1-30-2024

Laboratory Evaluation of Warm Mix Additives at Lower than Traditional Compaction Temperatures

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LABORATORY EVALUATION OF WARM MIX ADDITIVES AT LOWER THAN TRADITIONAL COMPACTION TEMPERATURES

by

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A Thesis

Submitted to the
Department of Civil and Environmental Engineering
College of Engineering
In partial fulfillment of the requirement
For the degree of
Master of Science in Civil Engineering
at
Rowan University
July 7, 2023

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Dedication

This thesis is dedicated to my beloved family, whose unwavering love, encouragement, and support have inspired and motivated me. I am deeply grateful to my parents for instilling a love of learning and a passion for knowledge. Their unwavering faith in me and their encouragement has been invaluable in shaping me into the person I am today.

To my dear siblings, thank you for always being there for me and endless support and love. Your presence in my life has been a true blessing.

To my friends, thank you for being my pillars of strength and supporting me in every step of this journey. Your friendship has been a source of joy, and I will always cherish our memories together.

Lastly, I dedicate this thesis to all those who aspire to make a positive difference in the world. May our collective efforts lead to a brighter future for all.

Acknowledgments

I want to express my most profound appreciation and gratitude to all those who have contributed to completing this thesis. First and foremost, I am profoundly grateful to my thesis advisor, Dr. Yusuf Mehta, for his infinite guidance, support, and encouragement throughout this journey. His invaluable feedback, insightful comments, and expertise have been instrumental in shaping the ideas and arguments presented in this work.

I am also indebted to the faculty and staff supervisors of the Department of Civil Engineering, Dr. Daniel Offenbacker and Dr. Mohamed Elshaer, for their encouragement, constructive criticism, and academic resources, which have been crucial in developing this thesis. Their unwavering encouragement, understanding, and patience have been a driving force behind my accomplishments.

I want to express my gratitude to the Cold Regions Research and Engineering Laboratory (CRREL) and the Department of Defense (DOD) for their generous support and funding of this research study, which was carried out as a component of DOD's research projects entitled " Use of Warm Mix Asphalt Technology as a Compaction Aid in Cold Regions."

Finally, I extend my gratitude to all those who have contributed to this research in any capacity, whether by participating in laboratory work or providing access to valuable resources. Your assistance has been invaluable to the success of this study. I am deeply honored and privileged to have had the opportunity to work on this thesis, and I extend my sincere appreciation to all those who have played a part in its completion.

Abstract

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LABORATORY EVALUATION OF WARM MIX ADDITIVES AT LOWER THAN TRADITIONAL COMPACTION TEMPERATURES
2022-2023
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The study aims to evaluate the impact of warm mix additives (WMA) on the properties and performance of asphalt binders and mixtures. Four WMA were added to PG 76-28 and PG 58-28. Performance grade testing (PG), critical temperature differential (ΔT_c), asphalt binder cracking device (ABCD), linear amplitude sweep test (LAS), and Fourier transform infrared spectroscopy (FTIR) tests were performed. Results showed that PG 76-28 modified with WMA binders lowered the high PG by at least one PG (6°C), while PG 58-28 modified with WMA binders did not change the PG. The enhancement in ΔT_c resulted solely from incorporating PG 76-28 into WMA binders compared to PG 58-28 modified binders. ABCD test results showed that using WMA did not change the low cracking temperature properties of the base binders. Similar findings were observed from the carbonyl and sulfoxide aging indices, in which the WMA reduced the aging susceptibility of asphalt binders between aging levels. The mixture study involved the evaluation of the impact of WMA type, binder grade, and compaction temperature when compacted at (300°F (149°C), 260°F (127°C), 220°F (104°C), and 180°F (82°C)). The mix design, Indirect Tensile Asphalt Cracking (IDEAL-CT), Asphalt Pavement Analyzer (APA), and Tensile Strength Ration (TSR) tests were conducted on mixes. Finally, asphalt mixture ranking was performed using the Analysis of Variance (ANOVA) to quantify the impact of WMA type, compaction temperatures, and binder type on produced mixtures.

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Chapter 1

Introduction

Background

Hot Mix Asphalt (HMA) is a widely utilized material for asphalt paving applications comprising aggregates and asphalt binders. The production process involves drying and mixing the aggregates with heated asphalt binders. The temperature range for HMA production generally falls between 300°F (148.9°C) and 325°F (162.7°C) for unmodified asphalt binders, while modified asphalt binders require even higher temperatures. These elevated temperatures thoroughly dry the aggregates and ensure their complete coating with a thin asphalt binder film. Moreover, it facilitates the workability of the mixtures and their compactability to a desired density, ultimately contributing to the durability and capacity of the mixture to endure repeated loading from traffic.

Recently, new technology has been introduced in most developed countries (i.e., the United States), enabling the paving of asphalt mixtures at lower temperatures than traditional HMA. These new technologies, known as Warm Mix Asphalt (WMA), can reduce temperatures in the range of 30°C (87°F) to 100°C (212°F) (Cheraghian et al. 2020). They are promoted as environmentally friendly alternatives to traditional HMA mixtures because they generate fewer greenhouse gas emissions by around 20% to 35% (Zaumanis 2014). The WMA technologies can decrease the viscosity of the asphalt binder through organic, chemical, and foaming technologies by introducing them into the heated asphalt binder under controlled temperature and pressure conditions.

Warm mix asphalt (WMA) has gained significant attention from the asphalt paving industry due to several advantages, such as a reduction in energy consumption because of lower production temperature(T. Calabi-Floody et al., 2020), the ability to transport the mixture over longer distances (Goh and You 2009), the ability to pave in cooler temperatures while maintaining mixture density(Hurley and Prowell 2006), higher percentages of Recycled Asphalt Pavement (RAP) incorporation (Xiao et al. 2016), and faster opening to traffic (Zaumanis 2014).

Problem Statement

The impact of using WMA technologies in asphalt binders and mixtures has been extensively studied by researchers, highway agencies, and state departments of transportation (DOTs) (Behnood 2020; Bennert et al. 2010; Hurley and Prowell 2006; Kumar et al. 2019; Liu and Li 2012). However, the feasibility of evaluating the performance properties of WMA at lower temperatures than the typical ones used for WMA (10°C to 90°C) or (50°F to 194°F) (Cheraghian et al., 2020) was not evaluated. In addition, a comprehensive evaluation of the impact of using a wide range of warm mix additives incorporated with different asphalt binders (modified and un-modified) and their effects on the rheological and physical properties of asphalt binders was not thoroughly evaluated.

Significant of Study

This study evaluated the impact of warm mix additives and binder grade on the degree of change in binder properties and mixture performance. In addition to this, This study also included the assessment of using WMA technologies as compaction aid for cold region paving applications by dropping the compaction temperature up to 180°F (82°C) to mimic paving in an ambient temperature below 50°F (10°C). Standard performance tests were conducted to analyze the effect of WMA on the binder rheological properties and performance of asphalt binders and mixtures. If such technologies are proven to enhance the density of compacted asphalt mixtures at lower temperatures than those used for WMA, the subsequent advantages will be provided:

- The improved density of compacted asphalt mixtures at lower temperatures can be achieved;
- Quick construction and deployment in cold-weather regions can be facilitated.

Goals & Objectives

This study aimed to evaluate the impact of binder grades (PG 58-28 and PG 76-28) as control HMA mixes and four WMA (three are chemical-based: Rediset, Evotherm, and Zycotherm) and one organic-based (Sasobit Redux) on binder and mixtures properties. It is worth mentioning that none of the foaming-based WMA was used. In addition, this study investigated the feasibility of compacting WMA at a lower temperature than the typical ones to be used beyond the paving season (i.e., when the temperature goes beyond 50°F (10°C) or after long hauling when the mix delivery temperature drops).

To accomplish this objective, the rheological properties of the WMA-modified binders were first investigated to observe any change in rheological properties due to the addition of WMA. Both short- and long-term aging were considered for binder rheology study. Furthermore, a short-term aging protocol was used for the mixture side to assess the impact of asphalt mixture performance. As the goal is to establish a low compaction temperature, only short-term aging for the study of the mixture was considered.

The study had the following specific objectives:

1. Evaluating the impact of binder grade, WMA type, and aging level on the degree of change in rheological and physical properties of WMA-modified asphalt binders,
2. Assessing the effect of binder grade and WMA type on the compactability and performance of WMA-modified mixtures and,
3. Investigating the impact of compaction temperatures, binder grade, and WMA types at (300°F, 260°F, 220°F, and 180°F) on volumetric and performance properties.
4. Select the best-performing WMA additives for full-scale evaluation.

Research Approach

The following tasks were conducted to achieve the goals and objectives of this project:

- Task 1. Perform a comprehensive literature review: This task comprehensively reviews the literature on warm mix additive technologies and various binder types that can be used with asphalt mixtures. Additionally, the potential impact of WMA types on laboratory and field performance mixes was reviewed.
- Task 2. Procure WMA, asphalt binders, and aggregates: Two different binder grades, PG 76-28 (modified binder) and PG 58-28 (un-modified binder), were collected. The best four types of WMA were obtained based on their laboratory performance from the literature review.

- Task 3. Blend WMA with asphalt binders and evaluate their rheological and physical properties.
- Task 4. Evaluation of the compactibility and performance of controls and WMA-modified mixtures. In this task, two mix designs were performed on asphalt mixtures and three performance tests.
- Task 5. Conduct a statistical analysis approach to determine the effectiveness of WMA and rank them as a compaction aid for cold region applications.
- Task 6. Prepare recommendations based on the findings and conclusion from this project.

Chapter 2

Literature Review

Introduction

Warm Mix Asphalt or WMA is a broad term that generally refers to technologies that enable the production of asphalt mixtures at temperatures lower than those used in conventional Hot Mix Asphalt (HMA). WMA technologies have gained significant attention as a means to decrease energy consumption and pollutant emissions, primarily due to increasing energy costs, global warming concerns, and stricter environmental regulations. While conventional HMA uses heat to decrease asphalt binder viscosity and dry aggregate during mixing, WMA decreases the viscosity of asphalt binder by introducing certain organic/chemical additives or injection water into hot asphalt binder. This viscosity reduction aids in adequate aggregate coating during mixing. It also enhances the workability of the mixtures and allows for mix paving at lower temperatures.

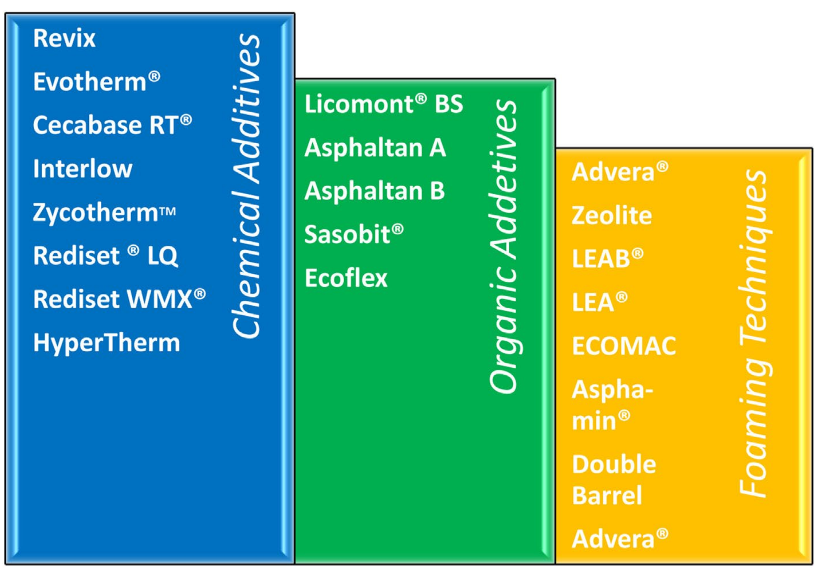
Although WMA technologies offer many advantages, there are concerns about using lower production temperatures to produce WMA mixtures. These concerns include the potential increased WMA-modified mixture rutting, cracking, and moisture-induced damage due to less aging of asphalt binder and insufficient aggregate drying. This chapter presents a literature review related to the challenges of warm mix technologies. The following sections provide a brief overview of the commercially available WMA technologies and the laboratory and field performance of WMA mixtures. The focus is on WMA produced using chemical/organic asphalt binders, referred to herein as chemical-based and organic-based. Additionally, the influence of WMA-modified asphalt binders on the rheological and physical characteristics is also included in this chapter.

Commercially Available WMA Technology

In recent years, there has been a rise in the number of WMA technologies available for preparing asphalt mixtures. These technologies can be classified into three categories based on the type of additive or production method used, as shown in **Figure *1***. The categories include WMA produced using organic/chemical additives or foaming the asphalt binder. A study by (Cheraghian et al. 2020) provided an up-to-date review of WMA technologies. The following subsections present a concise overview of the current WMA technologies.

Figure 1

Classification of WMA Techniques and Products



WMA Produced With the Use of Organic Additives

Sasobit Redux

Sasobit is a synthetic wax obtained through coal gasification, which is used as an organic additive to produce asphalt mixtures at lower temperatures. This wax additive reduces asphalt binder viscosity at high temperatures (i.e., above its melting point of 72-83 (°C) or 161- 181 (°F), making it easier to mix at lower temperatures. Additionally, Sasobit forms a crystalline structure within the asphalt binder at ambient temperatures, potentially improving the fatigue cracking resistance of the resulting mixtures (Almeida & Sergio, 2019).

According to the manufacturer (Sasol 2023), the ideal content of Sasobit Redux to be used as an additive ranges from 3% to 4% by weight of asphalt (Sasol 2023) binder. This recommended dosage can help reduce the production temperature of asphalt mixtures by 59°F (15°C) to 122°F (50°C**)** compared to HMA mixtures. However, it is not recommended to add Sasobit directly into the asphalt mixture as this could lead to uneven distribution of the additive. Instead, it is suggested to pre-blend Sasobit Redux with asphalt binder. It is important to note that using this technology, the cost of additives and the need for pre-blending might increase the overall production temperature cost of asphalt mixtures.

WMA Produced With the Use of Chemical Additives

Evotherm

MeadWestvaco (Kuang 2012), the manufacturer of Evotherm, offers three different types of Evotherm additives: Evotherm Emulsion Technology (ET), Evotherm Dispersed

Asphalt Technology (DAT), and Evotherm Third Generation (3G/Revix), The Evotherm ET additive works by introducing a water-based emulsion to the hot aggregates during mixing, which turns into steam upon contact with the aggregates and causes the asphalt binder to foam. MeadWestvaco uses a chemical package to produce a water-based emulsion, which includes additives to improve the WMA mixture's coating, adhesion, and workability. The Evotherm DAT technology is similar to Evotherm ET. However, the water-based emulsion can be injected directly into the mixtures into the asphalt binder line just before entering the mixing chamber.

Unlike previous Evotherm technologies, Evotherm 3G/Revix does not use a water-based emulsion or reduce the viscosity of the asphalt binder. Instead, it utilizes a water-free chemical additive package that reduces the internal friction of the mixtures, allowing the asphalt binder to behave as if it were heated to a high temperature. Like Evotherm DAT technology, the Evotherm 3G technology can be injected directly into the asphalt binder line or pre-blended with the asphalt binder at the mixing plant.

To produce WMA mixtures using any of the Evotherm technologies, the recommended dosage ranges between 0.4% and 0.7% of the total weight of the binder. This dosage is considered optimal and can result in producing WMA mixtures at temperatures 50°F (10°C) to 100°F (37.8°C) lower than traditional HMA mixtures produced with the same asphalt binder (Kuang 2012).

Rediset LQ

Rediset LQ is a chemical additive that enables the production of WMA mixtures at lower temperatures than traditional ones. The surfactants present in the additive reduce the surface tension of the asphalt binder and allow for efficient aggregate coating at lower temperatures. The reduction in the surface tension is also thought to enhance the workability of the asphalt mixtures, making them more compactable at lower temperatures (Cheraghian et al. 2020).

Like the Evotherm additive, Rediset LQ can be mixed with the asphalt binder before or during mixing. The ideal content of Rediset LQ to use is between 0.25 and 0.75 percent of the effective asphalt binder weight. Usually, this amount will not alter the rheology properties of the asphalt binder. It will help to produce WMA mixtures at temperatures that are 40°F (4.4°C) to 60°F (15.6°C) lower than those used for Producing HMA mixtures (Nouryon 2021).

Zycotherm

Zycotherm is a new type of antistrip additive that also provides the advantages of WMA technologies. It works well with all types of aggregates and requires lower dosage rates than traditional antistrips additives while improving the adhesion of bitumen to the aggregate. Zycotherm additive can lower the temperature during mix production and field compaction by up to 86°F (30°C). It provides benefits such as chemical bonding, complete coating, and consistent compaction (Cheraghian et al. 2020).

Zycotherm, unlike conventional antistrip additives, creates a solid and permanent chemical bond with both the aggregate and bitumen, leading to improved adhesion. According to Zydex, the manufacturer of Zycotherm additive, the resultant bond is not weakened by moisture, making the pavement more durable and extending its lifespan. In addition, Zycotherm is a versatile and eco-friendly additive that works with all types of aggregates and requires lower dosages than traditional antistrips. It is also non-corrosive and odorless (Zydex 2013).

The recommended range for the optimum content of Zycotherm additive to be used with an unmodified asphalt binder is between 0.03 and 0.1% by weight of the bitumen binder. To ensure easy workability for the polymer-modified binder (PMB) and Crown Rubber (CRPMB) or reclaimed Asphalt binder (RAP) / Reclaimed Asphalt Shingles (RAS) mixes, the recommended dosage of Zycotherm is between 0.07 to 0.125 percent, including extracted binder from RAP/RAS (Ali 2013).

