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Performance Evaluation Of Sustainable Pavement Materials

Robeam Solomon Melaku

PERFROMANCE EVALUATION OF SUSTAINABLE PAVEMENT MATERIALS

by

Robeam Solomon Melaku

Bachelor of Science in Civil Engineering, Addis Ababa University, 2009

Master of Science in Civil Engineering, Addis Ababa University, 2014

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PERMISSION

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NOMENCLATURE

DSR: Dynamic shear rheometer

DCT: disk-shaped compact tension

SCB: semi-circular bend

APA: Asphalt pavement analyzer

FI: flexibility index

RAP: reclaimed asphalt pavement

GF: fracture energy

MSCR: multiple stress creep recovery

LAS: linear amplitude sweep

SO: soy oil

WCO: waste cooking oil

WWS: wastewater sludge

CMOD: crack mouth opening depth

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DEDICATION

I dedicate this to my father, my family, and my beloved friends, especially, Sisay Asfaw, Dawit Admasu, and their families for all the support they provided me. May Elohim grant them eternal Shalom.

LIST OF PUBLICATIONS

Journals

[1] **R Melaku**, DS Gedafa
Impact of Wastewater Treatment Sludge (WWS) on Cracking Resistance of HMA Mixes at Lower Mixing Temperature Journal of Materials in Civil Engineering (under review)

[2] R Saha, R **Melaku,** B Karki, A Berg, DS Gedafa
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[3] **R Melaku**, DS Gedafa
"Effect of Wastewater Treatment Sludge (WWS) on Binder and HMA Performance" Transportation Research Record (under review)

[4] **R Melaku**, DS Gedafa
"Impact of Bio-oils and Wastewater Sludge (WWS) on the Performance of Binders and HMA with High RAP" International Journal of Pavement Engineering (to be submitted)

[5] **R Melaku**, DS Gedafa
"Evaluation of HMA Low-temperature Cracking Resistance using Rate Normalized Fracture Energy" International Journal of Pavement Engineering (to be submitted)

Conference Proceedings:

[1] R Saha, B Karki, A Berg, **R Melaku**, DS Gedafa
"Effect of RAP on cracking and rutting resistance of HMA mixes" Airfield and Highway Pavements 2017, 86-94

[2] DS Gedafa, A Berg, B Karki, R Saha, **R Melaku**
"Cracking and Rutting Performance of Field and Laboratory HMA Mixes" Journal of Materials in Civil Engineering 2019, 12-19

[3] DS Gedafa, B Karki, A Berg, R Saha, **R Melaku**
"Effect of Nanomaterials on Cracking and Rutting Resistance of HMA" Airfield and Highway Pavements

[4] B Karki, A Berg, R Saha, **R Melaku**, DS Gedafa
"Effect of Nanomaterials on Binder Performance" International Conference on Transportation and Development

ABSTRACT

In the United States (US), there are more than 2 million miles of paved roads. About 93 percent of those are surfaced with asphalt mixtures (flexible pavements). Shortage of natural resources, environmental impact of pavement life cycle and pavement distress are the major concerns of the pavement industry. Higher percentage Reclaimed Asphalt Pavement (RAP) usage, alternative asphalt pavement additives and development of performance related pavement analysis are the major factors to improve sustainability of the pavement. In this dissertation, extensive studies were conducted on the use of sustainable materials and performance analysis. Use of Waste Cooking Oil (WCO) and Soy Oil (SO) modified high percentage RAP asphalt pavement and the potential use of wastewater sludge (WWS) as compaction aid additive and Warm Mix Additive (WMA) were investigated. Rate dependent normalized low-temperature cracking performance analysis was also conducted to better differentiate between the mixes and for better correlation with mix design parameters. Results showed that using 15% SO and 12.5%WCO with 2.5%virgin binders as rejuvenator it is possible to recycle 85%RAP binders (72.5% based on aggregate weight) while maintaining similar performance as compared to the control Hot Mix Asphalt (HMA). The optimum dosage of WWS based on Performance Grade (PG) 58-28 binder was 1%. The use of 1% WWS as additive significantly improved the fatigue and low-temperature cracking performance of modified mixes compacted at 50°F lower compaction temperature than the control HMA. Based on the effect of WWS on field mixed lab compacted HMA project results, it is inferred that WWS is a potential pavement compaction aid and performance enhancer additive. Generally, it improved the cracking performance of the HMA and reduced the compaction effort by maintaining the rutting performance within the specifications limit. It was also concluded that WWS improved fatigue and low-temperature cracking resistance of the control (0 %), 40% RAP, and 60% RAP mixes using RAP from two different sources and different age. The effect of WWS on fatigue cracking performance increased with RAP content, while the effect of WWS on low-temperature cracking decreased with RAP content. The WWS can be used as a compaction aid for longer construction season and lesser energy consumption. Results also showed that rate normalized GF parameters better differentiate mixes with high RAP content. The results also correlated better with binder performance and percentages of RAP content in the mix.

Chapter 1 Introduction

Highways are the backbone of any nation transportation system and they form the foundation of a nation's economic prosperity by providing the ability to safely and efficiently transport people, products, and goods (Wang et al. 2005). The impact of highways on the environment is huge resulting from its life cycle activities which involve planning, design, material extraction, construction, usage, maintenance, and demolition (David 2008). Overall sustainability impacts associated with highways and pavements throughout their life, from "cradle" to "grave. The main life cycles of asphalt pavement include: Extraction of asphalt pavement, pavement material production mixing and processing and transport of material between facilities. Pavement sustainability is measured based on economy, reduction in environmental emission and improvement in engineering performance analysis. Use of recycling material and pavement additives are methods to utilize in asphalt industry to confirm sustainability (Kent et al. 2015).

In the United States, there are more than 2 million miles of paved roads. Asphalt pavements account for about 93 percent of paved roads. Flexible pavements can be either constructed of granular materials overlain with asphalt mixtures (conventional flexible pavements) or placed directly on the subgrade (full-depth pavements). Most of the flexible pavements are conventional flexible pavements (Kent, 2017). The asphalt mixtures are comprised of aggregate and asphalt binder mostly in the ratio of 95/5, by mass. Aggregates are mainly responsible for load carrying capacity, while the binder is used to glue the aggregates and resist water penetration into the pavement system. In addition to aggregates and asphalt binder, asphalt mixtures may contain one, or any combination of asphalt binder modifiers, and recycled materials, such as crumb rubber, polymers, reclaimed asphalt pavement (RAP), reclaimed asphalt shingles (RAS), and several other types of additives as modifiers or recycling agents.

The HMA is the most common type of asphalt mixes prepared and laid off between 300°F and 350°F. It is used when the working environment temperature is above 40°F.The WMA is a type of mix that is prepared and laid at a temperature 240°F to 290°F. It is used with warm mix additive materials such as wax, zeolite and emulsions to easily spread the mix at lower temperatures. Generally, WMA is less costly than HMA (Murgaz 2014). The main ingredients in asphalt pavement are briefly described.

1.1 Asphalt Binder

The vast majority of asphalt binders used throughout the world today are obtained from crude oil (petroleum) refining. At room temperature (25°C) asphalt binder is a highly viscous, black material whose primary purpose is to bind the aggregates in the production of asphalt mixtures for pavements. Asphalt binders are most typically classified by one of three grading systems, penetration grading, viscosity grading, or performance grading. The performance grading system, developed during the Strategic Highway Research Program (SHRP), selects an appropriate binder grade based on construction region climate, and is the most widely used asphalt grading system in the USA. For example, a performance grade (PG) 58-28 is intended for use in a climate which has an average seven-day maximum temperature of 58°C and a minimum pavement design temperature of -28°C. Performance grades are at 6°C interval in general (Brown et al, 2009). Recent and more advanced performance grade methods, such as multiple stress creep recovery (MSCR), linear Amplitude sweep (LAS), and other binder performance methods are discussed in the later parts of this dissertation.

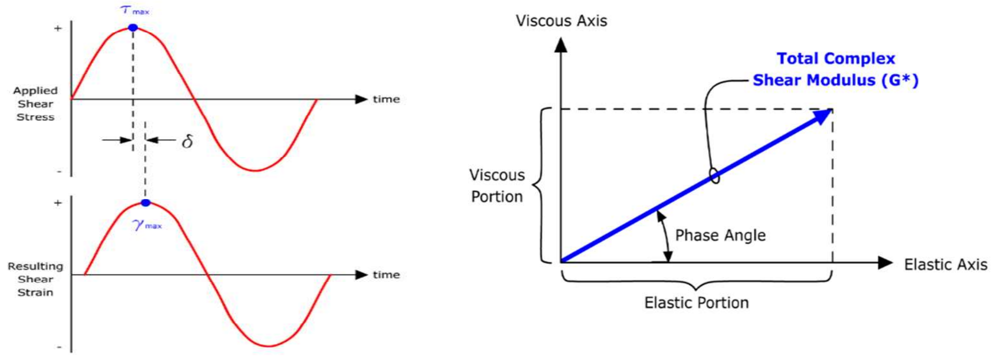
1.1.1 Binder Rheology

Binder rheology is the study of flow and deformation of binders to predict pavement performance. The three basic performance measures of asphalt binders are rutting, fatigue cracking and low-temperature cracking (Pavement Interactive, 2020).

1.1.2 Dynamic Shear Rheometer (DSR)

The viscoelastic nature of asphalt binder is measured depending on the temperature and the rate of loading. Elastic response of asphalt is a parameter to be considered at low-temperatures and short periods of loading, whereas the viscous response is measured at high temperature and long periods of loading (Michal et al. 2019).

The Dynamic Shear Rheometer (DSR) is utilized to evaluate the rutting and cracking potential of asphalt by applying a torque on a thin asphalt binder sample between a fixed and an oscillating parallel plate to apply a shear loading. The complex shear modulus (G^*) is the ratio of the shear stress to shear strain. Phase angle (δ) is the time lag between applied shear stress and the resulting shear strain as shown in Figure 1.1. Figure 1.2 shows the type of DSR used in this research along with a test specimen.



Phase angle parameter complex shear modulus parameter

Figure 1. 1 *Rheological Parameters of Asphalt Binder (Pavement Interactive, 2016)*

a. Measuring Instrument b. Sample specimen

Figure 1. 2 Dynamic Shear Rheometer (DSR) (Karik, 2017)

1.2 Aggregates

Aggregate materials are usually obtained largely from locally sourced, natural rock supplies. Rock formations, and the aggregates produced from them can be divided into three types, igneous, sedimentary, and metamorphic. Based on gradation aggregates are usually classified as coarse aggregates, fine aggregates, and mineral fillers. Coarse aggregates are those larger than the No. 4 (4.75-mm) sieve and sands are smaller than the No. 4 (4.75-mm) sieve, but larger than the No. 200 (0.075-mm) sieve, and mineral fillers are all smaller than No. 200 (0.0075 mm) sieve (Pavement Interactive, 2020).

1.3 Rejuvenators and Additives

Rejuvenators are products designed to restore original properties to aged (oxidized) asphalt binders by restoring the original ratio of resin rich soluble components of asphalt (Asphaltenes) to soluble molecular components of asphalt (Maltenes). A rejuvenator should not be applied to a pavement having an excess of binder on the surface such as that found in slurry seal (Pavement Interactive, 2020).

1.4 Bio-oils

Bio-oils are oils derived from the secondary product of industry and agriculture process used in asphalt industry to soften or rejuvenate the RAP binder (Pavement Interactive, 2020).

1.5 Wastewater Sludge

Wastewater treatment sludge (WWS) is an abundant by-product of wastewater treatment. In the United States, about 6.5 million metric dry tones of WWS are produced annually (NEBRA, 2007).

The disposable WWS comprises of alkali metal minerals of Al, Si, Fe, Ca, K and Mg (Anderson and Arthur 2001). Studies on the properties of WWS indicated that it consists of 59–88% weight by volume (w/v) of organic matter (Orhon and Artan 1995). The WWS can be further recovered through pyrolysis into ash, char, bio-absorbents, tar, and valuable biopolymers (Fytili et al. 2008). Evaluation of WWS as a warm mix asphalt additive is considered in this study due to the properties of WWS such as its usage as potential source for the production of the artificial zeolite-like chemicals. The chemicals are characterized by cation exchange capacity with surface area and pore radius containing moisture and chemicals such as, SiO2, Al2O3, Fe2O3, CaO, MgO, Na2O (Ferreira et al.2003; Pazos et al. 2010; Gordon and Yang 1998; Pazos et al. 2010).

1.6 Reclaimed Asphalt Pavement (RAP)

Reclaimed Asphalt Pavement (RAP) is essentially old pavement that is reclaimed for use. In its most common form, it is collected in loose granular form as a byproduct of pavement rehabilitation or reconstruction (Pavement Interactive year). Usage of RAP has two main advantages:

1. The RAP aggregate can be utilized instead of the virgin aggregate to reduce cost and wastage of material as well as saving the land fill.
2. The RAP asphalt binder can be used to replace a portion of virgin binder especially if it is used with rejuvenators.

Generally, usage of RAP has benefits on the economy by reduction of construction cost and conservation of natural construction resource as well as preserving the environment and energy usage by reducing the fuel consumption (Copeland et al. 2011). Currently, the state of North Dakota allows the usage of RAP up to 25% in asphalt mixtures. The limiting factor for the usage of high RAP asphalt mixtures is the high stiffness observed in such mixtures due to the aging of

RAP asphalt binder, which results in low workability. The inadequate workability of the asphalt mixtures prevents proper compaction in the field and can ultimately lead to premature field failure (Mogawer et al. 2012). The negative effect of high RAP is more visible in colder temperature areas due to the thermal cracking susceptibility of high RAP mixes. Studies showed that for high RAP usage it is necessary to do both binder and mix test (McDaniel et al. 2001).

1.6.1 Performance of High RAP

1.6.1.1 Rutting

Generally, rutting resistance is improved with the increase in RAP content due to the increase in stiffness. Study done on 50% RAP field and lab mix showed better rutting performance than the control (McDaniel et al. 2003; Huang et al.2004).

1.6.1.2 Cracking

Studies showed that the presence of aged binder deceases the fatigue cracking performance due to the high stiffness (West et al. 2013). Overlay mix with 35% RAP had half cracking resistance of the virgin mix if the same mix design is used (West et al. 2011). This shows generally RAP material has negative effect on cracking performance.

1.7 Problem statement

The main concern in using mixes with high RAP percentage is susceptibility to fatigue and low-temperature cracking due to the stiffness of aged binder (Valdes et al. 2011, Saha et al. 2017). Use of rejuvenators and warm mix additives can be some of the solutions suggested to improve the cracking performance. The other concern of usage of high RAP mix is difficulty to achieve the required compaction effect, especially in cold construction regions and long construction season. The use two bio oils, SO and WCO, as rejuvenators in high RAP mixes was investigated. Potential usage of WWS as performance enhancer, warm mix additive, and compaction aid material was also investigated. The other concerns of rejuvenated high RAP mixtures are lack of RAP content dependent low-temperature cracking performance analysis methods. Jung and Vinson (1994) stated the limitation of DCT fracture energy measurement to distinguish between high-strength/low toughness and low strength/high toughness mixtures, mixtures with high pick load/steep post peak slope, and low peak load/shallow post peak load, respectively. The DCT fracture energy (GF) also lacks a good correlation with low-temperature binder test results and mix design parameters (Tirupan et al. 2019, Saha et al. 2020). A comprehensive assessment of fracture energy normalized by post peak slope indices of load vs CMOD fracture curve was analysed by Yue Feng et al. (2017). Three variants of flexibility indices $G\mathrm{F}/\mathrm{i}n_{\mathrm{itial}}$, $G\mathrm{F}/\ (m_{\mathrm{initial}} - m_{\mathrm{final}})$, and $G\mathrm{F}/m_{\mathrm{average}}$ were used in the analysis. Normalized fracture energy was developed as fractured indices to get more information about the softening behaviour of the material. Results indicated that higher correlation was observed between the fracture energy and the normalized parameters, while higher coefficient of variation was observed for normalized fracture energy than the fracture energy (GF) parameter. The result lacked information about the correlations between the normalized index parameters with mix design parameters and binder test results. Utilization of bio-oils and wastewater sludge as pavement rejuvenator and pavement additives at optimum content is expected to bring better trade-off between pavement performance and RAP content in HMA. A general analysis post peak load CMOD-load and post peak load time (T)-load rate of change normalized DCT fracture energy parameter is also expected to differentiate between mixes with high RAP content. The correlation between the rate indexed normalized parameters with mix design parameters and binder test results were also investigated.

1.8 objectives

The main objective of this dissertation was to improve the sustainability of asphalt pavement. The specific objectives addressed in this dissertation were to:

- Evaluate the effect of bio-oils and wastewater sludge (WWS) on high RAP binder and mix.
- Determine the effect of wastewater sludge as compaction aid and WMA additive
- Develop new method of rate based low-temperature cracking performance analysis to better differentiate between mixes.

1.9 Organization of the Dissertation

This dissertation is organized in six chapters. Each chapter is briefly described.

Chapter 1 General introduction. Background, basic materials used in asphalt pavements, problem statement, and the objectives of the study were stated in this chapter.

Chapter 2 deals with the effect of SO and WCO on the rutting, fatigue cracking, and low-temperature cracking performance of high RAP binder and mix. The effect of WWS on SO and WCO modified mixes at lower compaction temperature was also investigated

Chapter 3describes the effect of WWS on the rutting, fatigue cracking, and low-temperature cracking on 0%, 40% and 60% RAP mixes of two different mix designs and RAP types.

Chapter 4 deals with the effect of WWS on the compaction effort at 50°F lower temperatures than the HMA on field mixed and lab compacted mixes. Two sets of projects from North Dakota were investigated

Chapter 5 includes the use of index based normalized fracture energy for low-temperature cracking analysis. Post load CMOD –load and Time -load rate normalized fracture energy were considered.

Chapter 6 summarizes the general conclusions, recommendations, limitations, future work, and contribution of the dissertation.

Chapter 2 Impact of Bio-oils and Wastewater Sludge (WWS) on the Performance of Binders and HMA

2.1 Background

In the United States, about 93 % of paved roads are asphalt concrete. Reclaimed Asphalt Pavement (RAP) is the most recycled material in the USA used in the construction of asphalt pavement to reduce the cost and environmental impact of pavement construction (Kent et al. 2017). Even though the use of RAP has a lot of advantages in most state departments of transportations, its use is limited to 25%-40% (Kent et al. 2017). The main reason for the limited usage of higher percentages of RAP material in HMA is due to the concern of increasing stiffness of the mixtures with high percentages of RAP, which is triggered by aged asphalt binder contained in RAP. Increasing RAP percentage renders the HMA susceptible to fatigue and thermal cracking (Valdes et al. 2011). Softer binder, recycling agents, and warm mix additives are some of the approaches suggested by researchers to reduce stiffness and improve the cracking performances of mixtures with high RAP content. (West et al.2009, Daniel et al. 2010)

Warm mix technologies, such as the artificial synthetic zeolite can reduce mixing and compaction temperature and help to maximize the use of high RAP percentages (FHWA. 2018).

Wen and Bhusal conducted a study on the rutting, cracking performances of waste cooking oil-based bio-asphalt on a binder and HMA. Results showed that addition of 10% and 30% of the bio-asphalt reduced the rutting and fatigue cracking performance of both binder and HMA while improved the low –temperature cracking performance of the base binder (Wen and Bhusal 2013)

Zargar et al. evaluated the rheological and chemical effect of WCO as a rejuvenating agent. The result showed that the addition of 3-4% WCO to aged binder resulted in a reduction of the stiffness to closer to the unaged binder. The addition of WCO to the RAP binder reduce the stiffness of the RAP binder by increase the amount of maltenes. (Zargar et al. 2012)

Vegetable-based materials, such as SO, can be used as rejuvenators due to their short-term renewable nature. Replacement of virgin binder by bio-oil(s) modified RAP binder in HMA could be a sustainable practice if better tradeoff is obtained between the amount of RAP replacement and performances of the HMA (Hill et al.2012). Addition of small dosages of soybean acidulated soap stock reduced the stiffness of the aged binder, increased their workability, and improved low-temperature performance (Elkashef et al. 2017).

Elkashef et al. studied binder and HMA the effects of addition 12% SO with the PG 58-28 virgin binder to rejuvenate 100% RAP mixture. Binder test results indicated that the soybean-derived rejuvenator improved both the low and high-temperature properties of the RAP binder by lowering the high and low critical temperature and improving the creep compliance of the RAP binder. HMA result also showed that SO rejuvenated mixture improved the low-temperature fracture energy more than the mix rejuvenated with virgin binder only (Elkashef et al. 2018).

The WWS contains silicate of alkali metal and alkali metal oxides, which can be a potential source for artificial syntactic zeolites -like chemicals (FHWA, 2016, Suárez et al. 2017). Zeolites minerals composed of hydrated aluminum silicates of alkali metals and alkaline earth metals. It is commonly used as warm mix additives (Woszuk et al. 2016), Sengozet al. 2013). For most zeolite-based WMA, organics and fatty amides, and chemical WMA the average dosage ranges from 1-2% by weight of   total bitumen content (FHWA, 2018, Rubio et al. 2012).

The effect of bio-oils (SO and WCO) at the optimum dosage as rejuvenator or softener expected to bring better trade off in RAP content and performance by modifying the aged binder was investigated. The effect of WWS on the performances of SO and WCO modified high RAP HMA at 50°F lower compaction temperature than the HMA with virgin binder was also investigated to determine the potential usage of WWS as performance enhancer and WMA.

2.2 Objectives

The objectives of the study are:

- To determine the optimum percentage of RAP, bio-oils (SO and WCO), WWS, and virgin binder that can produce high performing HMA as compared to the virgin binder;
- To analyze the performance of HMA using the optimum percentage of RAP, bio-oils (SO and WCO), and a virgin binder; and
- To explore the effect of WWS on low-temperature cracking, fatigue cracking, and compaction effort of the bio-oil modified high RAP mixes

2.3 Methodology

2.3.1 Experimental plan

Figure 2.1 shows the experimental plan. It consists of three phases. Modification of the RAP binder with the bio-oils to determine the rheology, preparation and testing of HMA with bio-oils and exploring the effect of WWS on the bio-oil modified HMA at lower compaction temperature.

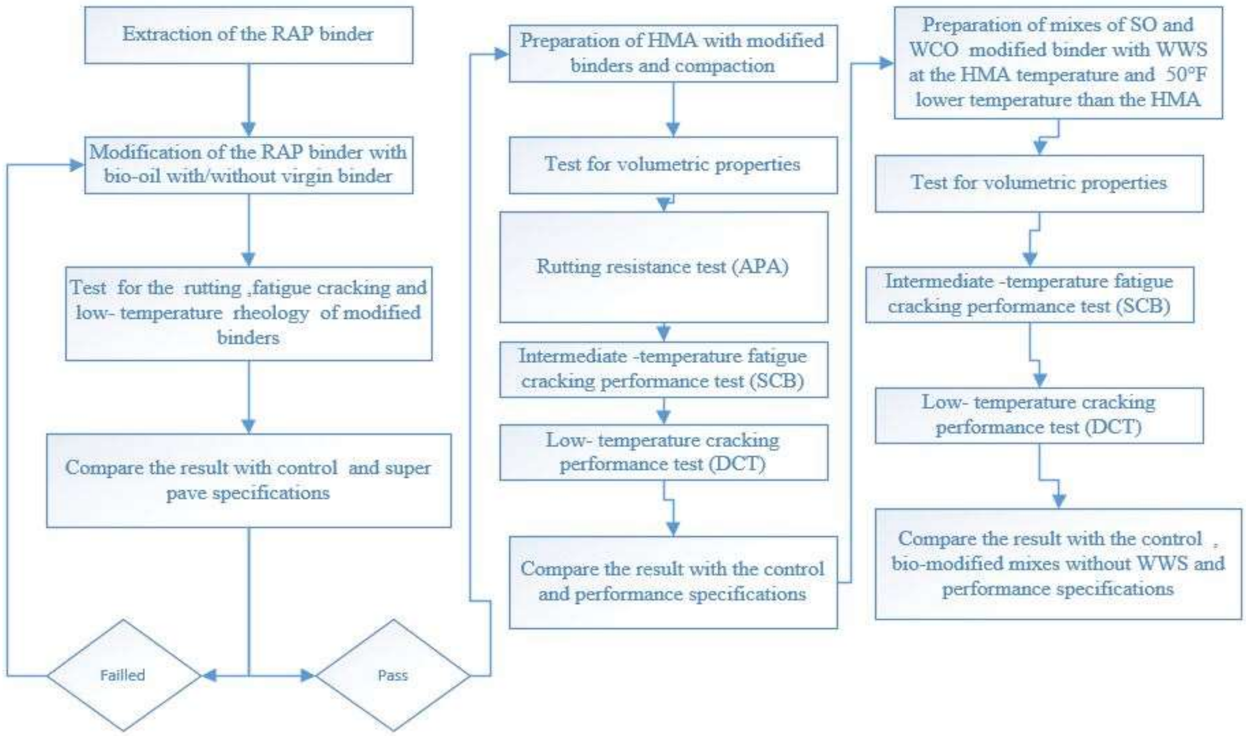


Figure 2. 1 Experimental Plan

2.3.2 Material selection

Virgin aggregates and RAP were collected from Highway-32 project in North Dakota. The PG 58-28 asphalt binder was used as a control binder with aggregates collected from Highway-32 site. The PG 58-28 binder was used as a control binder since it is commonly used in North Dakota, and it was the original grade of the RAP binder. The two bio-oils, SO from a commercial supplier and WCO from the University of North Dakota dining center, were used to modify the extracted RAP binder. Wastewater sludge (WWS) was collected from the Grand Forks wastewater treatment plant. The properties of the two bio-oils and WWS are shown in Table 2.1

Table 2. 1 Properties of SO, WCO, and WWS

Bio-oil type	SO	WCO	WWS
Viscosity (Stokes)	0.32-0.5	0.782	NA
Specific Gravity @25°C	0.925	0.914-0.917	1-1.1
Acidic Value	0.1	0.1	0.1-0.2
Flash Point(°C)	260	220-230	250

Note: NA= Not available

2.4.3 Binder Test Design

The rheology test of 100% RAP binder was tested first, followed by the modification of the RAP binder by WCO and SO. The bio-oil modification of the RAP binder was done based on a trial and error. Tests were on unaged, Rolling Thin Film Oven (RTFO), and Pressure Aged Vessel (PAV) aged samples using Dynamic Shear Rheometer (DSR). Rolling Thin Film Oven (RTFO) aged samples of each trial and error was tested until the high-temperature continuous PG of 58°C was obtained. Rolling Thin Film Oven (RTFO) sample was used to simulate short-term aging. The optimum percentages of the two bio-oils (SO and WCO) were found to be 15% of total binder content, which satisfied all the rheological properties except the unaged high-temperature performance was less than AASHTO M320 specification. To meet the specification, a replacement of the two bio-oils by the virgin PG 58-28 binder was done on the two modified binders (15%SO_85%RAP and 15%WCO_85%RAP). Replacement of 2.5% by volume of the bio-oil content (SO and WCO) with virgin PG 58-28 satisfied all the rheological performance of AASHTO M320 specification while maintaining the high-temperature continuous PG of the RAP binder to 58°C. Multiple stress creeps recovery (MSCR) for rutting performance, Linear Amplitude Sweep (LAS) for fatigue performance, and 4 mm parallel plate geometry DSR for low-temperature cracking performance tests were conducted on the control and all the selected bio-oil and bio-oil -virgin modified binders. The combinations included the virgin as a control (V), 15%SO_85%RAP(15SO),15%WCO_85%RAP(15WCO),12.5%SO_2.5Virgin_85%RAP(12.5SO_2.5V), 12.5%WCO_2.5Virgin_85%RAP (12.5WCO_2.5V), and 100%RAP (100RAP) binders.

