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16. Abstract

Developing recommendations to enhance the aging resistance of hot mix asphalt (HMA) pavement layers is essential due to the complex aging process that affects their physical and chemical properties over time. This study investigated the impact of long-term aging on HMA mechanical characteristics, such as cracking resistance, rheological performance, and chemical characteristics of associated binders. Binders were extracted and recovered from laboratory-aged HMA specimens previously prepared under a study at the University of Texas at El Paso (UTEP). These specimens included varying proportions of reclaimed asphalt pavement (RAP), binder contents, aggregate gradations, and additive dosages. While the previous work extensively recorded the cracking performance of these specimens using the Overlay Tester, no rheological and chemical testing was conducted on the recovered binders. This research filled the gap by determining the rheological and chemical properties of the recovered binders and analyzing how aging influences binder performance as a function of mixed variables. The outcomes of this study will support the development of optimized mix designs with enhanced aging resistance. Recommendations are provided for improving mix design criteria, enabling the construction of pavements with extended lifespans and superior performance under aging conditions.

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INVESTIGATION OF HOT MIX ASPHALT AGING EFFECT ON MECHANICAL PROPERTIES OF MIXES BASED ON THEIR BINDER PERFORMANCE RESULTS

FINAL REPORT
SPTC Project Number: CY1-UTEP-02

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List of Abbreviations and Acronyms

23 CFR 420 .... Code of Federal Regulations, Title 23, Part 420
AASHTO .... American Association of State Highway and Transportation Officials
AC .... Asphalt Content
CDD .... Cumulative Degree Days
CPR .... Crack Progression Rate
CTIS .... Center for Transportation Infrastructure Systems
DOT .... Department of Transportation
DSR .... Dynamic Shear Rheometer
FTIR .... Fourier Transform Infrared Spectroscopy
E* .... Dynamic Modulus
EPCC .... El Paso Community College
FHWA .... Federal Highway Administration
G* .... Complex Modulus
G-R .... Glover-Rowe
Grad .... Gradation
HMA .... Hot Mix Asphalt
HWTT .... Hamburg Wheel Tracking Test
LTPP .... Long-Term Pavement Performance
NAPA .... National Asphalt Pavement Association
NMAS .... Nominal Maximum Aggregate Size
NTL .... National Transportation Library
PG .... Performance Grade
OT .... Overlay Test
RAP .... Reclaimed Asphalt Pavement
RAS .... Reclaimed Asphalt Shingles
ROSA P .... Repository & Open Science Access Portal
r-HDPE .... Recycled High-Density Polyethylene
SPS .... Specific Pavement Studies
SPS-5 .... Specific Pavement Studies Category 5
TCE .... Trichloroethylene
TxDOT .... Texas Department of Transportation
UTC .... University Transportation Center
UTEP .... The University of Texas at El Paso
WMA .... Warm Mix Asphalt
δ .... Phase Angle

Executive Summary

This research investigated the impact of oxidative aging on the mechanical performance of hot mix asphalt (HMA) and proposed optimized long-term laboratory aging protocols. The study involved evaluating asphalt mixtures and binders under varying aging conditions using advanced techniques, including rheological and chemical characterizations.

Mixtures with varying reclaimed asphalt pavement (RAP) contents, asphalt content, aggregate gradations, and rejuvenator additive were examined. The findings revealed that aging significantly increases stiffness and reduces fatigue resistance. Furthermore, fatigue life and cracking resistance showed consistent degradation trends with prolonged aging, confirming the need for revised aging guidelines for mixture design.

This study provides a framework to correlate aged binder properties with mixture performance, offering valuable insights for the optimal design of asphalt pavements. The proposed methods can help practitioners improve the longevity and reliability of pavements by integrating aging effects into mechanistic-empirical models.

Chapter 1. Introduction

Problem Statement

Aging is a paramount concern that has a detrimental impact on the performance of asphalt pavements. Oxidative aging is mostly caused by the gradual deterioration of the material properties of the asphalt binder due to exposure to temperature, UV light, and air oxygen. Asphalt undergoes a loss of flexibility and stress relaxation capacity as it ages, leading to the development of different forms of pavement cracking, such as block cracking, thermal transverse cracking, and fatigue cracking. Furthermore, these problems ultimately undermine the structural soundness of asphalt pavements, resulting in early failures and higher maintenance expenses. Despite the extensive use of short-term and long-term aging procedures in laboratory settings, these approaches may not completely reproduce the intricacies of real-life aging conditions, which include complex interactions among asphalt binder, aggregates, and environmental variables. An urgent requirement exists to enhance laboratory aging techniques and gain a more thorough knowledge of how various mixture factors, including binder content, aggregate gradation, additive content, and the inclusion of reclaimed asphalt pavement (RAP), impact the aging process and fatigue performance of asphalt mixtures.

Objectives and Scope of Work

The main objective of this work is to comprehensively examine the impact of prolonged aging on the fatigue cracking characteristics of asphalt mixes and the properties of the recovered asphalt binder. This study aims to investigate the influence of different essential mixture elements, such as binder content, aggregate gradation, additive content, and RAP content, on the fatigue resistance and longevity of asphalt pavements. The study primarily investigates the impact of including RAP, a method that repurposes used materials, on the fatigue performance of the combination. This research also analyzes how varying amounts of RAP affect long-term aging. Furthermore, the study assesses the impact of binder content on improving or reducing fatigue resistance, aiming to determine the ideal equilibrium between flexibility and total pavement durability. Lastly, the study examines how various aggregate gradations, and the application of additives might alleviate the negative impacts of aging and improve the durability of asphalt pavements. The results of this study offer valuable perspectives and pragmatic recommendations for developing and maintaining asphalt mixtures that are more resilient. Ultimately, the findings will lead to prolonged lifespans on pavements.

By developing a thorough evaluation of the aging behavior of hot mix asphalt (HMA), this work contributes to the progress of asphalt technology. The acquisition of knowledge from this research will enable stakeholders, such as government agencies, contractors, and engineers, to make well-informed decisions regarding road design, maintenance, and rehabilitation. Enhancing the durability and longevity of asphalt pavements can guarantee safer and more seamless travel for the public, decrease the need for frequent road repairs, and mitigate the overall adverse conditions' consequences of highway infrastructure. The primary objective of this research project is to establish a higher benchmark for optimal road-building methods, therefore helping to develop a lasting heritage of effective transportation systems for future generations.

Chapter 2. Literature Review

This section presents a concise overview of the literature pertaining to several aspects of the aging of asphalt materials. Given the complexity of this topic, the literature review is divided into three sections. First, a literature study on the effects of RAP content on asphalt aging and crack performance is reported. Secondly, the effects of gradation on asphalt aging and crack performance are synthesized. Lastly, the impact of additive content on asphalt aging and crack performance is summarized.

Effect of RAP Content on the Fatigue Cracking Performance of Asphalt Mixes and Recovered Asphalt Binder

Since the 1970s, adding RAP to mixes has become more common due to rising oil prices and the desire to minimize virgin aggregates and asphalt binders in pavement construction. According to the National Asphalt Pavement Association (NAPA), over 76.2 million tons of RAP were utilized in the U.S. during the 2017 construction season, saving over 72 million tons of virgin aggregate and more than 3.8 million tons of asphalt binder (Williams et al., 2024).

Laboratory studies have indicated that blending between RAP and virgin binder influences high RAP content mixture performance. Mogawer et al. (2012) used plant-produced mixtures with varying RAP percentages to document their construction parameters, measure their dynamic moduli, predict their binder properties, and examine the influence of production parameters on their blending and performance. From low-temperature cracking characteristics, they concluded that higher RAP content could reduce resistance to low-temperature cracking, but a softer virgin binder can improve resistance. Dynamic modulus testing indicated increased stiffness with higher RAP contents, and reheating mixtures in the laboratory showed less sensitivity to the mixture modulus changing in higher RAP content mixtures. A decreased rutting potential in mixtures with higher RAP was documented from tests using the Hamburg wheel tracking test (HWTT). Workability testing showed minimal effects of RAP content, with improved workability when using softer virgin binders.

Cao et al. (2018) evaluated the crack resistance of asphalt mixtures containing up to 40% RAP at intermediate temperatures. Their study comprised seven plant-produced hot-mix asphalt mixtures. The mixtures with higher RAP content exhibit increased stiffness and indirect tensile strength but lower compliance, indicating the impact of RAP content on the mechanical properties of asphalt mixtures. The research emphasizes the detrimental effects of incorporating more RAP on the crack resistance of asphalt mixtures.

Mogawer et al. (2015) evaluated the impact of aging and rejuvenators on high RAP mixtures' fatigue cracking characteristics using advanced mechanistic models and testing methods. The study offered a new approach to understanding the behavior of these mixtures. They indicated that the long-term aging considered in their study did not substantially impact the fatigue characteristics of the high RAP mixture, regardless of the presence of rejuvenators.

Hong et al. (2010) compared the long-term performance of HMA with high RAP content and with HMA using virgin materials from FHWA's Long-Term Pavement Performance (LTPP) Specific Pavement Studies (SPS) Category 5 (SPS-5) test sections in Texas. The sections with RAP demonstrated smaller curvature values (the speed of rut development) compared to virgin HMA. Tarbox et al. (2012) compared the stiffness of mixtures containing various amounts of RAP as they aged with the stiffness of a comparable virgin mixture. They highlighted the need for additional analysis of binders extracted from aged mixtures to better understand how RAP mixtures age.

Sias et al. (2013) evaluated the effect of long-term oven aging of RAP mixtures, and how the addition of aged asphalt binders influences the overall properties and performance of the mixture. They examined four plant-produced mixtures containing 0%, 20%, 30%, and 40% RAP that were long-term oven-aged for two, four, and eight days at 85°C. They demonstrated that RAP mixtures stiffen at a slower rate than virgin mixtures when subjected to laboratory aging. They also indicated that the inclusion of aged binder results in a much slower rate of aging than virgin binder under laboratory conditioning. They demonstrated an increase in stiffness and a decrease in phase angle with aging.

Yin et al. (2017) proposed the concept of cumulative degree days (CDD) as a metric to quantify field aging. They evaluated the effect of different factors on the long-term aging characteristics of asphalt mixtures, including the incorporation of WMA technology, recycled materials, and aggregate absorption. They suggested that the long-term oven aging protocols of two weeks at 60°C (140°F) and five days at 85°C (185°F) can produce mixtures with equivalent in-service field aging of 7-12 months and 12-23 months, respectively, depending on the conditions.

Singh et al. (2012) investigated the effect of long-term oven aging on HMA mixes containing RAP using the dynamic modulus (|E*|) test. They found that higher amounts of RAP result in stiffer mixes with higher |E*| values, regardless of the binder grade. Long-term oven aging increased the |E*| of the compacted samples by 42% to 60%, depending on the specimen's RAP content and air void content.

Effect of Gradation on the Fatigue Cracking Performance of Asphalt Mixes and Recovered Asphalt Binder

Angularity, shape, texture, and gradation are the main aggregate characteristics that impact how well asphalt mixes perform (Moghaddam and Baaj, n.d.) The nominal maximum aggregate size (NMAS) is often used as a parameter to describe the size distribution of aggregates in an asphalt mix. Gradation curves are another useful tool for quantifying aggregate size distribution discrepancies more precisely. The majority of research in the literature points out that a suitable mix design depends on striking an appropriate balance between the volumetric properties of mixes and the quantity of raw ingredients (binder, aggregate, filler, and additives (Rocha et al., 2024).

De Freitas et al. (2005) constructed 17 asphalt slabs with three distinct gradations (fine, coarse, and average) using granite aggregates and limestone fillers. The slabs were subjected to an accelerated wheel-tracking system. At higher test temperatures, the slabs with coarse gradations displayed the onset of cracking earlier than the slabs with fine gradations.

Based on the WesTrack experimental data, Tsai et al. (2002) indicated that while fracture initiation in coarse mixes took longer than in mixes with fine gradations, bottom-up crack propagation was faster in coarse mixes than in fine mixes. The study, in summary indicated that the fatigue cracking resistance of mixes with larger aggregate size was higher than that of mixes with smaller aggregate size with the same air-void contents (Tsai et al., 2002).

Effect of Additive on the Fatigue Cracking Performance of Asphalt Mixes and Recovered Asphalt

Arega et al. (2013) studied the aging of fine aggregate mixtures. They found that the type of binder employed in their WMA mixes impacted their fatigue resistance. WMA mixes with PG 76-28 binder demonstrated comparable or superior resistance to fatigue cracking compared to conventional HMA mixtures with PG 76-28 binder. Nonetheless, WMA mixes, including PG 64-22 binders, exhibited notably varied fatigue lives, occasionally lower than the conventional HMA mixtures with PG 64-22 binders, suggesting that the binder-additive combination substantially impacted the material's mechanical response. The study, in summary, indicated that material type might have a greater influence on the fatigue resistance of asphalt mixtures than production temperature, and it also emphasized the significance of the type of binder and additive utilized (Agrega et al., 2013).

Elkashef et al. (2018) used a soybean rejuvenator to rejuvenate extracted RAP binders and assess the mixes' and binders' fatigue and thermal cracking behavior. They included a neat PG 58-28 binder, an extracted RAP binder, and the extracted binder rejuvenated with a 12% rejuvenator. The rejuvenated RAP binder demonstrated noticeably lower critical high and low temperatures than neat PG 58-28 binder, an extracted RAP binder without rejuvenator, indicating increased performance in both high- and low-temperature situations. Both the fatigue and Glover-Rowe parameters showed a considerable enhancement in the fatigue cracking resistance of the rejuvenated RAP binder. They showed that the soybean rejuvenator significantly increased the RAP binders' resistance to fatigue and thermal cracking. The rejuvenator's full potential could only be realized through proper blending, indicating that the order in which the rejuvenator is added and mixed is crucial for the best results (Elkashef et al., 2018).

Mohammadafzali et al. (2017) concentrated on the aging behavior of rejuvenated binders over an extended period based on their rheological characteristics. They found that the rejuvenator's type and dosage significantly affect the binder's longevity and rate of aging. Some rejuvenators slow the binder's aging process, while others accelerate it (Mohammadafzali et al., 2017).

Karki et al. (2016) studied the incorporation of rejuvenators in asphalt binders comprising recycled asphalt shingles (RAS) and RAP to ascertain the impact of varying rejuvenator dosages on the stiffness, oxidation, and cracking propensity of mixtures. The study emphasized the many advantages of using RAP and RAS in mixtures, including financial savings and less energy use. They demonstrated that rejuvenators may successfully lower the asphalt blends' stiffness and oxidation, increasing their resistance to cracking. The rejuvenator dosage based solely on performance-grade testing cannot ensure pavements' aging durability. This goal is more effectively achieved by combining Glower-Rowe characteristics with performance-grade tests (Karki et al., 2016).

Ongel et al. (2015) investigated how rejuvenators affected bitumen's aging characteristics, with a particular emphasis on using RAP as a substitute for conventional asphalt production. They showed that bitumen rejuvenators are essential for reducing bitumen stiffness and increasing their resistance to cracking. They observed that by combining an aged binder with a rejuvenator, bitumen may be made that exhibits rheological properties comparable to those of a virgin binder. They also observed that the differences in the chemical makeup between virgin bitumen and the rejuvenated binder might impact the long-term performance of mixes (Ongel et al., 2015).

Sadeghi et al. (2023) studied how well asphalt mixtures, including 0%, 50%, and 100% RAP and various rejuvenators, could resist cracking at 25°C and -12°C. They also used four different volumes of recycled high-density polyethylene (r-HDPE), alone and in conjunction with the rejuvenators. They found that mixes containing RAP behaved differently during fracture at 25°C and -12°C temperatures. They showed that adding RAP to mixtures decreased the cracking resistance and increased stiffness (Sadeghi et al., 2023).

Jiang et al. (2018) conducted experiments to evaluate the engineering of aged bitumen. They found that as the virgin binder aged, its softening point increased, and its penetration and ductility diminished. They restored those parameters to their initial values by incorporating a rejuvenator (Jiang et al., 2018).

Chapter 3. Materials and Methodologies

For this research, 48 asphalt mixes were gathered from the TxDOT 0-7061 study (Arras, 2023). Table 1 provides an overview of the testing matrix used in this study, detailing the combinations of RAP content, binder content, gradation, additive content, and aging durations analyzed. Each mix was subjected to a systematic set of tests, including mechanical performance evaluation (Overlay Test (OT)), rheological characterization (Dynamic Shear Rheometer (DSR)), and chemical characterization (Fourier Transform Infrared Spectroscopy (FTIR)). This matrix ensures comprehensive coverage of the interactions between these variables and their effects on asphalt aging and cracking performance.

Table 1. Experimental Matrix

Mix ID	1: RAP (%)	2: Asphalt Content (%)	3: Aggregate Gradation	4: Additive (%)	5: Aging Time (h)	Tests Conducted on The Mix	Tests Conducted on The Binder
San Antonio FM-3009	10/20/30	6	Control	3	0/ 22/ 46/ 118	Overlay Test	Frequency Sweep Test (DSR), FTIR
San Antonio FM-3009	30	6	Control	3/ 4.5/ 6	0/ 22/ 46/ 118	Overlay Test	Frequency Sweep Test (DSR), FTIR
Childress US-70	8	4.9/ 5.1/ 5.6	Control	0.3	0/ 22/ 46/ 118	Overlay Test	Frequency Sweep Test (DSR), FTIR
Childress US-70	8	5.6	Coarser/ Control/ Finer	0.3	0/ 22/ 46/ 118	Overlay Test	Frequency Sweep Test (DSR), FTIR

Methods

Sample Preparation and Aging Process

Short-Term Aging
To simulate short-term aging conditions typically experienced during the production and construction of asphalt pavements, loose asphalt mixtures were aged in a forced-draft oven at 135°C (275°F) for two hours. This temperature was chosen to replicate the oxidative condition during mixing and placement. Consistent heating and aging were ensured by maintaining the thickness of the loose material at 57 ± 13 mm (2.25 ± 0.5 in.), as recommended by prior studies (Kim et al., 2015). This uniformity minimizes variability in aging rates across the material and ensures the reliability of subsequent test results.

Long-Term Aging
Following short-term aging, the mixtures underwent long-term aging in an oven at 95°C (203°F), as shown in Figure 1. Table 2 shows that the aging durations were 0, 22, 46, and 118 hours, following the methodology described by Kim et al. (2015). This procedure replicates the extended oxidative aging experience during the service life of asphalt pavements.

Table 2. Aging Process

Protocol	Temperature (°C)	Pressure (psi)	Time (hrs)
Short-term (Loose mix)	135	Atmospheric	2
Long-term (Loose mix)	95	Atmospheric	0, 22, 46, 118

Figure 1. Loose mixture oven aging

Laboratory Testing Procedures

Mechanical Performance Evaluation: Overlay Test
The fatigue performance of asphalt mixtures was evaluated using the Overlay Test (OT), conducted in accordance with the TxDOT Test Procedure Tex-248-F. This test measures the susceptibility of mixtures to fatigue and reflective cracking under repeated loading.

