95% confidence interval) was selected, leading to an α-value of 0.025 in both directions for testing the statistical significance. Table 13 and Table 14 present the ANOVA summary for $J_{nr0.1}$ and $J_{nr3.2}$ of the extracted and recovered binders from eight asphalt mixtures. The p-values for both stress levels are less than 0.05 therefore there is a significant statistical difference between the results of different mixtures.

ANOVA results for analyzing ε_r for extracted and recovered binders of each mixture are presented in Table 15 and Table 16. The statistical analysis results indicate the presence of a significant difference between test results for eight mixtures.

Table 13. ANOVA results for analyzing $J_{nr0.1}$ for extracted and recovered binders of each mixture.

Groups	Count	Average	Variance	
H0R	3	0.49	0.02	
H25R	3	0.37	0.05	
WA0R	3	0.46	0.03	
WA25R	3	0.35	0.03	
WE0R	3	0.28	0.01	
WE25R	3	0.64	0.03	
WS0R	3	0.24	0.02	
WS25R	3	0.23	0.01	
Source of Variation	**SS**	**df**	**MS**	**P-value**
Between Groups	0.411	7	0.059	<0.0001
Within Groups	0.010	16	0.001	
Total	0.421	23		

Table 14. ANOVA results for analyzing $J_{nr3.2}$ for extracted and recovered binders of each mixture.

Groups	Count	Average	Variance	
H0R	3	0.82	0.03	
H25R	3	0.57	0.02	
WA0R	3	0.79	0.01	
WA25R	3	0.61	0.08	
WE0R	3	0.46	0.01	
WE25R	3	1.00	0.04	
WS0R	3	0.53	0.01	
WS25R	3	0.43	0	
Source of Variation	**SS**	**df**	**MS**	**P-value**
Between Groups	0.840	7	0.120	<0.0001
Within Groups	0.012	16	0.001	
Total	0.852	23		

Table 15. ANOVA results for analyzing $\varepsilon_{r0.1}$ for extracted and recovered binders of each mixture.

Groups	Count	Average	Variance	
H0R	3	56.67	0.06	
H25R	3	53.57	2.78	
WA0R	3	60.43	1.5	
WA25R	3	55.57	2.69	
WE0R	3	62.63	5.49	
WE25R	3	45.60	0.44	
WS0R	3	68.90	1.01	
WS25R	3	62.33	1.17	
Source of Variation	**SS**	**df**	**MS**	**P-value**
Between Groups	1037.19	7	148.17	<0.0001
Within Groups	92.60	16	5.79	
Total	1129.79	23		

Table 16. ANOVA results for analyzing $\varepsilon_{r3.2}$ for extracted and recovered binders of each mixture.

Groups	Count	Average	Variance
H0R	3	35.00	0.26
H25R	3	34.83	0.47
WA0R	3	38.97	1.5
WA25R	3	33.57	2.69
WE0R	3	53.23	5.49
WE25R	3	24.80	0.44

WS0R	3	44.83	1.01	
WS25R	3	41.47	1.17	
Source of Variation	**SS**	**df**	**MS**	**P-value**
Between Groups	1511.14	7	215.88	<0.0001
Within Groups	173.40	16	10.84	
Total	1684.54	23		

5.1.2. Linear domain rheological evaluation using DSR

G*/sin δ parameter: The DSR is used to evaluate the rutting and fatigue potential of the extracted and recovered asphalt binders. The extracted and recovered binders have been short-term aged using RTFO to evaluate the high-temperature performance of the asphalt binders. Figure 11 shows the G*/sinδ values for extracted and recovered binders from control and WMA mixtures. It is obvious from this figure that the WS25R binder with 3% of Sasobit and 25% RAP has the most capability to resist the rutting among all other binders. However, it is quite clear from the figure that the addition of RAP to the asphalt mixtures stiffens the binders consequently, increasing the rutting resistance. Figure 11. Figure 12 shows the correlation between the rutting factor, G*/sinδ, and $J_{nr3.2}$. This figure indicates that there is a good linear correlation between these parameters for the evaluated mixtures. It is indicated that as the $J_{nr3.2}$ decreases the mixture resistance to rutting increases. The results approved the findings from other studies in the literature (39,26).

To check the statistical difference of G*/sinδ results between eight mixtures, a one-way analysis of variance (ANOVA) was conducted. Table 17 shows the summary and results of ANOVA on G*/sinδ results for 24 samples. Based on ANOVA results, the p-value is lower than 0.05, therefore there is a significant statistical difference between the results of different mixtures.

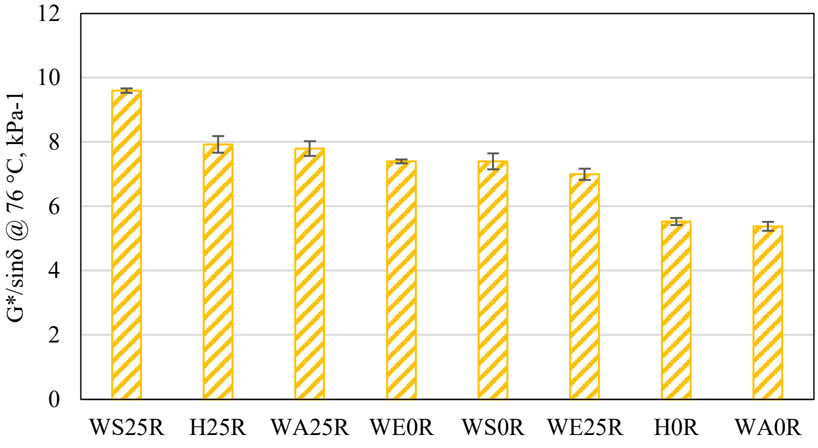

Figure 11. Rutting parameter G*/sinδ of extracted and recovered binders.

