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Evaluating Burner Fuel Savings and Pavement Performance from Lowering Asphalt Production Temperatures with Warm Mix Asphalt Additives

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ABSTRACT

This study evaluated the effects of producing warm mix asphalt (WMA) at lower temperatures, compared to conventional hot mix asphalt (HMA), on energy consumption and asphalt mixture performance at both material and pavement levels. Two field projects were conducted in Alabama. The first evaluated two chemical WMA additives, while the second assessed further temperature reductions using one of the WMA additives with a different mix design. Burner fuel usage was monitored during production to quantify energy savings. Laboratory testing using the Asphalt Mixture Performance Tester (AMPT) included dynamic modulus (|E*|), cyclic fatigue, and stress sweep rutting (SSR) tests. The FlexMAT™ v2.2 program was used to analyze mechanistic test results, and pavement performance—specifically, fatigue cracking and rutting—was evaluated using FlexPAVE™ v2.2 under representative traffic and climate conditions. In Experiment 1, limited temperature reductions resulted in no significant difference in burner fuel consumption among mixtures. In Experiment 2, production temperature reductions of 22°C (40°F) and 36°C (65°F) yielded burner fuel savings of approximately 8% and 19%, respectively. Across both experiments, WMA mixtures demonstrated lower mixture Glover–Rowe (*G-Rm*) values, indicating improved non-load-related cracking resistance, while cyclic fatigue indices (D^R and S_{app}) were similar to those of HMA control mixtures. However, WMA mixtures exhibited increased rutting susceptibility and higher Rutting Strain Index (RSI) values, especially at the lowest production temperature. FlexPAVE™ v2.2 modeling predicted slightly higher fatigue damage and rutting in WMA mixtures compared with HMA. Overall, the findings suggest that WMA technologies can substantially reduce burner fuel use while maintaining acceptable pavement performance, provided mix design adjustments are made to control rutting at lower production temperatures.

PRACTICAL APPLICATIONS

The findings of this study offer practical insights for highway agencies, contractors, and pavement engineers seeking to reduce energy consumption and environmental impacts from asphalt mixture production while maintaining satisfactory pavement performance. The implementation of WMA technologies can significantly lower burner fuel consumption, thereby reducing operational costs and emissions at production facilities. Additionally, WMA mixtures demonstrated improved cracking resistance, suggesting potential long-term durability benefits. However,

when production temperatures are significantly reduced, adjustments to the mixture design may be necessary to mitigate the increased risk of rutting susceptibility.

AUTHOR KEYWORDS

Warm Mix Asphalt (WMA); Burner Fuel Consumption; Cracking Resistance; Rutting Susceptibility; Dynamic Modulus, Cyclic Fatigue, Performance Modeling; Emissions.

INTRODUCTION

The asphalt paving industry continues to advance through the adoption of innovative technologies aimed at improving production efficiency, optimizing material usage, improving sustainability, and extending pavement service life. Among these innovations, warm mix asphalt (WMA), recycling agents, advancements in pavement recycling, and balanced mix design (BMD) approaches have demonstrated considerable potential to improve pavement performance and resource efficiency (Epps 2019; Sadeghi and Sabouri 2025).

WMA refers to asphalt mixtures produced and placed at significantly lower temperatures than conventional hot mix asphalt (HMA). These temperature reductions are achieved using technologies in three general categories: foaming technologies, organic (wax-based) additives, and chemical additives (Cheraghian et al. 2020). Water-based foaming increases binder volume and surface area, thereby reducing viscosity and improving workability. Wax-based additives also reduce binder viscosity, thereby improving workability. Surfactant-based chemical additives lower interfacial friction between the binder and aggregate, facilitating easier mixing and compaction.

Beyond improved compactability, WMA technologies offer several additional advantages, including reduced emissions, longer haul distances, extended paving seasons, and the ability to incorporate more recycled materials (Capitão et al. 2012; Rubio et al. 2012; Sukhija et al. 2022; Zaremotekhases et al. 2022). One of the primary motivations for adopting WMA is the opportunity to reduce energy consumption and greenhouse gas (GHG) emissions during production (Rubio et al. 2012; Sukhija et al. 2022). Reported energy savings vary depending on additive type, plant configuration, fuel source, aggregate moisture content, and production temperature. For

example, Sukhija et al. (2022) reported that WMA production reduced heat energy demand by 3–12%, with the highest reductions achieved using organic additives (4–12%), followed by chemical additives (3–10%) and foamed technologies (up to 9%). Almeida-Costa and Benta (2016) reported manufacturing energy reductions of approximately 18.4% and 8.6% for temperature drops of 46°C and 20°C, respectively, noting that fuel savings could offset additive costs. Similarly, West et al. (2014) documented an average burner fuel savings of 22.1% across six asphalt plants, corresponding to an average temperature reduction of 26.7°C. A multi-state study found that lowering the production temperature by approximately 30°C with a chemical WMA additive reduced burner fuel consumption by about 20% (NAPA 2024).

These energy savings translate directly to environmental benefits. For example, a study across five states observed an average 22.3% reduction in stack CO_2 emissions when WMA mixtures were produced 30°C below HMA temperatures (NAPA 2024). Croteau and Tessier (2008) estimated that each ton of WMA produced results in 4.1 to 5.5 kg less CO_2 equivalent emissions. According to the National Asphalt Pavement Association (NAPA), the use of WMA in the U.S. in 2022 led to a reduction of approximately 0.18 million metric tons of CO_2 equivalent—comparable to the annual emissions of 40,000 passenger vehicles (Williams et al. 2024).

In terms of performance, extensive research over the past two decades has examined the material and structural behavior of WMA mixtures. Lower production temperatures reduce oxidative aging, resulting in more flexible and less brittle mixtures (Dao et al. 2022; Yin et al. 2023). A field study revealed that chemical WMA exhibited lower stiffness than the corresponding HMA, and this difference persisted over time (Spadoni et al. 2022). Laboratory evaluations have also confirmed improved intermediate-temperature cracking resistance for WMA mixtures, as shown by higher Indirect Tensile Asphalt Cracking Test (IDEAL-CT) results (Sadeghi et al. (2025) and improved flexibility index and semi-circular bending performance (Rahman et al. (2022). While the extent of improvement depends on the additive type and test conditions, WMA mixtures generally demonstrate enhanced cracking performance (Padula et al. 2019).

Regarding rutting performance, most studies report that the slightly softer binders and lower aging associated with WMA production do not significantly compromise resistance to permanent deformation. For example, Bairgi et al. (2020) found that three WMA mixtures using foamed, Evotherm, and Cecabase additives showed slightly higher laboratory and field rutting than the control HMA; however, all sections exhibited acceptable field performance,

with only 2–3 mm of rut depth after five years. Similar findings have been reported in other studies (Bairgi et al. 2018; Wen et al. 2016). Long-term field trials have confirmed that WMA pavements generally perform comparably to HMA pavements after several years of service (McCarthy and Daniel 2018). Because the Superpave mix design system has largely eliminated rutting problems (West et al. 2018), current WMA research focuses on improving cracking resistance and lowering production temperatures while maintaining rutting within acceptable limits. A previous study reported mostly comparable laboratory cracking and rutting performance properties for plant-mixed WMA mixtures, while more significant differences were noted between lab-mixed samples (Sadeghi et al. 2025).

In addition to laboratory testing, pavement modeling tools such as the Federal Highway Administration's FlexPAVE™ have been used to predict long-term pavement performance. FlexPAVE™ integrates mixture properties, traffic loading, and climate data to simulate viscoelastic pavement responses (FHWA 2025) and aging effects through a calibrated model developed under NCHRP Project 09-54 (Kim et al. 2021). Studies have shown that FlexPAVE™ can predict rutting and cracking trends consistent with field performance (Ghanbari et al. 2022; Wang et al. 2016).

Despite the promising outcomes, uncertainties persist regarding the long-term performance of WMA, particularly under harsh environmental or heavy traffic conditions. For example, WMA test sections in Louisiana exhibited lower fatigue cracking than HMA after 5–8 years (Akentuna et al. 2022). While some chemical additives enhance moisture resistance, others may increase moisture sensitivity if reduced production temperatures limit aggregate drying (Fakhri et al. 2013) (Garcia Cucalon et al. 2017; Zaumanis 2014). Consequently, many agencies and contractors still use WMA primarily as a compaction aid rather than significantly lowering production temperatures. Continued long-term field evaluations, along with advanced mechanistic modeling, are crucial for validating WMA durability and supporting broader implementation under diverse climatic and traffic conditions.

Objectives and Scope

The primary objective of this study was to evaluate the impact of reducing asphalt production temperatures with WMA additives on burner fuel consumption, mixture fundamental properties, and predicted pavement performance. Two field demonstration projects were conducted, each including two WMA mixtures and one control HMA.

In the first project, two chemical WMA additives were evaluated against the control HMA. One of the WMA additives was used in the second project, which focused on evaluating the effects of further reducing the production temperature.

Burner fuel consumption was recorded during plant production to quantify energy savings. Fundamental mixture properties were evaluated using the Asphalt Mixture Performance Tester (AMPT), which included dynamic modulus, cyclic fatigue, and Stress Sweep Rutting (SSR) tests. The test results were analyzed using the FlexMAT™ program to assess material performance properties, while the FlexPAVE™ modeling tool was employed to predict pavement performance, including percent damage and rutting. Through this integrated experimental and modeling approach, the study provides a comprehensive assessment of the energy consumption and performance associated with reducing production temperatures using WMA additives.