Each specimen was securely bonded to the OT machine’s plates using epoxy adhesive, which was allowed to cure for 24 hours. The prepared samples were preconditioned at 25°C ± 0.5°C (77°F ± 1°F) for one hour before testing. A cyclic displacement-controlled load was applied using a triangular waveform, with a maximum displacement of 0.025 in. (0.06 cm) at a loading rate of 10 seconds per cycle. The cyclic loading aimed to replicate field conditions and evaluate crack propagation under repeated stress.

As illustrated in Figure 2, the OT setup includes a 0.16-inch (4 mm) gap between the plates, where crack initiation and propagation occur. The precise application of adhesive and proper alignment of the specimen ensured accurate results and minimized variability. This test enabled the study to assess the performance of asphalt mixtures under short-term and long-term aging conditions.

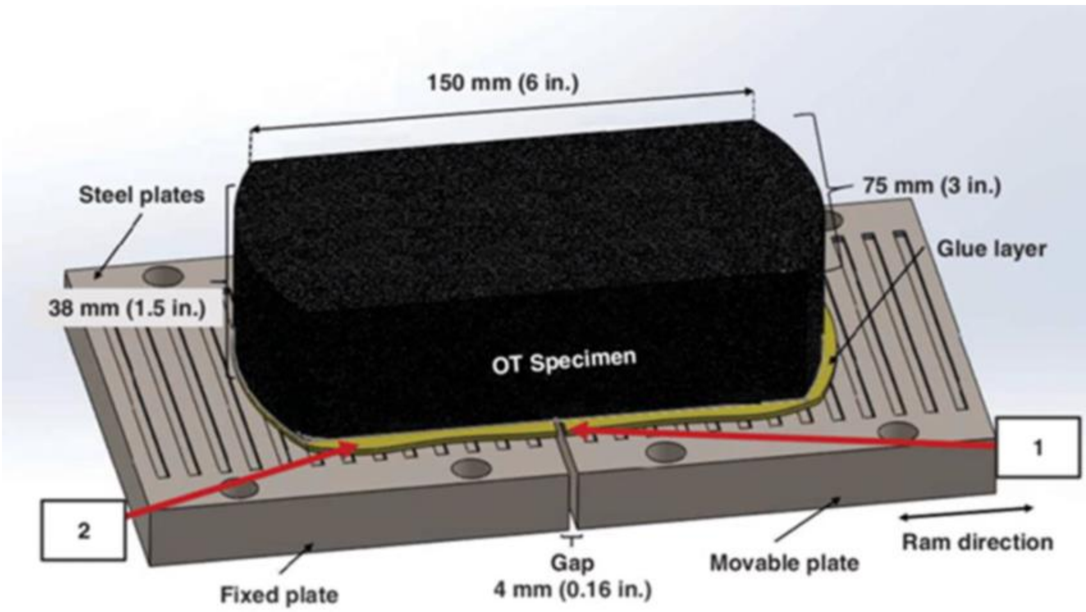

Figure 2. Overlay Test Schematic of Specimen Set Up (Tex-248-F)

Binder Extraction and Recovery

To analyze the properties of the aged asphalt binder, it was extracted and recovered from the mixtures using standardized procedures. Extraction was performed following ASTM D 8159 using an asphalt analyzer, as shown in Figure 3. The binder was dissolved in trichloroethylene (TCE) solvent, then filtered to separate it from the aggregate. Recovery of the extracted binder was conducted using a Rotavapor device, adhering to ASTM D 5404 standards. During this process, the TCE was evaporated, leaving behind the aged asphalt binder for further testing (Figure 4).

Figure 3. Asphalt Analyzer

Figure 4. Rotavapor Device

Rheological Tests: Dynamic Shear Rheometer

The viscoelastic properties of asphalt binders were evaluated using a Dynamic Shear Rheometer (DSR), as depicted in Figure 5. The tests were conducted following AASHTO T 315, with temperatures ranging from 15°C to 32°C and frequencies between 0.1 Hz and 30 Hz. The binder samples were prepared using 8 mm diameter molds and subjected to a sinusoidal shear stress, with the corresponding strain response measured. Key rheological parameters, including the complex modulus (G*) and phase angle (δ), were recorded. Figures 6 and 7 illustrate the DSR setup and sample preparation process. These measurements were used to construct master curves and calculate fatigue parameters, providing insight into the binders' performance under different aging conditions.

Figure 5. Dynamic Shear Rheometer

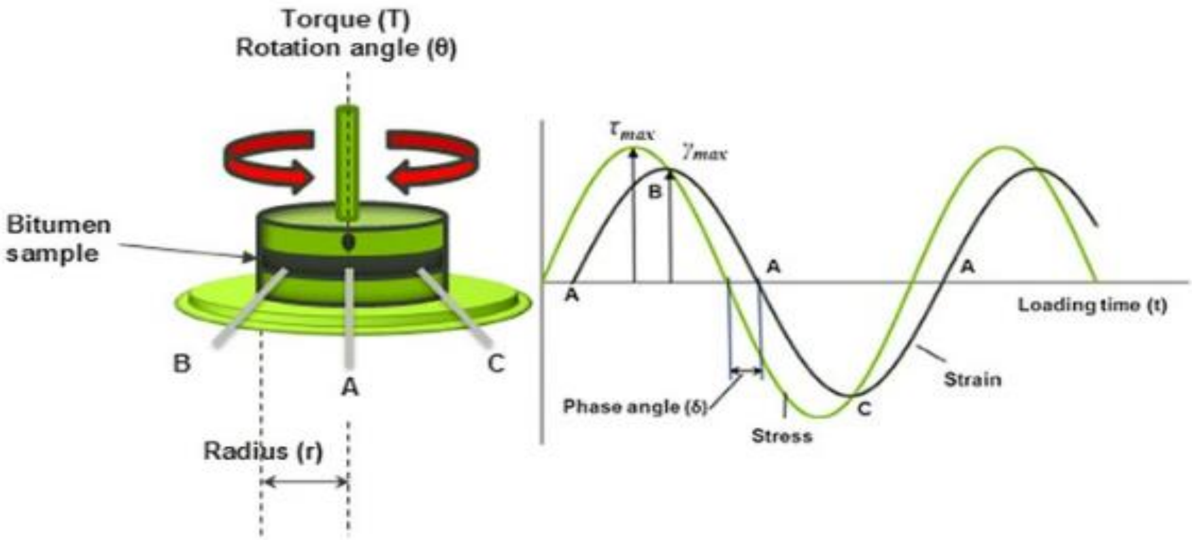

Figure 6. Dynamic Shear Rheometer

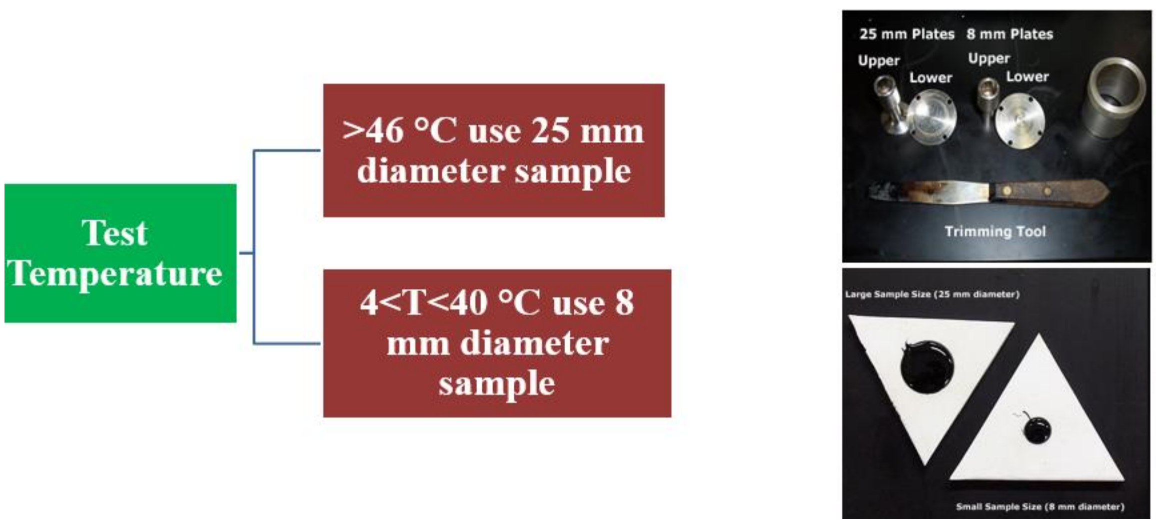

Figure 7. DSR sample molds, and conditions (Retrieved online from Pavement Interactive)

Chemical Characterization: FTIR Analysis

Fourier Transform Infrared Spectroscopy (FTIR) was utilized to assess the chemical changes in the aged asphalt binders, following ASTM E1252 standards. Binder samples were prepared as thin films to allow infrared radiation to pass through. The spectrometer recorded molecular absorption and transmission across a spectral range of 4000 cm^{-1} to 400 cm^{-1}, as shown in Figure 8. Key functional groups associated with aging, such as sulfoxides (1030 cm^{-1}) and carbonyls (1700 cm^{-1}), were identified and quantified. The presence of these groups indicates oxidation and other chemical changes due to aging, which correlate with changes in binder performance. The FTIR findings were correlated with the mechanical and rheological performance data to provide a comprehensive understanding of aging effects on asphalt binders and mixtures.

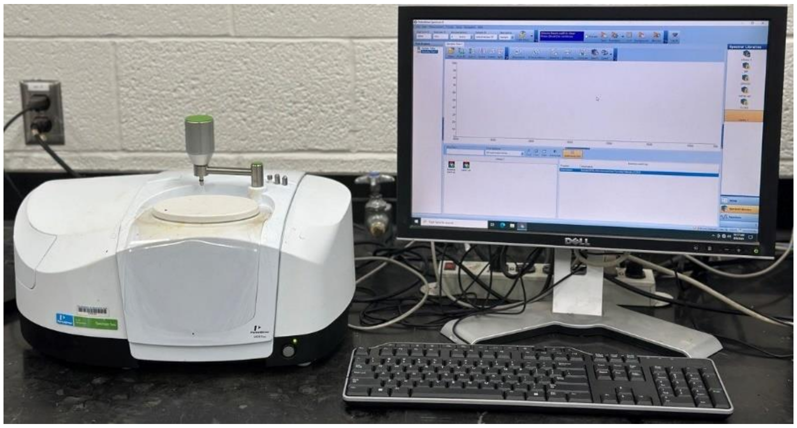

Figure 8. Fourier-transform infrared spectrometer

Data Analysis

Fatigue Parameter

Rheological data obtained from DSR tests were used to calculate fatigue parameters. The complex modulus (G*) and phase angle (δ) values were used to generate master curves and evaluate the fatigue resistance of the binders. One parameter of interest is the fatigue parameter, which has a threshold of 5000 kPa to indicate the onset of cracking. Equation 1 presents the calculation used for this parameter.

$$\text{Fatigue Parameter} = G^{*} \times \sin\delta$$

Where:

G^* = complex modulus

δ = phase angle

Equation 1. Fatigue Parameter

Glover-Rowe (G-R) Parameter

The Glover-Rowe parameter was calculated using G* and δ values measured at 15°C and a frequency of 0.005 radians/second. Thresholds of 180 kPa and 600 kPa were used to distinguish the onset of damage and severe damage, respectively, as per prior studies (Glover er al., 2009; Rowe, 2011).

$$G\text{-}R = |G^*| \times (\cos\delta)^2 \times \sin\delta$$

Where:

G^* = complex modulus

δ = phase angle

Equation 2. Glover-Rowe (G-R) Parameter

Chapter 4. Results and Discussions

Effect of RAP Content on the Fatigue Cracking Performance of Asphalt Mixes and Recovered Asphalt Binder

Figure 9, adapted from Arras (2023), shows the variation of CPR values from OT tests obtained for all mixes at different aging periods. Considering an upper limit of 0.45 when evaluating fresh asphalt mixtures for a balanced mix design according to Tex-248-F, all three unaged mixtures are crack-resistant. Mixes with 30% RAP exceed the limit after 46, and 118 hours long term aging, and mixes with 20% RAP exceed the limit after 118 hours long term aging. One should keep in mind that the 0.45 limit is for unaged material, so setting a limit for long-term aged mixes needs further research.

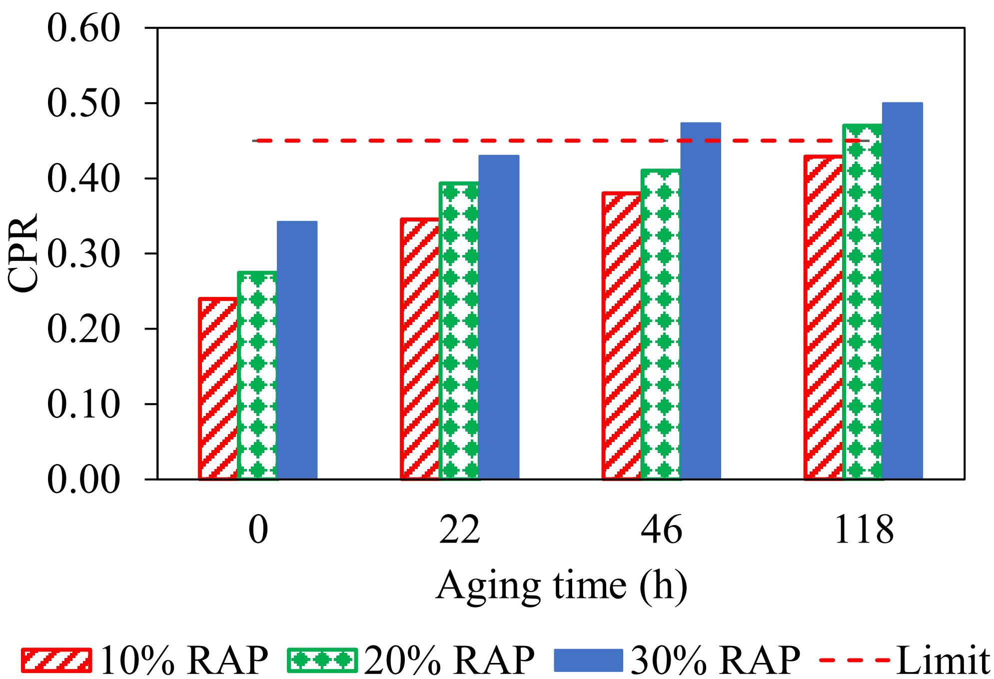

Figure 9. Mix Fatigue Parameters for Asphalt Mixes with 10%, 20%, and 30% RAP at Different Ages (Arras et al., 2023)

The rate of aging (R_t) of mixes with different RAP contents at different aging times is quantified using Equation 3:

$$R_t = \frac{(\mathrm{CPR_t} - \mathrm{CPR_0})}{\mathrm{CPR_0}}$$

Where:

Rt = rate of aging

CPR_t = crack progression rate at any given time

CPR_0 = initial crack progression rate

Equation 3. Rate of Aging

Table 3 shows the rate of change in CPR for different mixtures for all aging periods. Rt for the mixtures containing 30% RAP is the lowest in all aging periods compared to those with 20%, and 10% RAP. This outcome shows that 30% RAP makes the mixtures age less severely.

Table 3. Rate of Aging

Mix	R_t (22 h)	R_t (46 h)	R_t (118 h)
10% RAP	0.46	0.58	0.79
20% RAP	0.44	0.52	0.74
30% RAP	0.26	0.38	0.47

Figure 10 depicts the FTIR test results and reveals a relationship between aging time and the chemical composition changes in asphalt binders. Specifically, the absorbance peaks of the Carbonyl group (around 1700 cm^{-1} wavenumber), and sulfoxide group (around 1030 cm^{-1} wavenumber) show an upward trend as aging progresses. This increase in absorbance peaks indicates a rise in oxidation and degradation within the binder over time. These findings underscore the impact of aging on the chemical composition of asphalt, which can influence its performance and durability.

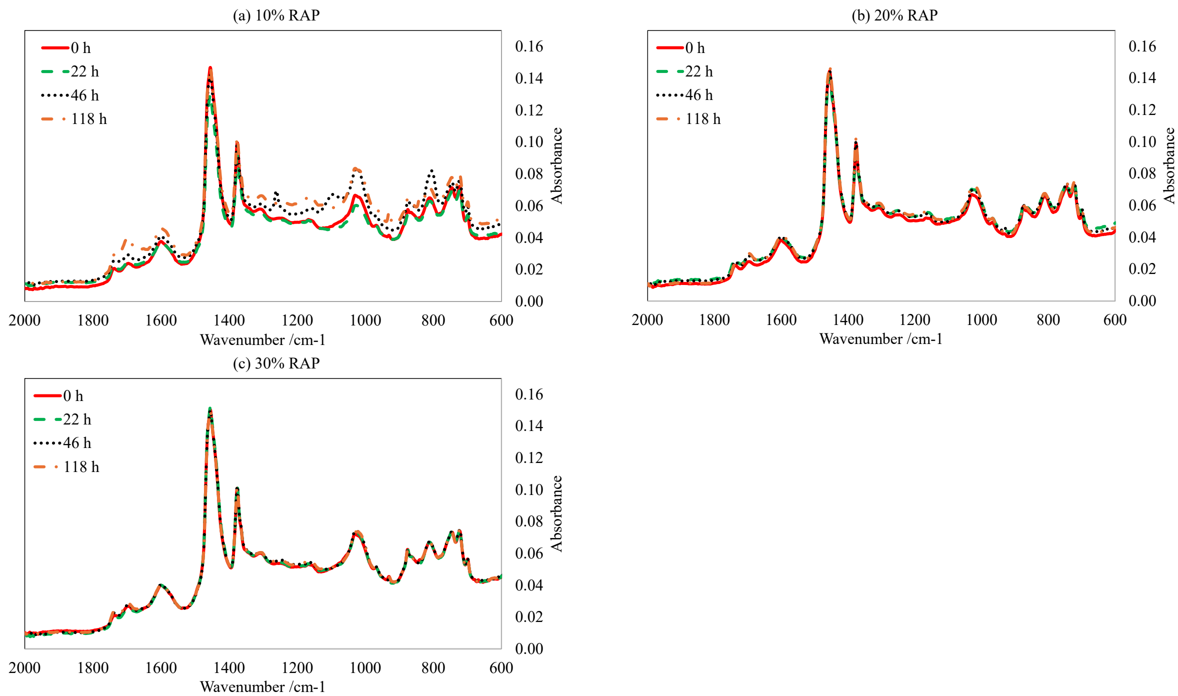

Figure 10. Comparison of the Functional Groups Containing the Carbonyl and Sulfoxide Groups in the Asphalt Binder of Each Mixture at Different Aging Periods (a) 10% RAP, (b) 20% RAP, (c) 30% RAP

Figure 11 shows the change in the carbonyl and sulfoxide absorbance peaks at a specific aging period for mixes with different RAP contents. By increasing the RAP content, the absorbance peaks increase without long-term aging (0 h). After 22, 46, and 118 hours long term aging by increasing the RAP content absorbance peaks decrease which means less oxidation and less aging in the mixes.

