This is the accepted manuscript version of the following article, which has been accepted for publication in Transportation Research Record, published by SAGE.

Effects of Reducing Production Temperatures Using Warm Mix Technologies on Burner Fuel Consumption and Mixture Performance Properties

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Word count: 7,587 words text + 6 tables x 250 words (each) = 9,087 words

Submission Date: April 4, 2025.

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ABSTRACT

This study evaluated the impact of using warm mix technologies (WMTs) to lower production temperatures on energy consumption and mixture performance characteristics. Two experiments were conducted using ALDOT-approved hot mix asphalt (HMA) designs. The first experiment compared two warm mix asphalt (WMA) mixtures, produced using chemical additives WMT1 and WMT2, with a control HMA mixture. The second experiment involved one control HMA mixture and one WMA mixture using WMT1 produced at multiple temperatures. Both experiments evaluated burner fuel consumption, intermediate cracking resistance using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) test, and rutting resistance using the Hamburg Wheel-Tracking Test (HWTT) and High-Temperature Indirect Tensile Test (HT-IDT). Experiment 1 used reheated plant-mixed, lab-compacted (RH-PMLC) and lab-mixed, lab-compacted (LMLC) specimens, while Experiment 2 used hot-compacted PMLC (H-PMLC) specimens. The results indicated that using WMTs at lower production temperatures can reduce energy consumption by approximately 20%, potentially lowering emissions. The cracking resistance of WMA mixtures was similar to that of the control HMA when using plant-mixed samples. However, significantly better cracking resistance was observed when using LMLC samples. Additionally, rutting and moisture resistance were comparable or reduced for WMA mixtures but still met the minimum rutting requirement. This study confirms that lowering the production temperature of WMA mixtures can reduce burner energy consumption and emissions without compromising mixture performance characteristics.

Keywords: Warm Mix Asphalt, Warm Mix Technologies, Energy Consumption, Cracking, Rutting

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INTRODUCTION

The emphasis on sustainability in Departments of Transportation (DOTs) and the asphalt industry has brought renewed attention to innovative efforts like the use of Warm Mix Technologies (WMTs), which can provide significant environmental and performance benefits (1). WMTs allow for production and compaction of Warm Mix Asphalt (WMA) at lower temperatures compared to traditional Hot Mix Asphalt (HMA), which can reduce energy consumption and lower emissions of greenhouse gases (GHGs). The use of WMTs not only benefits the environment but also extends the paving season, improves working conditions, and allows for longer haul distances, making it a versatile solution for sustainable asphalt pavement needs (2-4). Studies have reported energy consumption reductions ranging from 8% to 40% with WMA production compared to that of HMA, depending on the fuel type, energy source, and production temperature (2). A 2022 survey by the National Asphalt Pavement Association (NAPA) indicated that the use of WMTs in the U.S. reduced GHG emissions by 0.18 million metric tons of CO_2 equivalent, comparable to the annual emissions of 40,000 passenger vehicles (5).

WMTs can be classified into three categories: foaming technologies, organic or wax-based additives, and chemical additives. Foaming technologies involve injecting water into hot asphalt under high pressure, creating foamed asphalt by encapsulating water vapor as bubbles in the binder, which expands the binder volume and reduces its viscosity, enhancing workability (6). Organic additives lower production temperatures by reducing the viscosity of asphalt binders at temperatures above their melting points (7). Chemical additives, unlike the other WMTs, mostly have minimal effects on viscosity but improve aggregate coatability by reducing frictional resistance during binder-aggregate interactions (2, 8, 9). Chemical additives, such as Evotherm, Revix, Rediset, and Zycotherm, have become the most used WMTs (6, 10, 11), accounting for approximately 64% of WMA produced in 2022 (5). These additives have been reported to enhance workability and compaction and improve the adhesion between the binder and aggregates (12). Additionally, WMTs have been used to incorporate higher contents of recycled materials and alternative binders (13).

Despite the reported benefits, there remain concerns with the use of WMTs, including increased potential for rutting and moisture susceptibility due to residual moisture in aggregates from insufficient drying (14). Condensation in the baghouse can also lead to damp fines and potential corrosion (15). The primary concern with WMA is perceived initial reduced rutting resistance, likely due to lower mixing and compaction temperatures, which result in lower initial binder aging and decreased initial mixture stiffness. However, cracking resistance tends to be better as reduced aging improves flexibility. Some studies have reported equivalent or better rutting resistance for WMA compared to HMA (16, 17), while others have noted slightly higher rutting potential (18, 19). Laboratory-produced WMA mixtures with chemical additives have shown higher Flexibility Index (FI) and Cracking Tolerance Index (CT_{index}) values, indicating greater resistance to intermediate cracking (20, 21). However, field studies, such as those conducted in Louisiana, have shown lower fatigue cracking resistance in WMA test sections compared to control HMA sections after 5 to 8 years of service (22). The mixed performance results and operational concerns may explain why WMTs are often used primarily as compaction aids without reducing production temperatures.

Objectives and Scope

This study aimed to evaluate the impacts of reducing production temperatures using chemical WMTs on both the laboratory mixture performance properties and burner fuel consumption during production. Specifically, it assessed whether these WMTs could maintain or enhance the lab cracking and rutting performance of asphalt mixtures while also achieving energy

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and emission savings. The study compared WMA mixtures containing chemical additives with traditional HMA control mixtures, providing insights into the benefits and potential challenges of WMTs in low-emission asphalt production practices. The findings can be used by DOTs and contractors to effectively use WMTs within volumetric and Balanced Mix Design (BMD) frameworks, thereby promoting more sustainable and efficient asphalt production processes.

EXPERIMENTAL PROGRAM

Methodology

This study consisted of two experiments, as depicted in Figure 1. Experiment 1 involved two WMA mixtures (i.e., WMA1 and WMA2 utilizing WMT1 and WMT2) and a control HMA mixture. Initially, the production temperature was set at 320-330°F for HMA and 275-285°F for both WMA mixtures, with an intended target of reducing the production temperature by approximately 50°F. However, on the day of producing WMA1, the contractor was also producing another HMA mixture for a local municipal paving job with a target production temperature of 300-310°F, and there was an issue with the drag conveyor at the plant. Thus, the target production temperature of the two WMA mixtures was adjusted to 295-305°F, resulting in a production temperature reduction of around 25°F instead of the initially planned 50°F. During production, data on burner fuel consumption were collected for each mixture. Furthermore, component materials and plant mix samples were taken to prepare Lab-Mixed, Lab-Compacted (LMLC), and Reheated Plant-Mixed, Lab-Compacted (RH-PMLC) specimens for evaluating the rutting and cracking performance of the three mixtures.