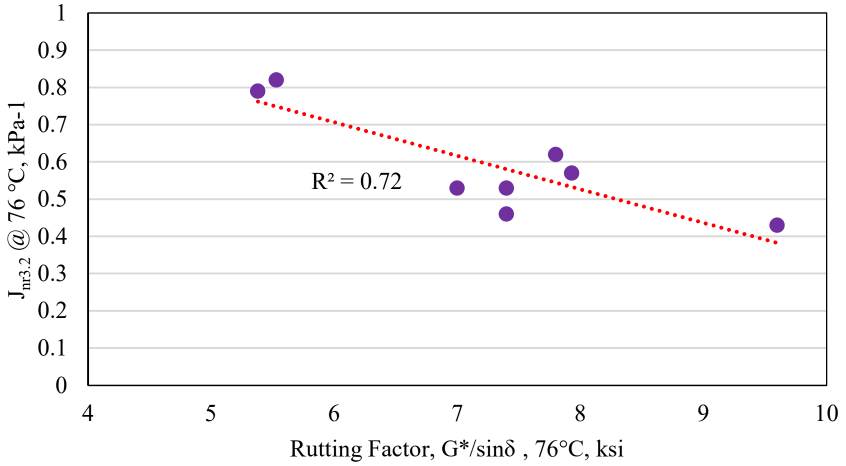

Figure 12. Rutting parameter G*/sinδ vs. $J_{nr3.2}$ @ 76°C.

Table 17. ANOVA results for analyzing G*/sinδ for extracted and recovered binders of each mixture.

Groups	**Count**	**Average**	**Variance**	
H0R	3	5.53	0.11	
H25R	3	7.93	0.26	
WA0R	3	5.38	0.14	
WA25R	3	7.80	0.23	
WE0R	3	7.40	0.06	
WE25R	3	5.67	0.17	
WS0R	3	7.39	0.25	
WS25R	3	9.59	0.07	
Source of Variation	**SS**	**df**	**MS**	**P-value**
Between Groups	45.01	7	6.43	<0.0001
Within Groups	0.51	16	0.03	
Total	45.51	23		

G*.sin δ parameter: The Superpave fatigue parameter for asphalt binders is G*.sin δ. This parameter indicates the asphalt binder's resistance to fatigue under traffic loading at intermediate temperatures. The Superpave specifies a higher limit for the fatigue parameter of 5,000 kPa for asphalt binders PAV-aged after they have been aged also in the RTFO. A lower value for G* or a lower value for phase angle (δ) is desirable to control fatigue cracking of asphalt binders. As the G* value gets higher, the asphalt binder becomes stiffer and more susceptible to fatigue cracking. On the other hand, as the phase angle (δ) gets lower, the asphalt binder becomes more elastic and thus more resistant to fatigue cracking. Table 18 shows the G*.sinδ parameter obtained from the DSR test at intermediate temperatures. As shown in Table 18, the increase in RAP content was associated with an increase in the G*.sinδ values and susceptibility to fatigue cracking. The results show that there is an inconsistency between the current Superpave parameter, G*.sinδ, and LAS test results. These results indicate that further evaluation of the LAS test is needed with WMA-RAP asphalt binders.

Table 18. Detailed results of G*.sinδ at 31°C.

Binder	Temp (°C)	G* (kPa)	δ(degree)	Sin δ	G*.sin δ
H0R	31	1387	48.0	0.770	1068
H25R	31	1509	44.0	0.690	2041
WA0R	31	676	49.0	0.754	510
WA25R	31	1676	45.3	0.710	1190
WE0R	31	1524	45.3	0.710	1082
WE25R	31	1682	45.0	0.710	1194
WS0R	31	2929	46.3	0.719	2106
WS25R	31	3182	43.5	0.688	2389

5.1.3. LAS test results

The LAS test is an accelerated test to characterize the fatigue performance of asphalt binder or mastic after long-term aging (*112*). The test was conducted at 31°C involving two stages in total. First, the sample was subjected to a frequency sweep (0.2–30 Hz) under strain-controlled mode (0.1%) using an 8 mm parallel plate with a 2 mm gap to determine the undamaged material property. In the second stage, the sample was tested using amplitude sweep with the strain level increasing linearly from 0.1% to 30% in 300 seconds at a frequency level of 10 Hz to get the fatigue damage property. The viscoelastic continuum damage (VECD) theory was applied to calculate the fatigue life of the sample.