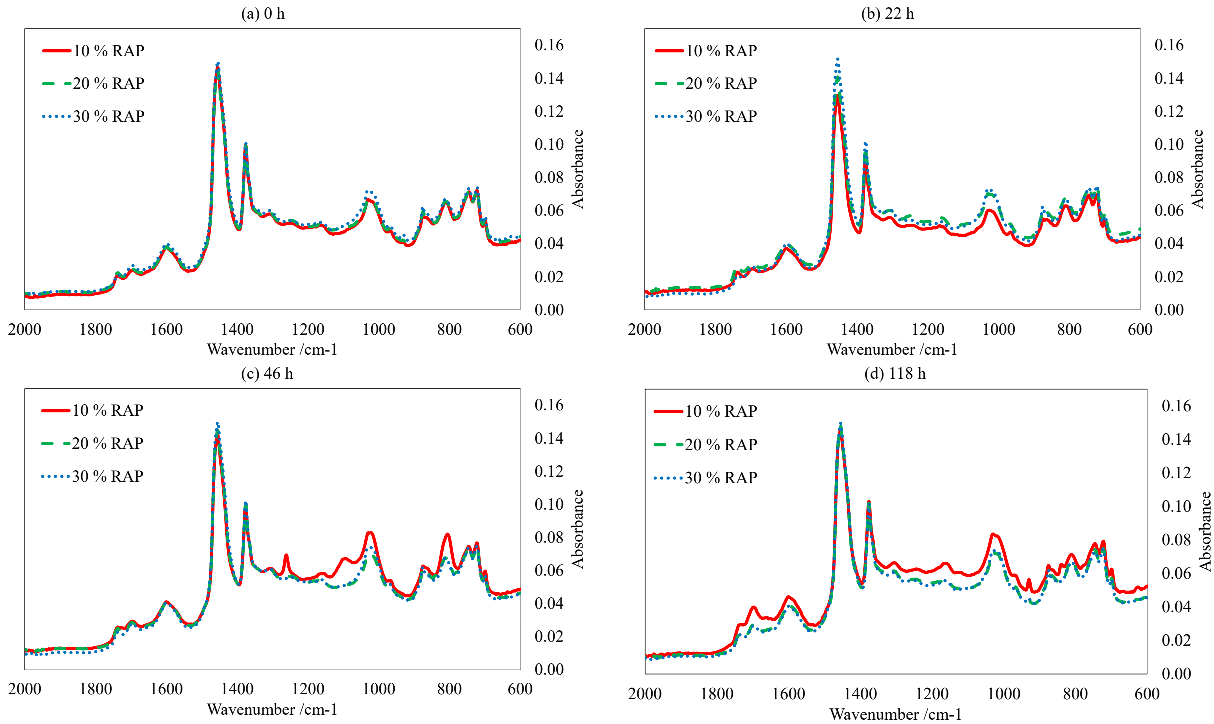

Figure 11. Carbonyl and Sulfoxide Functional Group Peak Comparison for all Mixes at Specific Aging Period (a) 0 h, (b) 22 h, (c) 46 h, (d) 118 h

Figure 12 shows the master curves for the aged binders extracted and recovered from mixtures containing 10%, 20%, and 30% RAP. The complex modulus (G*) of all aged binders was measured in the frequency sweep mode at 15, 19, 22, 25, 29, and 32°C using DSR. The rheological measurements corroborate that an increase in aging time results in an increase in complex modulus, meaning that aging stiffens the binder. In addition, the results reveal that the aging properties of asphalt mixes containing 10%, 20%, and 30% RAP differ noticeably. Interestingly, the 30% RAP blend is more resistant to the rate of aging. The G* for the 30% RAP at 118 hours of oven long term aging was lower than the G* for the 10% and 20% RAP at the same aging level across all frequencies. Even more remarkable is the fact that the master curves for 30% RAP at different aging durations stay closer together over a range. Conversely, the master curves for 10% and 20% RAP are more spread out. To a certain degree, the dispersion of the curves is proportional to the amount of RAP, with 10% RAP showing the most extensive spread. This finding highlights that increasing RAP content can reduce the rate of binder aging, as evidenced by the closer clustering of master curves for 30% RAP over different aging durations. This behavior suggests higher RAP content helps preserve binder rheological properties over time. Such preservation of binder qualities is crucial for enhancing the durability of asphalt pavements. However, further investigation into the aging mechanisms of high RAP mixtures is necessary to refine mix designs and optimize performance.

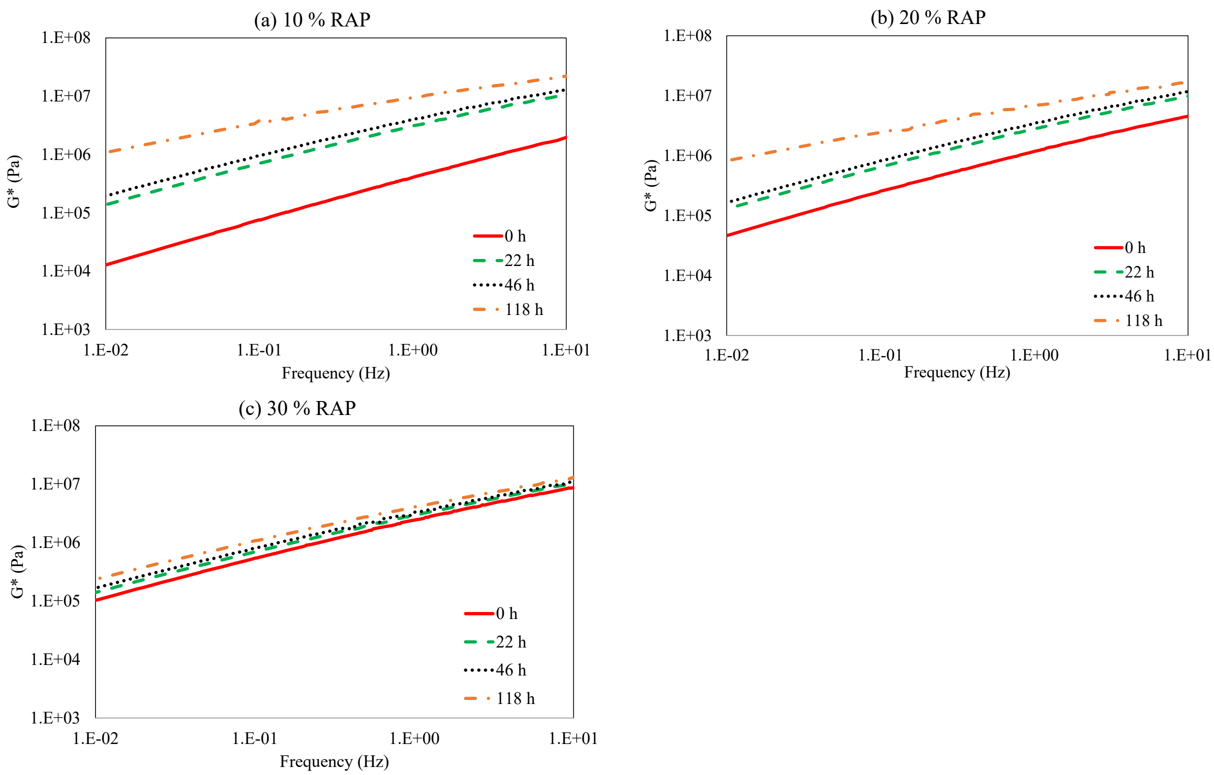

Figure 12. Comparison of Master Curves for Mixes with (a) 10% RAP, (b) 20% RAP, (c) 30% RAP

Figure 13 shows the variations of fatigue parameter *G*× Sin δ* with temperature for asphalt binders extracted and recovered from mixtures after different aging periods. While higher RAP content in the mix decreases the fatigue cracking resistance of minimally aged mixtures (0 hr. aging at 95°C), it may offer advantages in mitigating the negative effects of aging on fatigue resistance and crack performance when considering long-term aging. All 10%, 20%, and 30% RAP mixes exhibited decreased fatigue resistance as aging time increased. However, the 30% RAP mixes showed a smaller reduction in fatigue resistance with aging, implying a lower vulnerability to aging-related degradation.

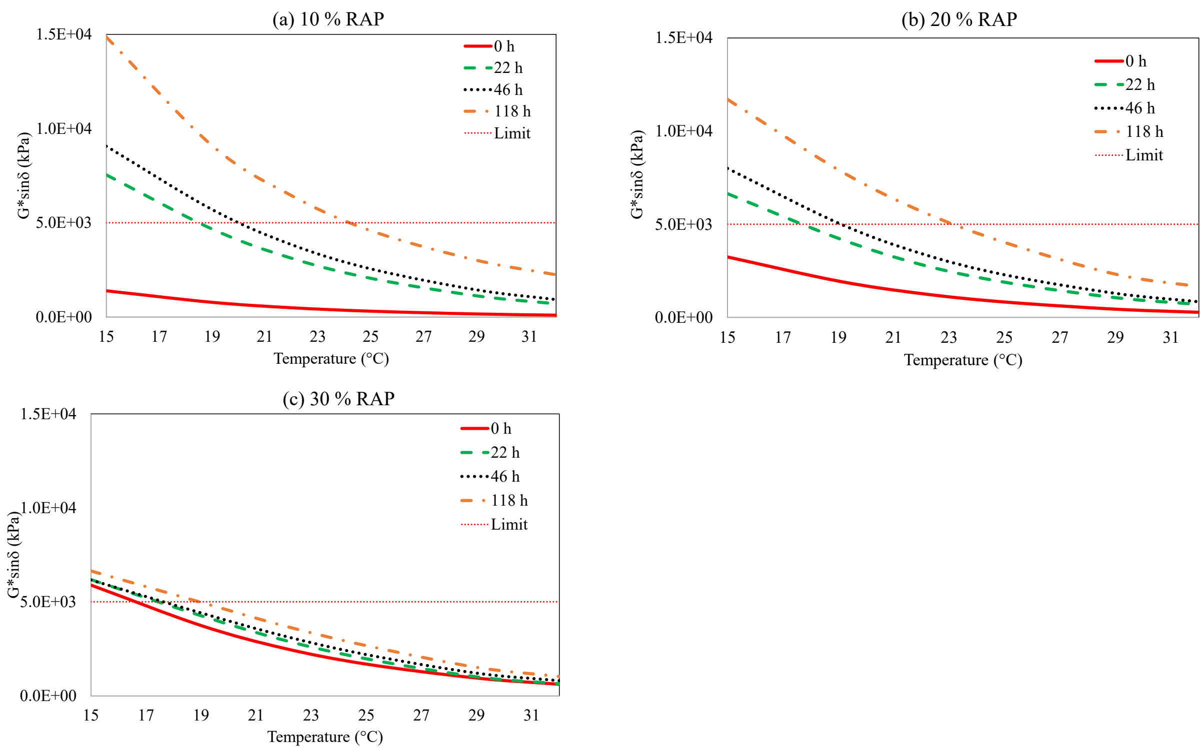

Figure 13. Comparison of Binder Fatigue Cracking Parameters for Mixes with (a) 10% RAP, (b) 20% RAP, (c) 30% RAP

As shown in Figure 14, the fatigue resistance ranking shifted as the materials were aged. At 0 hours aging at 95°C, the fatigue resistance of the aged binders was found to follow the order of first 10% RAP, second 20% RAP, and third 30% RAP, from best to worst. In contrast, after 118 hours of long term aging at 95°C, the fatigue resistance ranking was as follows: 30% RAP was the best, followed by 20% RAP, and then 10% RAP, and all binders had the fatigue resistance less than the 5000 kPa that is the allowable limit for fatigue parameter of long-term aged asphalt binders according to AASHTO T 315.

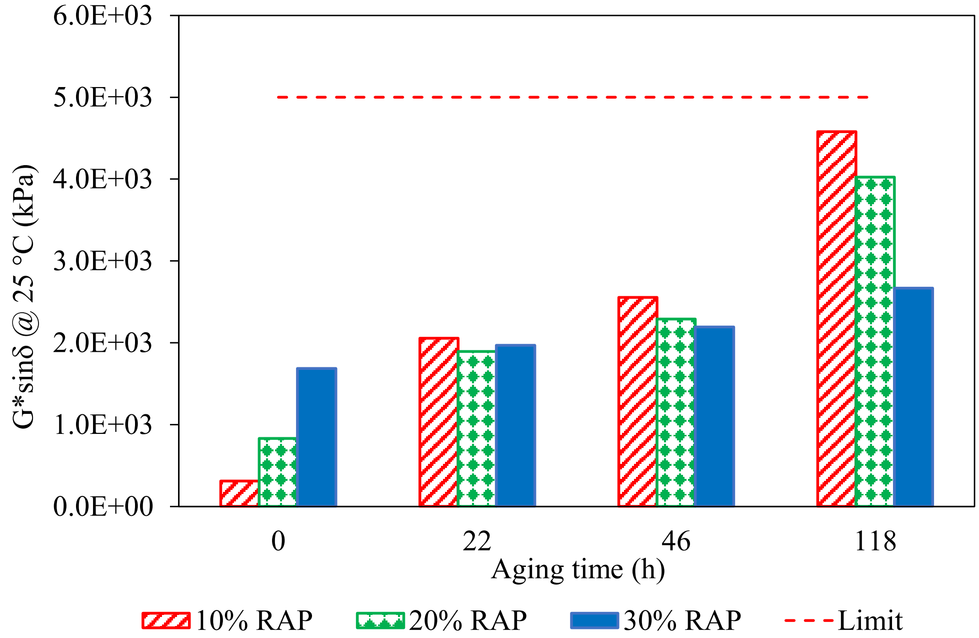

Figure 14. Comparison of Binder Fatigue Cracking Parameter for Mixes With 10, 20, and 30% RAP at 25 ˚C (77°F)

Figure 15 reports the black space diagram with G-R parameters for the different aged asphalt binders, with two reference lines marking the thresholds for crack initiation (G-R = 180 kPa) and significant cracking (G-R = 600 kPa). Higher complex modulus and lower phase angle values suggest an increased tendency for asphalt mixtures to crack in the field (Liang et al., 2015). As the G-R values increase or shift to the left, the likelihood of cracking in asphalt binders rises. All G-R values fall below the crack initiation threshold except for 10% and 20% RAP after 118 hours of long term aging at 95°C. The 30% RAP mixes consistently remained in the no-crack region, while the mixes with 10%, and 20% RAP entered the cracking regions after prolonged aging. This suggests that higher RAP content correlates with better binder performance in terms of resisting cracking under the studied aging conditions. However, further investigation would be necessary to confirm its impact on overall pavement performance and lifespan, considering factors such as mix design and field conditions.

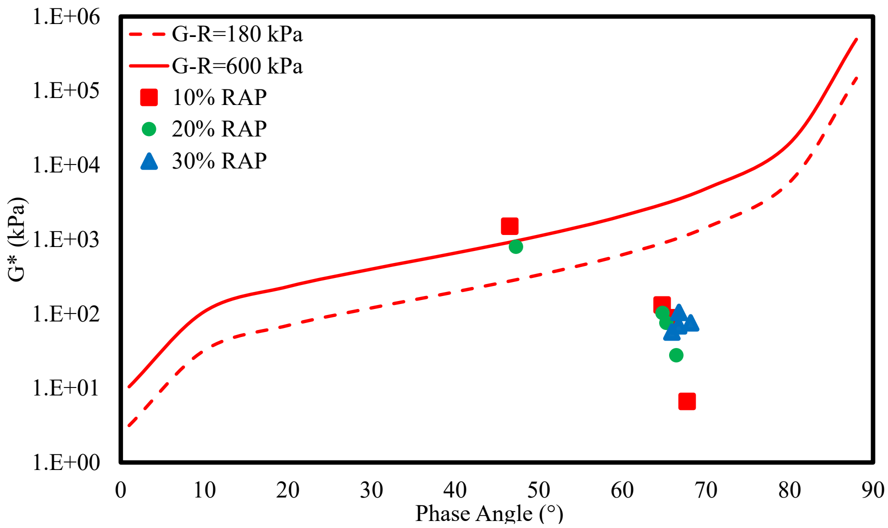

Figure 15. Variations in Glover-Rowe Parameter in Black Space Diagram for Binders Extracted from Mixes with 10%, 20%, and 30% RAP

Figure 16 shows the variations of the binder fatigue parameter (*G*× Sin δ*) and Figure 17, shows variations of the G-R parameter with the corresponding mix fatigue cracking parameter, crack progression rate (CPR) from all aged asphalt mixtures and binders. Binder fatigue parameters correlate better with CPR than the G-R parameter, as evidenced by the R^2 values in the plots. This result should warrant further investigation, as the relationship between the G-R parameter and CPR seems nonlinear.