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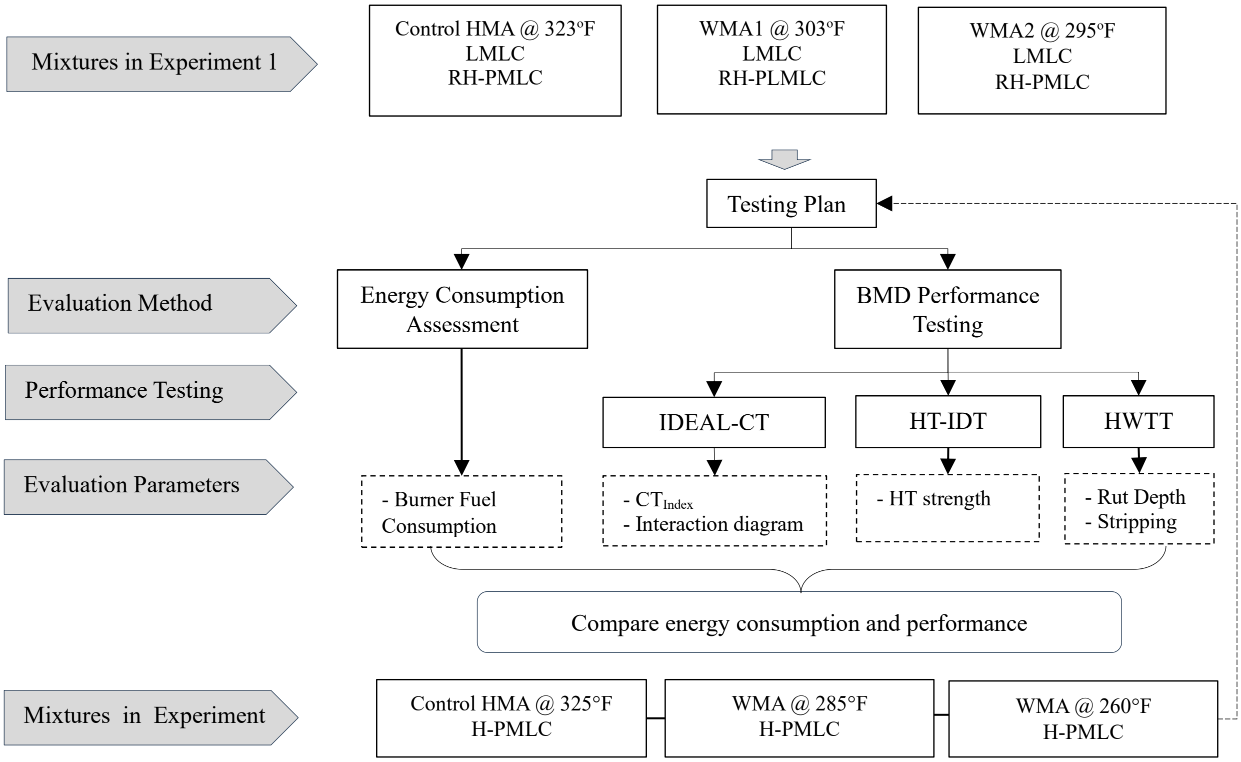

Figure 1 Experimental plan

In response to the limitations observed in Experiment 1, Experiment 2 was planned and conducted with another contractor using only WMT1. It involved one control HMA mixture and one WMA mixture using WMT1. The HMA mixture was produced at 320-330°F, while the WMA mixture was produced at multiple temperatures, starting from 320-330°F and gradually reduced to 260-270°F, with approximately 10°F reductions at each step. Additionally, the contractor planned the production of the WMA mixture on a day when no other mixtures were being produced at the asphalt plant. During production, data on fuel consumption by the burner were collected for each mixture. Plant mix samples were also taken when the production temperature reached around 285°F and at the lowest production temperature (approximately 260°F) to prepare Hot Plant-Mixed, Lab-Compacted (H-PMLC) specimens (i.e., without reheating) for evaluating the rutting and cracking performance of the HMA and WMA mixtures. More detailed information about the two experiments is provided in the following sections.

Asphalt Mix Designs

Table 1 displays the mix design details of HMA mixtures and the Alabama Department of Transportation (ALDOT) specification requirements for each mixture. According to ALDOT specifications, the mixtures were compacted at 60 gyrations for Superpave volumetric designs (23).

TABLE 1 Job Mix Formula (JMF) Properties and Acceptance Ranges

Mix Properties	Experiment 1		Experiment 2	
	JMF	ALDOT Limits	JMF	ALDOT Limits
NMAS (mm)	9.5	N/A	12.5	N/A
RAP (%)	20	Max 20	20	Max 20
RBR (%)	15.3	N/A	19.6	N/A
Asphalt Content (%)	5.5	Min 5.5	5.1	Min 5.1
Virgin Asphalt Content (%)	4.6	N/A	4.1	N/A
Air Voids (%)	4.0	4.0	4.0	4.0
VMA (%)	16.5	Min 15.5	15.1	Min 14.5
VFA (%)	75.8	N/A	73.5	N/A
D/P_{be}	1.16	0.6-1.4	0.77	0.6-1.4

Experiment 1

Experiment 1 was conducted at an asphalt plant in Montgomery, Alabama, as part of an overlay project on US-82 near Prattville, Alabama. The plant is a 2000 Model Astec double barrel green® drum mixer using recycled No. 2 fuel oil. The mixtures included a control HMA and two WMA mixtures. The WMTs used in the WMA mixtures were chosen based on their prior use in Alabama and were mixed with the virgin binder at the terminal at a rate of 0.5% by weight of the virgin binder. All mixtures had the same total asphalt content and aggregate gradation.

Each of the mixtures was produced on different days to minimize residual heat effects on energy consumption. Specifically, the control HMA mixture was produced in September 2023, with an average daily ambient temperature of 86.4°F (30.2°C). WMA1 was produced the following day under similar ambient temperature conditions. However, WMT2 did not arrive on time for production at the asphalt plant due to a shipment issue. As a result, WMA2 was produced in December 2023, with an average daily ambient temperature of 50.7°F (10.4°C), approximately 36°F (20°C) lower than the day of the HMA and WMA1 production. For each production day, the plant was allowed to stabilize and level out at the target production temperature before commencing fuel readings and materials sampling, minimizing the potential impact of residual heat. Table 2 summarizes the plant production parameters for the mixtures included in Experiment

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1. The average production temperature for the control HMA was within the planned range of 320-330°F. Similarly, the average production temperatures of WMA1 and WMA2 fell within the adjusted range of 295-305°F, reflecting production temperature drops of 20°F (11°C) and 28°F (16°C), respectively.

TABLE 2 Plant Production Parameters for the Mixtures in Experiment 1

Mix designation	Production Temp (°F)	Production Duration (hr.)	Total Tonnage (ton)	Average tonnage (tons/hr.)
HMA	323	6.5	945.3	145.4
WMA1	303	6.5	914.3	140.7
WMA2	295	3.5	522.0	149.1

Table 3 summarizes the mixing, conditioning, and compaction temperatures for the mixtures included in Experiment 1

TABLE 3 Mixing, Conditioning, and Compaction Temperatures for the Mixtures in Experiment 1

Mix Designation	RH-PMLC		LMLC	
	Plant Production Temp (°F)	Lab Reheat and Compaction Temps (°F)	Lab Mixing Temp (°F)	STA and Compaction Temps (°F)
HMA	323	275	325	275
WMA1	303	240	275	275 and 240
WMA2	295	240	275	275 and 240

Asphalt mixtures were sampled from the mixing plant and transported to the laboratory for performance testing. As per NAPA IS-145 guidelines (24) for specimen fabrication for BMD performance testing, the mixtures were split to the required sample size, reheated in an oven set to the initially planned compaction temperatures (i.e., 275°F for HMA and 240°F for WMA), and compacted using the Superpave gyratory compactor. The individual aggregate sources and asphalt binder were previously sampled and used to prepare LMLC samples. The LMLC samples were prepared at the production temperatures originally planned (i.e., 320-330°F for HMA and 275-285°F for WMA). After mixing, LMLC samples were short-term laboratory conditioned (STA) for 2 hours at 275°F (135°C) for HMA samples and 240°F (116°C) for WMA samples, as per AASHTO R30-22 (25). Additionally, another set of WMA mixtures was prepared and short-term laboratory conditioned for 2 hours at 275°F (135°C) to evaluate the sensitivity of WMA mixtures to aging temperature.

The mix design for Experiment 1 used a PG 76-22 polymer-modified virgin binder, constituting 4.6% of the total mix by weight. The virgin binder contained 2.5% Styrene-Butadiene-Styrene (SBS) polymer by weight of the binder. Even though the standard binder grade specified by ALDOT was PG 67-22 (26), which is different from AASHTO M320-23 performance grades (27), a PG76-22 binder was used to match the traffic-based grade bumping as per ALDOT's specifications (28). The design included 20% RAP with a 9.5 mm Nominal Maximum Aggregate Size (NMAS) fine-graded gradation meeting ALDOT's requirements, as shown in Figure 2.