WMA Produced Using Foaming Process

Aspha-mine

Aspha-mine is an artificial zeolite containing approximately 20 percent of the solidified water within its structure. This foaming additive is typically introduced into the mixing process shortly after or simultaneously by adding the asphalt binder into the mixing chamber. As the temperature rises, the water enclosed within its structure is released as steam, leading to the foaming of the asphalt binder. This foaming action temporarily reduces the viscosity of the asphalt binder, making it easier to work with at lower production temperatures than traditional methods (Cheraghian et al. 2020).

The recommended dosage of Aspha-min is approximately 0.3 percent of the total weight of the mixtures. To ensure an even distribution of Aspha-min within the mixture, employing a specialized distribution unit (nozzles) connected to the mixing plant is advisable (Rubio et al. 2012). Additionally, the use of Aspha-mine is expected to enable the production temperature of WMA mixtures at temperatures approximately 50°F lower than those typically used for traditional HMA mixtures (Ali 2013).

Advera

Advera is another synthetic zeolite that contains approximately 18% crystallized water within its structure, based on its total weight. Similar to Aspha-mine, Advera also foams Asphalt binders using the same method. However, the main distinction between the two additives lies in their particle distribution or gradation. Advera is a finely graded product consisting of particles that can pass through a sieve with a mesh size of #200, which means they are smaller than 74 microns. The Advera additive manufacturer (Corporation 2023) suggests using a finer-graded additive, which allows for more uniform distribution within the mixtures. This, in turn, may lead to improved foaming of the asphalt binder (Cheraghian et al. 2020).

Like Aspha-min, Advera is added directly to the batch plant or through a port in a drum plant. However, unlike Aspha-min, Advera does not necessitate using a distribution unit within the plant. This distinction can lead to the production of WMA mixtures using Advera technology that is more cost-effective compared to those produced with Aspha-mine. Additionally, the use of Advera is anticipated to enable the production of WMA mixtures at temperatures ranging from 50°F to 70°F lower than HMA production temperatures. (Ali 2013)

Types and Benefits of WMA

Approximately 420 million tons of asphalt mixture were produced in the United States (US) in 2019 alone (Williams et al. 2018). Hot mix asphalt (HMA) is the most conventional way of producing these mixtures. Due to the rapid cooling of loose asphalt mixtures during the late paving season, it is almost impossible to pave at a much lower than conventional temperature. WMA offers the benefits of extending paving seasons and allowing for longer haul distances in cold weather. This is possible because it was found that in laboratories, WMA technologies facilitate mixing and compacting asphalt mixes at lower than traditional temperatures; that is, by (50°F-122°F) without influencing their mechanical performance (Ali 2013; Capitão et al. 2012; Cheraghian et al. 2020; d'Angelo et al. 2008; Rubio et al. 2012; Silva et al. 2010; Vaitkus et al. 2016). Commercial WMA technologies are available as compaction aids for pavement construction. Among these technologies, Rediset, Evotherm, Zycotherm, HyperTherm, Cecasbase, etc., are known as chemical WMA. Sasobit, Ecoflex, etc., are organic types, whereas Advera, Zeolite, Asphamin, etc., are foaming types of WMAs (Cheraghian et al. 2020).

Impact of WMA on Rheological Properties of Asphalt Binders

Several research studies were conducted to evaluate the impact of WMA additives on the rheological and physical properties of asphalt binders. For instance, the high-temperature properties of asphalt binders blended with WMA additives were evaluated using parameters such as the shear modulus (G^*), phase angle (δ), dynamic viscosity (η^*), Superpave rutting factor ($G^*/\sin\delta$), high failure temperature, Superpave performance grade (PG), creep compliance, creep angle, and softening point for unaged or short-term aged WMA modified asphalt binders (Cheraghian et al. 2020; Hamzah et al. 2015; Xiao et al. 2012). In general, researchers reported that the $G^*/\sin\delta$ parameter had higher values by 30% for binders modified with organic-based (e.g., Sasobit) than that for those modified with chemical-based (e.g., Evotherm) or control (Xiao et al. 2012). Another study showed that using organic WMA additives (e.g., Sasobit) reduced rutting potential by 60% compared to the control (Abed et al. 2020). It was also reported that wax-based WMA-modified binders did not significantly increase the cracking temperature as determined by the asphalt binder cracking device (ABCD) test (Liu and Li 2012). However, due to less aging, fatigue cracking resistance was improved with the addition of a higher dosage of wax-based additives (Abed et al. 2020).

(Wang et al. 2012) reported that adding 2% of organic -WMA to crumb rubber binders (CRB) at a temperature of 76℃ significantly increased the rutting resistance ($G^*/\sin\delta$) by 134% compared to the values of control binders. (Liu and Li 2012) evaluated different dosages (0.8%, 1.5%. and 3.0%) of WMA organic-based. They found that the low cracking temperature resistance of WMA-modified binder was decreased with higher additive content. Another study (Kumar et al. 2019) investigated the impact of aging components using a viscosity grade (VG20) and CRMB60 as base binders. VG20 and crumb rubber-modified binders (CRMB60) were blended with a chemical WMA at two dosages of 0.4% and 0.5% at 150℃ and 165℃, respectively, for 30 minutes.

Furthermore, the modified binders underwent short-term aging at 138℃ (instead of 163℃ as per ASTM D2872) and 100℃ for long-term aging. All asphalt binders were subjected to short and long-term aging to capture the influence of production temperature and aging components on WMA-modified binders. In this study, all asphalt binders underwent short and long-term aging to capture the influence of production temperature and aging components on WMA-modified binders. A Fourier Transform Infrared Spectroscopy (FTIR) was performed to investigate the impact of aging by computing the carbonyl and sulphoxide groups for each asphalt binder. The result showed that the unaged WMA binders increased the carbonyl indices by approximately 30% compared to base binders, which can be related to aging during the WMA production process. (Hamzah et al. 2015) evaluated the impact of incorporating one chemical-based WMA and one binder grade using RAP asphalt mixtures. This study observed that adding chemical-based WMA did not significantly reduce the high and low critical temperatures of asphalt binders. In other research studies, similar results and conclusions were obtained (Abed et al. 2020; Arega et al. 2013; Wang et al. 2020).

Moreover, various performance and rheological parameters were used to assess the aging of asphalt binders. These include critical temperature differential (ΔT_c), crossover temperature (T_c), Glover-Rowe (G-R), rheological index (R-value), and other relevant parameters. The changes in these factors were assessed at different aging levels (Arega et al. 2013; Wang et al. 2019). Most studies used a Pressure Aging Vessel (PAV) to indicate 5 to 10 years of field aging (National Academies of Sciences and Medicine 2021; Tian et al. 2004).

(Kataware and Singh 2017) Assess the effects of different warm mix additives on PG grade, viscosity, and fatigue life performance. Results showed that WMA reduced viscosity when modified with a polymer-modified binder (PMB), pumped the high PG by one grade interval, and enhanced the fatigue life performance of asphalt binders. Other researchers also reported a performance improvement in WMA on asphalt binder properties (Ameri et al. 2020; Banerjee et al. 2012; Hajj and Bhasin 2018). Adding chemical WMA is foreseen to reduce viscosity, thus facilitating the potential for working at a reduced temperature. It is well-known that the viscosity of binders decreases with increased temperature. The impact of varying dosages of WMA on the viscosity of the Styrene Butadiene Styrene (SBS) binder was investigated (Kataware & Singh, 2017).

Kateware et al. 2017 reported that the addition of WMA reduced the viscosity of the polymer-modified binder (PMB) by more than 6%, which was in line with similar studies (Xiao et al., 2012) and (Mogawer et al., 2009a). On the other hand, incorporating the WMA might increase the viscosity of (PMB) as reported in several studies (Akisetty et al., 2009; Hossain et al., 2012; Kataware & Singh, 2017b). However, some researchers showed that WMA did not change the asphalt binder viscosity(Mogawer et al., 2009b) (Zhao et al., 2012) (Sadeq et al., 2016). Ali 2013 (A. W. Ali, 2013) reported that the optimum dosages of Rediset LQ range between 0.25 to 0.75 (%), Evotherm between 0.4 to 0.7 (%), Aspha-mine is around 0.3% and Sasobit between 3 to 4(%) by weight of asphalt binders.

(Wang et al. 2020) conducted a study to investigate the effect of crumb rubber and warm mix additives on the fatigue life performance of asphalt binders. Researchers found that adding a chemical-based WMA additive improved the fatigue performance of the neat asphalt binder, while a 16% decrease was observed in wax-based cases (Wang et al. 2020).

Impact of WMAs on Asphalt Mixtures

WMA is reliable in terms of fatigue performance (Wu et al. 2019), permanent deformation (Hurley et al. 2006), moisture sensitivity (Xiao et al. 2009), and ease of compaction (Hurley et al. 2006; Pereira et al. 2018). WMA's chemical and organic types improve workability at lower compaction temperatures (Button et al. 2007; Chen et al. 2019; Singh et al. 2017). Workability can be defined from a field perspective as placing and compacting efficiently to the desired mat density (Bennert et al. 2010; Capitão et al. 2012). It was reported that the long-term pavement performance in terms of longitudinal cracking, transverse cracking, rutting, and moisture resistance is similar to conventional HMA (National Academies of Sciences and Medicine 2017). With all these added benefits, the use of WMA technologies in producing asphalt mixtures and paving roadways is growing worldwide. The US had almost 38% of its total asphalt mixture production as WMA in 2019 (Williams et al. 2018).

WMA technologies can play a major role as compaction aids when producing and placing asphalt mixtures in cold weather environments. As commonly known, the compaction temperature of asphalt mixtures significantly impacts pavement performance and the overall ability to achieve target densities in the field. Scholz et al. (Scholz and Rajendran 2009) showed that a high percentage of premature pavement failures (i.e., rutting, moisture-induced damage, and raveling) is due to several factors, such as materials, aggregate quality, and mixing temperature. However, inadequate compaction is one of the major factors in the premature failure of pavements (Hurley and Prowell 2006; Scholz and Rajendran 2009). Several studies were conducted to assess the ability to use WMA additives as compaction aids for lowering the compaction temperatures of asphalt mixtures. Almeida et al. (2021) studied the impact of Sasobit Redux on asphalt mixtures containing waste plastic film flakes. In this study, three compaction temperatures (194° F, 212° F, and 230° F were used to compact mixes containing Sasobit Redux. Almeida et al. (Almeida and Sergio 2019) reported that the compactability of the WMA mix at lower temperatures was better than that of the control HMA. A 68°F (20°C) significant reduction in compaction temperature without affecting performance was reported using WMA (Almeida et al.

2021). However, as expected, the volumetric properties of the WMA mix (e.g., air voids) increased as compaction temperatures decreased. Similar observations in other studies also show that adding chemical WMA technologies improves the compaction of asphalt mixtures (Mo et al. 2012).

WMA is a potential alternative to HMA for optimizing asphalt mixtures when the placement temperature is crucial. (A. Ali et al., 2023) found that using WMA technologies as an alternative to HMA performed superior in volumetric and asphalt pavement performance compared to the traditional HMA. Moreover, Ali et al. (A. Ali et al., 2023) showed the potential of using the WMA mixes to compact asphalt mixtures as low as 190°F (82°C) without compromising HMA properties. Research, as exemplified by the work of (Zhang, 2010), assessed the use of WMA technologies (i.e., chemical, organic, and foaming technology) and one binder grade PG 64-28 by conducting the asphalt paving analyzer (APA), mix design, and tensile strength ratio (TSR) to determine the rutting, compactability, and moisture resistance, respectively for HMA and WMA mixtures. In this study, (Zhang, 2010) mixed the HMA mixtures at around 165°C and compacted at 135°C, while their corresponding WMA mixture was produced at around 135°C and compacted at 124°C. Per AASHTO T283 (TSR) and APA results, WMA-modified mixtures increased the rut resistance significantly, whereas they exhibited higher susceptibility to moisture damage than HMA mixtures.

Hurley and Prowell (Hurley et al. 2006) compacted asphalt mixtures containing different WMAs (Sasobit, Evotherm, Zeolite) at temperatures as low as 190°F. The researchers found that using Evotherm reduced the air voids of the asphalt the most, followed by Sasobit and Zeolite. The addition of these WMA additives did not increase the rutting susceptibility compared to the control mix at any temperature (300°F, 264°F, and 190°F). However, it was reported that using lower production temperatures (mixing and compaction) resulted in more rutting susceptibility due to the decreased aging of asphalt binders in WMA mixes. Researchers concluded that lower compaction temperatures might increase the potential for moisture damage in WMA asphalt mixtures (Hurley et al. 2006).

Bennert et al. compacted WMA mixtures for a fixed height to achieve 7% air voids and a standard density. The authors reported the gyration rate to compare the compactability of mixtures. They also reported that Rediset modified mixture resulted in air voids around 1% lower than the average HMA, whereas Sasobit appeared more compactable (Bennert et al. 2010).

Summary of the Literature

Based on a comprehensive review of the existing literature, the following conclusion can be derived:

- Warm mix additives did not significantly influence asphalt binders' rheological and physical properties (e.g., low-cracking temperature and aging) (Kumar et al. 2019; Liu and Li 2012).
- The use of warm mix additives improved the compactability and performance of the modified mixtures (Bennert et al. 2010; Hurley et al. 2006)
- WMA can increase the moisture susceptibility of the modified asphalt mixtures. Hence, WMA-modified asphalt mixtures reduce the mixtures' indirect tensile strength (ITS), leading to less moisture damage resistance.

Chapter 3

Experimental Program

Materials and Preparation

Two different binder grades were obtained with a performance grade of PG 58-28 used in roadways & PG 76-28 used in the airfield to investigate the impact of WMA on the rheological and performance of asphalt binder and mixtures. The first step of producing WMA binders was to modify samples of the neat PG 58-28 and PG 76-28 binders based on the manufacturer's recommendation. The dosages used in this study for each WMA additive, as recommended by the suppliers, are Sasobit Redux: 2%, Evotherm: 0.7%, Zycotherm: 0.1%, and Rediset: 0.5% (by binder weight) using the high shear mixer for 10 minutes. **Table 1** provides a detailed description of each warm mix additive. Moreover, WMA-modified binders underwent different aging levels to assess the impact of aging on their rheological and physical properties.

Table 1

Warm Mix Additives Used in this Study

Additive Name	Additive Source	Dosage (by binder weight)
Rediset LQ-1102	Chemical Product	0.5%
Evotherm M1	Chemical Product	0.7%
Zycotherm	Chemical Product	0.1%
Sasobit Redux	Organic Product	2.0%

As part of this research project, the asphalt mixture used in this study followed the New Hampshire Department of Transportation (NHDOT) specification. This study prepared asphalt mixtures using powder limestone as a mineral filler and used granite aggregate with a 12.5 mm nominal maximum aggregate size (NMAS). **Figure 2** presents the gradation for the aggregates used in this study. The asphalt mix was designed following the Superpave mix design procedure, selecting N_{design} as 75 gyrations. **Table 2** illustrates the mix design properties, including air void content (AVC%) and void in mineral aggregates (VMA%) for controls and WMA-modified asphalt mixtures at their manufacturer's recommended compaction temperatures. From **Table 2**, WMA modified with PG 76-28 required 5.8% binder content (Pb) to meet density and VMA requirements, whereas the unmodified binder met the requirements at 5.3% binder content. Specifically, the difference in (Pb) was 0.5% between PG 76-28 and PG 58-28 asphalt mixtures. The difference in binder content can be attributed to the different mixing temperatures for PG 76-28 at 340°F (171°C) and PG 58-28 at 310°F (154°C). Furthermore, this will impact the air voids of compacted samples in which modified (stiff) mixtures need more binder to fill the voids in the compacted mixtures than unmodified (soft) mixtures.