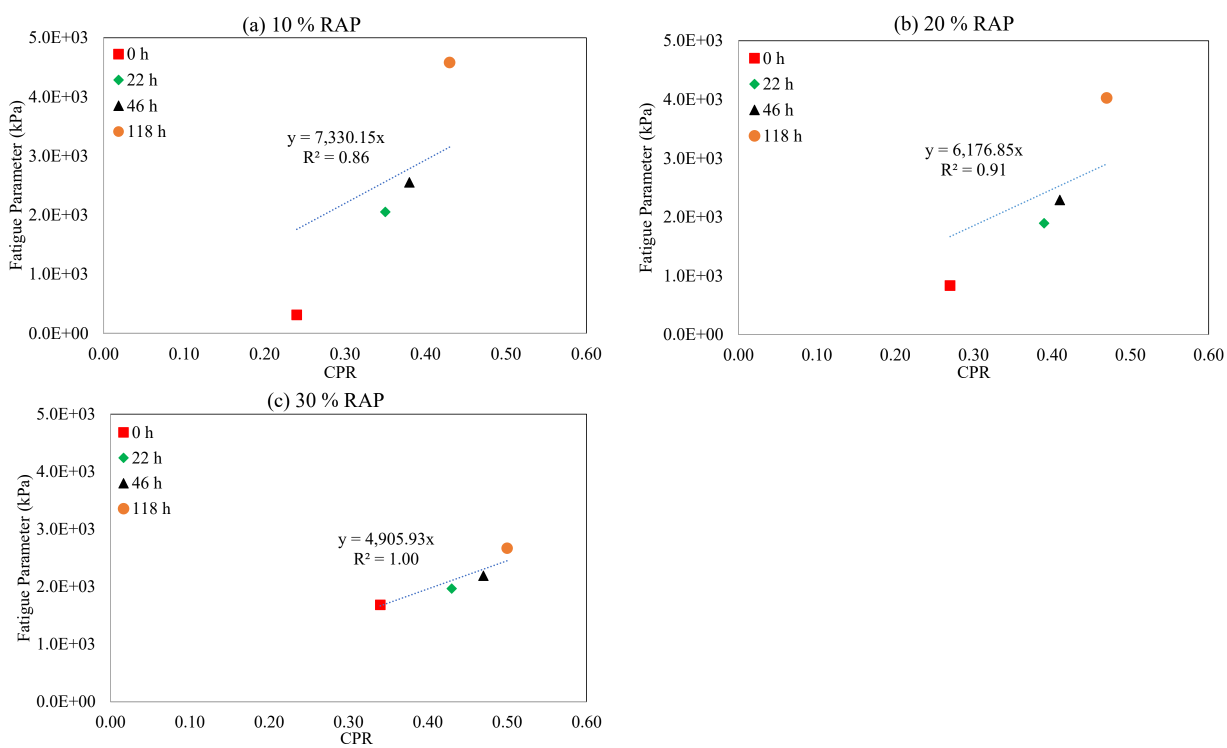

Figure 16. Correlation Between Asphalt Mix and Asphalt Binder Results, Fatigue Parameter vs CPR (a) 10% RAP, (b) 20% RAP, (c) 30% RAP

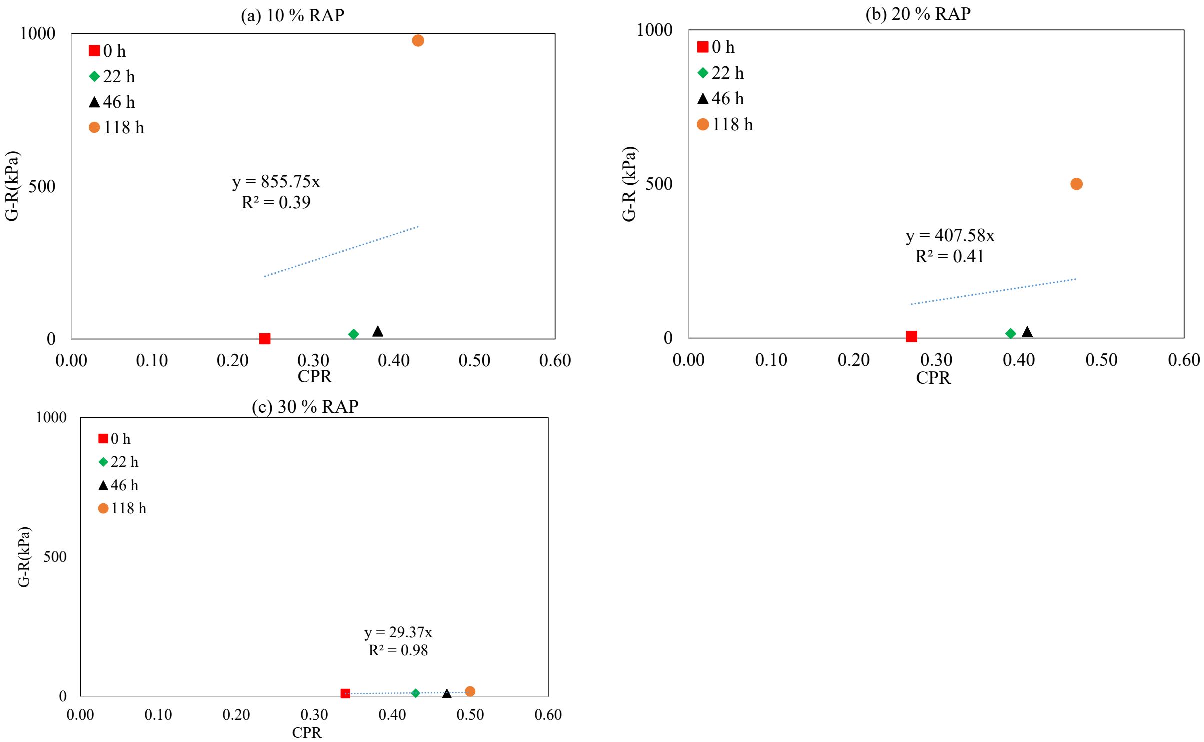

Figure 17. Correlation Between Asphalt Mix and Asphalt Binder Results, Glover-Rowe Parameter vs CPR (a) 10% RAP, (b) 20% RAP, (c) 30% RAP

Effect of Asphalt Content on the Fatigue Cracking Performance of Asphalt Mixes and Recovered Asphalt Binder

Figure 18, adapted from Arras (2023), shows the variation of CPR values from OT tests obtained for all mixes at different aging periods. Considering an upper limit of 0.45 when evaluating fresh asphalt mixtures for a balanced mix design according to Tex-248-F, all three unaged mixtures are crack-resistant. Mixes with 4.6% asphalt content (AC) exceed the limit after 46, and 118 hours long term aging, and mixes with 5.1% AC exceed the limit after 118 hours long term aging. These results highlight how lower binder content exhibits lower fatigue resistance as aging progresses.

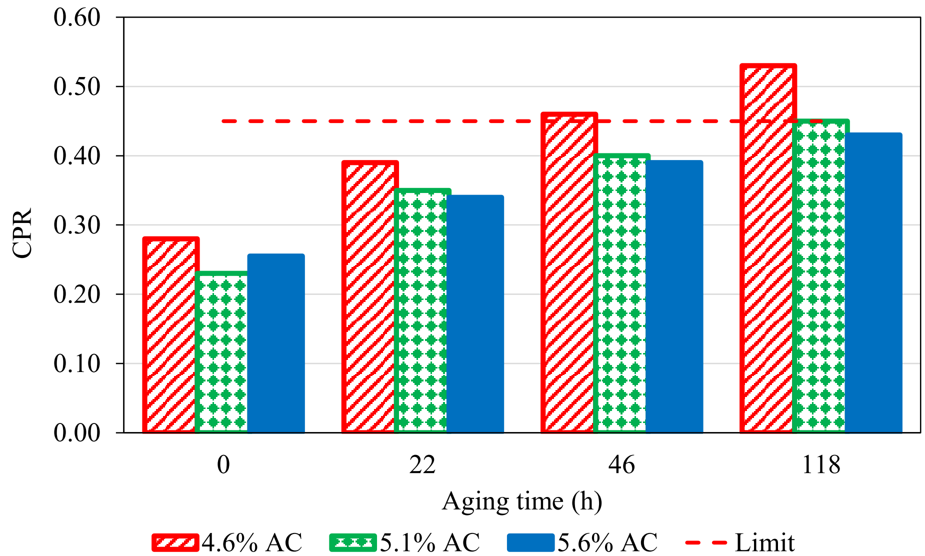

Figure 18. Mix Fatigue Parameters for Asphalt Mixes with 4.6% AC, 5.1% AC, and 5.6% AC at Different Ages (Arras, 2023)

The FTIR test findings highlight the rise in carbonyl absorbance peaks and identify the functional groups linked to aging. There is a clear correlation between the amount of age and the presence of carbonyl groups, as this rise corresponds with the chemical changes in the asphalt binder brought on by aging. These thorough investigations offer a thorough grasp of how asphalt mix aging and binder composition affect its mechanical and chemical characteristics, directing future mix design to improve pavement durability and performance. The FTIR test findings are shown in Figure 19, which also shows a correlation between asphalt binders' changes in chemical composition and aging time. In particular, as age occurs, the absorbance maxima of the sulfoxide group (about 1030 cm-1 wavenumber) and carbonyl group (approximately 1700 cm-1 wavenumber) exhibit an increasing tendency. A rise in oxidation and breakdown within the binder over time is shown by this increase in absorbance peaks. These results highlight how asphalt's chemical makeup changes with age, potentially affecting its longevity and performance.

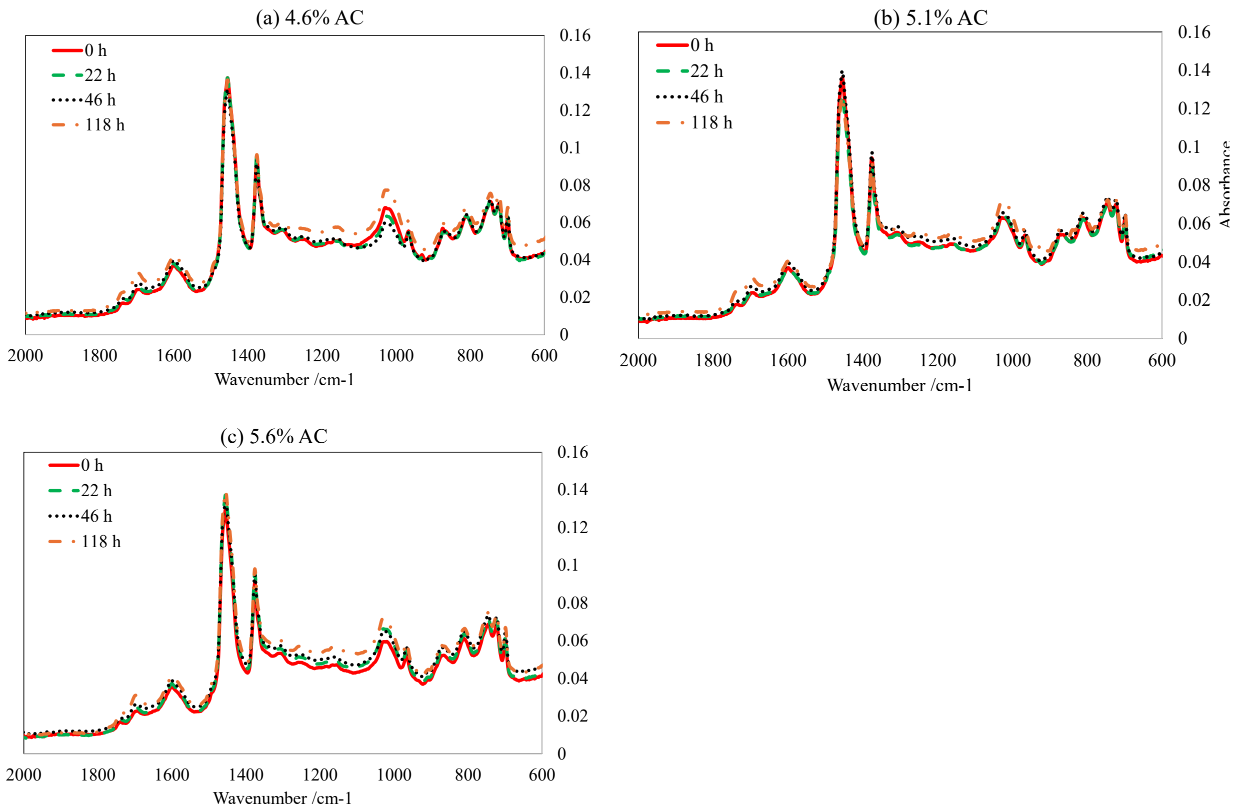

Figure 19. Comparison of the Functional Groups Containing the Carbonyl and Sulfoxide Groups in the Asphalt Binder of Each Mixture at Different Aging Periods (a) 4.6% AC, (b) 5.1% AC, (c) 5.6% AC (Control)

Figure 20 shows the change in the carbonyl and sulfoxide absorbance peaks at a specific aging period for mixes with different asphalt contents. By increasing the asphalt content before any aging, the absorbance peaks decrease; however, after aging, there cannot be a significant difference in the absorbance peak by changing the asphalt content.

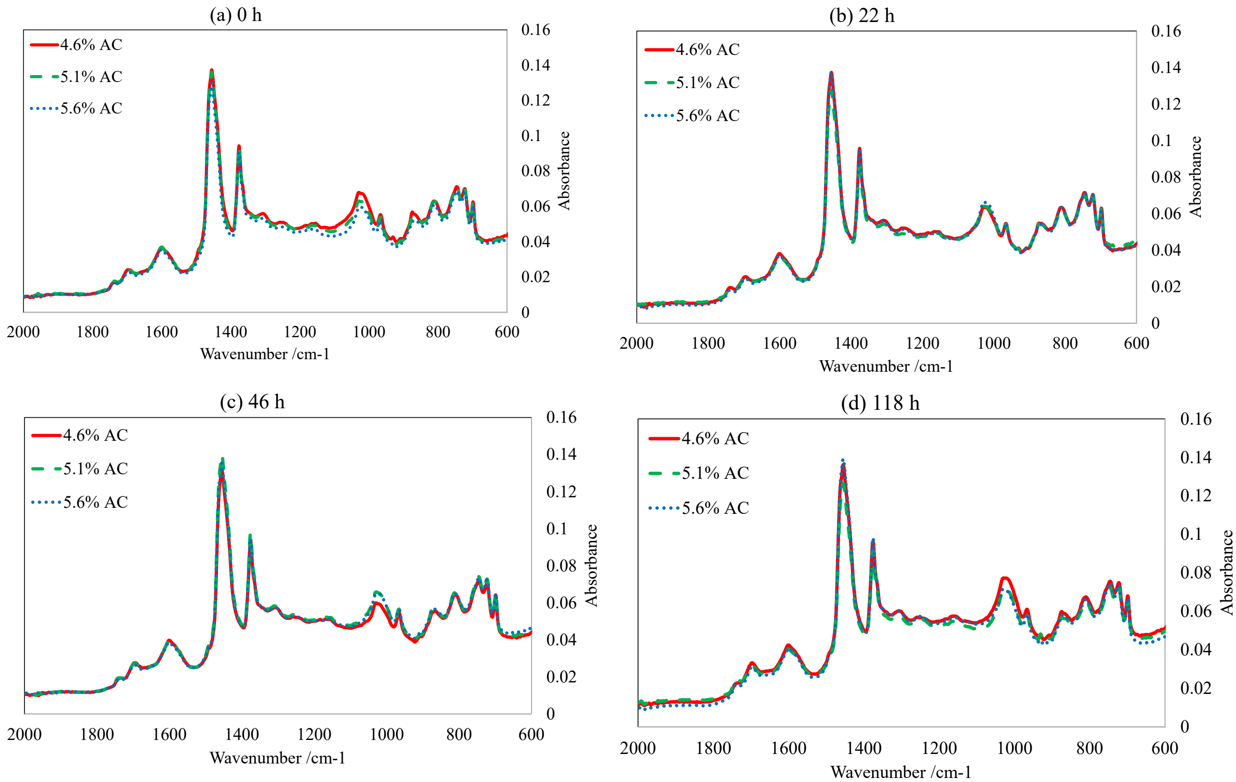

Figure 20. Carbonyl and Sulfoxide Functional Group Peak Comparison for All Mixes at Specific Aging Periods (a) 0 h, (b) 22 h, (c) 46 h, (d) 118 h

Figure 21 shows the master curves for the aged binders extracted and recovered from mixtures containing 4.6%, 5.1%, and 5.6% asphalt content. The complex modulus (G*) of all aged binders was measured in the frequency sweep mode at 15, 19, 22, 25, 29, and 32°C using DSR. The rheological measurements corroborate that an increase in aging time results in an increase in complex modulus, meaning that aging stiffens the binder. In addition, the results reveal that the aging properties of asphalt mixes containing 4.6%, 5.1%, and 5.6% asphalt contents are different before aging, but after aging, there is not a significant difference between them. The master curves reveal that mixes with lower binder content exhibit higher stiffness, which aligns with the observed higher complex modulus values and the fact that such mixes tend to have a thinner asphalt film thickness, as reported in Table 4.

Table 4. Estimated Asphalt Binder Film Thickness for Mixes with Different Asphalt Content

Asphalt Content (%)	Film Thickness (micrometer)
4.6	8.21
5.1	9.15
5.6	10.10

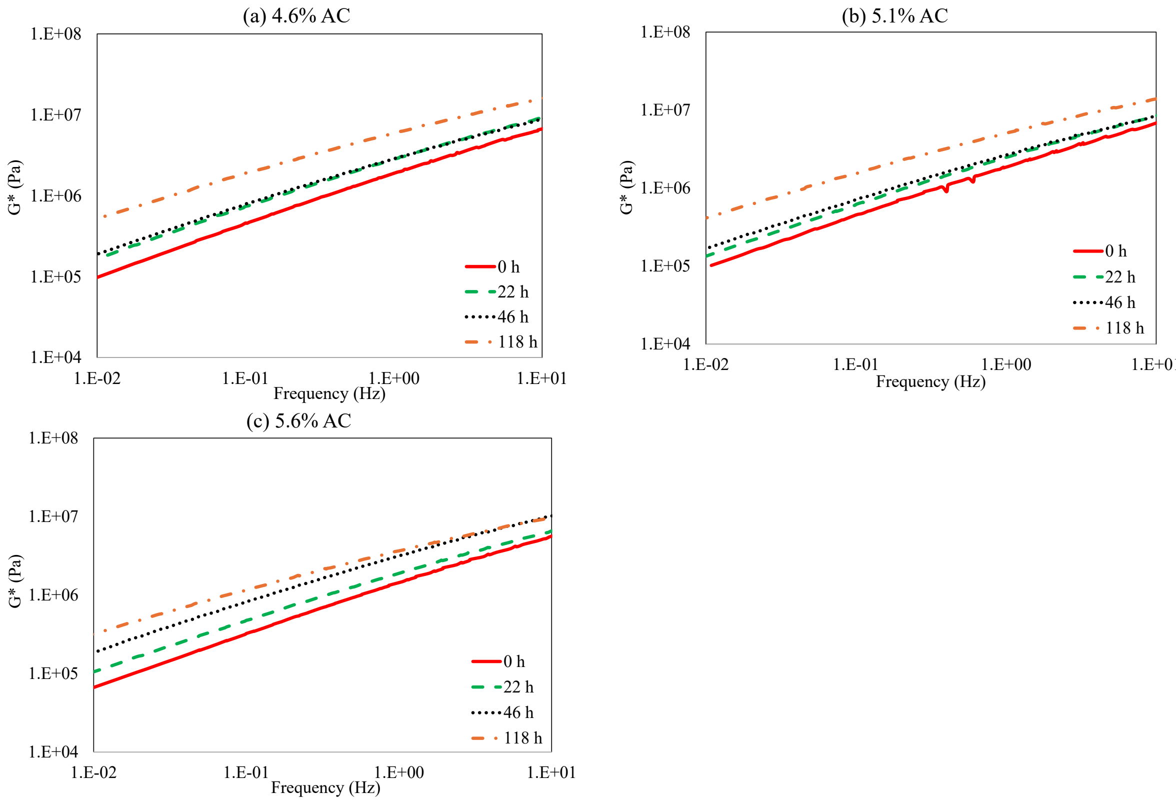

Figure 21. Comparison of Master Curves for Mixes with (a) 4.6% AC, (b) 5.1% AC, (c) 5.6% AC (Control)

Figure 22 shows the variations of fatigue parameter G*×Sin δ with temperature for asphalt binders extracted and recovered from mixtures after different aging periods. While higher asphalt content in the mix increases the fatigue cracking resistance of unaged mixtures, it may have a negligible effect on fatigue resistance and crack performance when considering long-term aging. All 4.6%, 5.1%, and 5.6% asphalt content mixes exhibited decreased fatigue resistance as aging time increased.