The percentages of WWS were selected based on PG 58-28 binder test result. Three samples were tested for all binder and performance analysis. All the binder and mix tests conducted in this research are summarized in Table 2.2

Table 2. 2 Test on Binders and Mixes

Types of Binders and Mixes	Test on Binders			Test on Mixes		
	Rutting (MSCR) @58°C	Fatigue Cracking (LAS) @19°C	Low-temperature Cracking(4mmDSR) @-18°	APA @58°	SCB @25°	DCT @-18°C
V	✓	✓	✓	✓	✓	✓
15SO	✓	✓	✓	✓	✓	✓
15WCO	✓	✓	✓	✓	✓	✓
12.5SO_2.5V	✓	✓	✓	✓	✓	✓
12.5WCO_2.5V	✓	✓	✓	✓	✓	✓
100R	✓	✓	✓	✓	✓	✓
15SO_(1%)WWS					✓	✓
V_(1%)WWS		✓	✓		✓	✓
15WCO_(1%)WWS					✓	✓
12.5SO_2.5V_(1%)WWS					✓	✓
12.5WCO_2.5V_(1%)WWS					✓	✓

2.3.4 RAP Binder Extraction

ASTM D 2172/D 2172M standard [21], and ASTM D 1856-95a Standard (ASTM, 2003) procedure were jointly used to extract the RAP binder . EnSolv-EX, an n-Propyl Bromide (nPB) solvent, was used in the extraction process. The Abson Method following ASTM D 1856-09 standard was then used to recover the extracted binder (Saha et.al 2020).

2.3.5 Rutting Resistance using Multiple Stress Creep Recovery (MSCR)

Multiple Stress Creep Recovery (MSCR) is the most currently used Superpave Performance Graded (PG) asphalt binder test following AASHTO T 350 (AASHTO.M332, 2019) and AASHTO M 332 (AASHTO.T350, 2019) using DSR. It indicates the rutting performance of the asphalt binder more accurately used for modified binders. The non–recoverable creep compliance at 3.2 kPa (Jnr_3.2) and percent recovery (%R) are the two main parameters to define the rutting performance of the binders. The Jnr_3.2 values of 4, 2, 1, and 0.5 are used as the maximum threshold values for standard, heavy, very heavy, and extreme traffic, respectively. The lower the Jnr value the stiffer the binder

2.3.6 Fatigue Cracking Resistance using Linear Amplitude Sweep (LAS)

Linear Amplitude Sweep (LAS) is a test carried out on PAV aged binders at an intermediate temperature to evaluate asphalt binder fatigue damage performance. The LAS test is composed of a frequency sweep to undamaged material properties followed by linear amplitude strain sweep test to analyze the binder damage performance. The test. The failure definition in the LAS test is defined as a 35% reduction in the initial modulus. The analysis is done based on fatigue law parameters A and B, which are model coefficients that depend on the material characteristics. In general, more fatigue resistant binders tend to have higher A values and lower absolute B values.

The number of cycles to failure calculated using Eq. (1) is generally used to compare the fatigue cracking performance between the binders (Hintz et al. 2011).

$$N_f = A(\gamma_{max})^B \tag{1}$$

N_f accounts for differences in pavement structure by changing depending on γmax. Higher strain values correspond to thinner pavements/heavier traffic loading while lower strain values may correspond to thicker pavements /lighter traffic loads.

The applied binder strain is estimated using the strain in the pavement layer multiplied by 50. Binder fatigue parameters (N_f) for two binder strain levels of 2.5% and 5% are used for the analysis in this study that corresponds to thicker pavement/ lighter traffic load and thinner pavement heavier traffic respectively indicating 500 and 1,000 micro strain in the pavement layer (Hintz et al. 2011).

2.3.7 Low-temperature Cracking Resistance

Low-temperature resistance was done using 4 mm parallel plate geometry following the method proposed by Sui et al. (Sui et al. 2011), Saha et.al 2020),Karki et.al 2018) The method was followed to generate a master curve at low-temperature PG + 10˚C. The master curve was then used to estimate the slope (m_r) and relaxation modulus G (t) at 60 seconds. Finally, these values were compared to Superpave PG binder specifications for 4 mm DSR (AASHTO, 2016, Saha et.al 2020). The Specifications recommend a maximum G (t) value of 300 MPa and a minimum (m_r) value of 0.3. Generally, a binder with a lower G (t) and a higher m_r binder is considered as a better low-temperature performing binder. In this study based on the binder grade of the control PG 85-28 the low –temperature DSR test was conducted at -18°C.The binder specification requirements used this study are summarized on Table 2.3

Table 2. 3 Binder Specification Limits

Performance	Sample condition	parameter	Criteria
Rutting	Unaged	G*/sin(δ)	≥1kpa
Rutting	RTFO aged	G*/sin(δ)	≥2.2kpa
Fatigue cracking	PAV aged	G*sin(δ)	≤5000pa
Low -temperature cracking	PAV aged	G(t)	≤300Mpa
	PAV aged	m_r	≥0.3
MSCR rutting test	RTFO aged	Jnr@3.2 Kpa	ST =4
	RTFO aged	Jnr@3.2 Kpa	MT=2
	RTFO aged	Jnr@3.2 Kpa	HT=1
	RTFO aged	Jnr@3.2 Kpa	ET≤0.5
ST =standard traffic ,MD medium traffic ,HT =heavy traffic ,ET extrema traffic			

2.3.8 Mix Design

The mix design used for highway 32 was adopted for this study. PG 58-28 virgin binder was used to prepare the control HMA. The RAP aggregate was treated as a stockpile with the virgin aggregates. It was first split in two proportion on the 4.75mm (No.4) sieve. The binder content of the RAP material was estimated using the ignition method following AASHTO T308-16 procedure and found to be 7.5%. The fraction of +4.75 mm and -4.75mm RAP material was selected to meet the Superpave gradation specification. The same gradation was used for the control and bio-oil modified HMA to determine binder effect. Based on the binder result to account for 85% of the RAP binder and 15% of bio-modifiers the total percentages of the RAP were 72.5% based on aggregate weight used. The remaining weight was redistributed to the other aggregates according to the job mix formula. The same gradation and mix design were used to prepare bio-oil modified mixes with WWS. Bio-oil modified mixes of 15% SO and WCO were considered for mix analysis to see the effect of unaged binder that does not meet AASHTO M320 specification. The effect of WWS on cracking and compaction effect was investigated on bio-oil modified mixes at 50°F lower compaction temperature than the HMA. The mix design and gradation of the HMA are shown in Table 2.4 and Table 2.5.

Table 2. 4 Mix Designs and Proportions of the Modified and Control Mixes

Virgin PG 58-28 HMA		**SO and WCO Modified HMA**	
Materials	Percent (%)	Materials	Percent (%)
Optimum Binder content(OBC)	6.4	Optimum Binder content(OBC)	6.4
Bio -oil modifiers as a % of OBC	0	Bio -oil modifiers as a % of OBC	12.5/15
Virgin binder as %of (OBC)	100%	Virgin binder as% of OBC	2.5/0
Binder from the dry RAP aggregate as % of OBC	0	Binder from the RAP as % of OBC	85
Crushed Rock	29	Crushed Rock	8
Crushed Fines	37	Crushed Fines	10
Washed Dust	13	Washed Dust	3.5
Washed Sand	21	Washed Sand	6
RAP	0	RAP	72.5

Table 2. 5 Gradation of Bio-oil Modified with High RAP HMA

Sieve	**Bio-oil modified & control HMA Gradation**	**Unmodified 100%RAP Gradation**	**Lower Control Pt**	**Upper Control Pt**
5/8"	100	100	100	100
1/2"	93.35	97.50	90	100
3/8"	81.03	87.65		
#4	59.44	68.41	40	70
#8	41.37	47.88		
#16	30.27	34.48		
#30	20.23	23.19	15	35
#50	11.19	13.89		
#100	6.32	9.01		
#200	3.48	5.58	2	7

2.3.9 Mixing and Preparation

The virgin aggregates were heated at 325°F. The RAP binder was heated separately to make it workable at 230°F for 1 hr. The bio-modifiers and the binder were blended and heated at 270°F for 1hour. The heated materials were mixed in the laboratory maintaining a standard mixing temperature of 300°F. After mixing, each batch was short-term aged for 2 hours at the compaction temperature of 290 °F. After 2 hours, a pre-weighed amount of mix was poured into the mold and compacted using Superpave Gyratory Compactor (SGC). A cylindrical sample of 150 mm diameter and 75 mm thick was compacted for rutting resistance test. For fatigue and low-temperature cracking resistance test 150 mm diameter and 100 mm height were compacted initially, which were further resized to 50 mm thickness according to the specification requirement. Volumetric properties of the specimens were tested to conform to 7±0.5 % air void requirement.

The same bio-oils modified mix was replicated by using 1% WWS in addition to other binders. The WWS was kept at room temperature and added to the bio-modifiers prior to mixing with the aggregate. The compaction was done at 240° F, which is 50 °F lower than the HMA compaction temperature. Only fatigue and low-temperature performance tests were conducted on the mixes with WWS since rutting is not a major concern on high RAP content HMA mixes.

2.4 Testing

2.4.1 Rutting Resistance using APA

Rutting resistance test was conducted in accordance with AASHTO T 340. Dry conditioned specimens were used for the test using binder high temperature grade of 58°. The samples were conditioned inside the APA testing chamber for 6 hours before testing. A pressure of 100 psi was applied to the testing sample for 8,000 cycles. According to the Asphalt Pavement Analyzer (APA) performance specification for North Dakota highways rut depth of 7 mm is considered to be fair for moderate traffic level of 0.3 to <3 million design equivalent single axle loads (ESALs) (Suleiman, 2008).the lower the rutting depth mix is considered as better rutting performing mix

2.4.2 Fatigue Cracking Resistance Using SCB

The semi-circular bending (SCB) test was used to determine the fatigue cracking resistance of the mix following the Illinois-Flexibility Index Tester (I-FIT) protocol. 50±2 mm samples were used. The samples were conditioned for 2 hours and tested at 25°C. The test was run, and the data were post-processed for calculating the fracture energy and Flexibility Index (FI) using the I-FIT software. The FI values of 2.0 and 6.0 appear to be cut-off values distinguishing poor- (less than 2.0), intermediate- (2.0 to 6.0), and good-performing (greater than 6.0) (Al-Qadi et al. 2015). The higher the fracture energy and flexibility index mix is the better fatigue cracking performance.

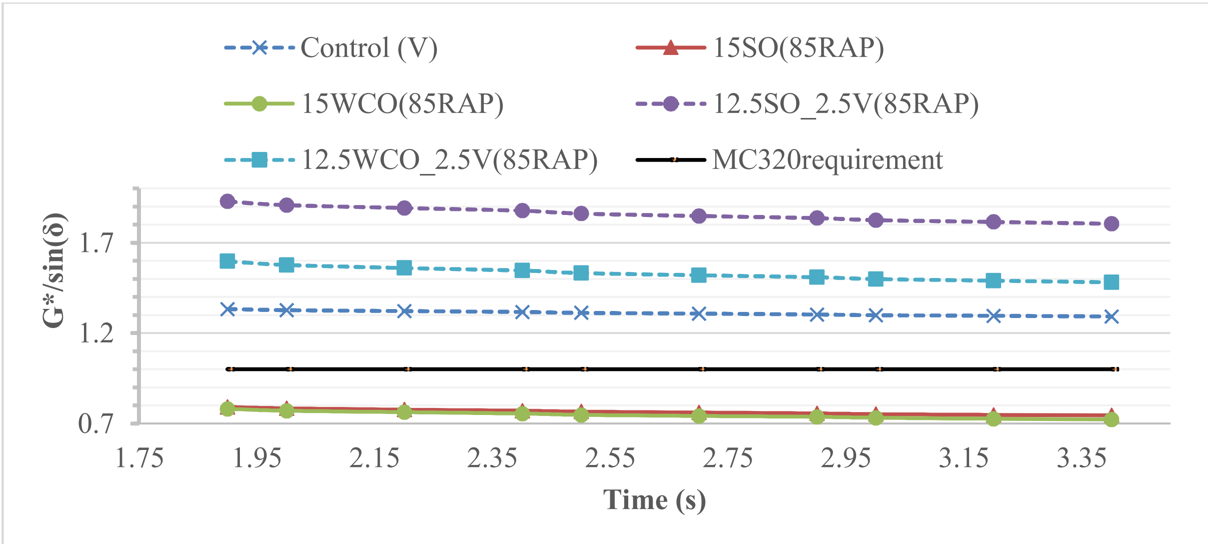
2.4.3 Low-temperature Cracking Resistance Using DCT

Disk-shaped Compact Tension (DCT) test following ASTM D 7313 standard specification was used to determine the low-temperature cracking resistance of the specimens. Fracture energy (Gf) of the specimen was used to measure the low-temperature cracking resistance of the HMA specimen. The specimens were conditioned for 8 hours and tested at low –temperature PG + 10°C of the binder (-18˚C). Crack Mouth Opening Displacement (CMOD) rate of 0.017 mm/s was used for the test(r). Studies recommended for cold temperature regions like North Dakota the threshold fracture energy value of 400, 460, and 690 J/m2 for low, intermediate, and high traffic level, respectively (Hussain et al.2016, Saha et al. 2017, Saha et.al 2020, Gedafa et al. 2019). The higher fracture energy mix is considered as better performing mix.

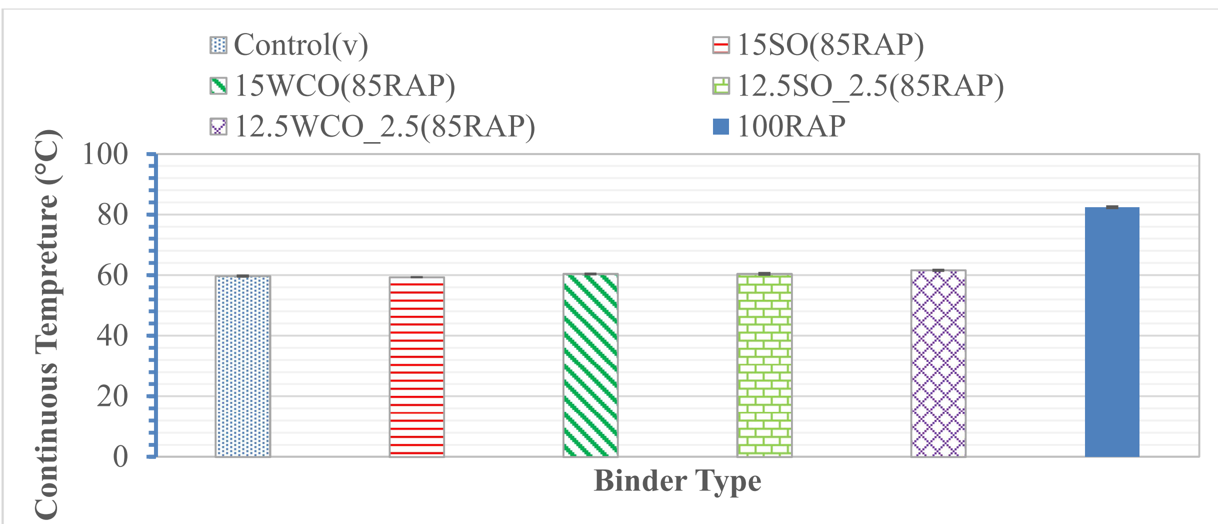
2.5 Results and Discussions

2.5.1 Effect of Bio-oils on Binder Rheology

Error! Reference source not found.(a) Shows G*/ (sin δ) value of bio-oils modified unaged binders. The 15% SO and 15% WCO modified binders showed less than the AASHTO M320 Specification value (1kpa). Replacement of 2.5% of the two bio-oils with the virgin PG 58-28 binder improved the unaged G*/sin (δ) value and maintained the RTFO high-temperature continuous PG of 58°C. Figure 2.2(b) shows the continuous PG of all the modified binders. Four RTFO aged samples of each modified binders were tested. All modified binders reduced the continuous high-temperature PG of the RAP from 82°C to 58°C.



(a) Unaged G*/sin (δ) Value of the Bio-oil Modified Binders



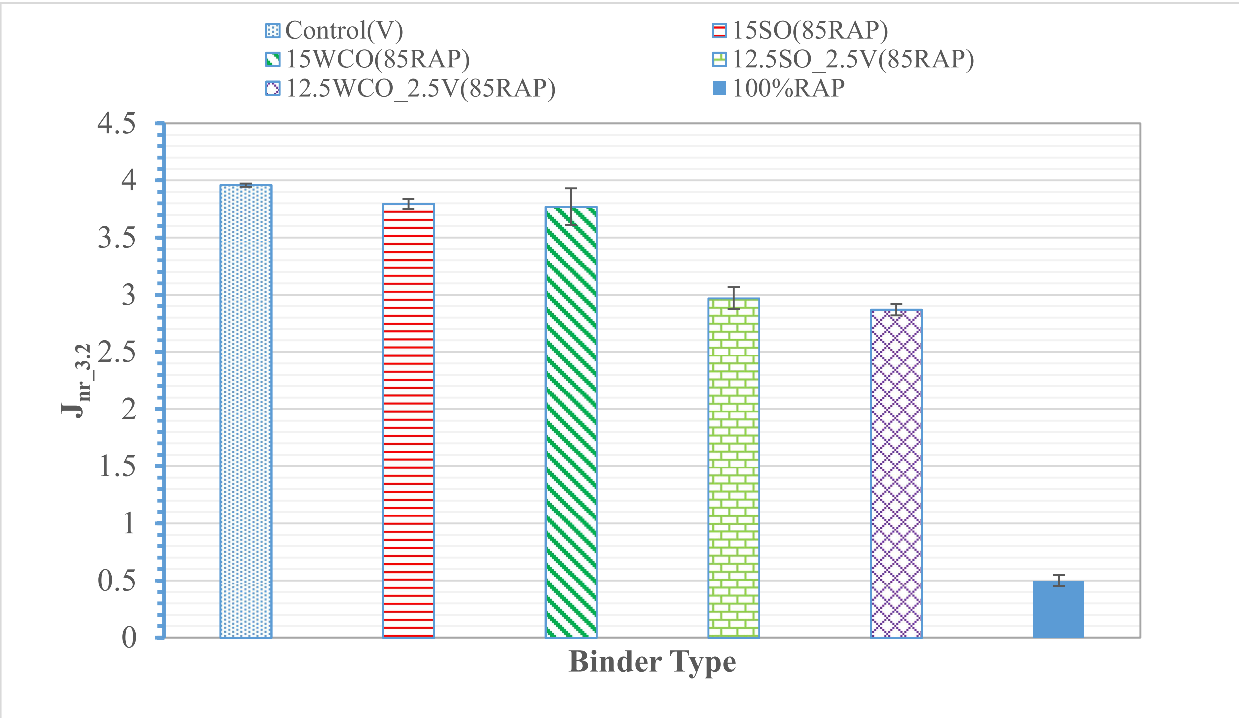
(b) Continuous PG Grade of RTFO Aged Modified Binders at 58 °C

Figure 2. 2 Modified Binder Rheology test Results

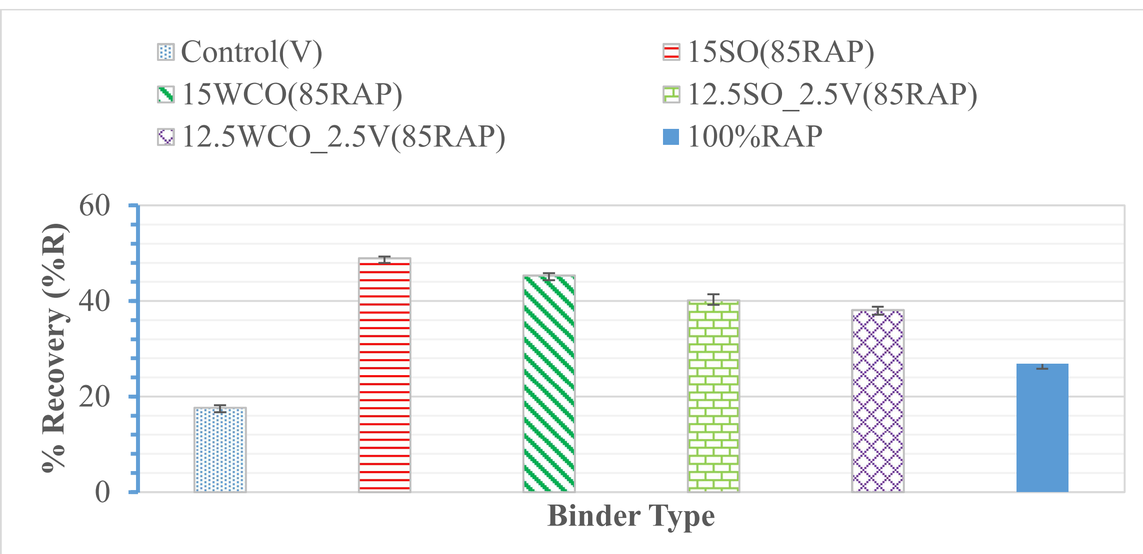
2.5.1.1 Rutting Resistance

Figure 2.3 (a) shows MSCR Jnr_3.2 value of modified binders. Results indicated that all modified binders satisfied the Jnr_3.2 AASHTO M332 requirement for standard traffic. All bio-modified binders resulted in a better high-temperature rutting performance than the virgin binder. The 15SO and 15WCO modified RAP binders had approximately 5% less Jnr value than the control binder whereas12.5SO_2.5V and 12.5WCO_2.5V modified had approximately 25% less Jnr value than the control binder. This indicates that the bio-oil - virgin modified RAP binder had better rutting resistance than both the virgin and bio-oil modified RAP binders without a virgin binder. This could be due to the relative softening potential of the bio-oils as compared to the virgin binder. The SO has better-softening potential than WCO at high temperature.

Percent recovery results displayed in Figure 2.3(b) showed that all modified binders have approximately 60% higher recovery potential than the virgin binder. Generally, SO modified RAP binders have approximately 7% higher recovery potential than WCO modified RAP binders. This shows that at high temperature, SO has performed better than WCO in terms softening and improving the elastic nature of modified RAP binder.



(a)$J_{nr\_3.2}$ Result of the RTFO Aged Modified Binders @58°C



(b) %Recovery Result of the RTFO Aged Modified Binders @58°C

Figure 2. 3 Rutting Resistance Using MSCR

2.5.1.2 Fatigue Cracking Resistance

The LAS test was conducted on PAV aged modified and control binders at 19° C. Table 2.3 shows that SO modified binders had higher “A “value than WCO modified binders. The 15SO has 80% more “A” value than the virgin and approximately10% higher “A” value than all other modified binders. The “B “parameter showed that all modified binders had less fatigue cracking performance than the virgin binder. The 15SO and 15WCO had nearly the same “B” value and about 7% higher than corresponding 12.5SO _2.5V and 12.5WCO _2.5V, respectively. The replacement of 2.5% SO with virgin binder showed a significant reduction in the number of cycles to failure than the replacement of the same amount of WCO by the virgin binder. This could be due to the higher softening potential of the SO than WCO which confirms the result done by other researchers (Elkashef et al. 2018). The number of cycles to failure result indicated that 15SO modified binders had better fatigue cracking performance than all other binders. Based on the number of cycles to failure, all bio-oil modified binders performed better in fatigue cracking resistance than the virgin binder.

Table 2. 3 Fatigue Cracking Resistance of Modified Binders @ 19°C **Using** LAS

Binder type	Control (V)	15SO (85RAP)	15WCO (85RAP)	12.5SO_2.5V (85RAP)	12.5WCO_2.5 (85RAP)	100RAP
A .avg	12353.3	70966.7	39766.7	31442.8	39248.4	30407.6
St.D.	859.8	2263.8	5655.8	3943.5	4766.7	10447.6
COV (%)	6.96	3.19	14.22	12.54	12.15	34.36
Bavg.	-2.4760	-2.8873	-2.8570	-3.0137	-3.0606	-3.8520
St.D.	0.01	0.02	0.03	0.01	0.06	0.19
COV (%)	0.39	0.76	0.88	0.42	2.05	4.96
Nf_2.5avg	1279	5052	2908	1985	2384	854
St.D.	100.05	56.36	474.06	228.13	344.25	127.58
COV (%)	7.82	1.12	16.30	11.50	14.44	14.93
Nf_5avg	230	656	402	245	287	59
St.D.	19.47	52.16	72.00	26.27	49.05	0.62
COV (%)	8.47	7.95	17.91	10.70	17.08	1.06

2.5.1.3 Low-Temperature Cracking Resistance

Relaxation modulus and master curve slope for different PAV aged modified binders are shown in Figure 2.4 since the RAP binder is already aged, PAV aging of 100% RAP was not done in this study. Both bio-oil modified RAP binders without a virgin binder (15SO and 15WCO) were found to have significantly lower G (t) and approximately 10% higher m_r Value than the virgin binder. The SO modified binders had better low-temperature cracking resistance than WCO modified binders. This could be due to the relatively higher softening performance of SO than WCO. Replacements of 2.5% of both bio-oils by virgin PG 58-28 binder resulted in a 36% reduction in the low-temperature m_r values. This indicates that the bio-oils have better-softening potential than the virgin binder, which confirms previous research (Elkashef et al. 2018).