Figure 2

Aggregates Gradation Used in this Study

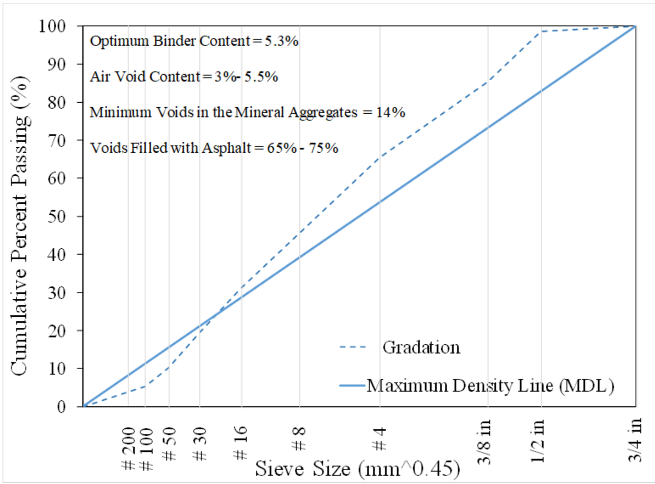


Table 2

Mix Design for Control Mixtures at 300°F (PG 58-28) and 320°F (PG 76-28)

Mix Type	WMA Rate (%)	P_b (%)^a	P_b (%)^b	G^a_{mm}	G^b_{mm}	G^a_{mb}	G^b_{mb}	AVC^a	AVC^b	VMA^a	VMA^b
Control	-	5.3	5.8	2.6	2.5	2.4	2.4	5.3	3.7	16.6	16.0
Rediset	0.5	5.3	5.8	2.6	2.5	2.4	2.4	4.8	3.6	16.4	16.2
Evotherm	0.7	5.3	5.8	2.6	2.5	2.5	2.4	4.6	3.7	16.3	16.1
Zycotherm	0.1	5.3	5.8	2.6	2.5	2.4	2.4	5.0	3.7	16.8	16.2
Sasobit Redux	2.0	5.3	5.8	2.6	2.5	2.4	2.4	4.5	3.1	16.6	15.8

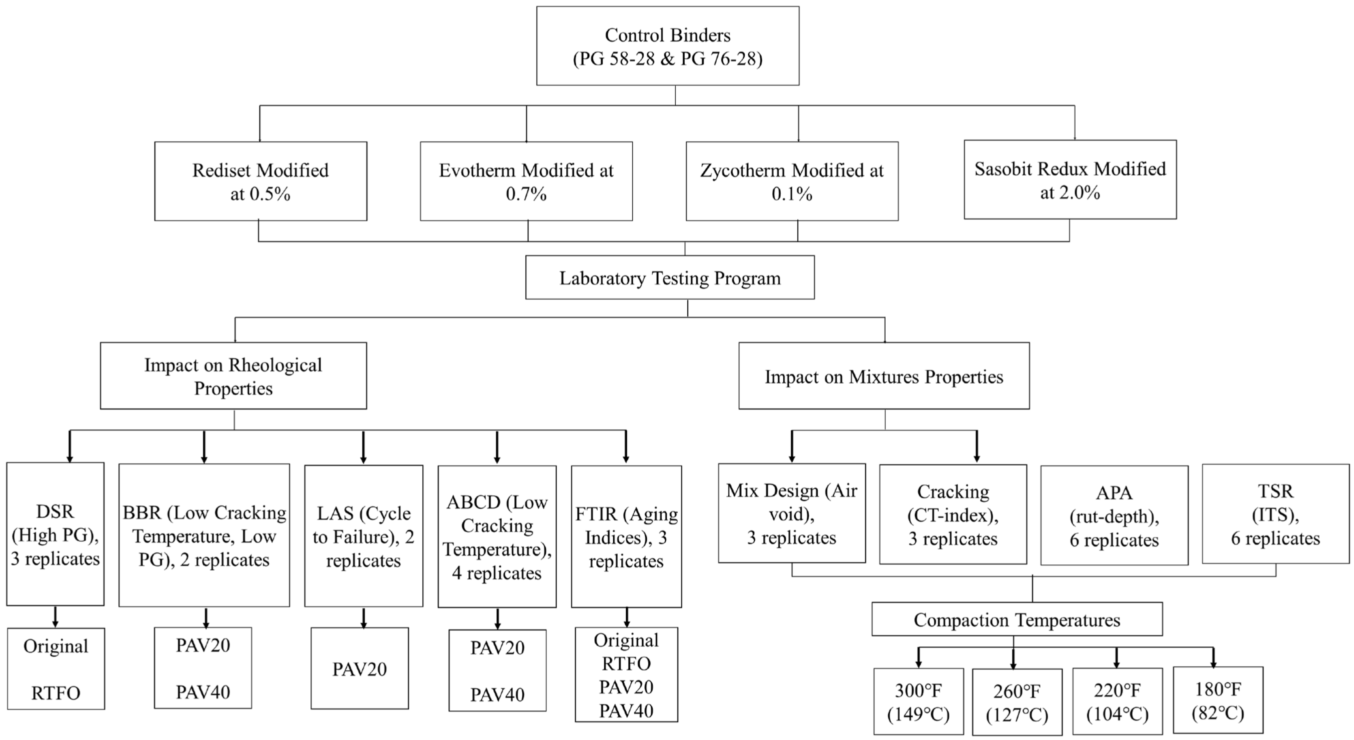
Note. a = PG 58-28; b = PG 76-28

Testing Program

Figure 3 presents a comprehensive testing plan to evaluate the impact of WMA on the rheological and performance properties of the asphalt binders and mixtures. Firstly, PG 58-28 and PG 76-28, which contain Styrene-butadiene- Styrene (SPS) (less than 1% Polyphosphoric Acid), were modified with WMA binders to produce the modified asphalt binders. The blending process involved using a high-shear mixer (2000 RPM) for 10 minutes at a temperature of 302 °F and 345°F for PG 58-28 and PG 76-28, respectively. Secondly, the experimental program was conducted to assess the performance grade (PG) low cracking temperature using a bending beam rheometer (BBR). The asphalt binder cracking device (ABCD) was used to evaluate the low cracking temperature and determine the fatigue life performance using linear amplitude sweep (LAS). In addition, the impact of aging on WMA was assessed by Fourier transform infrared spectroscopy (FTIR). In this test, three different aging levels were considered: (a) rolling thin film oven (RTFO-aged at 163°C), (b) pressure aging vessel (PAV20), and (c) extended long-term aged (PAV40). This study also involved the evaluation of the volumetric properties, cracking, rutting, and moisture resistance of asphalt mixtures using Superpave gyratory compactor (SGC), indirect tensile asphalt cracking (IDEAL-CT), asphalt pavement analyzer (APA), and tensile strength ratio (TSR) tests. The provided mixing temperatures obtained from the manufacturers for PG 76-28 (345°F) and PG 58-28 (310 °F) modified with WMA binders were used to produce asphalt mixtures. Before compaction, mixes were aged for short-term aging (2h) and compacted at four compaction temperatures.

Figure 3

Experimental Plan



Note. DSR: Dynamic Shear Rheometer; BBR: Bending Beam Rheometer; LAS: Linear Amplitude Sweep test; ABCD: Asphalt binder Cracking Device; FTIR: Fourier Transform Infrared Spectroscopy; CT-index: Crack tolerance index. RTFO = rolling thin film oven; PAV = pressure aging vessel

All the testing protocols followed in this study are described in the following sections:

Binder Testing Program

Short, Long, and Extended Long-Term Aging

The three binder aging levels considered in this study included (a) short-term aging using a rolling thin film oven (AASHTO T 240, RTFO-aged), (b) long-term aging using a pressure aging vessel (PAV) for 20 hours, and (c) extended long-term aging using a PAV for 40 hours. The short-term aging of the asphalt binders was conducted according to the AASHTO T240 specification. In particular, 35 ± 0.5 grams of binders for each bottle was used at 325°F ± 1.8°F (163℃ ± 1.0℃) for 85 minutes. Additionally, RTFO sample materials were further aged at a temperature of 212°F (100℃) to long and extended long-term aging using PAV according to AASHTO R28 specification.

Performance Grade (PG)

The neat and WMA-modified binders' high continuous performance grade (HPGcont.) was determined according to the AASHTO M 320 specifications. In particular, the dynamic shear rheometer (DSR) at 10 rad/s frequency was used to obtain the complex shear modulus (G^*) and phase angle (δ) of each binder as described in AASHTO T 315. To determine the high continuous temperature grade, a 25 mm plate with a 1-mm gap was used in the DSR. For low temperatures grades, the stiffness and m-value for each binder were recorded at the 60s using the Bending Beam Rheometer (BBR, AASHTO T313) test. Specification requirements for high and low-performance grades are tabulated in **Table 3**.

Table 3

Superpave Binder for Performance Grade

Test Method	Test Parameter	Aging Level	Specification Requirement
DSR (AASHTO T315)	G^* / sing δ	Unaged binder	≥ 1.0 KPa at 10 rad/s
		RTFO	≥ 2.2 KPa at 10 rad/s
BBR (AASHTO T313)	Creep Stiffness (S)	PAV20	≥ 300 MPa
	M-value (relaxation)	PAV40	≥ 0.300

Critical Temperature Differential (ΔT_c)

ΔT_c, or the temperature difference, can be measured by analyzing the low-temperature grades determined from the creep stiffness and m-value at 60 seconds. The decrease in ΔT_c indicates greater susceptibility to cracking for the asphalt binder. Furthermore, a strong correlation was observed between ΔTc and field cracking performance (Anderson et al. 2011). The researcher established two limits for ΔT_c based on their findings. The first limit is -2.5°C, indicating a warring for future asphalt cracking. The second limit is -5°C, which indicates the need to replace the asphalt binder. These limitations provide a guideline for determining the asphalt condition and the subsequent maintenance required.

Low Cracking Temperature (ABCD)

The cracking temperature of modified, un-modified, and WMA-modified binders was determined using the asphalt binder cracking device test (ABCD) as per the AASHTO T387 specification. This test provides a set of four metal mold rings that can be attached to the strain gauges, software (for data collection), and a chamber for colling the binders samples. For measuring the cracking temperature, the difference in thermal expansion and contraction of the metal and the specimens was recorded using the software. A dropping temperature rate of 68°F/h was considered during the test (Liu and Li 2012). In addition, as the contraction between the metal and binder samples increases, thermal stresses are generated in the specimen molds. Higher strains at failure values indicate better low-cracking temperature performance. The final cracking temperature, cooling rate per hour, and strain jump were obtained at the end of the test cycle. This study used an average of four replicates tested at PAV20 aging level for each binder as a final low-cracking temperature value.

Fatigue Life Performance (LAS)

The linear amplitude sweep test (LAS) was used to characterize the fatigue life behavior of WMA-modified asphalt binders according to AASHTO TP 101-14. The LAS test uses the viscoelastic continuum damage (VECD) methodology to evaluate the fatigue properties of the asphalt binder (Test 2010). The test was performed by DSR equipment using an 8 mm parallel plate geometry at the intermediate temperature (i.e., 25°C, expected intermediate pavement temperature)(Kataware and Singh 2018). In the first stage, before shear amplitude sweep loading, the material undamaged parameter (α) was determined by performing a frequency sweep test. In the first stage, a constant strain of 0.1% was applied to the binder sample in the 0.1 to 30 Hz range. After that, the samples were subjected to a shear strain loading from 0.1% to 30% at 10Hz. All binder samples tested in this study were conditioned for long-term (PAV20) aging following the AASHTO R28 specification.

Fourier Transform Infrared Spectroscopy (FTIR)

This test evaluated the specimens at different aging levels, including the original state of the binder (unaged-binder), RTFO-aged, PAV20, and PAV40. The FTIR test measures the absorption of infrared radiation within a specific range of wavelengths, allowing for the identification of various chemical components present in the tested materials. In particular, the oxidation of the binder leads to increased levels of carbonyl and sulfoxide components in the asphalt binder. By comparing the carbonyl and sulfoxide groups, the impact of aging on different asphalt binders can be determined (Petersen et al. 1993). It was reported that the aging process changes the chemical and mechanical characteristics of the asphalt binder, resulting in stiffer, more viscous, and brittle binders (Abu Qtaish et al. 2018). The Attenuated total reflectance (ATR) mode was used to run the samples, and 32 scans were obtained for each binder. FTIR test was conducted on an average of three samples for each binder and aging condition. The aging indices were also calculated using the following equations for each test run (Jamal and Giustozzi 2022)

$$\text{Carbonyl Index (CI)} = \frac{A_{carbonyl\,(1680-1750)}}{A_{CH2(1410-1495)} + A_{CH3(1360-1390)}} \quad (1)$$

$$\text{Sulphoxide Index (SI)} = \frac{A_{sulphoxide\,(1060-980)}}{A_{CH2(1410-1495)} + A_{CH3(1360-1390)}} \quad (2)$$

Where A is the area under the absorbance peaks, this analysis calculates areas under the absorbance peaks, and it was evaluated using the spectrograph optical spectroscopy software.

Mixture Testing Program

Mix Design

The compactibility of WMA modified with PG 58-28 asphalt mixtures was evaluated using the Marshall and SGC compactors to determine which compaction method reflects the impact of WMA at lower compaction temperatures. Three samples for each mix (or testing combination) were prepared at the same binder content (5.3%) for each compactor and tested at four different compaction temperatures. Before compaction, the PG 58-28 and WMA-modified asphalt mixtures were conditioned for 2 h at their compaction temperature. For WMA modified with PG 58-28 mixes, SGC samples were compacted at 75 gyrations, whereas the samples produced using a Marshall compactor were compacted to 75 blows per side.

The mix design of WMA modified with PG 76-28 asphalt binder was compacted and evaluated at traditional temperature and lower than traditional temperature using the Superpave Gyratory compactor (SGC). For each mix, three samples were prepared at a binder content of 5.8% (by total mixture weight) and tested at four different compaction temperatures. Before compaction, the PG 76-28 and WMA-modified asphalt mixtures were conditioned for 2 h at their compaction temperature and compacted at 75 gyrations.

Cracking Performance

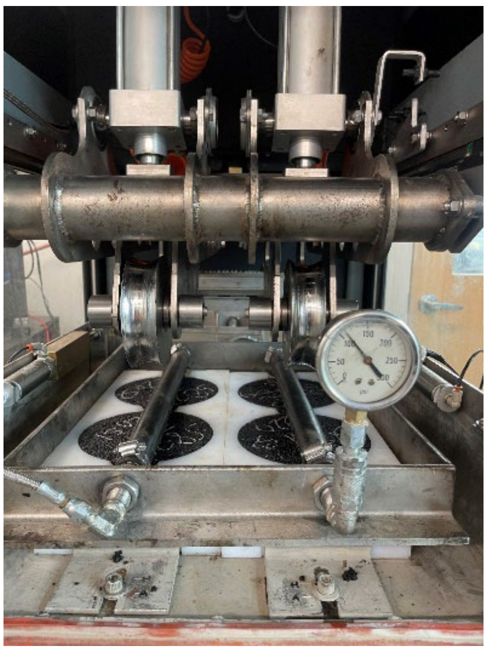
The sensitivity of cracking for control and WMA-modified mixtures was characterized using the indirect tensile asphalt cracking test (IDEAL-CT). This test determines a cracking tolerance index (CT_{index}), facilitating a relative performance comparison between asphalt mixtures. A higher CT_{index} value indicates greater cracking performance. This index is calculated using the load-displacement curves generated from breaking compacted asphalt mix samples. In this study, IDEAL-CT was performed at 77°F (25°C) (According to ASTM D8225 specification), and a 50 mm/min monotonic displacement rate was applied. Three replicates were produced for each asphalt mix and compaction temperature. Each sample prepared for this test was compacted to a height of 62.0 mm ± 1.0mm, 150 mm diameter, and 7% ± 0.5% target air void level.

Rutting Performance

The susceptibility of all asphalt mixtures to rutting was assessed using the asphalt pavement analyzer (APA) test. The test was conducted according to the AASHTO T 340 standard. In this test, six cylindrical samples were prepared for each mix. The testing temperature of PG 58-28 modified with WMA was 136°F (58°C), whereas PG 76-28 modified with WMA was subjected to testing at a temperature of 169°F (76°C), representing a high PG of the control binder. During the test, specimens were preheated for at least 6 hours at the mentioned temperatures. Pressurized to 100 psi, a rubber hose is placed on the molded samples. A metal wheel is applied to apply 100 lbs of load on the pressurized hose, as shown in **Figure 4.** The test is continued for a total of 8,000 loading passes. Before and after loading cycles, two rut depth values per sample were measured, and an average manual rut depth value for all specimens was reported. Six APA specimens (per mix combination) were compacted to a height of 75 mm ± 2.0 mm and an air void level of 7 % ± 0.5%. The passing criteria for rut depth (5 mm) were considered based on updated Federal Aviation Administration (FAA) P401 mix criteria (Gierhart 2019).

Figure 4

APA Rutting Test Setup



Moisture Sensitivity

The moisture susceptibility of control and WMA mixtures was determined according to AASHTO T 283 using the universal testing machine (UTM). Six cylindrical samples, three unconditioned samples (UC), and three moisture-conditioned samples (MC) for each mix (or testing combination) were prepared and tested at a temperature of 77°F (25°C). Each sample prepared for this test was compacted to a height of 95 mm ± 5mm, 150 mm diameter, and 7 ± 0.5 % target air void level.

Chapter 4

Discussion of Binder Testing Results

The Effect of the WMAs on the Rheological and Performance Measures

Performance Grading Testing Results

The high continuous PG (HPGcont.) for the PG 76-28, PG 58-28, and WMA modified binders at their manufactured recommended dosages are plotted in **Figure 5**. To understand the impact of WMA additives on the HPGcont. and LPGcont. of PG 76-28-modified binders, performance grade results of PG76-28 modified with WMA are shown in **Figure 5(a-c)**. The measured high-performance grades, as shown in **Figure 5(a)**, were obtained as 82℃, 70℃, 70℃, 82℃, and 76℃ for PG 76-28, Rediset, Evotherm, Zycotherm, and Sasobit Redux, respectively. It is worth mentioning that the obtained PG 76-28 binder was found to be PG 82-28, as seen in **Figure 5(a).** In particular, adding PG 82-28 to WMA had at least one high PG (6°C) lower than what was measured for control (82℃). This reduction in HPG_{cont} for Rediset and Evotherm could be due to the SPS polymer in PG 82-28. The modified WMA with the same asphalt binder did not change the low continuous PG (LPGcont.) at the PAV20 aging level except for the Sasobit Redux modifier that changed the LPGcont. (from -28℃ to -22℃) at the extended long-term aging. For PG 58-28, adding WMA showed no impact on HPGcont. (same as control 58℃) as shown in Figure 2(b-d). At the PAV20 oxidation level, modifying the PG 58-28 with WMA did not alter the low continuous PG except for the Sasobit Redux, which showed an LPGcont. (i.e., -22℃) compared to the control (i.e., -28℃). Further oxidation of the binders to PAV40 pumped the low continuous PG (i.e., -28℃ to -22℃), as seen in Figure 2(d). The consistent increase in low continuous PG for Sasobit Redux modifier is because Sasobit Redux starts to crystallize between 72-83°C and solidifies at any temperature below that range. Sasobit Redux can alter the hydrocarbon chain length in the binder and impart stiffness, thus reducing the ability of the modified binder to relax the accumulated strain in low-temperature conditions(Caputo et al., 2020). These observations suggest that all WMA as modifiers should not significantly impact the rutting and cracking only for PG 58-28 modified binders.