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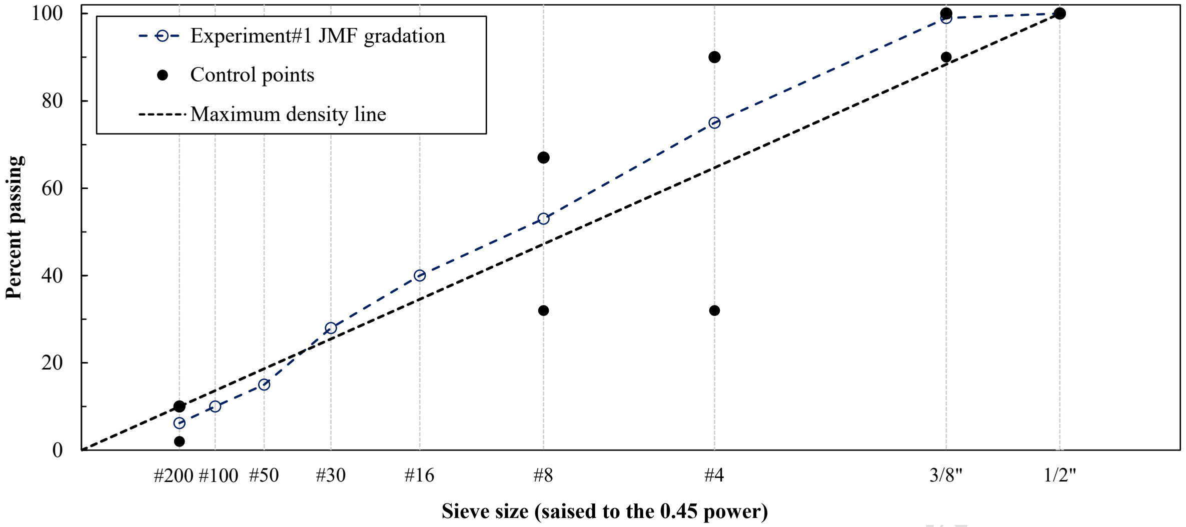

Figure 2 Design aggregate gradation for the first experiment

The moisture content of the aggregate blend was 2.0%, determined based on the moisture contents of the individual aggregates measured as per AASHTO T255-22 before the production of the control HMA mixture. Table 4 presents the quality control volumetric properties of the mixtures used in Experiment 1. Compared to the JMF, the average air void content and VMA of WMA2 showed the highest reduction, but most properties were comparable for all mixtures. During production, there were no indications of compaction issues for the control HMA and WMA mixtures.

TABLE 4 Volumetric Quality Control Data for the Mixtures in Experiment 1 compared to JMF

Mix Properties	HMA	WMA1	WMA2	JMF
Asphalt Content (%)	5.50	5.53	5.44	5.50
Air Voids (%)	3.96	4.18	3.70	4.17
VMA (%)	16.0	16.6	15.4	16.5
VFA (%)	75.3	74.8	75.9	74.7
D/P_{be}	1.22	1.07	1.15	1.16

Experiment 2

Experiment 2 was designed to evaluate how further reduction of WMA production temperature affects energy consumption and performance properties. WMT1 used in Experiment 1 was selected for use in Experiment 2. The experiment was conducted at another asphalt plant in Ariton, Alabama. The plant is a 2017 CMI E3 model drum mixer equipped with four silos and twin RAP cold feeds using recycled No. 2 fuel oil. The mixtures were produced in June 2024 with the average daily ambient temperature within 70.0±1°F (21.1±0.5°C) for the production days. On the first day, the control HMA mixture, designated as HMA-325F, was produced at a target temperature of 325°F. Fuel measurements and material sampling began after the plant had stabilized at this temperature. The next day began with the standard production of HMA. After stabilizing under typical HMA production conditions, the production temperature was gradually lowered to achieve the target temperatures for WMA, which were 285°F (141°C) and 260°F (127°C). Once production stabilized at these temperatures, fuel readings and material sampling commenced to minimize the effect of residual heat. All mixtures were kept at their expected compaction temperature and hot-compacted in a laboratory located at the asphalt plant to produce H-PMLC samples. Table 5 summarizes the plant production variables for this experiment.

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TABLE 5 Plant Production Parameters for the Mixtures in Experiment 2

Mix designation	Production temp (°F)	Compaction temp (°F)	Production duration (hr.)	Total Tonnage (ton)	Average tonnage (tons/hr.)
HMA-325F	325	280-290	8.0	1881.3	235.2
WMA-285F	285	250-260	2.5	604.6	241.8
WMA-260F	260	230-240	4.0	1084.6	271.1

The WMT1 was dosed at 0.5% of the virgin asphalt binder, the same as in the first experiment. The mixture included a 12.5 mm NMAS with 20% RAP and a PG 67-22 asphalt binder. The design gradation used in this experiment is presented in Figure 3.

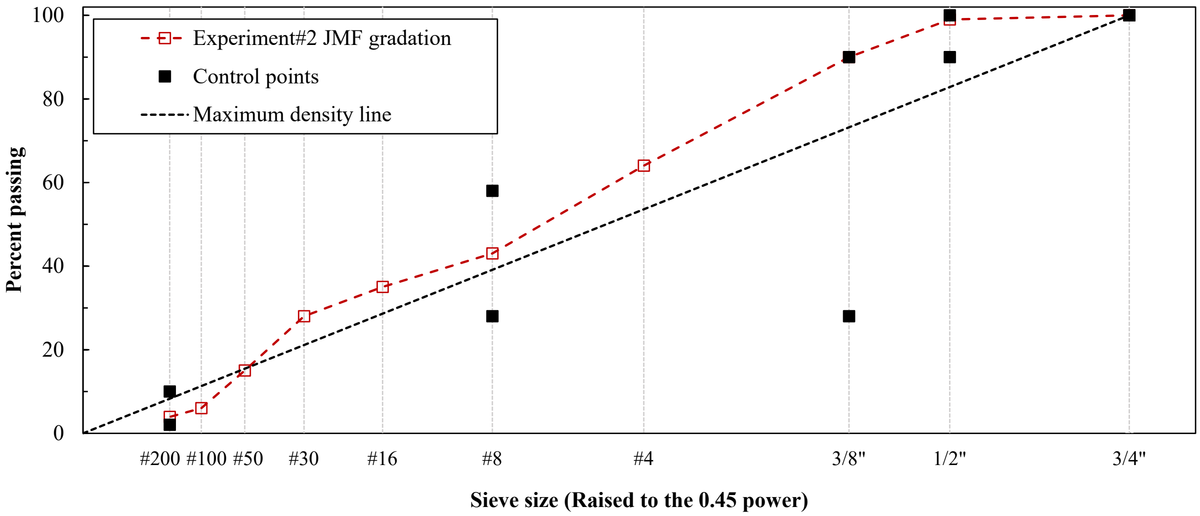

Figure 3 Design aggregate gradation for the second experiment

Moisture content for different aggregates was determined according to AASHTO T255-22 prior to the production of each mixture. The moisture content of the aggregate blend was measured at 2.6% for the HMA-325F mixture. For the WMA mixtures produced at 285°F and 260°F, the moisture contents were measured at 2.8% and 2.9%, respectively.