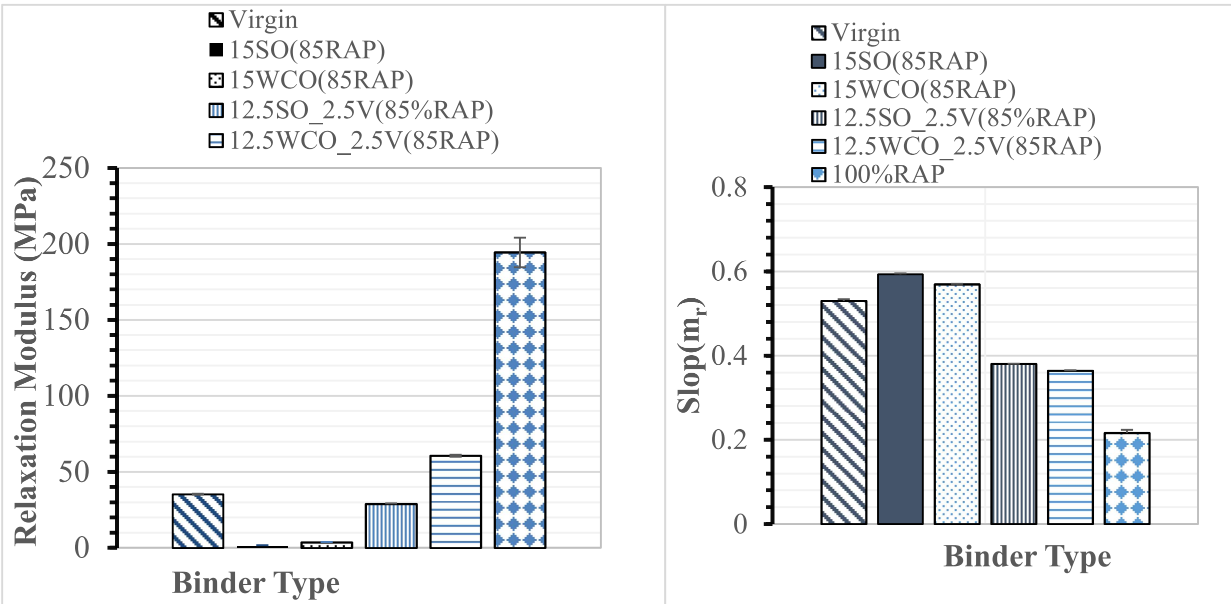
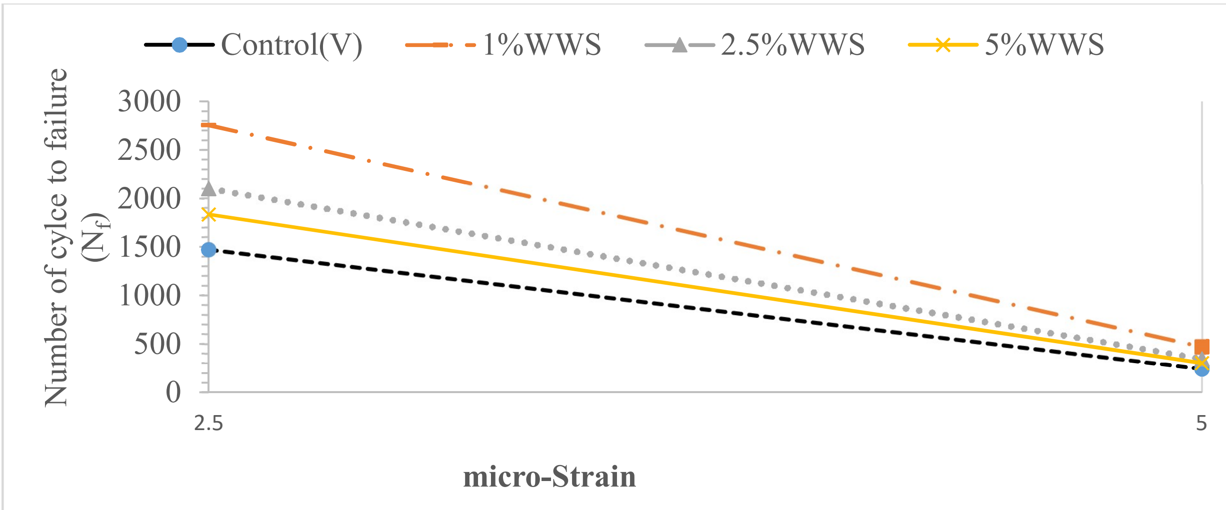


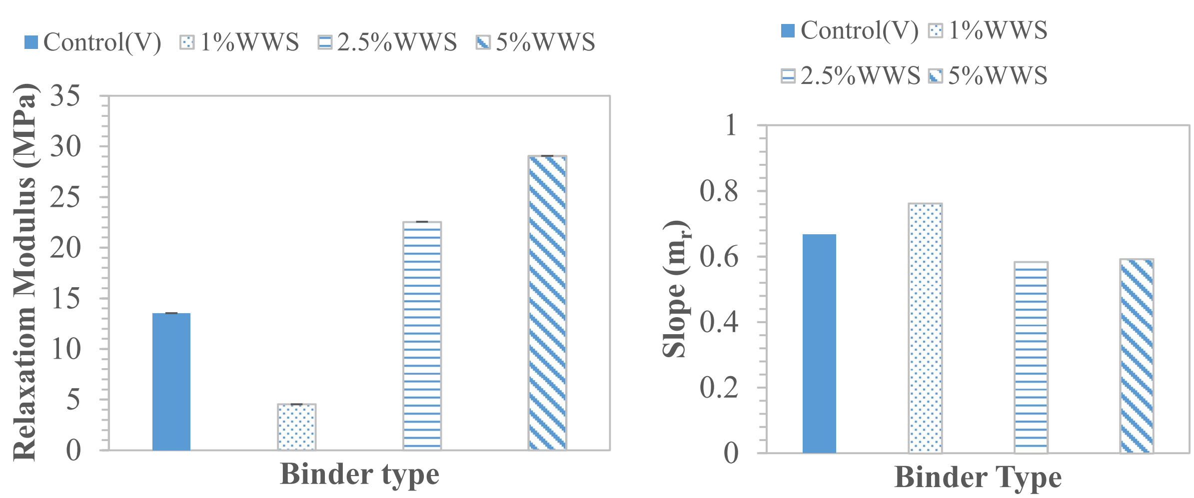
Figure 2. 4 Relaxation Modulus and Slope (m_r)

2.5.2 Effect of WWS on Binder

Figure 2.5 shows N_f result from LAS fatigue cracking resistance test and G (t) and m_r result from 4 mm parallel plate DSR low-temperature cracking resistance test. Effect of different dosages of WWS on PG 58-28 binder was evaluated. PG 58-28 binder was selected since the continuous PG grade of all modified binders is 58°F. Results indicated that 1%WWS by the weight of total binder dosage was found to be better fatigue and low-temperature cracking resistant. The WWS caused the binder to foam significantly. The foaming effect was expected due to the water content in WWS (FHWA, 2016, Suárez et al 2017). This indicated that WWS can potentially be used as a compaction aid.



(a) Number of Cycle to Failure of WWS Modified Binder



(b) Low -temperature Resistance of WWS Modified Binder

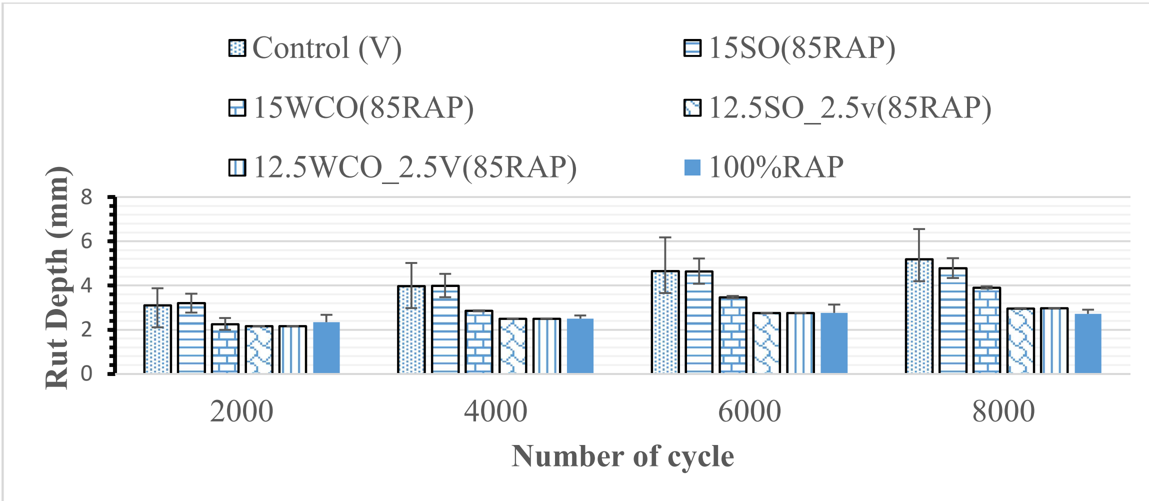
Figure 2. 5 Effect of WWS on Low-temperature Cracking Resistance of Modified Binder

2.5.3 Effect of Bio-oils on HMA

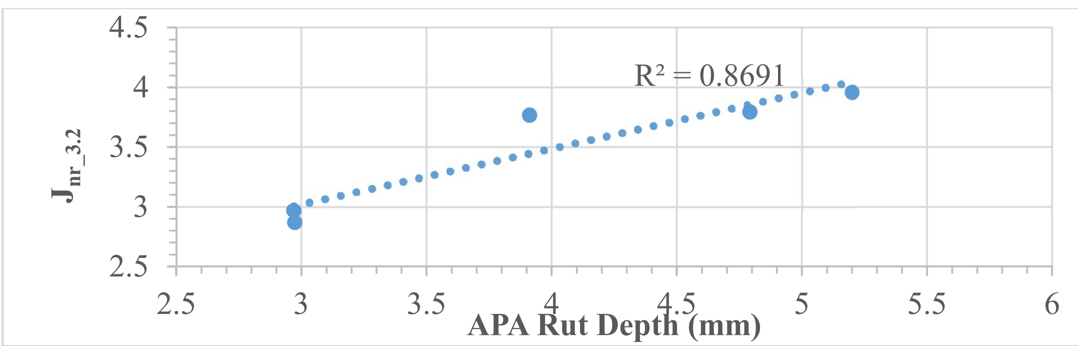
Based on binders' rheology results, all the four selected modifiers along with virgin and 100% RAP were selected to create HMA specimens. The same mix design was replicated and compacted at a temperature of 240°F using 1% WWS on bio-oils and control modified HMA and tested for cracking resistance. Three important performance properties of the asphalt mixes are discussed in the following sections.

2.5.3.1 Rutting Resistance

A summary of the APA test results of all modified and control HMA tested at 58° C are shown in Figure 2.6 (a). Three samples were tested for each modified binder HMA. Test results showed that the rut depths for all the specimens were well below the failure criterion, 7mm, used in the study. The maximum rut depth among the specimens is 5.19 mm observed for the virgin HMA specimen. The 15SO and 15WCO modified HMA showed 8% and 25% less rut depth than the virgin HMA. The 12.5SO_2.5V and 12.5WCO_2.5V modified HMA showed 42% and 37% less rut depth than the control mix. A 2.5% replacement of WCO by virgin showed approximately 15% less rut depth than the same percentage replacement of SO by the virgin binder. This could be due to the relative softening potential of SO compared to WCO. Generally, WCO modified HMA was found to have better rutting resistance than SO modified HMA. Figure 2.6 (b) shows that the correlation between MSCR Jnr_3.2 values of binder test and APA rut depth of the HMA. It's found that the MSCR test result correlates well with the APA rut depth with coefficient of determination (R^2) value 0.87.

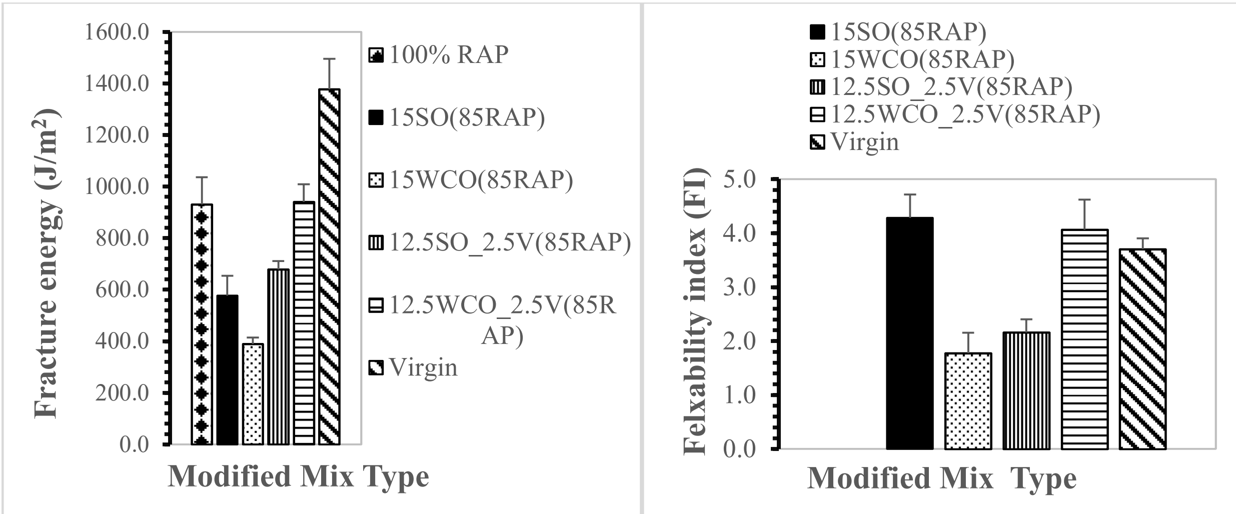


(a) Average Rut Depth



(b) Correlation between Binder MSCR Test and APA HMA Rut Depth

Figure 2. 6 Effect of Bio-oils on Rutting Resistance of HMA

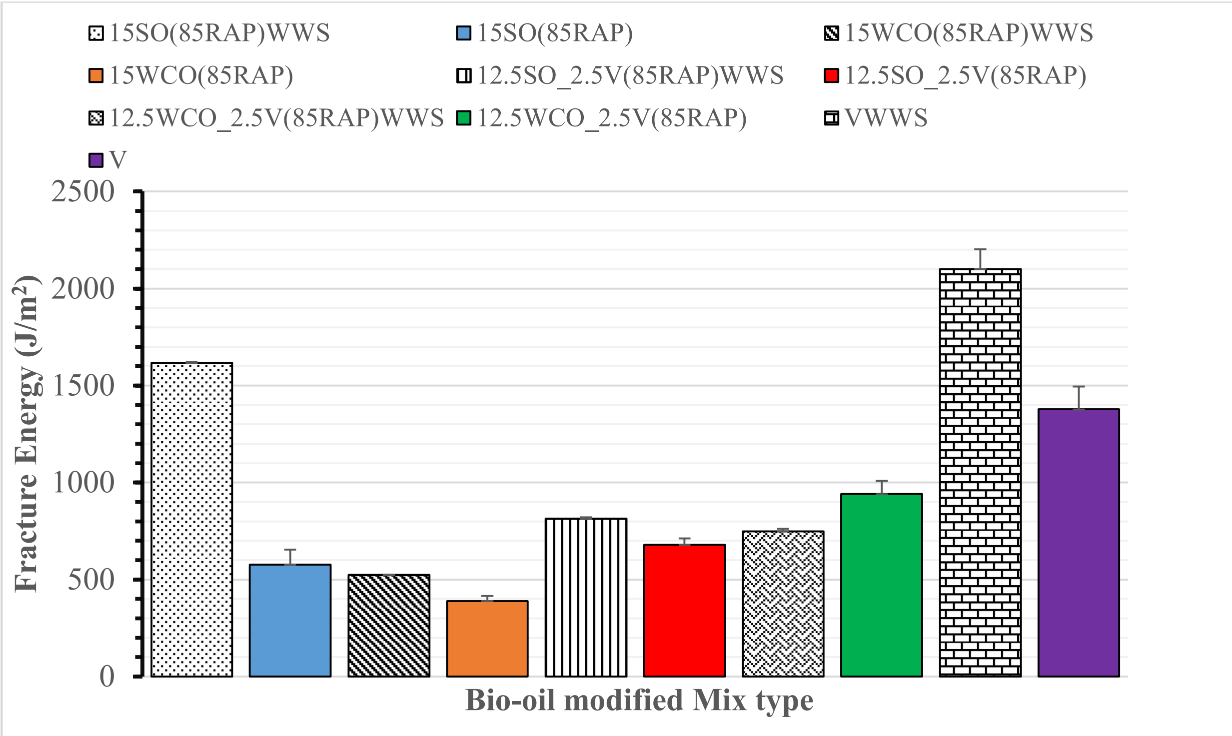


(a) Fracture Energy (b) Flexibility Index

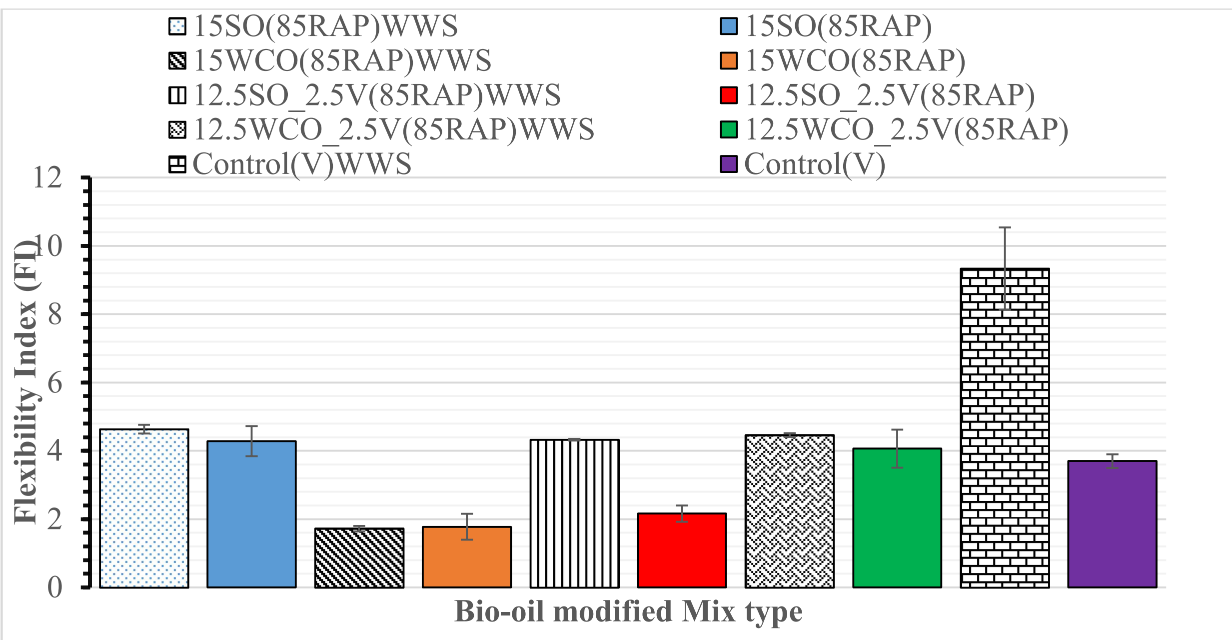
Figure 2. 7 Fracture Energy and Flexibility Index of Bio-oil Modified Mixes

2.5.3.3 Effect of WWS on Fatigue Cracking Resistance

All bio-oil modified HMAs were tested with 1% WWS by weight of the total binder. The samples were compacted at 240°F. Figure 2.8 (a) and (b) show the fracture energy and flexibility index comparison of the bio-oil modified binders with and without WWS, respectively. The results show that there is a significant improvement in fracture energy and FI for WWS modified mixes. The fracture energy increased by an average of 64% and 25 % for the 15SO and 15WCO modified HMA, respectively. Use of WWS on 12.5SO_2.5V modified HMA increased the fracture energy by 16% whereas the use of WWS with 12.5WCO_2.5V modified HMA decreased the fracture energy by 20%. This could be due to the relatively higher softening nature of SO than WCO. The FI value was increased for all WWS modified HMA. The FI value improved by 7% and 50% for 15SO and 12.5SO_2.5V modified HMA, respectively whereas by 3% and 9% for 15WCO and 12.5WCO_2.5V modified HMA, respectively. This indicates that SO works better with WWS than WCO. This also shows that the shortcoming of SO with virgin binder on fatigue resistance shown in this study and other research (Elkashef et al. 2018) can be mitigated by using WWS. Modification of the control HMA by WWS resulted in an increase in FI value by 60%. This indicates that WWS works better in the presence of the virgin binder. The FI value indicated that the application of 1%WWS on the bio-oil modified mix resulted in better fatigue cracking resistance than the control mix, expect for 15WCO HMA.



(a) Fracture Energy of Bio-oil Modified Mixes With and Without WWS



(b) Flexibility Index of Bio-oil Modified Mixes with and without WWS

Figure 2. 8 Effect of WWS on Fatigue Cracking Resistance

2.5.3.4 Low-temperature Cracking Resistance

Figure 2.9 Summarizes the low –temperature fracture energy of all bio-oil modified and control HMA. The 100% of RAP HMA showed the least low- temperature fracture energy as expected. All modified HMA except 12.5SO_2.5V HMA resulted in higher low-temperature fracture energy than the control HMA and passed the minimum threshold fracture energy value for intermediate traffic (460 J/m^2). This confirms results obtained by other researchers (Elkashef et al. 2018, Wen et al. 2013). In addition, 15SO and 15WCO modified HMA have the same low-temperature cracking resistance potential. The results exhibited 12.5WCO_2.5V HMA resulted in 12% higher low-temperature fracture energy than 15WCO HMA whereas 12.5SO_2.5V HMA resulted in a 37% reduction in fracture energy as compared to 15SO HMA. This could be due to the relative softening potential of SO than the virgin binder as confirmed by other study (Elkashef et al. 2018).

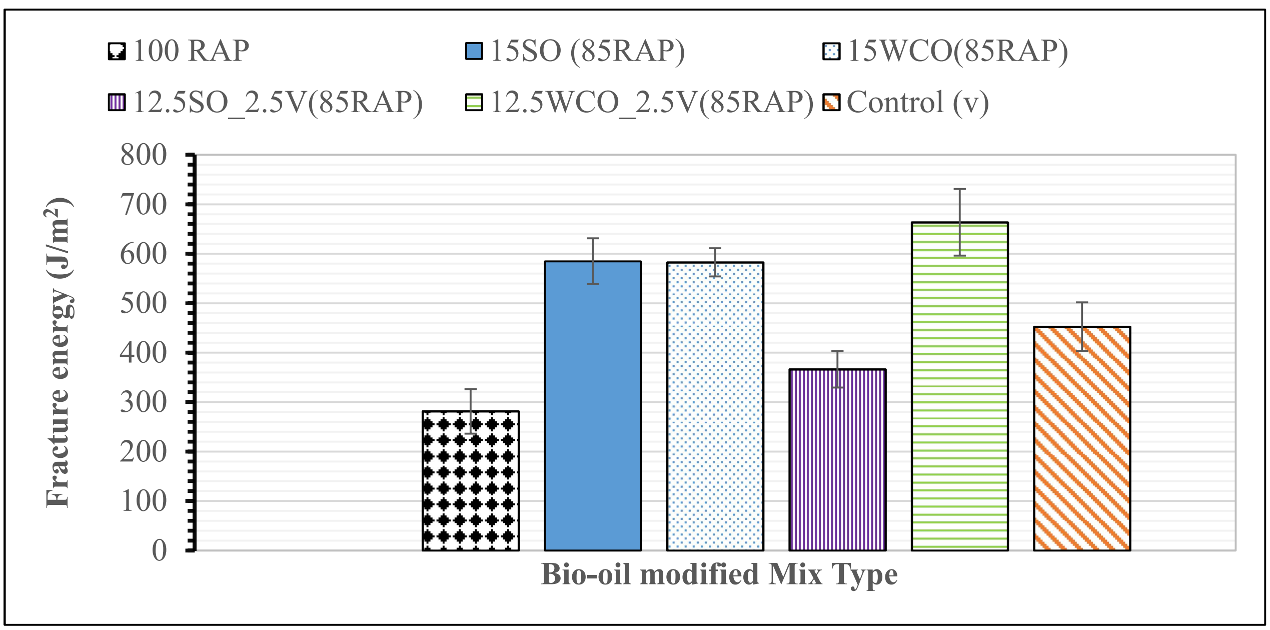


Figure 2. 9 Low- temperature Fracture Energy of Modified HMA

2.5.4 Effect of WWS on Low -temperature Cracking Resistance

Figure 2.10 shows the low-temperature fracture energy results of WWS modified HMA. The use of WWS increased fracture energy of 15SO and 15WCO by an average of 9% whereas increased by an average of 45% for 12.5SO _2.5V, 12.5WCO_2.5V, and control mix. This indicates that WWS works better in the presence of a virgin binder. This is expected since the foaming takes place with the binder. The result also indicated that application of 1%WWS increased the low-temperature cracking resistance of all modified binder HMA and virgin binder HMA significantly.

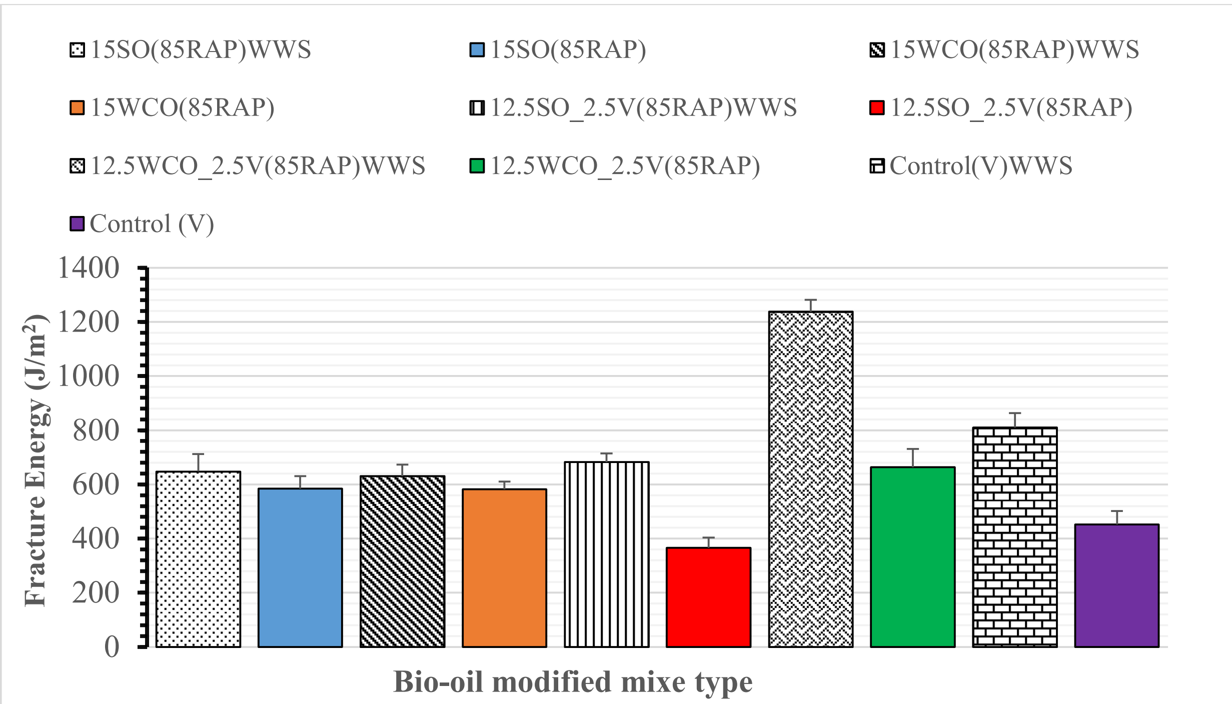


Figure 2. 10 Effect of WWS Low-temperature Cracking Resistance

2.5.4.1 Effect of WWS on Compaction Effort

Fig 2.11 shows the bulk specific gravity (G_{mb}) of the mix with and without WWS. The result showed that the G_{mb} of the mix with WWS is higher than that of the mix without WWS. This indicates that WWS improved the compatibility of the mix and confirms similar trend as zeolite based warm mix additive.