Stiffness and Stress Relaxation of WMA Modified Asphalt Binders

Figure 6 illustrates the impact of WMA on the stiffness and the m-value that were determined using the bending beam rheometer at -18°C and -24°C. A higher m-value (stress relaxation) indicates better low-cracking performance. Stress relaxation values of Rediset and Sasobit Redux showed insignificant change when modified with PG 76-28. At the same time, the addition of Evotherm and Zycotherm had higher stress relaxation values by approximately 4% and 6%, respectively, compared to the PG 76-28. Adding WMA to PG 58-28 did not impact the stress relaxation of the control binder except for Sasobit Redux, which exhibited a reduction around 5% lower than the control. This reduction in stress relaxation can be attributed to the stiffening effect of organic wax, which is the main component of Sasobit Redux. The impact of WMA on asphalt binder stiffnesses is shown in **Figure 6 (c-d)**. The stiffness results for PG 76-28 modified with WMA exhibited insignificant change, while adding Zycotherm modifiers reduced the stiffness by approximately 10% compared to PG 76-28, as shown in **Figure 6 (c)**. Stiffness values for PG 58-28 modified binders were lower by around 15% compared to control (**Figure 6 (d)**).

Figure 5

Measured Performance Grade for Modified, Un-Modified, and Wma-Modified Binders: (a-c) PG 76-28 and (b-d) PG 58-28

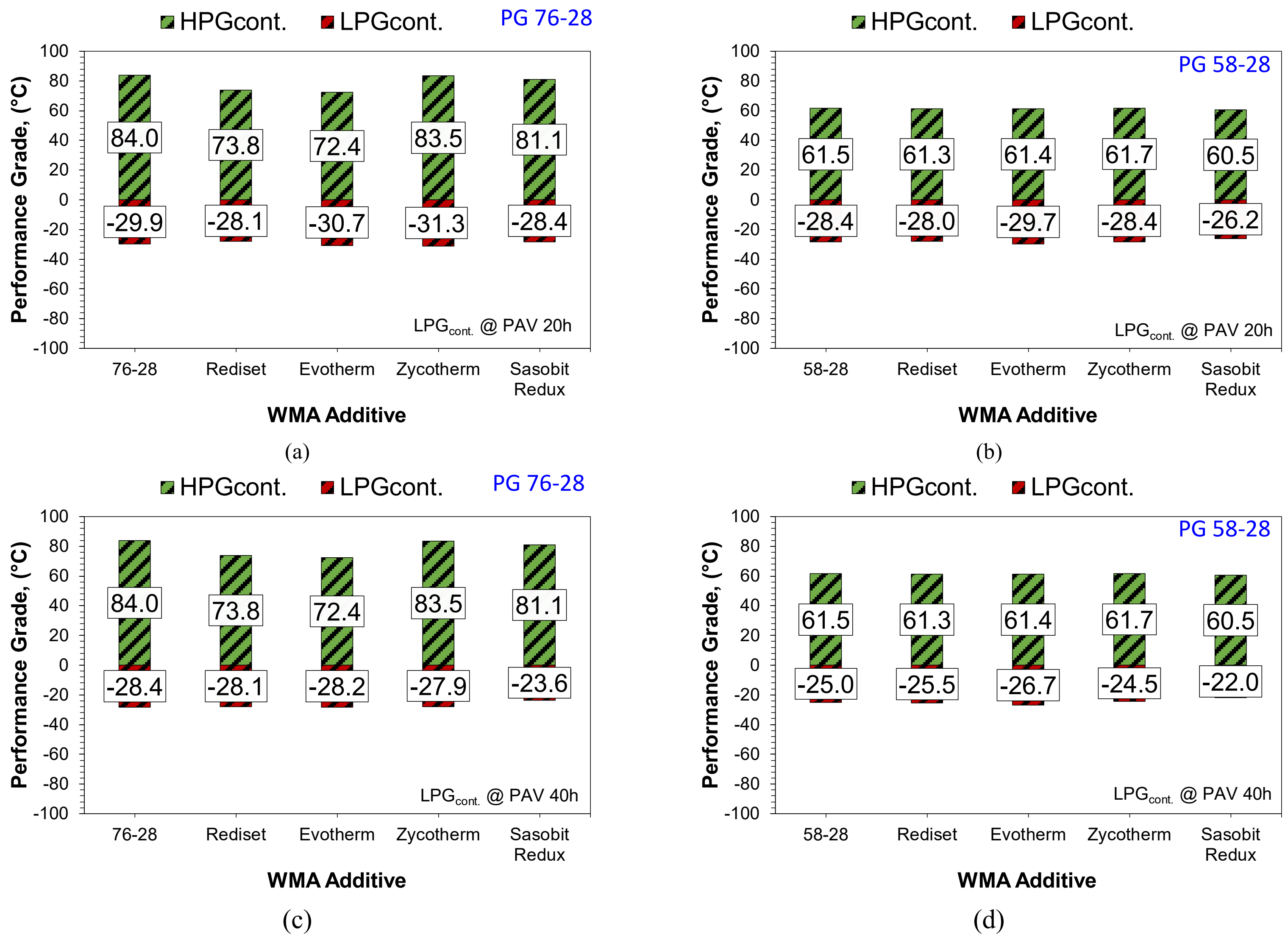
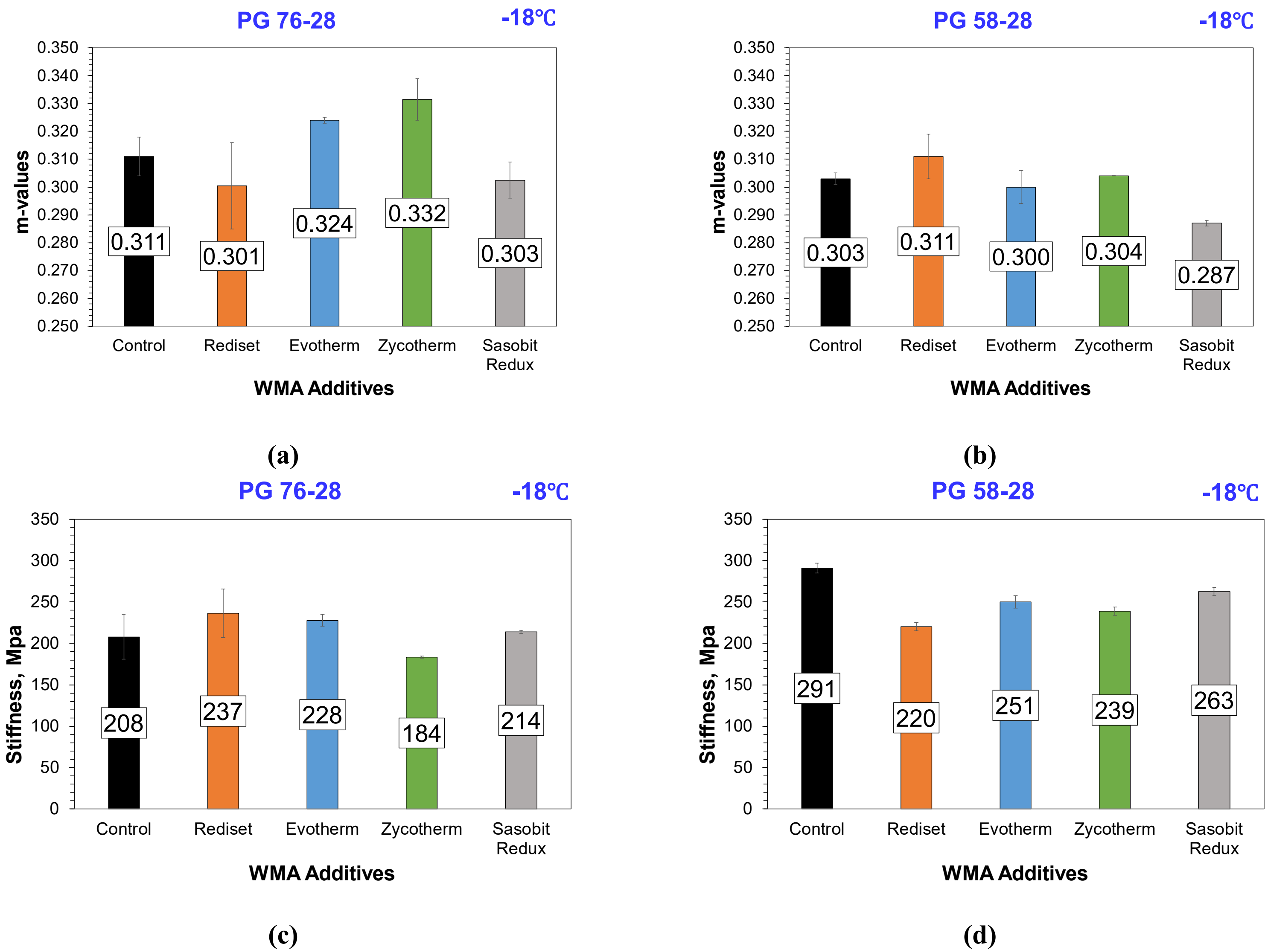


Figure 6

Low-Temperature Behavior of PAV-Aged WMA-Modified Binders: (a-b) m-Value; (c-d) Creep Stiffness

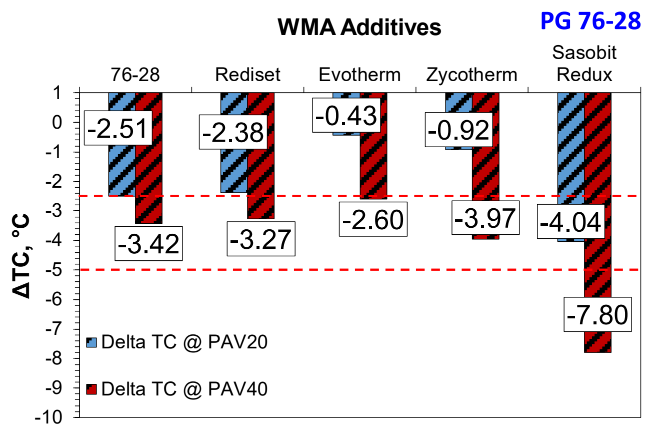


Critical Temperature Differential (ΔT_c)

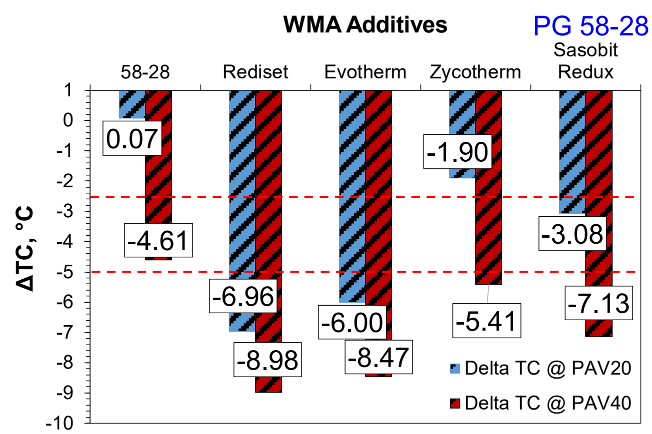
Figure 7 presents the ΔT_c values for all asphalt binders at PAV aging levels. Lower ΔT_c values indicate lower cracking resistance for asphalt binders. From **Figure 7(a)**, the PG 76-28 modified with Rediset, Evotherm, and Zycotherm additives increased the ΔT_c values by 5%, 83%, and 63%, respectively, at the PAV20 aging level. This increase in ΔT_c values with the addition of WMA shows that the low cracking resistance of asphalt binders can be improved. However, only Sasobit Redux exceeded the high severity threshold limit of -5°C at its PAV40 aging level, indicating the lowest cracking resistance. As mentioned previously, Sasobit Redux crystalline structure may impact the binder hydrocarbon chain, causing it to be more crack-prone. As reported in a recent study, ΔTc is unsuitable for polymer-modified asphalt (PMA) binders(Lesueur et al., 2021). The ΔT_c results of PG 58-28 modified with WMA are shown in **Figure 7(b)**. A tech brief from the Federal Highway Administration (FHWA) states that for colder climate states, it is more suitable to use PAV40 to quantify ΔT_c(Administration, 2021). It was observed that all WMA modified with PG 58-28 exceeded the threshold of -5°C at the PAV40 aging level, so low cracking resistance was observed for WMA-modified binders. Overall, WMA modified with a PG 76-28 enhanced the ΔT_c above the low severity threshold, whereas WMA modified with PG 58-28 did not improve the ΔT_c above the low severity threshold of -2.5°C. These findings show that adding WMA at their manufacturer's recommended dosages only to PG 76-28 degrades WMA-modified binders' low cracking temperature performance.

Figure 7

ΔTc Values at PAV20 and PAV40 Oxidation Levels: (a) PG 76-28, (b) PG 58-28



(a)



(b)

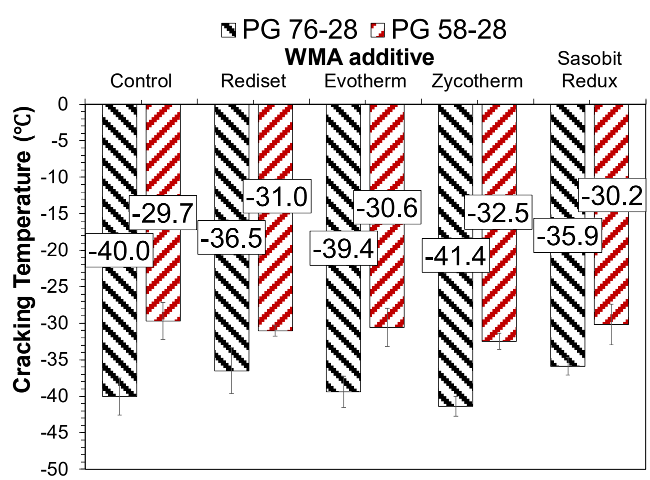
Note. The dotted lines show the threshold values of -2.5°C and -5°C.

Low-Cracking Temperature of Controls and WMA Modified Binders

The cracking temperatures of binders were obtained by employing the ABCD test. For the ABCD test, PAV20-aged specimens were tested. **Figure 8** illustrates the effect of different binder grades and WMA on the cracking temperatures of asphalt binders. The error bars in **Figure 8** indicate the standard deviation of 4 replicates for each binder. The PG 76-28 cracking temperatures modified with WMA exhibited insignificant low cracking temperature as control (-40°C). In particular, the addition of Sasobit Redux increased the low cracking temperature by approximately 10% compared to the control. In contrast, PG 58-28 modified with WMA did not significantly alter the low cracking temperature compared to the control (-28°C), as shown in **Figure 8.** Regardless of the binder grade, adding WMA did not impact the low cracking temperature of asphalt binders, thus leading to the benefits of using WMA without affecting the low cracking temperatures of control

Figure 8

Cracking Temperatures Based on ABCD Test

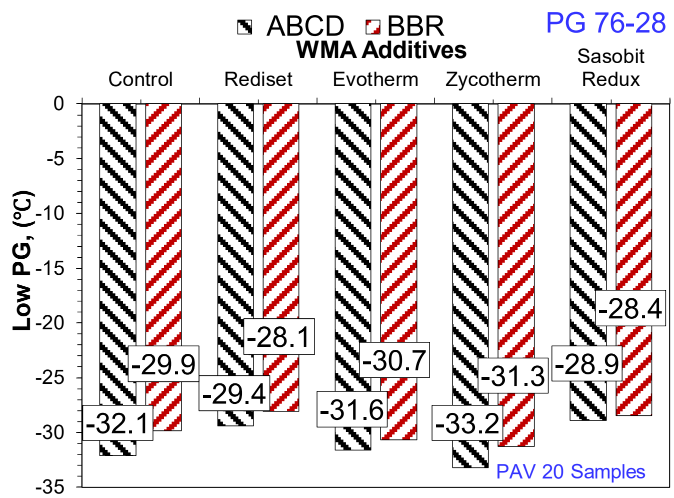


Comparison of Low-Performance Grade Using BBR and ABCD Tests

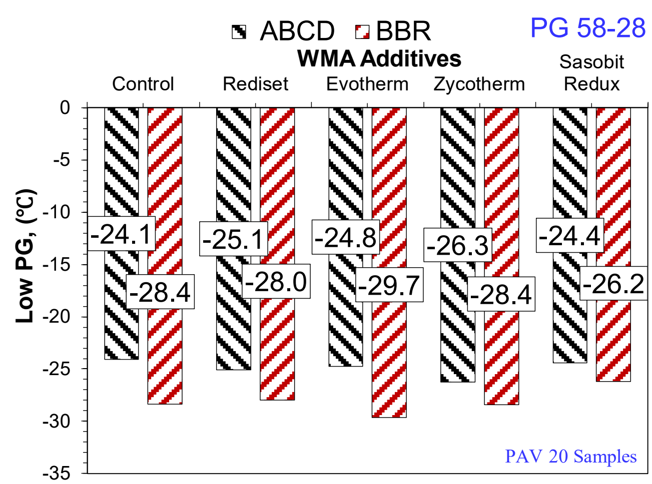
It is considered that the binder properties usually have the most influence on the mixture cracking temperatures(Fortier & Vinson, 1998). For this purpose, the BBR and ABCD tests were used to assess the low-performance grade of PAV20-aged samples. Two replicates were used at each temperature for the BBR test, whereas four replicates were prepared for the ABCD test. As shown in **Figure *9* (a)**, the impact of WMA modified with PG 76-28 showed identical low PG as the control binder (-28°C) for both tests. The addition of WMA to PG 58-28 displayed a low PG as the control (-28°C) except for the Sasobit Redux (-28°C to -22°C) when assessed using the BBR test (as seen in **Figure *9***(b)). On the other hand, the ABCD test result for PG 58-28 WMA modified binders showed a low PG (-22°C), which differs from BBR (-28°C) for the same binders. It can be concluded that evaluation of the low-performance grade for PG 58-28 modified with WMA binders using ABCD captured the change in LPG more accurately than BBR. In summary, the $LPG_{cont.}$ were obtained the same for the PG 76-28 modified with WMA binders for the ABCD and BBR test. The unchanged PG for PG 76-28 modified binders can be justified due to the presence of polymer in the PG 76-28 binder. Overall, this variation in low-performance grade can be attributed to the measured reduction in strength or fracture toughness characteristics between different tests (Kim et al., 2015) and the methodology used to prepare and test the specimens (i.e., cooling rate/h).

