INFLUENCE OF CHEMICAL WARM MIX ADDITIVE ON THE PERFORMANCE OF BITUMINOUS BINDERS AND BITUMINOUS MIXTURES CONTAINING WASTE PLASTIC COATED COARSE AGGREGATES

Submitted in partial fulfilment of the requirements

for the award of the degree of

Doctor of Philosophy

By

T. Arjun Kumar

714003

Department of Civil Engineering

NATIONAL INSTITUTE OF TECHNOLOGY

WARANGAL

JUNE 2023

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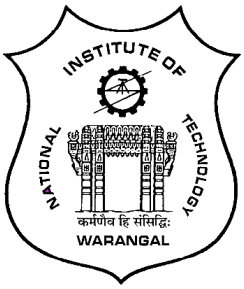

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CERTIFICATE

This is to certify that the thesis entitled **"INFLUENCE OF CHEMICAL WARM MIX ADDITIVE ON THE PERFORMANCE OF BITUMINOUS BINDERS AND BITUMINOUS MIXTURES CONTAINING WASTE PLASTIC COATED COARSE AGGREGATES"** being submitted by Mr. T. Arjun Kumar for the award of the degree of DOCTOR OF PHILOSOPHY to the Department of Civil Engineering of NATIONAL INSTITUTE OF TECHNOLOGY, WARANGAL is a record of bonafide research work carried out by him under my supervision and it has not been submitted elsewhere for the award of any degree.

Dr. VENKAIAH CHOWDARY
Thesis Supervisor and Professor
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APPROVAL SHEET

This thesis entitled **"INFLUENCE OF CHEMICAL WARM MIX ADDITIVE ON THE PERFORMANCE OF BITUMINOUS BINDERS AND BITUMINOUS MIXTURES CONTAINING WASTE PLASTIC COATED COARSE AGGREGATES"** by Mr. Arjun Kumar Tirumali is approved for the degree of Doctor of Philosophy.

Examiners

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Supervisor

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Chairman

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DECLARATION

This is to certify that the work presented in the thesis entitled **"INFLUENCE OF CHEMICAL WARM MIX ADDITIVE ON THE PERFORMANCE OF BITUMINOUS BINDERS AND BITUMINOUS MIXTURES CONTAINING WASTE PLASTIC COATED COARSE AGGREGATES"** is a bonafide work done by me under the supervision of Dr. Venkaiah Chowdary and was not submitted elsewhere for the award of any degree. I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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Dedicated to

My Father, Mother, and Wife

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ABSTRACT

The majority of Indian roads are constructed with bituminous pavements for the surface course using Hot Mix Asphalt (HMA) technology. This technology involves the production of bituminous mixture at relatively higher mixing and compaction temperature. At these temperatures, inordinate oxidation and degradation of the bituminous binders occur due to aging. Furthermore, these higher temperatures requires higher energy consumption and emits harmful greenhouse gases which causes environment pollution and endangers the people who are involved in the various construction activities. Recently, various scientists and government agencies focused on reducing the working temperature of bituminous mixture which in turn consume less energy and less emission of greenhouse gases. In this direction, Warm Mix Asphalt (WMA) additives have been developed and practiced around the world to produce bituminous mixtures at reduced temperatures. Many researchers reported that the use of WMA additive reduces the stiffness of binders during short-term and long-term aging. However, very few researchers have reported the possible reason for stiffness reduction by analysing the formation of oxidation compounds during aging. The performance of the bituminous mixture will also depend on the rheological properties of the binder and the type of additives. Therefore, the present study investigates the influence of WMA additive on the changes in chemical and rheological characteristics of binders occurring during the aging process. Reduction in production temperatures results in bituminous mixtures that are more susceptible to rutting, whereas higher production temperatures results in mixtures that are susceptible to cracking and moisture damage. Inorder to overcome these issues, waste plastic has been incorporated in HMA and WMA mixtures using a dry process. However, the major disadvantage of the dry process is that the shredded waste plastic is added to whole fractions of preheated aggregate in the pug mill. Fused plastic tends to agglomerate with fine aggregate particles, and result in the formation of small lumps which may lead to underperformance of bituminous mixtures. Hence, the present study used an enhanced process, in which shredded waste plastic is initially introduced with preheated coarse aggregate, followed by the addition of fine aggregates and binder.

Therefore, the first phase of the present study was focused on evaluating the influence of WMA additive on functional chemical group characteristics, and rheological performance of bituminous binders. Two unmodified binders (VG20, VG40), two modified binders (PMB40, CRMB60), and a chemical warm mix additive (Evotherm) were selected for this study. To assess the chemical and rheological characterstics of all binders, a comprehensive laboratory

testing was carried out using Fourier transform infrared (FTIR) spectrometer, and dynamic shear rheometer at various aging conditions. FTIR spectrometer was used to quantify various aging indices such as carbonyl index and sulfoxide index whereas dynamic shear rheometer was used to evaluate the rheological performance of bituminous binders in terms of Superpave rutting parameter, fatigue parameter, Shenoy's parameter, non-recoverable creep compliance, zero shear viscosity, low shear viscosity, fatigue life, Glover-Rowe parameter, cracking initiation and the significant cracking threshold at various aging conditions using amplitude sweep, frequency sweep, multi-stress creep and recovery tests.

The second phase of the present study was focused on evaluating moisture-induced damage and rutting performance of HMA and WMA mixtures containing waste-plastic-coated coarse aggregates. Bituminous mixtures were prepared in the laboratory using Bituminous Concrete grading 2. The waste plastic consists of only shredded Low Density Polyethylene (LDPE) milk packets. The short-term aged mixtures were compacted to prepare specimens with a target air voids of 4% and 7% whereas the specimens for long-term aging were compacted to 4% air voids. The performance of bituminous mixtures towards moisture-induced damage was evaluated by carrying out dry as well as wet indirect tensile strength tests at 25^{o}C for all aging conditions. Rutting performance was evaluated by performing a dry wheel tracking test on all mixtures at 60^{o}C temperature for all aging conditions. The entire data obtained through tests on bituminous binders and bituminous mixtures was critically analysed to quantify aging indices and rheological parameters for bituminous binders, and moisture-induced damage and progression of rut depth for bituminous mixtures.

From the test results, it was observed that the addition of Evotherm additive in the base binder reduces the carbonyl index, and sulfoxide index. It indicates that the addition of an Evotherm additive in the base binder undergoes less aging. It was also observed that the addition of Evotherm additive in the control binder increases all rutting parameters except for non-recoverable creep compliance where reverse trend was observed. It indicates that addition of Evotherm in control binders increases the rutting potential. Furthermore, it was observed that the addition of Evotherm in the control binder increases the fatigue parameters which indicates a beneficial effect and resistance toward fatigue cracking. From the bituminous mixture test results, it was observed that the addition of LDPE-coated coarse aggregate (LCA) in HMA mixtures through the enhanced process improved the resistance against moisture-induced damage and permanent deformation. In the case of WMA mixture test results, it was observed that the addition of LCA has very less effect on moisture-induced damage performance whereas

resistance toward permanent deformation has been increased. Among all rutting parameters, the low shear viscosity has a better correlation with the rut depth of HMA and WMA mixtures.

KEYWORDS: Aging indices, Evotherm additive, fatigue parameters, FTIR, HMA mixture, LDPE-waste plastic coated aggregate, moisture-induced damage test, rutting parameters, rutting test, and WMA mixture.

TABLE OF CONTENTS

Page no.

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BC	Bituminous Concrete
BIS	Bureau of Indian Standard
CRMB	Crumb Rubber Modified Bitumen
DSR	Dynamic Shear Rheometer
EBC	Evotherm-modified-Bituminous concrete
ECRMB	Evotherm-modified-Crumb Rubber Modified Bitumen
EVG	Evotherm-modified-Viscosity Grade
EPMB	Evotherm-modified-Polymer Modified Bitumen
FHWA	Federal Highway Administration
FTIR	Fourier Transform Infra-red
G-R	Glower-Rowe
HMA	Hot Mix Asphalt
IR	Infra-red
IS	Indian Standard
IRC	Indian Roads Congress
kPa	kilo Pascal
LAS	Linear Amplitude Sweep
LVDT	Linear Variable Differential Transformer
LA	Long-term Aged
LBC	Bituminous Concrete mixture containing LDPE-coated coarse aggregate
LCA	LDPE-coated-Coarse Aggregate
LDPE	Low-density-Polyethylene
LEBC	Bituminous concrete mixture containing LDPE-coated-coarse aggregate and Evotherm additive
LSV	Low-Shear Viscosity
MoRTH	Ministry of Road Transport and Highways
MPa	Mega Pascal
msa	Million Standard Axle
MSCR	Multi-Stress Creep and Recovery
OBC	Optimum Binder Content

PAV	Pressure Aging Vessel
PMB	Polymer Modified Bitumen
WMA	Warm Mix Asphalt
MID	Moisture-Induced Damage
ITS	Indirect Tensile Strength
RTFO	Rolling Thin Film Oven
SA	Short-term Aged
SBS	Styrene Butadiene Styrene
SPI	Society of Plastics Industry
TSR	Tensile Strength Ratio
UA	Unaged
VG	Viscosity Grade
WLF	William Landel Ferry
ZSV	Zero-Shear Viscosity

NOTATIONS

G^*	Complex modulus
ω	Angular frequency
°	Degree
$G^*/\sin\delta$	Superpave rutting parameter
$G^*.\sin\delta$	Superpave fatigue parameter
δ	Phase angle
J_{nr}	Non-recoverable creep compliance
A	Absorption
T	Transmittance in FTIR spectroscopy
$A_{1660\text{-}1800}$	Absorption of IR light in wavenumber from 1660 to 1800 cm^{-1}
$A_{1010\text{-}1050}$	Absorption of IR light in wavenumber from 1010 to 1050 cm^{-1}
$A_{1350\text{-}1510}$	Absorption of IR light in wavenumber from 1350 to 1510 cm^{-1}
$A_{1560\text{-}1660}$	Absorption of IR light in wavenumber from 1560 to 1660 cm^{-1}
$A_{715\text{-}713}$	Absorption of IR light in wavenumber from 715 to 713 cm^{-1}
τ_{max}	Maximum applied shear stress
γ_{max}	Maximum shear strain
T	Maximum applied torque in DSR
$\%\gamma_{unr}$	Unrecoverable strain percentage
N_f	Fatigue life
σ	Stress
USS_{10}	Unrecoverable shear strain at end of 10 s
J_{nri}	Non-recoverable creep compliance of i^{th} cycle
η^*	Complex viscosity
η_o	Zero shear viscosity
K, m	Simplified Cross model parameters
f_{red}	Reduced frequency
f	Frequency

VMA	Voids in Mineral Aggregate
VFB	Voids Filled with Bitumen
α_t	Shift factor
C_1 and C_2	Constant in WLF equation
Δ, α, β, and γ	Sigmoidal model parameters
η'	Dynamic viscosity
G'	Storage modulus
G''	Loss modulus
G_{mm}	Theoretical Maximum Specific Gravity
G_{mb}	Bulk specific gravity

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Economic development of any country is dependent on the condition and performance of its roads because it impacts pace, pattern and structure of development. The total road network in India is about 64 lakh km, and it is categorized into expressways, national highways, state highways, major district roads, and other low-volume roads. Majority of these roads comprise of bituminous pavements. A bituminous pavement from the bottom consists of natural subgrade, compacted subgrade, sub-base course, base course, and bituminous layers as shown in the Figure 1.1. The top two layers consists of bituminous mixtures constructed mostly using Hot Mix Asphalt (HMA). The HMA mixtures generally contain about 95% of aggregates and 5% of bituminous binders measured by the weight of bituminous mixtures. The bituminous mixtures are produced and compacted to a very high temperature of about 148 to 176^{o}C (Corrigon et al., 2016) to dry the moisture in the aggregates, and also to reduce the viscosity the binder to fully coat the aggregates.

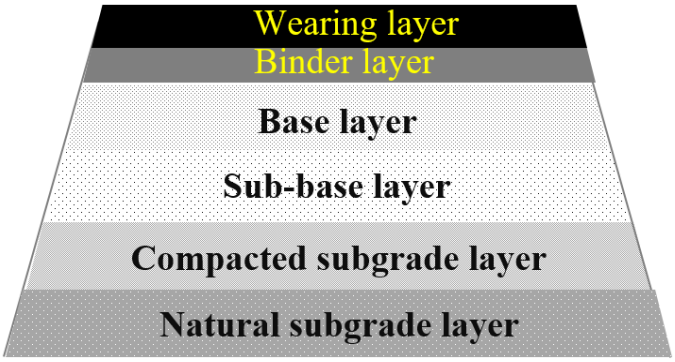


Fig. 1.1 Cross-section of a flexible pavement

The higher production temperatures of HMA results in emission of harmful greenhouse gases such as carbon dioxide, methane, and nitrogen oxides contributing to environmental pollution apart from higher energy consumption and negatively impacting the health of construction workers who are exposed to such environment on a regular basis (Mazumder *et al.*, 2016). Further, higher HMA production temperatures can result in oxidation and volatilization of bituminous binders resulting in cracking of bituminous layers. Based on the production temperatures, bituminous mixtures are classified as cold mix asphalt, half-warm mix asphalt, warm mix asphalt, and HMA as shown in Figure 1.2. In order to reduce the production and

compaction temperatures of bituminous mixtures, pavement technologists and academicians across the world introduced the Warm Mix Asphalt (WMA) technology.