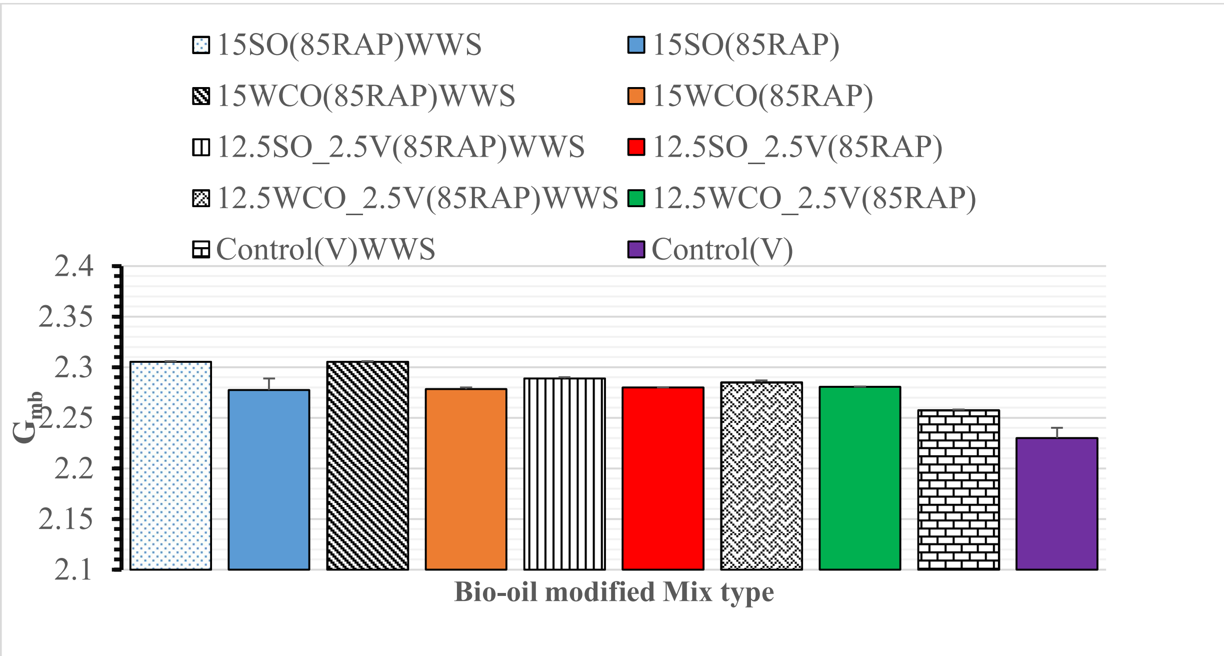


Figure 2. 11 Effect of WWS on the Bulk Specific Gravity of Modified Mixes

2.6 Summary

Based on this study the following summary is provided

- Based on binder and mix results, it was concluded that 15% SO and 12.5%WCO_2.5%V are better potential rejuvenators.

- Fatigue and low-temperature cracking resistance of modified high RAP HMA was better than control HMA and rutting resistance was maintained within the specification limit.

- The SO has better softening and rejuvenating performance than WCO at high, intermediate, and low-temperature when used without a virgin binder.

- Replacement of 2.5%WCO by virgin binder has a positive effect on rutting, fatigue cracking, and low-temperature cracking resistance whereas replacement of the same percentages of SO by virgin binder has a negative effect on fatigue and low-temperature cracking resistance, respectively. This could be due to better softening performance of SO as compared to WCO.

- By using 15 SO and 12.5WCO_2.5V as modifiers higher percentages of RAP (up to 85% binder base or 72.5% aggregate base) can be used with improved rutting, fatigue cracking, and low-temperature cracking resistance as compared to control HMA.

- The WWS works better in the presence of virgin binder as the foaming takes place with the binder.

- The use of WWS in mixes results in better cracking resistance and compaction effort at 50°F lower compaction temperature than the HMA. This indicates that WWS is a potential compaction aid additive.

Chapter 3 Use Wastewater Sludge (WWS) as a Performance and Compaction Aid on Field Mixed and Laboratory Compacted HMAs

3.1 Introduction

Wastewater treatment sludge (WTS) is an abundant byproduct of wastewater treatment. In the United States, about 6.5 million metric dry tones of WTS is produced annually (NEBRA 2007). Sustainability issues, such as shortages of disposal landfill and an increase in WTS disposal costs create an urgent need to find new, more economical, and environmentally sound methods of recycling WTS. Due to the moisture holding capacity, draining potential, high organic and complex inorganics composites WTS has been utilized in a building material products, such as brick, artificial lightweight aggregate, slugs, and Portland cement (DRRSS 2002; Spinasa 2001; Okuno and Takahashi 1997; Lin etal. 2012).

The disposable WTS comprises of alkali metal minerals of Al, Si, Fe, Ca, K and Mg. Furthermore, it contains organic material with a highly complex mixture of molecules coming from proteins and peptides, lipids, polysaccharides, and plant macromolecules containing phenolic structures (Anderson and Arthur 2001).Studies on the properties of WTS indicated that it consists of 59–88% weight by volume (w/v) of organic matter (Orhon and Artan 1995).

Mohammed et al. (1995) evaluated the potential usage of sewage sludge ash as a replacement for mineral filler in asphaltic paving mixes used in Bahrain using marshal test specifications. The study evaluated volumetric and high-temperature performance. Results indicated an increase in the compacted mix density and void filled with asphalt while the mix still satisfied the minimum stability requirement at an elevated temperature up to 80°C.

WTS can be used as a potential source for the production of the artificial zeolite-like chemical, which is characterized by cation exchange capacity with surface area and pore radius containing moisture and chemicals such as SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O (Ferreira et al.2003; Pazos etal. 2010; Gordon and Yang 1998).

Zeolites contain water in their structures driven off by heat and other solutions pushed through the structure, which made them suitable as Warm Mix Asphalt (WMA) additive that causes the foaming of asphalt binder (FHWA 2018). Burak etal. (2013) conducted a study on the comparison of natural zeolite, organic chemical, and synthetic zeolite WMA using DSR. The result indicated that for all additives the complex modulus (G*) increase with at higher frequencies and lower temperature, attribute to improve the elastic properties of the sample. Warm mix technologies such as the artificial synthetic zeolite can reduce mixing and compaction temperature by 54°F than the regular HMA (FHWA 2018).

WMA additives such as zeolites, advera, and alpha-min can be used at the same production temperatures as conventional HMA to lubricant and facilitate the compaction process of HMA, especially in HMAs of high RAP content, cold temperature construction region, and longer distance between project construction, and HMA production plant(Faheem et al. 2018).

A study was done on the use of zeolite advera on HMA and 20°F less WMA without and with 15% of RAP. Results indicated that both with RAP and without RAP WMA showed 0.74% and 0.4% increase in air void, respectively. Results also indicated that the compaction energy for the WMA was lower than the compaction energy for the corresponding HMA mixes (Goh and You 2011).

Mogawer et .al. (2012) Reported that the use of a wax-based WMA additive in mixes containing 40% RAP had minimal effect on the workability of the mixes with polymer modified and unmodified binder.

Tao and Mallick (2009) Compared the bulk specific gravity (BSG) of a 100% RAP mix against 100% RAP mix plus (1.5%, 2.0%, and 5.0%) Sasobitas well as a 100% RAP mix plus (0.3%, 0.5%, and 0.7%) Advera zeolite. All mixes were prepared at 125°C. The result indicated that a higher BSG value for the 1.5% Sasobit and 0.3% Advera mixes in comparison with the HMA without WMA additive, which indicates better compaction level.

Zhao et al. (2012) studied the rutting performance of plant-produced foamed WMA mixes with 0%, 30%, 40%, and 50% RAP ratios, and compared the rutting level with that of similar HMA mixes. Asphalt pavement analyzer (APA) test was used. The authors reported that at 0% RAP, the HMA mix had better rutting resistance than that of the WMA mix.

Studies conducted on the fatigue resistance of WMA mixes with high RAP contents did not seem to show a consensus on the effect of RAP incorporation on the fatigue life of WMA mixes. While some indicated the higher sensitivity of WMA than HMA mixes to RAP addition (Goh and You 2011), other researchers pointed out the variability in fatigue resistance with respect to binder modification (Mogawer et al. 2012).

For most zeolite based WMA, organics and fatty amides, and chemical WMA the average dosage ranges from 1-2% by weight of bitumen or 0.23-0.3 by weight of the total mix (Rubio et al. 2011; FHWA 2018).

Understanding the effects of WTS on the performances of pavement material will promote the consideration of WTS as a sustainable pavement additive. In this study the effect of

WTS on the performance of binders and field mixed, lab compacted HMA was investigated. Furthermore, the effect of WTS on the compaction effort and performance of HMA compacted at 50°F lower compaction temperature than the HMA was evaluated.

- To investigate the effect of WWS on the binders rutting, fatigue cracking and low-temperature cracking resistance performance.
- To analyze the effect of WWS on the rutting, fatigue cracking and low-temperature cracking performances of field mixed, and laboratory compacted HMAs
- To investigate the effect of WWS on a compaction effort and performance of field prepared HMA compacted at 50°F lower temperature than the HMA

3.2 Methodology

3.2.1 Test Design

The experimental design is summarized in Figure 3.1. It consists of two stages. The first stage is analysis of effect of 1%WWS on the binder performance rheology. Followed by second stage, to analyze the effect of 1%WWS on the field prepared, lab compacted HMA of binders used on stage one.

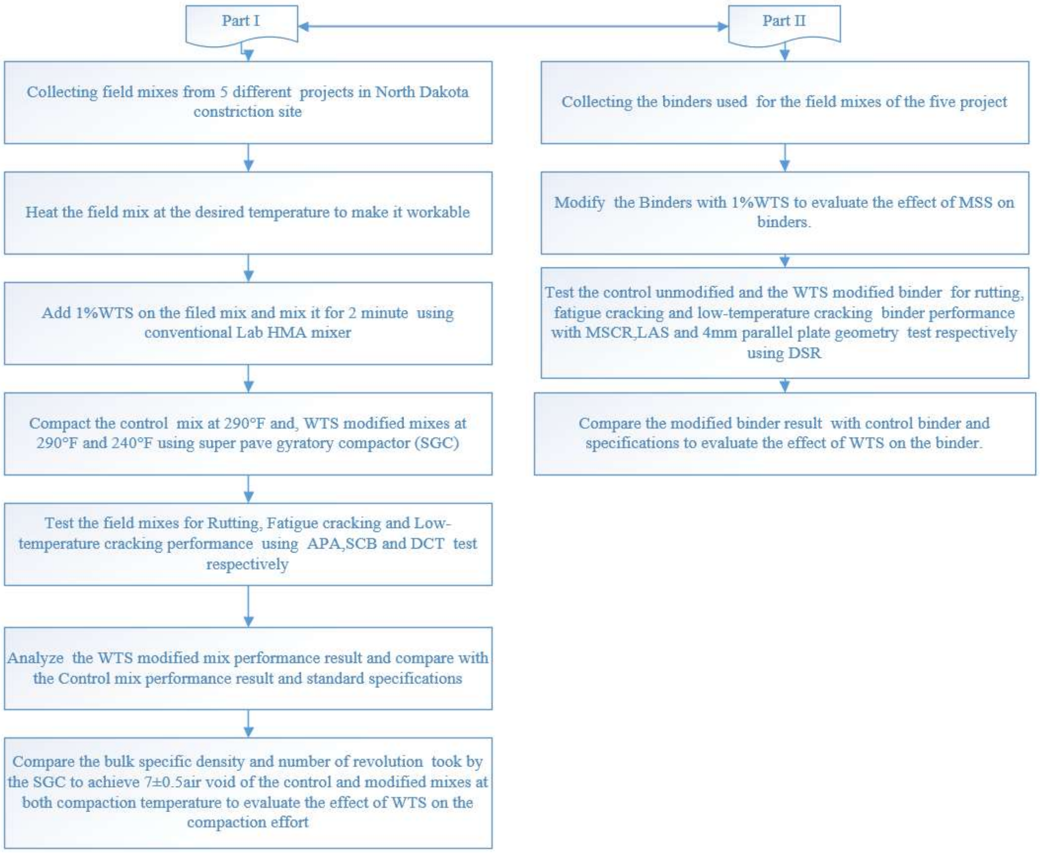


Figure 3. 1 Experimental Design

3.2.2 Material Selection

Field mixes from five different projects in North Dakota were collected. The projects were collected from districts of Minot (M), Valley City (VC), Williston (W) and Bismarck (B1and B2). The binder used for each project HMA also collected to analyze the effect of 1% WWS on the binder rheology. Waste water sludge WWS collected from North Dakota Wastewater treatment municipal was used with binders and field prepared HMA. The properties of WWS is shown in Table 3.1.

Table 3. 1 Properties of WWS

Material	WWS
Viscosity (Stokes)	NA
Specific Gravity @25°C	1.03-1.05
Acidic Value	0.1-0.2
Flash Point (°C)	250

Note: NA= Not available

3.2.3 Binder Tests

In this study binders used for the field mixes modified with 1%WWS along with unmodified control binder were tested to investigate the effect of WWS. MSCR high- temperature rutting, LAS intermediate-temperature fatigue and low–temperature thermal cracking resistance performance rheology test is conducted using DSR.

Table 3. 2 Test on Binders and Mixes

	Test on Binders			Test on Mixes		
Types of Modified Binders and Mixes	**Rutting (MSCR)**	**Fatigue Cracking (LAS)**	**Low-temperature Cracking(4mmDSR)**	**APA**	**SCB**	**DCT**
B1(C)	✓	✓	✓	✓	✓	✓
B1(WWS)@290°F	✓	✓	✓	✓	✓	✓
B1(WWS)@240°F				✓	✓	✓
M(C)	✓	✓	✓	✓	✓	✓
M(WWS)@290°F	✓	✓	✓	✓	✓	✓
M(WWS)@240°F				✓	✓	✓
W(C)	✓	✓	✓	✓	✓	✓
W(WWS)@290°F	✓	✓	✓	✓	✓	✓
W(WWS)@240°F				✓	✓	✓
B2(C)	✓	✓	✓	✓	✓	✓
B2(WWS)@290°F	✓	✓	✓	✓	✓	✓
B2(WWS)@240°F				✓	✓	✓
VL(C)	✓	✓	✓	✓	✓	✓
VL(WWS)@290°F	✓	✓	✓	✓	✓	✓
VL(WWS)@240°F				✓	✓	✓

Field mixed HMA projects were selected based on Performance Grade (PG) of binder used, percentages of RAP in the HMA, and optimum binder content. The mix design parameters and gradation of each field mix are shown in Table 3. 3.

Table 3. 3.Mix Parameters and Gradation of the Field HMA

Field HMA	B1	M	W	B2	VL
Binder Type	58S-34	64S-28	58V-28	58S-34	58S-28
%RAP	0	0	13	18	25
OBC	5.4	5.8	5.5	6	5.9
Gradation					
Size					
5/8"	100	100	100	100	100
1/2"	96.9	95	96.9	92.7	96.7
3/8"	85	82.5	87.2	82.4	85
#4	60.2	59.1	63.5	63.7	61.8
#8	42.8	37.1	40.9	42.6	45.7
#16	31	24.1	27.6	27.2	28.4
#30	20.7	15.2	18.6	17.6	18.6
#50	11.5	8.9	11	11.3	11.9
#100	7.1	6.3	7.2	7.3	7.3
#200	5.4	5.1	5.4	5.4	5.2

3.2.4 Mixing and Preparation

Field mix materials were heated and made workable. The WWS was kept at room temperature of 77°F before mixing. The heated HMAs mixed with 1% WWS for two minutes. The mixes were batched based on the weight required to achieve the specimen thickness and air void the requirement of 7±0.5. Each batch was oven heated to maintain the desired compaction temperatures. Two compaction temperatures were used to compact the WWS modified mixes, the HMA compaction temperature (290°F) and 50°F lower compaction temperature (240°F). The control unmodified HMA is compacted at a temperature of 290°F. The compaction is done using Superpave Gyratory Compactor (SGC). Compaction pressure and compaction angle were maintained to 600±60kPa and 1.25±0.02˚, respectively. A cylindrical sample of 150 mm diameter and 75 mm height was compacted for high-temperature rut depth analysis. For fatigue and low-temperature performance test 150 mm diameter and 100 mm, height was compacted initially. This, was further resized to 50 mm height according to the specification requirement. Volumetric properties of the specimens were tested to conform to the 7±0.5 % standard air void requirement.

3.2.5 Mix Testing

Rutting resistance was conducted in accordance with AASHTO T 340, SCB test was used to determine the fatigue cracking resistance of the mix following the Illinois-Flexibility Index Tester (I-FIT) protocol and DCT test was used to determine the low-temperature cracking resistance of the specimen. (Suleiman 2008, Al-Qadi et al.2015, Hussain et al. 2016).

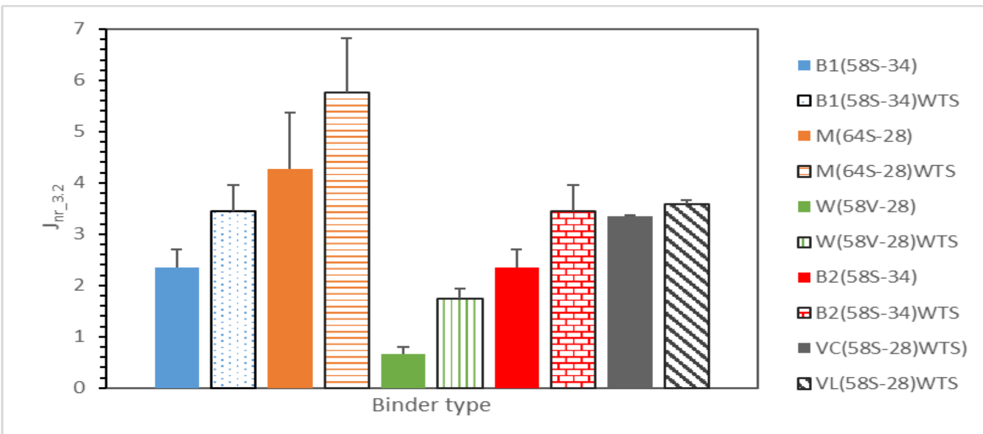
3.3 Results and Discussions

3.3.1 Effect of WWS on Binder Rheology

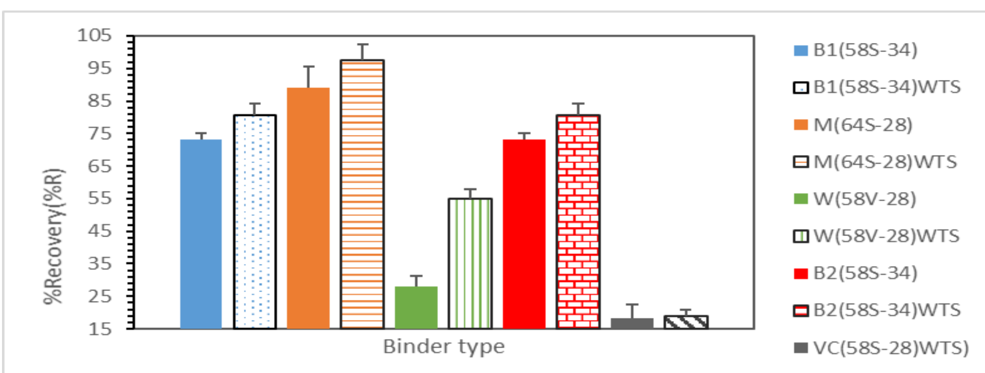
3.3.1.1 Rutting Resistance

The non-recoverable compliance (J_{nr}) value of the modified and control binders at 3.2 kPa is showed in Figure 3.1 (a). Results indicated that modification of all binders with 1%WWS resulted in an increase of $J_{nr\_3.2}$ value. This indicates that WWS softness and reduces the stiffness of the binders. Addition of 1%WWS resulted in an increase in the Jnr_3.2 value by an average of 61% and 32% for 58V-28(W) binder and 58S-34(B1and B2) binders respectively. PG 64S-28(M) binder has an average of 20% more Jnr_3.2 value than PG58S-28(VL) binder. This indicates that WWS has better-softening potential on a relatively stiffer PG binder. For the same PG binder modified with 1%WWS stiffer binder (W) has 60% more increase in the Jnr_3.2 value than the standard binder (VC). This could be due to the highly polymeric nature of PG58V-28(W) than

PG58S-28(VC) binder. Figure 3.1 (b). Shows the Percent recovery (%R) of all modified binders have a better recovery than the unmodified binders. The percent recovery of 1% WWS modified PG58V-28(W) binder is approximately 40% higher on the highly polymeric stiff binder. Results also a modification of PG 58S-28(B1 and B2), and PG64S-28(M) resulted in the same 9% increase in percent recovery. While PG58S-28(VC) binder increased by 3%. This shows that the effect of 1%WWS on the %r every increase with the same trend for both high temperature and low-temperature PG shifting.



(a) (a) The $j_{nr\_3.2}$ Result of the RTFO Aged Binders



(b) % Recovery (%R) result of the RTFO aged binders

Figure 3. 2 Effect of WWS on Rutting Resistance of Modified Binders;

3.3.1.2 Fatigue Cracking Resistance

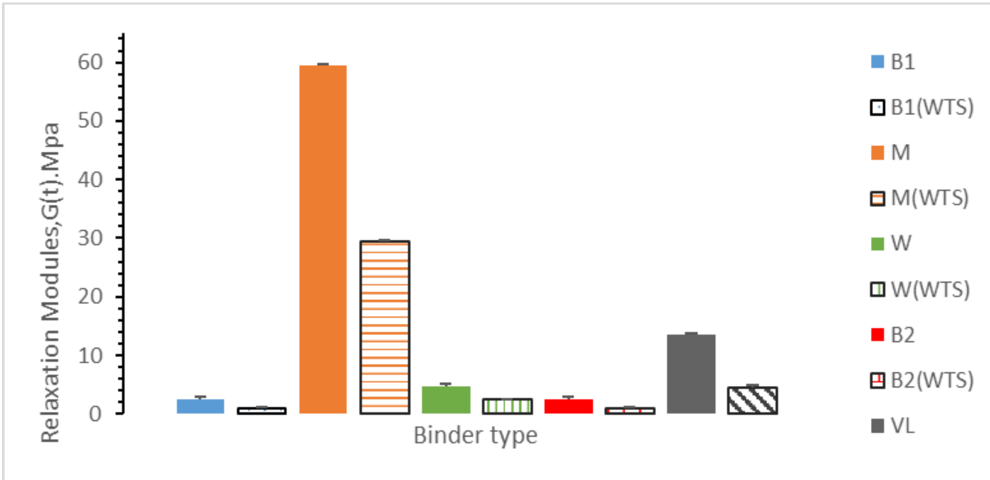
Linear Amplitude Sweep (LAS) test is conducted on the PAV aged modified and control binders at the intermediate testing temperature. Results of fatigue law parameters A and B and the number of cycle to failure at 2.5 and 5 micro shear strain level is presented in Table 3.3. The A value of PG58S-34(B1and B2), PG64S-28(M), PG58V-28(W), and PG58S-28(VC) binders increased by 9%, 45%, 35%, and 54% respectively. The absolute B value of PG58S-34(B1and B2), PG64S-28(M) and PG58S-28(VC) is increased by 0.4%, 0.45%, and 1.4%. While, the absolute B value increased by 4% for PG58V-28 (W) binder. This indicates that for the same PG grade binder the effect of 1%WWS on softer binderPG58S-28 (VC) exhibited 9% higher and 5%lower A and B fatigue low parameters than stiffer highly polymeric binder of PG58V-28 (W). PG58S-28 (VC) modified binder has 8% higher and 1% lower A and B values than PG64S-28 binder. This indicates that WWS has better fatigue performance effect on relatively stiffer binders. Modification of PG58S-28 binder with 1%WWS resulted in better fatigue performance than the control PG58S-34 (B1and B2) binder. A number of the cycle to failure at two applied micro shear strain levels (2.5and 5) results indicated the application of WWS on the binder has enhanced the fatigue cracking performance of the PG58-28 (VL) and polymer modified PG58V-28 (W) binders while it showed a negative effect on PG64-28 M). Application of WWS on PG58-34 (B1and B2) did not show any significant difference than the unmodified binder. This shows that the fatigue performance of the WWS modified binder is not consistent throughout all binders.

Table 3. 4 Effect of WWS on Fatigue Cracking Resistance using LAS of binders

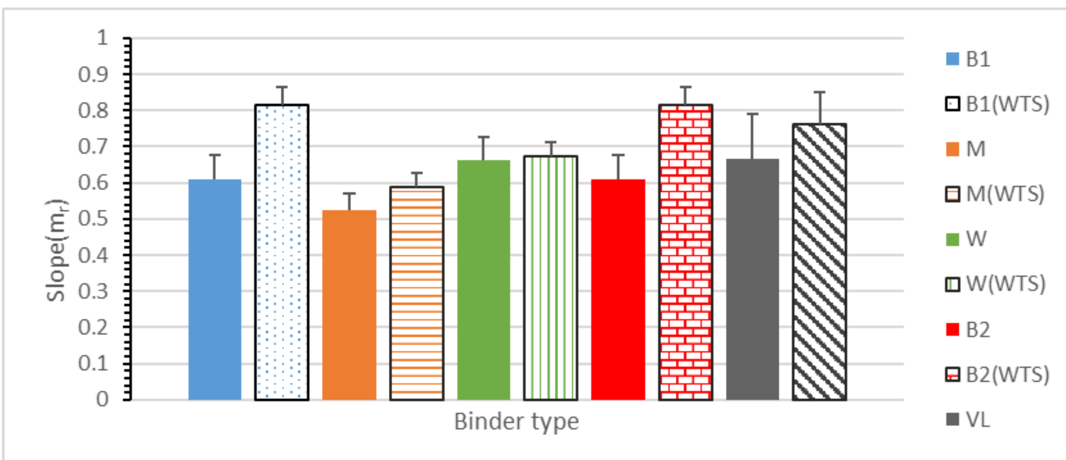
Binder type	**N_f@2.5**	**N_f@5**	**A**	**B**
B1(58S-34)	1268	211	1.4E+04	-2.59
B1(58S-34)WWS	1165	195	1.2E+04	-2.58
M(64S-28)	2351	430	2.3E+04	-2.45
M(64S-28)WWS	1286	237	1.2E+04	-2.44
W(58V-28)	2293	396	2.4E+04	2.54
W(58V-28)WWS	3248	524	3.6E+00	2.63
B2(58S-34)	1268	211	1.4E+04	-2.59
B2(58S-34)WWS	1165	195	1.2E+04	-2.58
VC(58S-28)	1473	242	1.6E+04	-2.60
VC(58S-28)WWS	2757	472	3.5E+04	-2.57

3.3.1.3 Low-temperature Cracking Resistance

Relaxation modulus and master curve slope for different PAV aged modified binder are shown in Figure 3.3 (a) and (b). Results indicated that modification of all binders with WWS showed significant improvement in low-temperature cracking performance. Relaxation modulus (Gt) result showed the application of 1%WWS decreased the G(t) value of PG58S-34(B1and B2), PG64S-28(M), PG58V-28(W), and PG58S-289VC) by 62%,50%,50%, and 66% respectively. While resulted in increase in m_r value by 25%, 11%, 2%, and12% respectively.PG58S-28(VC) and PG58S-34(B1andB2) binders showed better low-temperature cracking resistance performance than PG64S-28(M) and PG58V-28(W) binders. This indicates that WWS has better low-temperature performance on relatively softer binders. One percent WWS modified PG58S-28(VC) binder has 16% higher G (t) and 12%lower m_r value than 1% WWS modified PG58V-28(W) binder. This indicates that for the same grade binder WWS worked better on relatively low polymeric softer binders.