Table 6 displays the quality control volumetric properties of the mixtures used in Experiment 2. Average air void content and VMA dropped during production compared to the JMF. During production, The WMA mixtures exhibited slightly lower average air void contents and slightly higher VFA values compared to the control HMA, but the differences were minimal. Furthermore, no compaction issues were observed during field compaction. These marginal changes indicate that reducing production temperatures using WMTs would not significantly impact the volumetric properties of asphalt mixtures

TABLE 6 Volumetric Quality Control Data for the Mixtures in Experiment 2 compared to JMF

Mix Properties	HMA-325F	WMA-285F	WMA-260F	JMF
Asphalt Content (%)	5.03	5.09	5.13	5.1
Air Voids (%)	3.47	3.36	3.24	4.0
VMA (%)	14.2	14.2	14.4	15.1
VFA (%)	75.6	76.3	77.5	73.5
D/P_{be}	0.73	0.85	0.87	0.77

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Energy Consumption Data Collection and Analysis

In this study, both asphalt plants used recycled No. 2 oil as burner fuel. This oil was stored in on-site cylindrical tanks and monitored by analog gauges. The data collected included the burner fuel consumption, measured in gallons every 30 minutes, as well as the tonnage of the asphalt mixture produced during each interval. This data was used to calculate the amount of recycled oil required to produce one short ton of asphalt mixture for each 30-minute period using Equation 1. An energy intensity value of 140,000 British thermal units (BTU) per gallon was applied to determine the energy required to produce one short ton of asphalt mixture (29). The collected data was then combined for all intervals to calculate the average and variability of energy consumption for each asphalt mixture. This approach provided a detailed understanding of energy consumption patterns and helped evaluate the efficiency of the asphalt production process for each mixture in the experiments.

$$E_i = 140000 \times \frac{V_i}{M_i} \qquad \text{Equation 1}$$

Where:

E_i = energy consumption during interval i (btu/ton)
V_i = volume of diesel used during interval i (gallon)
M_i = tonnage of asphalt mixture produced during interval i (ton)

Laboratory Testing

In addition to analyzing the volumetric properties, this study also performed the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) as per ASTM D8225-19 to assess cracking. For evaluating rutting, the Hamburg Wheel-Tracking Test (HWTT) and High-Temperature Indirect Tensile Test (HT-IDT) were conducted as per AASHTO T324-23 and ALDOT-458, respectively.

Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

The IDEAL-CT was conducted at 25°C using a minimum of four cylindrical specimens preconditioned for two hrs. in an environmental chamber and loaded in compression across the diameter to induce tension (30). The test was conducted on specimens 150 mm in diameter and 62 mm in height, with target air voids of 7±0.5%, in accordance with ASTM D8225-19. A monotonic load is applied to the specimen at a constant displacement rate of 50 mm/min. The measure of cracking performance, the CT_{index}, is calculated based on the failure energy, slope, and displacement at 75% of the post-peak load, and the thickness and diameter of the specimen (Equation 2). CT_{index} is the resulting parameter from the IDEAL-CT test to characterize the cracking properties of the mixture. a higher value of CT_{index} is desired for better cracking resistance.

$$CT_{index} = \frac{t}{62} * \frac{G_f}{|m_{75}|} * \frac{L_{75}}{D} \qquad \text{Equation 2}$$

Where:

G_f = failure energy (J/m^2)
m_{75} = slope at 75% of post-peak load (kN/mm)
l_{75} = displacement at 75% post-peak load (mm)
t = thickness of sample (mm)
D = specimen diameter (mm).

Hamburg Wheel-Tracking Testing (HWTT)

The HWTT test, as per AASHTO T 324, is widely utilized in asphalt mix design. This test simulates repeated loading on asphalt mix specimens to assess rutting and moisture resistance. During the test, a 158 lbs. steel wheel moves at a rate of 52±2 passes per minute across a pair of specimens submerged in water at a specified temperature. Two pairs of 150mm gyratory samples compacted to 62mm height and 7±0.5% air void content were tested at the temperature of 50°C in this study. The accumulated deformation from loading is measured as the number of wheel passes increases to interpret the test results for rutting evaluation. The HWTT curve typically consists of three phases: post-compaction, creep, and stripping. The post-compaction phase reflects the initial consolidation of the specimen, usually occurring within the first 1,000 passes. The creep phase involves a nearly constant rate of deformation due to visco-plastic flow, starting after the post-compaction phase. The stripping phase begins when the asphalt binder-aggregate bond starts to degrade, leading to moisture damage initiation.

High-Temperature Indirect Tensile Test (HT-IDT)

The HT-IDT test, as per ALDOT 458, is an indirect tensile strength (ITS) test performed at a constant loading rate of 50 mm/min. The only difference is that it is conducted on specimens conditioned at a high temperature rather than 25°C. Typically, the test is carried out at the high temperature experienced by the pavement during service. Alternatively, the high-performance grade (PG) temperature of the binder can also be used. For each mix, four 150mm by 62mm gyratory samples at 7±0.5% air voids were conditioned for 1hr. in a water bath set to 50°C and tested. The resulting parameter is the high-temperature ITS, and a higher value is desired for better resistance to rutting.

RESULTS AND DISCUSSIONS

The study results are organized into two sections for each experiment, following the same structure. Statistical analysis using Tukey's Honestly Significant Difference (HSD) test was conducted for each test using a one-way Analysis of Variance (ANOVA) at a significance level of 0.05 ($\alpha = 0.05$) to identify significant differences, assuming a normal population distribution for each factor level, similar variances, and independent data. Normality and similar variances were assessed for each comparison using the Anderson-Darling Normality Test and Levene's test, respectively. Statistical groupings are indicated within the columns using letters, where mixtures not sharing any common letters are statistically different. For figures that include both RH-PMLC and LMLC samples, lowercase letters denote groupings for RH-PMLC samples, while uppercase letters represent groupings for LMLC samples.

Results of Experiment 1

Energy Consumption Results for Experiment 1

Figure 4 illustrates the average burner fuel consumption during the production of the mixtures in Experiment 1. The energy consumption for all mixtures was generally similar. While the production of WMA1 required slightly less fuel, the difference was not statistically significant, likely due to the adjusted production temperatures. Initially, the planned production temperatures for the WMA mixtures were supposed to be between 275°F-285°F. However, they were ultimately increased to 295°F-305°F, resulting in a 25°F drop rather than the intended 50°F compared to the HMA production temperature. Additionally, the WMA2 mixture was produced at a lower ambient temperature in December 2023.

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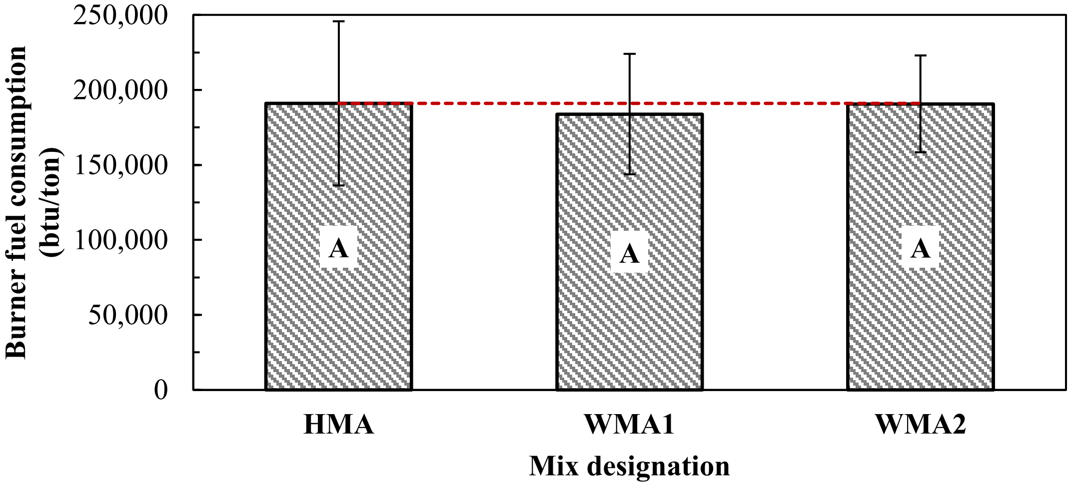

Figure 4 Average burner fuel consumption for the mixtures in the Experiment #1

IDEAL-CT Results for Experiment 1

Figure 5 presents the average CT_{Index} results for both RH-PMLC and LMLC mixtures corresponding to four to six replicates tested for each mixture. LMLC WMA mixtures were aged under two STA conditions: 2 hours at 275°F, similar to the control HMA, and 2 hours at 240°F as specified by AASHTO R30-22 for WMA mixtures [30].