METHODOLOGY

Experimental Plan

This study was structured in three main phases:

1. Quantifying energy savings associated with producing WMA at reduced temperatures
2. Evaluating mixture performance using IDEAL-CT, Hamburg Wheel-Tracking Test (HWTT), and High-Temperature Indirect Tensile Test (HT-IDT)
3. Assessing the fundamental properties using the AMPT tests and predicting the pavement performance of WMA mixtures compared to conventional HMA.

The findings from Phases 1 and 2 have been previously published (Sadeghi et al. 2025). This paper will concentrate on the results of Phase 3, with a brief overview of Phase 1 included to emphasize the environmental significance of the performance outcomes. This context will facilitate an understanding of the mechanistic testing and modeling conducted during Phase 3. It is also essential to note that while direct comparisons were made within each experiment, cross-experiment comparisons were not conducted due to the different mixture designs and materials used.

As illustrated in Fig. 1, two field experiments were conducted, each involving two WMA mixtures and one control HMA. The first phase involved monitoring burner fuel consumption during asphalt mixture production to assess energy savings. In the second phase, mixture performance was evaluated through AMPT testing, including dynamic modulus, cyclic fatigue, and SSR tests. The resulting data were analyzed using FHWA's FlexMAT™ v2.2 to evaluate material performance properties. Pavement performance, in terms of predicted percent damage and rutting, was assessed using FlexPAVE™ v2.2.

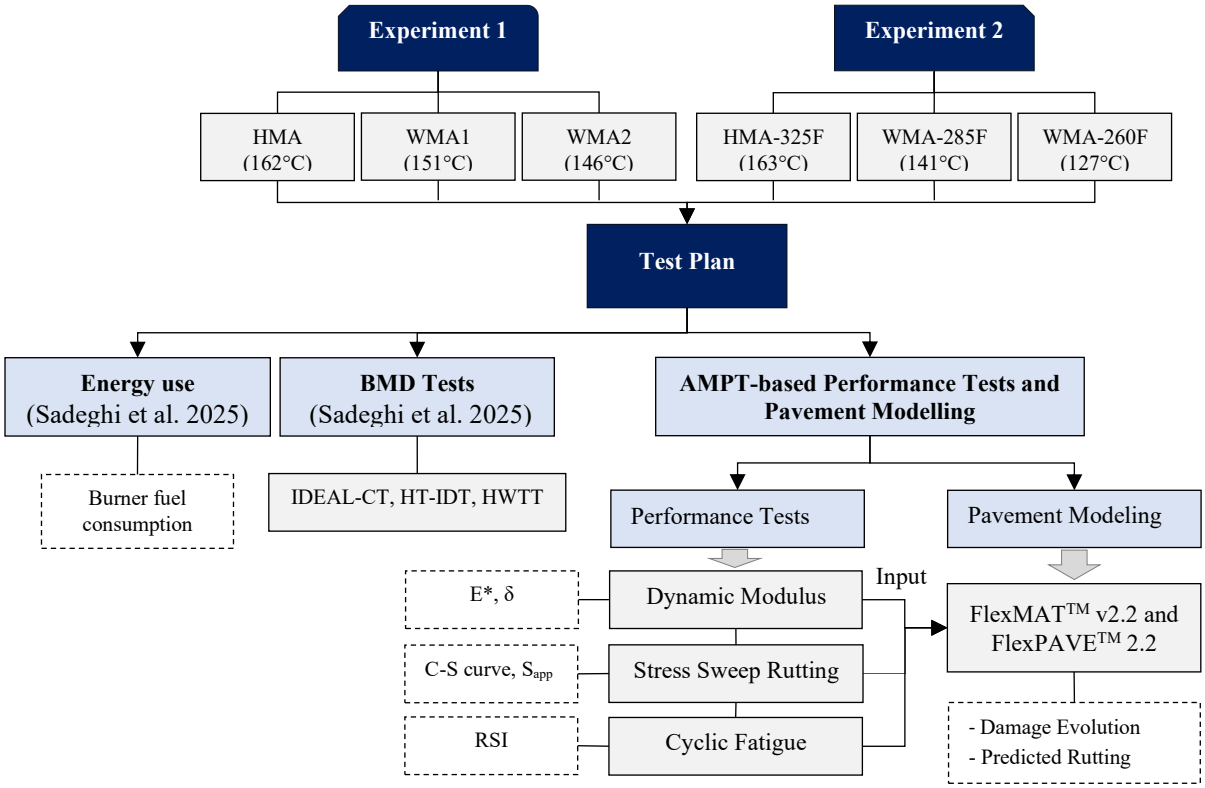

Fig. 1. Test plan for Experiments 1 and 2

Experiment 1

The first experiment was conducted at an asphalt plant in Montgomery, Alabama, as part of an overlay project on U.S. Route 82 near Prattville. The facility operated a 2000 model Astec Double Barrel Green® drum mixer using recycled No. 2 fuel oil. Three mixtures were produced: one control HMA and two WMA mixtures (WMA1 and WMA2), containing different chemical additives.

All mixtures were produced using the same aggregate gradation and binder content. A PG 76-22 asphalt binder modified with 2.5% styrene-butadiene-styrene (SBS) polymer was used to meet ALDOT's traffic-based grade-bumping requirements (ALDOT 2022). The chemical WMA additives were terminally blended into the virgin binder at a dosage of 0.5% by weight, as recommended by the suppliers. WMA1 was a bio-based chemical additive with a relative density of 0.97 and viscosity of 127 cP at 25°C, while WMA2 was a bio-based chemical additive with a density of 0.98 g/mL, viscosity of 210 cP at 25 °C, and an open-cup flash point of 211°C. All mixtures included 20% Reclaimed Asphalt Pavement (RAP) and were designed as a fine-graded blend with a nominal maximum aggregate size (NMAS) of 9.5 mm (Fig. 2).

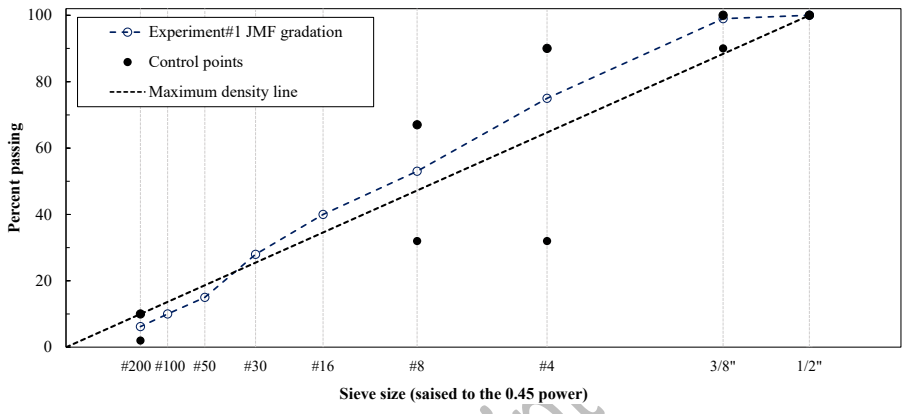

Fig. 2. Aggregate gradation used in Experiment I

To minimize residual heat effects, each mixture was produced on a separate day. The control HMA was produced in September 2023 under an average ambient temperature of 30.2°C (86.4°F), followed by WMA1 the next day under similar conditions. WMA2 was produced in December 2023 due to a shipping delay, under significantly cooler ambient conditions (10.4°C or 50.7°F), around 20°C lower than the temperatures during the HMA and WMA1 production.

Target production temperatures were 160–166°C (320–330°F) for the HMA and 135–141°C (275–285°F) for the WMA mixtures. However, operational constraints—such as concurrent HMA production and mechanical issues—led to deviations. The actual average production temperatures were 162°C (323°F) for the HMA, 151°C (303°F) for WMA1, and 146°C (295°F) for WMA2, corresponding to temperature reductions of approximately 11°C (20°F) and 16°C (28°F), respectively. The average aggregate moisture content was 2.0%, measured in accordance with AASHTO T255-22 (AASHTO 2022).

Burner fuel consumption was measured during production. Each plant run was allowed to stabilize at the target temperature before recording fuel usage and sampling to minimize the influence of residual heat. Loose mix samples were collected and transported to the laboratory, where Reheated Plant-Mixed Lab-Compacted (RH-PMLC) specimens were prepared following NAPA IS-145 guidelines (NAPA 2023). Compaction temperatures were approximately 135°C (275°F) for HMA and 116°C (240°F) for the WMA mixtures.

Experiment 2

Building on findings from the first experiment, a second field study was designed to evaluate the effects of more aggressive temperature reductions using the same WMA additive as in WMA1. This experiment was conducted at a different asphalt plant in Ariton, Alabama, equipped with a 2017 model CMI E3 drum mixer, four storage silos, and twin RAP cold feed systems. Recycled No. 2 fuel oil was again used as burner fuel. The experiment included one control HMA and one WMA mixture, with the latter produced and evaluated at two different target temperatures. All mixtures used the same aggregate gradation and binder content. A PG 67-22 binder was used for all mixtures, with the WMA binder terminally blended with 0.5% additive (by weight of virgin binder). The aggregate blend was fine-graded with an NMAS of 12.5 mm (Fig. 3).