(a) Relaxation Modulus G (t)



(b) Slope (m_r) of the Binders

Figure 3. 3 Effect of WWS on Low-temperature Cracking Resistance of Binders

3.3.2 Effect of Bio-oils on HMA Mix

The effect of 1% WWS on the performance and compaction effect of the HMA was evaluated at HMA compaction temperature (290°F), and 50°F less temperature (240°F) than the HMA compaction temperature. Three important performance properties of the HMA mix measured in the tests are discussed in the following sections.

3.3.2.1 Rutting Resistance

Summary of the APA rut test results of all modified binder HMA tested at high-temperature PG for 8000 cycles are shown in Figure 3.4. Four samples were tested from each modified and control virgin HMA. At 290°F compaction temperature, the rutting resistance increased for the mixes with low optimum binder content (B1 and W) whereas rutting resistance decreased for relatively higher optimum binder content (M, B2, and VL). This is expected since the foaming and softening effect will be enhanced with the presence of higher content of binder. Generally, the rut depth of mixes compacted at 240°F is higher than that of the mixes that are compacted at 290°F.This could be as a result of increasing temperature facilitate the foaming and softening of the mix which helps further the compaction effort. All modified and control mix rutting values satisfied the rutting requirement limits set by this study. For the same binder PG and compaction temperature, 1% WWS modified mixes with 18% RAP (B2) has increased the rut depth by 28%. While HMA without RAP (B1) reduced the rut depth by 8%. This is not expected but this could be due to the higher optimum binder content of B2 than B1. Use of 1% WWS on the highly polymeric stiffer binder of PG 58V-28(W) HMA reduced the rut depth by 13%. While it increased the rut depth on the HMA with the same PG but softer binder 58S-28(V) by 23% at the same compaction temperature. This is expected as the stiffness of the binder improves the rutting performance, and as the softening effect of the WWS is more significant on softer binders as indicated in the binder result.

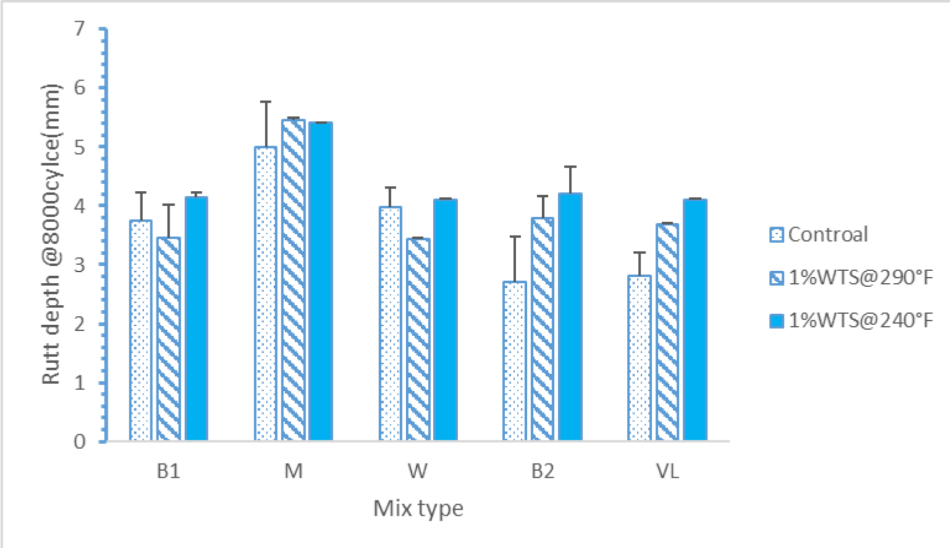
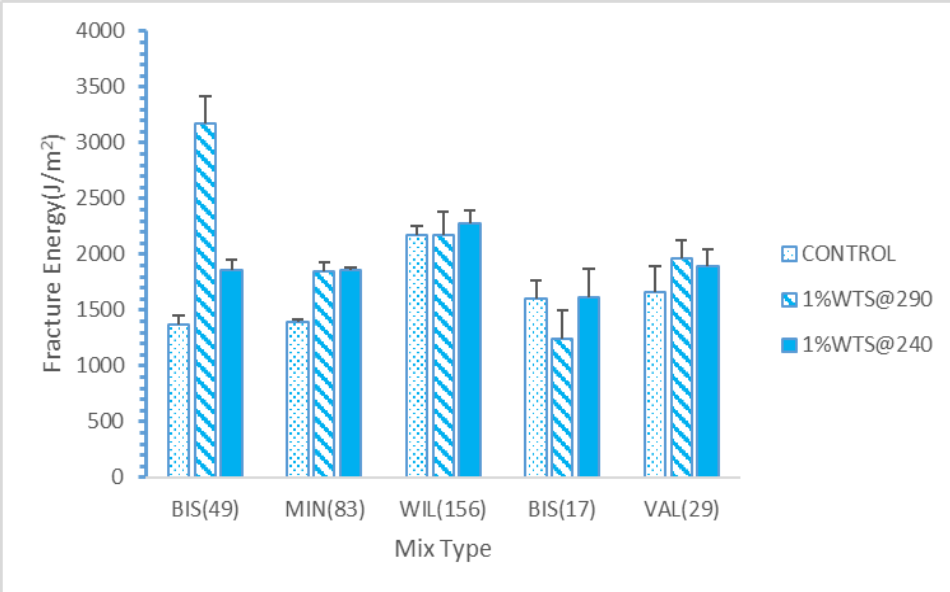


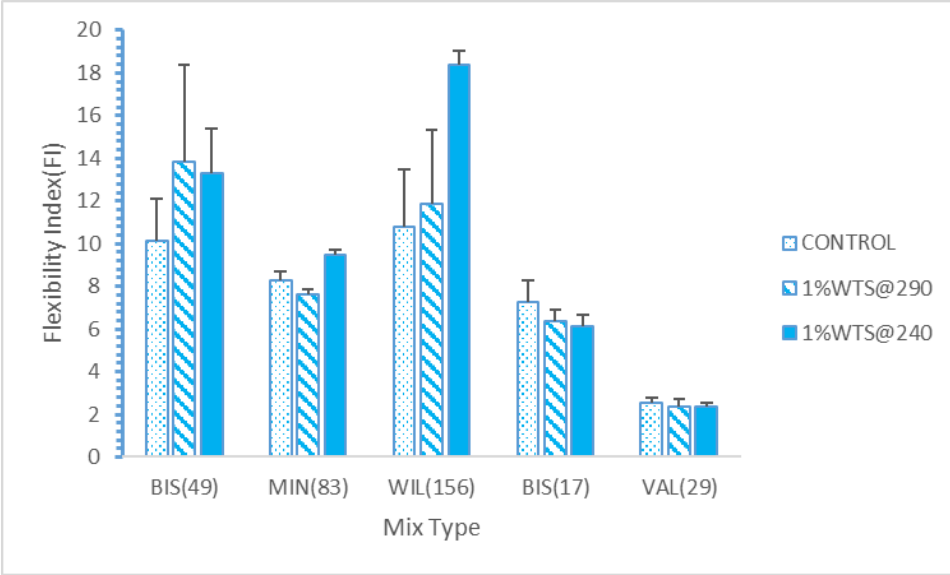
Figure 3. 4 Average Rut Depth

3.3.2.2 Fatigue Cracking Resistance

Figure 3.5 (a) summarizes the fracture energy of the mixes. Results indicated that for the same binder grade at 290°F compaction temperature the Fracture energy increased by 56% for the 0% RAP HMA (B1), and reduced for the by 24% for the mix with 18% RAP HMA (B2). This is expected as the presence of RAP stiffens the mix and reduce the fracture energy. Generally, for WWS modified HMA the fracture energy decreased with increase in RAP content. This is expected as the RAP stiffness the HMA. There is no significant difference for and the fracture energy of samples compacted at 290°F and 240°F except for the softer binder mix without RAP (B1). Figure 3.5 (b) summarizes the FI of the HMAs. The result indicates that WWS improved FI value for the softer binder without RAP HMA (B1) and for relatively highly polymeric polymer binder HMAs (W) at both compaction temperature (290°F and 240°F). While there is no significant effect on the other HMAs. This indicates that WWS works better in fatigue cracking performance for softer and relatively elastic binder HMAs



(a) Fracture Energy



(b) Flexibility Index

Figure 3. 5 Effect of WWS on Fatigue Cracking Resistance

3.3.2.3 Low-temperature Cracking Resistance

Figure 3.6 summarizes the low –temperature fracture energy of modified and control HMAs. Results indicated that at 290°F compaction temperature all mixes with 1%WWS showed improvement in low-temperature cracking performance except for PG58V-28(W) binder HMA. This could be due to relatively higher polymeric nature and low-temperature cracking performance of the binder that made the contribution of WWS insignificant. Modification of HMA containing RAP (B2 and VL) increased the fracture energy by an average of 21% and 28% respectively. While modification of mixes with the same low-temperature grade binder without RAP (B1and M) only increased the fracture energy by 2% and 9% respectively. This indicates that the effect of WWS on low-temperature is higher for the mixes with RAP. This is an unexpected result but this could be due to the higher optimum binder content of the HMAs with the RAP. The low-temperature fracture energy performance of the mix at 240°F is the same as the control mix for HMAs without RAP (B1and M). While, for HMAs with RAP (B2 and VC) the low- temperature fracture energy at 240°Fcompaction temperature is 12% higher than the respective control HMA compacted at 290°F. For 18% and 25%, RAP content HMAs (B2 and VC) WWS modified HMAs compacted at 290°F the fracture energy is 11% and 20%higher than HMAs compacted at 240°F. This could be possible as the increase in temperature makes the HMA more workable. For stiffer binder HMA modified with 1% WWS (M) the fracture energy at 290°F compaction temperature is 10% higher than WWS modified HMA compacted at 240°F.while, there is no significant difference on fracture energy of WWS modified B1 and W HMAs compacted at 290°F and 240°F. This indicates that the effect of WWS low-temperature fracture energy is dependent on is temperature, RAP content, and biodegrade.

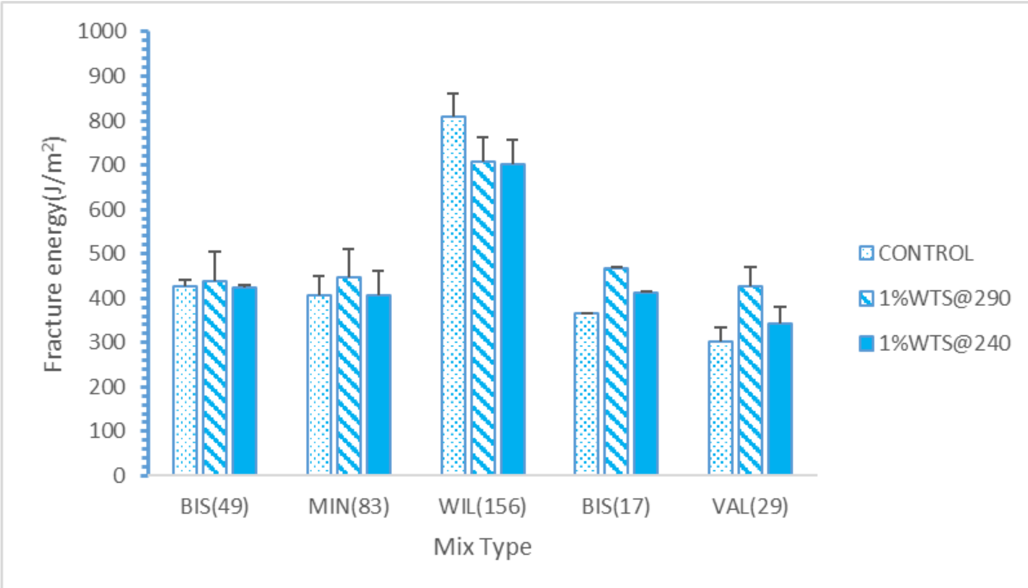
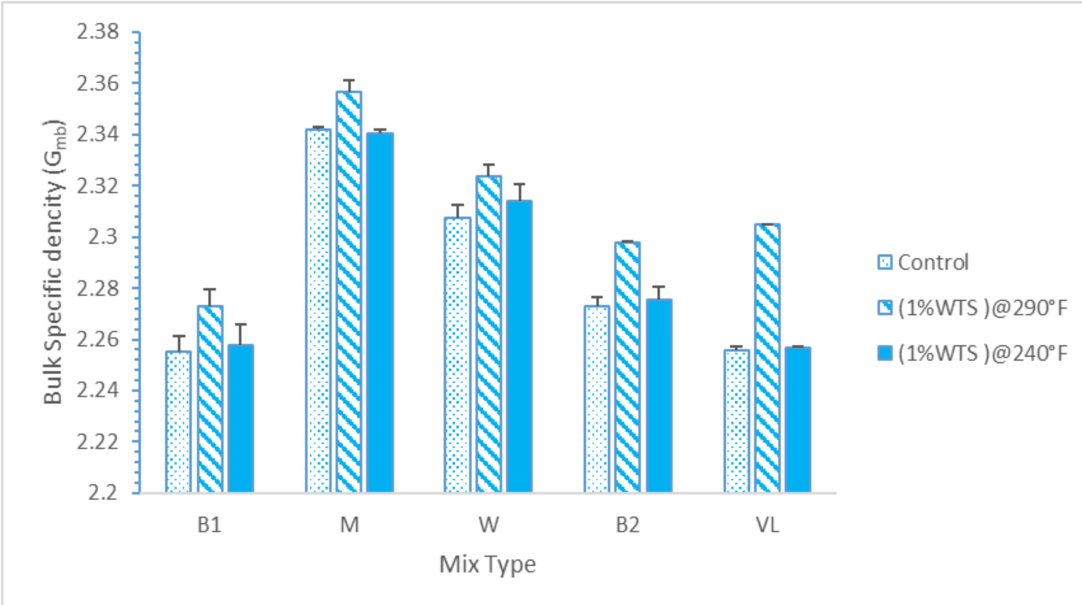


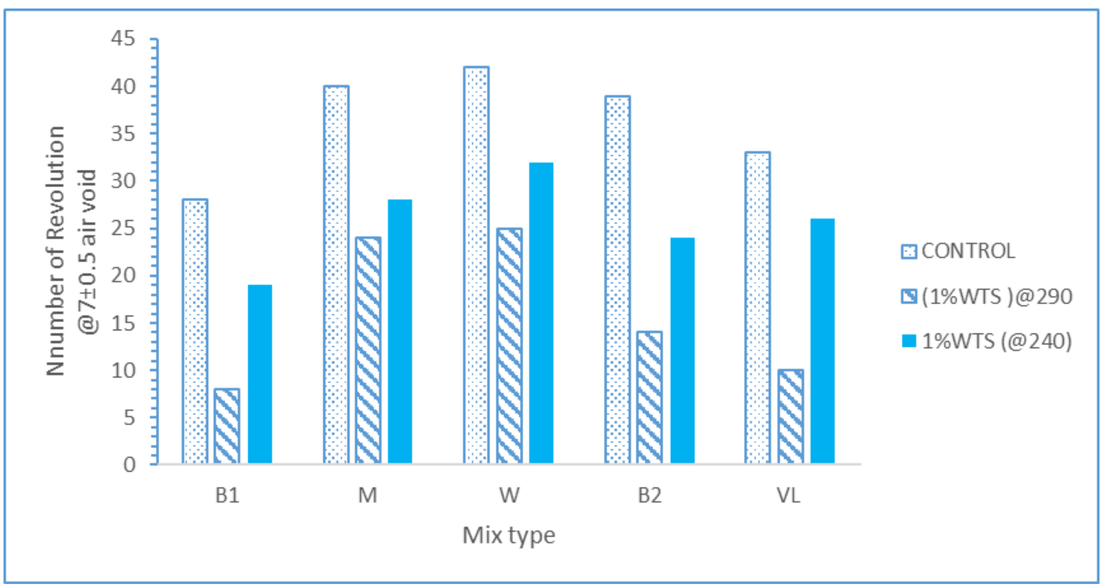
Figure 3. 6 Effect of WWS on Low- temperature Resistance of Modified Mixes

3.3.3 Effect of WWS on the Compaction Effort

Figure 3.7 (a) shows the bulk specific gravity of the WWS modified and control mixes from 5 projects at 290°F and 240°F compaction temperature. Results showed that the density of the 1%WWS modified mix at 290°F is larger than the control mix while G_{mb} value of the control and the 1%WWS modified mix compacted at 240°F is almost the same. This indicates that WWS helped the compaction effort. In addition, Figure 3.7(b) Shows the number of revolution took to compact the samples at the level of standard air void (7±0.5). Results indicated that at the 290°F compaction temperature the number of revolution for 1%WWS modified mixes is less than by an average of 60% than the control HMAs. While at the 240°Fcompaction temperature the number of revolution for the 1% WWS modified binder is 30% less than the control mix without WWS. This indicates less effect is required for the mixes for mixes modified with WWS. This will make WWS a potential compaction aid pavement additive.



(a) G_{mb} for 7±0.5 Air void



(b) **Number of revolution for 7±0.5 air-void**

Figure 3. 7 Effect of WWS on Compaction Level

3.4 Summary

The binder result showed that WWS applied at 1% improved for the fatigue cracking and low-temperature cracking performance of the binders. Based on the HMA performance test results, it can be summarized as:

- WWS improved the cracking potential especially in a mix containing RAP and maintained the rutting performance within the specification limit. This indicates that it can be used as a potential pavement rejuvenator. Based on the density and compaction effort result the study concluded that WWS could be used as a potential compaction aid and performance aid additive to reduce compaction effort and reduce compaction energy. WWS can be used as a compaction aid when the HMA compaction temperature drops up to 240°F for areas like North Dakota due to low-temperature construction season and long distance between mix plant and construction site

Chapter 4 Impact of Wastewater Treatment Sludge (WWS) on Cracking Resistance of HMA Mixes at Lower Mixing Temperature

4.1 Introduction

Wastewater treatment sludge (WWS) is an abundant by-product of wastewater treatment. In the United States, about 6.5 million metric dry tones of WWS is produced annually (NEBRA 2007). Sustainability issues, such as shortages of disposal landfill and an increase in WWS disposal costs create an urgent need to find new, more economical, and environmentally sound methods of recycling WWS. Due to the moisture holding capacity, draining potential, high organic and complex inorganics composites WWS has been utilized in a building material products, such as, brick, artificial lightweight aggregate, slugs, and Portland cement (Sede and Anderson 2002; Spinosa 2001; Okuno and Takahashi 1997; Lin et al. 2012).

The disposable WWS comprises of alkali metal minerals of Al, Si, Fe, Ca, K and Mg (Sede and Anderesn 2002). Studies on the properties of WWS indicated that it consists of 59–88% weight by volume of organic matter (Orhon and Artan 1995). The WWS can be further recovered through pyrolysis into ash, char, bio-absorbents, tar, and valuable biopolymers (Fytili and Zabaniotou 2008). WWS can be a potential source for the production of artificial zeolite like chemicals, which are characterized by cation exchange capacity with surface area and pore radius containing moisture and chemicals such as, SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O (Ferreira et al. 2003; Pazos et al. 2010; Gordon and Tsung-Yin 1998). Melaku et al. (2019) concluded WWS can be used as a compaction aid while improving cracking resistance of the mixes. These findings initiated the evaluation of WWS as Warm Mix Asphalt (WMA) additive in this study.

Sol et al. (2019) evaluated the effect of industrial zeolite by-products (obtained from the petroleum refining process) in the manufacturing of WMA by the technique of indirect bitumen foaming while the design and evaluation of the mechanical performance of WMA that included these by-products was compared with that of traditional hot mix asphalts (HMAs). The results indicated that the zeolite mixes resulted in lower cracking resistance than the control HMA. Other studies done on the effects of Sasobit and wax organics WMA additives on asphalt mixtures at low-temperature showed that all WMA additive negatively impact the low-temperature cracking performance compared with the control mixture(Liu and Peng 2012; Edwards et al. 2006; Medeiros et al. 2011).

For most zeolite- based WMA, organics and fatty amides, and chemical WMA the average dosage ranges from 1-2% by weight of optimum bitumen content (Rubio et al. 2011; FHWA 2018).

4.2 Problem Statement

Studies indicated that RAP usage during the 2017 construction season was estimated to have reduced the need for 3.8 million tons (21.5 million barrels) of asphalt binder and more than 72 million tons of aggregate, with a total estimated value of more than $2.1 billion (Kent and Copeland 2017). Even though the use of RAP has significant advantages its practical usage is limited to an average of 25% in most states, particularly those in the cold climate regions, such as North Dakota (Kent and Copeland 2017). The main reason for the limited usage of higher percentages of RAP material in HMA is due to the concern of increasing stiffness of the mixtures with high percentages of RAP, which is triggered by aged asphalt binder contained in RAP. As RAP content increases, cracking resistance decreases in general (Gedafa et al. 2018). Studies showed that negative effect of the RAP content on fatigue cracking performance can be mitigated by using WMA additives (Mogawer et al. 2012; Zhao et al. 2012).

Understanding the use of WWS as a WMA additive can open a door for detail investigation of WWS to improve the sustainability of pavement construction. In this chapter the effects of 1.5% WWS as a WMA additive on fatigue cracking and low-temperature cracking performance of control (0% RAP), 40%RAP and 60%RAP mixes were investigated. The WWS modified mixes were mixed at 40°F below control HMA mixing temperature. Two sources of RAP were used in this research: RAP from highway 17 and RAP from I-29. A 1.5% WWS dosage was selected based on lab experiment and literature.

4.3 Objectives

The main objectives of this chapter are:

- To analyze the effect of WWS on the fatigue cracking and low-temperature cracking resistance of the control (0%RAP), 40% RAP, and 60% RAP HMA.
- To investigate the potential use of WWS as a WMA additive.

4.4 Methodology

4.4 .1 Experimental Plan

RAP sources and mix design from Highway-17 and I-29 project were used to evaluate the effects of WWS on the fatigue cracking and low-temperature cracking performance in this study. High temperature continuous temperature, LAS intermediate temperature and 4 mm parallel plate low-temperature tests were conducted on the extracted RAP binder of two sources to evaluate the aging conditions of the RAPs Three different mixes were prepared in the lab with 0% RAP (control), 40% RAP, and 60% RAP content modified with 1.5% WWS. The WWS modified mixes were prepared at 260°F, which is 40°F less than the control HMA mixing temperature (300°F). All mixes were short-term aged for 2 hour at the compaction temperature of 290°F. Superpave gyratory compactor was used to compact 150 mm diameter and 100 mm height samples volumetric properties of the specimens were tested to confirm to 7±0.5 % air void requirement. The samples were resized to 50 mm thickness according to the standard specification requirement. Fatigue cracking and low -temperature cracking resistances were determined using SCB and DCT, respectively.

4.4.2 Material Selection

The aggregate and RAP were collected from North Dakota Department of Transportation (NDDOT) I-29 and highway-17 projects. The mix designs used for those projects were adopted. PG 58-28 virgin binder was in both RAP source. The WWS was collected from Grand Forks Wastewater treatment plant. The properties of WWS is shown in Table 4. 1.

Table 4. 1 Properties of WWS

Property	Result
Viscosity (Stokes)	Not applicable
Specific Gravity @25°C	1.03-1.05
PH value	7.6
Flash Point (°C)	250

4.4.3 Mix design and Sample Preparation

Mix design of the control HMA is shown in Table 4. 2. The 40% and 60 % RAP is replaced in the mix and the remaining aggregates were distributed according to the Job mix formula. Filler material was not controlled in this project, while gradation of the mixes was kept within Superpave requirements. The amount of virgin binder was reduced to account the binder from the RAP. The virgin aggregate was heated at 325°F for six hrs. And the RAP material was heated at 230°F for two hrs. The virgin binder was heated at 270°F and WWS was kept at room temperature. The virgin and RAP aggregate were mixed together. The aggregates are then mixed with the virgin binder for control HMA mixes. For WWS modified mixes, WWS was mixed with binder prior to mixing with the aggregates following national asphalt pavement association practical guide standard for high RAP mixes (Newcomb et al. 2007). WWS modified mixes were prepared at 260°F, which is 40°F lower temperature than the control mixing temperature.

Table 4. 2 Mix Design Parameters

Materials	Percent	
	Mix with highway 17 RAP	**Mix with I-29 RAP**
Binder	6.4	5.4
RAP Asphalt Content	7.6	6.2
Crushed Rock	38	24
Natural Fines	25	12
Washed Dust	19	41
Dirty Dust	18	23

4.5 Testing

4.5.1 RAP Binder

The RAP binders were extracted in the laboratory following the ASTM D 2172/D 2172M standard (ASTM 2011) and ASTM D 1856-95a Standard (ASTM. 2003) procedure jointly. EnSolv-EX, an n-Propyl Bromide (nPB) solvent, was used in the extraction process. RAP binder from the extracted solution was then recovered by the Abson Method following ASTM D 1856-09 standard.

4.5.2 Binder Test

Continuous high temperature performances grad testes, Linear Amplitude Sweep (LAS) and 4mm DSR low-temperature rheology tests were conducted on the RAP binders to analyze the rutting, fatigue cracking and low –temperature cracking performance.

4.5.3 Asphalt Mix Test

The SCB test was used to determine the fatigue cracking resistance of the mix following the Illinois-Flexibility Index Tester (I-FIT) protocol. Two parameters are used to compare the fatigue cracking performance between the mixes. DCT test was used to determine the low-temperature cracking resistance of the specimen. The test was conducted in accordance with ASTM D 7313 (ASTM 2013). It determines the fracture energy (G_f) to measure the cracking resistance of the HMA specimen. The specimens were conditioned for eight hours as well as tested at low – temperature performance grade PG + 10°C of the binders.