The maximum and average coefficient of variation (COV) of CT_{Index} for all of the mixtures were found to be 20.4% and 13.3%, respectively. Statistical comparison of all RH-PMLC mixtures revealed similar CT_{Index} values and the same statistical groupings. This indicates that the plant-produced WMA mixtures demonstrated comparable cracking characteristics to the control mixture. For the LMLC mixtures, WMA mixtures that were STA-conditioned for 2 hours at 275°F (similar to the control HMA) showed no statistically significant improvements in CT_{Index} compared to the control HMA mixture, as indicated by the group 'BC' in Figure 5. In contrast, for STA at 240°F, WMA mixtures showed greater improvements in terms of CT_{index} values, with WMA1 achieving a statistically significant improvement in CT_{Index} indicated by the group 'A.' These results suggest that producing WMA mixtures at significantly lower temperatures can enhance their cracking properties, a benefit that would not be observed otherwise with insufficient temperature reductions. Additionally, the results highlight the importance of STA conditioning at appropriate temperatures to fully realize the performance benefits of WMA mixtures.

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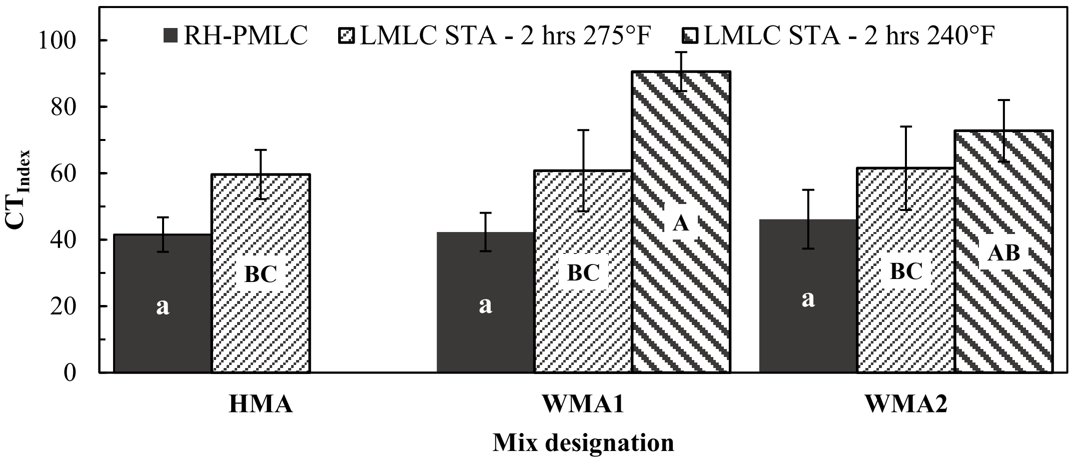

Figure 5 $\mathrm{CT_{Index}}$ results for the mixtures in the Experiment #1

To better understand the mixture properties associated with the $\mathrm{CT_{Index}}$ results, an IDEAL-CT interaction diagram analysis was conducted. The interaction diagram is created by plotting the average failure energy on the y-axis against the average l_{75}/m_{75} on the x-axis, with contour lines of different $\mathrm{CT_{Index}}$ values for reference (31, 32). In this diagram, failure energy reflects the toughness of the mixture, while l_{75}/m_{75} indicates the mixture's relative ductile-brittle behavior. Higher values for both parameters lead to an increase in $\mathrm{CT_{index}}$ or cracking performance improvement, moving the mix towards the upper right corner of the diagram.

Figure 6 presents the interaction diagram for Experiment 1 mixtures, with contour lines representing $\mathrm{CT_{index}}$ values. Regarding RH-PMLC mixtures, WMA mixtures exhibited comparatively lower failure energy than the corresponding control mixture but a higher l_{75}/m_{75}, resulting in no significant changes in the final $\mathrm{CT_{Index}}$ values. In contrast, among the LMLC mixtures, there was a significant increase in l_{75}/m_{75} with minimal or no change in failure energy, resulting in an increase in $\mathrm{CT_{index}}$ It indicates that STA at a lower temperature does not influence the failure energy parameter, but it improves relative ductile-brittle behavior, which helps better resist cracking.

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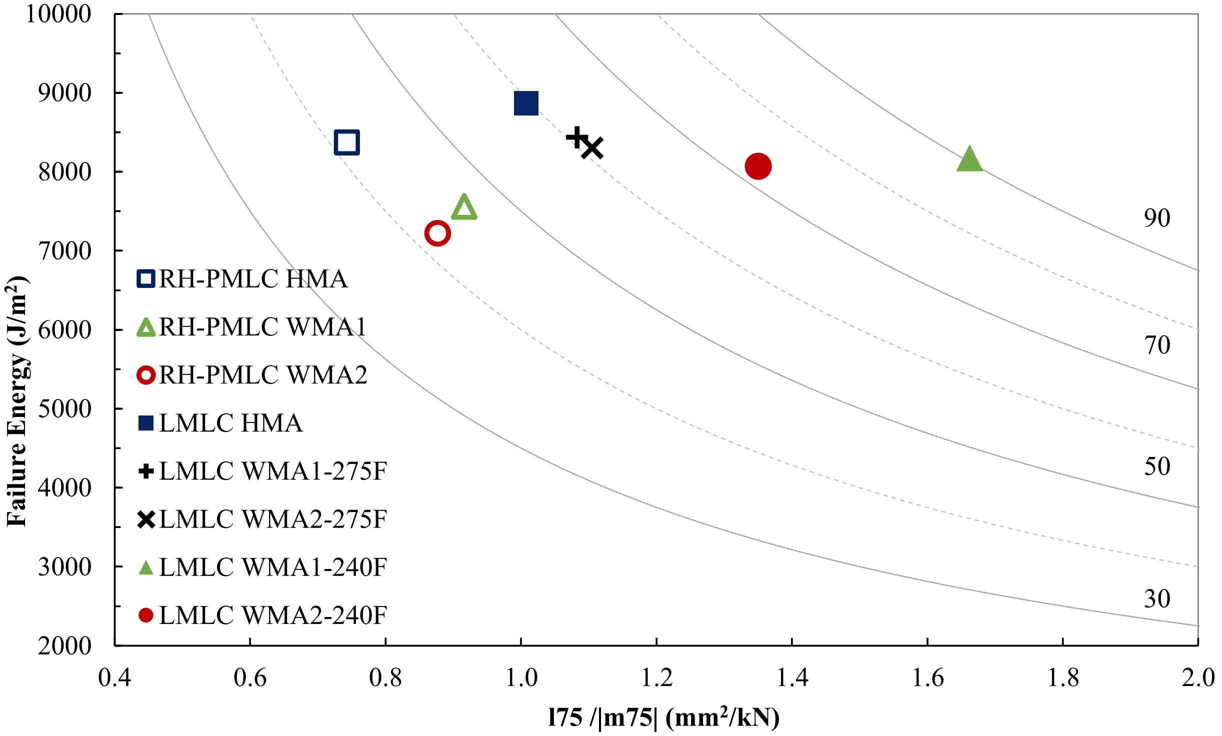

Figure 6 IDEAL-CT interaction plot for the mixtures in Experiment #1 (contour lines representing CT_{index} values)

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HWTT Results for Experiment 1

Figures 7 and 8 show the HWTT rut depth versus the number of passes for RH-PMLC and LMLC samples, representing the average values for two HWTT replicates tested for each mixture. Figure 7 shows slightly increased rut depths for both WMA mixes, indicating lower rutting resistance. Although WMA2 showed a tertiary flow in HWTT testing, no physical evidence of stripping was observed, and overall rutting stayed relatively low. Despite the differences, the total rut depth at 20,000 passes was below 5 mm in all the mixtures, which indicates adequate rutting resistance. For the LMLC mixtures in Figure 8, STA at 275°F yielded similar rut depths for HMA and WMA mixtures. However, STA at 240°F resulted in increased rut depth for WMA2.