A and B parameters: Figure 13 and Figure 14 show the LAS test A and B parameters, respectively. As Figure 13 shows, the extracted and recovered binders from all mixtures with RAP have higher values of A parameter. Moreover, extracted and recovered binders from WMA mixtures containing RAP have higher values of the A parameters compared to the HMA mixtures which indicate better performance of the incorporation of RAP and WMA additives to resist fatigue damage, specifically, it is more highlighted in the WS25R. As Figure 14 shows, by incorporating WMA technologies and RAP materials, the absolute value of the B parameter increases gradually. HMA mixtures without RAP have about the same B parameter value as the mixtures with RAP, whereas, by incorporating RAP and WMA technologies, the absolute value of the B parameter also increases.

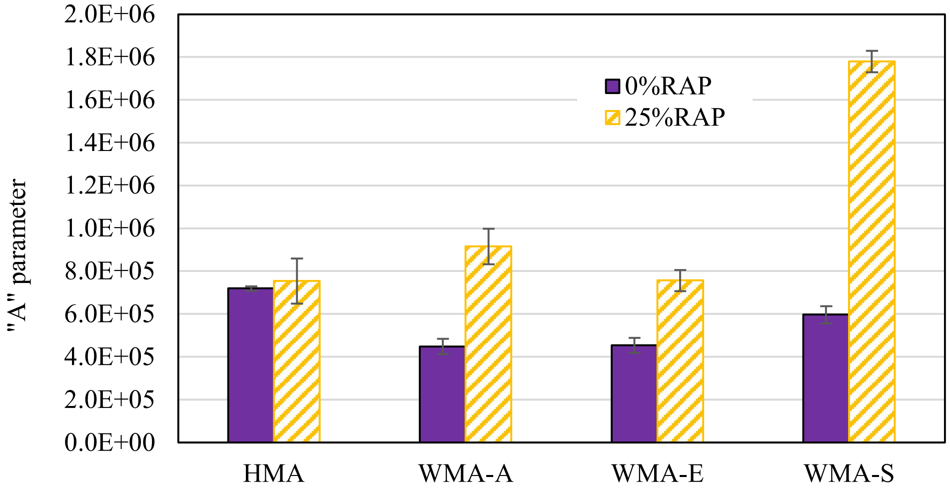

Figure 13. Results of the A parameter from the LAS test.

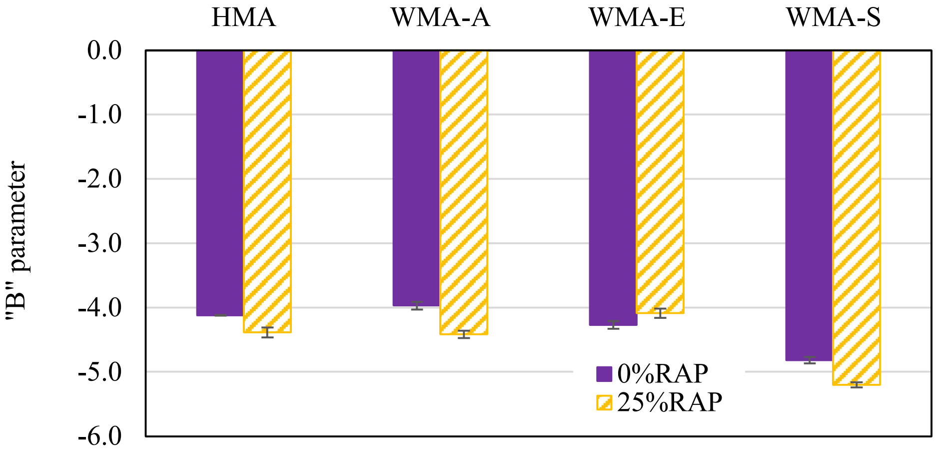

Figure 14. Results of the B parameter from the LAS test.

Fatigue life (N_f): The fatigue life (N_f) of extracted and recovered asphalt binders at the strain levels of 2.5% and 5% are calculated using the VECD approach (Figure 15 and Figure 16) and the parameters are listed in Table 19. The relationship between integrity parameter (C) and damage intensity (D) was calculated by the VECD theory for eight types of extracted and recovered asphalt binders. The integrity parameter is equal to 1 when no damage occurs (D = 0). Then the value of C declines with the increase of D until C is equal to 0, representing the complete damage of asphalt binder. Curve fitting coefficients C1 and C2 are shown in Table 19. Apparently, lower values of C1 and C2 are desirable for better fatigue cracking resistance of asphalt binder. However, based on the results illustrated in Table 19, due to the unsteady rate of changes in parameters C1 and C2, the effects of these two parameters cannot be considered for determining the fatigue performance.

Figure 15 shows that extracted binders from HMA mixtures containing 25% RAP have lower fatigue life due to the higher strain sensitivity. However, according to Figure 15, the incorporation of RAP binder and WMA technologies improved the fatigue performance of the extracted and recovered binders. Similar conclusions can also be found in literature (*65*,*111*,*30*,*112*).

WE25R exhibits higher fatigue life (N_f) compared to the other WMA and HMA extracted binders. Moreover, WS25R and WA25R have relatively similar N_f to the H0R. Hence WMA additives contribute to fatigue potential and the effect of Evotherm is more obvious. Meanwhile, the reduction of N_f for H25R indicates that aged binders coming from RAP materials would degrade the fatigue performance under strain-controlled load mode.