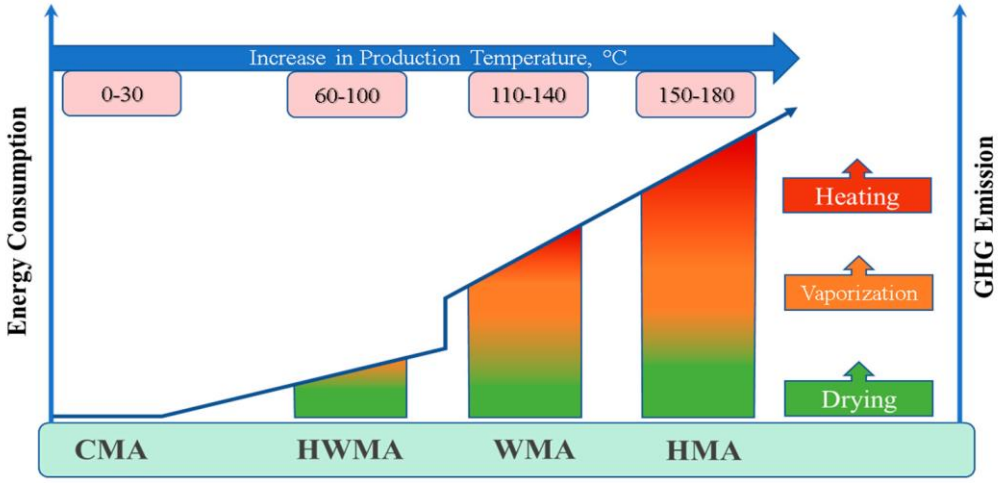


Fig. 1.2 Classification of mixes based on production temperatures (Milad *et al.*, 2022)

1.2 TYPES OF WMA TECHNOLOGIES

WMA technology was first developed in Europe. Warm mix asphalt is defined as the mixture that is produced, placed and compacted at 10 to 38°C lower than that of HMA without compromising the properties of HMA (Prowell *et al.*, 2012). The prime objective of WMA technology is to improve coating of aggregates with bitumen and to enhance the workability of bituminous mixtures. WMA technologies are mainly categorized into three types which include foaming technology, organic additives, and chemical additives. In foaming based technique, cold water is introduced in the hot bitumen leading to vaporization of water and subsequent increase in the volume of bitumen. This in turn reduces the binder viscosity and thereby enhances the binder coating and improves the workability of bituminous mixtures. In organic additives, a small amount of wax is added to decrease the viscosity of bitumen thereby lowering the production temperature of bituminous mixtures. In the case of chemical additive, it consists of chemical packages which include emulsifying agent, anti-stripping agent, surfactant and adhesion promoter to reduce surface friction between binder and aggregate which allows bituminous mixtures to be produced and constructed at relatively lower temperatures.

1.2.1 Advantages of WMA technology

The major advantage of using the WMA technologies include: reduction in fuel consumption, lower emissions, extended paving seasons, longer hauling distance, reduction in wear and tear of warm mix plant, reduced binder ageing, higher usage of Reclaimed Asphalt Pavement (RAP) material, reduction in cooling rate of the mix, usage of stiffer binders, and relatively healthy working conditions for the pavement workers (Kheradmand *et al.*, 2014). Figure 1.3 shows a

comparison between HMA and WMA in terms of production temperatures, requirement of additives, energy consumption, emission of gases, and cost.

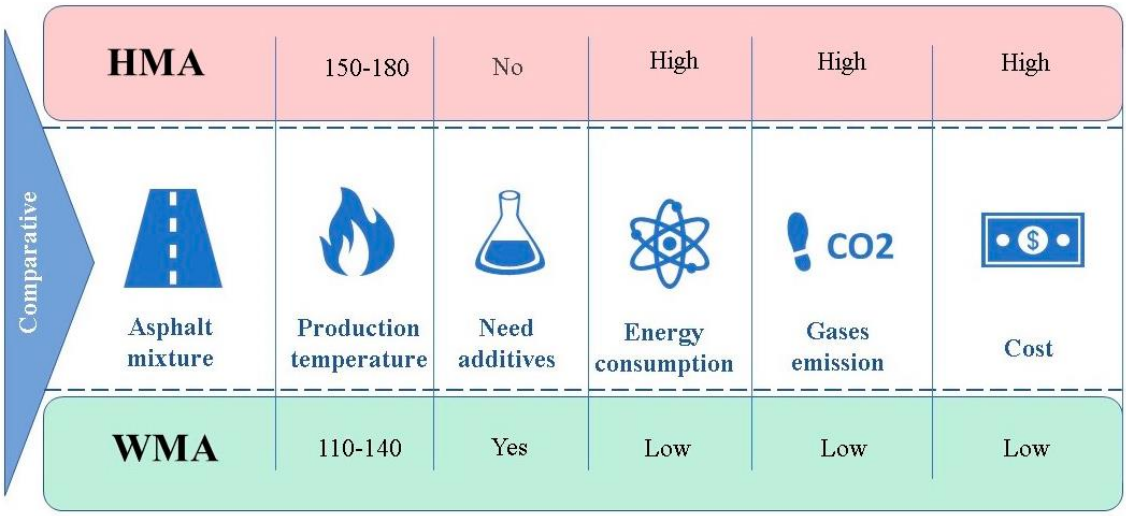


Fig. 1.3 Comparison of HMA and WMA (Milad *et al.*, 2022)

1.2.2 Major issues with WMA technology

There are two major issues with warm mix asphalt technologies: (i) as the production temperatures of WMA are relatively lower, moisture might not evaporate completely from the aggregates resulting in bituminous mixtures that are more susceptible to moisture damage, (ii) lower production temperatures of WMA results in reduced aging in bituminous binders leading to a reduction in stiffness of the binders that are more prone to rutting. In order to overcome the moisture resistance of WMA mixtures, one of the solutions is to coat the aggregates with compatible plastics.

Table 1.1 Types of plastics (IRC: SP: 98, 2013)

Thermoplastics	Thermosets
Low density polyethylene (LDPE)	Urea-Formaldehyde
High density polyethylene (HDPE)	Alkyd
Polyethylene terephthalate (PET)	Bakelite
Polypropylene (PP)	Epoxy
Poly Vinyl Chloride (PVC)	Melamine

1.3 TYPES OF WASTE PLASTIC

Waste plastics are classified into two categories: thermoplastics and thermosets. Thermoplastics are those plastics which can be reshaped with the application of heat and pressure whereas thermosets are those plastics which get set after application of heat and cannot be subsequently softened. The list of thermoplastics and thermosets are shown in Table 1.1. It is important to

note here that all types of plastics cannot be blended with bituminous mixtures. Thermosets are not suitable for blending with bituminous mixtures whereas within thermoplastics, only Low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE) can be blended with bituminous mixtures (IRC: SP: 98, 2020) as other types of thermoplastics can emit toxic gases upon heating and they may not melt at typical production temperatures adopted for bituminous mixtures. According to the Society of the Plastics Industry (SPI), the type of plastics can be classified based on its resin identification coding system given in 1988. The resin identification code for LDPE and HDPE are 4 and 2, respectively as shown in Figure 1.4.

Fig. 1.4 Types of plastics based on resin identification code (MoUHA, 2019)

Fig. 1.5 Incineration of waste plastic (Cosier, 2022)

1.3.1 Major issues with waste plastic

Waste plastics cause a serious pollution to the environment due to its non-biodegradable nature. According to United Nations environment program (UNEnvironment, 2020), global waste

plastic generation is more than 300 million tonnes per annum. According to the Swachh Bharat mission waste plastic management report (MoUHA, 2019), India generates about 9.4 million tonnes per annum of waste plastic out of which only 5.6 million tonnes of waste plastic (60%) is recycled and the remaining 3.8 million tonnes of waste plastic (40%) are discarded or littered in the environment. The government agencies around the world dispose the waste plastic either through incineration or by landfilling. Incineration or burning of plastics (Figure 1.5) releases harmful gases such as Dioxins, Furans, Mercury, Polychlorinated Biphenyls, and Halogens into the atmosphere which is dangerous to vegetation, animals and humans. Further, disposing of waste plastics through landfilling (Figure 1.6) leads to contamination of ground water and water bodies (Figure 1.7), and pollutes the soil. The major issues related to waste plastic disposal are shown pictorially though Figures 1.5 to 1.7.

Fig. 1.6 Landfilling with waste plastic (Banerjee, 2022)

Fig. 1.7 Accumulation of plastic waste near shoreline (Jatinverma, 2019)

1.3.2 Current practices of incorporating waste plastic in bituminous mixtures

One of the safe disposal solutions to waste plastics is to blend it with bituminous mixtures. Waste plastic is incorporated in bituminous mixtures using two processes, namely the wet and dry processes. In the wet process, modified bitumen binders are prepared by adding and mixing

shredded waste plastic with hot bituminous binders. In the case of the dry process, aggregates are preheated and shredded waste plastics are added and mixed with the whole fraction of aggregates to prepare plastic-coated aggregates (IRC: SP: 98, 2020). Many researchers in the past have carried out laboratory investigations in terms of the performance of waste plastic modified binders and waste plastic modified bituminous mixes for the construction of highways. The major issues with the wet process is due to phase separation between bitumen binder and plastic (Liang *et al.*, 2019). Several studies in India and around the world determined the optimum dosages of LDPE waste plastic in bituminous mixtures through Marshall mix design and preferred using dry process. Improvement in Marshall parameters was reported by several researchers (Awwad and Shbeeb, 2007; Al-Hadidy and Yi-Qui, 2009; Vasudevan *et al.*, 2012; Rajasekaran *et al.*, 2013; Sarang *et al.* 2014). Further, the usage of LDPE waste plastic in bituminous mixtures improved the rutting resistance and moisture resistance (Punith and Veeraragavan, 2011; Martin-Alfonso *et al.*, 2019; Almeida *et al.*, 2020). Addition of waste plastic directly to the whole fraction of preheated aggregate consisting of coarse and fine aggregates results in melting of waste plastic at high temperature which in turn gets adhered to fine aggregates more easily than on to the coarse aggregates in a pugmill. This results in agglomeration of fine aggregate particles, and relatively less amount of coating on coarse aggregates. Hence, in order to avoid improper coating of LDPE waste plastic over the aggregates, only coarse aggregates were coated with LDPE waste plastic (Radeef *et al.*, 2021). Such an approach would used in the current study.

1.4 RESEARCH OBJECTIVES

The following objectives are defined for the present study:

1. To quantify the influence of production process and Evotherm on the formation of aging compounds in unmodified and modified binders. Also, to characterize the influence of Evotherm on the rheological response of unmodified and modified binders.
2. To investigate the permanent deformation and moisture resistance characteristics of short-term and long-term aged dense bituminous mixtures consisting of coarse aggregate coated with waste plastic.
3. To evaluate the impact of Evotherm on the permanent deformation and moisture resistance characteristics of short-term and long-term aged dense bituminous mixtures. To correlate the rheological parameters of bituminous binders with permanent deformation in bituminous mixtures.

1.5 SCOPE OF THE WORK

The scope of the current research work is limited to the following:

1 Two grades of unmodified binders (VG20, VG40) and two types of modified binders (CRMB60, PMB40) are used for the current study and are blended with one type of chemical warm mix additive (Evotherm). The chemical and rheological characterization of all binders are carried out using FTIR spectrometer and dynamic shear rheometer, respectively.

2 All the laboratory tests performed in the current study are limited only to one dense gradation (bituminous concrete grading II) wherein the coarse aggregate only fraction is coated with one type of waste plastic (LDPE). The mechanical performance of all bituminous mixtures is evaluated using indirect tensile strength test and wheel tracking test.

3 For the correlation studies, only binder rutting parameters and mixture rut depth are considered.

1.6 ORGANIZATION OF THE THESIS

The thesis entitled "influence of chemical warm mix additive on the performance of bituminous binders and bituminous mixtures containing waste plastic coated coarse aggregates" is organized into the following seven chapters.

Chapter 1 initially highlights the issues with hot mix asphalt and the need for warm mix asphalt. The solution to the issues with warm mix asphalt is presented with a focus on the usage of low density polyethylene waste coated coarse aggregates. The objectives identified for the current research study are also presented.

Chapter 2 includes a critical review of past research works. The entire review of literature is segregated into four sections consisting of the performance of warm mix asphalt binders, aging compounds in warm mix asphalt binder, performance of warm mix asphalt mixtures, and performance of bituminous mixtures blended with waste plastic. At the end, the entire literature was summarized by emphasizing the gaps observed in the literature.

Chapter 3 provides the methodology framework adopted to fulfill the objectives. Initially the materials used are presented along with the basic properties of binders and aggregates. The equipment used for characterization of bituminous binders and mixtures are also presented in detail along with the sample preparation process and the relevant test protocols.

Chapter 4 is mainly focused on the chemical characterization of control and Evotherm-modified bituminous binders using Fourier-transform infrared spectroscopy at unaged, short-term aged, and long-term aged conditions. The data analysis and quantification of aging compounds is presented in terms of carbonyl index and sulfoxide index.

Chapter 5 presents the results obtained from rheological investigation of control and Evotherm-modified binders using dynamic shear rheometer at various aging conditions. Binder performance parameters are quantified for distresses such as rutting and fatigue cracking.

Chapter 6 presents the results obtained from characterization of bituminous mixtures in terms of rutting and moisture damage where the influence of Evotherm was quantified for bituminous mixtures with and without low density polyethylene waste.