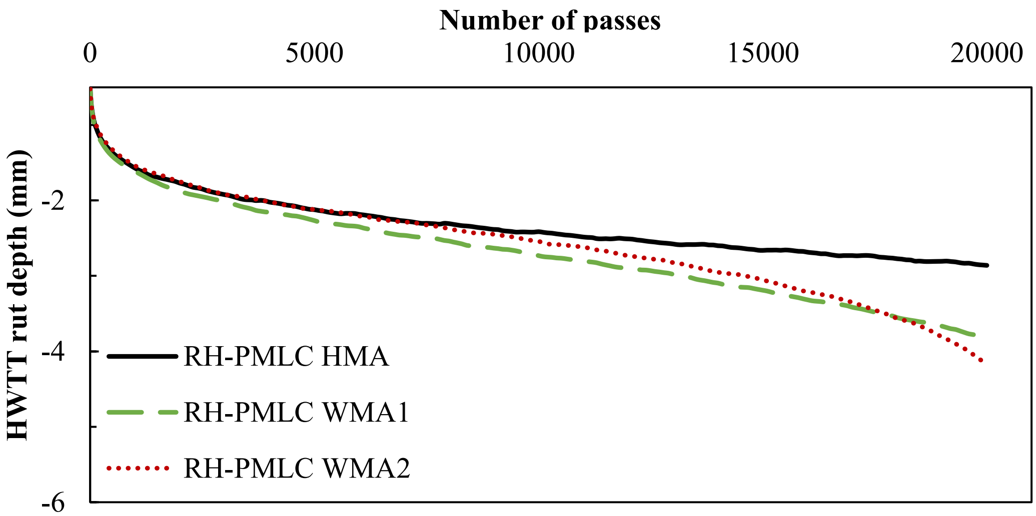

Figure 7 Average HWTT rut depth versus the number of passes for RH-PMLC mixtures in Experiment 1

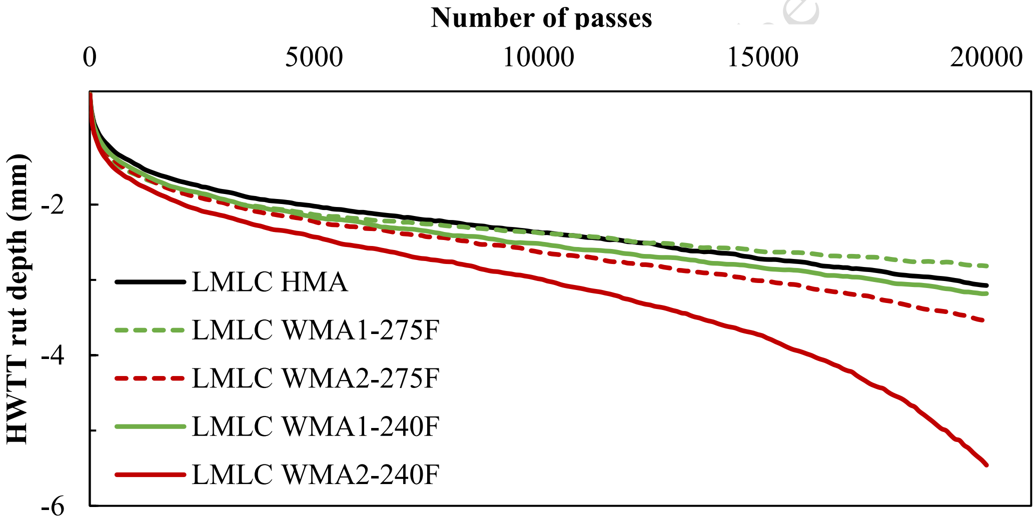

Figure 8 Average HWTT rut depth versus the number of passes for LMLC mixtures in Experiment 1

Figure 9 shows the final rut depths after 20,000 passes. The WMA mixtures showed slightly higher values, especially at the lower STA temperature. However, since the final rut depths remain well below the ALDOT-specified limit of 10mm for PG 76-22 binders (33), these mixtures demonstrate acceptable resistance to rutting. Additionally, the maximum and average COV of rut depth for all mixtures shown in Figure 9 were 36.3% and 14.4%, respectively.

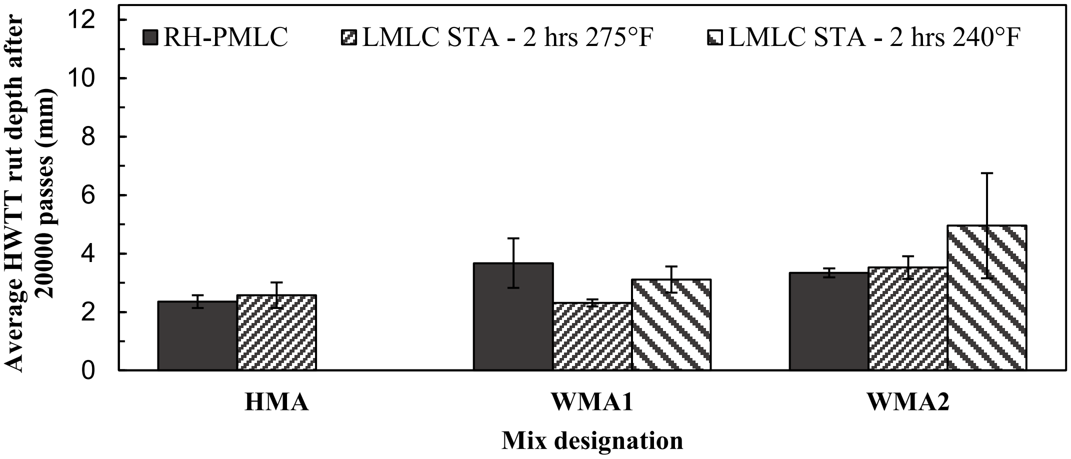

Figure 9 HWTT final rut depth after 20000 passes for the mixtures in Experiment 1

HT-IDT Results for Experiment 1

Figure 10 illustrates the average HT-IDT strength at 50°C for Experiment 1 mixtures, utilizing four test replicates for each mixture. The maximum and average COV for all of the mixtures were found to be 5.3% and 3.3%, respectively. In the case of RH-PMLC mixtures, WMA1 demonstrated equivalent HT-IDT strength to the control, while WMA2 exhibited reduced strength. Regarding LMLC samples, similar statistical groups were observed for STA at 275°F, but both WMA mixes showed significant decreases at 240°F, consistent with HWTT results. Notably, all HT-IDT strength values exceeded the ALDOT threshold (≥20 psi) (34), indicating adequate rutting resistance for all mixtures in Experiment 1.

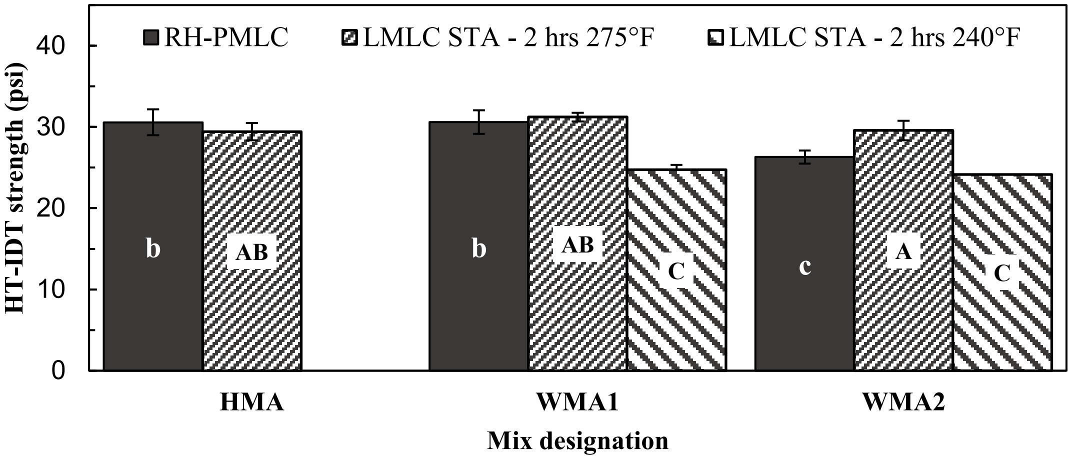

Figure 10 HT-IDT strength for the mixtures in Experiment 1

In summary, Experiment 1 showed that RH-PMLC WMA mixtures exhibited cracking performance comparable to the control HMA. However, LMLC specimens of WMA mixtures prepared at lower temperatures demonstrated better resistance to cracking. Additionally, rutting and moisture resistance in WMA mixtures were either comparable or lower. The findings suggest the possibility of enhancing cracking resistance with WMTs at reduced temperatures while also highlighting potential reductions in rutting resistance.