Figure *9*

Measured Low-Performance Grade of WMAs Modified With Different Binder Grades Using ABCD and BBR tests: (a) PG 76-28 and (b) PG 58-28



(a)



(b)

Impact of WMA-Modified Binders on Fatigue Life Performance

To further evaluate how the binders performed against fatigue after modification was assessed next. **Figure 10** shows the damage characteristic curves and the fatigue life performance of WMA-modified binders. **Figure 10 (a-b)** presents the damage intensities versus materials integrities for WMA-modified binders. Adding WMA to PG 76-28 and PG 58-28 binders showed different damage intensities than the control binder. It is well-established that with the increased material integrity, the binder has a lower potential for fatigue damage (Wang et al., 2020). As shown in **Figure 10 (a-b)**, It is worth mentioning that for different binder grades, WMA binders displayed higher material integrity than control binders at the end of the fatigue life.

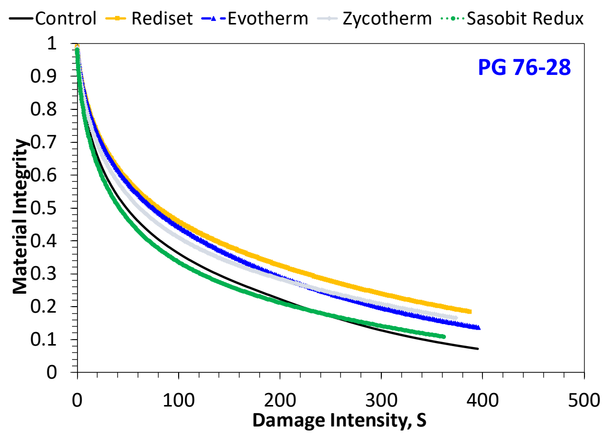
To better understand the impact of binder grade and WMA modifiers, different applied shear strains (%) versus the fatigue life was plotted in **Figure 10 (c-d)**. The highest fatigue life improvement was for Evotherm and Zycotherm modified with PG 58-28 by approximately 170% and 137%, respectively, compared to PG 58-28. All WMA modified with PG 58-28 binders increased the fatigue life performance, while a reduction was observed for PG 76-28 modified with WMA binders at 2.5% strain. The decrease in fatigue life percentages was 64%, 79%, 28%, and 62% for Rediset, Evotherm Zycotherm, and Sasobit Redux, respectively, compared to PG 76-28. However, considering the higher shear strain (10%), the fatigue life of PG 58-28 modified with WMA binders became very marginal. PG 76-28, modified with WMA binders, reduced the fatigue life performance compared to the control by at least 25% at 2.5% shear strain. It can be concluded that PG 58-28, modified with Sasobit Redux and Evotherm additives, showed the highest fatigue life performance, while when modified with PG 76-28, both additives displayed the lowest fatigue life performance. Overall, it can be said that adding WMA to modified asphalt binders may reduce fatigue life performance.

Aging Impact on Modified Warm Mix Additives

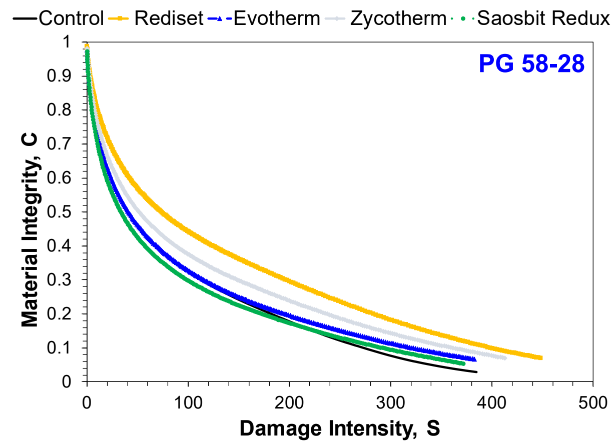
Figure 11 illustrates the carbonyl and sulphoxide indices at different aging levels for controls and WMA-modified binders. The sulphoxide indices of PG 76-28 modified binders are shown in **Figure 11 (a)**. It can be seen that the addition of WMA tended to be more susceptible to aging at PAV levels. The highest change in sulphoxide index was observed for the Evotherm modifier, showing that Evotherm modifiers have the most significant susceptibility to age when modified with PG 76-28 at PAV aging levels, corresponding with fatigue life performance results presented previously (**Figure 10**). For PG 58-28 WMA modified binders, sulphoxide indices were observed to be the lowest for Evotherm and Zycotherm at un-aged and RTFO levels. Rediset and Evotherm-modified asphalt binder exhibited the highest growth in the sulphoxide index at PAV levels, corresponding with ΔT_c findings presented previously (**Figure** *7*)**.** The impact of adding WMA on the carbonyl index is also demonstrated in **Figure 11**. It was observed that adding WMA modifiers exhibited higher carbonyl values when aged at PAV20 level compared to the control binder, indicating that adding Warm Mix Additives might increase the susceptibility to age. For both binder grades, Evotherm-modified asphalt binders show the highest growth in sulphoxide index for the same aging level (most tendency to age).

Figure 10

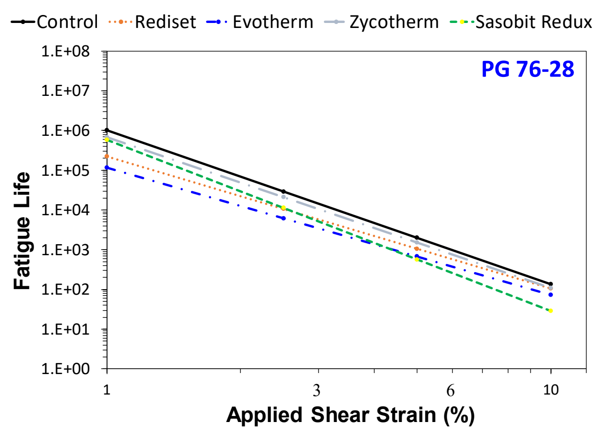
LAS Results : (a-b) Material Integrity Versus Damage Intensity and (c-d) Fatigue Life Versus Applied Shear Strain



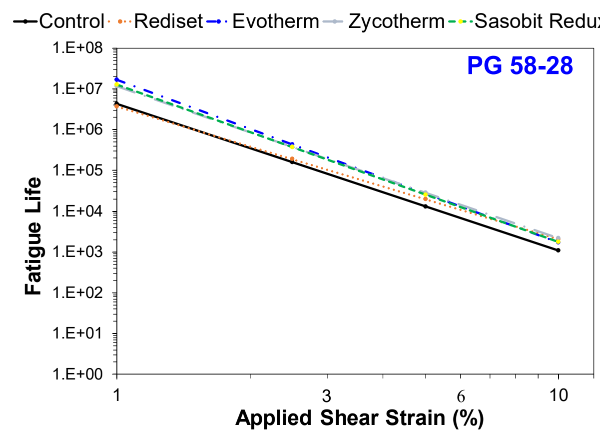
(a)



(b)



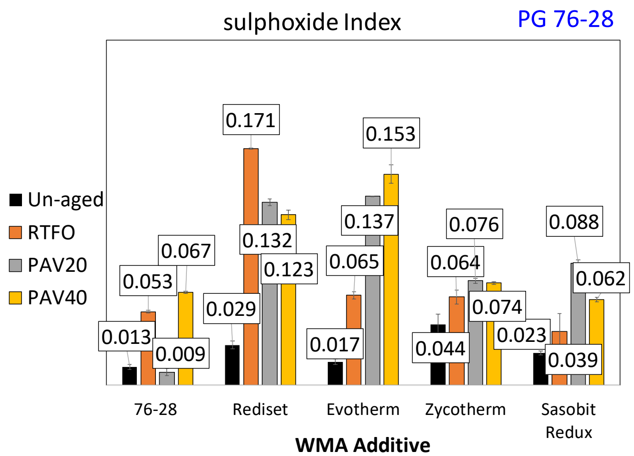
(c)



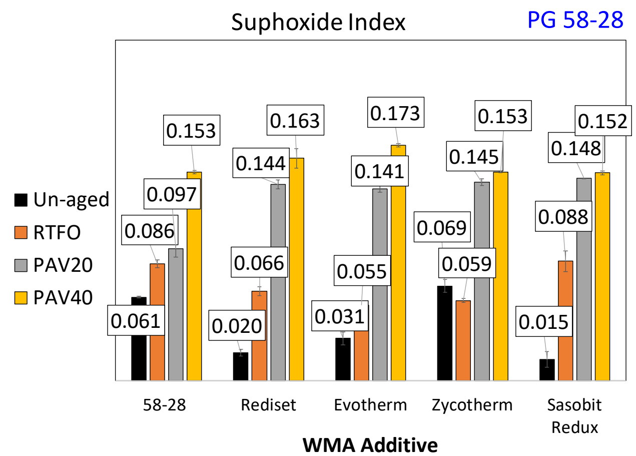
(d)

Figure 11

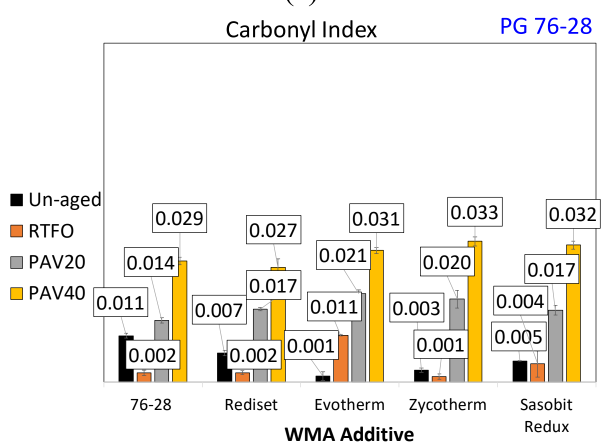
Aging Indexes at Un-aged, RTFO, and PAV Aging Levels: (a-b) Sulphoxide Indices and (c-d) Carbonyl Indices



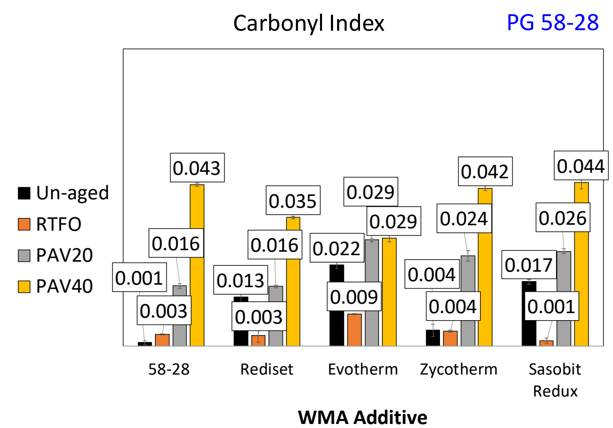
(a)



(b)



(c)



(d)

Chapter 5

Discussion of Mixtures Testing Results

Mix Design of WMA Modified with PG 58-28 Asphalt

The compactability of asphalt mixtures was evaluated using Marshall and SGC compactors. Using both compactors is to determine which compaction method reflects the impact of adding WMA additives. It was reported that the density of Marshall compacted samples is sensitive to mixture compaction temperature, whereas SGC compacted samples seemed insensitive (Bennert et al. 2010). **Figure 12** presents the bulk specific gravity (G_{mb}) and air voids result for Marshall and SGC asphalt mixtures for WMA modified with PG 58-28. In **Figure 12 (a&b)**, WMAs showed higher density at all compaction temperatures than control mixtures. At 260°F (127°C) compaction temperature, it was observed that WMA mixtures modified with Sasobit Redux, Rediset, and Zycotherm had a higher density using Marshall compactor with an increase in G_{mb} by 2%, 1%, and 1% compared to control. This aligns with the previous study (Bennert et al. 2010). As shown in **Figure 12 (c&d),** at all compaction temperatures, WMA-modified mixtures were more compactable than the control. The % increase in compactability at different compaction temperatures between Marshall and SGC compactors was tabulated in **Table 4**. From **Table 4**, At 260°F (127°C) compaction temperature, it was observed that WMA mixtures modified with Sasobit Redux, Rediset, and Zycotherm had the higher compactability using Marshall compactor with a reduction in air void by 28%, 18%, and 17% compared to control. It was noted that regardless of the compaction method, Sasobit Redux modified asphalt mixtures showed the best compactable mix among the other mixtures, as shown in **Table 4.**

Table 4

Percentage (%) Increase in Compactability Among WMA Modified with PG 58-28 for Marshall and SGC

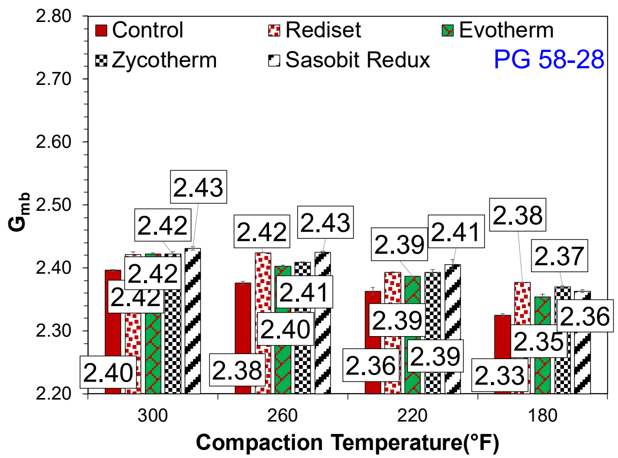
Reference Binder	Sample ID	Compaction Temperature (°F)							
		300		260		220		180	
		SGC	M.	SGC	M.	SGC	M.	SGC	M.
PG 58-28	Rediset	9	12	15	18	4	11	8	19
	Evotherm	13	14	13	7	10	5	8	7
	Zycotherm	6	15	8	17	0	11	11	18
	Sasobit Redux	15	23	22	28	10	19	8	14

Note. M.: Marshall compactor, and SGC: Superpave Gyratory Compactor

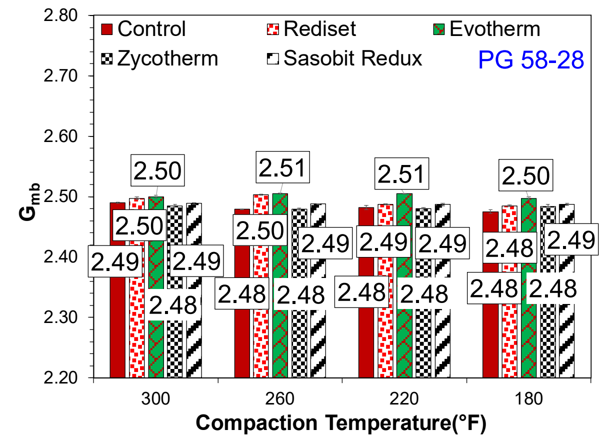
Overall, the impact of adding WMAs was more seen in asphalt mixtures prepared with the Marshall compactor than in the SGC. This can be attributed to the fact that using Superpave gyratory compactor is not sensitive to the change in the compaction temperature as the Marshall compactor, which was confirmed by studies conducted by (Bennert et al. 2010) and (Hurley and Prowell 2006). While lowering the compaction temperature, Marshall-produced samples cooled down more compared to SGC samples, as it takes more time to put 75 blows on both sides in Marshall samples. As the Marshall method is already known to be temperature sensitive, the compaction effort always produces a sample with higher air voids. So, to use WMA with Marshall, it is essential to set a higher compaction temperature than SGC and find the optimum binder content for Marshall samples (Li et al. 2011; Li et al. 2016). The air voids for Marshall compacted samples did not satisfy the NHDOT mix design requirements (i.e., air voids of 3 to 5.5%). This is because of the same binder content (i.e., 5.3%) between SGC and Marshall samples. Therefore, the performance tests were completed using SGC compacted samples.

Figure 12

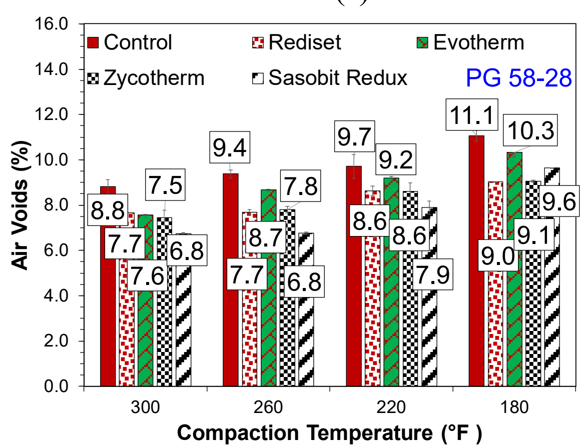
Bulk Specific Gravity (G_{mb}) and Air Void Results of WMA Modified with PG 58-28 Asphalt Mixtures



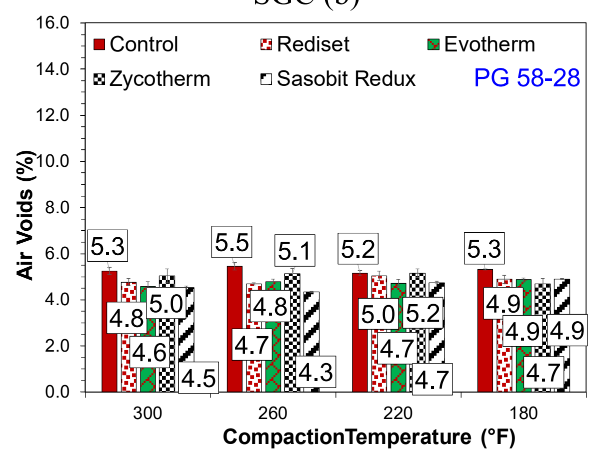
Marshall (a)



SGC (b)



Marshall (c)



SGC (d)

Impact of WMA-Modified Mixtures on Air Void

This study conducted two laboratory mix designs at lower-than-recommended compaction temperatures. The impact of binder grade, WMA type, and compaction temperature on air voids results is shown in **Figure 13**. As expected, lowering the compaction temperature from 300°F up to 180°F increased the air void of all asphalt mixtures. It can be seen that WMA showed more than a 0.2% reduction in air voids compared to the control mixtures for both binders modified with WMA, even at low compaction temperatures. WMA modified with PG 76-28 generally exhibited a higher air void than WMA modified with PG 58-28. Rediset-modified control mixtures had a higher reduction in compactability by more than 0.1% at all compaction temperatures. Regardless of the impact of binder grade, the asphalt mixture modified with Sasobit Redux showed the best compactable mixtures, providing the highest compactable mixture even as low as 180°F. It was observed that the air voids of PG 76-28 exceeded the air voids requirement for NHDOT (air voids between 3.0 to 5.5 %), whereas all WMA-modified mixtures satisfied the requirement. A 0.5 difference (5.8% to 5.3 %) in binder content was needed for PG 76-28 (more binder) to achieve the air voids range. **Figure 14** illustrates the air void versus the compaction temperatures at 5% constant air voids. From **Figure 14,** adding WMA significantly reduced the compaction temperature by approximately 15%, 19%, and 40% for Evotherm, Zycotherm, and Sasobit Redux, respectively. Overall, for PG 58-28 modified asphalt mixtures, the best compactable mixtures were Sasobit Redux, followed by Evotherm and Rediset, whereas, for PG 76-28 modified mixtures, Sasobit Redux, followed by Zycotherm and Evotherm were observed to have the higher compatibilities.