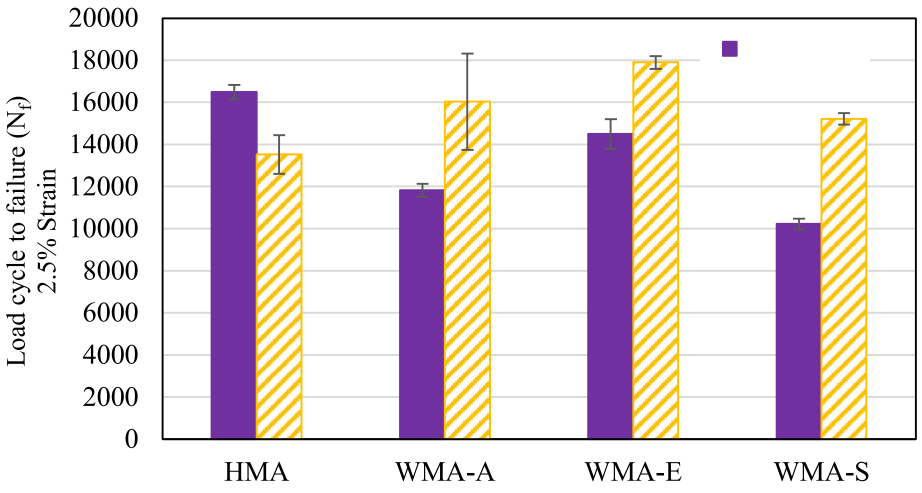

Figure 15. The fatigue life of extracted and recovered binders at 2.5% strain level.

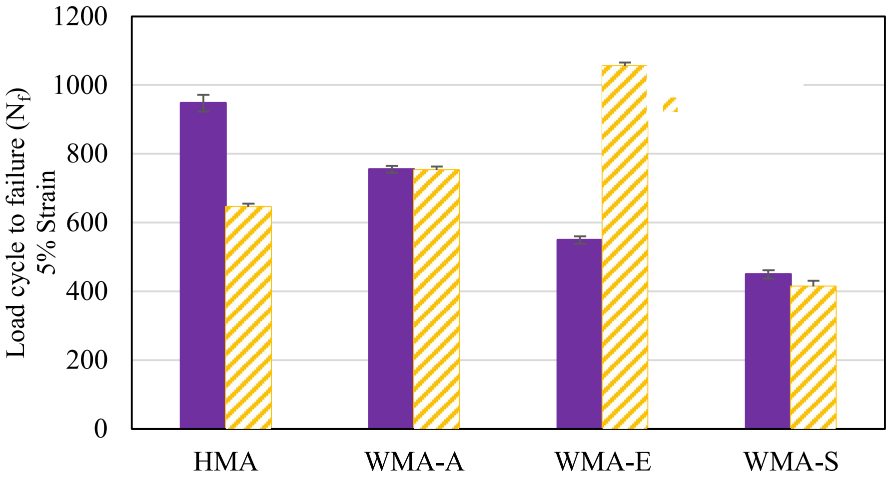

Figure 16. The fatigue life of extracted and recovered binders at a 5% strain level.

Table 19. Parameters from the LAS test using VECD analysis.

Asphalt binder	C0	C1	C2	α	A	B
H0R	1	0.106	0.362	2.0605	719,450	-4.121
H25R	1	0.092	0.416	2.193	754,350	-4.386
WA0R	1	0.085	0.426	1.984	448,800	-3.968
WA25R	1	0.077	0.460	2.209	915,500	-4.417
WE0R	1	0.094	0.385	2.083	454,500	-4.269
WE25R	1	0.091	0.397	2.043	757,000	-4.086
WS0R	1	0.095	0.440	2.409	597,000	-4.818
WS25R	1	0.105	0.399	2.6	1,780,000	-5.200

5.1.4. Four-mm Plate DSR test results

In this study, the low-temperature rheological properties of extracted and recovered binders have been evaluated using a dynamic shear rheometer with 4 mm parallel plates (4-mm DSR). There are certain statistical correlations between complex modulus measured by 4-mm DSR and creep stiffness by BBR and between phase angle and m-value (*114*). The extracted and recovered binders of mixtures in this study have been PAV-aged after they have been aged also in the RTFO to determine the low-temperature performance of the extracted and recovered asphalt binders. Table 20 shows the testing plan for extracted and recovered binders using DSR. Master curves at a reference temperature of -12°C are constructed for all the extracted and recovered binders, as shown in Figure 17. There is no consistent conclusion about the effect of WMA additives on the low-temperature performance of the WMA-RAP mixtures in the literature. Based on the master curves shown in Figure 17, for mixtures containing 0% and 25% RAP, there is no significant difference between the WMA mixtures and the HMA control mix, and generally, all the mixtures are expected to have similar low-temperature performance.