Experiment 2

In the second experiment, one WMA additive was used to reduce the production temperature to 285°F (141°C) and 260°F (127°C), compared to the control HMA mixed at 325°F (163°C). This section presents the results for the three mixtures using H-PMLC samples.

Energy Consumption Results for Experiment 2

Figure 11 depicts the average burner fuel consumption during production for Experiment 2 mixtures. The results show an average energy reduction of 8% at a production temperature of 285°F and 19% at 260°F. While the WMA mixture produced at 285°F did not exhibit a statistically significant reduction in energy consumption compared to the control HMA mixture produced at 325°F, a notable 19% reduction was observed at 260°F. Additionally, the reduction in energy usage followed a non-linear trend, with the rate of reduction increasing as the temperature decreased further.

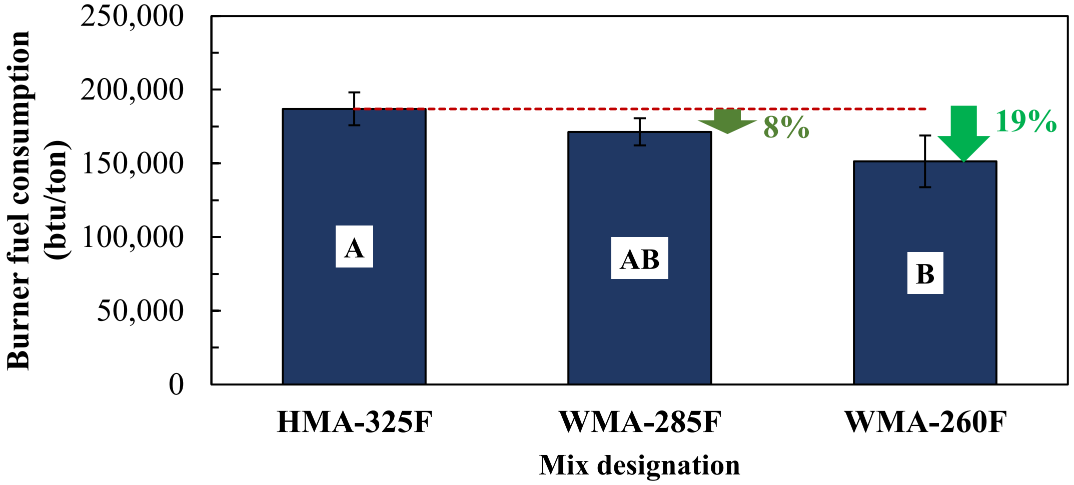

Figure 11 Average burner fuel consumption for the mixtures in the Experiment 2

IDEAL-CT Results for Experiment 2

The average CT_{Index} results of four replicates tested for each mixture are presented in Figure 12. The maximum and average COV of CT_{Index} for all of the mixtures were found to be 19.6% and 18.4%, respectively. The WMA mixtures produced at 285°F and 260°F exhibited comparable CT_{Index} values and fell within the same statistical groups as the control HMA produced at 325°F. This indicates similar cracking resistance using WMTs despite the 65°F reduction in production temperature. Additionally, slightly lower failure energy and slightly higher l75/m75 were observed for WMA mixtures, but no statistical difference was found between the mixtures. For instance, the failure energy of WMA-285F and WMA260F decreased from 6881.3 J/m^2 (HMA) to 6221.2 and 6441.4, respectively, while l75/m75 increased from 1.623 mm^2/kN (HMA) to 1.642 and 1.682 respectively. The results appear to contradict the lab IDEAL-CT results observed in the first experiment, suggesting the presence of factors other than aging that impact the cracking performance of plant-produced WMA mixtures.

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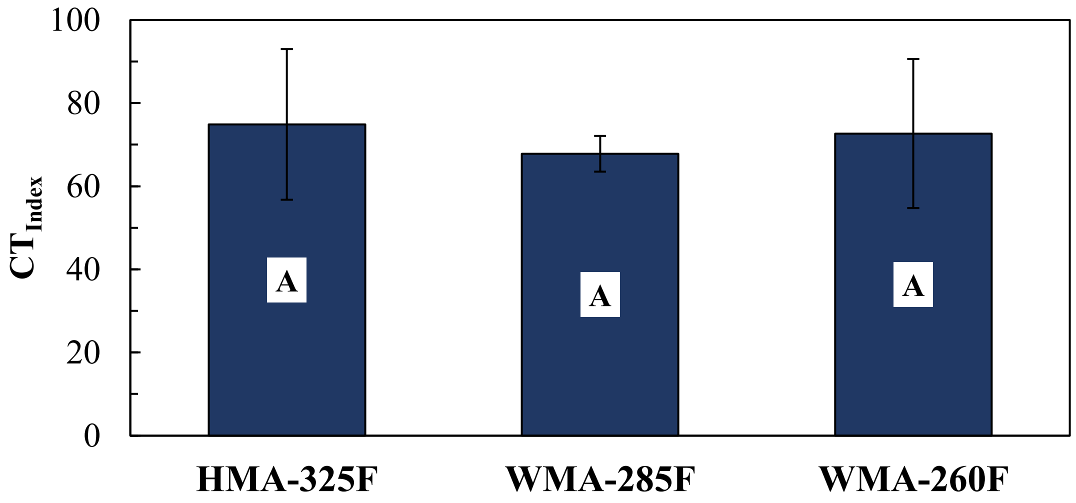

Figure 12 CT_{Index} results for H-PMLC samples in Experiment 2

HWTT Results for Experiment 2

Figures 13 and 14 show the average HWTT rut depth results of two pairs of samples tested for each mixture. The maximum and average COV of rut depth for all of the mixtures were found to be 33.4% and 23.4%, respectively. These mixtures exhibited higher rut depths than those in the first experiment, and the stripping phase was observed for the two WMA samples. Visual inspection of the test specimens revealed exposed aggregates in the wheel ruts of the HWTT specimens for the WMA mixtures. This exposure may be caused by aggregates being pushed out of the mix due to the tertiary flow of the WMA specimens and ground along the wheel paths. Another possible factor might be incomplete drying of aggregate, a common concern with WMA mixtures, which researchers have found to increase the moisture susceptibility of WMA mixtures (35, 36). However, all the mixtures satisfied the HWTT rut depth threshold, 10 mm rut depth at 10,000 passes for a PG 67-22 virgin binder, indicating acceptable rutting resistance.

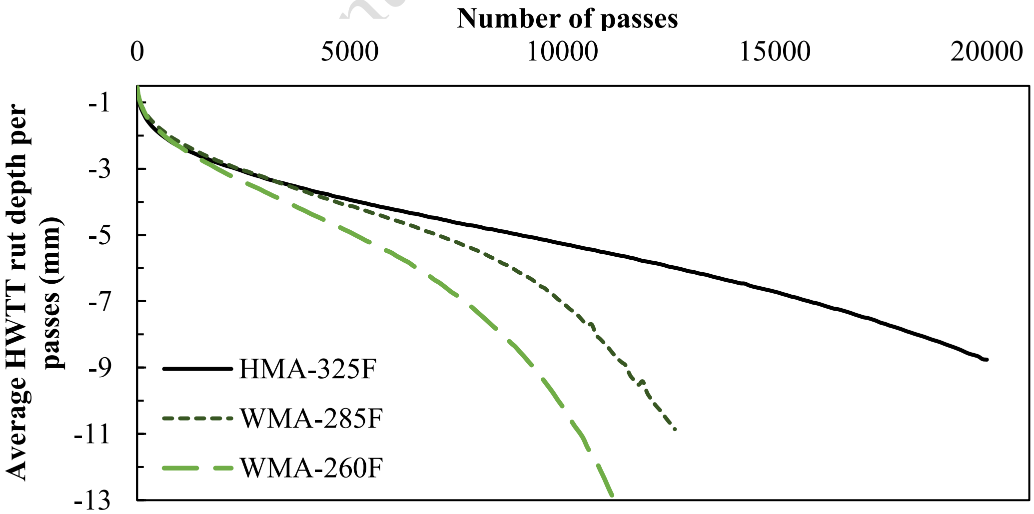

Figure 13 Average HWTT rut depth versus the number of passes for H-PMLC samples in Experiment 2