Chapter 7 summarizes the entire work and presents the conclusions drawn from the current study. The scope for further study is also presented at the end.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

The production temperatures of hot mix asphalt vary from 140 to 170°C, depending on the grade of unmodified bitumen (IRC: SP: 105, 2019). However, the recommended production temperature of hot mix asphalt consisting of modified bitumen is generally higher than the hot mix asphalt consisting of unmodified bitumen which further depends on the modifier type and dosage. At such higher production temperatures of hot mix asphalt, undue oxidation and degradation of binders occur apart from higher energy consumption and emission of harmful greenhouse gasses and fumes that are hazardous to the health of construction workers. The production temperature of bituminous mixtures can be significantly lowered with the use of warm mix asphalt additives thereby reducing the energy consumption, and emission of greenhouse gasses and fumes. Even though the reduction in viscosity of bitumen at elevated temperatures is the only means of achieving better coating of bitumen over the aggregates surfaces, the same can be achieved by warm mix asphalt technology through reduction in viscosity of the bitumen or increasing the volume of bitumen or reducing the surface tension at the interface between bitumen and aggregates depending upon the type of warm mix asphalt additive (IRC: SP: 101, 2019).

The air pollution due to hot mix plants can be minimized with the adoption of warm mix asphalt technology. However, significant water and soil pollution is caused by single-use plastics. These waste plastics are disposed of traditionally through land-filling or incineration. The incineration pollutes the environment and affects the living beings due to emission of harmful gasses and fumes. Similarly, the land-filling pollutes the soil and groundwater. One of the safe disposable solutions to waste plastic is to blend it in bituminous mixtures through wet process or dry process. In the wet process, waste plastic is blended directly with bitumen whereas in the direct process, the waste plastic is blended with hot aggregates. Not all waste plastics can be blended with bituminous mixtures as the melting points of some plastics can exceed the production temperatures of bituminous mixtures and some waste plastics can release toxic gasses (IRC: SP: 98, 2020). The current chapter presents a comprehensive review of literature related to four broad areas including: performance of warm mix asphalt binders, aging

compounds in warm mix asphalt binders, performance of warm mix asphalt mixtures, and performance of bituminous mixtures blended with waste plastic.

2.2 PERFORMANCE OF WMA BINDERS

Arega et al. (2011) evaluated the influence of five WMA additives (Cecabase RT 945, Evotherm DAT [Dispersed Asphalt Technology], Evotherm 3G [Third Generation], Rediset WMX, and Sasobit) and reduced short-term aging temperature (143°C) on the rheological properties of bituminous binders with different natural wax contents (two PG 64-22 binders with low wax content, and two binders with higher wax content including PG 76-22 and PG 76-28). The binders without WMA additive were short-term aged at 163°C whereas the binders with WMA additive were short-term aged at 143°C. The short-term aging durations was also increased from 85 minutes to 170 minutes to simulate additional aging of the binder during longer hauling distances or prolonged storage durations in heated silos. Subsequently, all the binders were long-term aged at 100°C. All the WMA binders short-term aged at 143°C exhibited a reduction in rutting resistance compared to the HMA binders with an exception to Sasobit. The rutting resistance was less for HMA binders aged at 143°C compared to 163°C and also for bituminous binders with higher natural wax content. No specific trends were reported for fatigue resistance.

Xiao et al. (2012) evaluated the influence of four WMA additives (Cecabase, Evotherm, Rediset, and Sasobit) on the rheological properties of five bituminous binders (PG 52-28, PG 58-28, PG 64-16, PG 64-22, and PG 76-22). High temperature rheological properties were measured in terms of complex shear modulus and phase angle apart from other rheological properties at 60°C. All WMA additives exhibited no change in the grade of the binder except Sasobit for PG 76-22 binder. Overall, the rheological properties of WMA binders were superior compared to HMA binders where WMA binders with Sasobit exhibited superior performance followed by Evotherm, Rediset, and Cecabase additives even though the difference is not significant for these three WMA additives.

Banerjee et al. (2012) evaluated the influence of long-term aging on the rheological properties of PG 64-22 binder blended with four WMA additives (Cecabase RT 945, Evotherm 3G, Sasobit, and Rediset WMX). The binders without WMA additive were short-term aged at 163°C whereas the binders with WMA additive were short-term aged at 143°C. Subsequently, all the binders were long-term aged at 60°C in an environmental room with durations of 0, 2, 5, 11, 22, 35, 67, and 132 days. The rheological properties were evaluated in terms of complex shear modulus at three temperatures (40, 52, and 64°C) and ten loading frequencies (0.1 to 25 Hz) to

develop master curves at 60°C. The complex shear modulus of HMA binder was higher followed by WMA binders in the decreasing sequence for Sasobit, Cecabase, Evotherm, and Rediset additives. Similar to increase in loading frequencies, the increase in aging duration exhibited higher complex shear modulus resulting due to oxidation of the polar function group. Even though the decrease in complex shear modulus represents decreased resistance towards rutting, the resistance towards fatigue would be higher.

Yu et al. (2014) evaluated the influence of Evotherm DAT on the rheological properties of crumb rubber modified bitumen produced by blending the base binder (PG 64-22) with 18% crumb rubber modifier by weight of the base binder. The viscosity of binder reduced with increase in dosage of WMA additive at temperatures above 100°C and converged at 160°C. Addition of WMA additive improved the intermediate and high temperature rheological properties, and improved the sensitivity to temperature.

Abbas et al. (2016) evaluated the influence of aging on the rheological properties of two bituminous binders (PG 64-22, PG 70-22) blended with one WMA additive (foaming technology). Both the HMA and WMA binders were aged at identical conditions. The rheological properties were evaluated on unaged and aged binders apart from recovered binders from aged bituminous mixtures. The rheological properties of aged WMA binders were lower than aged HMA binders indicating that the aging of foamed WMA mixtures would be lower than that of the HMA mixtures.

Abdullah et al. (2016) evaluated the influence of one chemical WMA additive on the rheological properties of 80/100 bitumen. Both the HMA and WMA binders were aged at identical conditions. The rheological properties were evaluated on unaged and aged binders. The rheological properties of aged WMA binders were lower than aged HMA binders.

Lakshmi Roja et al. (2016) evaluated the influence of short-term aging on the rheological properties of VG30 binder blended with two WMA additives (Evotherm, and Sasobit). The binders without WMA additive were short-term aged at 163°C whereas the binders with WMA additive were short-term aged at 143°C. The rheological properties were evaluated in terms of dynamic modulus and phase angle at six temperatures (25 to 75°C in increments of 10°C) and at various loading frequencies (50 to 1 Hz) to develop master curves at 35°C. Irrespective of the aging condition, the dynamic modulus of WMA binder with Sasobit (compared to WMA binder with Evotherm and VG30 binder) was higher at all temperatures with an exception at 75°C. Such behavior was due to melting of Sasobit after 85°C and complete dissolution at

115°C. The unaged WMA binder with Sasobit exhibited higher dynamic modulus due to possible aging during the production of WMA binder. WMA binders with Evotherm exhibited lower dynamic modulus and higher phase angle than the VG30 binder.

Ferrotti et al. (2017) evaluated the influence of two chemical WMA additives (Code-A, Code-B) on the rheological properties of two bituminous binders (70/100, PMB). The influence of chemical additives on unmodified bitumen was negligible whereas significant changes were reported such as reduction in viscosity-temperature susceptibility, increased rutting resistance at higher temperatures.

Yu et al. (2017) evaluated the influence of Evotherm DAT on the rheological properties of crumb rubber modified bitumen produced by blending the base binder (60/70) with 18% crumb rubber modifier by weight of the base binder. Evotherm was blended in three different forms: (A) Evotherm blended with prepared crumb rubber modified bitumen, (B) Evotherm and crumb rubber modifier are directly blended with base bitumen, and (C) mixture consisting of crumb rubber modifier soaked in Evotherm was blended with bitumen. It was concluded that irrespective of the preparation process (A, B, C), WMA binders exhibited degraded high temperature performance, similar intermediate temperature performance, and improved low temperature performance compared to HMA binders.

Behl & Chandra (2017) evaluated the influence of aging on the rheological properties of two bituminous binders (VG30, PMB40) blended with three WMA additives (Evotherm, Rediset, and Sasobit). The binders without WMA additive were short-term aged at 163°C whereas the binders with WMA additive were short-term aged at both reduced temperature and 163°C. WMA binders with base binder as VG30 was short-term aged at 115°C whereas WMA binders with base binder as PMB40 was short-term aged at 135°C. All the WMA and HMA binders were long-term aged at 100°C. Aging index defined as the ratio of viscosities of aged and unaged binder was determined for binders recovered from HMA and WMA mixtures. Recovered binders from WMA mixtures exhibited lower aging compared to the recovered binders from HMA mixtures. The rutting resistance of WMA binders with Sasobit exhibited was higher compared to the HMA binders whereas the WMA binders with Rediset and Evotherm exhibited slightly lower and comparable rutting resistance, respectively compared to the HMA binders. WMA binders with Rediset and Evotherm exhibited higher fatigue performance compared to the HMA binders whereas the WMA binders with Sasobit exhibited lower fatigue performance compared to the HMA binders. WMA binders with Evotherm performed better than the Rediset and Sasobit additives in terms of low temperature cracking.

Kataware & Singh (2017) evaluated the influence of three WMA additives (Advera, Rediset, and Sasobit) on the rheological properties of polymer modified bitumen (PG 76-XX). The binders without WMA additive were short-term aged at 163°C whereas the binders with WMA additive were short-term aged at 143°C. All the WMA and HMA binders were long-term aged at 100°C. The viscosity of WMA binders with Sasobit and Rediset was lower than the HMA binder for viscosities measured at 120 and 135°C. However, the viscosity of WMA binder with Advera was higher than the HMA binder at these temperatures. WMA binder with Sasobit bumped the high temperature performance grade by one level and exhibited improved rutting and fatigue performance compared to the HMA binder. WMA binder with Rediset degraded the high temperature performance grade of HMA binder and exhibited reduced rutting and fatigue performance compared to the HMA binder. WMA binder with Advera degraded the high temperature performance grade of HMA binder and exhibited similar rutting and fatigue performance as that of the HMA binder. Overall, WMA binders with Sasobit exhibited superior performance followed by Advera and Rediset additives.

Ferrotti et al. (2018) evaluated the influence of aging on the rheological properties of foamed bitumen where the base binder was 70/100 (PG 64-22). The HMA binder was short-term aged in a RTFO at 163°C and also at 123°C for 75 minutes. WMA and HMA mixtures were prepared with the same base bitumen. HMA mixture short-term aging was carried out at 160°C for four hours whereas WMA mixture short-term aging was carried out at 110°C for four hours. Rheological tests were performed on the recovered binders from HMA and WMA mixtures apart from unaged base binder and short-term aged base binder at two different aging levels. The main objective was to identify the RTFO test temperature for WMA binder. Based on the rheological studies, it was concluded that the recovered HMA binder exhibited higher aging levels compared to HMA binder short-term aged at 163°C whereas recovered WMA binder exhibited lower aging levels compared to HMA binder short-term aged at 163°C. Further, recovered HMA binder exhibited higher aging levels compared to recovered WMA binder.

Kataware & Singh, (2018) evaluated the influence of three WMA additives (Advera, Rediset, and Sasobit) on the rheological properties of unmodified AC-30 bitumen (PG 70-XX). The binders without WMA additive were short-term aged at 163°C whereas the binders with WMA additive were short-term aged at 143°C. All the WMA and HMA binders were long-term aged at 100°C. The viscosity of all the three WMA binders was lower than the HMA binder for viscosities measured at 135°C. WMA binder with Sasobit bumped the high temperature performance grade by one level and exhibited improved rutting and fatigue performance

compared to the HMA binder. WMA binder with Rediset and Advera had no effect on the high temperature performance grade of HMA binder and exhibited reduced rutting and fatigue performance compared to the HMA binder. Overall, WMA binders with Sasobit exhibited superior performance followed by Advera and Rediset additives.

Kataware & Singh, (2018b) evaluated the influence of three WMA additives (Advera, Rediset, and Sasobit) on the intermediate temperature fatigue cracking performance of three bituminous binders (AC-30 bitumen (PG 70-XX), polymer modified bitumen (PG 76-XX), crumb rubber modified bitumen (PG 88-XX)). The binders without WMA additive were short-term aged at 163°C whereas the binders with WMA additive were short-term aged at 143°C. All the WMA and HMA binders were long-term aged at 100°C. DSR was used to evaluate the performance of binders in terms of fatigue parameter and fatigue failure whereas Double Edge Notch Test (DENT) was used to evaluate the performance of binders in terms of Crack Tip Opening Displacement (CTOD). HMA and WMA binders consisting of unmodified bitumen and crumb rubber modified bitumen exhibited similar performance based on fatigue parameters and CTOD. WMA binders with Sasobit improved the fatigue life and decreased the ductile performance. WMA binders with Rediset improved the ductile performance of unmodified and crumb rubber modified binders and decreased the fatigue life of polymer modified bitumen. WMA binders with Advera improved the fatigue life whereas unmodified and crumb rubber modified binders degraded the ductile performance. There was no consensus among the three intermediate temperature fatigue cracking performance indicators.