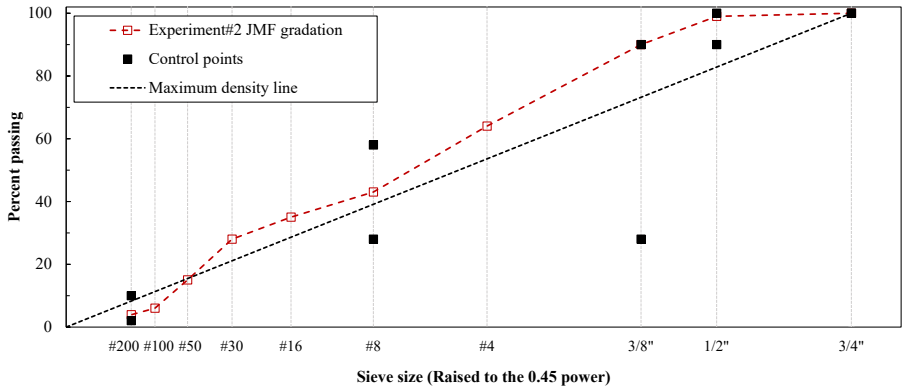

Fig. 3. Aggregate gradation used in Experiment 2

Production was carried out in June 2024, under relatively stable ambient temperatures averaging approximately 21°C (70°F). On the first day, the control HMA (HMA-325F) was produced at 163°C (325°F). On the second day, WMA production commenced after the plant stabilized at HMA conditions and was then progressively cooled to 141°C (285°F) and 127°C (260°F). Fuel consumption and mix samples were recorded after thermal stabilization at

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each temperature. RH-PMLC specimens were prepared by reheating the loose mixtures to their respective compaction temperatures—approximately 140°C (285°F) for the HMA, and 124°C (255°F) and 113°C (235°F) for the WMA samples—prior to immediate compaction, following NAPA IS-145 procedures (NAPA 2023).

Mix Designs, Quality Control Data, and Production Variables

Volumetric properties of the asphalt mixtures were evaluated based on contractor-reported Quality Control (QC) data and compared against the Job Mix Formula (JMF) and Alabama Department of Transportation (ALDOT) acceptance criteria. Volumetric specimens were compacted to 60 gyrations in accordance with ALDOT specifications. Across both experiments, asphalt content closely matched JMF targets. Air voids and voids in mineral aggregate (VMA) showed reductions—typically within one percent—but remained consistent among mixtures within each experiment. These observations suggest that producing WMA at lower temperatures did not significantly affect volumetric properties. Table 1 summarizes the QC data, JMF targets, and ALDOT criteria for all mixtures.

Table 1. Volumetric QC data compared to JMF and ALDOT criteria

Experiment	Mixture	Asphalt Content (%)	Air Voids (%)	VMA (%)	VFA (%)	D/P_{be}
Experiment 1	QC-HMA	5.50	3.96	16.0	75.3	1.22
	QC-WMA 1	5.53	4.18	16.6	74.8	1.07
	QC-WMA 2	5.44	3.70	15.4	75.9	1.15
	JMF	5.50	4.17	16.5	74.7	1.16
	JMF acceptance	≥ 5.5	4.0	≥ 15.5	N/A	0.6-1.4
Experiment 2	QC-HMA-325F	5.03	3.47	14.2	75.6	0.73
	QC-WMA-285F	5.09	3.36	14.2	76.3	0.85
	QC-WMA-260F	5.13	3.24	14.4	77.5	0.87
	JMF	5.10	4.4	15.1	73.5	0.77
	JMF acceptance	≥ 5.1	4.0	≥ 14.5	N/A	0.6-1.4

Table 2 presents production-related parameters, including production temperature (Based on one-time readings recorded by the plant monitoring system), duration, total tonnage, and average production rate for each mixture.

Table 2. Production temperature and tonnage data

Experiment	Mixture	Temp	Duration (hr.)	Tonnage (t)	Production rate (t/hr)
Experiment 1	HMA	162°C (323°F)	6.5	945.3	145.4
	WMA1	151°C (303°F)	6.5	914.3	140.7
	WMA2	146°C (295°F)	3.5	522.0	149.1
Experiment 2	HMA-325F	163°C (325°F)	8.0	1881.3	235.2
	WMA-285F	141°C (285°F)	2.5	604.6	241.8
	WMA-260F	127°C (260°F)	4.0	1084.6	271.1

234 **Energy Consumption Data Collection and Analysis**

235 Both asphalt plants used recycled No. 2 fuel oil as the burner fuel, stored in on-site cylindrical tanks equipped with
236 analog gauges. Fuel usage was recorded in gallons at 30-minute intervals during production, along with the
237 corresponding tonnage of asphalt mixture produced. These data were used to calculate burner fuel consumption per
238 short ton for each time interval using Eq. (1):

$$E_i = 140000 \times \frac{V_i}{M_i} \quad (1)$$

239 where:

240 E_i = energy consumption during interval i (BTU/ton)

241 V_i = volume of diesel used during interval i (gallon)

242 M_i = tonnage of asphalt mixture produced during interval i (ton)

243 An energy intensity factor of 140,000 BTU per gallon of fuel was applied, consistent with U.S. Environmental
244 Protection Agency data (Environmental Protection Agency 2024). The interval data were then aggregated to determine
245 the average burner fuel consumption and associated variability for each mixture.

246 The interval data were then aggregated to determine the average energy consumption and its variability for each
247 asphalt mixture. This method enabled a detailed evaluation of energy demand during production and facilitated direct
248 comparisons of energy efficiency across different mixtures and production temperatures. It should be noted that energy
249 consumption from hot oil heaters—used to heat the asphalt binder—was not included in this analysis.

250

251 **Laboratory Testing**

252 The performance properties of the asphalt mixtures were evaluated using the AMPT. Three tests were conducted:
253 dynamic modulus (|E*|), cyclic fatigue, and SSR. The results from these tests served as required input parameters for
254 subsequent pavement performance modeling of asphalt layers using the FlexPAVE™ program.

255

256 ***Dynamic Modulus Test***

257 The dynamic modulus (|E*|) test was conducted in accordance with AASHTO TP132-23 (AASHTO 2023) on small
258 cylindrical specimens (38 mm diameter × 110 mm height), compacted to 7.0 ± 0.5% air voids. Testing was performed

at three temperatures (4°C, 20°C, and 40°C) and three loading frequencies (10, 1, and 0.1 Hz) at each temperature. A sinusoidal compressive load was applied to induce axial peak-to-peak strains of 70–75 microstrain (με).

The resulting data were used to construct |E*| master curves using time–temperature superposition in accordance with AASHTO R84 (AASHTO 2021). The master curve was fitted using a sigmoidal model, as shown in Eq. (2):

$$log|E^*| = \delta + \frac{(\text{Max} - \delta)}{1 + e^{\beta + \gamma log f_r}} \quad (2)$$

where, $|E^*|$ = dynamic modulus, MPa; ; δ, β, γ = fitting parameters, Max= the limiting minimum modulus, MPa; and f_r= reduced frequency at the reference temperature, Hz.

The reduced frequency was calculated using the Arrhenius equation, as shown in Eq. (3).

$$log f_r = log f + \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad (3)$$

where: f_r= Reduced frequency at the reference temperature, Hz; f= Reduced frequency at the test temperature, Hz; T_r= Reference temperature, °K; T= Test temperature, °K; ΔE_a= Activation energy (treated as a fitting parameter)

The cracking resistance of the mixtures was evaluated using the Glover–Rowe parameter ($G\text{-}R_m$). This evaluation followed the original formula developed for asphalt binders, but it used the (|E*|) test results. Lower $G\text{-}R_m$ values indicate better cracking resistance. $G\text{-}R_m$ was calculated based on Eq. (4) with a temperature and frequency combination of 20°C and 5 Hz (Oshone et al. 2019; Zhang et al. 2022).

$$G\text{-}R_m = \frac{|E^*|(\cos(\delta))^2}{\sin(\delta)} \quad (4)$$

Cyclic Fatigue Test

Cyclic fatigue testing was conducted following AASHTO T411-24 (AASHTO 2024) using small specimens (38 mm diameter × 110 mm height) with 7.0 ± 0.5% air voids and a 70 mm axial gauge length. Tests were performed at 21°C and 10 Hz and appropriate strain rates resulting in failure between 2,000 and 80,000 cycles. Strain levels employed

were in the range of 450–475 με for Experiment 1 and 375–450 με for Experiment 2, reflecting differences in mixture composition and, more notably, the effect of the polymer-modified binder in the first experiment.

FlexMAT™ v2.2 was used to analyze the laboratory test results. While the dynamic modulus data were analyzed and presented using the sigmoid and Arrhenius models, the cyclic fatigue analysis within FlexMAT™ v2.2 employed the 2S2P1D model and polynomial shift functions for dynamic modulus characterization. Key outputs included the damage characteristic curve (C–S curve), which plots pseudo stiffness versus damage, and the damage ratio (D^R) failure criterion, proposed by Wang and Richard Kim (2019) and Wang et al. (2022). Both were used in the FlexMAT™ v2.2 software (FHWA 2025) to calculate the cyclic fatigue index (S_{app}), where higher values for both parameters indicate better fatigue performance.

Stress Sweep Rutting (SSR) Test

SSR testing followed AASHTO TP134-22 (AASHTO 2022) using large cylindrical specimens (100 mm diameter × 150 mm height), compacted to 7.0 ± 0.5% air voids. Tests were performed at the low temperature (TL) of 26.2°C and high temperature (TH) of 51.2°C, determined based on the project locations. A constant confining pressure of 69 kPa was maintained during the test.