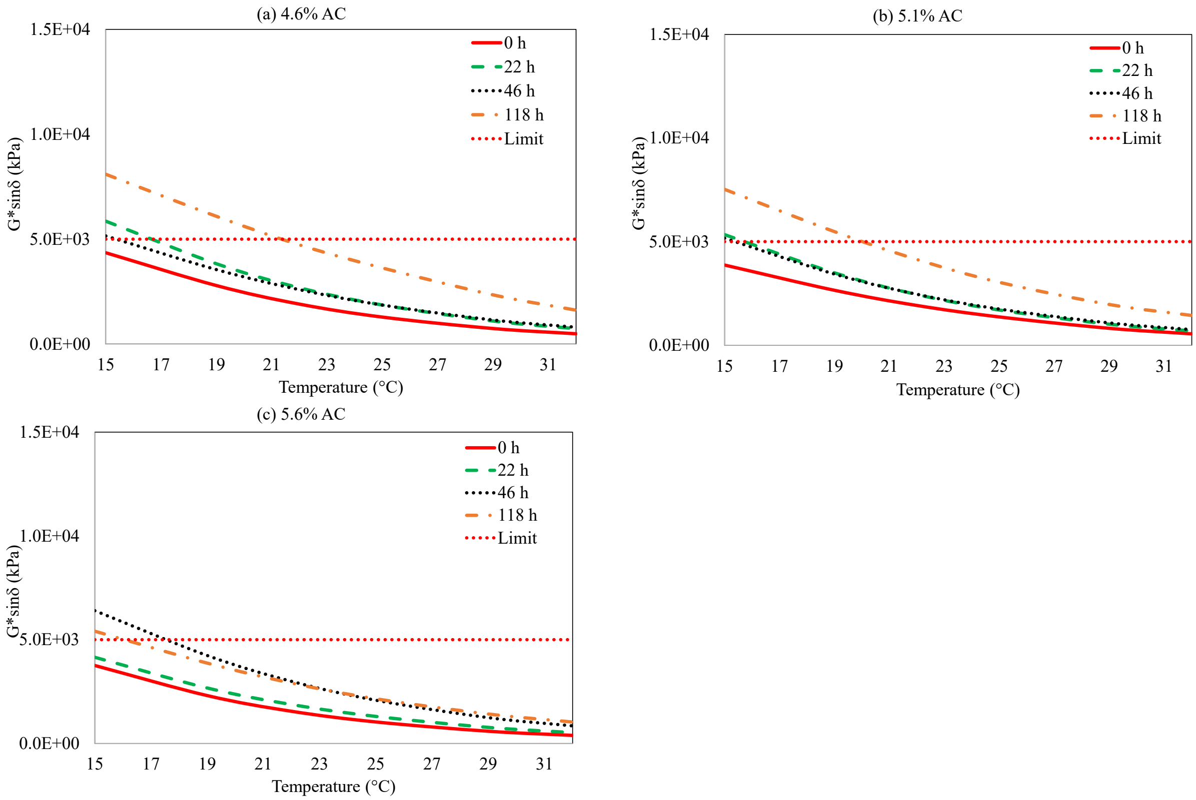

Figure 22. Comparison of Binder Fatigue Cracking Parameters for Mixes with (a) 4.6% AC, (b) 5.1% AC, (c) 5.6% AC

As shown in Figure 23, the fatigue resistance ranking shifted as the materials were aged. At 0 hours aging at 95°C, the mix with highest asphalt content, (5.6% AC), has the highest resistance against fatigue cracking; however, the effect is negligible, and after 118 hours of long term aging at 95°C, the fatigue resistance ranking for all mixes with 4.6, 5.1, and 5.6% AC are almost the same.

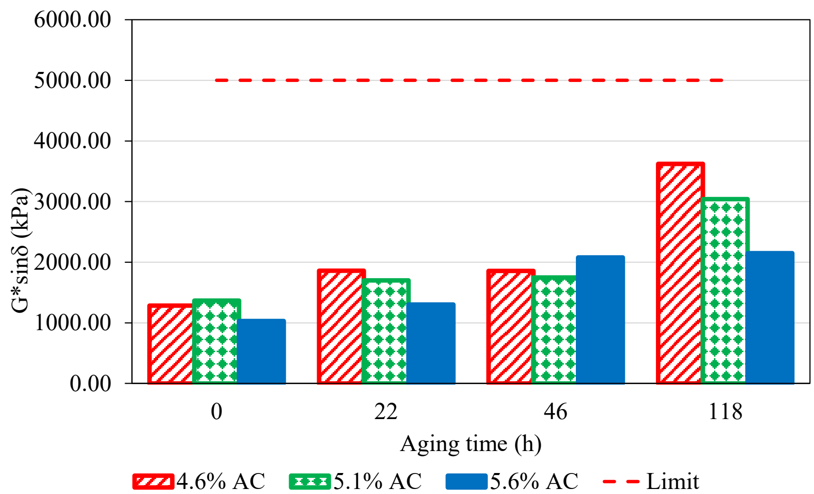

Figure 23. Comparison of Binder Fatigue Cracking Parameter for Mixes with 4.6, 5.1, and 5.6% Asphalt Content at 25°C (77°F)

Figure 24 reports the black space diagram with G-R parameters for the different aged asphalt binders, with two reference lines marking the thresholds for crack initiation (G-R = 180 kPa) and significant cracking (G-R = 600 kPa). Higher complex modulus and lower phase angle values suggest an increased tendency for asphalt mixtures to crack in the field. As the G-R values increase or shift to the left, the likelihood of cracking in asphalt binders rises. All G-R values fall below the crack initiation threshold. The black space diagrams, employing the Glover-Rowe parameter, provide insight into the cracking potential of the mixes. With increased aging time, the Glover-Rowe parameter shifts indicate a higher susceptibility to cracking, particularly in mixes with lower binder content. Despite these shifts, all mixes remain within the no-block cracking region, suggesting that while aging impacts cracking behavior, the changes in binder content do not lead to significant cracking issues within the tested parameters.

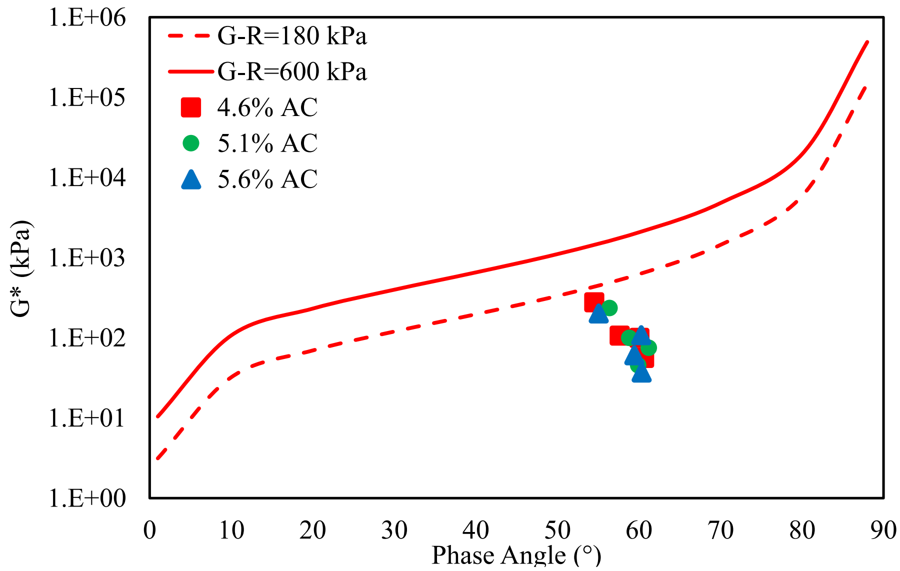

Figure 24. Variations in Glover-Rowe Parameter in Black Space Diagram for Different Binders Extracted from Mixes with 4.6, 5.1, and 5.6% Asphalt Content

Figure 25 illustrates the correlation between fatigue cracking results of asphalt mixes and asphalt binders. This figure demonstrates a strong relationship between the fatigue resistance of the mixes and the properties of the binders used. Specifically, it shows that mixes with binders that have higher fatigue parameter values tend to exhibit lower fatigue resistance during mixture testing (higher CPR). Figure 26 shows the correlation between Glover Rowe values of recovered binders and the (CPR) of the asphalt mixes. Again, there is a good correlation between binder and mixture results, binders with higher G-R relate to less asphalt mixture fatigue cracking resistance.

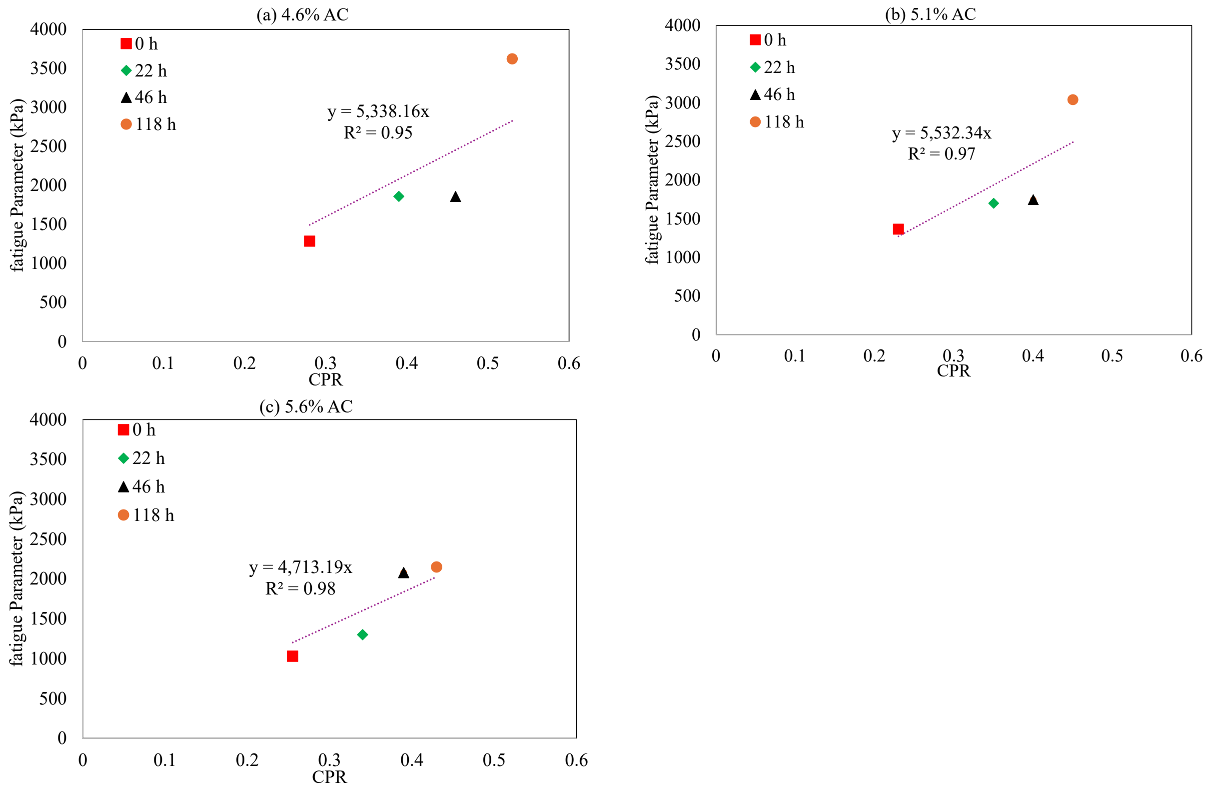

Figure 25. Correlation Between Asphalt Mix and Asphalt Binder Results, Fatigue Parameter vs CPR @ 25 ˚C for Mixes with (a) 4.6% AC, (b) 5.1% AC, (c) 5.6% AC

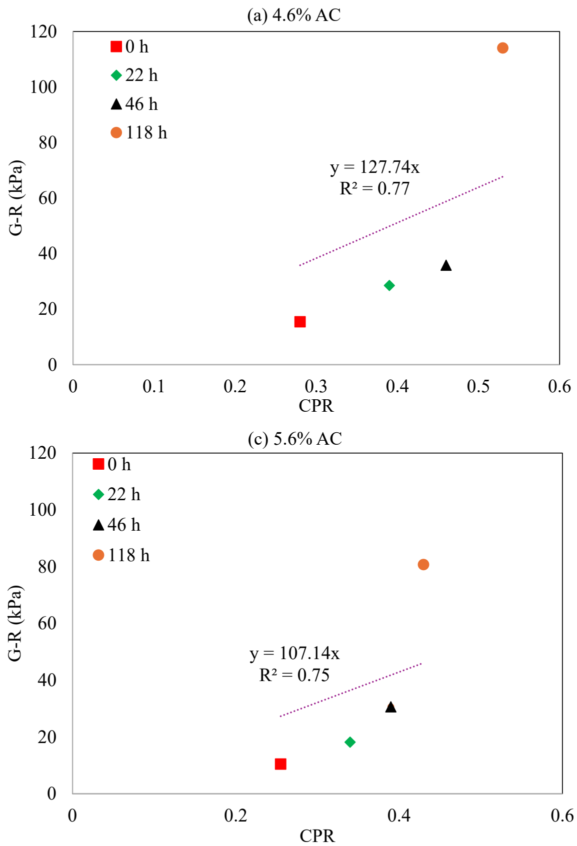

Figure 26. Correlation Between Asphalt Mix and Asphalt Binder Results, Glover-Rowe Parameter vs CPR for Mixes with (a) 4.6% AC, (b) 5.1% AC, (c) 5.6% AC

Effect of Gradation on the Fatigue Cracking Performance of Asphalt Mixes and Recovered Asphalt Binder

Figure 27, adapted from Arras (2023), shows the variation of CPR values from OT tests obtained for all mixes at different aging periods. Considering an upper limit of 0.45 when evaluating fresh asphalt mixtures for a balanced mix design according to Tex-248-F, all three unaged mixtures are crack-resistant. Mixes with Finer Gradation exceed the limit after 118 hours long term aging.

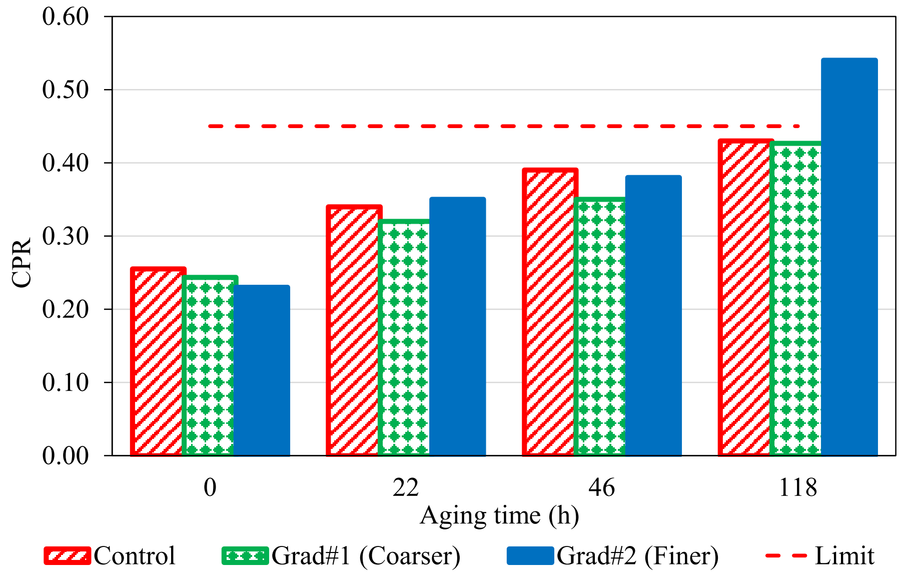

Figure 27. Mix Fatigue Parameters for Asphalt Mixes with Different Gradation at Different Ages (Arras, 2023)

Figure 28 presents the FTIR test results, identifying the functional groups associated with aging, explicitly highlighting the increase in carbonyl absorbance peaks. This increase correlates with the chemical changes in the asphalt binder due to aging, demonstrating a direct relationship between aging duration and the presence of carbonyl groups. These detailed analyses provide a comprehensive understanding of how aging, and gradation influence the mechanical and chemical properties of asphalt mixes, guiding future mix design to enhance pavement performance and longevity. Figure 28 depicts the FTIR test results and reveals a relationship between aging time and the chemical composition changes in asphalt binders. Specifically, the absorbance peaks of the Carbonyl group (around 1700 cm-1 wavenumber), and sulfoxide group (around 1030 cm-1 wavenumber) show an upward trend as aging progresses. This increase in absorbance peaks indicates a rise in oxidation and degradation within the binder over time. These findings underscore the impact of aging on the chemical composition of asphalt, which can influence its performance and durability.

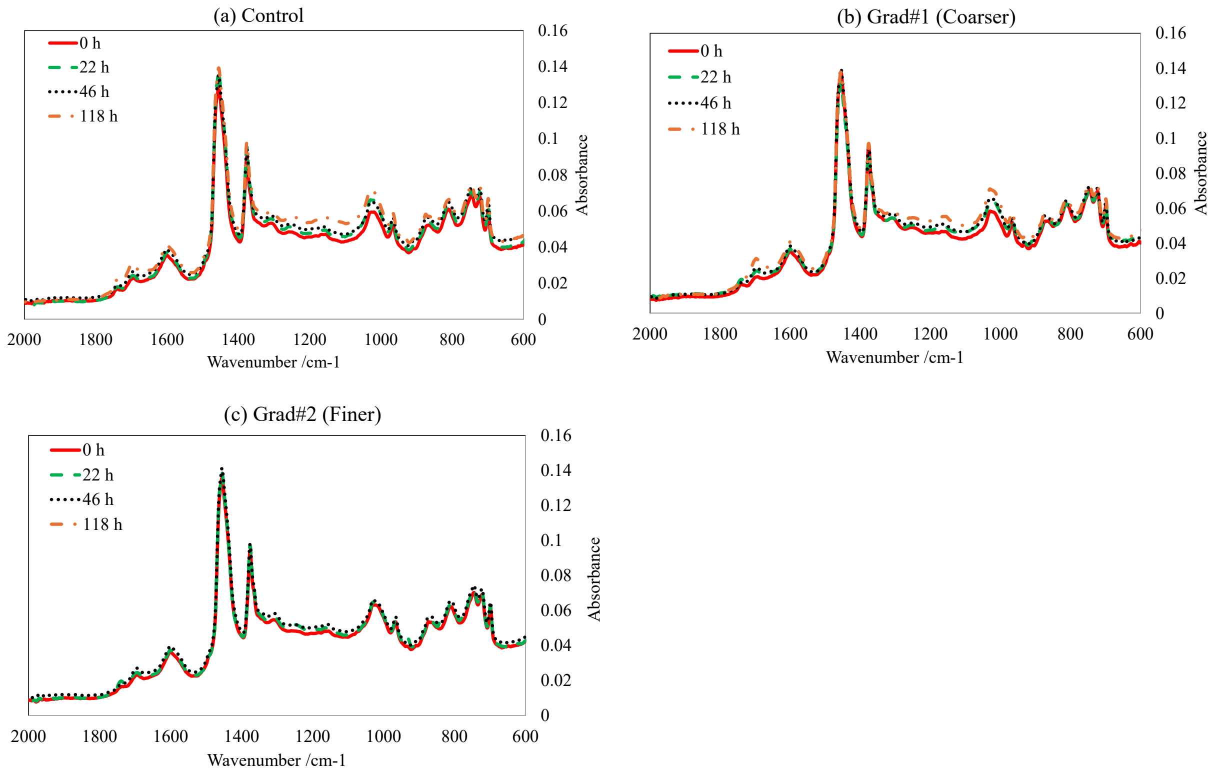

Figure 28. Comparison of the Functional Groups Containing the Carbonyl and Sulfoxide Groups in the Asphalt Binder of Each Mixture at Different Aging Periods (a) Control Mix, (b) Grad#1 (Coarser), and (c) Grad#2 (Finer)

Figure 29 shows the carbonyl and sulfoxide absorbance change peaks at a specific aging period for mixes with different gradations. After aging, no significant difference in the absorbance peak was observed when changing the gradation.