Kataware & Singh (2019) evaluated the influence of three WMA additives (Advera, Rediset, and Sasobit) on the rheological properties of crumb rubber modified bitumen (PG 88-XX). The binders without WMA additive were short-term aged at 163°C whereas the binders with WMA additive were short-term aged at 143°C. All the WMA and HMA binders were long-term aged at 100°C. The viscosity of WMA binders with Sasobit was lower than the HMA binder for viscosities measured at 120 and 135°C. However, the viscosity of WMA binder with Advera was higher than the HMA binder at these temperatures. The viscosity of the WMA binder with Rediset was similar to the HMA binder at these temperatures. The high temperature performance grade of WMA binders with Sasobit and Advera was the same as HMA binder. However, the WMA binder with Rediset degraded the high temperature performance grade by one level. WMA binders with Sasobit and Advera exhibited improved rutting performance compared to the HMA binder whereas the WMA binder with Rediset reduced the rutting performance compared to the HMA binder. All the WMA binders exhibited improved fatigue

performance compared to the HMA binder. Overall, WMA binders with Sasobit exhibited superior performance followed by Advera and Rediset additives.

Kataware & Singh (2020) evaluated the influence of three WMA additives (Advera, Rediset, and Sasobit) on the rheological properties of polymer modified bitumen (PG 76-22). The binders without WMA additive were short-term aged at 163°C whereas the binders with WMA additive were short-term aged at 143°C. WMA binders with Sasobit and Advera exhibited improved rutting performance compared to HMA binder. However, WMA binder with Rediset exhibited reduced rutting performance compared to HMA binder. WMA binder with Advera degraded the high temperature performance grade of HMA binder. WMA binders were effective in reducing the short-term aging susceptibility of HMA binder. Overall, WMA binders with Sasobit exhibited superior performance followed by Advera and Rediset additives.

Abed et al. (2020) evaluated the influence of two WMA additives (Cecabase, and Sasobit) on the rheological properties of 40/60 grade bitumen. Both the HMA and WMA binders were short-term aged at 163°C for 75 minutes. All the WMA and HMA binders were long-term aged at 90°C. The rheological properties were evaluated through frequency sweep test at all aging levels, MSCR test, linear amplitude sweep test, low temperature creep stiffness test, and the Glower Rowe parameter. WMA binders with Sasobit improved the stiffness, fatigue cracking, and rutting performance whereas WMA binders with Cecabase degraded the stiffness and rutting resistance whereas the fatigue performance improved. Both the WMA additives retarded the binder aging. Further, the Glower-Rowe parameter and fatigue life were well correlated. WMA binders with Cecabase improved the low temperature cracking resistance due to its lower stiffness whereas WMA binders with Sasobit degraded the low temperature cracking resistance due to its higher stiffness. The WMA binders with Cecabse are recommended for cold regions where low temperature cracking is critical whereas WMA binders with Sasobit are recommended for hot regions where rutting is critical.

Ameri et al. (2020) evaluated the influence of two WMA additives (Polypropylene wax, and Slax wax) on the rheological properties of crumb rubber modified bitumen with base bitumen as PG 64-22. Both the HMA and WMA binders were short-term aged at 163°C. All the WMA and HMA binders were long-term aged at 100°C. WMA binders with Polypropylene wax and Slax wax reduced the viscosity of the crumb rubber modified asphalt. WMA binders with Polypropylene wax improved the high temperature performance grade by one level whereas WMA binders with Slax wax degraded the high temperature performance grade of crumb rubber modified asphalt. WMA binders with Polypropylene wax improved the rutting resistance

whereas WMA binders with Slax wax degraded the rutting resistance of crumb rubber modified asphalt. WMA binders with Polypropylene wax degraded the rutting resistance whereas WMA binders with Slax wax improved the rutting resistance of crumb rubber modified asphalt.

Bhat and Mir (2022) evaluated the influence of two WMA additives (Sasobit, and Zycotherm) on the rheological properties of nano-Al_2O_3 modified AC-10 (PG 64-XX) bitumen. The binders without WMA additive were short-term aged at 163°C whereas the binders with WMA additive were short-term aged at 143°C. All the WMA and HMA binders were long-term aged at 100°C. Blending of WMA additives reduced the viscosity of HMA binders. WMA binders improved both the rutting and fatigue performance of nano-Al_2O_3 modified HMA binders. WMA binders with Sasobit exhibited stiffer response compared to Zycotherm additive. WMA binders with Sasobit degraded the fatigue performance in terms of Superpave fatigue parameter compared to Zycotherm additive whereas the fatigue performance in terms of number cycles to failure obtained through linear amplitude sweep test improved compared to Zycotherm additive.

2.3 AGING COMPOUNDS IN WMA BINDERS

Xiao et al. (2012) evaluated the influence of four WMA additives (Cecabase, Evotherm, Rediset, and Sasobit) on five bituminous binders (PG 52-28, PG 58-28, PG 64-16, PG 64-22, and PG 76-22) using Fourier Transform Infrared (FTIR) analysis. It was reported that the vibrations at wavenumber 1598 cm^{-1}, 1012 cm^{-1}, and 719 cm^{-1} correspond to C=C stretch, C−O stretch, and C−H bend and these peak positions were used to analyze the influence of WMA additives on HMA binders. The reduction in absorbance of WMA binders compared to HMA binders was more noticeable at these wavenumbers for PG 76-22 due to reduction in densities of the selected vibrations. Based on FTIR analysis, it was concluded that the base binder type plays an important role in the response characteristics of WMA binders.

Yu et al. (2014) evaluated the influence of Evotherm DAT on crumb rubber modified bitumen using FTIR analysis. Based on the FTIR analysis, it was concluded that there was no chemical reaction between Evotherm DAT and crumb rubber modified bitumen. However, there was a reduction in transmittance peaks due the effects of water and surfactants present in Evotherm DAT.

Abbas et al. (2016) evaluated the influence of aging on two bituminous binders (PG 64-22, PG 70-22) blended with one WMA additive (foaming technology) using FTIR analysis. Both the HMA and WMA binders were short-term aged at identical conditions. Carbonyl (C=O) and

sulfoxide (S=O) functionalities were selected to quantify the aging undergone by HMA and WMA binders. It was reported that the carbonyl and sulfoxide peaks appear at wavenumber 1700 cm^{-1} and 1030 cm^{-1}, respectively. It was observed that the increase in carbonyl index is more consistent compared to the sulfoxide index and suggested carbonyl index as a better indicator for aging. Based on FTIR analysis, it was concluded that the absorbance of PAV aged binders is higher followed by RTFO aged binders and unaged binders. Further, the carbonyl index and sulfoxide index of WMA binders was lower than the HMA binders at identical aging conditions indicating that the WMA binders age less compared to HMA binders.

Abdullah et al. (2016) evaluated the influence of one chemical WMA additive on 80/100 bitumen using FTIR analysis. Both the HMA and WMA binders were aged at identical conditions. Carbonyl (C=O) and sulfoxide (S=O) functionalities were selected to quantify the aging undergone by HMA and WMA binders. It was reported that the carbonyl and sulfoxide peaks appear at wavenumber 1700 cm^{-1} and 1030 cm^{-1}, respectively. It was reported that the carbonyl absorbance increased gradually with short-term aging whereas it increased rapidly with long-term aging. Based on FTIR analysis, it was reported that the carbonyl absorbance of unaged WMA binders was higher than that of unaged HMA binders whereas the carbonyl absorbance of aged WMA binders was lower than that of aged HMA binders. The sulfoxide absorbance of WMA binders was always higher than that of HMA binders irrespective of the aging conditions.

Ferrotti et al. (2017) evaluated the influence of two chemical WMA additives (Code-A, Code-B) on two bituminous binders (70/100, PMB) using FTIR analysis. Aromatic (C=C), Carbonyl (C=O) and sulfoxide (S=O) functionalities were selected to quantify the influence of WMA additives on HMA binders. It was reported that the carbonyl, aromatic, and sulfoxide peaks appear at wavenumber 1700 cm^{-1}, 1600 cm^{-1}, and 1030 cm^{-1}, respectively. It was concluded that the addition of WMA additives to HMA binders exhibited no significant changes in terms of the structural indices.

Yu et al. (2017) evaluated the influence of Evotherm DAT on crumb rubber modified bitumen using FTIR analysis. Based on the spectra of Evotherm, it was reported that C–H is the predominant functionality in Evotherm in addition to the presence of O–H and S=O functional groups. It was also reported that Evotherm scarcely contains any C=O compounds whereas sulfur-containing organics are present in Evotherm. It was concluded that there is chemical interaction between crumb rubber modified bitumen and Evotherm due to the hydrogen bond generated between the O–H/N–H group of rubber and –COO– group of Evotherm.

Behl & Chandra (2017) evaluated the influence of aging on two bituminous binders (VG30, PMB40) blended with three WMA additives (Evotherm, Rediset, and Sasobit) using FTIR analysis. The binders without WMA additive were short-term aged using Rolling Thin Film Oven (RTFO) at 163°C for 85 minutes whereas the binders with WMA additive were short-term aged at both reduced temperature and 163°C. WMA binders with base binder as VG30 was short-term aged at 115°C whereas WMA binders with base binder as PMB40 was short-term aged at 135°C. All the WMA and HMA binders were long-term aged using Pressure Aging Vessel (PAV) at 100°C. FTIR analysis was also carried out on recovered binders from bituminous mixtures. Carbonyl (C=O) and sulfoxide (S=O) functionalities were selected to quantify the aging undergone by HMA and WMA binders. It was reported that the carbonyl and sulfoxide peaks appear at around wavenumber 1700 cm^{-1} and 1030 cm^{-1}, respectively. Based on FTIR analysis, it was concluded that the absorbance of WMA binders was lower than the HMA binders at all aging conditions indicating that the WMA binders age less compared to HMA binders.

Ferrotti et al. (2018) evaluated the influence of aging on HMA and foamed WMA binder prepared with 70/100 (PG 64-22) as the base binder using FTIR analysis. The HMA binder was short-term aged in a RTFO at 163°C and also at 123°C for 75 minutes. WMA and HMA mixtures were prepared with the same base bitumen. HMA mixture short-term aging was carried out at 160°C for four hours whereas WMA mixture short-term aging was carried out at 110°C for four hours. Binders were recovered subsequently from HMA and WMA mixtures. Carbonyl (C=O) and sulfoxide (S=O) functionalities were selected to quantify the aging undergone by HMA and WMA binders. It was reported that the carbonyl and sulfoxide peaks appear at wavenumber 1700 cm^{-1} and 1030 cm^{-1}, respectively. Based on FTIR analysis, it was concluded that the recovered HMA binder exhibited higher aging levels compared to HMA binder short-term aged at 163°C whereas recovered WMA binder exhibited lower aging levels compared to HMA binder short-term aged at 163°C. Further, recovered HMA binder exhibited higher aging levels compared to recovered WMA binder.

Kataware & Singh (2018a) evaluated the influence of three WMA additives (Advera, Rediset, and Sasobit) on unmodified AC-30 bitumen (PG 70-XX) using FTIR analysis. The binders without WMA additive were short-term aged using Thin Film Oven (TFO) at 163°C for five hours whereas the binders with WMA additive were short-term aged at 143°C. All the WMA and HMA binders were long-term aged using PAV at 100°C. Carbonyl (C=O) and sulfoxide (S=O) functionalities were selected to quantify the aging undergone by HMA and WMA

binders. It was reported that the carbonyl and sulfoxide peaks appear at wavenumber 1700 cm^{-1} and 1030 cm^{-1}, respectively. Based on FTIR analysis, it was concluded that the addition of WMA additives increased the absorbance of both carbonyl and sulfoxide functionalities and the absorbance of both the functionalities increased with the increase in dosage of the WMA additives.

Ameri et al, (2020) evaluated the influence of two WMA additives (Polypropylene wax, and Slax wax) on crumb rubber modified bitumen with base bitumen as PG 64-22 using FTIR analysis. Both the HMA and WMA binders were short-term aged using RTFO at 163°C for 85 minutes. All the WMA and HMA binders were long-term aged using PAV at 100°C. It was reported that the vibrations between wavenumbers 2915 and 2852 cm^{-1}, 1458 and 1375 cm^{-1}, 850 and 725 cm^{-1} correspond to C–H stretching, C–H bending, and C=C bending and these peak positions were used to analyze the influence of WMA additives on HMA binders. Based on FTIR analysis, it was concluded that all the HMA and WMA binders exhibited similar absorption peaks without any chemical reactions between WMA additives and the base binder. Further, the magnitude of absorption peaks was higher for WMA binders compared to HMA binders.

2.4 PERFORMANCE OF WMA MIXTURES

Hurley & Prowell (2006) evaluated the use of Evotherm in bituminous mixtures. The compactibility of bituminous mixtures improved with Evotherm for both Superpave Gyratory Compactor (SGC) and vibratory compactor. It was reported that the addition of Evotherm does not statistically affect the resilient modulus of bituminous mixtures and does not increase the rutting resistance of bituminous mixtures. Further, moisture resistance of bituminous mixtures improved with the usage of Evotherm additive.

Tao et al. (2009) evaluated the performance of WMA-extracted specimens from the test sections constructed with Evotherm-DAT technology. It was reported that the performance of WMA mixtures satisfied the specification limits. Further, the construction of test sections using WMA additives at lower air temperatures was successfully demonstrated in China.

Akisetty et al. (2011) correlated some of the mechanical properties of bituminous mixtures with both the rheological properties of bituminous binders (PG 64-22, and PG 64-22 + 10% crumb rubber) blended with two WMA additives (Asphamin, and Sasobit) and some other mechanical properties of bituminous mixtures. The bituminous mixtures were prepared with two different aggregates (granite, and schist). The addition of Sasobit reduced the viscosity of HMA binders

whereas addition of Asphamin had no significant effect on viscosity of HMA binders. WMA additives improved the high temperature performance of HMA binders. Even though the usage of crumb rubber modified increased the mixing and compaction temperatures, addition of WMA additives subsequently reduced these temperatures. Bituminous mixtures with schist aggregates had better correlations compared to granite aggregates.