Figure 13

Impact of Binder Grade and Compaction Temperature on Air Void Results of WMAs Modified Mixtures

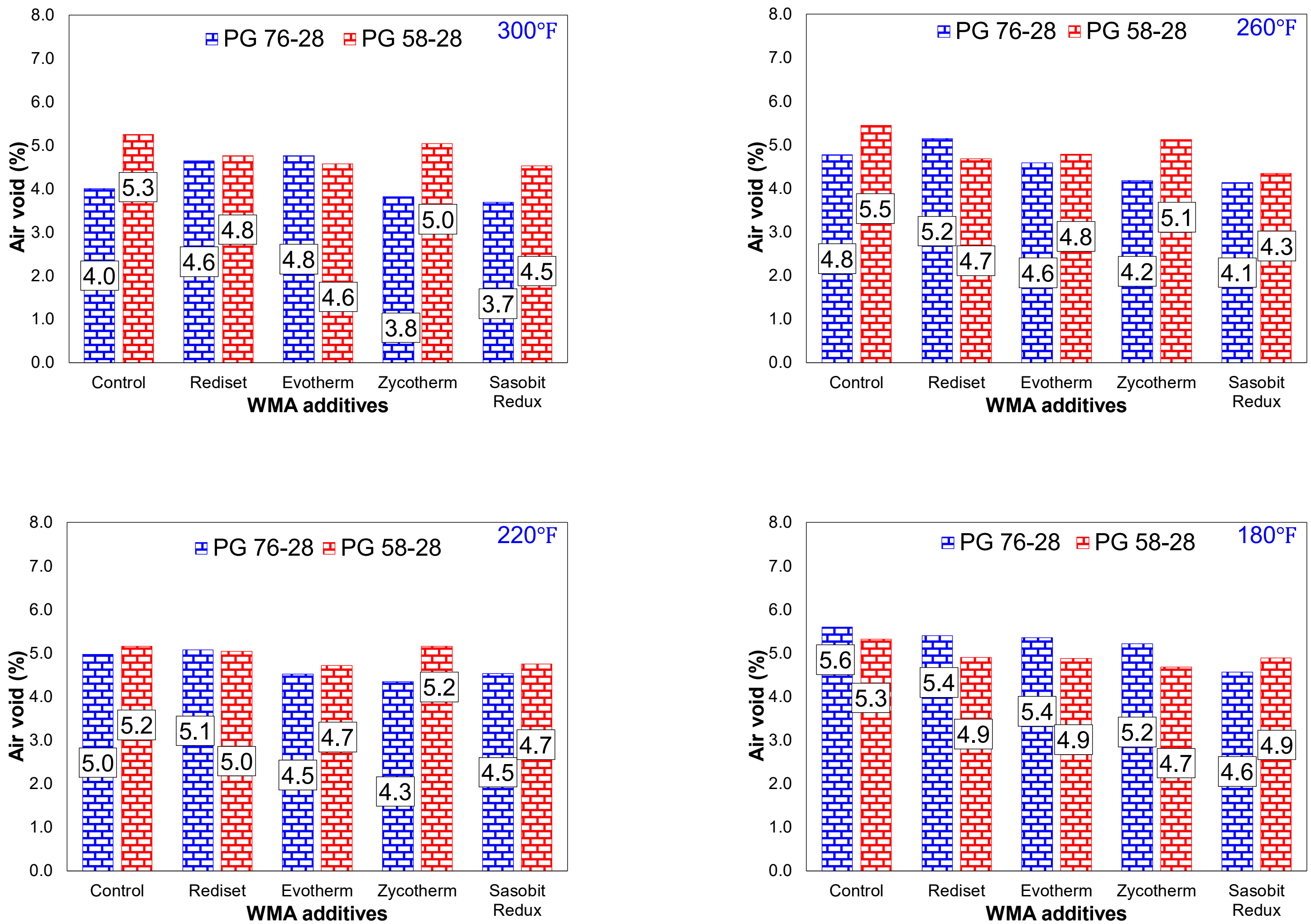
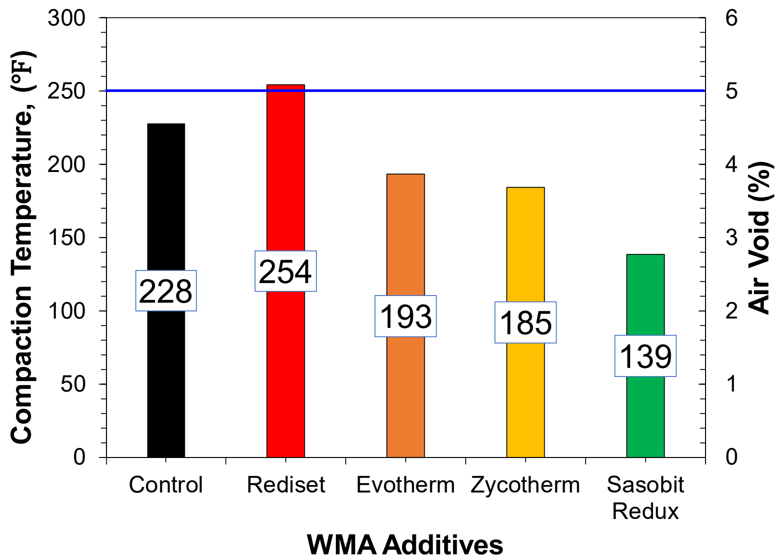


Figure 14

Impact of Compaction Temperature on PG 76-28 at a 5% Constant Air Void

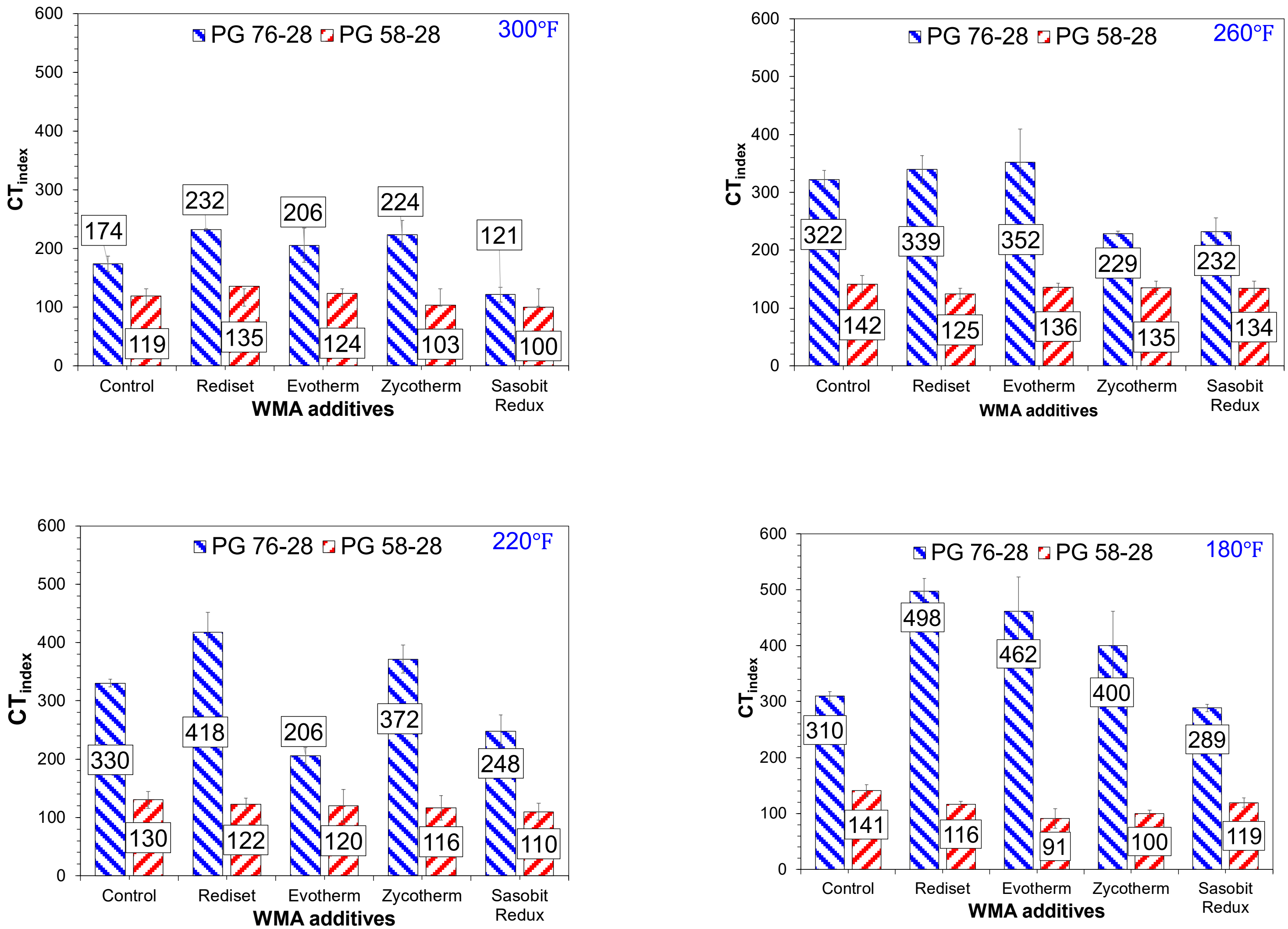


Impact of Binder Grade, WMA Type, and Compaction Temperature on Cracking Performance

Figure 15 presents the cracking performance results for controls and WMA-modified asphalt mixtures at different compaction temperatures. In this test, a representative of 3 samples for each mixture was prepared and compacted to 7%± 0.5%. As seen in **Figure 15** 300°F (149°C), only Rediset and Evotherm-modified asphalt mixtures with PG 58-28 had 12% and 4% improvement on the CT_{index}, respectively, compared to control. On the other hand, the improvement in cracking performance was observed at 25% and 16% for the same modified mixtures compared to PG 76-28. It was observed that at a compaction temperature of 260°F (127°C), Sasobit Redux and Zycotherm WMA-modified mixtures reduced the cracking resistance by more than 25% compared to PG 76-28, whereas the percent reduction in cracking resistance for the same mixtures was 5% compared to PG 58-28. From **Figure 15**, lowering the compaction temperature from 300°F (149°C) to 260°F (127°C), the crack resistance increased for PG 58-28 modified with WMA binders. The same mixtures showed lower cracking resistance at 220°F (104°C) to 180°F (82°C) compared to PG 58-28. These findings showed that organic-based (i.e., Sasobit Redux) negatively affected the cracking performance of mixtures when modified with PG 76-28. It is worth mentioning that the most remarkable improvement in CT_{index} values was noticed for PG 76-28 modified with chemical-based WMA by more than 20% compared to control at 180°F (82°C). The different behavior of WMA performance is in line with the ΔT_c obtained for both asphalt binders (see **Figure 7**). Overall, it must be emphasized that the IDEAL-CT test is insufficient to determine the cracking performance of asphalt mixtures due to the high variabilities. The change in CT_{index} between PG 76-28 and PG 58-28 is due to the PG 76-28 (stiff) will have higher resistance to deformation, whereas PG 58-28 (soft) will have lower deformation resistance (lower CT_{index}) compared to the stiff binder.

Figure 15

IDEAL-CT Results for WMA Modified Asphalt Mixtures



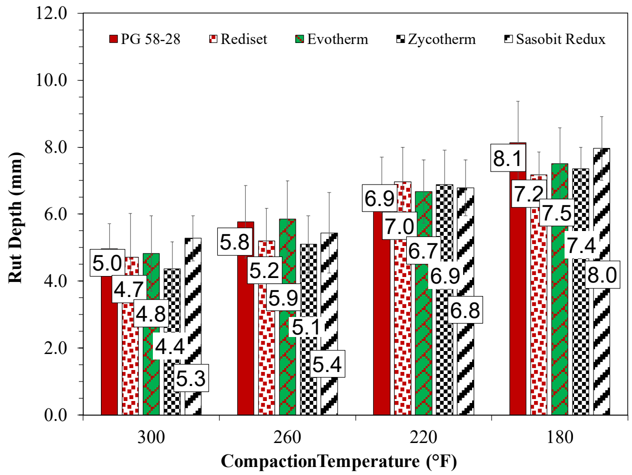
Effect of WMA Modified Asphalt Mixtures on Rutting Resistance

Figure 16 (a) presents the manual measurement of rut depth results. Decreasing compaction temperatures increased the rut depth for all asphalt mixtures. The satisfied rut depth value of (5 mm) for asphalt mixtures was considered (Gierhart 2019). It was observed from air void results (**Figure 13**) that as the air voids increased, the susceptibility of asphalt mixtures to rutting increased. For example, at 300°F (149°C), Zycotherm and Rediset PG 58-28 modified mixtures showed better resistance to rutting compared to control by 12% and 6%, respectively. In contrast, Evotherm and Sasobit Redux asphalt mixtures showed similar rut depth values at 4.8 mm and 5.3 mm compared to the PG 58-28. The highest rut depth values were observed at 180°F (82°C) for the PG 58-28 asphalt mixture, which showed a rut depth of 8.1 mm, followed by Sasobit Redux at 8.0 mm. At 260°F (127°C) and 220°F (104°C), rut depth values increased by 16%, 26%, 12%, 26%, and 21% for Control, Rediset, Evotherm, Zycotherm, and Sasobit Redux, respectively.

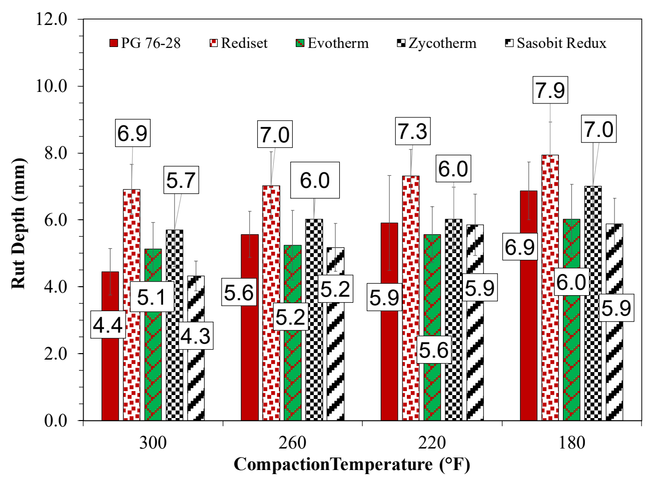
Figure 16 (b) illustrates the WMA modified with PG 76-28 manual rut depth values. It can be seen that PG 76-28 WMA modified mixtures showed higher rut depth values than the control at 300°F (149°C). As the compaction temperature decreased from 300°F to 260°F or (149°C to 127°C), Evotherm and Sasobit redux 76-28 asphalt mixtures reduced the rutting susceptibility by more than 5% and 5%, respectively. For the same temperature range, Rediset and Zycotherm reduced the rutting resistance by 20% and 7 %, respectively. At low compaction temperatures of 220°F -180°F (104°C-82°C), higher rut depth values were observed for all asphalt mixtures. Overall, incorporating WMA into asphalt binders improved the rutting resistance for asphalt mixtures at all compaction temperatures.