Oshone et al. (*115*) related |G*| and S, as well as δ and m-value using a simple equation that can be used to translate one parameter to the other. Equation 4 estimates S from DSR data only based on |G*|, and Equation 5 shows the relationship between m-value and phase angle from DSR data.

$$S(t) = 1.28\,|G^*(\omega)| + 19.2 \qquad [4]$$

$$\text{m-value} = 0.008\,\delta + 0.1 \qquad [5]$$

Table 21 shows the calculated S and m-value for eight extracted and recovered binders at -12°C using Equation 4 and 5. Moreover, an essential rheological index, delta Tc (ΔTc), which is the difference between the critical temperature based on stiffness limit Tc(S) and the critical temperature based on relaxation rate Tc(m) has been determined based on the 4-mm DSR results. ΔTc has shown to correlate with cracking in the field and values below -5°C difference is assumed to be prone to significant low-temperature cracking and are likely to get accepted as possible limits (*116*). Based on the results, all the extracted and recovered binders from WMA mixtures meet the stiffness and m-value criteria at -12 °C and have lower stiffness and higher m-values compared to the extracted and recovered binders from HMA control mixtures. Moreover, the higher value of ΔTc (less negative) was obtained for extracted and recovered binders from WMA mixtures containing no RAP. WE25R and WS25R exhibit the lowest ΔTc (least negative) compared to the other WMA and HMA extracted binders containing RAP which indicate the better performance of these mixtures against low-temperature cracking.

Table 20. Testing plan using DSR.

Extracted and Recovered Binders	Number of replicates	Test temperature (°C)	Type of test	Aging Level
H0R	3	0, -6, -12, -18	Strain sweep, frequency sweep	PAV
WA0R, WE0R, WS0R	3	0, -6, -12, -18	Strain sweep, frequency sweep	PAV
WA25R, WE25R, WS25R	3	0, -6, -12, -18	Strain sweep, frequency sweep	PAV

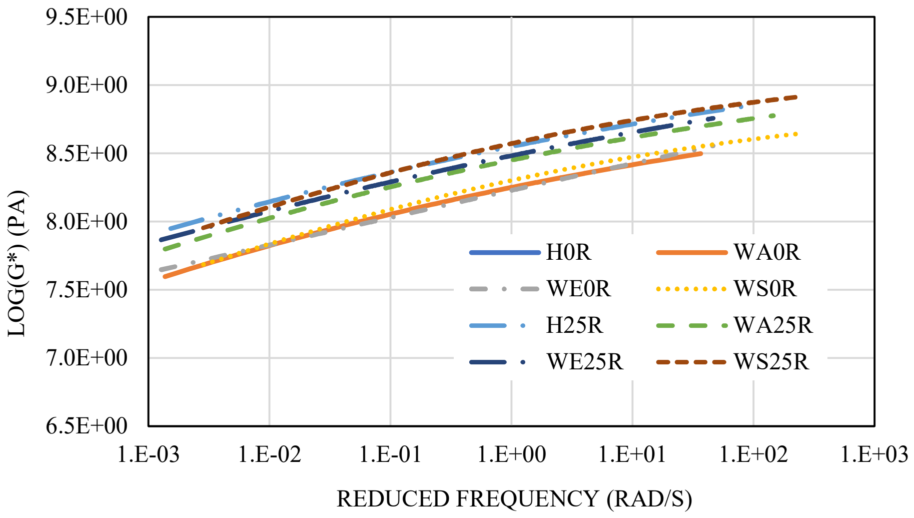

Figure 17. Extracted and recovered master curves at a reference temperature of -12 °C.

Table 21. Stiffness, m-value, and ΔTc results at −12 °C using DSR.

Extracted and Recovered Binders	Creep Stiffness (Mpa)	m-value	Delta Tc (degrees)
H0R	219	0.29	-6.10
WA0R	121	0.32	-4.49
WE0R	145	0.31	-1.21
WS0R	115	0.34	-1.50
H25R	325	0.23	-8.70
WA25R	210	0.30	-5.30
WE25R	185	0.31	-2.40
WS25R	213	0.33	-3.23

5.2. Asphalt Mixture Performance Test Results

5.2.1. LWT test results

Figure 18 illustrates the average permanent deformation depth for the twelve asphalt mixtures evaluated in this study. It is shown that the mixture WS25R is the most resistant mixture to permanent deformation, whereas the mixture H0R containing no RAP and no recycling agent is the least resistant to rutting. It is observed that the addition of RAP to the HMA decreases the terminal rut depth as compared to the HMA mixture with no RAP. However, the addition of RAP to the WMA mixtures does not show a notable impact on the permanent deformation of the WMA mixtures as compared to the HMA mixtures with no RAP. It is also noted that the Sasobit has the best performance among the other WMA technologies and mixtures containing Sasobit have the lower value of the rut depth. It should be noted the increasing rate of RAP content significantly decreases the terminal rut depth in both HMA and WMA mixtures. As shown in Figure 19, generally all the mixtures are expected to perform similarly against moisture damage. No tertiary regions were seen in the asphalt mixtures studied (no stripping inflection points); therefore, no susceptibility to moisture damage as measured by the LWT could be observed.