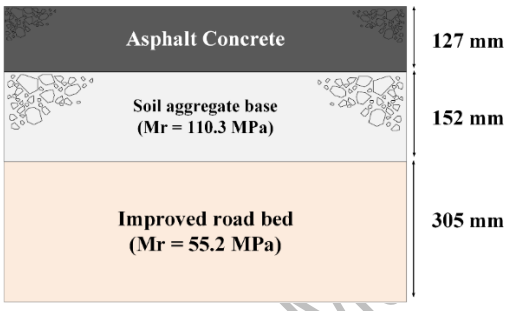
Each test included three 200-cycle loading blocks at deviatoric stress levels of 483, 689, and 896 kPa for TL, and 689, 483, and 896 kPa for TH. Each cycle consisted of a 0.4-second loading time, followed by rest periods of 1.6 seconds (TL) or 3.6 seconds (TH). Permanent deformation data were recorded and then analyzed using FlexMAT™ v2.2, which also calculated the Rutting Strain Index (*RSI*). The *RSI* is calculated by dividing the permanent deformation of an asphalt layer by its thickness after 20 years of traffic loading, assuming 30 million 18-kip standard Equivalent Single Axle Load (ESAL). Lower RSI values indicate higher rutting resistance.

Pavement Modeling using FlexPAVE™

FlexPAVE™ v2.2 was used to predict the long-term pavement performance of a pavement structure utilizing the mixtures evaluated in the study. FlexPAVE™ is a mechanistic pavement analysis and design tool that accounts for moving traffic loads, temperature gradients, and asphalt aging over time (FHWA 2025; Wang et al. 2016). Fatigue

307 performance was predicted using the Simplified Viscoelastic Continuum Damage (S-VECD) model and input data
308 from cyclic fatigue testing (Eslaminia and Guddati 2016), while rutting performance was estimated based on SSR test
309 data and a permanent strain shift model (Ghanbari et al. 2022).

310 The modeled pavement structure consisted of three layers: a 127 mm (5 in.) asphalt concrete surface, a 152 mm (6 in.)
311 unbound aggregate base, and a 305 mm (12 in.) improved subgrade (Fig. 4). The resilient modulus values for the base
312 and subgrade were 110.3 MPa (16.0 ksi) and 55.2 MPa (8.0 ksi), respectively, following Alabama Department of
313 Transportation (ALDOT) design recommendations. Material inputs for the asphalt layer were derived from AMPT
314 testing and processed using FlexMAT™ v2.2. Site-specific climate and traffic conditions from the first project location
315 were incorporated into the program. Additional inputs included a 20-year design life, an 18-kip axle load, 765 axles
316 per day, 120 psi tire pressure, and a vehicle speed of 50 mph. Level III aging inputs—comprising RAP content,
317 Recycled Binder Ratio (RBR), and high-temperature performance grades of both virgin and RAP-recovered binders—
318 were used to simulate aging effects. Outputs included fatigue damage and rut depth progression over time. Thermal
319 cracking was not evaluated, as FlexPAVE™ v2.2 does not currently support thermal cracking prediction.



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321 *Fig. 4. Representative pavement Structure used for Modeling*
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RESULTS AND DISCUSSION

Burner Fuel Consumption Results

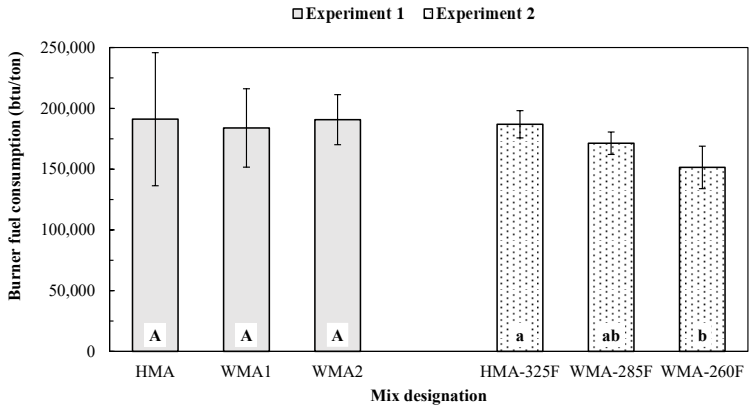

Fig. 5 presents the average burner fuel consumption for each mixture across both experiments, with error bars indicating ± one standard deviation. Statistical comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test in conjunction with one-way analysis of variance (ANOVA) at a 95% confidence level ($\alpha = 0.05$). Statistical groupings are denoted by letters above each bar—uppercase letters correspond to mixtures from Experiment 1, and lowercase letters correspond to those from Experiment 2. This convention is consistently used throughout the subsequent statistical comparisons in this section.

In Experiment 1, WMA1 exhibited slightly lower fuel consumption than the control HMA and WMA2; however, the differences were not statistically significant. This modest reduction in WMA1 can be attributed to its lower production temperature—approximately 11°C (20°F) below that of the control HMA—produced under similar ambient conditions. WMA2, produced at an even lower temperature (approximately 16°C or 28°F below the HMA), did not yield measurable energy savings, likely due to its production occurring on a much colder day, with ambient temperatures approximately 20°C (36°F) lower than those during HMA and WMA1 production, which may have offset potential fuel savings.

In Experiment 2, the effect of temperature reduction was more pronounced. Compared to the control HMA produced at 163°C (325°F), WMA mixtures produced at 141°C (285°F) and 127°C (260°F) reduced burner fuel consumption by approximately 8% and 19%, respectively. The reduction for the 127°C WMA was statistically significant. These findings confirm that substantial reductions in production temperature can yield meaningful energy savings without compromising production efficiency.

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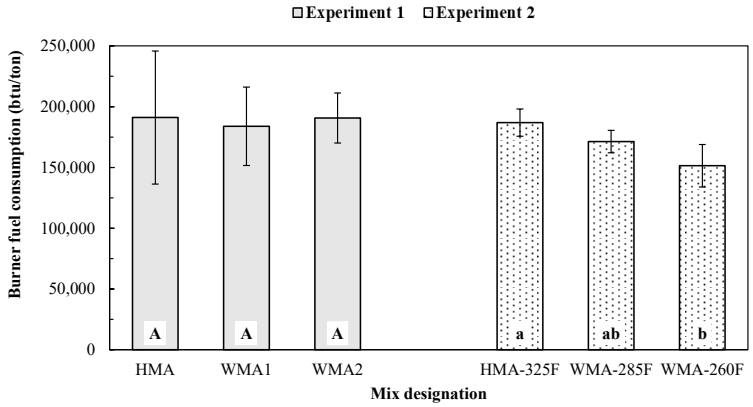


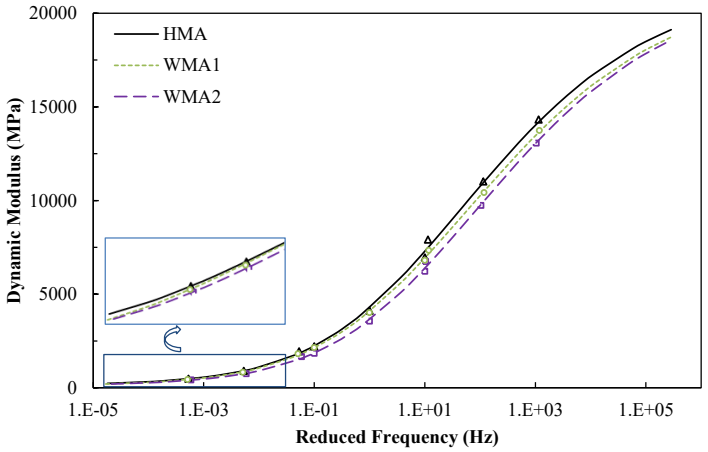
Fig. 5. Average Burner Fuel Consumption Results (Sadeghi et al. 2025)

AMPT Performance Tests

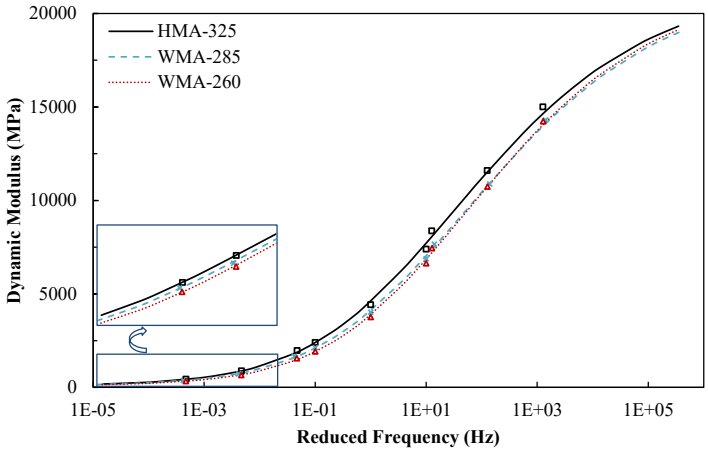
Dynamic Modulus (|E|) and Phase Angle (δ) Results*

Dynamic modulus (|E*|) master curves are presented in Fig. 6. The plots show |E*| on a numerical scale, with log–log insets illustrating behavior at the lowest reduced frequencies. The master curves were developed in accordance with AASHTO R84 (AASHTO 2021), independent of FlexMAT™ processing.