Figure 16

Manual APA Measurements Rut Depth: (a) PG 58-28 Mixes and (b) PG 76-28 Mixes



(a)



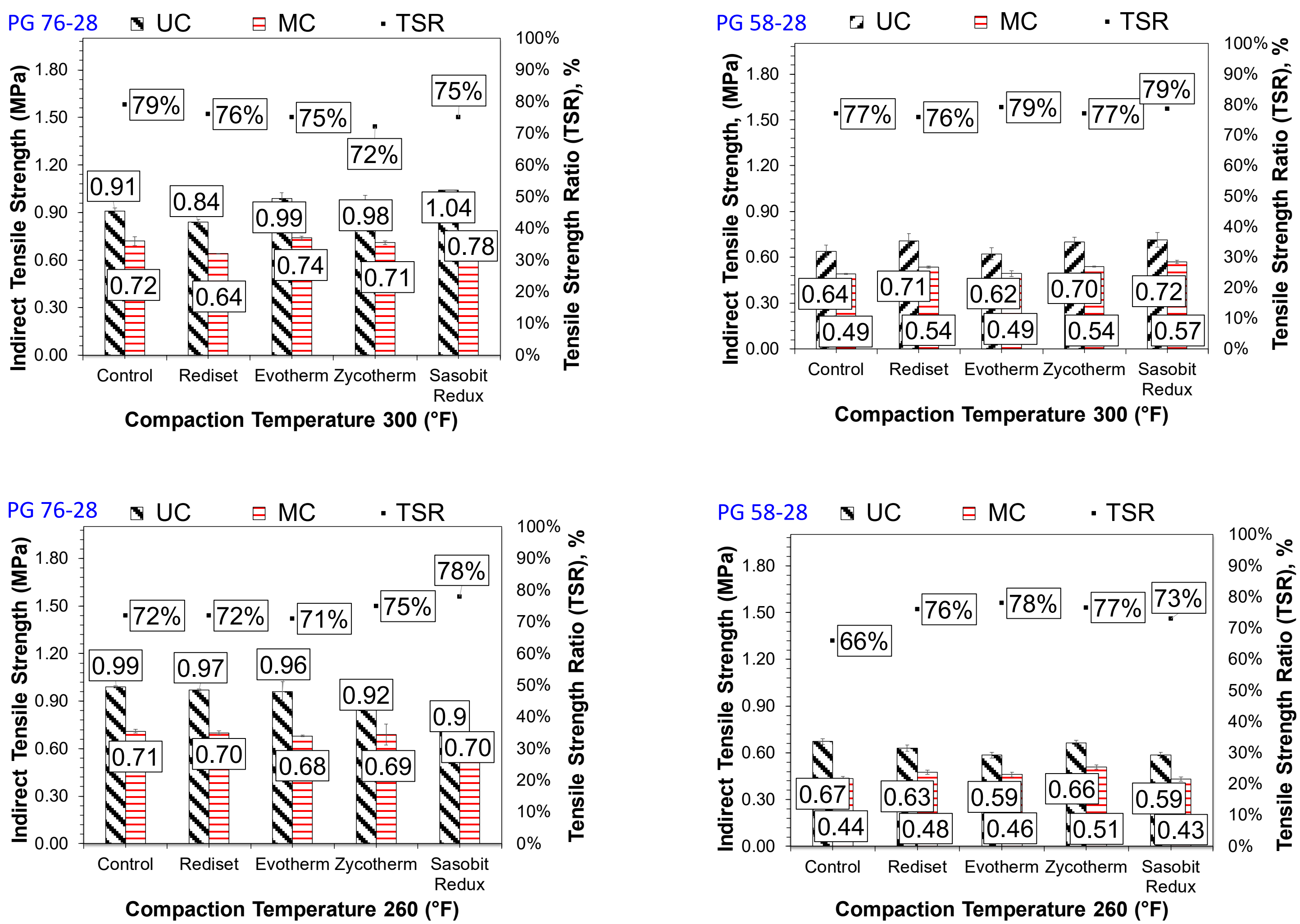
(b)

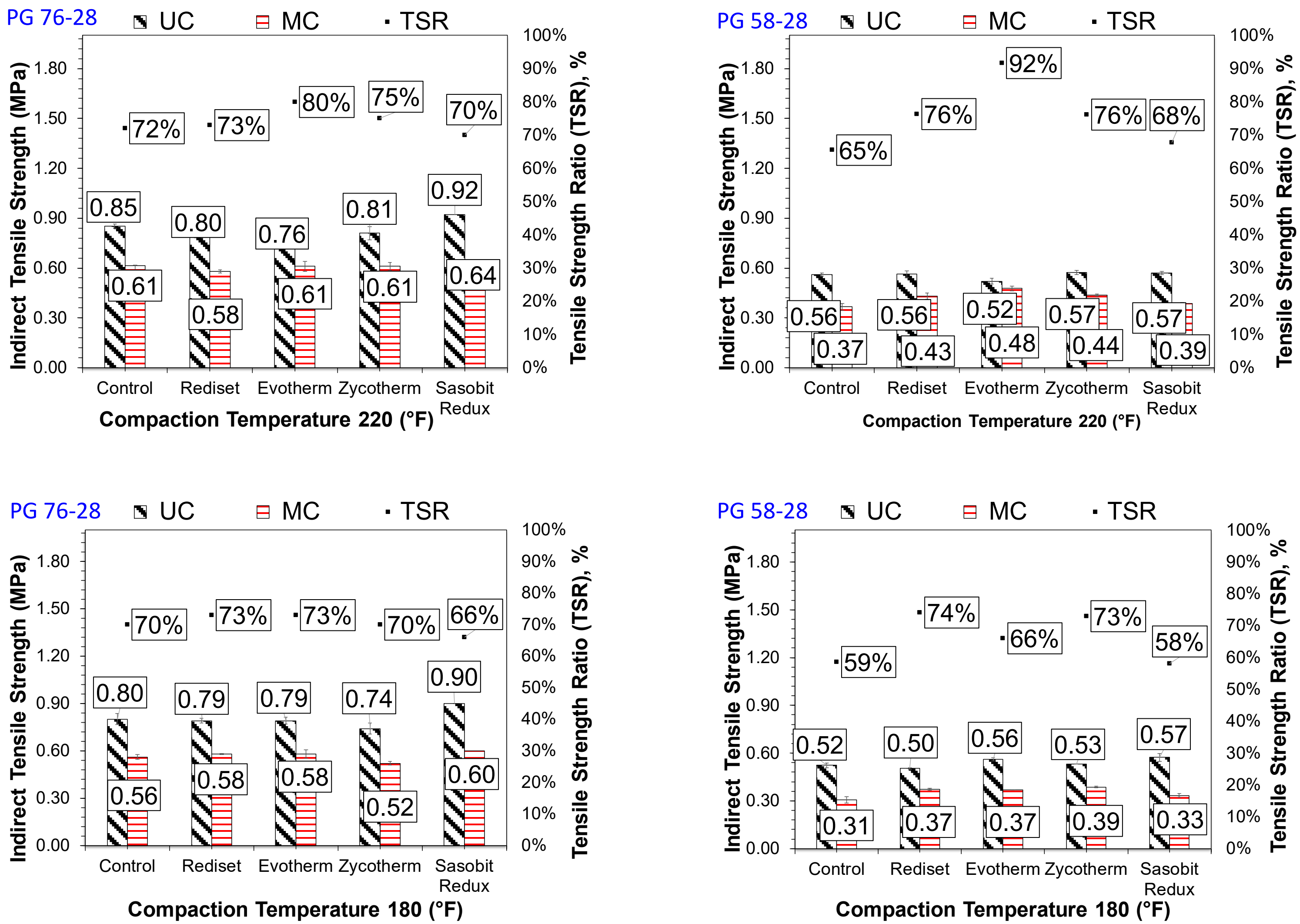
Effect of WMA Modified Asphalt Mixtures on Moisture Susceptibility

Figure 17 presents the results of the Tensile Strength ratio (TSR) for asphalt mixtures at four compaction temperatures. The chemical-WMA-modified mixtures improved the moisture resistance compared to control mixtures, whereas organic-based ones reduced the moisture susceptibility. For example, at 300°F (149°C) and 260°F (127°C), the WMA modified with PG 58-28 improved the moisture resistance more than the addition to PG 76-28 mixture. At 300°F, Sasobit Redux and Evotherm mixtures modified with PG 58-28 showed the highest TSR value of 79%. All asphalt mixtures at (300°F) satisfied the airfield asphalt paving requirement mentioned in the Unified Facilities Guide Specification (i.e., TSR value minimum 75% passing). Lowering the compaction temperature to 260°F dropped the TSR values for PG 58-28 (14%) and Sasobit Redux (8%) compared to 300°F. Rediset, Evotherm, and Zycotherm mixes showed similar TSR values at all compaction temperatures. WMA-modified mixtures had higher TSR values than PG 58-28. On the other hand, adding WMAs to PG 76-28 did not significantly improve the moisture resistance compared to PG 76-28. As the compaction temperature decreased from 300°F to 220°F, the TSR values were dropped for control (9%), Rediset (4%), and Sasobit (7%). It is worth mentioning that regardless of the binder type, the Evotherm had significantly improved moisture resistance at 220°F. This is most probably due to its chemical composition (100% fatty amine), which is the main structure of Evotherm, and the optimum compaction temperature recommended by manufacturers as a little over 220°F. These findings show that the addition of WMA did not significantly influence the moisture resistance of the control binders, even at low compaction temperatures.

Figure 17

Moisture Damage Results for All WMA modified Asphalt Mixtures




PG 76-28
UC
MC
TSR
Indirect Tensile Strength (MPa)
Tensile Strength Ratio (TSR), %
0.00
0.30
0.60
0.90
1.20
1.50
1.80
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
72%
73%
80%
75%
70%
0.85
0.80
0.76
0.81
0.92
0.61
0.58
0.61
0.61
0.64
Control
Rediset
Evotherm
Zycotherm
Sasobit Redux
Compaction Temperature 220 (°F)
PG 58-28
UC
MC
TSR
Indirect Tensile Strength (MPa)
Tensile Strength Ratio (TSR), %
65%
76%
92%
76%
68%
0.56
0.56
0.52
0.57
0.57
0.37
0.43
0.48
0.44
0.39
Control
Rediset
Evotherm
Zycotherm
Sasobit Redux
Compaction Temperature 220 (°F)
PG 76-28
UC
MC
TSR
Indirect Tensile Strength (MPa)
Tensile Strength Ratio (TSR), %
70%
73%
73%
70%
66%
0.80
0.79
0.79
0.74
0.90
0.56
0.58
0.58
0.52
0.60
Control
Rediset
Evotherm
Zycotherm
Sasobit Redux
Compaction Temperature 180 (°F)
PG 58-28
UC
MC
TSR
Indirect Tensile Strength (MPa)
Tensile Strength Ratio (TSR), %
59%
74%
66%
73%
58%
0.52
0.50
0.56
0.53
0.57
0.31
0.37
0.37
0.39
0.33
Control
Rediset
Evotherm
Zycotherm
Sasobit Redux
Compaction Temperature 180 (°F)

Chapter 6

Statistical Analysis

A multi-factor Analysis of Variance (ANOVA) was conducted to evaluate whether the performance of warm mix asphalt additives modified with PG 75-28 and PG 58-28 binders and the impact of testing compaction temperatures is statistically significant. This ANOVA analyzed the compactability of WMAs at all compaction temperatures and the sensitivity to tensile strength ratio, Asphalt Pavement Analyzer(APA), Indirect Tensile Strength (ITS), and crack tolerance index (CT_{index}) of all asphalt mixtures. The analysis was performed for each performance test separately; each test was analyzed to evaluate the statistical significance of modified WMA mixtures (i.e., Rediset, Evotherm, Zycotherm, and Sasobit Redux) compared to control and four different compaction temperatures (i.e., 300°F (149℃), 260°F (127℃), 220°F (104℃), and 180°F (82℃)) compared to 180°F (82℃). Finally, the ranking of both WMA additives compared to control binders and compaction temperatures compared to 180°F (82℃) were determined. Performance tests were ranked based on the mean difference provided by ANOVA analysis. The mean difference was considered the average value for each WMA additive at all compaction temperatures. The analysis of ANOVA was performed at a 95% confidence level, providing a p-value < 0.05, indicating a statistical significance among asphalt mixtures.

Table 5 presents the results of WMA among each other and as compared to PG 58-28 for compactability (air void) and performance tests (TSR, APA, ITS, and CT_{index}) at all compaction temperatures. As seen in **Table 5**, WMA-modified mixtures showed p-values less than 0.05, which means a significant impact among WMA additives. In particular, WMA significantly impacted all binder levels on compactability compared to other tests.

For the APA performance test, modified WMA mixtures showed a p-value > 0.05, indicating that the WMA additive had the same performance as the control.

Table 6 shows the ANOVA statistical analysis for compaction temperature results for PG 58-28 modified with WMA. Compaction temperatures showed a p-value <0.05, indicating that compaction temperature significantly impacted asphalt mixtures performance compared to 180°F.

Table 7 provides the ranking based on ANOVA analysis of additive performance. For the ranking of WMA, the mean difference of each WMA material was compared to the control and between the materials themselves. A similar ranking system was applied for temperature as well. The mean difference was considered for additive performance ranking by averaging the values obtained for all temperatures for each additive. Similarly, the mean difference was considered for temperature ranking by averaging the values obtained for all additives for each compaction temperature. It was seen that each WMA additive has its strengths and weaknesses at each performance test, while WMA additives showed similar rutting performance compared to the control.

Table 5

ANOVA Statistical Analysis Results for WMA Modified Asphalt Mixture with PG 58-28 for Laboratory Tests

		TSR		ITS		APA		CT_{index}		Compactability	
Reference Binder	Sample ID	Mean	p-val.	Mean	p-val.	Mean	p-val.	Mean	p-val.	Mean	p-val.
PG 58-28	Evotherm	-11.91*	**<.001**	0.038*	**<.003**	0.241	0.953	19.000*	**0.046**	0.533*	**<0.001**
	Rediset	-8.687*	**<.001**	0.036*	**<.004**	0.433	0.707	7.750	0.764	0.425*	**<0.001**
	Sasobit Redux	-2.657	0.276	0.011	0.749	0.066	1.000	17.083	0.09	0.658*	**<0.001**
	Zycotherm	-8.735*	**<.001**	0.0420*	**0.009**	0.391	0.777	19.000*	**0.046**	0.258*	**<0.001**
Evotherm	Rediset	3.223	0.123	-0.001	1.00	0.191	0.979	-11.250	0.440	-0.108*	**0.006**
	Sasobit Redux	9.253*	**<.001**	-0.026	0.064	-0.175	0.985	-1.916	0.998	0.125*	**0.001**
	Zycotherm	3.175	0.133	-0.004	0.993	0.150	0.992	0.000	1.000	-0.275*	**<0.001**
Rediset	Sasobit Redux	6.030*	**<.001**	-0.025	0.093	-0.366	0.816	9.333	0.620	0.233*	**<.001**
	Zycotherm	-0.048	1.00	-0.002	0.999	0.041	1.000	11.250	0.440	-0.166*	**<.001**
Sasobit Redux	Zycotherm	-6.078*	**<.001**	0.022*	0.159	0.325	0.872	1.916	0.998	-0.400*	**<.001**

*: The mean Difference is significant at the p-value < 0.05 level.

b: Adjustment for multiple comparisons: least significant difference (equivalent to no adjustment)

Table 6

ANOVA Statistical Analysis for Compaction Temperatures Performance Results For PG 58-28 and Modified WMA Asphalt Mixtures

		TSR		**ITS**		**APA**		**CT$_{index}$**		**Compactability**	
Reference Temp.	Compaction Temperature	Mean	p-val.	Mean	p-val.	Mean	p-val.	Mean	p-val.	Mean	p-val.
180 (°F)	220	-9.101*	**<.001**	-0.030*	**<.005**	0.793	0.058	-3.733	0.920	0.073*	**0.038**
	260	-7.542*	**<.001**	-0.071*	**<.001**	2.060*	**<.001**	-18.866*	**0.014**	-0.113*	**<.001**
	300	-11.150*	**<.001**	-0.148*	**<.001**	2.793*	**<.001**	3.266	0.945	0.086*	**0.010**
220 (°F)	260	1.558	0.553	0.040*	**<.001**	1.266*	**<.001**	-15.133	0.064	-0.186*	**<.001**
	300	-2.049	0.317	-0.117*	**<.001**	2.000*	**<.001**	7.000	0.637	0.013	0.957
260 (°F)	300	-3.608*	**0.020**	-0.076*	**<.001**	0.733	0.09	22.133*	**0.003**	0.200*	**<.001**

*: The mean Difference is significant at the p-value < 0.05 level.

b: Adjustment for multiple comparisons: least significant difference (equivalent to no adjustment)

Table 7

ANOVA Analysis Ranking for Additives Performance Based on Mean Difference for PG 58-28 and WMA Modified Asphalt Mixtures.

		TSR%		**ITS**		**APA**		**CT$_{index}$**		**Compactability**	
Reference Binder	Sample ID	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
Control	Evotherm	-11.910*	1	0.038*	2	0.241	N/A	19.000*	1	0.533*	2
	Rediset	-8.687*	3	0.036*	3	0.433	N/A	7.750	3	0.425*	3
	Sasobit Redux	-2.657	4	0.011	4	0.066	N/A	17.083	2	0.658*	1
	Zycotherm	-8.735*	2	0.042*	1	0.391	N/A	19.000*	1	0.258*	4

Note. N/A means a ranking was not done due to insignificance performance.

Overall, the statistical analyses showed that a range of temperatures (i.e., 260°F–220°F) is suitable for compacting WMA-modified asphalt mixtures with PG 58-28 and a range of (300°F-260°F) for PG 76-28 modified WMA mixtures. Overall, WMA additives and compaction temperatures were shown to have a statistically significant impact with a p-value less than 0.05 on asphalt pavement performance. In the rutting performance test, it was seen that WMA modified with PG 58-28 are not statistically significant to each other, while compaction temperature did play a significant role. On the other hand, WMA modified with PG 76-28 showed the opposite trend for rutting resistance in which compaction temperature did not play a significant role, whereas WMA additives were statistically significant to each other.

Table 8 presents the ANOVA ranking statistical analysis for compaction temperature performance based on the mean difference for asphalt mixtures. As seen in Overall, the statistical analyses showed that a range of temperatures (i.e., 260°F–220°F) is suitable for compacting WMA-modified asphalt mixtures with PG 58-28 and a range of (300°F-260°F) for PG 76-28 modified WMA mixtures. Overall, WMA additives and compaction temperatures were shown to have a statistically significant impact with a p-value less than 0.05 on asphalt pavement performance. In the rutting performance test, it was seen that WMA modified with PG 58-28 are not statistically significant to each other, while compaction temperature did play a significant role. On the other hand, WMA modified with PG 76-28 showed the opposite trend for rutting resistance in which compaction temperature did not play a significant role, whereas WMA additives were statistically significant to each other.