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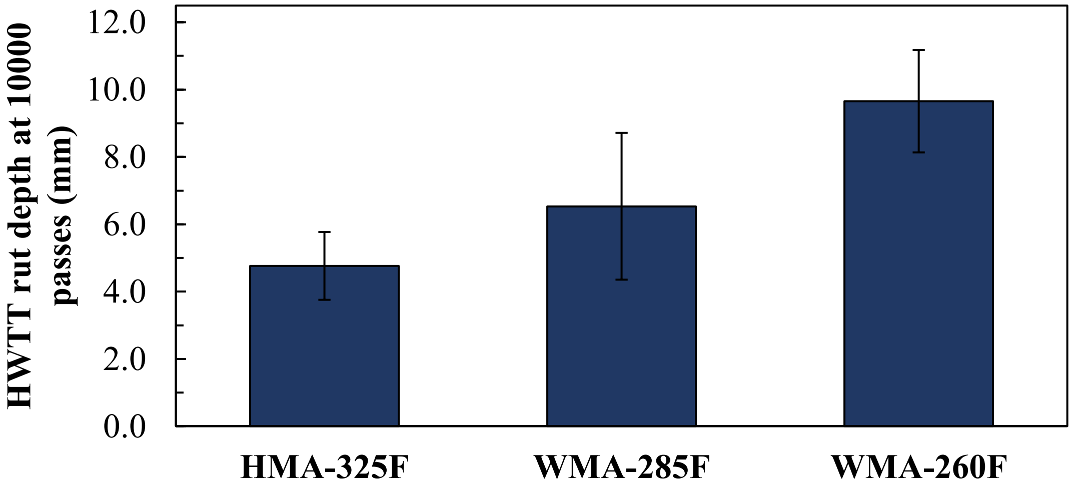

Figure 14 HWTT final rut depth after 10000 passes for H-PMLC samples in Experiment 2

HT-IDT Results for Experiment 2

Figure 15 presents the average HT-IDT strength obtained using four replicates tested for each mixture at 50°C. The maximum and average COV for all of the mixtures were found to be 8.9% and 7.6%, respectively The results showed statistically lower HT-IDT strength for WMA mixes compared to HMA. The trend is consistent with HWTT results.

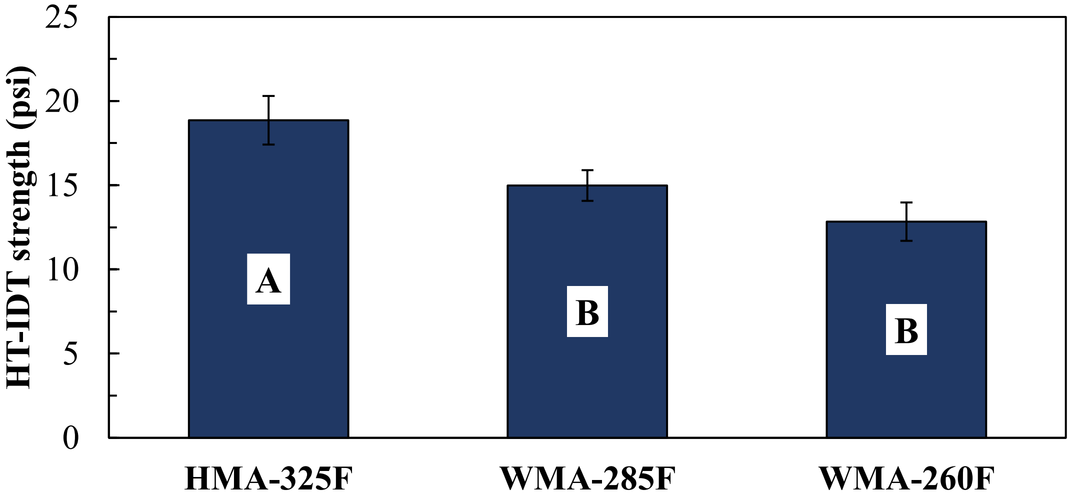

Figure 15 HT-IDT strength for H-PMLC samples in Experiment 2

SUMMARY AND CONCLUSIONS

The purpose of this study was to assess the impact of using WMTs to lower production temperatures on energy consumption and laboratory performance characteristics. Two experiments were conducted using ALDOT-approved HMA designs. The first experiment included two WMA mixtures, produced using chemical additives WMT1 and WMT2, and a control HMA mixture. The second experiment involved one control HMA mixture and one WMA mixture using WMT1 produced at multiple temperatures. Evaluations in both experiments included burner fuel consumption, intermediate cracking resistance using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) test, and rutting resistance using the Hamburg Wheel-Tracking Test (HWTT) and

High-Temperature Indirect Tensile Test (HT-IDT). Additionally, Experiment 1 used RH-PMLC and LMLC specimens for performance testing, while Experiment 2 used H-PMLC specimens. The key findings from this study are as follows:

- Energy Consumption Reduction: The use of WMTs in the production of asphalt mixtures has demonstrated a notable capacity for reducing energy consumption. In Experiment 2, it was observed that WMTs led to a reduction in burner fuel consumption by 8% and 19% when production temperature decreased by 40°F (20°C) and 65°F (36°C), respectively. However, asphalt plants are typically optimized for HMA temperatures rather than WMA temperatures. Additionally, various plant-specific factors can influence energy consumption when lowering production temperatures. Therefore, contractors are encouraged to assess the energy savings specific to their individual plants when using WMA technologies to reduce production temperatures.
- Volumetric Properties: Compatible volumetric properties were found for WMA mixtures in the second experiment with slightly lower lab air voids and slightly higher VFA.
- Cracking Performance: In both experiments, the cracking resistance of WMA mixtures was similar to that of the control HMA when using plant-mixed samples. However, significantly better cracking resistance was observed for LMLC WMA samples. The STA temperature was identified as a significant factor affecting the cracking performance of laboratory-mixed WMA. This emphasizes the need for further research to identify the factors that lead to different trends in the cracking test results of laboratory-mixed and plant-produced WMA mixtures.
- Rutting Resistance and Moisture Susceptibility: The rutting and moisture resistance of WMA mixtures were found to be comparable to or lower than those of HMA. It is important to assess the rutting resistance of WMA mixtures to ensure that reduced production temperatures do not compromise the rutting resistance of these mixtures.

The results of this study support the use of WMTs at reduced production temperatures in order to achieve substantial energy savings and emission reductions. Furthermore, WMTs demonstrate the potential for enhancing cracking performance within a Balanced Mix Design framework. However, it is important to carefully consider the rutting resistance and moisture susceptibility of WMA mixtures to ensure their long-term performance and durability.

FUNDING STATEMENT

The research project is funded through the Climate Challenge grant provided by the Federal Highway Administration to the Alabama Department of Transportation (ALDOT).

AUTHOR CONTRIBUTION

The authors confirm their contribution to the paper as follows: study conception and design: Benjamin Bowers, Heather Dylla, Nam Tran, Zane Hartzog, Surendra Gatiganti; data collection: Mohammad Sadeghi, Zane Hartzog, Heather Dylla, Rohit Vangala, Surendra Gatiganti; analysis and interpretation of results: Mohammad Sadeghi, Nam Tran, Biswajit Bairgi, Amir Jafarmilajerdi, Surendra Gatiganti; draft manuscript preparation: Mohammad Sadeghi, Biswajit Bairgi, Nam Tran, Surendra Gatiganti. All authors reviewed the results and approved the final version of the manuscript.

DECLARATION OF CONFLICTING INTERESTS

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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DATA ACCESSIBILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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