In Experiment 1 (Fig. 6a), both WMA mixtures exhibited lower |E*| values across all temperatures and frequencies compared to the control HMA, with WMA2 showing the largest reduction. The lower stiffness observed at high and intermediate frequencies suggests enhanced flexibility and potentially improved resistance to thermal and fatigue cracking. However, the reduced |E*| values at low frequencies—representative of higher pavement temperatures—suggest a decrease in rutting resistance. A similar trend was observed in Experiment 2 (Fig. 6b), where both WMA mixtures showed lower |E*| values than the control HMA. The WMA mixture produced at 127°C (260°F) exhibited the lowest stiffness, suggesting that production temperature significantly influences mixture modulus.



a) Experiment 1 Results



b) Experiment 2 Results

Fig. 6. Dynamic Modulus Master Curves

Phase angle (δ) diagrams are shown in Fig. 7. In Experiment 1 (Fig. 7a), WMA mixtures exhibited slightly higher δ values at intermediate and high frequencies, indicating more viscous behavior. This suggests greater energy dissipation and enhanced resistance to intermediate- and low-temperature cracking. At low frequencies, WMA mixtures showed lower δ values, reflecting more elastic behavior that may help reduce permanent deformation at high service temperatures. Similar behavior was observed in Experiment 2 (Fig. 7b).

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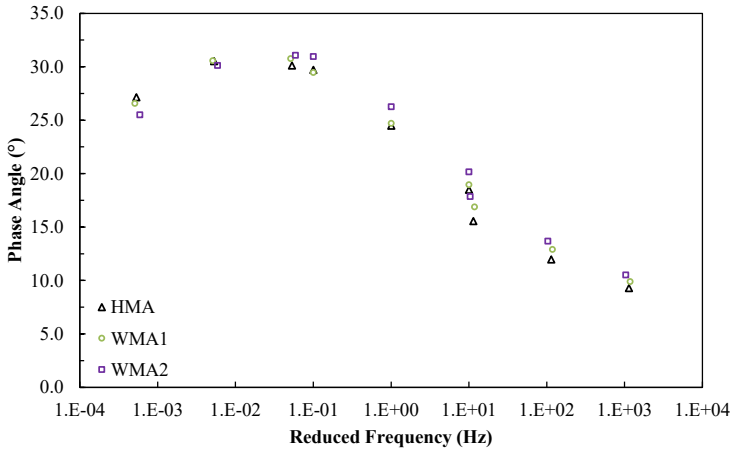
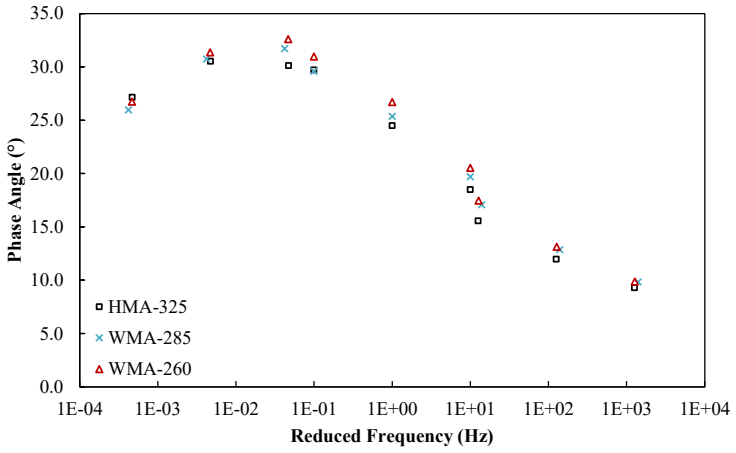


a) Experiment 1 mixtures



b) Experiment 2 mixtures

Fig. 7. Phase Angle Results

Glower Rowe Parameter

The mixture Glover-Rowe parameter (G-R_m), calculated from |E*| and δ, quantifies mixture stiffness and brittleness to assess non-load-related cracking resistance. According to NCHRP Project 09-58, recommended thresholds for G-R_m are 8,000 MPa for short-term aged and 19,000 MPa for long-term aged mixtures (Kim et al. 2021).

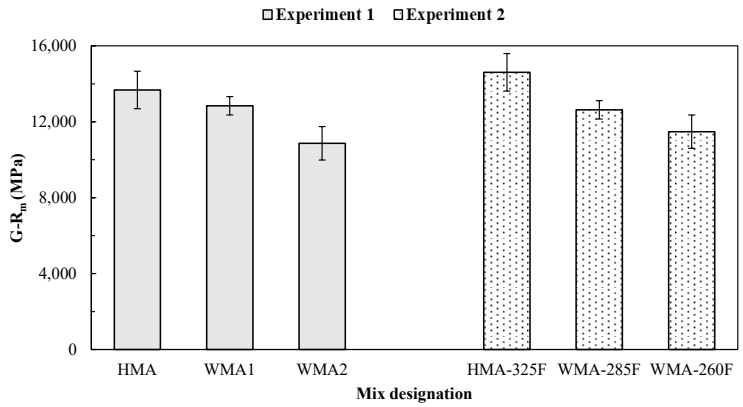


Fig. 8 presents the *G-Rm* results. Average values were obtained from fitted master curves based on three replicate specimens per mixture, with error bars representing the standard deviation of *G-Rm* calculated individually for each replicate. In Experiment 1, both WMA mixtures showed lower G-Rm values than the control HMA, with WMA2 exhibiting the greatest reduction. Similar results were observed in Experiment 2, where the WMA produced at 127°C (260°F) had the lowest G-Rm value. These findings indicate that lowering production temperatures improved mixture flexibility and resistance to non-load-related (thermal or block) cracking.

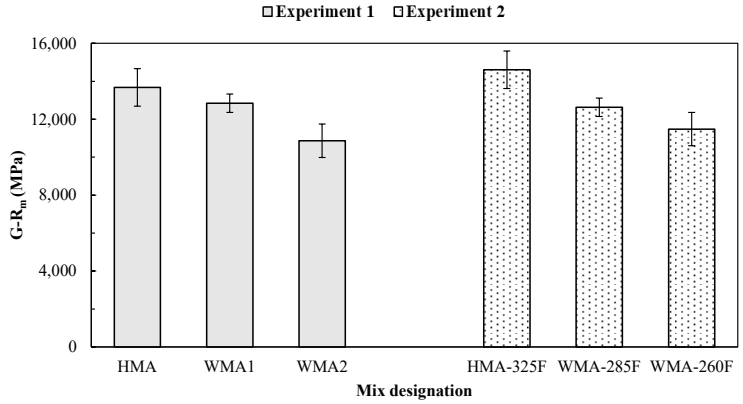


Fig. 8. G-Rm cracking susceptibility index results

Black space diagrams of |E*| versus δ on a logarithmic scale (Fig. 9) further support these observations. A shift toward the lower-right quadrant corresponds to lower *G-Rm* values and enhanced resistance to block or thermal cracking. In both experiments, WMA mixtures shifted consistently in this direction, with WMA2 and WMA-260F mixtures showing the most pronounced improvements.

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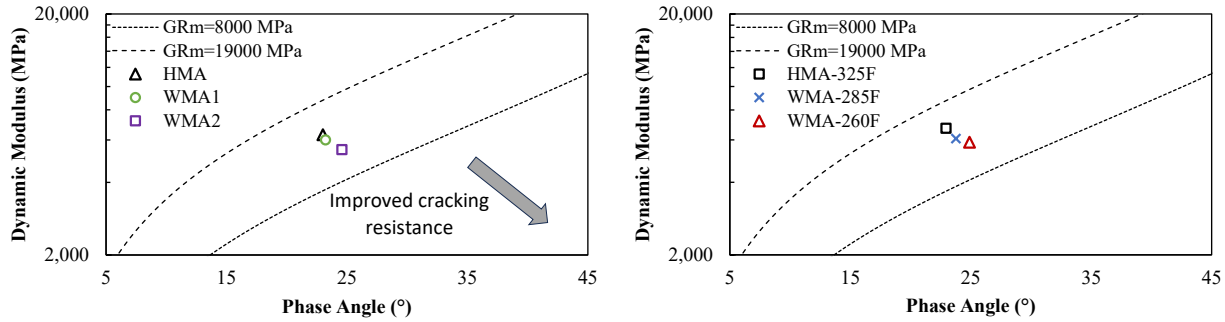

a) Experiment 1 mixtures *b) Experiment 2 mixtures*

Fig. 9. Mixture Black Space Diagrams

Cyclic Fatigue Test Results

Cyclic fatigue performance was evaluated using FlexMAT™ v2.2, which applies the S-VECD model to generate damage characteristic (*C*-*S*) curves (Fig. 10). In these curves, pseudo-stiffness (*C*) decreases as damage (*S*) accumulates. In a fatigue damage tolerance (toughness) perspective, a steeper and shorter C-S curve indicates rapid stiffness degradation and faster fatigue damage progression (Kim et al. 2021).

WMA mixtures in both experiments exhibited shorter and flatter *C*-*S* curves than their HMA counterparts, suggesting that while WMA mixtures absorbed strain energy effectively at early stages, damage accumulated more rapidly after initiation. Across the full range of S values, the C–S curves for control HMA mixtures consistently lie above those of the WMA mixtures, suggesting higher stiffness and slower damage progression (Wang et al. 2022). A stiffer mix under the same load amplitude would experience lower strain, which generally translates to longer fatigue life (Wang et al. 2022).