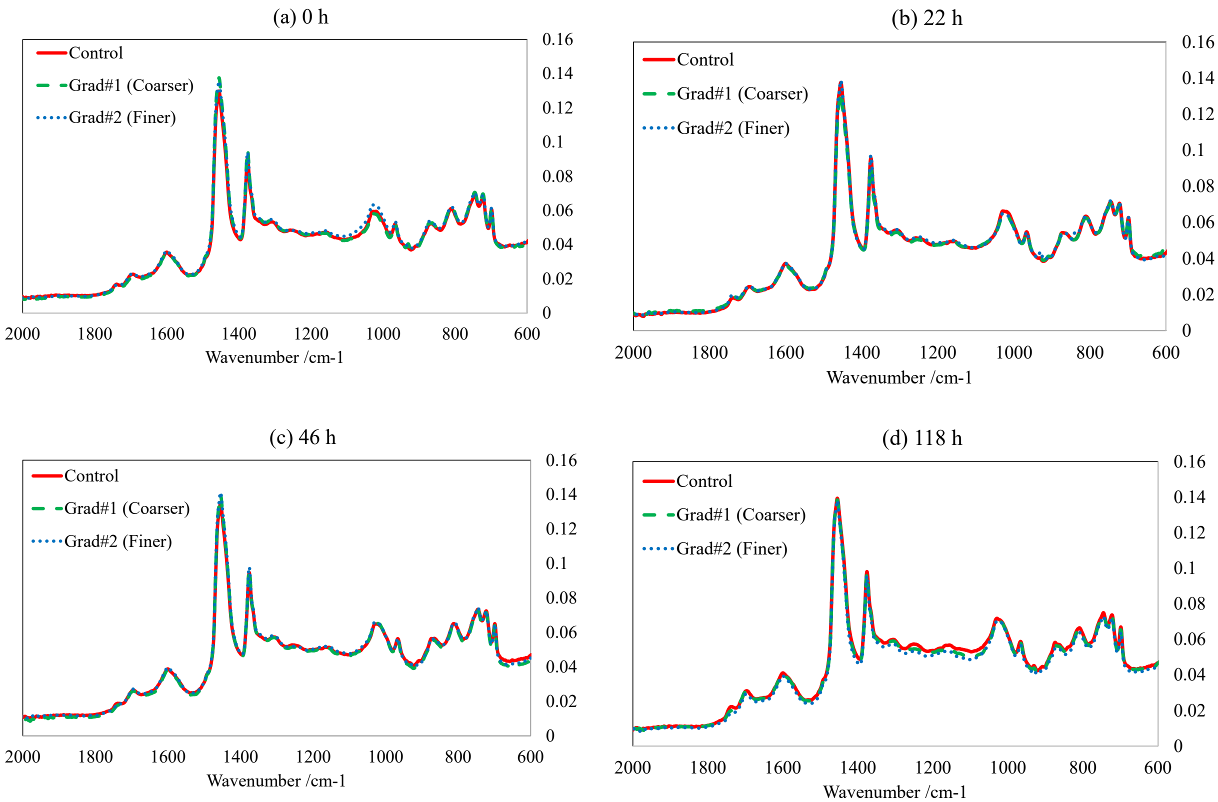

Figure 29. Carbonyl and Sulfoxide Functional Group Peak Comparison for All Mixes at Specific Aging Period (a) 0 h, (b) 22 h, (c) 46 h, (d) 118 h

Figure 30 shows the master curves for the aged binders extracted and recovered from mixtures with different gradations. The complex modulus (G*) of all aged binders was measured in the frequency sweep mode at 15, 19, 22, 25, 29, and 32°C using DSR. The rheological measurements corroborate that an increase in aging time results in an increase in complex modulus, meaning that aging stiffens the binder. The master curve plots reveal that mixes with finer gradation exhibit higher stiffness, which aligns with the observed higher complex modulus values and the fact that such mixes tend to have a thinner asphalt film thickness.

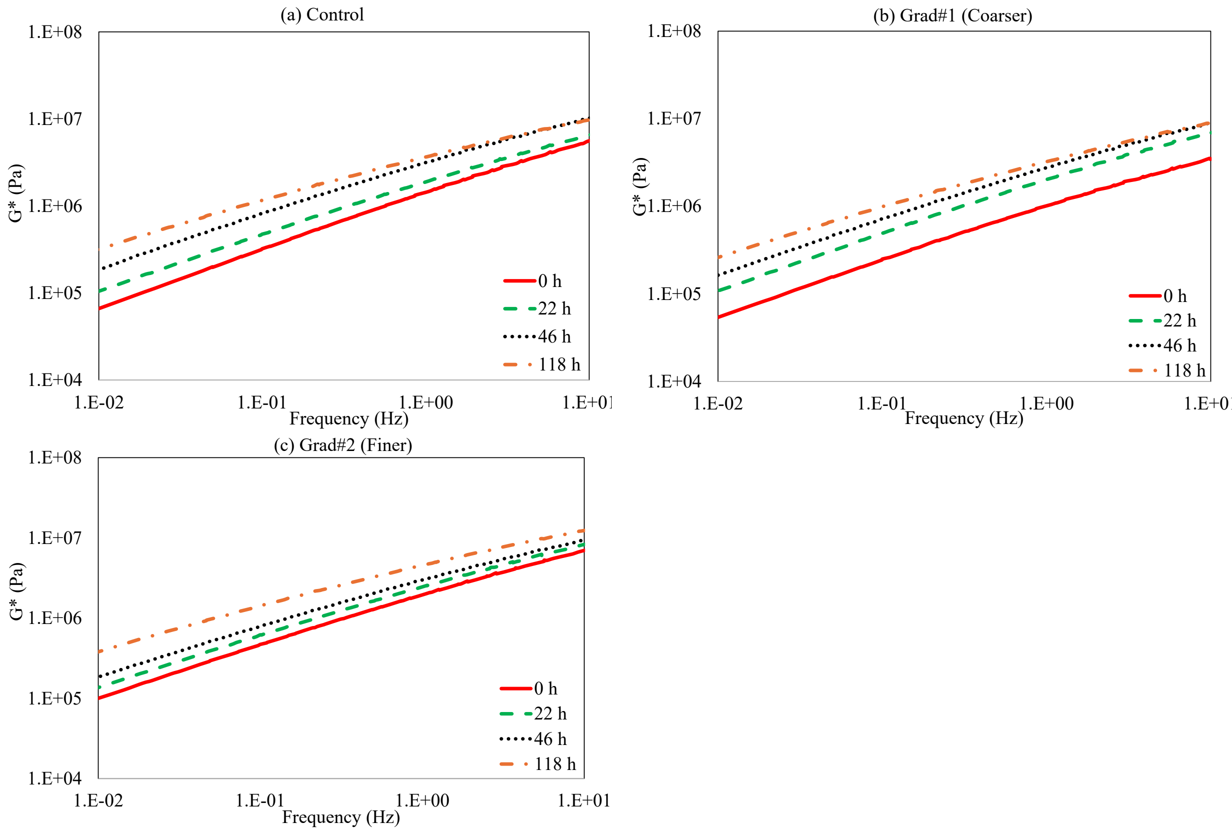

Figure 30. Comparison of Master Curves for Mixes with Different Aggregate Gradation (a) Control Mix, (b) Grad#1 (Coarser), and (c) Grad#2 (Finer)

Figure 31 shows the variations of fatigue parameter G*×Sin δ with temperature for asphalt binders extracted and recovered from mixtures after different aging periods. All the mixes with different aggregate gradations exhibited decreased fatigue resistance as aging time increased. This figure highlights how finer gradation exhibits lower fatigue resistance as aging progresses.

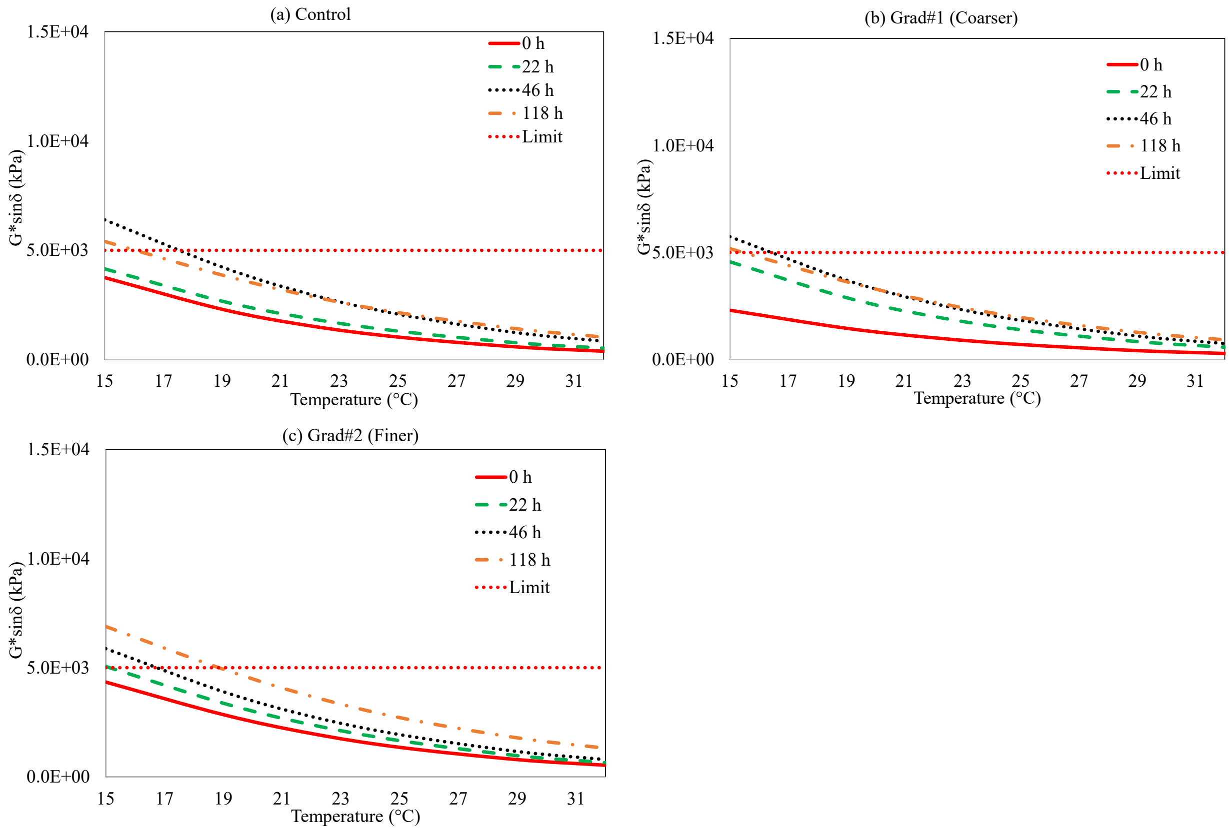

Figure 31. Comparison of Binder Fatigue Cracking Parameters for Mixes with Different Aggregate Gradation (a) Control Mix, (b) Grad#1 (Coarser), and (c) Grad#2 (Finer)

As shown in Figure 32, the fatigue resistance ranking shifted as the materials were aged. At 0 hours long term aging at 95°C, the mix with coarser gradation (Grad#1) has the highest resistance against fatigue cracking; however, after 118 hours of long-term aging at 95°C, the fatigue resistance ranking for all mixes is almost the same.

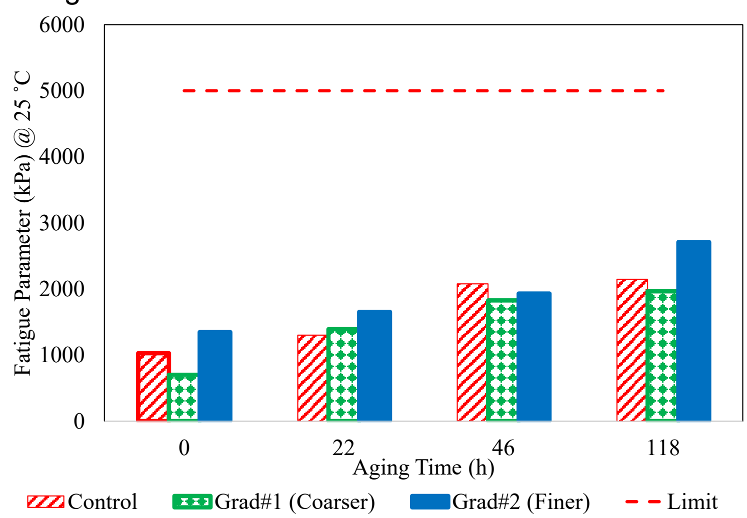

Figure 32. Comparison of Binder Fatigue Cracking Parameter for Mixes with Different Aggregate Gradation, Control Mix, Grad#1 (Coarser), Grad#2 (Finer) at 25°C (77°F)

Figure 33 reports the black space diagram with G-R parameters for the different aged asphalt binders, with two reference lines marking the thresholds for crack initiation (G-R = 180 kPa) and significant cracking (G-R = 600 kPa). Higher complex modulus and lower phase angle values suggest an increased tendency for asphalt mixtures to crack in the field. As the G-R values increase or shift to the left, the likelihood of cracking in asphalt binders rises. All G-R values fall below the crack initiation threshold. The black space diagrams, employing the Glover-Rowe parameter, provide insight into the cracking potential of the mixes. With increased aging time, the Glover-Rowe parameter shifts indicate a higher susceptibility to cracking. Despite these shifts, all mixes remain within the no-block cracking region, suggesting that while aging impacts cracking behavior, the changes in gradation do not lead to significant cracking issues within the tested parameters.

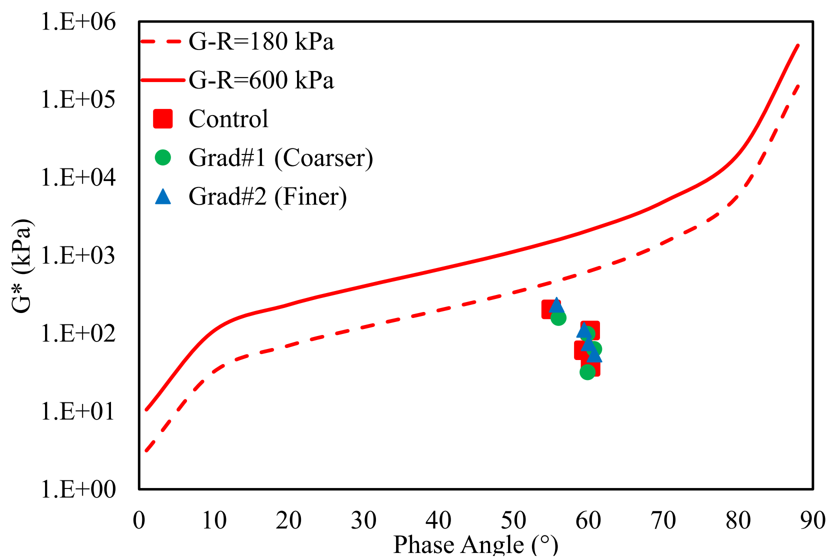

Figure 33. Variations in Glover-Rowe Parameter in Black Space Diagram for Different Binders Extracted from Mixes with Different Aggregate Gradation, Control Mix, Grad#1 (Coarser), Grad#2 (Finer)

Figure 34 illustrates the correlation between fatigue cracking results of asphalt mixes and asphalt binders. This figure demonstrates a strong relationship between the fatigue resistance of the mixes and the properties of the binders used. Specifically, it shows that mixes with binders that have higher fatigue parameter values tend to exhibit lower fatigue resistance during mixture testing (higher CPR). Figure 35 shows the correlation between Glover Rowe values of recovered binders and the (CPR) of the asphalt mixes. Again, there is a good correlation between binder and mixture results, binders with higher G-R relate to less asphalt mixture fatigue cracking resistance.

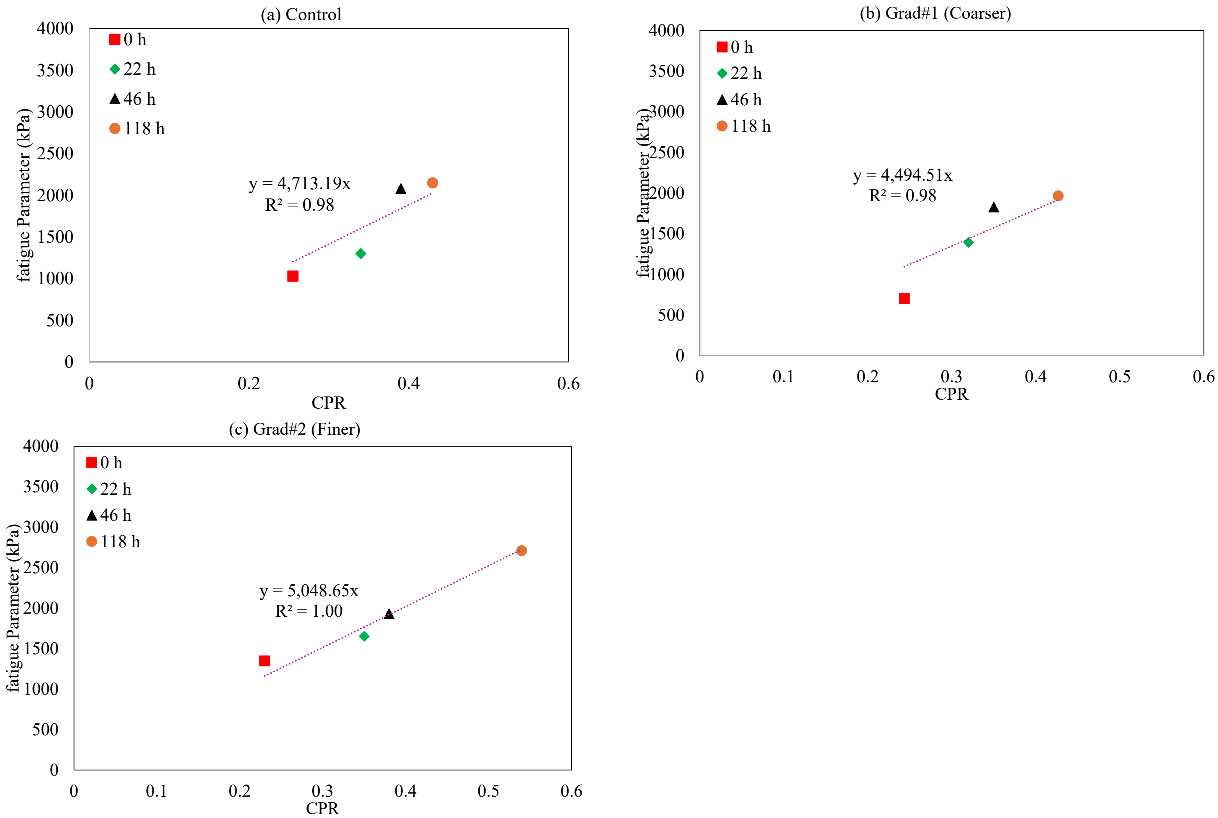

Figure 34. Correlation Between Asphalt Mix and Asphalt Binder Results, Fatigue Parameter vs CPR for Mixes with Different Aggregate Gradation (a) Control Mix, (b) Grad#1 (Coarser), and (c) Grad#2 (Finer)