Table 8, lowering the compaction temperatures statistically impacted asphalt mixture performance (i.e., p-value <0.05).

Table *9* presents the results of WMA among each other and as compared to PG 76-28 for compactability (air void) and performance tests (TSR, APA, ITS, and CT_{index}) at all compaction temperatures. As seen in **Table *9***, WMA-modified mixtures showed p-values less than 0.05, which means a significant impact among WMA additives. In particular, WMA significantly impacted all binder levels on compactability compared to other tests. For the APA and moisture damage performance tests, modified WMA mixtures showed a p-value > 0.05, indicating that the WMA additive had the same performance as the control.

Table 10 shows the ANOVA statistical analysis for compaction temperature performance results for PG 76-28 and modified WMA asphalt mixtures. Compaction temperatures showed a p-value <0.05, indicating that compaction temperature significantly impacted asphalt mixtures performance compared to 180°F.

Table 11 and Table 12 provides the ranking based on ANOVA analysis of additive performance and compaction temperatures . The exact process was followed for ranking PG 76-28 modified with WMA as PG 58-28 mixtures. Similarly, the mean difference was considered for additives and compaction temperatures. It was seen that each WMA additive has its strengths and weaknesses at each performance test. As seen in **Table 12,** lowering the compaction temperatures statistically impacted asphalt mixture performance.

Overall, the statistical analyses showed that a range of temperatures (i.e., 260°F–220°F) is suitable for compacting WMA-modified asphalt mixtures with PG 58-28 and a range of (300°F-260°F) for PG 76-28 modified WMA mixtures. Overall, WMA additives and compaction temperatures were shown to have a statistically significant impact with a p-value less than 0.05 on asphalt pavement performance. In the rutting performance test, it was seen that WMA modified with PG 58-28 are not statistically significant to each other, while compaction temperature did play a significant role. On the other hand, WMA modified with PG 76-28 showed the opposite trend for rutting resistance in which compaction temperature did not play a significant role, whereas WMA additives were statistically significant to each other.

Table 8

ANOVA Analysis Ranking for Compaction Temperatures Based on Mean Difference for PG 58-28 Modified Asphalt Mixtures

		TSR%		ITS		APA		CT_{index}		Compactability	
Reference Temperature (°F)	Compaction Temperature	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
180	220	-9.101*	2	-0.030*	3	0.793	3	-3.733	2	0.073*	3
	260	-7.542*	3	-0.071*	2	2.060*	2	-18.866*	1	-0.113*	1
	300	-11.150*	1	-0.148*	1	2.793*	1	3.266	3	0.086*	2

Table 9

ANOVA Statistical Analysis Results for Performance and Compactability of PG 76-28 Modified with WMA Asphalt Mixtures

		TSR		ITS		APA		CT_{index}		Compactability	
Reference Binder	Sample ID	Mean	p-val.	Mean	p-val.	Mean	p-val.	Mean	p-val.	Mean	p-val.
Control	Evotherm	-4.851	0.097	0.044*	**0.033**	0.250	0.955	-77.583*	**0.006**	0.025	0.987
	Rediset	-1.154	0.973	0.040	0.058	-1.375*	**0.004**	-87.500*	**0.001**	-0.216*	**<0.001**
	Sasobit Redux	-0.599	0.998	-0.011	0.929	0.466	0.688	61.500*	**0.043**	0.700*	**<0.001**
	Zycotherm	-2.437	0.700	0.043*	**0.038**	-0.400	0.794	-21.833	0.837	0.400*	**<0.001**
Evotherm	Rediset	3.697	0.307	-0.003	0.999	-1.0625*	**<0.001**	-9.916	0.990	-0.241*	**<0.001**
	Sasobit Redux	4.252	0.184	-0.055*	**0.004**	0.216	0.973	139.083*	**<0.001**	0.675*	**<0.001**
	Zycotherm	2.414	0.707	-0.000	1.000	-0.650	0.376	55.750	0.080	0.375*	**<0.001**
Rediset	Sasobit Redux	0.555	0.998	-0.052*	**0.007**	1.841*	**<.001**	149.000*	**<.001**	0.916*	**<.001**
	Zycotherm	-1.283	0.960	-0.002	1.000	0.975	0.067	65.666*	0.026	0.616*	**<.001**
Sasobit Redux	Zycotherm	-1.838	0.866	0.055*	**0.005**	-0.866	0.128	-83.333	0.003	-0.300*	**<.001**

Table 10

ANOVA Statistical Analysis for Compaction Temperatures Performance Results For PG 76-28 and Modified WMA Asphalt Mixtures

		TSR		ITS		APA		CT_{index}		Compactability	
Reference Temperature (°F)	Compaction Temperature	Mean	p-val.	Mean	p-val.	Mean	p-val.	Mean	p-val.	Mean	p-val.
180	220	-2.326	0.523	-0.019	0.459	0.300	0.784	32.666	0.320	0.473*	**<.001**
	260	-2.349	0.514	-0.077*	**<.001**	0.180	0.942	96.866*	**<.001**	0.746*	**<.001**
	300	-4.818*	**0.034**	-0.126*	**<.001**	0.533	0.352	200.133*	**<.001**	1.153*	**<.001**
220	260	-0.023	1.000	0.058*	**<.001**	-0.120	0.982	64.200*	**0.008**	0.273*	**<.001**
	300	-2.492	0.463	-0.106*	**<.001**	0.233	0.884	167.466*	**<.001**	0.680*	**<.001**
260	300	-2.468	0.472	-0.048*	**0.003**	0.353	0.687	103.266*	**<.001**	0.406*	**<.001**

*: The mean Difference is significant at the p-value < 0.05 level.
b: Adjustment for multiple comparisons: least significant difference (equivalent to no adjustment)

Table 11

ANOVA Analysis Ranking for Additive Performance Based on Mean Difference for PG 76-28 and WMA Modified Asphalt Mixtures

		TSR%		**ITS**		**APA**		**CT$_{index}$**		**Compactability**	
Reference Binder	Sample ID	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
Control	Evotherm	-4.8517	1	0.0442*	1	0.2500	4	-77.5833*	1	0.0250	4
	Rediset	-1.1542	3	0.0408	3	-1.3750*	1	-87.5000*	2	-0.2167*	3
	Sasobit Redux	-0.5992	4	-0.0117	4	0.4667	2	61.5000*	3	0.7000*	1
	Zycotherm	-2.4375	2	0.0433*	2	-0.4000	3	-21.8333	4	0.4000*	2

Note. N/A means a ranking was not done due to insignificance performance.

Table 12

ANOVA Analysis Ranking for Compaction Temperatures for PG 76-28 and Modified WMA Asphalt Mixtures

		TSR%		ITS		APA		CT$_{index}$		Compactability	
Reference Temperature (°F)	Compaction Temperature	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
180	220	-2.326	3	-0.019	3	0.300	2	32.666	3	0.473*	3
	260	-2.349	2	-0.077*	2	0.180	3	96.866*	2	0.746*	2
	300	-4.818*	1	-0.126*	1	0.533	1	200.133*	1	1.153*	1

Chapter 7

Summary, Conclusions, and Recommendations

Summary

This study evaluated the effect of various warm mix additives (WMA) and two control binders on the laboratory performance of asphalt binders and mixtures. Four different WMA (Rediset, Evotherm, Zycotherm, Sasobit Redux) were selected with dosage rates of 0.5%, 0.7%, 0.1%, and 2%, respectively, by binder weight, as recommended by the manufacturer. Four compaction temperatures (300°F (149°C), 260°F (127°C), 220°F (104°C), and 180°F (82°C) were considered to evaluate the mix design and performance of asphalt mixtures. The evaluation process involved preparing two control mixes, PG 58-28 (un-modified) and PG 76-28 (modified), and four WMAs-modified asphalt mixtures. The binder content used for PG 58-28 was 5.3%, whereas, for PG 76-28, it was 5.8% (by total weight of the mixtures). Three performance tests were performed, including rutting, cracking, and moisture susceptibility. Finally, all asphalt mixtures were analyzed using the ANOVA statistical procedure to determine if there were significant differences in performance between the WMA mixes and the control (HMA) mixes.

This study also investigated the change in the rheological properties due to adding WMA to control asphalt binders. The WMA-modified binders undergo different oxidative conditioning, including RTFO-aged, PAV20, and PAV40. Performance Grade was conducted on each binder to assess the influence of the WMA on both high and low-performance grades. BBR test was performed to evaluate the influence of aging level and WMA on low-temperature performance based on the ΔTc parameter. The cracking temperature and fatigue life performance of WMA-modified binders were investigated using the ABCD and LAS tests, respectively. The low-performance grade of asphalt binders was compared using ABCD and BBR tests. Finally, the change in chemical indices of asphalt binders was also evaluated using the FTIR test at different aging levels.

Conclusion

Based on the findings from the laboratory experimental plan, the following set of findings were drawn:

WMA-Modified Binders

- WMA modified with PG 76-28 reduced the high-temperature PG by at least one grade (6°C) compared to un-modified binders. In particular, Rediset and Evotherm (chemical-based additives) degraded the high PG by two grades 12°C (from 82°C to 70°C) compared to control. Regarding the PG 76-28 low PG, only the Sasobit Redux pumped the low PG from (-28°C) to (-22°C) compared to the control at the PAV 40 aging level.
- For PG 58-28, no change was observed in high (58°C) and low (-28°C) PG due to the addition of WMA. These changes in high PG indicate that WMA can reduce the rutting resistance of modified asphalt binders.
- ΔT_c values for chemical-based modified with PG 76-28 asphalt binder were observed to increase compared to organic-based. The percentages increase in ΔT_c for Rediset, Evotherm, and Zycotherm modified with PG 76-28 were as follows: 5%, 83%, and 63%, respectively, in comparison to control, whereas

ΔT_c was significantly decreased for all WMA-modified with PG 58-28 by approximately 95% compared to control.

- ΔT_c was used to justify the change in chemical composition (sulphoxide index) caused by aging and relates to the performance of the asphalt binders. As such, it can be concluded that adding chemical/organic-based WMA additives for un-modified asphalt binders can degrade the low-temperature cracking resistance at PAV20 and PAV40. In contrast, modifying WMA with modified asphalt binder can enhance the low-cracking temperature except for organic-based WMA at the PAV20 aging level.
- BBR testing at -18°C and -24°C showed that using organic-based WMA for both binders can increase the low-temperature cracking as the stress relaxation was observed to be lowered by 5%. However, adding chemical-based WMA showed higher stress relaxation capability by approximately 6% for both binders. These findings showed that adding WMA did not significantly influence the low-cracking temperature of asphalt binders.
- ABCD test results demonstrated that the percent reduction in low-cracking temperature was less than 10% for WMA modified with PG 58-28. However, adding WMA to PG 76-28 increased the cracking temperature by the same percentage. Regardless of binder grade, this finding shows that adding WMA did not significantly change the low-cracking temperature of control binders.
- The comparison of low PG between ABCD and BBR tests showed that with the addition of WMA to PG 76-28, identical low PG (-28°C) was observed for both tests. The difference in low PG between the tests for WMA modified with PG

58-28 was approximately one interval (6°C), thus showing that the measured reduction in strength or fracture toughness characteristics or the measured low PG between tests can significantly impact the low-temperature cracking of un-modified binders.

- The fatigue life performance was improved for WMA modified with PG 58-28 than for PG 76-28. Fatigue life at a 2.5% strain level for WMA modified with PG 58-28 was approximately 170%, 133%, and 137% higher than the control for Evotherm, Zycotherm, and Sasobit Redux compared to control. The percent reduction in fatigue life was more than 20% for all WMA modified with PG 76-28 compared to control. This observation suggests that adding WMA to different binder grades can significantly influence the asphalt binders fatigue life performance (cracking resistance).
- The impact of aging on WMA was assessed using carbonyl and sulfoxide aging indices obtained from FTIR analyses. Adding WMA to PG 58-28 reduced the sulphoxide index by more than 20% compared to control at un-aged and RTFO levels. On the other hand, the sulphoxide values for WMA modified with PG 76-28 significantly increased by more than 93% at the PAV20 aging level compared to the control. The findings from FTIR testing demonstrated that WMA is more susceptible to age at the PAV40 aging level than the control binder.
- Overall, the comprehensive binder test results showed different binder properties behaviors due to adding warm mix additives to different binder grades at different aging levels.

WMA-Modified Mixtures

- Air voids measured at 260°F for Sasobit Redux, Rediset, and Zycotherm modified with PG 58-28 had higher compactability using Marshall compactor with a reduction in air voids by 28%, 18% and 17%, respectively, compared to control. In contrast, G_{mb} measured for the same modified mixtures had higher density using the Marshall compactor, increasing G_{mb} by 2%, 1%, and 1% compared to the control. Overall, the Marshall compacted specimens reflected the impact of different types of WMA, whereas the SGC compacted samples did not reflect.
- The impact of binder grade (i.e., PG 76-28 and PG 58-28) on WMA modified with PG 58-28 showed higher compactability with a reduction in air void by more than 15%, whereas the improvement in the compactability was noted as 5% for WMA modified with PG 76-28. This finding shows that regardless of binder grade, WMA helps to compact better even at low compaction temperatures.
- The cracking resistance (Ct_{index}) results at all compaction temperatures were higher by more than 5% for all WMA modified with PG 76-28 compared to PG 58-28. Adding WMA to PG 58-28 reduced the cracking resistance by 10%. ΔT_c had a strong relationship with the change in asphalt mixture performance (CT_{index}) and was directly related to the performance of asphalt mixtures. It can be concluded that higher resistance to cracking was observed with PG 76-28 than with PG 58-28 modified WMA mixes.
- The Tensile Strength Ratio (TSR) results for the Rediset, Evotherm, and Zycotherm were found to be higher (by approximately 10%) than the PG 58-28 mixtures at 260°F (126°C), 220°F (104°C), and 180°F (82°C). TSR values were dropped by at

least 5% for WMA modified with PG 76-28 when lowering the compaction temperatures from 300°F (149°C) to 220°F (104°C). This finding suggests that chemical-based WMA modified both binders at a temperature as low as 220°F (104°C) provide approximately the same (less than 5%) moisture-induced performance compared to conventional HMA mixes at 300°F (149°C), whereas organic did not.

- The APA results for WMA modified with PG 58-28 compacted at 300°F (149°C), 260°F (126°C), and 220°F (104°C) showed a reduction in rutting by around 28%, 33%, 28%, 36%, and 22% for PG 58-28, Rediset, Evotherm, Zycotherm, and Sasobit Redux).
- Based on ANOVA analysis, it can be said that WMA did not significantly impact the rutting resistance of asphalt mixtures compared to the PG 58-28. On the other hand, for PG 76-28 modified mixes, the rutting resistance was significant.
- ANOVA analysis evaluated the significance of WMA modified with PG 58-28, PG 76-28, and compaction temperatures on compactability and mixture performance. WMA mixtures showed p-values less than 0.05, which means a significant impact among WMA additives and compaction temperatures. For the rut depth performance test, modified WMA mixtures with PG 58-28 showed a p-value > 0.05, indicating that the WMA additive had the same performance as the control.
- The ANOVA statistical analysis was also conducted on PG 76-28 WMA modified mixes. It was found that WMA mixtures showed p-values less than 0.05, which means a significant impact among WMA additives and compaction temperatures. The moisture and rut depth resistance for WMA modified with PG 76-28 showed a

p-value > 0.05, indicating that the WMA additive had the same performance as the control.

- Overall, the comprehensive mixture test results showed different mix properties behaviors at low compaction temperatures by adding warm mix additives to different binder grades.

Future Recommendations

Based on the conclusion of this study, the following recommendations were drawn:

Future Recommendations for Industry/Government Agencies

This study evaluated only two types of binder grades from one source and one source of aggregate, along with 4 WMA additives. Based on this laboratory-limited study, some future recommendations were drawn:

- **WMAs Type & Rheological properties:** Evaluate the laboratory cracking performance (CT_{index}) of WMA-modified asphalt binders with a different type of WMA (Rediset, Evotherm, Zycotherm, Sasobit Redux, etc.) by using ΔT_c to evaluate their low-temperature cracking behavior.
- **WMAs Type & Low-Cracking Temperature:** Identify the impact of WMA on the low cracking temperature of un-modified asphalt binders, considering the ABCD test to correlate with CT_{index}.
- **Different Compaction Methods:** The impact of adding WMA to an un-modified asphalt binder was seen when using a Marshall compactor rather than SGC. Hence, it is recommended to use the Marshall compactor method for the laboratory evaluation of the compactability (density) of un-modified asphalt binders.

- **Mix Design and WMA types:** All WMA-modified mixtures significantly improved the compactability of mixes even as low as 180°F (82°C). In particular, WMA additives (Sasobit Redux, Evotherm) can be used to achieve the highest compactable mixtures.
- **WMAs Type & Moisture damage**: Compacting WMA mixtures at a temperature as low as 220°F (104°C) provides the same moisture-induced performance compared to conventional HMA mixes at 300°F (149°C).
- **Compaction Temperature:** The range of temperatures (i.e., 220°F (104°C) – 260°F (127°C)) is suitable for compacting WMA-modified with PG 58-28. For WMA modified with PG 76-28, a range of (300°F (149°C)- 260°F (127°C)) is applicable. Although each drop in the temperature range affected the performance, this specific range is suggested because it has the lowest impact on mix design and mixtures performance.

Future Recommendations for Researchers

- ❖ Using Marshall compactor to evaluate the mix design at the optimum binder content and the potential impact on mixture performance.
- ❖ Consider the long-term effect of WMA on asphalt mixtures by considering different oxidation (long-term aging and extended long-term aging) and compare it to similar compaction levels in the airfield.

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