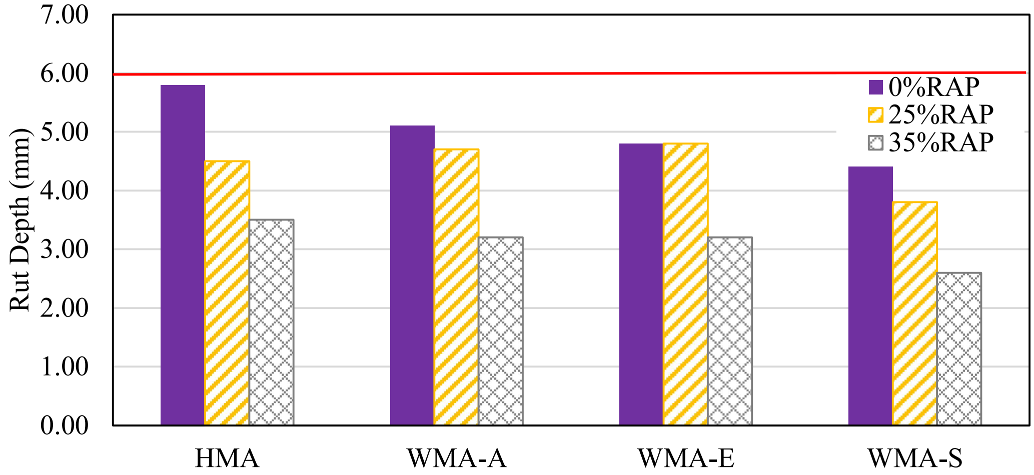

Figure 18. LWT average rut depth vs. mixture type.

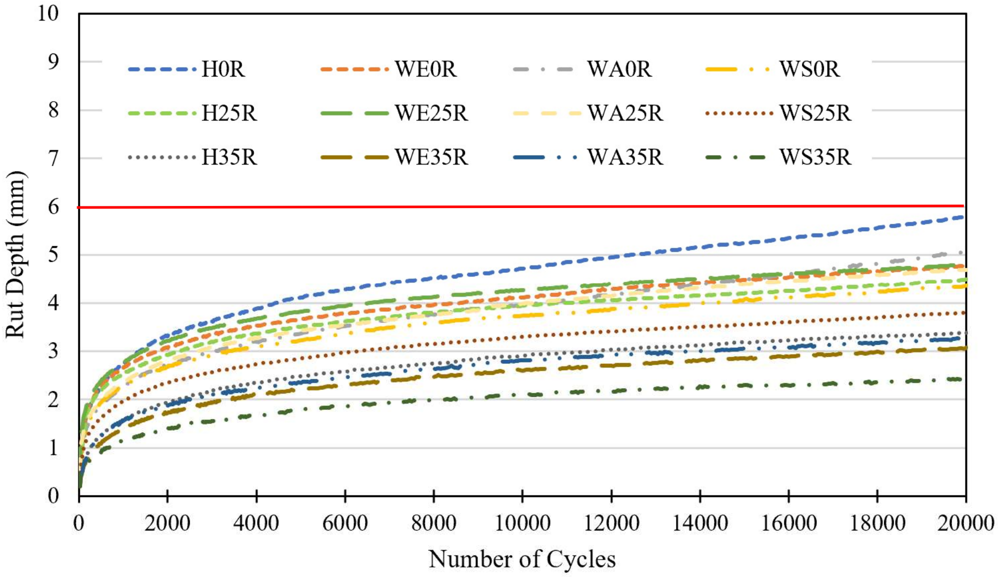

Figure 19. LWT average rut depth vs. the number of passes per mixture type.

These findings agree with the results shown in Table 12 for the MSCR test results. The mixture containing Sasobit and 25% RAP has a lower value of the J_{nr}. Higher stiffness, the lower value J_{nr}, and, therefore, it is expected to be the most resistant to permanent deformation. Based on the findings from MSCR and LWT test results for the mixtures without RAP, WMA mixtures have better performance than the HMA control mix. Although it is expected to have a softer mixture by decreasing the temperature and adding the WMA additives, the WMA mixtures with no RAP have better performance compare to the HMA control mix. For mixtures containing 25% RAP, there is no significant difference between the WMA mixtures and the HMA control mix. It should be noted that the close value of the J_{nr} and rut depth for the H25R and W25R mixtures can come from the use of a rejuvenator in the H25R mixture. It can be concluded that the incorporation of WMA technology, rejuvenator, and RAP showed promising results in the rutting resistance and moisture susceptibility of the asphalt mixtures.

Figure 20 illustrates the characterization laboratory test correlation between the non-recoverable creep compliance, J_{nr}, (measured at an applied constant stress of 3.2 kPa and a testing temperature of 76°C), and the LWT rut depth (permanent deformation) measured at 20,000 passes at a testing temperature of 50°C for the asphalt mixtures evaluated in this study. A decrease in the non-recoverable creep compliance indicates an improved resistance to rutting damage. This figure shows that as the J_{nr} decreases the rut depth also decreases. It is indicated in Figure 20 that there is a strong linear correlation between the non-recoverable creep compliance, J_{nr}, and LWT test results. This confirmed the findings from other studies in the literature (*26*,*39*,*40*).

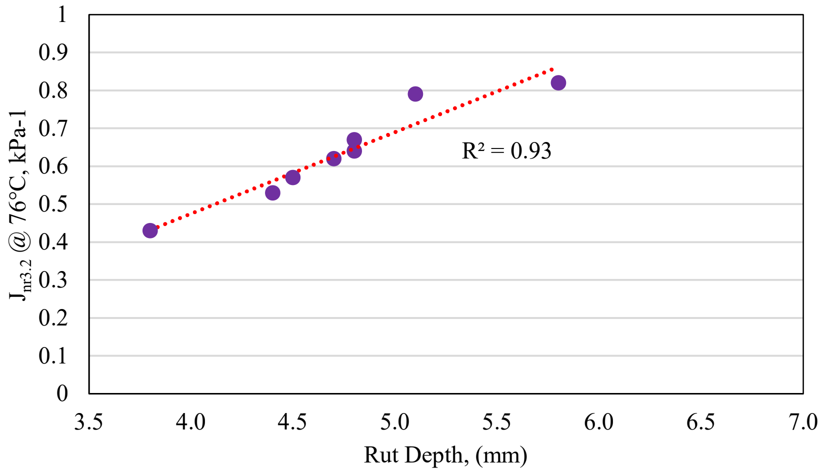

Figure 20. MSCR $J_{nr3.2}$ @ 76°C vs. LWT rut depth.