Buss and Williams (2013) evaluated the performance of WMA and HMA mixtures using the Mechanistic-Empirical Pavement Design Guide (MEPDG) through dynamic modulus. The performance of HMA and WMA mixtures through MEPDG was evaluated in terms of rutting, International Roughness Index (IRI), and alligator cracking. The WMA additives included Evotherm, Sasobit, and Astec Double Barrel Green foaming. It was reported that there was negligible difference between the performance of HMA and WMA mixtures.

Safaei et al. (2014) evaluated the influence of two warm mix additives (Evotherm 3G, and foaming technology) on aging and fatigue performance of bituminous binders (PG 70-22) and bituminous mixtures consisting of 19% RAP. HMA mixtures were subjected to short-term aging in a forced draft oven at 135°C for four hours whereas the WMA mixtures were subjected to short-term aging in a forced draft oven at 117°C for two hours. All the HMA and WMA mixture specimens were subjected to long-term aging in a forced draft oven at 85°C for two different durations (two days and eight days). Binders were recovered from short-term aged bituminous mixtures and long-term aged bituminous mixture specimens. It was reported that the fatigue performance of HMA mixtures was superior compared to the corresponding WMA mixtures at short-term aged and two days of long-term aged conditions. However, the difference in fatigue performance of HMA and WMA mixtures was negligible at eight days of long-term aging. The fatigue life of HMA and WMA mixtures correlated well with the fatigue life of recovered HMA and WMA binders.

Lee & Kim (2014) evaluated the influence of five warm mix additives (Evotherm 3G, foaming technology, two emerging organic additives, and one emerging chemical additive) on moisture resistance of bituminous mixtures consisting of 19% RAP and PG 70-22 binder. It was reported that the dynamic modulus reduction due to moisture conditioning was lower in WMA mixtures with Evotherm compared to the remaining WMA additives.

Leng et al. (2014) evaluated the influence of two warm mix additives (Evotherm 3G, and Rediset) on performance of bituminous mixtures (stone matrix asphalt, SMA) consisting of 8% fine fractionated recycled asphalt pavement (FRAP) and PG 76-22 binder (2 levels of grade

bump achieved by 12% ground tyre rubber (GTR) from PG 64-22). It was reported that the tensile strength and complex modulus of WMA mixtures was lower than the HMA mixtures whereas the rutting resistance and fracture resistance of WMA mixtures was similar to that of HMA mixtures.

Suleiman and Mandal (2014) evaluated the rutting resistance of WMA and HMA overlays. The WMA overlays were constructed using Evotherm 3G chemical WMA additive. Dry and wet-conditioned rutting tests were conducted using asphalt pavement analyzer on WMA and HMA cored specimens. It was concluded that the WMA specimens exhibited degraded rut resistance compared to the HMA specimens.

Mohammad et al. (2015) evaluated the mechanical characterization of WMA and HMA mixtures. The WMA additives included Evotherm, foaming, foaming + latex, and Rediset. Performance of HMA and WMA mixtures was evaluated using dynamic modulus, flow number, loaded wheel tracking test, indirect tensile strength test, semicircular bend (SCB) test, thermal stress restrained specimen test (TSRST), and Lottman moisture susceptibility test. The rut resistance of WMA mixtures was slightly lower than that of HMA mixtures. It was concluded that the performance of WMA mixtures was similar or better than WMA mixtures.

Lu & Saleh (2016) investigated the performance of WMA mixtures consisting of RAP varying from 0 to 70% by weight of WMA mixtures. The base binder was 80/100, whereas the WMA additives used were Evotherm 3G along with a rejuvenator termed as Sylvaroad. Performance of HMA and WMA mixtures was evaluated using moisture susceptibility test, fatigue test, dynamic creep test, dynamic modulus test, and wheel tracking test. Addition of Evotherm 3G and Sylvaroad additive reduced the viscosity of the binder. It was concluded that the WMA mixtures exhibited higher moisture resistance compared to HMA mixtures, whereas the fatigue and rutting resistance of HMA mixtures was better compared to WMA mixtures. Further, addition of RAP to WMA mixtures resulted in improved rutting resistance.

Bower et al. (2016) evaluated the performance of field mixtures constructed with Sasobit, Gencor, Aquablack, and ALmix water injection WMA technologies. It was reported that the WMA binders exhibit lower complex shear modulus and less resistance to rutting and fatigue compared to HMA binders. The stiffness and fatigue resistance of WMA mixtures were compared to HMA mixtures.

Abdullah et al. (2016) evaluated WMA mixtures consisting of chemical WMA additive and nano clay at various mixing and compaction temperatures using 70/80 base binder. The performance tests consisted of resilient modulus, dynamic creep, asphalt pavement analyzer rutting, moisture susceptibility, and indirect tensile fatigue test. WMA mixtures exhibited lower resilient modulus, similar moisture susceptibility, rut, creep slope strain, and fatigue life compared to HMA mixtures.

Bairgi et al. (2017) evaluated the performance of field mixtures constructed with four WMA additives (Cecabase, Evotherm, Foaming, and Cecabase). The performance was evaluated based on Hamburg Wheel Tracking Test (HWTT), TSR test, and field rutting distress surveys. The performance of WMA mixtures in terms of resistance to rutting was equivalent or better compared to HMA mixtures. The use of Evotherm improved the resistance towards moisture damage.

Cucalon et al., (2017) evaluated the performance of HMA and WMA mixtures prepared with four WMA additives (Evotherm, foaming technology, Sasobit, and Rediset), two base binders (PG 64-22, and PG 76-22), and two types of aggregates (limestone, and gabbro). The crack growth rate was faster for HMA and Sasobit mixtures compared to other WMA additives when gabbro aggregate was used. Limestone aggregate exhibited a slower crack growth rate before and after aging.

Raab et al. (2017) evaluated the rutting and fatigue characteristics of HMA and WMA mixtures for various WMA additives. The performance of WMA mixtures towards fatigue resistance was better than HMA mixtures whereas the resistance towards rutting was inferior.

Roja et al. (2017) evaluated the rheological and mechanical characteristics of binders as well as mixtures. WMA additives such as Sasobit and Evotherm were used with VG30 base binder. The performance was evaluated in terms of dynamic modulus, wheel tracking, repeated creep and recovery test. WMA mixtures with Sasobit were more resistant towards rutting compared to the Evotherm additive.

Yang et al. (2017) evaluated the performance of HMA mixtures and WMA mixtures with Evotherm. Crumb rubber modified bitumen was used as the base binder. WMA mixtures exhibited equivalent rut resistance and low-temperature resistance compared to HMA mixtures whereas the fatigue resistance and moisture resistance of WMA mixtures was superior to HMA mixtures.

Arefin et al. (2018) evaluated the effect of short-term and long-term aging on the dynamic modulus of WMA and HMA mixtures. The materials included four asphalt binders (PG 64-22, PG 64-28, PG 70-22, and PG 76-22), limestone aggregate, and foaming technology. At all aging conditions, dynamic modulus of WMA mixtures was lower compared to HMA mixtures at the selected temperatures and frequencies.

Bairgi et al. (2018) evaluated the influence of WMA additives (Evotherm, Cecabase, and Cecabase) on the rutting performance of WMA and HMA mixtures. The performance of WMA mixtures was equivalent or better than HMA mixtures in terms of rutting. However, the rutting resistance of WMA mixtures with Evotherm additive was lower than that of HMA mixtures.

Syed et al. (2019) evaluated various rutting parameters like Superpave rutting parameter, Shenoy's parameter, non-recoverable creep compliance, and percentage recovery of binder extracted from five test sections which consisted of one HMA and four WMA mixtures. The non-recoverable creep compliance correlated well with mixture rutting. It was concluded that WMA with foamed asphalt, Cecabase, and Evotherm performed better than control HMA with regard to rutting performance.

Bairgi et al. (2020) evaluated the influence various WMA technologies (foaming, Evotherm, Cecabase-1, and Cecabase-2) in terms of rutting characteristics. Rut tests were performed using HWTT where rutting performance in the field was evaluated using Mandl's pavement profile system. The laboratory and field test results revealed that rutting potential was higher for HMA mixtures compared to that of HMA mixtures.

Bazzaz et al. (2020) evaluated the rutting potential of binders and mixtures using a master curve for dynamic modulus of binder and mixtures. MSCR and frequency sweep tests were carried out on PG 64-22 binder and SBS-modified PG 76-22 binder blended with and without Evotherm M1. Dynamic modulus tests were also carried out on mixtures for these combinations. The presence of Evotherm M1 reduced the stiffness of bituminous binder and bituminous mixtures.

Doyle et al. (2021) constructed one HMA and three WMA test sections to evaluate the rutting performance of field and laboratory produced mixtures consisting of various WMA additives (foaming technology, Sasobit, and Evotherm). Accelerated pavement tests and Falling Weight Deflectometer (FWD) tests were carried out on the test sections. Asphalt pavement analyzer and Hamburg wheel tracking tests were carried out on field-cored and plant-produced laboratory compacted specimens. The rut depth of WMA mixtures with Evotherm was more

compared to that of the control HMA mixtures for both field and laboratory compacted specimens. The difference between rutting resistance of field specimens and laboratory specimens was significantly higher.

Jattak et al. (2021) evaluated the influence of bottom ash on moisture resistance of WMA mixtures consisting of 60/70 grade bitumen blended with Evotherm 3G. The mixing and compaction temperatures of HMA mixtures were 165 and 155°C, respectively, whereas the corresponding temperatures for WMA mixtures were 140 and 130°C, respectively. The fine aggregate was replaced with bottom ash with a replacement proportion of 20%. The moisture resistance of WMA mixtures without bottom ash was higher than that of HMA mixtures without bottom ash. Even upon inclusion of bottom ash, the moisture resistance of WMA mixtures with bottom ash was higher than that of HMA mixtures with bottom ash. However, the moisture resistance of HMA mixtures with bottom ash was lower than that of the moisture resistance of HMA mixtures without bottom ash. Similarly, the moisture resistance of WMA mixtures with bottom ash was lower than that of the moisture resistance of HMA mixtures without bottom ash.

2.5 PERFORMANCE OF BITUMINOUS MIXTURES BLENDED WITH WASTE PLASTIC

Panda and Mazumdar (2002) evaluated the performance of bituminous mixtures prepared using 80/100 bitumen blended with reclaimed polyethylene (low-density polyethylene, LDPE) at 160°C at a stirring rate of 3000 rpm and stirring time of 20 minutes. LDPE-waste plastic of size 3 mm x 3 mm was blended at an optimum dosage of 2.5% by weight of bitumen and the corresponding optimum bitumen content was 5.8%. The optimum bitumen content increased with increase in dosage of LDPE-waste plastic. The blending temperatures corresponding to dosages of 2.5%, 5.0%, 7.5%, and 10.0% were 160, 170, 180, and 200°C, respectively. Even though HMA mixtures with waste plastic exhibited higher moisture resistance and resilient modulus compared to HMA mixtures without waste plastic, the fatigue life was less for HMA mixtures with waste plastic compared to HMA mixtures without waste plastic.

Awwad and Shbeeb (2007) demonstrated the use of LDPE and High Density Polyethylene (HDPE) plastics in bituminous mixtures in dry process. These plastics were utilized in two forms (grinded and not-grinded) with dosages of 6% to 18% (in increments of 2%) by weight of bitumen added to coarse aggregates at temperatures in the range of 180 to 190°C. The selected binder was of 60/70 grade with optimum bitumen content of 5.4% where limestone

was used as the aggregate with silica as the filler. Grinded plastics resulted in improved properties compared to not-grinded plastics due to improved surface area and the optimum plastic content reported was 12% where HDPE plastics resulted in improved Marshall properties compared to LDPE plastics.

Punith and Veeraragavan (2007) used LDPE with various proportions by weight of 80/100 grade bitumen in wet process. The performance of bituminous mixtures was evaluated through dynamic creep test in unconfined mode, indirect tensile strength test, resilient modulus test, and Hamburg wheel tracking test. The performance of LDPE-modified mixtures was better compared to conventional mixtures and the recommended dosage of polyethylene by weight of bitumen was 5%.

Al-Hadidy and Yi-qiu (2009) investigated the use of LDPE plastic in SMA mixtures using wet process at various dosages of LDPE starting from 0 to 8% in increments of 2%. The change properties of LDPE-modified asphalt binders was evaluated in terms of penetration, ductility, and softening point. The performance of SMA mixtures was evaluated through Marshall test, indirect tensile strength test, tensile strength ratio, and low-temperature performance. The changes in properties of LDPE-modified asphalt binders consisted of reduction in penetration and increase in softening point. The Marshall stability, indirect tensile strength, and tensile strength ratio were higher for LDPE modified mixtures compared to control mixtures. Further, the stiffness modulus and modulus of rupture were higher for LDPE modified bituminous mixtures compared to the control mixtures.

Attaelmanan et al. (2011) investigated upon the use of HDPE plastic in pellet form at the various dosage rates of 1%, 3%, 5%, and 7% for modifying 80/100 grade bitumen at 170^{o}C temperature by blending at 3000 rpm for 2 hours. The change properties of bituminous binders were evaluated in term of penetration, softening point, ductility, temperature susceptibility, and uniformity. The performance of bituminous mixtures was evaluated through Marshall test, moisture susceptibility test, and low-temperature performance test. The optimum dosage of HDPE plastic was reported as 5%. Increase in dosage of HDPE plastic resulted in decrease of penetration and increase of softening point. Further, increase in dosage of HDPE in bituminous mixtures resulted in increased Marshall stability, decreased flow, increased indirect tensile strength, increased tensile strength ratio, increased stiffness modulus, and increased modulus of rupture. The use of HDPE plastics improved the binder rutting resistance and also improved the resistance of bituminous mixtures towards rutting and flexural cracking.