4.6 Results and Discussions

4.6.1 RAP Binder Test Results

Table 4.3 shows the continuous high temperature performance grade, Linear Amplitude Sweep (LAS) number of cycles to failure for fatigue cracking performance and 4mm DSR low-temperature cracking performance of the RAP binder. Results showed that I-29 RAP binder has lower high temperature continuous performance grade, better number of cycles to failure at 2.5% and 5% strain level, and better low- temperature performance than highway 17 RAP binder. This shows that I-29 RAP is relatively softer and less aged RAP than highway 17 RAP.

Table 4. 3. RAP Binder Rheology Test Result

RAP type	High temperature continuous grade(°C)	LAS fatigue Performance		Low-temperature cracking performance	
		$N_{f2.5}$	N_{f5}	G(t),mpa	Mc
I-29	75.8	4945	661	36	0.44
Highway 17	84.2	381	37	24	0.26

4.6.2 Fatigue Cracking Fracture Energy

Figures 4.1 and 4. 2 show the fatigue cracking fracture energy results of mixes with RAP from Highway 17 and I-29. Generally, 1.5% WWS by weight of total asphalt content modification of Highway 17 and I-29 RAP mixes, have a positive effect on the fracture energy. For mixes with RAP from highway 17 as shown in Fig .1 the fracture energy decreased by 11% for the virgin mix, and increased by 30% and 34% for 40% RAP and 60% RAP content mixes, respectively. This shows that the fracture energy increases with the increase in RAP content. This could be, due to the stiffness of the mix with high RAP content that might resulted higher Peak load which, leads to higher fracture energy. This is expected since the presence of RAP increase the stiffness and maximizes the peak load this is also an indication that fracture energy alone is not sufficient to compare fatigue cracking performance between the mixes, especially for mixes containing high RAP. The fracture energy of 40%RAP and 60% RAP mix modified with 1.5% WWS of total binder weight is 15% higher than the unmodified 0%RAP mix that shows better load damage resistance.

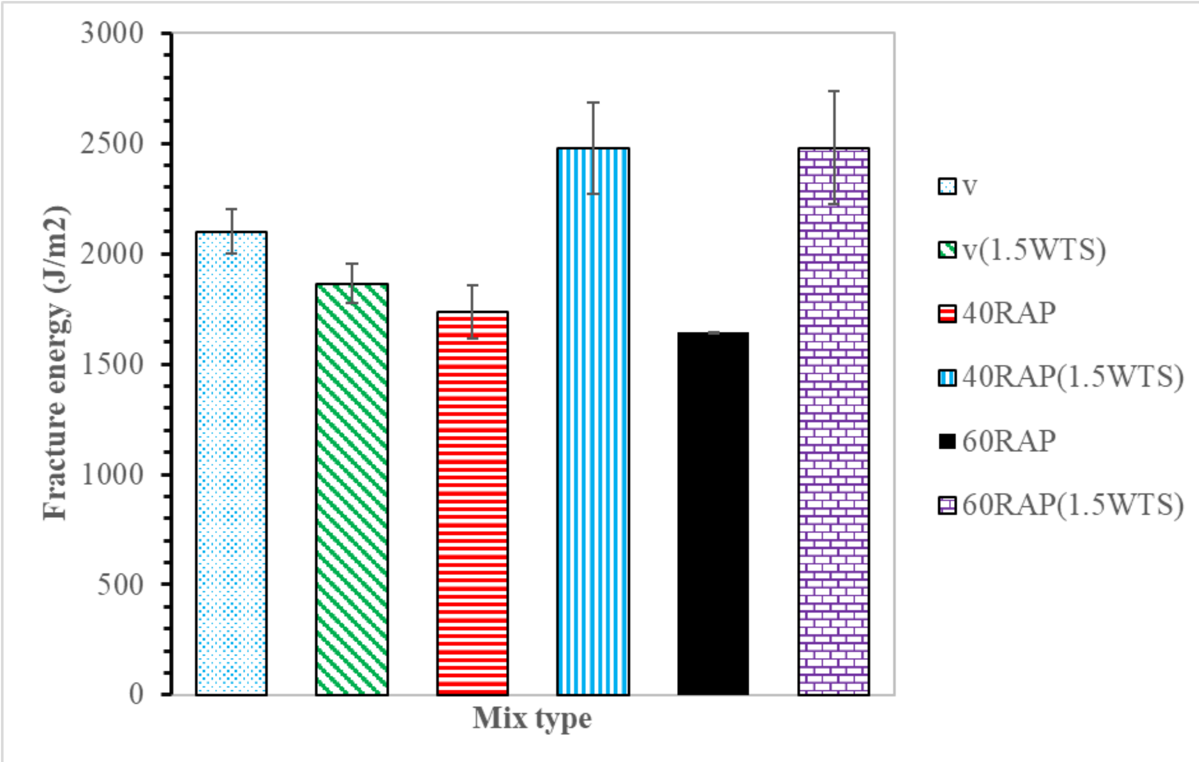


Figure 4. 1 Fracture Energy of Highway 17 RAP Mixes

For mixes with RAP from I-29the fracture energy increased by 18%, 30%, for 0% RAP and 40%RAP mixes while reduced by 25% for 60% RAP mix as shown in Figure 4.2. The fracture energy of unmodified control mix is 27% higher and 37% lower than 60% RAP and 40% RAP content WWS modified mixes respectively. This shows that 1.5% WWS by total binder weight modification can be used to improve the fracture energy of the mix with the RAP and its effect decreased with increase in RAP content. The fracture energy result is not consistent between highway 17 RAP mixes and I-29 RAP mixes. This could be due to source of RAP and mix design parameters such as gradation and optimum binder content.

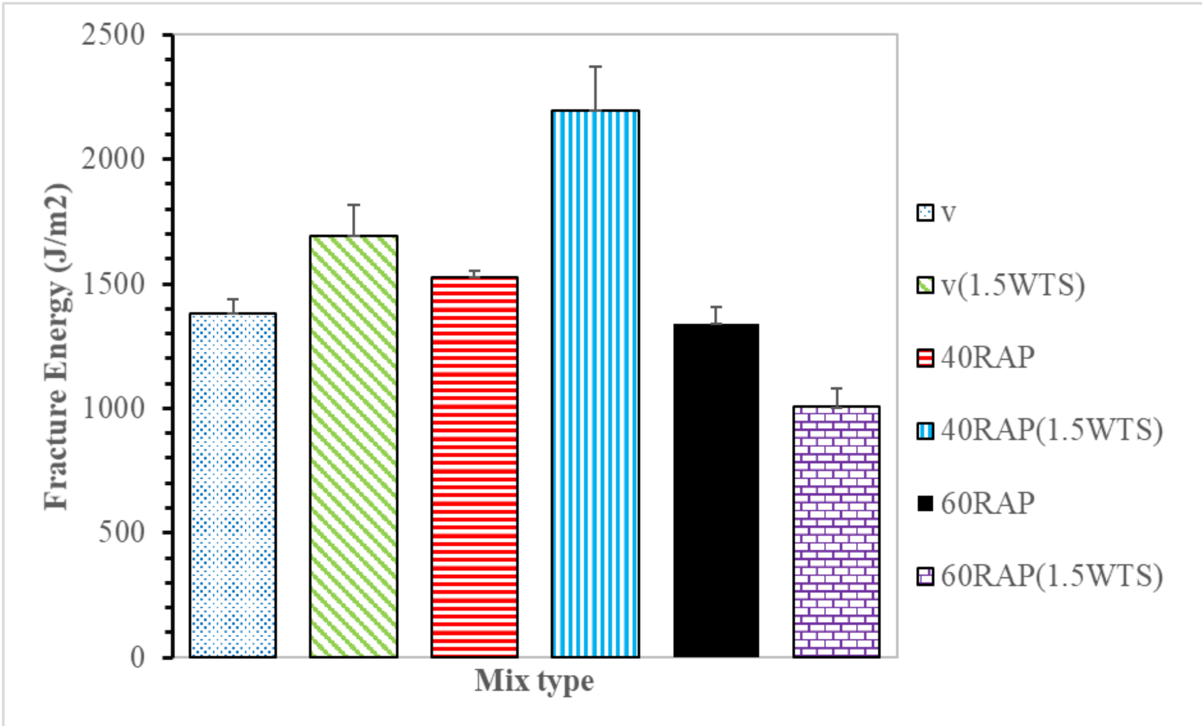


Figure 4. 2 Fracture Energy of I-29 RAP Mixes

4.6.3 Fatigue Cracking Resistance in terms of Flexibility Index

Figure 4. 3 and Figure 4. 4 shows the flexibility index of mixes with highway 17 RAP and I-29 RAP, respectively. Three samples were tested for each mix and the result is summarized

For mixes with RAP from Highway 17 shown Figure 4. 3. Modification of 1.5% WWS by total binder weight resulted in an increase of FI value by 13%, 70% and 84% for 0%, 40% and 60% RAP mixes respectively. The increase in FI value is more significant for the mix with RAP than the mixes control (0% RAP) mixes. This could be an indication that as the mix gets stiffer the effectiveness of WWS is more perceptible. This also confirms the same trend as other research done on the effect of WMA additive on the mixes with the RAP (Goh et al. 2011). Other factors such as gradation also might have contributed for the result as well. Modification of 40% RAP and 60%RAP mixes by 1.5% WWS of total binder weight changed the fatigue cracking performance flexibility index from 1.8 and 0.85 to 6.12 and 5.2 respectively. Improving the fatigue performances of the mixes from poor and brittle to the good and fair fatigue cracking performance mixes respectively, according to the criteria set by the researches (Ozer et al. 2016). the result also confirms that WWS have similar effect to the WMA additives used by other studies (Mogawer et al. 2012; Goh et al. 2011).

For mixes with RAP from I-29 shown in Figure 4. 4 the FI improved by 5%, 35% and 72% for 0%, 40%, and 60%RAP mixes, respectively. This shows similar trend with Highway-17 RAP mixes. That is, WWS has a positive effect on improving the fatigue cracking performance and the FI increases with the increase in RAP content. FI value of 40% RAP mixes modified with 1.5%WWS of total binder weight has nearly the same performance as that of the unmodified 0%RAP mix, which is only 9% difference. Modification of 40% and 60%RAP mixes by 1.5WWS changed the fatigue cracking performance FI values from 2.16 and 0.57 to 3.33 and 2.02 respectively. Improving the fatigue performances of the mixes from poor and brittle to the fair fatigue cracking performance mixes. According to the criteria set by the researches (Ozer et al. 2016). Even though I-29 RAP binder have better fatigue cracking performance and less aging than highway 17 RAP binder The FI value of mixes with I-29 RAP is significantly less than that of highway 17 RAP mixes. This could be due to higher binder content of mixes with highway 17 RAP than mixes with I-29 RAP beside the variation in gradation. This is also an indication that WWS works better for stiffer mixes with higher binder content. Application of WWS on the two RAP source mix significantly helped to mitigate the negative fatigue cracking performance induced by the RAP content and the improvement is also increased with increase in RAP content that confirms to similar result with WMA additives effect on mixes with RAP done by other studies (Mogawer et al. 2012; Goh et al. 2011).

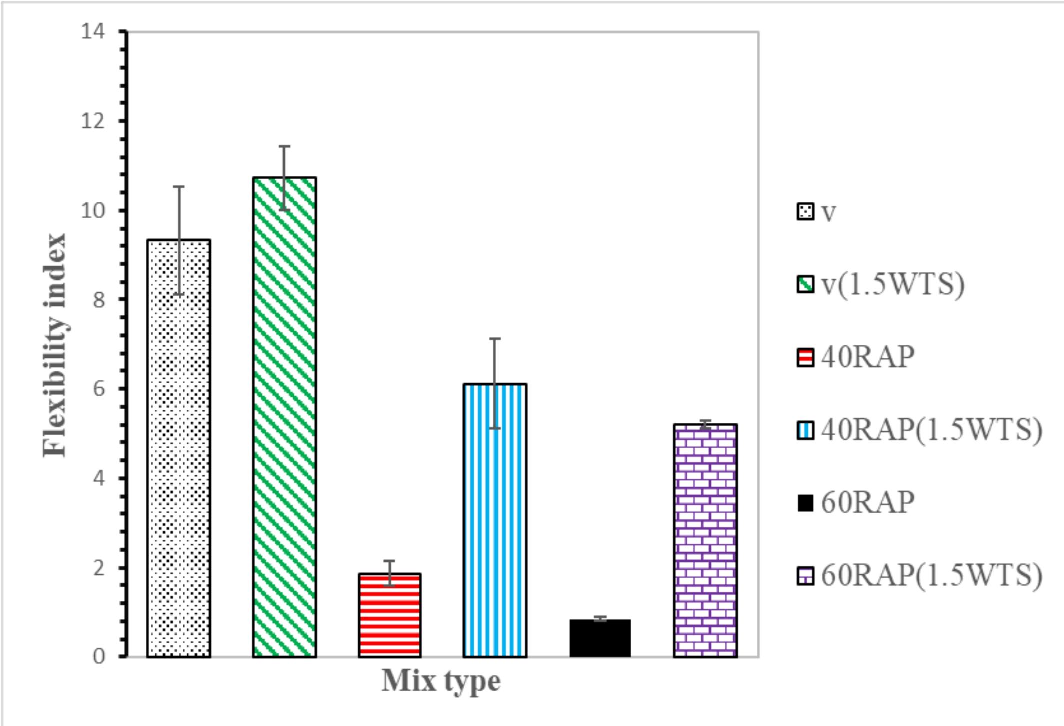


Figure 4. 3 Flexibility Index of Mixes with Highway 17 RAP

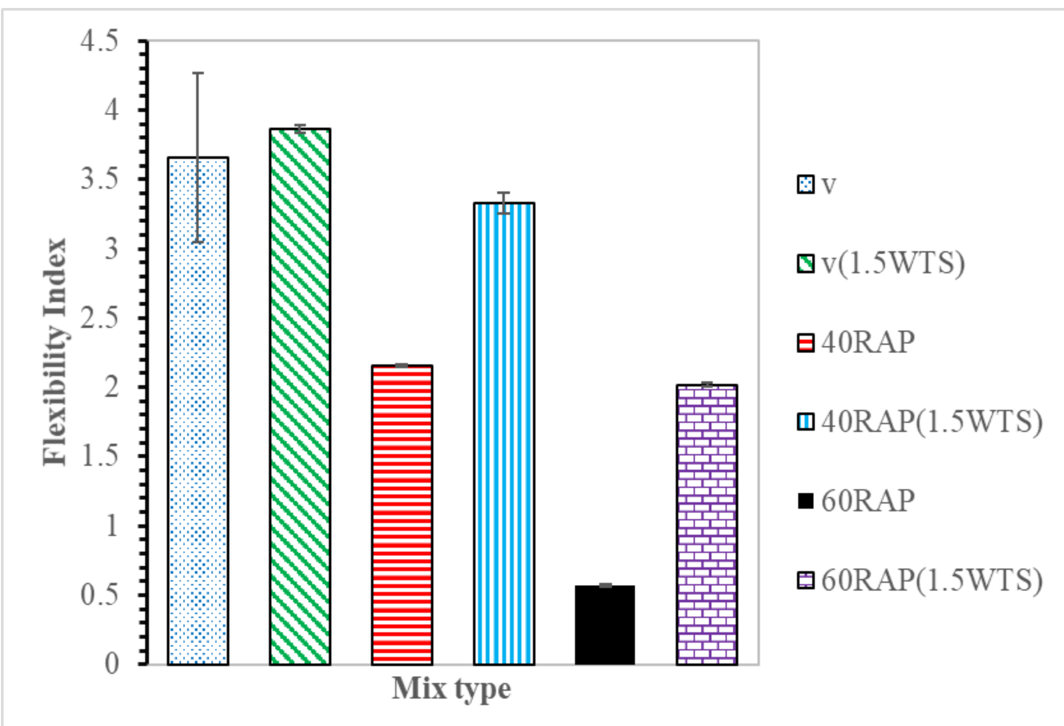


Figure 4. 4 Flexibility Index of Mixes with I-29 RAP

4.6.4 Low-temperature Cracking Resistance

Figure 4. 5 and Figure 4. 6 shows the low-temperature fracture energy performance of WWS modified mixes with Highway -17 and I-29 RAP, respectively. Figure 4. 5 shows that 1.5% WWS modification of mixes containing 0%, 40% and 60% RAP resulted in an increase of the fracture energy by 55%, 30% and 18% respectively. This shows that WWS as a positive effect on improving the low-temperature cracking performance. The effect decreases with increase in RAP content. This is expected since the same dosage of WWS is used 0%RAP, 40%RAP and 60%RAP mixes and the foaming of WWS depends on the amount of virgin binder in the mixes. Other factors such as gradation might also have affected the result. The fracture energy of 1.5%WWS modified 40% RAP is 24% higher than the unmodified control mix, while 1.5%WWS modified 60% RAP mixes is only 4% lower than the unmodified control mix. This indicate that WWS is a potential additive in mitigating low-temperature cracking negative effect induced by RAP. Modification of 0% RAP mix by 1.5%WWS improved the fracture energy from 411 J/m^2 to 917 J/m^2, resulting in improvement from the standard traffic performance to high traffic performance according to the minimum criteria set by literature (Hussain et al. 2016). Modification of 40% RAP by 1.5%WWS resulted the fracture energy shift from 379J/m^2 to 541.5J/m^2.This is, from failing to meet the standard minimum criteria of 400 J/m^2 to above the minimum limit criteria energy for medium traffic (Hussain et al. 2016). While, modification 60%RAP mix by 1.5%WWS resulted shifting from 318J/m2 to 392 J/m2 resulting only 2%less value than the minimum requirement used by this research (400 J/m^2).

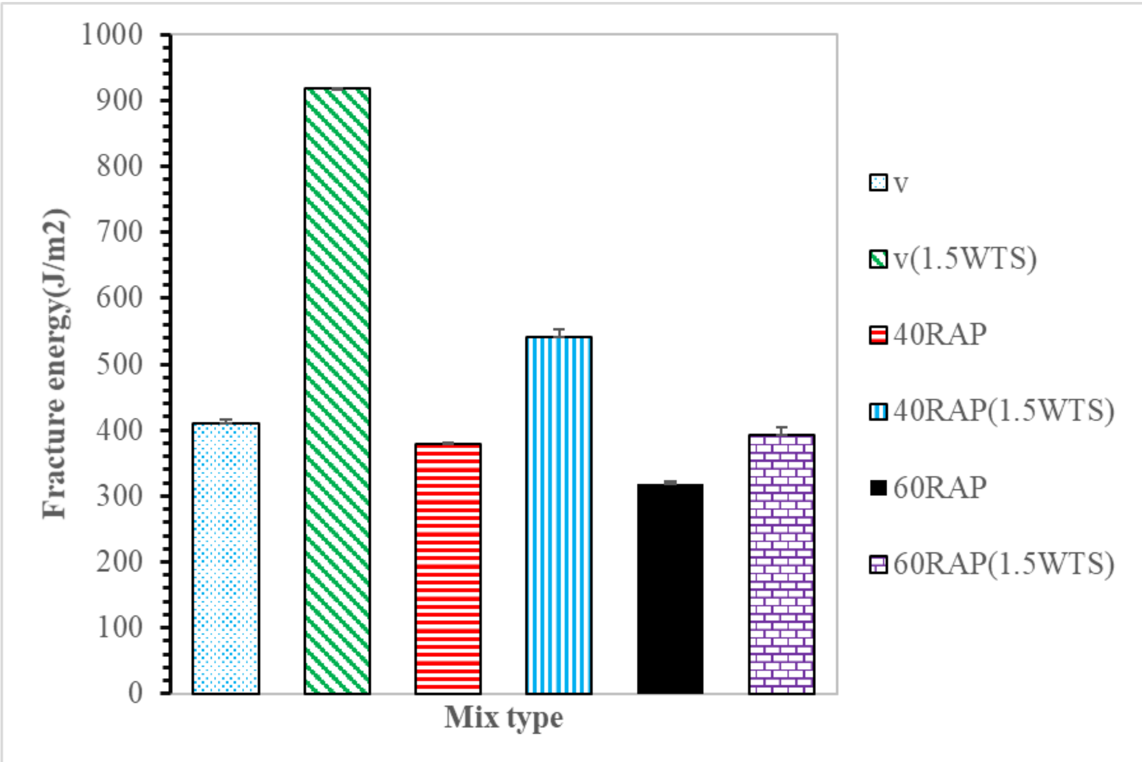


Figure 4. 5 Low-temperature Fracture Energy of Mixes with Highway 17 RAP

Figure 4. 6 shows low-temperature fracture energy of WWS modified mixes with RAP from I-29 source. Results indicated that 1.5%WWS resulted in an increase of the fracture energy by 37%, 17% and 13% for 0%, 40% and 60% RAP content mixes respectively. The effect decreases with increase in RAP content that shows the same trend as that of Highway -17 RAP mixes. This could be due to the foaming effect of WWS depends on the amount of virgin binder presence in the mix. For I-29 RAP mixes the fracture energy of 1.5% WWS modified 40%RAP mix has 6% higher fracture energy than unmodified control mix and 1.5% WWS modified 60%RAP mix has only 10%less fracture energy than the 0%RAP unmodified mix. Modification of 0% RAP control mix by 1.5% WWS resulted in a shifting of the fracture energy from 362 J/m^2 to 579 J/m^2 improving the result from failing to meet mix the minimum standard criteria 400J/m2 to above the medium traffic criteria performance limit 460 J/m^2 (Hussain et al. 2016). Result from

two different RAP source and two mix design indicated the consistency of the WWS additive in improving the low-temperature cracking performance for control (0%RAP), 40%RAP and 60%RAP mixes unlike other WMA additive in the literature which fails to improve the low-temperature performance (Liu and Peng 2012; Edwards et al. 2006; Medeiros et al. 2011; Sol-Sánchez et al. 2019). Relatively lower fracture energy is resulted from I-29 mix than Highway -17 mixes this could be due to the relatively lower binder content of I-29 mixes than Highway 17 mixes, with a gradation difference between the mix may also affected the results.

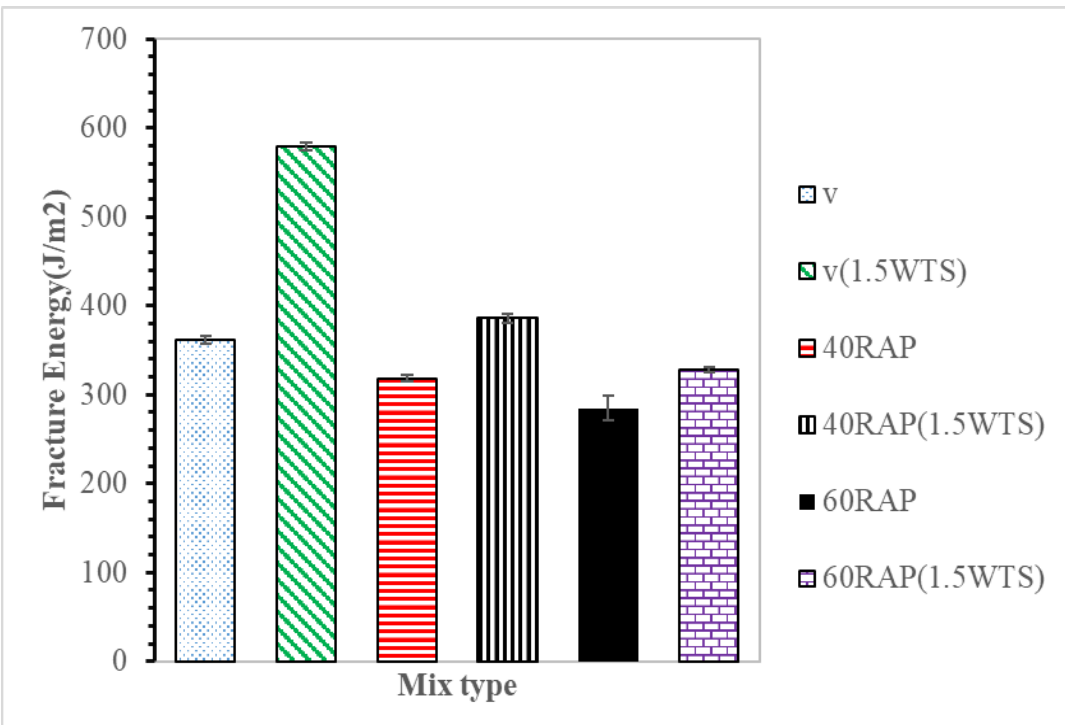


Figure 4. 6 Low-temperature Fracture Energy of Mixes with I-29 RAP

4.7 Summary

WWS is abundantly available additive that need to be investigated to be used in asphalt pavement industry. It improved both fatigue and low-temperature cracking performance of mixes with RAP and without RAP. The improving effect of WWS on fatigue cracking performance increased with increase in RAP content. While the effect of WWS on low-temperature performances still increased but not as significant as that of fatigue cracking with the increase in RAP content. For the 40% RAP modified with 1.5% WWS modified mixes it was possible to obtain similar or better cracking performance result than the unmodified 0% RAP mix. This made WWS potential additive to be used with RAP. By using WWS it is possible to reduce the mix preparation temperature lower that the actual HMA mixing temperature.

Chapter 5 Evaluation of HMA Low-temperature Cracking Resistance using Rate Normalized Fracture Energy

5.1 Background

Low-temperature cracking is one of the most critical distresses in asphalt pavements that affects the performance of the road particularly in colder areas (Jung and Vinson 1994). Qualitative evaluation of thermal cracking resistance of different asphalt mixes can be done by tests, such as Thermal Stress Restrained Specimen Test and Asphalt Concrete Cracking Device (Monismith et al. 1965, Kim et al. 2009, Velasquez et al. 2011). However, relatively complex specimen preparation, and appropriate parameter interpretation procedures of these test made Disc-Shaped Compacted Tension (DCT)preferred low- temperature cracking resistant test. Currently, DCT test is one of the most commonly used method to analyse low- temperature cracking resistance of asphalt using fracture energy (GF). Studies have shown that although the concepts of the test are useful, using DCT test fracture energy to differentiate between asphalt mixtures is challenging, especially for high reclaimed asphalt pavement (RAP) content mixes, due to the insensitivity of the fracture energy parameter to RAP (Al-Qadi et al.2015; Johanneck et al.2015; Gedafa et al. 2019; Karki et al. 2018).

Jung and Vinson (1994) also stated the limitation of fracture energy measurement to distinguish between high-strength/low toughness and low strength/high toughness mixtures, mixtures with high pick load/steep post peak slope, and low peak load/shallow post peak load, respectively. The DCT fracture energy (GF) also lacks a good correlation with low-temperature binder test results and mix design parameters (Tirupan etal. 2019, Saha et al.2020).