Figure 21 indicates the characterization laboratory test correlation between the Rutting Factor, G*/sinδ at 76°C, and the LWT rut depth (permanent deformation) measured at 20,000 passes at a testing temperature of 50°C for the asphalt mixtures evaluated in this study. This figure shows that there is a fair linear correlation between the Rutting Factor and rut depth test results. For mixtures to be rut resistant and exhibit higher stiffness, this necessitates a higher G* value and a lower phase angle. The higher the rutting factor value indicates a mixture of greater resistance to permanent deformation. It is illustrated in Figure 21 that as the Rutting Factor increases the rut depth decreases. This is a desirable trend since higher rutting factor values indicate an asphalt mixtures stronger propensity for rut resistance.

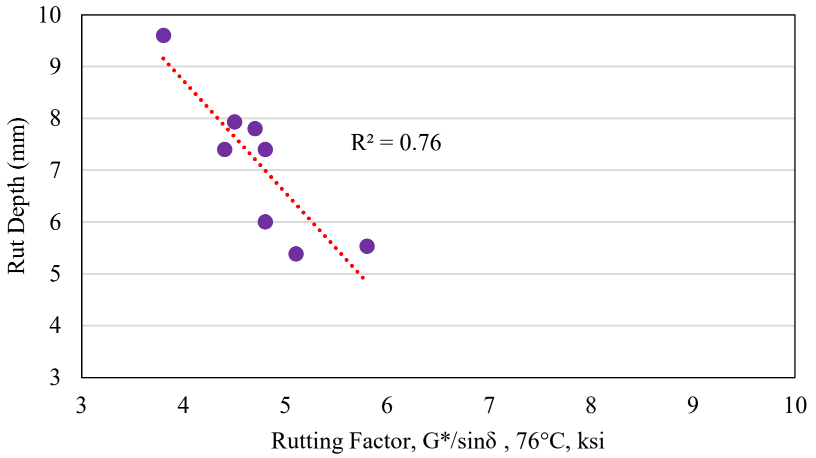

Figure 21. LWT rut depth vs. rutting factor, G*/sinδ.

5.2.2. SCB test results

Figure 22 shows a comparison of J_c for HMA and WMA mixtures containing 0%, 25%, and 35% RAP. According to previous studies, asphalt mixtures should achieve a minimum J_c value of 0.5 kJ/m^2 to minimize intermediate-temperature cracking susceptibility (*119*). SCB test results showed that the J_c value for the HMA mixture containing RAP is almost similar or lower than the HMA mixture with no RAP. This confirmed the findings from other studies in the literature (*120*). However, J_c values for WMA mixtures containing RAP are higher than that of WMA mixtures containing no RAP and the rate of increase keeps increasing by increasing the rate of RAP content in WMA mixtures. The results approved the findings from other studies in the literature (*53*). This observation indicates that WMA additives were effective to accommodate RAP incorporation, specifically with the usage of Sasobit additive. Based on the Jc value for WS0R, the addition of Sasobit yielded the lowest J_c values and as a result a stiffer mixture among all the mixtures. It is consistent with the results from the LWT and MSCR tests.

Based on the previous studies, there is not a consistent conclusion regarding the effect of RAP on intermediate temperature properties of asphalt mixtures. Findings from a study by Lu and Saleh (*83*) showed that, although, incorporation of WMA showed degradation in fracture properties, further addition of RAP up to 40% showed consistent improvement in fracture properties. Additionally, based on LAS test results, considering the response under the cyclic loading condition, improvement in fatigue life with the incorporation of RAP and WMA technologies was been observed.

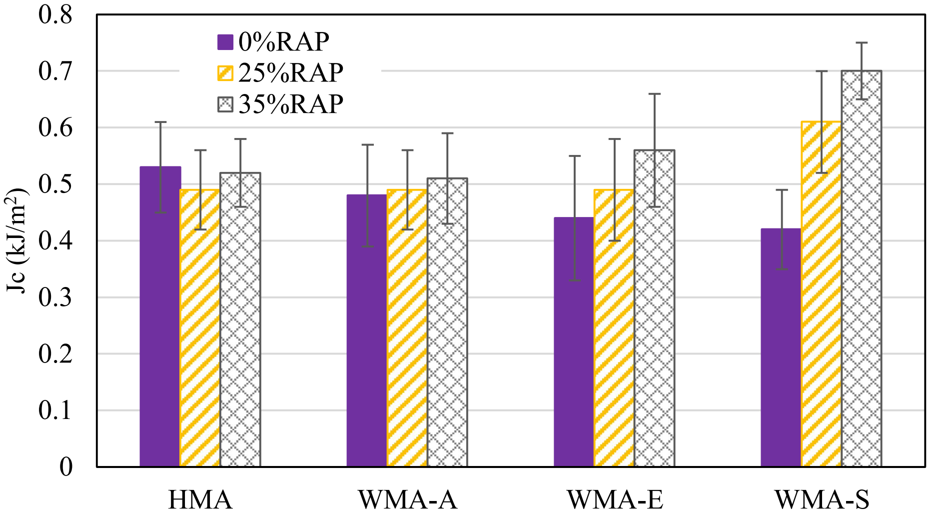

Figure 22. Critical strain energy release rate (J_c) for HMA and WMA mixtures.