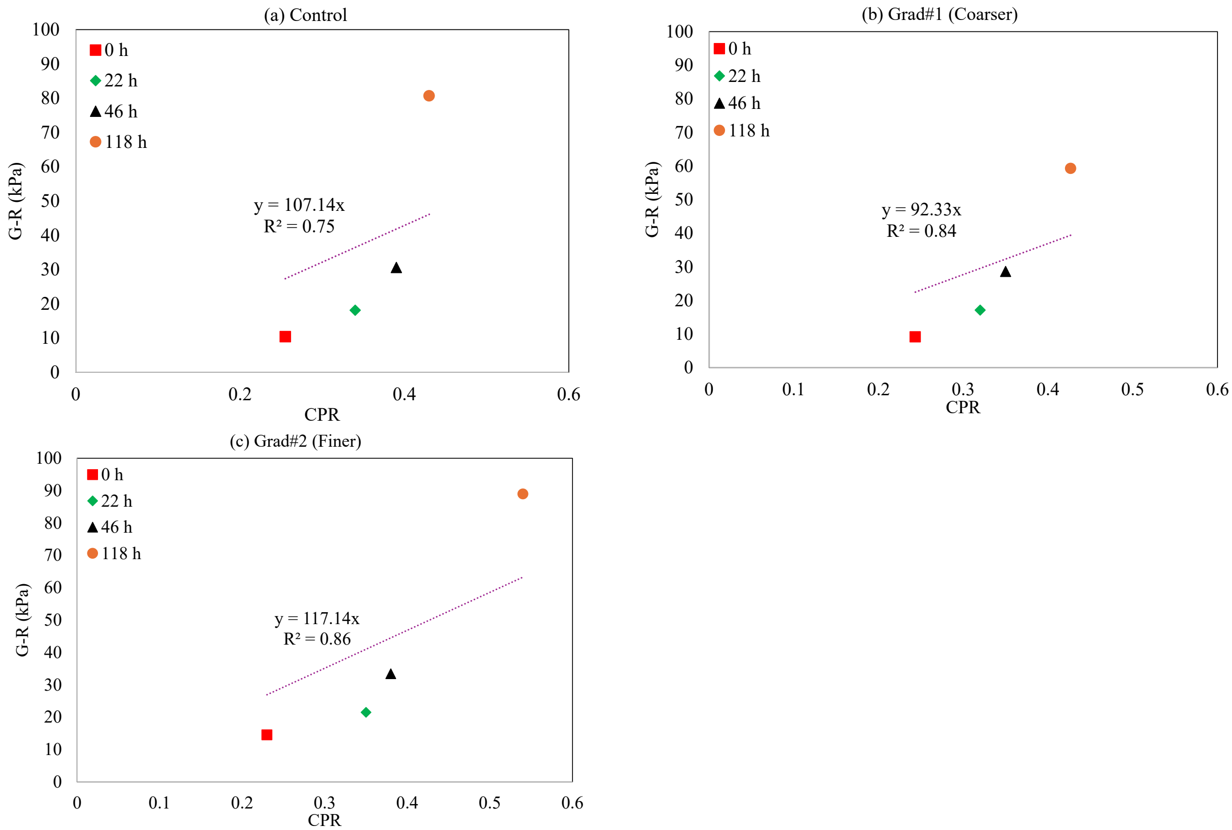

Figure 35. Correlation Between Asphalt Mix and Asphalt Binder Results, Glover-Rowe Parameter vs CPR for Mixes with Different Aggregate Gradation (a) Control Mix, (b) Grad#1 (Coarser), and (c) Grad#2 (Finer)

Effect of Additive Content on the Fatigue Cracking Performance of Asphalt Mixes and Recovered Asphalt Binder

Figure 36, adapted from Arras (2023), shows the variation of CPR values from OT tests obtained for all mixes at different aging periods. Considering an upper limit of 0.45 when evaluating fresh asphalt mixtures for a balanced mix design according to Tex-248-F, all three unaged mixtures are crack-resistant. Mixes with 3% additive exceed the limit after 46 hours long term aging, mixes with 4.5% additives exceed the limit after 118 hours long term aging, and mixes with 6% additives does not exceed the limit. One should keep in mind that the 0.45 limit is for unaged material, so setting a limit for long-term aged mixes needs further research.

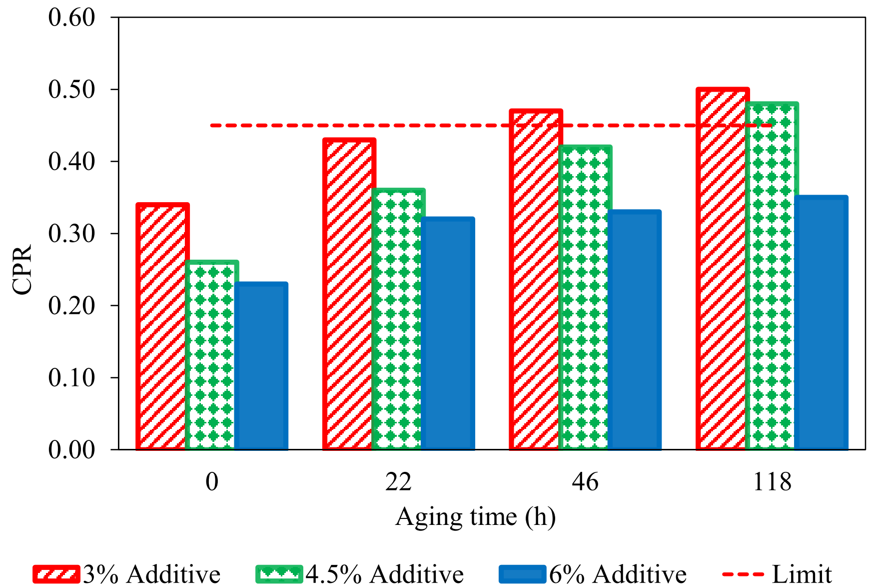

Figure 36. Mix Fatigue Parameters for Asphalt Mixes with Different Additive Content at Different Ages, 3%, 4.5%, and 6% Additive (Arras 2023)

Figure 37 presents the FTIR test results, identifying the functional groups associated with aging, specifically highlighting the increase in carbonyl absorbance peaks. This increase correlates with the chemical changes in the asphalt binder due to aging, demonstrating a direct relationship between aging duration and the presence of carbonyl groups. These detailed analyses provide a comprehensive understanding of how aging and additive content influence the mechanical and chemical properties of asphalt mixes, guiding future mix design to enhance pavement performance and longevity. Figure 37 depicts the FTIR test results and reveals a relationship between aging time and the chemical composition changes in asphalt binders. Specifically, the absorbance peaks of the Carbonyl group (around 1700 cm-1 wavenumber), and sulfoxide group (around 1030 cm-1 wavenumber) show an upward trend as aging progresses. This increase in absorbance peaks indicates a rise in oxidation and degradation within the binder over time. These findings underscore the impact of aging on the chemical composition of asphalt, which can influence its performance and durability.

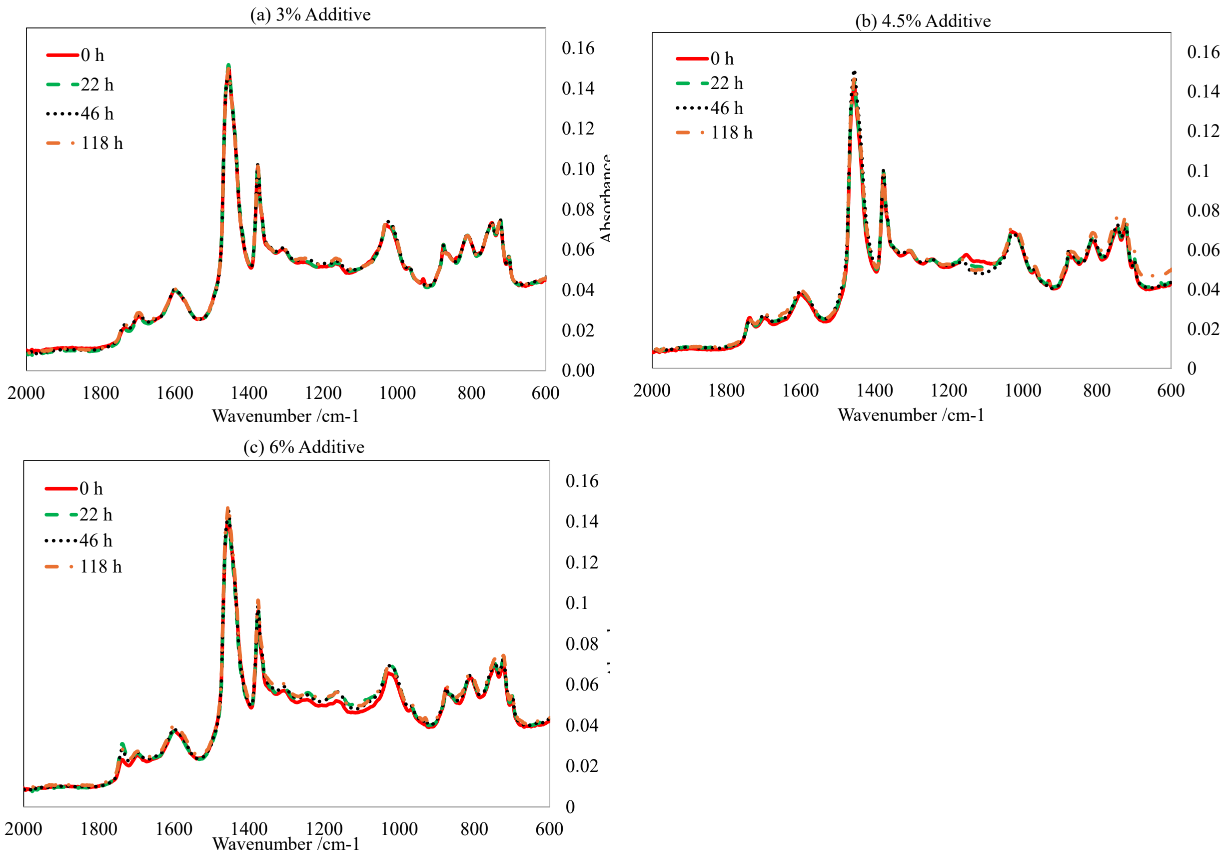

Figure 37. Comparison of the Functional Groups Containing the Carbonyl and Sulfoxide Groups in the Asphalt Binder of Each Mixture at Different Aging Periods (a) 3% additive, (b) 4.5% additive, (c) 6% additive

Figure 38 shows the change in the carbonyl and sulfoxide absorbance peaks at a specific aging period for mixes with different additive content.

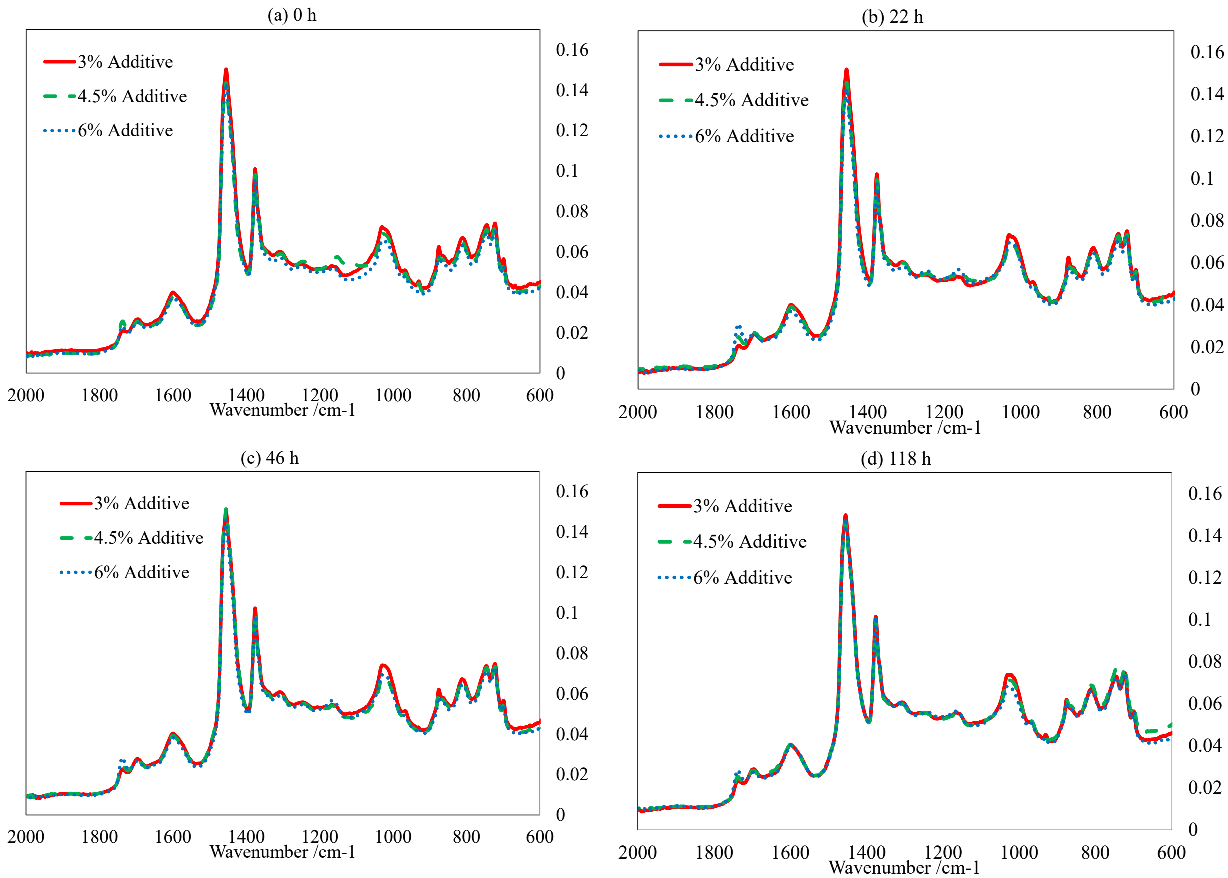

Figure 38. Carbonyl and Sulfoxide Functional Group Peak Comparison for All Mixes at Specific Aging Period (a) 0 h, (b) 22 h, (c) 46 h, (d) 118 h

Figure 39 shows the master curves for the aged binders extracted and recovered from mixtures with different additive content. The complex modulus (G*) of all aged binders was measured in the frequency sweep mode at 15, 19, 22, 25, 29, and 32°C using DSR. The rheological measurements corroborate that an increase in aging time results in an increase in complex modulus, meaning that aging stiffens the binder. The master curve plots reveal that mixes with different additive content exhibit almost similar stiffness, which aligns with the observed almost similar complex modulus values.

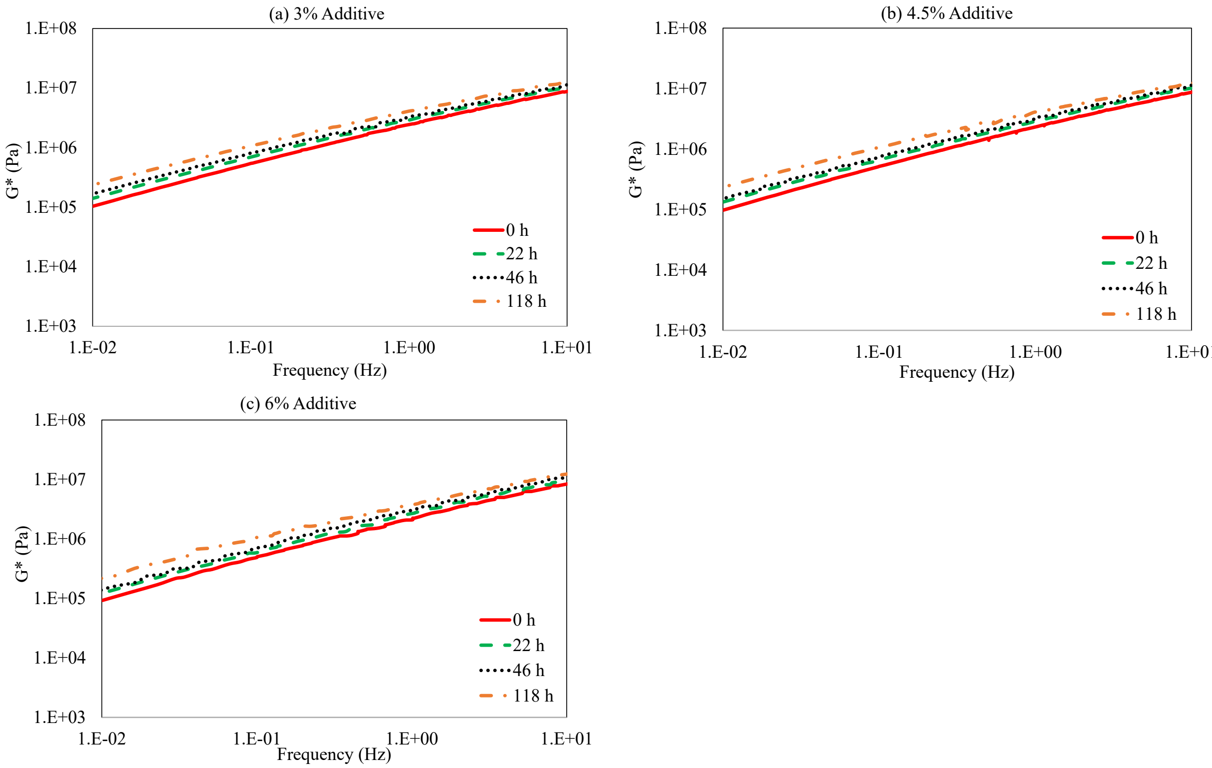

Figure 39. Comparison of Master Curves for Mixes with Different Additive Content (a) 3% additive, (b) 4.5% additive, (c) 6% additive

Figure 40 shows the variations of fatigue parameter G*× Sin δ with temperature for asphalt binders extracted and recovered from mixtures after different aging periods. All the mixes with different additive content exhibited decreased fatigue resistance as aging time increased. This figure highlights the similarity in fatigue resistance for mixes with different additive content as aging progresses.