Punith and Veeraragavan (2011) evaluated the mechanical characteristics such as tensile strength, permanent deformation, fatigue induced damage, and moisture susceptibility of Open Grade Friction Course (OGFC) mixtures blended with and without LDPE waste plastic in dry process. The use of LDPE plastic improved the tensile strength, resistance to rutting, resistance to fatigue damage, and resistance to moisture damage.

Yuanyuan and Zhongda (2011) evaluated the performance of bituminous mixtures blended with polyethylene in dry process. The performance of resulting bituminous mixtures was evaluated in terms of rutting, low-temperature cracking, and moisture damage wherein the performance of all the three indicators improved.

Rajasekaran et al. (2013) evaluated the influence of various types of waste plastics (polypropylene, LDPE, and PE foam) on the performance of bituminous mixtures in which the waste plastics were introduced in dry process. The dosage rates ranged from 0 to 15% in increments of 5% added by weight of bitumen for all types of plastics. The use of waste plastics improved the stability and binding properties.

Sarang et al. (2014) used waste plastic in SMA mixtures to evaluate its influence on drain-down test results, Marshall mix design parameters, and tensile strength ratio. Dry process was adopted to blend waste plastics in SMA mixtures at the dosages rates starting from 0 to 16% in increments of 4% blended by weight of bitumen. The use of plastics improved the stability and tensile strength ratio of SMA mixtures, and also reduced binder draindown.

Karmakar and Tapas Kumar Roy (2015) evaluated the change in properties of 60/70 grade bitumen blended with waste LDPE milk pouches using penetration test, softening point test, elastic recovery test, storage stability test, and morphological tests. Increase in dosage of waste plastic decreased the penetration of bitumen and increased the softening point. The elastic recovery was higher at 2% by weight of bitumen compared to the control binder. It was reported that a lower dosage of the plastic in the binder improves the elastic recovery and gets distributed homogeneously in the binder.

Das et al. (2018) evaluated the influence of LDPE waste plastic blended with bituminous mixtures in dry process. The performance of bituminous mixtures was evaluated in terms of moisture susceptibility, stiffness, fatigue, and rutting for unaged and aged conditions. Unaged plastic-modified mixtures performance was fair in terms of moisture susceptibility, acceptable in terms of workability, better in terms of resistance to traffic compaction, and exhibited higher

stiffness, higher rutting resistance, and slightly lower fatigue resistance. The performance of LDPE waste plastic blended bituminous mixtures improved upon aging.

Martin-Alfonso et al. (2019) evaluated the performance of LDPE waste plastic blended bituminous mixtures in dry process by selecting various types of mixtures such as bituminous concrete, high modulus mixtures, and porous asphalt mixtures using various binder grades. The performance of binders was evaluated through softening point test and oscillatory shear temperature sweep test at 10 rad/s where the temperature was varied from 30 to 120°C. The performance of bituminous mixtures improved in terms of Marshall stability, ITS, TSR, rutting, and fatigue resistance.

Ullah et al. (2021) evaluated the performance of bituminous mixtures consisting of natural aggregates partially replaced with LDPE and HDPE aggregates obtained through processing of the waste plastics. The replacement rates were 0 to 25% in increments of 5% by weight of aggregates and the binder was of 60/70 grade. Partial replacement of 15% aggregates with waste plastics resulted in better performance of bituminous mixtures in terms of Marshall stability, rut resistance, resilient modulus, and dynamic modulus.

Radeef et al. (2021) evaluated the performance of bituminous mixtures blended with waste plastic (5-10 mm size LDPE) through conventional dry process and an enhanced process where waste plastic was added to pre-heated (180°C) coarse aggregate and mixed to coat plastic over the surface of the coarse aggregate. LDPE-waste plastic of size 5 to 10 mm was blended at dosages of 0.5% and 1.0% by weight of aggregates. The plastic coated coarse aggregate was added to the fine aggregate followed by 60/70 grade hot bitumen to prepare plastic-modified bituminous mixtures. The HMA mixtures consisting of LDPE-waste plastic blended through enhanced process exhibited higher resistance to moisture damage and rutting compared to HMA mixtures without waste plastic and HMA mixtures consisting of LDPE-waste plastic blended through conventional dry process.

2.6 SUMMARY

In this chapter, a detailed review of literature is presented with a focus on performance of WMA binders, formation of aging compounds in WMA binders, performance of WMA mixtures, and performance of bituminous mixtures blended with waste plastic. Initially, the literature pertaining to the performance of WMA binders blended with various additives has been presented. The review of literature is confined only to non-foaming WMA additives and primarily includes organic and chemical additives. WMA binders offer a reduction in

bituminous mixture production temperature. At such temperatures there can be a reduction in the formation of aging compounds. Essentially, bituminous binders harden due to oxidation and volatilization of the lighter fractions present in it, resulting in an increased stiffness. While the increased stiffness is considered advantageous as it minimizes the initial damage due to rutting, it should be limited as excessive stiffness results in a reduction in fatigue life of the pavement. Past studies reported that the use of WMA additives reduces the stiffness of binders during aging. The compounds formed due to aging include sulfoxides, anhydrides, carboxylic acid, and ketones. Among these compounds, the carbonyl (carboxylic acid and ketones) and sulfoxide functionalities have been commonly used to quantify the aging in the material. FTIR spectroscopy has been successfully used to quantify the variation in carbonyl and sulfoxide functionalities across different aging conditions for HMA binders. The advantage of using FTIR spectroscopy here is that the vibrations corresponding to carbonyl and sulfoxide compounds occur in regions where there is minimal interference due to the vibrations of other functionalities present in bitumen. The WMA additive can also contain carbonyl and sulfoxide functionalities or lead to the formation of the same on its interaction with bitumen. Hence, it is also necessary to study the spectra of the WMA additive and its interaction with bitumen. Such an exercise will help in differentiating the carbonyl/sulfoxide compounds present in the WMA additive, those formed on interaction and that formed during the aging of WMA binders.

Unlike the HMA binder, the WMA binder is mixed with aggregates in a bituminous mix plant at relatively lower temperatures. However, in order to produce WMA binder, bitumen is heated to its mixing temperature that can range from 140 to 170°C depending on the type and grade of the binder. Thus, it is necessary to quantify the aging in the base binder during the production of WMA binder as such studies are scarcely available except for modified binders where the production temperatures and blending times are relatively higher. Considering the reduced mixing temperatures offered by WMA technology, some of the studies adopted reduced short-term aging temperatures for WMA binders whereas the corresponding temperature for HMA binders was 163°C. However, some of the studies preferred to maintain the short-term aging temperatures identical for both WMA and HMA binders. Such a practice will help in comparing the variation in aging compounds in both HMA and WMA binders at identical aging temperatures.

Even though the use of warm mix additives in general reduce the mixing and compaction temperatures, chemical warm mix additives have been widely preferred by several researchers across the world as these additives do not significantly alter the binder viscosity unlike the

organic additives and foaming technologies. In general, chemical additives reduce the internal friction between the aggregate and binder thereby improving the binder coating over the aggregates as they are emulsifiers and surfactants. Chemical additives are also termed as tensioactive additives as these additives reduce the binder surface tension without theoretically affecting the rheological properties. Some of the studies reported a marginal change in rheological properties of WMA binders blended with chemical additives compared to HMA binders. Several chemical additives are being used globally and the relative performance of binders and mixtures depends on the type of chemical additive, its dosage and the choice of binder apart from the type of aggregates due to their diverse range of mechanisms. Similar to the organic additives, some of the chemical additives reduce the binder viscosity due to the presence of rheology modifiers in addition to the surfactants. The surfactant-based chemical additives reduce the surface tension of the binder thereby improving its wetting ability due to reduced contact angles. It is observed that the performance of WMA binders primarily depend on the type of WMA additive and the base binder. Thus, it is necessary to evaluate the performance of a specific chemical warm mix additive blended with different bituminous binders.

Based on the review of literature, it is observed that the WMA binders exhibiting better performance compared to HMA binders need not necessarily exhibit similar trends when tested for the performance of bituminous mixtures. Thus, it is essential to evaluate the relative performance of both HMA and WMA mixtures. Further, the influence of air voids can lead to different levels of aging which again varies significantly for HMA and WMA binders. The recommended maximum air void content for bituminous mixtures is 8% which corresponds to 92% of G_{mm}. Thus, a newly constructed bituminous layer is compacted to 6 to 8% air voids with an average of 7% air voids. At these air voids, moisture is likely to penetrate into the bituminous mixtures. At the same time, bituminous mixtures with such air voids are likely to rut more due to secondary compaction resulting from vehicular movement. It is important to note here that WMA binders exhibit better resistance to cracking as they undergo less aging compared to HMA binders. Further, due to lower stiffness of WMA binders compared to HMA binders, they are more prone to rutting. Therefore, it is necessary to evaluate the moisture resistance and rutting resistance of bituminous mixtures prepared with 7% target air voids. The air voids in a bituminous layer at the end of design life would reach a limiting value of approximately 4% which is considered as the design air voids. At initial 7% air voids, the bituminous mixtures would have undergone short-term aging and at terminal 4% air voids, the bituminous mixtures would have undergone long-term aging. As reduction in air voids and aging occur

simultaneously in bituminous mixtures, it is necessary to evaluate the performance of both HMA and WMA mixtures in terms of resistance to moisture damage and resistance to rutting. To evaluate the effect of air voids, the aging condition should remain the same whereas to evaluate the effect of aging, the air voids should remain the same in the specimens. Therefore, it is necessary to evaluate the moisture resistance and rutting resistance of short-term aged bituminous mixtures prepared with higher target air voids of 7%. At the same time, it is necessary to evaluate the moisture resistance and rutting resistance of long-term aged bituminous mixture specimens prepared with lower target air voids of 4%. Thus, at same 4% air voids, the influence of long-term aging of bituminous mixtures can be quantified in terms of resistance to rutting and moisture damage.

Several researchers in the past reported that moisture susceptibility of WMA mixtures is a major cause of concern. The moisture resistance of WMA mixtures can be lower than that of HMA mixtures due to reduced production temperatures resulting in incomplete drying of aggregates. At the same time, the reduction in production temperatures results in bituminous mixtures that are more susceptible to rutting. Previous studies recommended using Reclaimed Asphalt Pavement (RAP) materials in WMA mixtures in order to improve its rutting resistance. The performance evaluation of long-term aged bituminous mixture specimens can address such issues. At the same time, previous studies also recommended blending waste plastic with bituminous mixtures in the dry process in order to improve the moisture resistance and rutting resistance of bituminous mixtures. The major disadvantage of the dry process is that the shredded waste plastic is added to whole fractions of preheated aggregate in the pug mill. Fused plastic tends to agglomerate with fine aggregate particles, and result in the formation of small lumps which may lead to the underperformance of bituminous mixtures. Therefore, the dry process of blending waste plastic to aggregates needs to be altered by adopting one of the innovative techniques reported in the literature by initially adding the shredded waste plastic to preheated coarse aggregate, followed by the addition of fine aggregates and binders. Thus, the implications of coating the complete fraction of aggregates with waste plastic and coarse-aggregate only fraction with waste plastic on moisture resistance and rutting resistance of both HMA and WMA mixtures need to be explored. Even though the HMA binder rutting parameters correlate well with the HMA rutting parameters, it is necessary to correlate the HMA and WMA binder rutting parameters with the permanent deformation in HMA and WMA mixtures so that the most suitable rutting parameter can be identified especially for WMA mixtures.

2.7 RESERCH GAPS

Based on the summary of the comprehensive literature review, the following research gaps are identified:

1 The quantification of aging compounds (carbonyl, sulfoxide) during the production process for Evotherm-modified binders are scarcely studied. Considering the reduced mixing temperatures offered by the WMA technology, some of the studies adopted a reduced short-term aging temperature whereas the corresponding temperature for HMA binders was 163^{o}C. However, some of the studies preferred to maintain the same short-term aging temperatures for both HMA and WMA binders. Thus, there is a need to evaluate the relative performance of HMA and WMA binders that are subjected to identical aging conditions.

2 Several chemical warm mix additives are being used globally and the relative performance of binders and mixtures depends on the type of chemical additive, its dosage, the type of binder and the type of aggregates due to their diverse range of mechanisms. Thus, there is a need to evaluate the performance of a specific chemical warm mix additive blended with different bituminous binders that are subjected to different aging conditions.

3 Based on the literature review, it is observed that the WMA binders exhibiting better performance compared to HMA binders need not necessarily exhibit similar trends when tested for performance of bituminous mixtures. Thus, there is a need to evaluate the relative performance of both HMA and WMA mixtures. Further, the influence of air voids can lead to different levels of aging and moisture damage depending on the type of binders and the type of warm mix additive. Thus, there is a need to evaluate the moisture resistance and rutting resistance of bituminous mixtures prepared with different target air voids and aging conditions.

4 The moisture resistance of WMA mixtures can be lower than that of HMA mixtures due to reduced production temperatures resulting in incomplete drying of aggregates. At the same time, the reduction in production temperatures results in bituminous mixtures that are more susceptible to rutting. Previous studies recommended using RAP materials in WMA mixtures to address such issues. However, the performance evaluation on long-term aged mixtures can address such issues. Some studies also recommended using waste plastic in bituminous mixtures to improve the moisture resistance and rutting resistance of bituminous mixtures. However, the current practice of blending waste plastic to whole aggregate fraction results in formation of small lumps as the fused

plastic tends to agglomerate with fine aggregate particles resulting in underperformance of bituminous mixtures. Thus, there is a need to use a better process which can overcome such problems.