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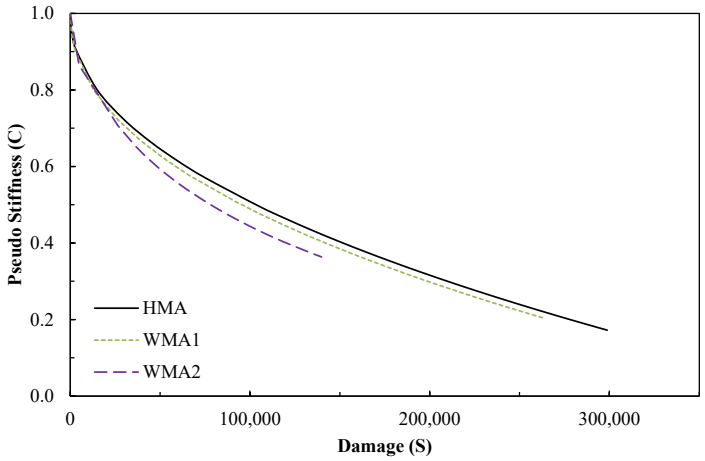
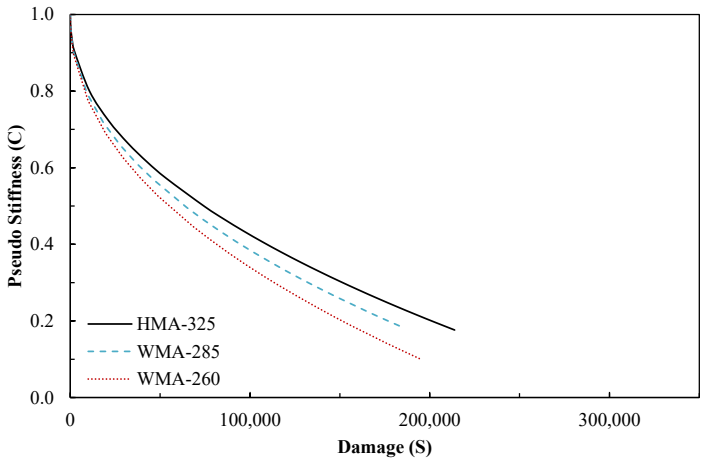


a) Experiment 1 mixtures



b) Experiment 2 mixtures

Fig. 10. Damage Characteristics Curve (C-S curve) Results

FlexMAT™ also calculates two key fatigue parameters: the D^R failure criterion and the apparent damage capacity (S_{app}) (Fig. 11 and 12). D^R represents fatigue damage tolerance (toughness), whereas the S_{app} parameter accounts for the combined effects of stiffness and toughness. Across both experiments, D^R and S_{app} values were similar between WMA and HMA mixtures, indicating comparable overall fatigue performance. In Experiment 2, consistent D^R and S_{app} values across all mixtures confirmed that further reductions in production temperature did not impact fatigue resistance.

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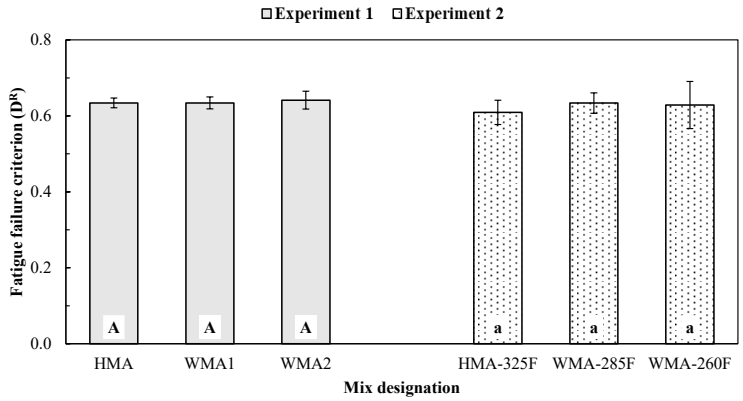

Fig. 11. Fatigue Failure Criterion (D^R) Results

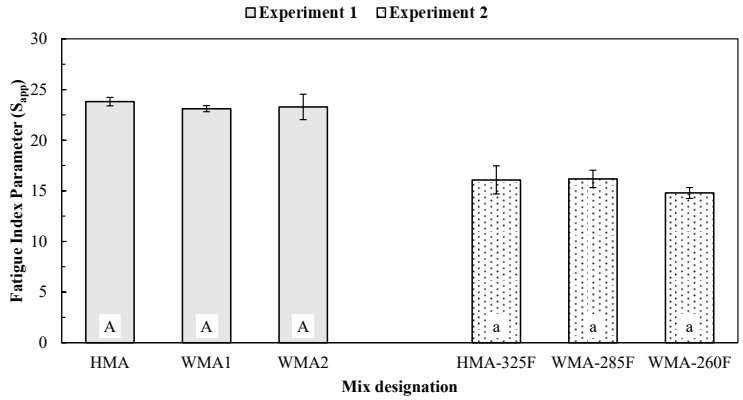

Fig. 12. Fatigue Index Parameter (S_{app}) Results

Stress Sweep Rutting Results

Fig. 13 presents the *RSI* results, calculated from the SSR test to estimate the average permanent strain accumulated over 20 years of traffic loading (assuming 30 million ESALs). In both experiments, WMA mixtures exhibited higher RSI values than the control HMA, indicating increased susceptibility to rutting. In Experiment 1, WMA1 had the highest RSI, underscoring the influence of additive type. In Experiment 2, RSI values increased with decreasing production temperature, with the WMA produced at 127°C (260°F) showing the highest rutting potential. These results are consistent with the dynamic modulus findings, which showed lower stiffness for WMA mixtures. The overall trends suggest that while lower production temperatures improve flexibility and cracking resistance, they may also reduce rutting resistance—particularly at the lowest production temperatures.

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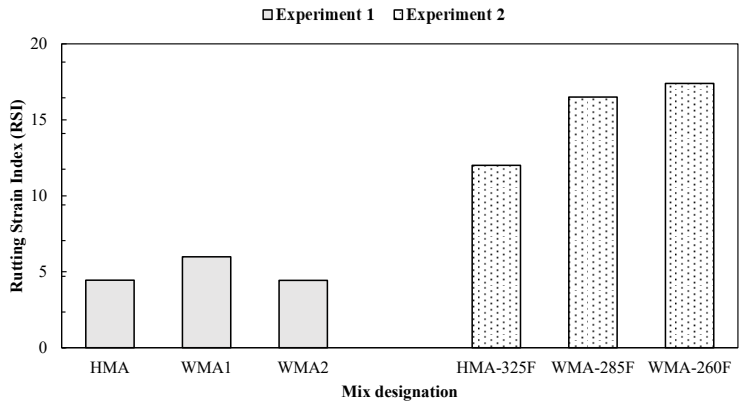

Fig. 13. RSI Rutting Index Results

5.5 Performance Modeling Using FlexPAVE™

Analysis of Damage Evolution

FlexPAVE™ modeling was conducted using a three-layer pavement structure, with asphalt surface layer properties derived from AMPT test results. Predicted fatigue damage evolution over a 20-year design life is shown in Fig. 14.

In Experiment 1 (Fig. 14a), both WMA mixtures exhibited higher cumulative predicted fatigue damage than the control HMA. After 20 years, WMA1 exhibited a 1.9% increase in damage, while WMA2 showed a 6.0% increase. These results suggest that WMA1 performed comparably to the control HMA in predicted fatigue resistance, despite the higher damage predicted.

In Experiment 2 (Fig. 14b), reducing the production temperature by 22°C (40°F) for WMA-285F resulted in only a 0.3% increase in fatigue damage compared to the control HMA. A 36°C (65°F) temperature reduction for WMA-260F led to a 1.8% increase in predicted fatigue damage. These modest increases indicate that significant temperature reductions can be achieved without substantially impacting long-term predicted fatigue performance when using chemical WMA additives.

It is essential to note that, although the same additive (WMA1) was used in both experiments, a direct comparison across experiments is not appropriate due to differences in materials, mix designs, and reheating and compaction temperatures. Therefore, predicted performance trends should be interpreted within each experiment independently.

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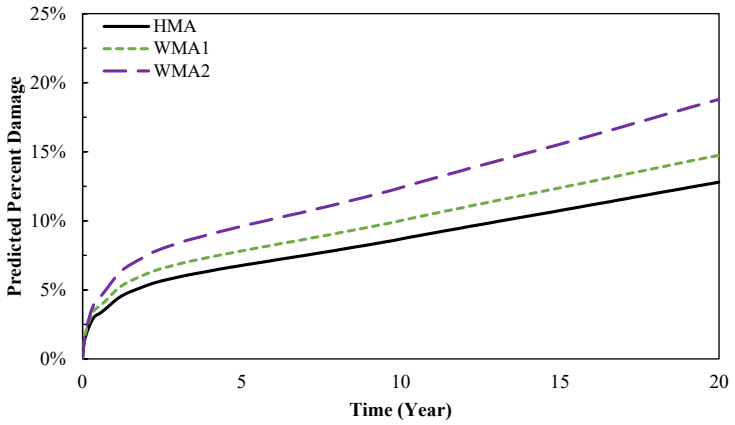
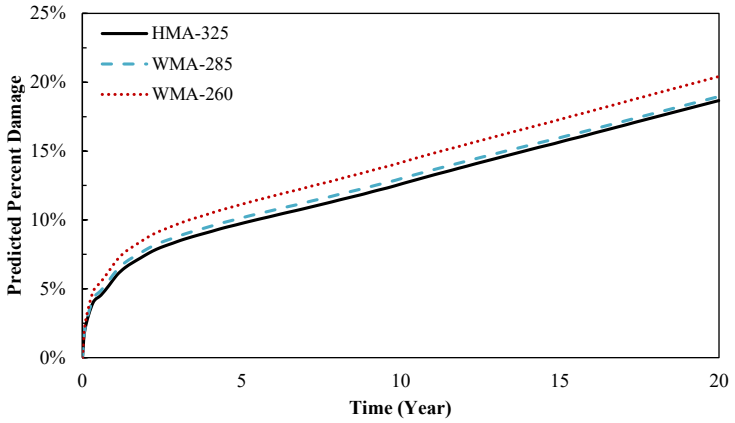