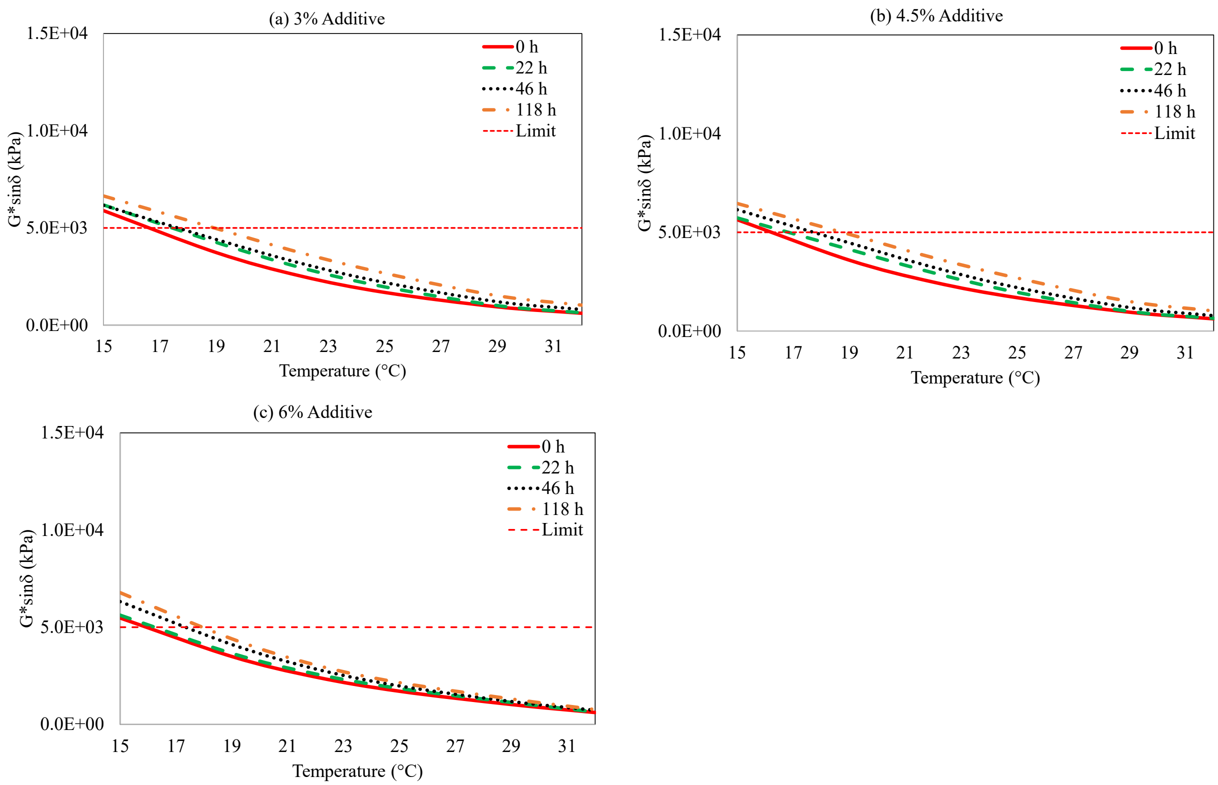

Figure 40. Comparison of Binder Fatigue Cracking Parameters for Mixes with Different Additive Content (a) 3% additive, (b) 4.5% additive, (c) 6% additive

As shown in Figure 41, at 0 hours aging at 95°C, all mixes have almost similar resistance against fatigue cracking; however, after 118 hours of long-term aging at 95°C, the fatigue resistance for the mix with 6 % additive content is higher than the mixes with 4.5%, and 3% additive content.

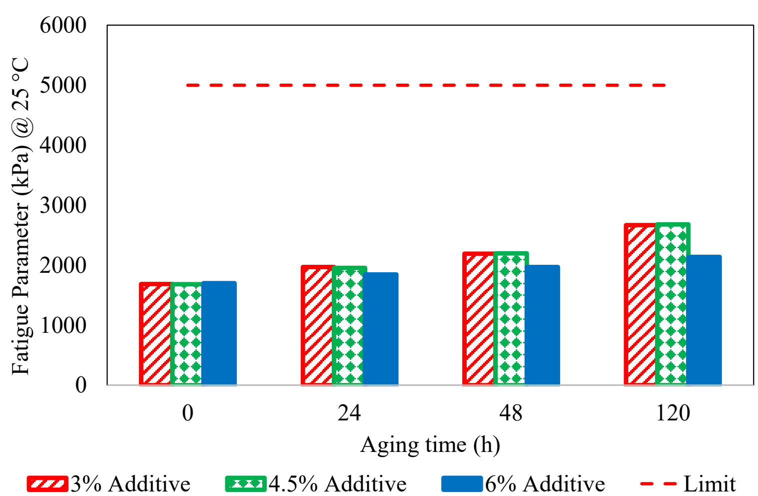

Figure 41. Comparison of Binder Fatigue Cracking Parameter for Mixes with Different Additive Content 3%, 4.5%, and 6% Additive at 25°C (77°F)

Figure 42 reports the black space diagram with G-R parameters for the different aged asphalt binders, with two reference lines marking the thresholds for crack initiation (G-R = 180 kPa) and significant cracking (G-R = 600 kPa). Higher complex modulus and lower phase angle values suggest an increased tendency for asphalt mixtures to crack in the field. As the G-R values increase or shift to the left, the likelihood of cracking in asphalt binders rises. All G-R values fall below the crack initiation threshold. The black space diagrams, employing the Glover-Rowe parameter, provide insight into the cracking potential of the mixes. With increased aging time, the Glover-Rowe parameter shifts indicate a higher susceptibility to cracking. Despite these shifts, all mixes remain within the no-block cracking region, suggesting that while aging impacts cracking behavior, the changes in additive content do not lead to significant cracking issues within the tested parameters.

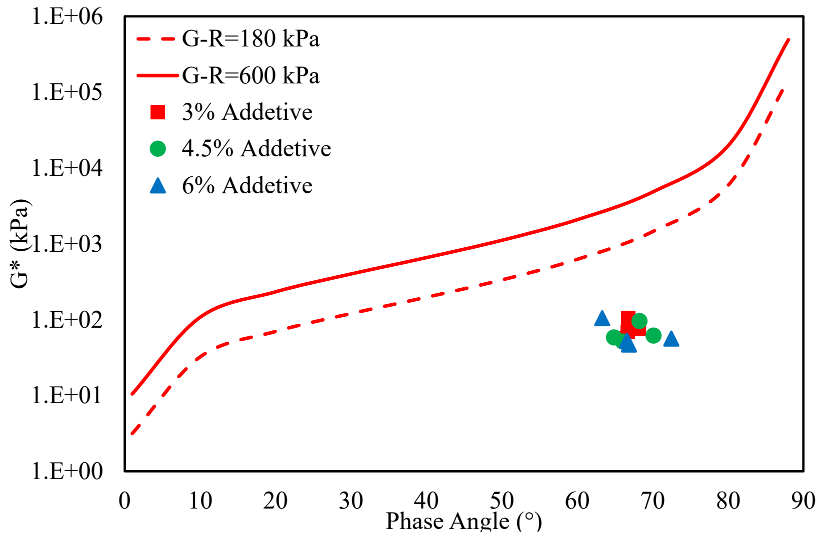

Figure 42. Variations in Glover-Rowe Parameter in Black Space Diagram for Different Binders Extracted from Mixes with Different Additive Content 3%, 4.5%, and 6% Additive

Figure 43 illustrates the correlation between fatigue cracking results of asphalt mixes and asphalt binders. This figure demonstrates a strong relationship between the fatigue resistance of the mixes and the properties of the binders used. Specifically, it shows that mixes with binders that have higher fatigue parameter values tend to exhibit lower fatigue resistance during mixture testing (higher CPR). Figure 44 shows the correlation between Glover Rowe values of recovered binders and the (CPR) of the asphalt mixes. Binders with higher G-R relate to less asphalt mixture fatigue cracking resistance.

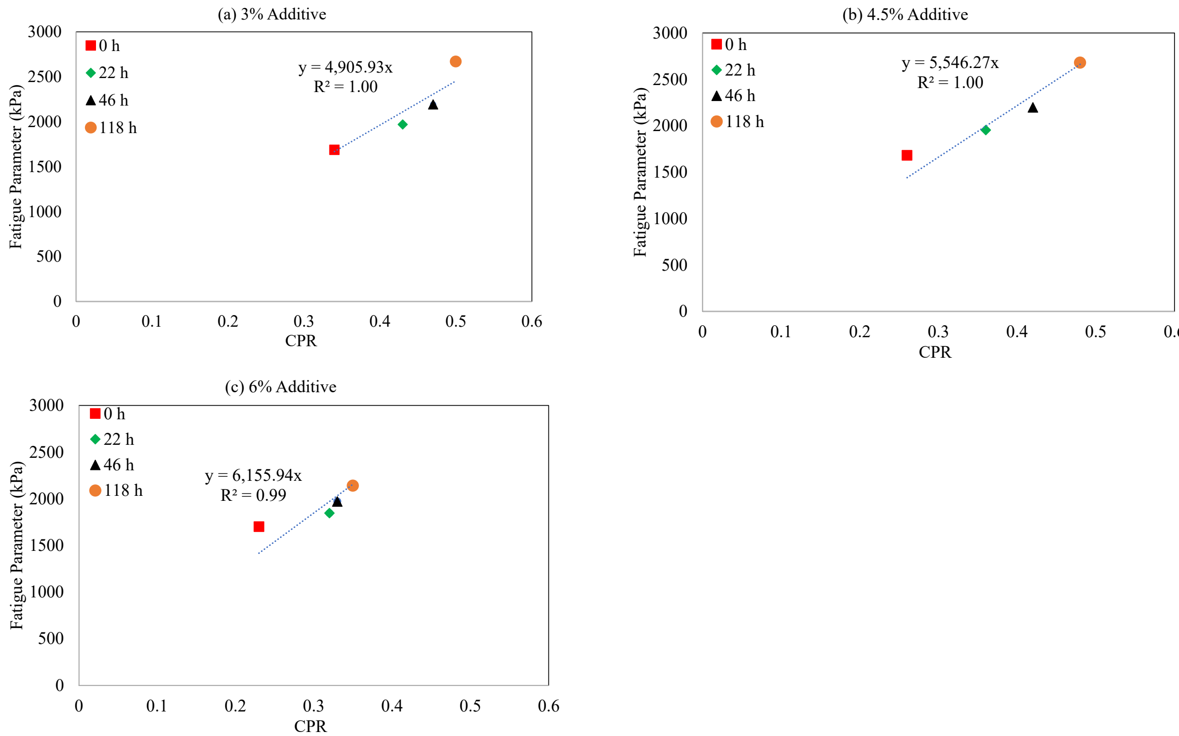

Figure 43. Correlation Between Asphalt Mix and Asphalt Binder Results, Fatigue Parameter vs CPR for Mixes with Different Additive Content (a) 3% additive, (b) 4.5% additive, (c) 6% additive

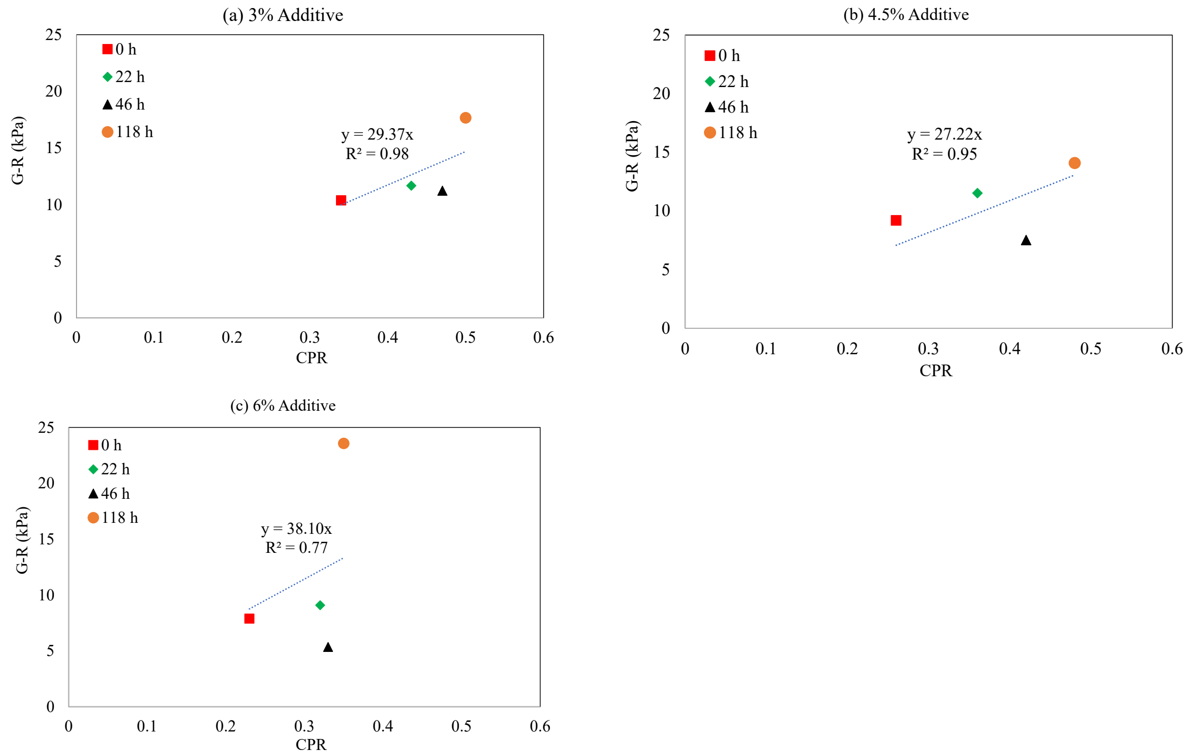

Figure 44. Correlation Between Asphalt Mix and Asphalt Binder Results, Glover-Rowe Parameter vs CPR for Mixes with Different Additive Content (a) 3% additive, (b) 4.5% additive, (c) 6% additive

Chapter 5. Conclusions and Recommendations

Conclusions

This study investigated the impact of long-term aging on the mechanical properties of hot mix asphalt (HMA) mixes, focusing on the effects of RAP content, binder content, aggregate gradation, and additive content. The key findings are summarized as follows:

- RAP Content: Increasing RAP content in HMA mixes generally enhances stiffness and reduces fatigue resistance. However, higher RAP content (30%) showed a lower rate of aging, indicating better preservation of binder properties over time. The chemical analysis revealed that higher RAP content reduces oxidation and degradation, suggesting less susceptibility to aging and similar long-term performance to mixtures with lower RAP contents.
- Binder Content: Higher binder content improves initial fatigue resistance but shows negligible differences in long-term aging effects. All mixes exhibited decreased fatigue resistance with prolonged aging. The rheological properties indicated that mixes with higher binder content maintain better flexibility initially but converge in performance after extended aging.
- Aggregate Gradation: The chemical and rheological analyses confirmed that aggregate gradation negligibly influences the aging behavior and mechanical properties of HMA mixes.
- Additive Content: The inclusion of additives improved the fatigue resistance of HMA mixes. Mixes with higher additive content (6%) performed better after long-term aging than those with lower additive content. The chemical analysis indicated that additives help mitigate the negative effects of aging, enhancing the durability of asphalt binders.

Recommendations

Based on the findings of this study, the following recommendations are proposed to improve the aging resistance and overall performance of HMA mixes:

- Optimizing RAP Content: Utilize higher RAP content (up to 30%) in HMA mixes to enhance performance and reduce material costs. Ensure proper blending and processing to maintain performance. Conduct further research to refine the aging models and optimize the mix design for high RAP content.
- Adjusting Binder Content: Maintain an optimal binder content that balances initial flexibility and long-term durability. Consider the specific environmental and loading conditions when determining the binder content. Implement performance-based specifications that account for the aging characteristics of binders.
- Selecting Appropriate Aggregate Gradation: Tailor the gradation based on the expected service life and traffic conditions. Develop guidelines for aggregate selection that consider the aging behavior and mechanical properties of HMA mixes.
- Incorporating Additives: Include additives in HMA mixes to improve aging resistance and enhance fatigue performance. Select additives based on their compatibility with the binder and overall mix design. Perform long-term field evaluations to validate the laboratory findings and adjust the additive dosages accordingly.

Future Research Directions

Investigate the combined effects of multiple variables (e.g., RAP content, binder type, and additives) on the aging behavior of HMA mixes. Develop advanced aging protocols that better simulate real-world conditions and provide more accurate predictions of pavement performance. By implementing these recommendations, practitioners can design and construct asphalt pavements with extended lifespans and reduced maintenance costs. The findings of this study contribute to the advancement of asphalt technology and provide valuable insights for future research and practice.

Chapter 6. Implementation of Project Outputs

The findings from this research provide valuable insights into the aging behavior of HMA and offer practical recommendations for enhancing the durability and performance of asphalt pavements. This chapter outlines the steps for implementing the project outputs, focusing on the application of the research findings in real-world scenarios, the development of guidelines and standards, and the dissemination of knowledge to stakeholders.

Application in Pavement Design and Construction

Utilize the research findings to develop optimized HMA mix designs incorporating higher RAP content, appropriate binder content, and suitable aggregate gradation and additives. These designs should enhance aging resistance and improve the overall performance of asphalt pavements. Implement the recommended mix designs in pilot projects to evaluate their performance under field conditions. Monitor and document the performance to validate the laboratory findings and make necessary adjustments.

Develop performance-based specifications that incorporate the aging characteristics of asphalt binders and mixtures. These specifications should guide the selection of materials and mix designs to ensure long-term durability and resistance to fatigue cracking. Collaborate with transportation agencies and industry stakeholders to adopt these specifications in pavement design and construction practices.

Implement best practices for producing and placing HMA mixtures to minimize aging during construction. This includes controlling mixing temperatures, ensuring proper compaction, and using appropriate additives. Train construction personnel on the importance of these practices and provide guidelines for their implementation.

Development of Guidelines and Standards

Develop comprehensive guidelines for using RAP in HMA mixtures based on the research findings. These guidelines should cover selecting RAP materials, blending procedures, and quality control measures to ensure consistent performance. Promote the adoption of these guidelines by state and local transportation agencies to encourage the use of RAP in pavement construction.

Establish standardized aging protocols for laboratory testing of asphalt mixtures. These protocols should simulate real-world aging conditions and provide reliable predictions of long-term pavement performance. Work with standard-setting organizations, such as ASTM and AASHTO, to incorporate these protocols into existing standards and testing procedures.

Current Status

The research team has shared the findings of this report with the TxDOT Materials and Tests Division to incorporate aging specifications into their standards.

Chapter 7. Technology Transfer and Community Engagement and Participation (CEP) Activities

The research team has developed PowerPoint presentations to share the findings of this research with transportation agencies. The presentations developed can help to organize workshops and training programs to disseminate research findings and recommendations to industry professionals, transportation agencies, and academic institutions. These programs should focus on the practical application of the research outputs and provide hands-on training for implementing the recommended practices. Also, online training SPTC modules and resources can be elaborated to reach a broader audience and facilitate continuous learning.

The research has participated in CEP activities, including online training modules on various topics. Additionally, this research provided hands-on laboratory experience to two El Paso Community College undergraduate students, Angel Salinas and Armando Gutierrez.

Chapter 8. Invention Disclosures and Patents, Publications, Presentations, Reports, Project Website, and Social Media Listings

Presentations:

- Investigation of Hot Asphalt Aging Effect on Binder Performance, Annual COURI Symposia, UTEP, El Paso, April 27, 2024.
- Enhancing Pavement Durability: The Impact of Reclaimed Asphalt Pavement Content on Long-Term Aging and Crack Resistance, IAI Summit Conference, August 12-14, 2024.
- Enhancing Pavement Durability: The Impact of Reclaimed Asphalt Pavement Content on Long-Term Aging and Crack Resistance, CTIS Research Connect, November 21, 2024.

Publications:

- Effect of RAP Content on Crack-Susceptibility of Aged Asphalt Mixtures and Binders. Journal Paper. (under-review).

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