5 Limited studies have been carried out to evaluate the performance of bituminous mixtures consisting waste plastic coated coarse aggregates. Thus, there is a need to evaluate the performance of bituminous mixtures consisting of waste plastic coated coarse aggregates.

6 Even though HMA binder rutting parameters correlate well with HMA rutting parameters, there is a need to correlate the HMA and WMA binder rutting parameters with the permanent deformation in HMA and WMA mixtures. This will help in selection of a best rutting performance indicator for the bituminous mixtures.

CHAPTER 3
METHODOLOGY

3.1 GENERAL

In order to accomplish the study objectives, the methodology adopted for the current study is depicted through a flowchart shown in Figure 3.1. This study used four control binders namely VG20, VG40, PMB40, and CRMB60 and these binders were doped by a chemical warm mix additive, Evotherm, to prepare Evotherm-modified binders such as EVG20, EVG40, EPMB40, and ECRMB60. The experimental investigation for the present work was carried out in three phases. In the first phase, spectral and rheological evaluations were carried out on HMA and WMA binders at unaged, short-term aged, and long-term aged conditions. The spectral evaluation of binders was carried out with the help of FTIR spectroscopy. It is used to evaluate the influence of adding Evotherm additive into the base binders for possible changes in aging compounds. For the rheological investigation, a dynamic shear rheometer was used to perform various tests such as amplitude sweep test, frequency sweep test, multiple stress creep and recovery test, and linear amplitude sweep (LAS) test in the laboratory to evaluate the effect of adding Evotherm to the base binder in terms of Superpave rutting parameter, Shenoy's parameter, non-recoverable creep compliance, zero shear viscosity, low-shear viscosity, fatigue life, Glover-Rowe parameter, aging durations at which binder exhibits cracking initiation and significant cracking threshold.

In the second phase, the performance of bituminous mixtures containing control and low-density-polyethylene waste plastic coated coarse aggregate with and without Evotherm additive in the base binders was evaluated for permanent deformation and moisture damage resistance. The short-term aged mixtures were compacted to prepare specimens with target air voids of 4% and 7% whereas the specimens for long-term aging were compacted to 4% air voids. The target air voids are selected to simulate the in-place air voids in newly constructed bituminous layer and an aged pavement. To quantify the influence of aging, the short-term aged bituminous mixtures were also compacted to the same target air voids of 4% as that of the long-term aged specimen. The permanent deformation resistance of the bituminous mixtures was evaluated with the help of dry wheel tracking test whereas moisture damage resistance was evaluated with the help of the indirect tensile strength test. In the third phase, bituminous binders and mixture test results were correlated between rut depth and all binder rutting parameters. The materials and equipment used for the present research work and the relevant test protocols including

sample preparation procedures and the process adopted for analyzing the test results are elaborated in this chapter.

3.2 MATERIALS

The present research work utilized the following materials: aggregates, bituminous binders, low density polyethylene waste plastic, and Evotherm additive. The properties of aggregates, types and properties of bituminous binders, processing of low density polyethylene waste plastic, blending dosages of Evotherm additive with bituminous binders along with the mixing parameters are presented in this section.

3.2.1 Aggregates

Crushed aggregates were procured from a local stone crushing plant. The physical properties of aggregates were measured in accordance with the relevant Bureau of Indian Standards (BIS) test protocols, and the results thus obtained were checked for conformity with the specifications of Ministry of Road Transport and Highways (MoRTH, 2013). The test results are compared with the MoRTH (2013) specifications for aggregates intended to be used in bituminous concrete surface course. Table 3.1 presents the test results on aggregates used in the current study and all the results satisfied the specification limits.

Table 3.1 Physical properties of aggregates

Property	Results	Specification (MoRTH, 2013)
Cleanliness	3.90%	Max. 5% passing 0.075 mm sieve
Combined flakiness and elongation index	27%	Max. 35%
Los Angeles abrasion value	21.89%	Max. 30%
Aggregate impact value	15.82%	Max. 24%
Soundness using Sodium Sulphate	2%	Max. 12%
Water absorption	0.60%	Max. 2%
Retained coating of bitumen over aggregates	99%	Min. 95%

3.2.2 Bituminous binders

Two viscosity grade binders (VG20, VG40), and two modified binders (PMB40, CRMB60) were used in the present study. The physical properties of unmodified and modified binders were measured in accordance with the relevant BIS test protocols, and the results thus obtained were checked for conformity with the specifications given in IS 73 (2018) for unmodified binders, IS-15462 (2019) for polymer modified bitumen, and IS-17079 (2019) for crumb rubber modified bitumen. The test results on VG20 and VG40 binders are presented in Table 3.2 and the test results on CRMB60 and PMB40 are presented in Table 3.3. The test results on all the four binders satisfied the relevant specification limits.

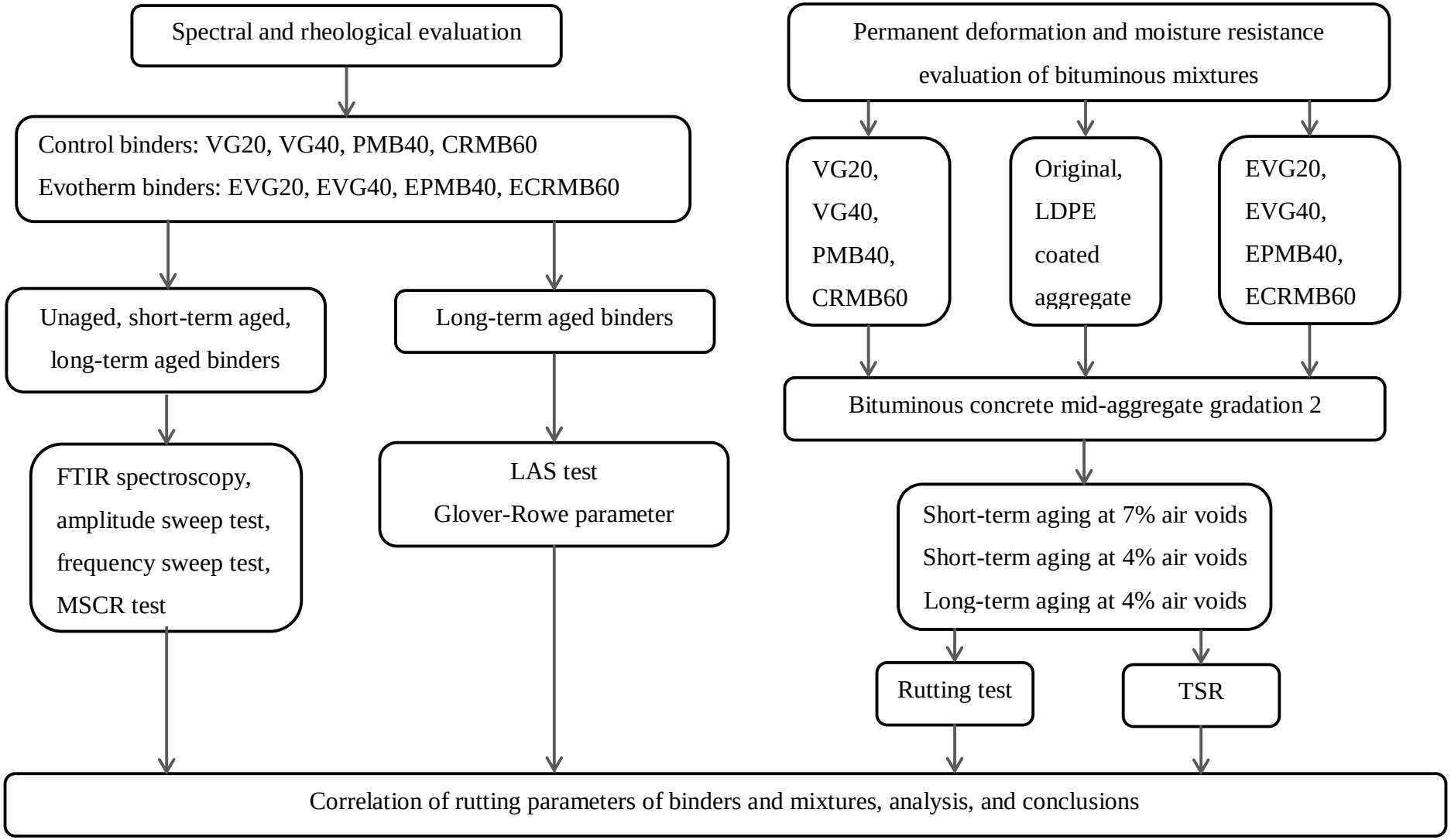


Fig. 3.1 Methodology adopted for performance evaluation bituminous binders and mixtures

Table 3.2 Physical properties of VG20, and VG40 binders

Characteristics	VG20		VG40	
	Result	**Specification (IS 73, 2018)**	**Result**	**Specification (IS 73, 2018)**
Penetration at 25°C, 100 g, 5 s, 0.1 mm	64	Min. 60	55	Min. 35
Absolute viscosity at 60°C, Poises	2276	1600-2400	4414	3200-4800
Kinematic viscosity at 135°C, cSt	359	Min. 300	451	Min. 400
Flash point (Cleveland open cup), °C	315	Min. 220	255	Min. 220
Solubility in trichloroethylene, %	99	Min. 99	99	Min. 99
Softening point (R&B), °C	51	Min. 45	56	Min. 50
Tests on residue from RTFO: a. Viscosity ratio at 60°C b. Ductility at 25°C, cm	 1.2 100	 Max. 4 Min. 50	 1.3 47	 Max. 4 Min. 25

Table 3.3 Physical properties of PMB40 and CRMB60 binders

Characteristics	PMB40		CRMB60	
	Result	**Specification (IS 15462, 2019)**	**Result**	**Specification (IS 17079, 2019)**
Penetration at 25°C, 100 g, 5 s, 0.1 mm	NA	NA	36	50-20
Softening point (R&B), °C	67	Min. 65	64	Min. 60
Flash point (Cleveland open cup), °C	268	Min. 230	275	Min. 220
Elastic recovery at 15°C, %	80	Min.70	70	Min. 60
Separation difference in softening point, °C	1	Max. 3	2	Max. 4
Viscosity at 150°C , Poise	11	12	12	6-12
Test on residue from RTFOT: a. Loss in mass, % b. Change in softening point, ˚C c. Reduction in penetration, %	 0.8 NA NA	 Max. 1 NA NA	 0.82 2 24	 Max. 1.0 Max. 5 Max. 35

3.2.3 Evotherm additive

The chemical warm additive selected for the current study is Evotherm. It works based on surfactant technology and contains chemistry packages. It is mostly used for improving coating, adhesion, and workability of bituminous mixtures (Prowell et al. 2012). Based on literature (Behl et al., 2015; Kök et al., 2019; Kuang, 2012; Oliveira et al., 2013; Roja et al., 2018), Evotherm additive dosage of 0.4% by weight of bitumen was selected for unmodified binders (VG20, VG40) whereas 0.5% dosage by weight of bitumen was selected for modified binders (PMB40, CRMB60). The parameters as suggested by the manufacturer of Evotherm additive were adopted for the production of WMA binders in the current study and are shown in Table 3.4. The selected mixing parameters reflects the field mixing conditions and ensures homogeneous mixing of Evotherm and bitumen.

Table 3.4 Parameters adopted for production of WMA binders

S. No.	Binder	Dosage	Mixing temperature	Mixing rate	Mixing duration
1.	VG20	0.4%	150°C	1200 rpm	30 minutes
2.	VG40	0.4%	165°C	1200 rpm	30 minutes
3.	PMB40	0.5%	165°C	1200 rpm	30 minutes
4.	CRMB60	0.5%	165°C	1200 rpm	30 minutes

3.2.4 Low density polyethylene waste plastic

Disposed milk pouches made of low density polyethylene (LDPE) were collected from National Institute of Technology, Warangal hostel mess. These milk pouches were initially cleaned and dried. LDPE waste plastic is made of thermoplastic materials with Society of the Plastic Industry (SPI) code number 4. The waste plastic was shredded such that the maximum width and length are always less than 2 mm as recommended by IRC: SP: 98, 2020. A sample milk pouch collected for the present study is shown in Figure 3.2(a) whereas Figure 3.2(b) shows the shredded waste plastic.

(a) (b)

Fig. 3.2 (a) LDPE waste-plastic, and (b) shredded LDPE waste plastic

3.3 EQUIPMENT USED FOR CHARACTERIZATION OF BINDERS

Two major equipment were used to quantify the variation in aging compounds and to evaluate the rheological characteristics of HMA and WMA binders. This includes FTIR spectrometer and dynamic shear rheometer. Perkin Elmer Spectrum 100 FTIR spectrometer as shown in the Figure 3.3(a) was used to quantify the variation in aging compounds for both HMA and WMA binders subjected to unaged, short-term aged, and long-term aged conditions. Anton Paar MCR 52 dynamic shear rheometer as shown in Figure 3.3(b) was used to evaluate the rheological properties of both HMA and WMA binders.