a) Experiment 1 mixtures



b) Experiment 2 mixtures

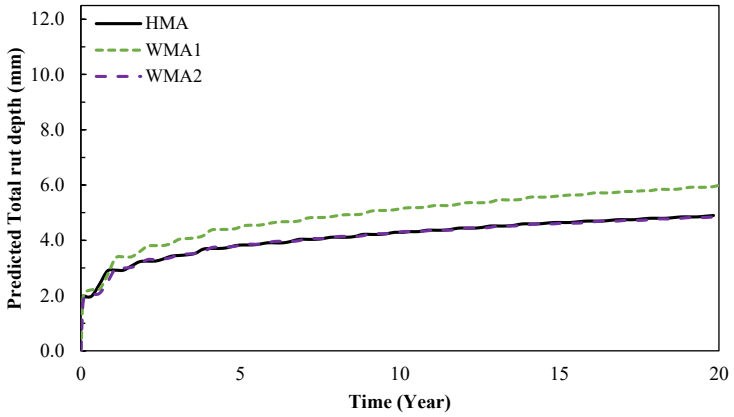
Fig. 14. Predicted Percent Damage Using FHWA's FlexPAVETM Modeling

Rutting Prediction

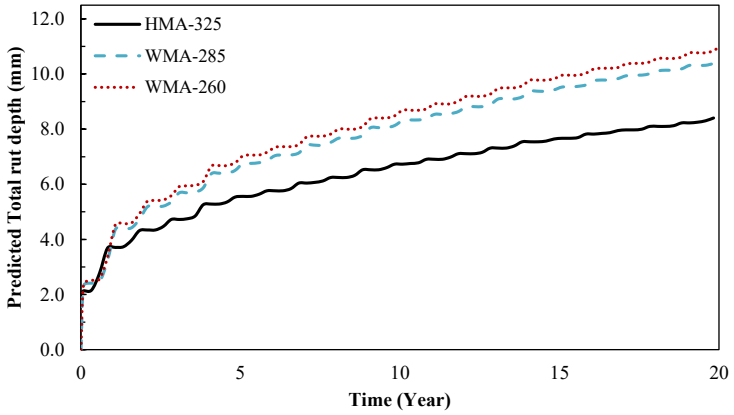
Predicted total rut depths are presented in Fig. 15. In Experiment 1 (Fig. 15a), WMA1 exhibited the highest predicted rut depth (6.0 mm), while WMA2 and the control HMA showed similar values (approximately 4.9 mm). These results align with the laboratory RSI data, indicating that WMA2 maintained rutting resistance comparable to that of the control, despite its lower stiffness.

In Experiment 2 (Fig. 15b), predicted rut depths were higher overall, primarily due to the use of an unmodified PG 67-22 binder rather than the polymer-modified PG 76-22 used in Experiment 1. WMA mixtures exhibited greater rutting than the control HMA, with WMA-285F and WMA-260F showing 2.1 mm and 2.6 mm higher rut depths,

454 respectively. The marginal difference between these two WMA mixtures suggests that additional temperature
455 reductions beyond 141°C (285°F) had a limited effect on rutting performance.



a) Experiment 1 mixtures



b) Experiment 2 mixtures

456 *Fig. 15. Predicted Total Rut Depth Using FHWA's FlexPaveTM Modeling*
457

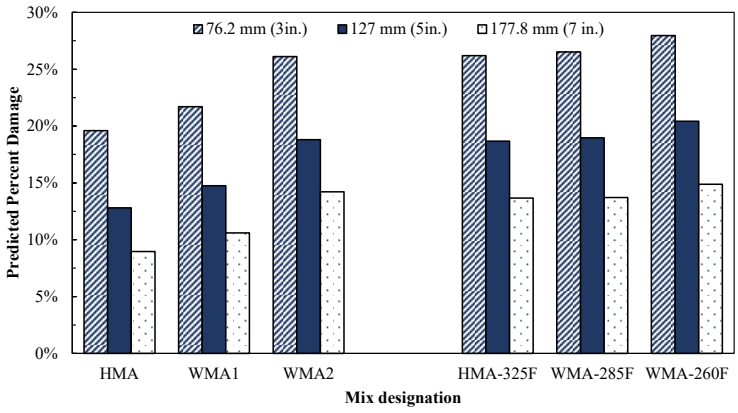
458 Overall, the FlexPAVE™ modeling results indicated that WMA mixtures can achieve long-term fatigue
459 performance comparable to conventional HMAs, with a modest increase in predicted rutting susceptibility. Because
460 FlexPAVE™ v2.2 does not currently model thermal cracking, future inclusion of this feature would likely further
461 highlight the benefits of WMA mixtures for improving low-temperature performance.

Effect of Layer Thickness

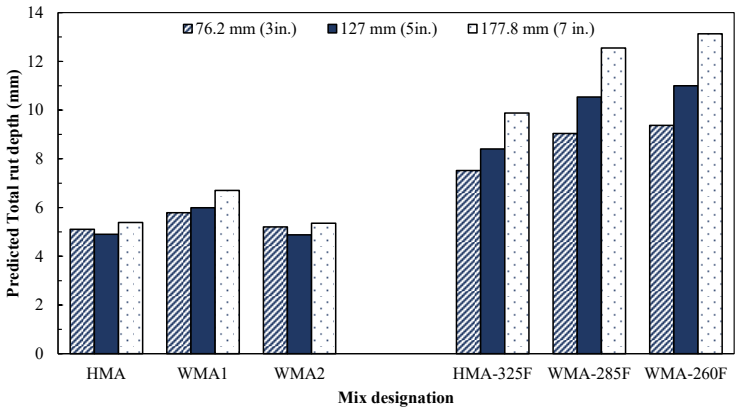
The influence of asphalt layer thickness on pavement performance was also evaluated using FlexPAVE™. Three surface thickness scenarios were modeled: a standard 127 mm (5 in.) layer, a thinner 76.2 mm (3 in.) layer, and a thicker 177.8 mm (7 in.) layer.

As shown in Fig. 16, increasing the asphalt layer thickness consistently reduced predicted fatigue damage for all mixtures, which aligns with the expected reduction in tensile strain at the bottom of the asphalt layer. However, rutting behavior exhibited different trends between experiments. In Experiment 1, variations in layer thickness resulted in only minor changes in predicted rutting, with no discernible trend. In Experiment 2, predicted rutting increased slightly with thicker asphalt layers, likely due to the softer binder and higher internal strain levels in these mixtures.

Importantly, variations in asphalt thickness did not alter the relative performance ranking between WMA and HMA mixtures. This consistency reinforces the robustness of the findings and indicates that WMA mixtures can be reliably implemented across typical pavement thickness ranges without impacting performance.



a) Predicted Percent Damage



b) Predicted Total Rut Depth

Fig. 16. Predicted Percent Damage and Total Rut Depth for Different Asphalt Layer Thicknesses

CONCLUSIONS

This study evaluated the effects of reducing asphalt production temperatures using chemical WMA additives on burner fuel consumption, mixture performance properties, and predicted pavement performance. Two field experiments were conducted using approved mix designs. Experiment 1 compared two chemical WMA additives with a conventional HMA control, while Experiment 2 focused on further reducing production temperatures using one of the WMA additives used in the first experiment. Key findings are summarized as follows:

- **Energy Consumption**: In Experiment 1, moderate reductions in production temperature did not yield measurable burner fuel savings. In Experiment 2, reducing production temperatures by 22°C (40°F) and 36°C (65°F) resulted in approximately 8% and 19% decreases in burner fuel usage, respectively, compared to the control HMA.
- **Cracking Performance**: AMPT testing showed that WMA mixtures produced at lower temperatures exhibited lower Glover–Rowe (*G-Rm*) values, indicating improved non-load-related cracking resistance. Fatigue parameters, including the D^R and the S_{app}, remained comparable between WMA and HMA mixtures, suggesting that reducing production temperatures did not affect fatigue performance.
- **Rutting Performance:** SSR test results indicated that WMA mixtures were more susceptible to permanent deformation than the control HMA, especially at the lowest production temperature. These findings underscore the importance of evaluating rutting potential when implementing significant reductions in production temperature.
- **Predicted Performance**: FlexPAVE™ modeling showed that WMA mixtures generally achieved similar fatigue performance to conventional HMA, with only modest increases in predicted rutting. The results suggest that temperature reductions are feasible without affecting overall pavement durability.

Overall, this research demonstrates that WMA technologies can substantially reduce burner fuel consumption and associated greenhouse gas emissions while maintaining acceptable performance. With appropriate mix design adjustments, WMA can offer a viable and sustainable solution for reducing asphalt production temperatures and enhancing energy efficiency in pavement construction.

DATA AVAILABILITY STATEMENT:

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

ACKNOWLEDGEMENTS:

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REFERENCES

AASHTO (2021). "AASHTO R84-17 (2021): Standard Practice for Developing Dynamic Modulus Master Curves for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)."ASTM Compass.