Low-temperature cracks operate in three phases: crack initiation, crack growing, and crack propagating with time, so accessing how quickly the crack will propagate through the material helps understand the ductility characteristics of the mix and solve the limitations set by DCT fracture energy. Asphalt mixes with low resistance to cracking will develop more cracks and their severity will increase quicker when compared with the mixes with high resistance. In order to assess such a behaviour, it is beneficial to conduct post peak rate dependent time (T)-load and crack mouth opening displacement (CMOD) – load indexed normalized fracture energy parameters. Analysis of such parameters are used to better describe the softening effect of the sample that could be used to differentiate the low –temperature cracking performance between mixes, especially for high RAP content mixes (Dave et al. 2013).

5.2 Problem Statement

A comprehensive assessment of fracture energy normalized by post peak slope indices of load vs CMOD fracture curve was analysed by Yue Feng et al. (2017). Three variants of flexibility indices GF/in_{itial}, $GF/(m_{initial} - m_{final})$, and $GF/m_{average}$ were used in the analysis. Normalized fracture energy was developed as fractured indices to get more information about the softening behaviour of the material. A geometric index fracture strain tolerance was also developed. Results indicated that higher correlation was observed between the fracture energy and the normalized parameters, while higher coefficient of variation was observed for normalized fracture energy than the fracture energy (GF) parameter. The result lacked information about the correlations between the normalized index parameters with mix design parameters and binder test results.

In this study post peak load CMOD-load and post peak load time (T)-load rate of change normalized DCT fracture energy parameter were explored to differentiate between mixes. The correlation between the rate indexed normalized parameters with mix design parameters and binder test results was also explored.

5.3 Objectives

Specific research objectives included:

- Evaluation of HMA low-temperature cracking resistance using rate normalized fracture energy to differentiate low-temperature resistance of different mixes.
- Finding normalized fracture energy that better correlates with binder relaxation slope value (m_r).
- Understanding the effect and correlation of rate normalized fracture energy with RAP content.

5.4 Methodology

In this research two types of post-peak load rate dependent normalized fracture energy parameters were explored. The first one was CMOD-load and the second one was time (T)-load rate of change of normalized fracture energy parameters. The analysis was done first by taking the average (Aveg) rate of change of fracture curve values between the peak- load and end- load as shown in Figure 5. 1 and Figure 5. 2. The rate and the normalized fracture energy were then calculated using Equations 5. 1 to 5. 4.

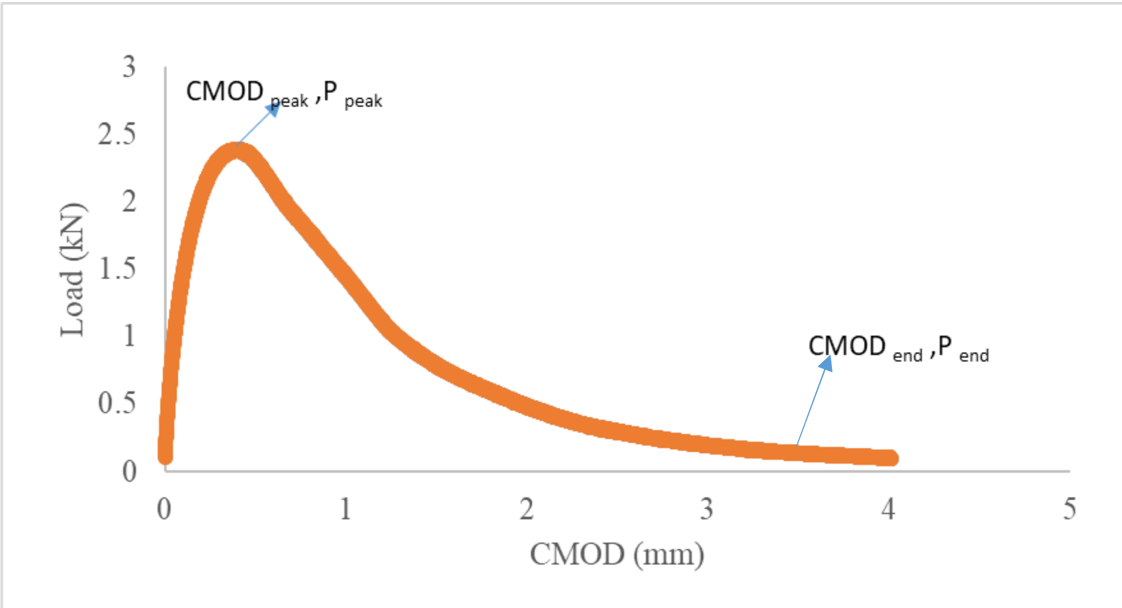


Figure 5. 1 Average CMOD –Load Rate of Change

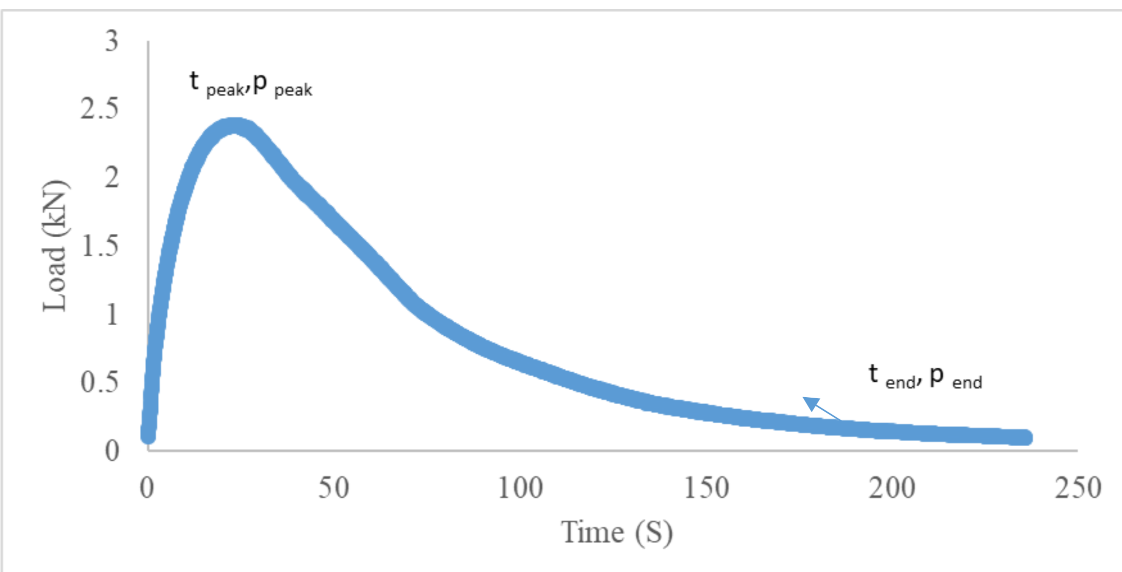


Figure 5. 2 Average Time-Load Rate of Change

$$\Delta CMODAve = \frac{P_{peak} - P_{end}}{CMOD_{peak} - CMOD_{end}} \quad (5.1)$$

$$GF_{CMODAve} = GF * \Delta CMODAve \quad (5.2)$$

$$\Delta TAve = \frac{P_{peak} - P_{end}}{t_{peak} - t_{end}} \quad (5.3)$$

$$GF_{tAve} = GF * \Delta TAve \quad (5.4)$$

Where;

$\Delta CMODAve = Average\ change\ in\ crack\ mouth\ opening$

$GF_{CMODAve}$ = Average crack mouth opening normalized fracture energy

$\Delta TAve = Average\ chjange\ of\ crack\ time$

GF_{tAve} = Change in average time normalized fracture enenrgy

The second analysis was done by fitting the rate of change of post-peak COMD-load and time-load curve to the 4th order polynomial curve. The 4th order curve fit was selected since it has a correlation coefficient of more than 99% with the poste peak load COMD-Load and time-load fracture energy curves. The curve fitting is shown in Figure 5. 3 and Figure 5. 4 for the CMOD and time fracture curve, respectively. Calculation of rate of change and normalized fracture energies are shown in Equations 5.5 to 5. 8.

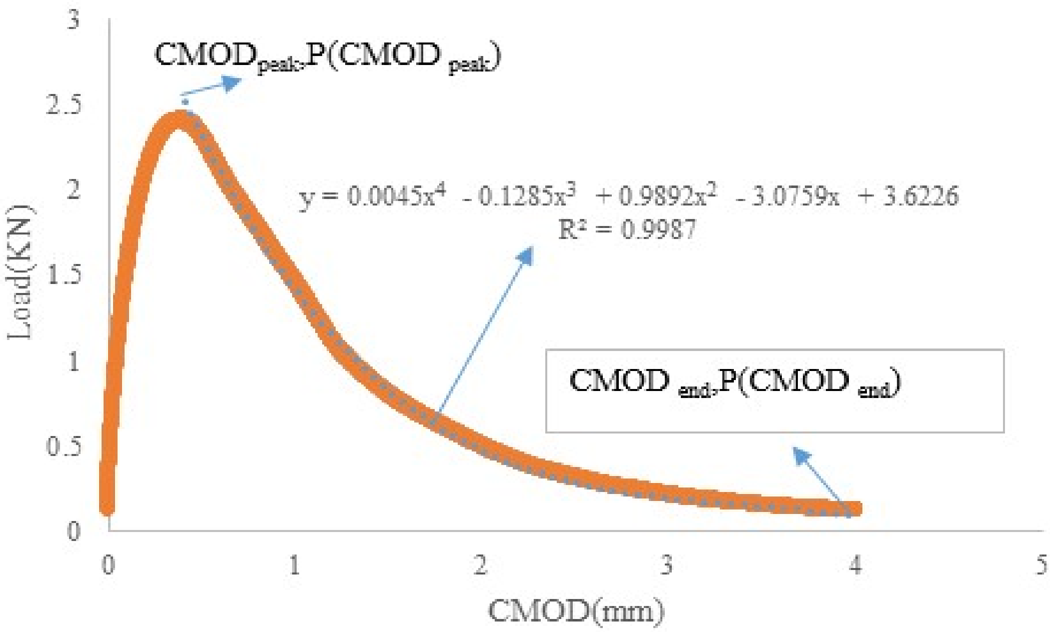


Figure 5. 3 Fourth Order CMOD-Load Rate of Change

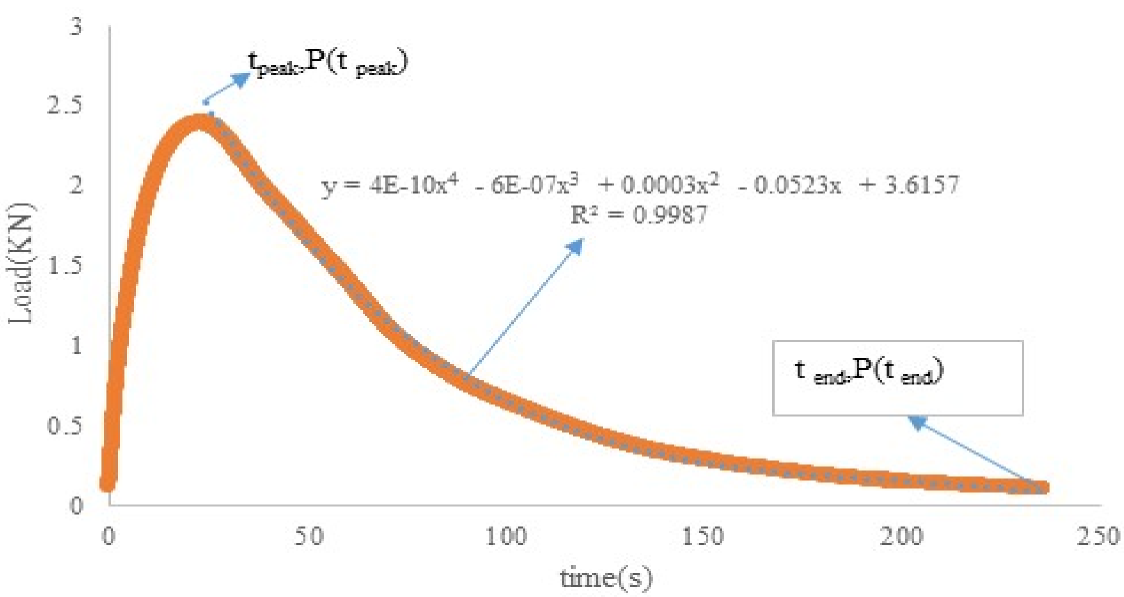


Figure 5. 4 Fourth Order Time-load Rate of Change

$$\Delta CMOD4th = \frac{P(CMOD\ peak) - P(CMOD\ end}{CMOD_{peak} - CMOD_{end}} \tag{5.5}$$

$$GF_{CMOD4th} = GF * \Delta CMOD4th \tag{5.6}$$

$$\Delta T4th = \frac{P(t\ peak - P(t\ end)}{t_{peak} - t_{end}} \tag{5.7}$$

$$GF_{t4th} = GF * \Delta T4th \tag{5.8}$$

Where;

$\Delta CMOD4th = 4th\ order\ change\ in\ crack\ mouth\ opening$

$GF_{CMOD4th}$ = 4^{th} order crack mouth opening normalized fracture energy

$\Delta TA4th = 4th\ order\ chjange\ of\ crack\ time$

GF_{t4th} = Change in 4th order time normalized fracture enenrgy

The rate normalized fracture energy results were compared with each other and DCT fracture energy (GF) to differentiate low-temperature cracking resistance of mixes. Correlation of the normalized parameters with RAP content and low-temperature binder test creep slope (m_r) was also analysed.

5.6 Materials and Mix Design

Two sets of different projects were used in this research. The first set included lab prepared lab compacted mixes where two bio-oils, soy oil (SO) and waste cooking oil (WCO), were used to modify high RAP mixtures (85% by binder weight or 72.5% based on aggregate weight). PG 58-28 virgin binder was used in the mix. Four different dosages of bio-oils: 15%SO (15SO), 12.5%SO _ 2.5%virgin binder (12.5SO_2.5V), 15%WCO (15WCO), 12.5%WCO_2.5virign binder (12.5WCO_2.5V), and Control (V) were used for the analysis. The optimum binder content (OBC) of the control mix was 6.4%. For 15% bio-modified mixes 85% of the OBC was obtained from the RAP material, while the remaining 15% of OBC is replaced by bio-oils Bio-oil modified mixes 12.5% of OBC was replaced by bio-oils ,2.5%of OBC was replaced by virgin binder while the remaining 85% OBC is derived from the RAP material.

The second set composed of four different field mixed lab compacted conventional HMA mixes with different mix designs. Field mixes were collected from four project sites: Bismarck (B), Minot (M), Williston (W), and Valley city (VL). Different the binder type, the percentages of RAP and the optimum binder content (OBC) of each projects for comparison. The mix design parameters of the two projects are shown on Table 5.1 and Table 5.2, respectively.

Table 5. 1 Mix Designs of Bio- modified Project

Virgin PG 58-28 HMA		**SO and WCO Modified HMA**	
Materials	**Percent (%)**	**Materials**	**Percent (%)**
Optimum Binder content(OBC)	6.4	Optimum Binder content(OBC)	6.4
Bio -oil modifiers as a % of OBC	0	Bio -oil modifiers as a % of OBC	12.5/15
Virgin binder as % of OBC	100%	Virgin binder as% of OBC	2.5/0
Binder from the dry RAP aggregate as % of OBC	0	Binder from the RAP as % of OBC	85
Crushed Rock	29	Crushed Rock	8
Crushed Fines	37	Crushed Fines	10
Washed Dust	13	Washed Dust	3.5
Washed Sand	21	Washed Sand	6
RAP	0	RAP	72.5

Table 5. 2 Field Mixed Lab Compacted Project Mix Parameters

Field HMA	**B**	**M**	**VL**	**W**
Binder Type	58S-34	64S-28	58S-28	58V-28
%RAP	18	0	25	13
OBC	6	5.8	5.9	5.5

5.7 Results and Discussions

Table 5.3 shows the fracture energy and binder test relaxation slope mr values of average of 3 samples tested for each project. The result was taken from previously completed projects and used as a basis for comparison.

Table 5. 3 Title Fracture Energy and Binder m_r of the Project

Bio-oil Modified Project			**Field Mixed Lab Compacted Projects**		
Mix	**GF(J/m2)**	**Slope(m_r)**	**Mix**	**GF(J/m^2)**	**slope (m_r)**
V	474.5	0.53	B	398	0.61
15SO	591.3	0.59	M	454.5	0.53
15WCO	329	0.57	VL	320.75	0.67
12.5SO_2.5V	602.5	0.38	W	809.7	0.66
12.5WCO_2.5V	669.5	0.36			

5.7.1 Comparisons of Rate Normalized Fracture Energy Parameters

For bio-oil modified mixes, 76% of normalized fracture energy have lower coefficients of variation than the fracture energy (GF) result while the remaining 24% results indicate an average of 6% higher coefficient of variations than GF as shown in Table 5. 4. For field mixed lab compacted mixes 80% of normalized rate fracture energy had lower variation than the GF while the remaining

20% resulted in higher coefficients of variation as shown in Table 5. 5. The GFcmod4th coefficient of VL is significantly higher than the rest of the projects, which could be an outlier. Overall it can be concluded that the coefficient of variations of all normalized fracture energy except GFt4th is lower than GF. Better and lower coefficient of variation was observed for the normalized fracture energy parameters developed in this research than GF unlike another indexed parameter research (Yuefeng Zhu 2017).

Table 5. 4 Rate Normalized Fracture Energy Parameters of Bio-oil Modified High RAP project

Average Results						**Coefficients of variations**				
Projects	**V**	**15 SO**	**15 WCO**	**12.5 SO 2.5V**	**12.5 WCO 2.5V**	**V**	**15 SO**	**15 WCO**	**12.5 SO 2.5V**	**12.5 WCO 2.5V**
GF	475	591.3	602.5	329.0	699.5	4.62	11.4	0.12	0.43	11.02
$GF_{cmod4th}$	589	732.3	836.1	384.0	452.6	0.12	1.35	0.14	0.21	7.78
GF_{t4th}	36	141.5	48.2	7.8	16.0	4.34	14	0.10	0.32	11.74
$GF_{cmodAve}$	689	748.4	796.4	263.4	456.7	0.24	2.23	0.14	0.45	0.39
GF_{tAve}	12	12.7	13.5	3.1	6.6	0.24	2.24	0.14	0.30	2.24

Table 5. 5 Normalized Indexed Fracture Energy Parameters of Field Mixed Lab Compacted Projects

Average Results						**Coefficients of Variations**				
Project	GF	GFcmod Ave.	GFcmod 4th	GFt 4th	GFt Ave.	GF	GFcmod Ave.	GFcmod 4th	GFt 4th	GFt Ave.
B	398.0	750.78	1172.02	23.6	11.1	14.6	3.14	11.97	6.35	5.21
M	454.5	816.80	5440.22	59.1	5.95	22.2	5.59	21.98	32.73	27.64
VL	320.8	635.54	666.91	41.5	10.8	13.3	0.41	69.06	25.10	0.41
W	809.7	655.64	662.65	7.69	11.2	8.1	1.50	1.94	12.16	1.50

Figure 5.5 shows the graphical representation of rate normalized fracture energy values and conventional fracture energy values. The higher the value the better low-temperature cracking resistance since both higher post-peak load and shallow post-peak curve (lower rate of load reduction) of CMOD -load or time- load curve indicate better ductility as well as higher fracture energy values. A similar trend was observed for GFcmodAve, GFcomd4th, GFtAve, GFt4th parameters that showed 15SO and 15WCO mixes had better low-temperature cracking resistance followed by the control mix whereas 12.5WCO_2.5V and 12.5SO_2.5V had lower low-temperature cracking resistance relatively. This is expected based on binder creep slope (mr) values shown in Table 5. 3.

The result of GF shows different trends that 12.5WCO_2.5V project was the lowest low-temperature cracking resistant mix, which contradicted the binder test result. A 12.5SO-2.5V mix was found to be the least low-temperature cracking resistant mix according to both the normalized fracture energy parameters and conventional fracture energy (GF). The normalized fracture energy parameters resulted in approximately similar results for 15%SO and 15%WCO, only 12% difference for average slope rate normalized parameters (GFcmodAve and GFtAve) and only 12% difference for 4^{th} order curve normalized parameters (GFcomd4th and GFt4th).

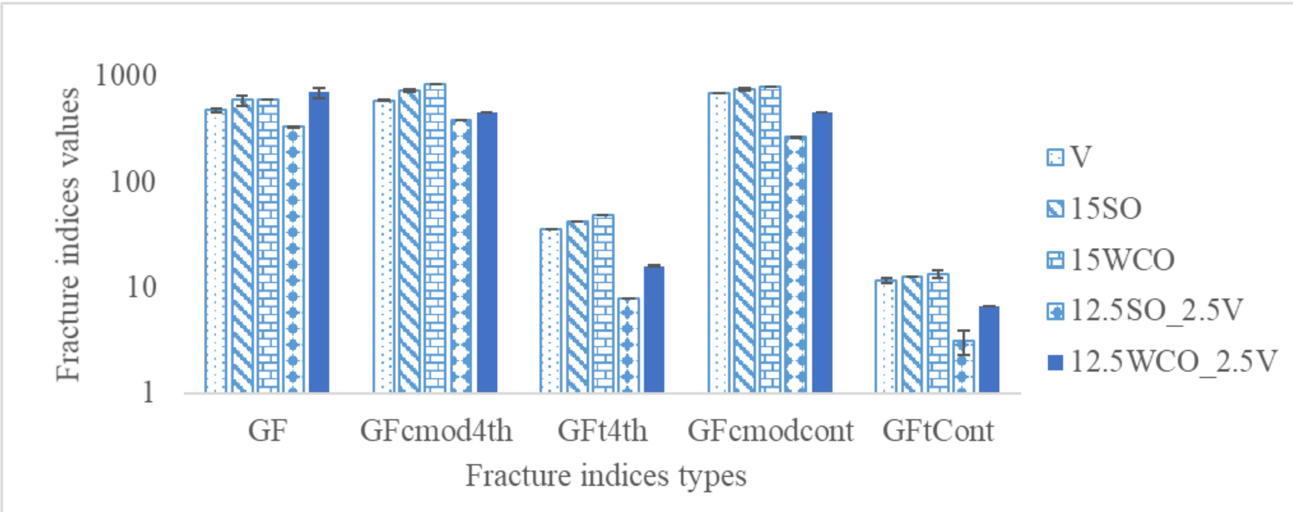


Figure 5. 5 Comparison of GF and Rate Normalized GF for Bio-oil Projects

Figure 5. 6 shows the rate normalized fracture energy results of field mixed lab compacted projects. GFcmodAve, GFcomd4th, GFtAve and GFt4th results showed the same trend. Project M was the lowest low-temperature cracking resistant mix. This could be due to the mix being virgin and binder type used, which is relatively higher in polymeric binder compared to other mixes. Other mix design parameters, such as gradation might also have contributed to the result. The VL and W had relatively lower low-temperature cracking resistance. This could be due to the combinations of binder content and RAP content in the mixes as shown in Table 5. 2. The GF showed a different trends than the normalized fracture energy parameters.

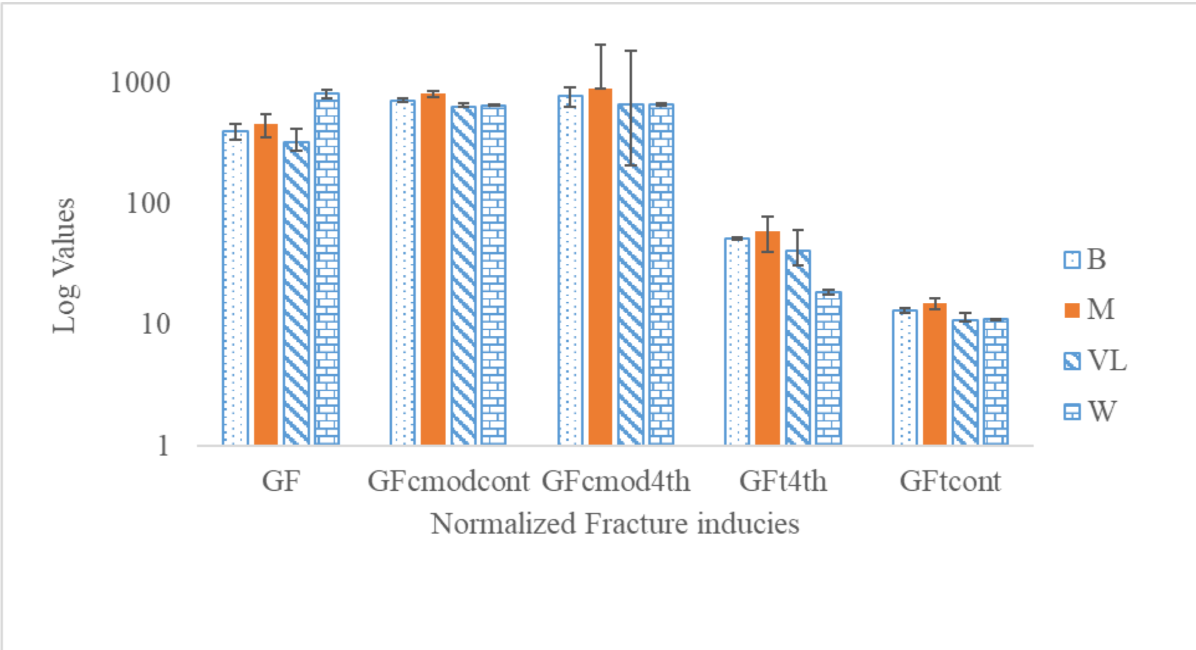


Figure 5. 6 Comparison of GF and Rate Normalized GF for Field Mixed Projects

5.7.2 Coefficient of Determination of GF with Rate Normalized GF of Bio-oil Modified Project

Figure 5. 7 shows the correlation between the normalized parameters. The poor linear correlation (R^2) was observed between GF and normalized fracture energy parameters with a maximum of two percent.