6. CONCLUSION

The produced asphalt mixtures in this study contain 0%, 25%, and 35% RAP to investigate the effects of using WMA technologies (organic, chemical, and foaming) on the performance of mixtures containing RAP. The objective of this study is to enhance the performance of asphalt mixtures containing RAP in Region 6 using different WMA technologies. The following conclusion and findings can be summarized:

- The addition of 35% RAP material significantly increased the rutting resistance of asphalt mixtures and binders while the incorporation of Sasobit as WMA additive, would lead to better high-temperature performance. Moreover, the correlation between the G*/sinδ parameter, MSCR, and LWT test results was strong at all the tested strain levels, and it was concluded that this is an effective binder test in predicting asphalt mixtures' rutting performance.
- Based on the SCB test results, WMA technologies used to produce asphalt mixtures at reduced mixing and compaction temperatures did not compromise the fracture resistance of the produced mixtures. Further, incorporating RAP contents up to 35% in the WMA mixtures yielded similar or better fracture performance. Additionally, based on the LAS test results, considering the response under cyclic loading condition, improvement in fatigue life with the incorporation of RAP and WMA technologies was observed.
- Results of the LAS test showed all the three WMA additive exhibited almost similar effects on the fatigue performance of asphalt binder. However, incorporation of RAP binder and WMA technologies improved the fatigue performance of the extracted and recovered binders, and the effect of chemical technology is a more obvious comparison to the other WMA additives and HMA mixtures.
- The discrepancy between the G*/sinδ parameter and the LAS test results was fairly high. However, further research is still needed.
- Based on the LAS test results, WMA technology showed the potential to be incorporated with RAP materials in producing asphalt mixtures and it could enhance the fatigue resistance of asphalt binder.
- Results of 4-mm DSR test show that all the extracted and recovered binders from WMA mixtures meet the stiffness and m-value criteria at -12°C and have lower stiffness and higher m-values compared to those from HMA mixtures. Moreover, the higher value of ΔTc (less negative) was obtained for binders from WMA mixtures containing no RAP. WE25R and WS25R exhibit the lowest ΔTc (least negative) compared to the other WMA and HMA binders containing RAP which indicate the better performance of these mixtures against low-temperature cracking.
- Above all, the results showed that based on the applied WMA technology, WMA mixtures have almost similar or better performance than HMA mixtures, whereas there is a significant reduction in air pollution and cost.

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APPENDIX A: RAP stockpiles and binder properties

Table 22 illustrates the gradation and properties of the RAP stockpiles that have been used in this work.

Table 22. RAP properties and % passing for fine and coarse RAP sources.

Sieve Size	Fine RAP (%)	Coarse RAP (%)
25.0mm - 1"	100.00	100.0
19.0mm - 3/4"	100.0	97.6
12.5mm - 1/2"	99.7	76.7
9.5mm - 3/8"	96.2	51.1
4.75mm - No. 4	70.5	31.4
2.36mm - No. 8	50.0	22.2
1.18mm - No. 16	38.3	17.6
0.600mm - No. 30	30.9	14.6
0.300mm - No. 50	20.4	10.2
0.150mm - No. 100	12.1	6.0
0.075mm - No. 200	8.7	3.7
% Crushed	99.5	99.7
Fineness Modulus F.M.	4.7	6.7
%AC	4.7	3.1
G_{sb}	2.548	2.542

APPENDIX B: Rejuvenator properties

A high-performance rejuvenator selected and used for the mixtures of this project enhances the low-temperature performance of aged binder to allow incorporation of high levels of recycled bituminous material while maintaining or lowering compaction temperature requirements. The product can be used in HMAs, as well as asphalt emulsions and emulsified rejuvenator applications. It is formulated for high compatibility with binder, especially aged and oxidized binders, and improving durability and cracking resistance as measured by industry-accepted experimental methods. Typical properties of the used rejuvenator are presented in Table 23.

Table 23. Typical properties of used rejuvenator.

Typical Properties	Value	Method
Appearance	Brown Homogenous Liquid	Visual
Color	14+	AOCS Td 1a-64
Density @ 20 °C, g/ml	0.92 - 0.95	ASTM D1475
Viscosity @ 40°C, cSt	45-60	AOCS Ja 10-87
Flash Point °C, COC	>290	AOCS Cc 9a-48
N-Heptane Insoluble, %	Nil	ASTM D3279
RTFO Viscosity Index	> 1.10	ASTM D2872
RTFO Mass Loss, %	> 1.000%	ASTM D2872
PAV Viscosity Index	> 1.10	ASTM D6521
RTFO Mass Loss, %	> 1.000%	ASTM D2872
PAV Viscosity Index	> 1.10	ASTM D6521