AASHTO (2022). "AASHTO T255-22 Standard Method of Test for Total Evaporable Moisture Content of Aggregate by Drying."

AASHTO (2022). "AASHTO TP134-22 Standard Method of Test for Stress Sweep Rutting (SSR) Test Using Asphalt Mixture Performance Tester (AMPT)."

AASHTO (2023). "AASHTO T132-23 Standard Method of Test for Determining the Dynamic Modulus for Asphalt Mixtures Using Small Specimens in the Asphalt Mixture Performance Tester (AMPT)."

AASHTO (2024). "AASHTO T411-24 Standard Method of Test for Determining the Damage Characteristic Curve and Failure Criterion Using Small Specimens in the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test."

Akentuna, M., Mohammad, L. N., Boateng, K. A., and Cooper Jr, S. (2022). "Warm Mix Asphalt demonstration projects in Louisiana: Case study of five to eight years of field performance." *Transportation Research Record*, 2676(9), 148-158.

ALDOT (2022). "Standard Specifications for Highway Construction, Section 424 (d)."https://www.dot.state.al.us/publications/Construction/Specifications.html.

Almeida-Costa, A., and Benta, A. (2016). "Economic and environmental impact study of warm mix asphalt compared to hot mix asphalt." *Journal of Cleaner Production*, 112, 2308-2317.

Bairgi, B. K., Rahman, A. A., Tarefder, R. A., and Larrain, M. M. M. (2020). "Comprehensive evaluation of rutting of warm-mix asphalt utilizing long-term pavement performance specific pavement studies." *Transportation Research Record*, 2674(7), 272-283.

Bairgi, B. K., Tarefder, R. A., Syed, I., Mendez, M. M., Ahmed, M., Mannan, U. A., and Rahman, M. T. "Assessment of Rutting Behavior of Warm-Mix Asphalt (WMA) with Chemical WMA Additives towards Laboratory and Field Investigation." *Proc., International Conference on Transportation and Development 2018*, American Society of Civil Engineers Reston, VA, 264-272.

Capitão, S., Picado-Santos, L., and Martinho, F. (2012). "Pavement engineering materials: Review on the use of warm-mix asphalt." *Construction and Building Materials*, 36, 1016-1024.

Cheraghian, G., Falchetto, A. C., You, Z., Chen, S., Kim, Y. S., Westerhoff, J., Moon, K. H., and Wistuba, M. P. (2020). "Warm mix asphalt technology: An up to date review." *Journal of Cleaner Production*, 268, 122128.

Croteau, J.-M., and Tessier, B. "Warm mix asphalt paving technologies: a road builder's perspective." *Proc., Annual Conference of the Transportation Association of Canada, Toronto*, Citeseer.

Dao, D. V., Nguyen, N.-L., Nguyen, M. H., Ly, H.-B., and Truong, V. Q. (2022). "Evaluation of cracking resistance of warm mix asphalt incorporating high reclaimed asphalt pavement content." *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 236(12), 2550-2560.

Environmental Protection Agency (2024). "Managing Used Oil: Answers to Frequent Questions for Businesses." <https://www.epa.gov/hw/managing-used-oil-answers-frequent-questions-businesses>. (July 31, 2024).

Epps, J. A. (2019). "Innovative asphalt pavement technology: paving the way for the world's roadways." *Transportation Research Record*, 2673(1), 1-16.

Eslaminia, M., and Guddati, M. N. (2016). "Fourier-finite element analysis of pavements under moving vehicular loading." *International Journal of Pavement Engineering*, 17(7), 602-614.

Fakhri, M., Ghanizadeh, A. R., and Omrani, H. (2013). "Comparison of fatigue resistance of HMA and WMA mixtures modified by SBS." *Procedia-Social and Behavioral Sciences*, 104, 168-177.

FHWA (2025). "Federal Highway Administration Asphalt Material Analysis Tools ", <https://highways.dot.gov/turner-fairbank-highway-research-center/software/flexmat>. (June 19, 2025).

Garcia Cucalon, L., Kassem, E., Little, D. N., and Masad, E. (2017). "Fundamental evaluation of moisture damage in warm-mix asphalts." *Road Materials and Pavement Design*, 18(sup1), 258-283.

Ghanbari, A., Underwood, B. S., and Kim, Y. R. (2022). "Development of a rutting index parameter based on the stress sweep rutting test and permanent deformation shift model." *International Journal of Pavement Engineering*, 23(2), 387-399.

Kim, Y. R., Castorena, C., Saleh, N. F., Braswell, E., Elwardany, M., and Rad, F. Y. (2021). *Long-term aging of asphalt mixtures for performance testing and prediction: Phase III results*.

McCarthy, L., and Daniel, J. (2018). "Increasing WMA implementation by leveraging the state-of-the knowledge." *Final Report, NCHRP Project*, 20, Task 01.

NAPA (2023). "NAPA IS-145 Guide on Asphalt Mixture Specimen Fabrication for BMD Performance Testing."

NAPA (2024). "NAPA Quarterly: Pioneering Sustainable Pavements, Volume 29, Number 2, Summer 2024."

Oshone, M., Sias, J. E., Dave, E. V., Epps Martin, A., Kaseer, F., and Rahbar-Rastegar, R. (2019). "Exploring master curve parameters to distinguish between mixture variables." *Road Materials and Pavement Design*, 20(sup2), S812-S826.

Padula, F. R., Nicodemos, S., Mendes, J. C., Willis, R., and Taylor, A. (2019). "Evaluation of fatigue performance of high RAP-WMA mixtures." *International Journal of Pavement Research and Technology*, 12, 430-434.

Rahman, M. A., Zaman, M., Ali, S. A., Ghabchi, R., and Ghos, S. (2022). "Evaluation of mix design volumetrics and cracking potential of foamed Warm Mix Asphalt (WMA) containing Reclaimed Asphalt Pavement (RAP)." *International Journal of Pavement Engineering*, 23(10), 3454-3466.

Rubio, M. C., Martínez, G., Baena, L., and Moreno, F. (2012). "Warm mix asphalt: an overview." *Journal of cleaner production*, 24, 76-84.

Sadeghi, M., Bairgi, B. K., Hartzog, Z., Gatiganti, S. C., Vangala, R. R., Jafarmilajerdi, A., Dylla, H., Tran, N., and Bowers, B. (2025). "Effects of Reducing Asphalt Production Temperatures Using Warm Mix Technologies on Burner Fuel Consumption and Mixture Performance Properties." *Transportation Research Record*, 03611981251352508.

Sadeghi, M., and Sabouri, M. (2025). "Cracking indices and effects of synthetic fibres on the mechanical properties of cold recycled asphalt mixtures." *Road Materials and Pavement Design*, 1-24.

Spadoni, S., Ingrassia, L. P., Mariani, E., Cardone, F., and Canestrari, F. (2022). "Long-term performance assessment of a warm recycled motorway pavement." *Case Studies in Construction Materials*, 17, e01451.

Sukhija, M., Saboo, N., and Pani, A. (2022). "Economic and environmental aspects of warm mix asphalt mixtures: A comparative analysis." *Transportation Research Part D: Transport and Environment*, 109, 103355.

Wang, Y., Norouzi, A., and Kim, Y. R. (2016). "Comparison of fatigue cracking performance of asphalt pavements predicted by pavement ME and LVECD programs." *Transportation Research Record*, 2590(1), 44-55.

Wang, Y., and Richard Kim, Y. (2019). "Development of a pseudo strain energy-based fatigue failure criterion for asphalt mixtures." *International Journal of Pavement Engineering*, 20(10), 1182-1192.

Wang, Y. D., Underwood, B. S., and Kim, Y. R. (2022). "Development of a fatigue index parameter, Sapp, for asphalt mixes using viscoelastic continuum damage theory." *International Journal of Pavement Engineering*, 23(2), 438-452.

Wen, H., Wu, S., Mohammad, L. N., Zhang, W., Shen, S., and Faheem, A. (2016). "Long-term field rutting and moisture susceptibility performance of warm-mix asphalt pavement." *Transportation Research Record*, 2575(1), 103-112.

West, R., Rodezno, C., Julian, G., Prowell, B., Frank, B., Osborn, L. V., and Kriech, T. (2014). *Field performance of warm mix asphalt technologies*.

West, R., Rodezno, C., Leiva, F., and Yin, F. (2018). "Development of a framework for balanced mix design." *Project NCHRP*, 20-07.

Williams, B. A., Willis, J. R., and Shacat, J. (2024). "Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2022."

Yin, F., West, R., Powell, B., and DuBois, C. (2023). "Short-term performance characterization and fatigue damage prediction of asphalt mixtures containing polymer-modified binders and recycled plastics." *Transportation Research Record*, 03611981221143119.

Zaremotekhases, F., Sadek, H., Hassan, M., and Berryman, C. (2022). "Impact of warm-mix asphalt technologies and high reclaimed asphalt pavement content on the performance of alternative asphalt mixtures." *Construction and Building Materials*, 319, 126035.

Zaumanis, M. (2014). "Warm mix asphalt." *Climate change, energy, sustainability and pavements*, Springer, 309-334.

Zhang, R., Sias, J. E., and Dave, E. V. (2022). "Evaluation of the cracking and aging susceptibility of asphalt mixtures using viscoelastic properties and master curve parameters." *Journal of traffic and transportation engineering (English Edition)*, 9(1), 106-119.