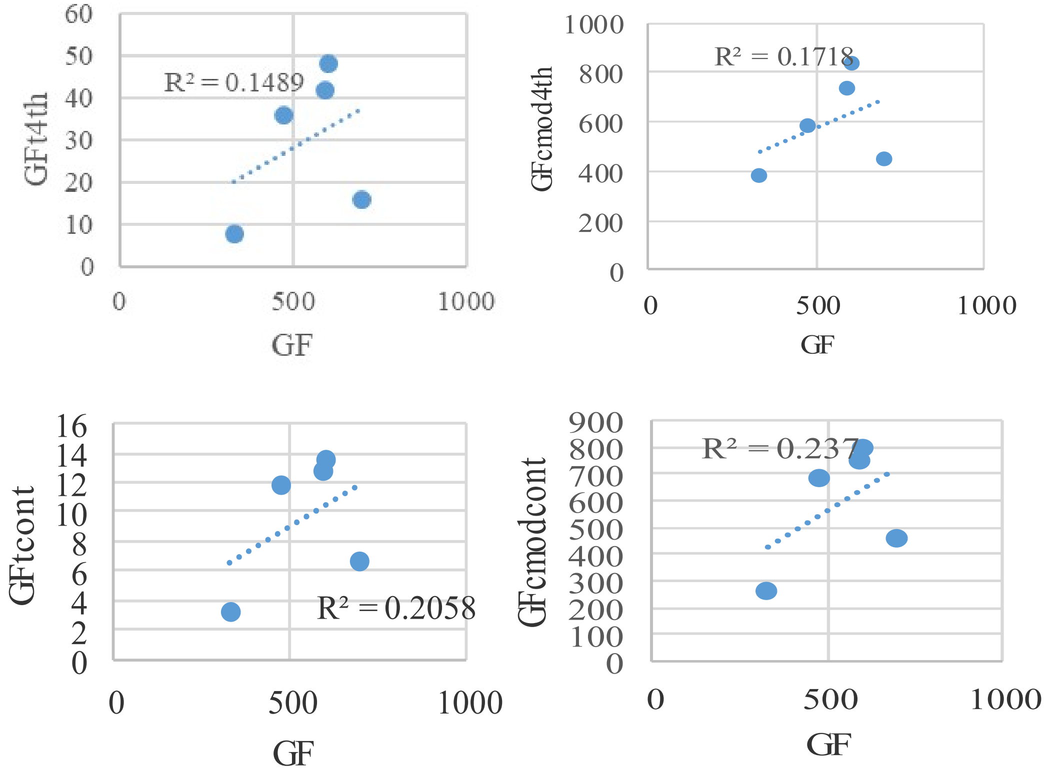


Figure 5. 7 Correlation of Fracture Energy with Rate Normalized Fracture Energy

5.7.3 Coefficient of Determination between Rates Normalized GF of Bio-oil Modified Project

Figure 5.8 shows the correlation between the rate normalized parameters. A very good correlation coefficient (R^2), which is an average of 95% was observed between the normalized fracture energy parameters. The minimum correlation between the normalized fracture energy parameters was 85%. Compared with GF correlation, the normalized fracture energy parameters showed a minimum of 76% improvement in correlation coefficient to each other

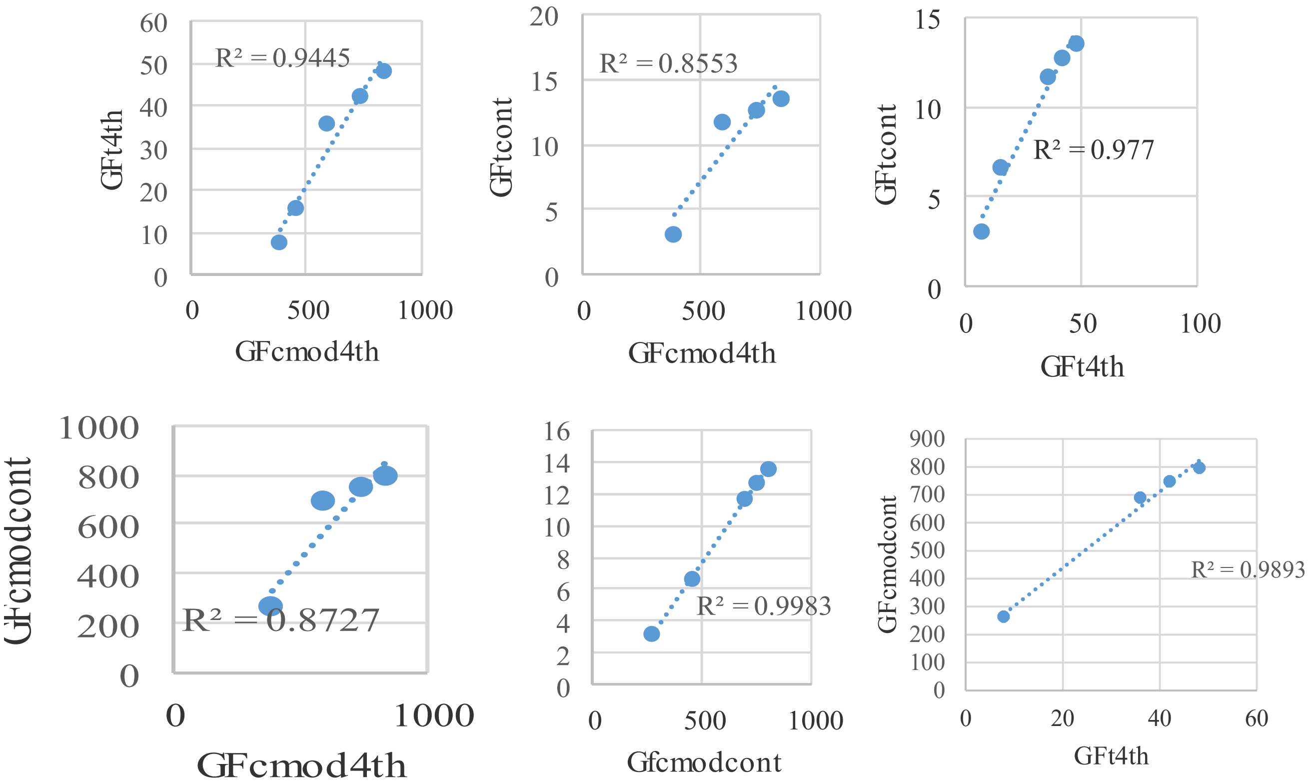


Figure 5. 8 Correlations of Rate Normalized Fracture Energy with Each Other

5.7.4 Comparison of Coefficient of Determination (R2) GF with Rate Normalized GF for Field Mixed Lab Compacted Projects

Figure 5.9 shows the correlation between GF and normalized GF parameters. The coefficient of determination (R^2) for GF and normalized fracture energy parameters is very low, with a maximum of 6% except for GF with GFt4th parameter.

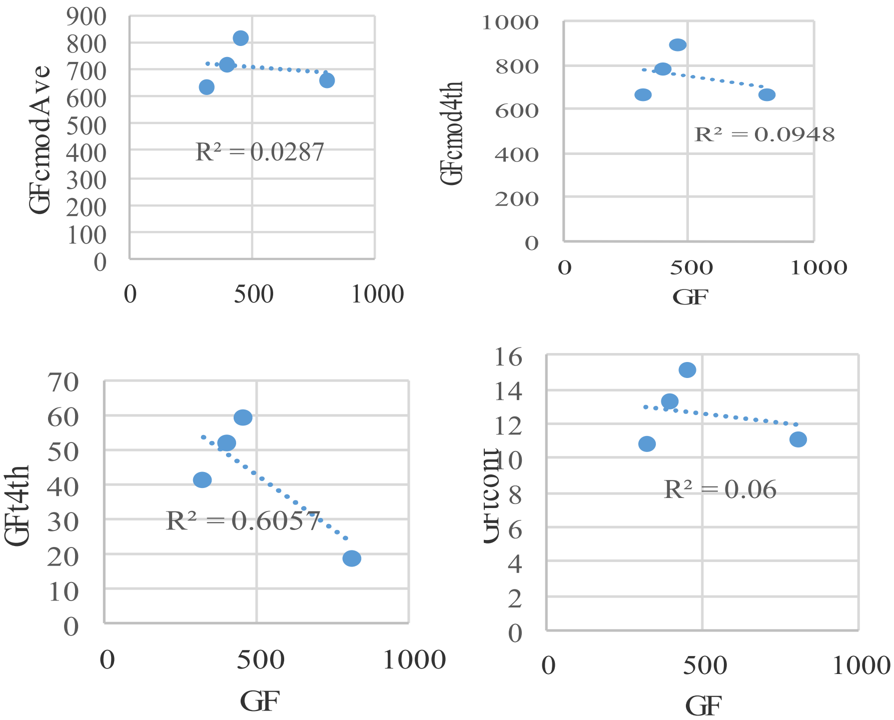


Figure 5. 9 Correlation of Fracture Energy with Rate Normalized Fracture Energy Parameters

5.7.5 Rate normalized GF of Bio-oil Modified Projects

Figure 5. 10 shows the coefficient of determination for the relationship between the rates normalized fracture energy parameters. A good coefficient of determination, which is an average of 60% was observed between GF4th and all other normalized parameters. A very good coefficient of determination, an average of 95% was observed between all other normalized parameters, which shows a minimum of 90% improvement compared to the GF. This indicated that the same property is considered in analysing of normalized fracture energy parameters.

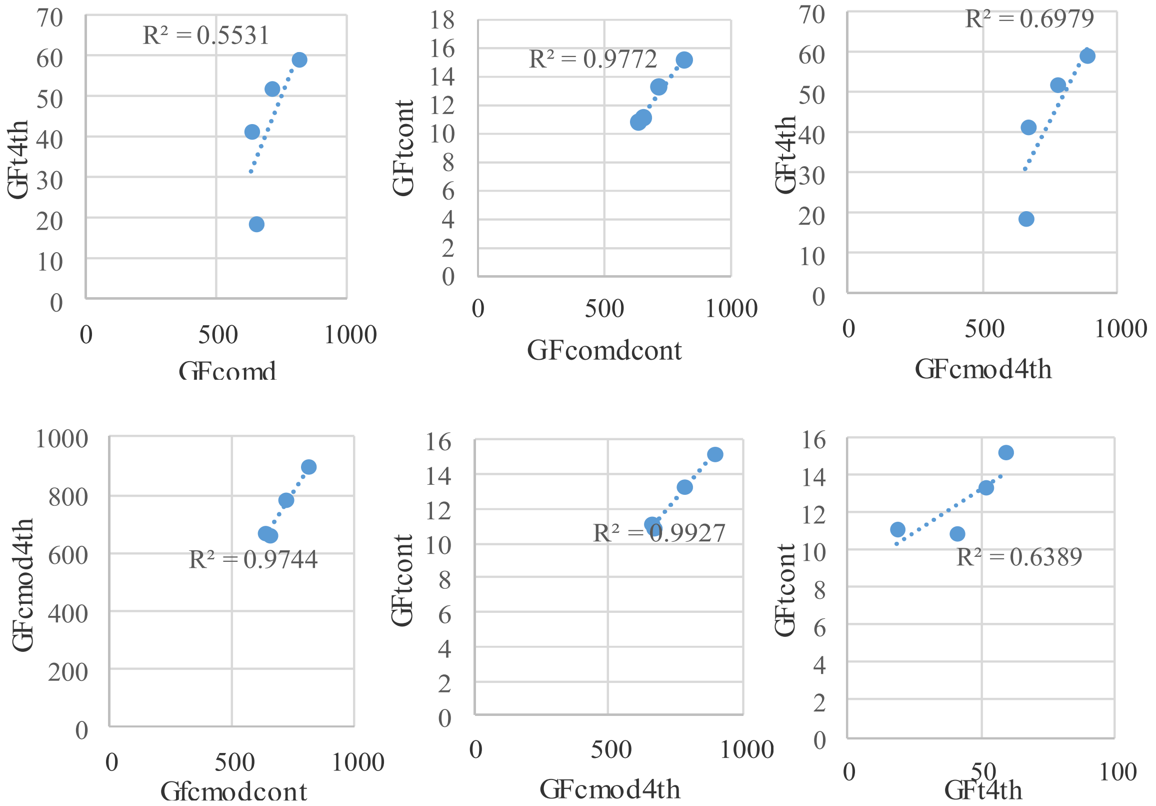


Figure 5. 10 Correlations of Rate Normalized Fracture Energy Parameters with Each Other

5.7.6 Normalized Parameters and GF with Binder Test (m_r) result

Figure 5.11 shows the coefficient of determination of rate normalized fracture energy and DCT fracture energy (GF) with binder test relaxation slope (m_r). The coefficient of determinations of GF are very poor as shown in Fig 5.11 whereas the coefficient of determination between low-temperature binder test creep slope value (m_r) and GFcmodAve, GFcomd4^{th,} GFtAve and GFt4th is 86.8%, 84.7%, 83.6%, and 91.1%, respectively. This is an average of 86%, resulting in a 97% improvement when compared to GF values. This makes normalized fracture energy parameters better parameters to classify low-temperature cracking resistance especially for high RAP mixed with the same mix design parameters. For bio-oil modified project results coefficient of determination of all normalized fracture energy are better parameters to differentiate low-temperature cracking resistance of mixes. This shows that the rate of load reduction with respect to the CMOD and time (softening effect) is a critical parameter to be included in the low-temperature analysis of the DCT result.

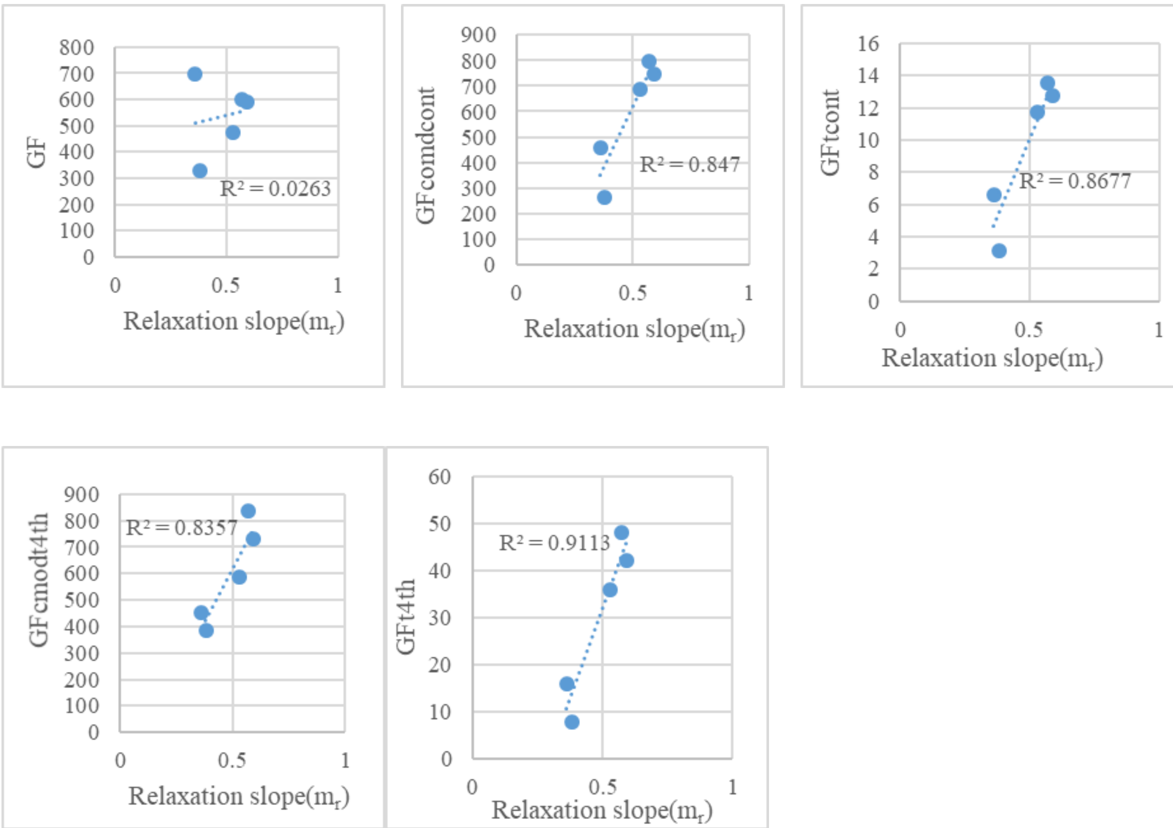


Figure 5. 11 Correlation of Normalized Fracture Energy Parameters with Binder m_r

Figure 5. 12 shows the coefficient of determination for rate normalized fracture energy with binder test low- temperature relaxation slope (m_r) values. The coefficient of determination of fracture energy (GF) with low-temperature binder test creep slope was very poor, about 6%. Coefficient of determination for rate normalized fracture energies with low-temperature relaxation slope (m_r) is 94. %, 94%, 94%, and 90% for GFcmodAve, GFtAve, GFcomd4th, and GFt4th, respectively. This coefficient of determinations showed an average of 93% improvement for normalized GF parameters as compared to the GF value. This indicates that rate normalized

fracture energy parameters have an advantage in both classifying the mixes and understanding the binder effect on the mix than conventional fracture energy (GF).

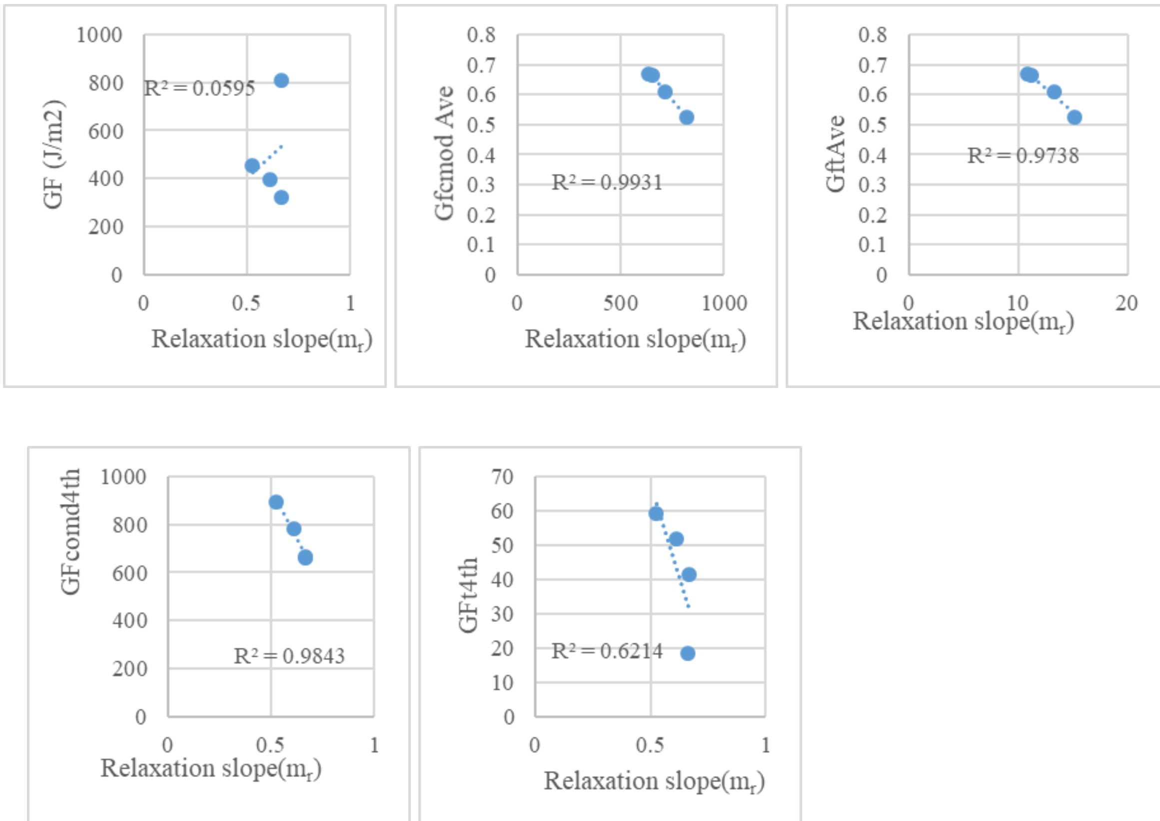


Figure 5. 12 Correlations of Normalized Fracture Energy Parameters with Binder m_r

5.7.7 Correlation of Rates Normalized Fracture Energy Parameters with Percentages of RAP Used

Figure 5.13 shows the coefficient of determination of rate normalized fracture energy parameters with RAP content used in the mix. Results showed that GF and GFt4th have poor correlation with RAP content, only 9% and 10.7%, respectively. The coefficient of determination of GFcmodAve, GFtAve, GFtAve, and GFt4th with the percentages of RAP content is 75.5%, 63.7%, and 60.7% for GFcmodAve, GFtAve, and GFcmod4th, respectively. GFcmodAve, GFtcont, and GFcmodAve showed approximately 85% improvement in coefficient of determination value than

GF while GFt4th showed a 16% improvement as compared to GF. This shows that index normalized fracture energy parameters, GFcmodcont, GFtcont, and GFcomd4th, are better to determine the effect of RAP

content on low-temperature cracking resistance.

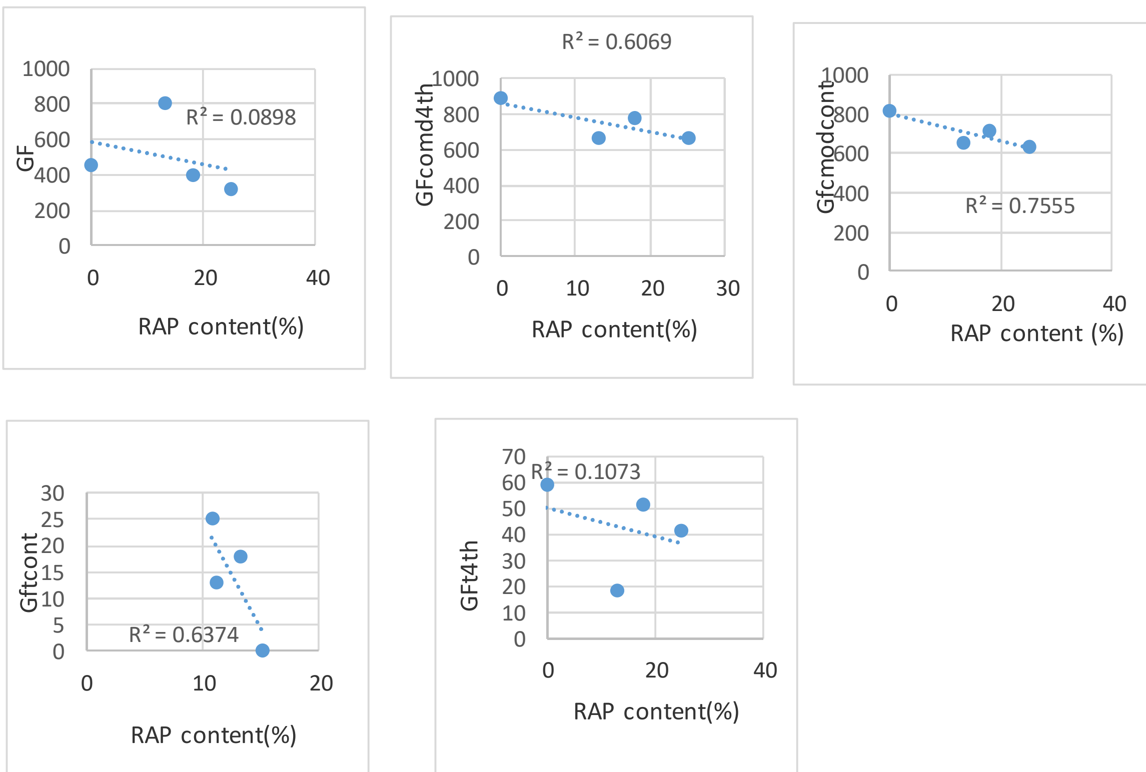


Figure 5. 13 Correlation of Normalized Fracture Energy Parameters with Percentages of RAP Content

5.8 Summary

Rate normalized fracture energy parameters better differentiate low-temperature cracking performance between mixes especially for high RAP mixes. They are also better correlated with both binder test results and mix parameters. The post peak load rate normalized fracture energy parameters can be utilized as an additional parameter with fracture energy result since the limit is not proposed for the normalized parameters.

Better correlation is observed among normalized fracture energy parameters than GF. This shows that post peak load rate dependent normalized fracture energy evaluation is better to differentiate between low-temperature cracking resistances between mixes and to evaluate the mix design and binder test effect of the mixes. Rate dependent fracture energy parameters can be used as additional performance parameters to supplement information about the low-temperature performance.

Chapter 6 Conclusions

Pavement sustainability is generally insured based on the three key factors: economy, environment and performance. Based on the compressive work of this dissertation by maximizing the use of bio-oil modified reclaimed asphalt pavement (RAP) the economy will be improved since it saves the use of both virgin asphalt and aggregate. Utilizing wastewater sludge both as compaction aid material as well as warm mix asphalt additive reduces the fuel consumption and gas emitted to the environment. Usage of bio-oils and wastewater sludge also solve the land fill problem required to dispose waste by-products. Include performance effect and then conclude sustainability. . Investigations of rate based low-temperature fracture energy on the mixes helped to better differentiate as well as understand the effect of each material and mix design parameters on the performance.

Based on the overall investigations of the dissertation the following finding are concluded

- By using 15 SO and 12.5WCO_2.5V as modifiers higher percentages of RAP (up to 85% binder base or 72.5% aggregate base) can be used with improved rutting, fatigue cracking, and low-temperature cracking resistance as compared to control HMA.
- The use of WWS in mixes results in better cracking resistance and compaction effort at 50°F lower compaction temperature than the HMA. This indicates that WWS is a potential compaction aid additive
- The WWS improved the cracking potential especially in a mix containing RAP and maintained the rutting performance within the specification limit. This indicates that it can be used as a potential pavement rejuvenator.

- Rate normalized fracture energy parameters better differentiate low-temperature cracking performance between mixes especially for high RAP mixes. They are also better correlated with both binder test results and mix parameters. The post peak load rate normalized fracture energy parameters can be utilized as an additional parameter with fracture energy result since the limit is not proposed for the normalized parameters.

- Combination of WWS with bio-oil in the presence of small amount of virgin binder is suitable to achieve better fatigue cracking and low-temperature while satisfying rutting performance criteria in general.

6.1 Recommendations

- For all bio-oil modified mixes the tests were performed in a controlled environment. A large-scale field test is necessary to make more generalized conclusions.

- More research needs to be done on different bio-oils and different RAP content and sources.

- The effect of WWS as a rejuvenator for high RAP HMA without other bio-oils need to be investigated.

- Different dosage of WWS on lab mixed, lab compacted mixes needs to be determined.

- Effect of WWS on higher than 60% RAP percentage of mixes needs to be investigated.

- More tests on different mix design projects need to be conducted for a better generalization.

6.2 Limitations

Some of the limitation of this dissertation are the limited number of samples tested to make concrete conclusion. Shortage or unavailability of testing equipment's such as bending beam remoter (BBR), chemical analysis equipment and dynamic modulus test hindered the detailed analysis of the experiment.

6.3 Future Work

- Finite element Analysis of the projects
- Developing a limiting criteria for rate normalized fracture energy induces
- Testing more potentially available bio-oils
- Analysing the effect of WWS as emulsion material
- Possibility of modifying WWS for large scale use and apply for paten.

6.4 Main Contributions of the Dissertation

This dissertation contributed two main things to the body of pavement engineering .The first one is the introduction of wastewater sludge (WWS) as performance enhancer, compaction aid, and WMA material. This opens a door for further extensive use of WWS in the pavement system. The second is the concept of rate based normalized fracture energy analysis for high RAP HMA. This is a new way of the differentiating the performances of high RAP mixes which gives relatively better information than DCT fracture energy . This will lead to further development of analysis methods that can be more suitable for high RAP mixes.

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