(a) (b)

Fig. 3.3 (a) FTIR spectrometer, and (b) dynamic shear rheometer

3.4 EQUIPMENT USED TO EVALUATE BITUMINOUS MIXTURES

Major equipment used to evaluate the mechanical characteristics of HMA and WMA mixtures in terms of resistance to moisture damage and resistance to permanent deformation are indirect tensile strength apparatus and wheel tracking device, respectively. Indirect tensile strength apparatus as shown in Figure 3.4(a) was used to determine the resistance to moisture damage of all types of the bituminous mixtures used in this study as per AASHTO T 283 (2014) protocol. Wheel tracking device as shown in Figure 3.4(b) was used to evaluate the resistance to permanent deformation of various types of bituminous mixtures used in the study. A dry wheel was run on the compacted specimen of diameter 150 mm and height 100 mm at a test temperature of 60°C. Progression of permanent deformation was recorded with the help of LVDTs till the specimen reaches 15 mm rut depth or 20,000 passes.

(a) (b)

Fig. 3.4 (a) Indirect tensile strength test apparatus, and (b) wheel tracking device

3.5 EQUIPMENT USED FOR AGING OF BITUMINOUS BINDERS AND BITMINOUS MIXTURES

The short-term and long-term aging of bituminous binders and bituminous mixtures was carried out in the laboratory using the following equipment: rolling thin film oven, pressure aging vessel, and forced draft oven. Rolling thin film oven was used for short-term aging of binders whereas pressure aging vessel was used for long-term aging of binders. The short-term and long-term aging of bituminous mixtures was performed using a forced draft oven. The details of all these equipment are presented in this section.

3.5.1 Short-term aging of binders

Short-term aging of HMA and WMA binders was carried out in the laboratory using Rolling Thin Film Oven (RTFO) as shown in the Figure 3.5(a). All the HMA binders used in the study were short-term aged as per the ASTM Standard test protocol (ASTM D2872, 2022). The bituminous binder weighing 35 ± 0.5 g was poured into each glass container shown in Figure 3.5(b). The glass container with the sample was placed inside the vertical carriage, and samples were rotated at 15 ± 0.2 rpm for short-term aging at 163°C for 85 minutes with an airflow of 4000±200 mL/min (ASTM D2872, 2022). In order to quantify the variation in aging compounds, the WMA binders were also short-term aged at 163°C. However, to evaluate the influence of Evotherm additive on rheological properties of control binders, HMA binders were short-term aged at 163°C whereas WMA binders were short-term aged at 138°C.

(a) (b)

Fig. 3.5 (a) Rolling thin film oven, and (b) glass container

Fig. 3.6 (a) Pressure aging vessel, (b) samples after long-term aging, and (c) vacuum degassing oven

3.5.2 Long-term aging of binders

The long-term aging of HMA and WMA binders was carried out using pressure aging vessel as shown in Figure 3.6(a). All the short-term aged samples were long-term aged as per the ASTM D6521 (2022) protocol. For long-term aging, 50 ± 0.5 g of short-term aged binder was poured in a pan and kept in the pressure aging vessel for 20 hours at 100°C by maintaining a pressure of 2.10 ± 0.1 MPa. After long-term aging, gases entrapped inside the bituminous binder was removed with help of a vacuum degassing oven by applying absolute pressure of 15 ± 2.5 kPa for the duration of 30 ± 1 minutes.

3.5.3 Short-term and long-term aging of bituminous mixtures

Forced draft oven as shown in Figure 3.7 was used for short-term aging and long-term aging of HMA and WMA mixtures. All the HMA mixtures were short-term aged as per AASHTO R 30(2015), wherein HMA mixtures were kept in oven for the period of 4 h ± 5 min at 135 ± 3°C. All the WMA mixtures were short-term aged for 4 hours at 110°C, that is, 25°C lower temperature than HMA mixtures. Further, the compacted HMA and WMA specimens were long-term aged for 120 ± 0.5 h at 85 ± 3°C.

(a) (b)

Fig. 3.7 (a) Short-term aging of bituminous mixtures, and (b) long-term aging of compacted bituminous mixture specimens

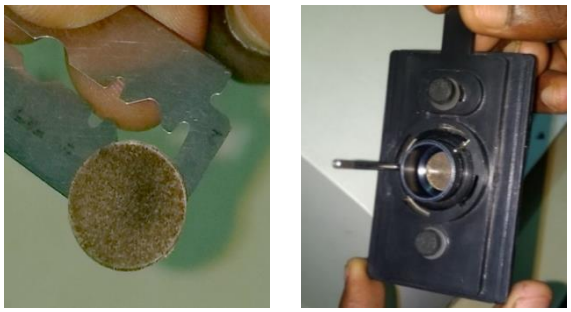
3.6 QUANTIFICATION OF AGING COMPOUNDS USING FTIR SPECTROSCOPY

FTIR spectroscopy is used to quantify the variation in carbonyl and sulfoxide functionalities for both HMA and WMA binders under unaged, short-term aged, and long-term aged conditions. The short-term aging (SA) for the control and Evotherm-modified binders was carried out at 163°C using a rolling thin film oven (RTFO). Even though some of the previous studies adopted lower short-term aging temperatures for WMA binders, the current study adopted identical short-term aging temperature for both HMA and WMA binders. This will help in comparing the variation in carbonyl and sulfoxide functionalities at identical aging temperature for both HMA and WMA binders. Such practice was adopted in the past for WMA binders (Abbas et al., 2016; Abdullah et al., 2016). The long-term aging (LA) was performed on the short-term aged HMA and WMA binders using a Pressure Aging Vessel (PAV) at 100°C. Subsequently, the effect of aging and the addition of Evotherm additive in the control binders was evaluated and quantified in terms of aging indices such as carbonyl index and sulfoxide index.

3.6.1 Selection of solvent

The type of solvent to be used for sample preparation using the solvent-cast method for FTIR testing must be selected carefully because the selected solvent might affect the spectra. Hence, tetrahydrofuran (THF) solvent was selected for preparing the sample for FTIR testing because it does not have the problem of hydrogen bonding and dimer formation with the bituminous binder (Peterson, 1986).

(a) (b) (c)



(d) (e)

Fig. 3.8 Accessories for FTIR sample preparation: (a) porcelain mould, (b) pellet assembly, (c) KBr hydraulic press, (d) pellet sample, and (e) sample holder

3.6.2 FTIR sample preparation

The FTIR sample preparation procedure adopted for HMA and WMA binders at unaged, short-term aged, and long-term aged conditions is the same. The accessory required for FTIR sample preparation is shown in Figure 3.8. Initially, the bitumen-solvent solution was prepared by dissolving 0.5 g of bituminous binder in THF solvent at a 10% weight-to-volume ratio. A small volume of this bitumen-solvent was sprayed on potassium bromide (KBr) powder and mixed in porcelain mould. This mixture powder was poured into a pellet assembly and pellets were made by applying 10 tons of load using KBr hydraulic press. To avoid moisture absorption, the prepared pellets were kept under sodium light. Later, these pellets were kept in the sample holder and used to measure the spectra using FTIR spectrometer.

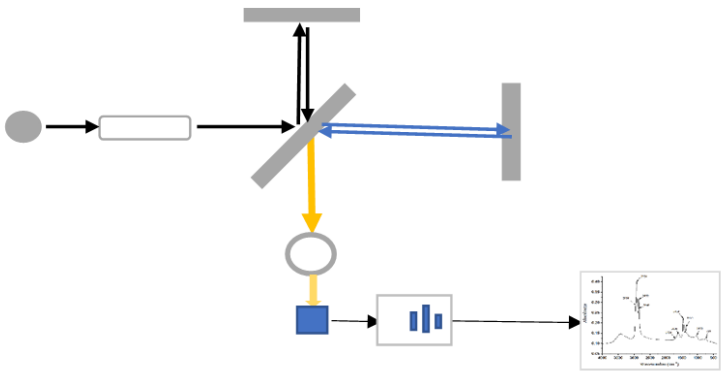


Fig. 3.9 Block diagram of FTIR spectrometer

3.6.3 FTIR testing

FTIR testing was carried out in transmittance mode using PerkinElmer Spectrum 100 FTIR spectrometer at 4 cm^{-1} resolution. The block diagram of the FTIR spectrometer is shown in Figure 3.9. It mainly consists of the light source, collimator, beam splitter, fixed mirror, movable mirror, sample holder, detector, and computer. A light source of an infra-red (IR) beam was passed through a collimator and incident the beam splitter, some part of the beam will be reflected and transmitted to the fixed mirror and movable mirror. The beam will be reflected from both the mirrors and interfere with each other to combine the beam. The combined beam will hit the prepared bituminous pellet sample at a particular frequency which might be having a similar bond frequency to the functional group. Due to this, the functional group present in the bituminous pellet will absorb the light, and very less transmitted light will be captured by the detector. This procedure will be repeated by varying the position of the movable mirror and an interferogram will be generated. Finally, with the help of a mathematic tool, Fourier transformation was adopted and spectra were measured. The absorption of infrared light by the functional group present in the material is estimated using Equation (3.1).

$$A = 2 - \log_e T \qquad \text{Eq. (3.1)}$$

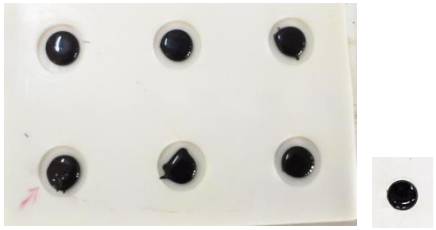
Where, *A* is absorption in percentage, and *T* is transmittance in percentage.

3.7 RHEOLOGICAL CHARACTERISATION OF BINDERS

The main focus of rheological characterization is to evaluate the influence of adding Evotherm additive to HMA binders in terms of rutting parameters, fatigue parameters, and initial cracking threshold and the significant cracking threshold at different aging conditions.

3.7.1 Sample preparation for DSR testing

The silicone mould method was used for the preparation of samples required to perform tests on DSR using 25 mm and 8 mm parallel plate geometries. In this method, bituminous binder was heated to a pourable consistency and subsequently poured into the silicone mould. The silicone mould along with the samples for 25 mm and 8 mm geometries are shown in Figures 3.10(a) and 3.10(b), respectively. The mould was covered in order to avoid contamination, and stored for a period of 24 h at ambient room temperature. Demoulding of the sample was done only after keeping the silicone mould along with the sample inside the freezer for 10 minutes as per the code BS EN 14770 (2012).



(a) (b)

Fig. 3.10 (a) Sample mould for 25 mm geometry, and (b) sample mould for 8 mm geometry

3.7.2 Thermal equilibrium time

Thermal equilibrium time is defined as the time at which complex modulus remain constant over a period of time for a constant oscillatory loading. This time was determined to study the influence of adding Evotherm additive to HMA binders. It was determined by following the appendix X4 test procedure of ASTM D7175 (2015). The oscillatory sweep test was performed by applying a constant frequency of 10 rad/s and a small strain at 30 second interval on unaged, short-term aged, and long-term aged samples of HMA and WMA binders. As the maximum pavement temperature in India is about 60°C in most of the regions, the following test temperatures were used to determine the thermal equilibrium time at various aging conditions as shown in Table 3.5. A linear model was fitted to the complex modulus data to determine the thermal equilibrium time at critical temperature of 60°C as well as for other pavement working temperatures like 45°C and 50°C.

Table 3.5 Test temperatures for thermal equilibrium time

Binders	**Temperature, ^{o}C**		
	Unaged bitumen	**Short-term aged bitumen**	**Long-term aged bitumen**
VG20 , EVG20	40, 55, 65	40, 55, 65	60
VG40, EVG40	40, 55, 65	40, 55, 65	60
PMB40, EPMB40	40, 55, 65	40, 55, 65	60
CRMB60, ECRMB60	40, 55, 65	40, 55, 65	60

3.7.3 Amplitude sweep test

The schematic diagram of amplitude sweep test is shown in Figure 3.11 where strain was varied at a constant frequency. The amplitude sweep test was carried out on both HMA and WMA binders using a DSR with strain amplitude varying from 0.01% to 100%, frequency of 10 rad/s, and temperature of 60^{o}C for unaged, short-term aged, and long-term aged conditions using a 25 mm parallel plate geometry. The DSR was operated with the help of Rheoplus software as per the standard test method for determining the rheological properties of asphalt binder using a dynamic shear rheometer (ASTM D7175, 2015). The data was recorded continuously for

dynamic modulus (G^*), phase angle (δ), and superpave rutting parameter ($G^*/\sin\delta$). This data was extracted and tabulated at 12% strain, and 10% strain for unaged, short term aged, and long-term aged conditions as per the ASTM D7175 standard. Later, Shenoy's parameter was estimated for control and Evotherm-modified binders.

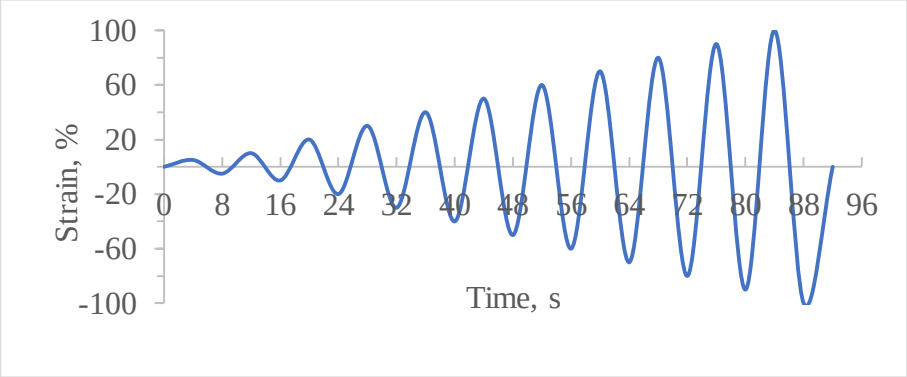


Fig. 3.11 Schematic diagram of amplitude sweep test

3.7.4 Multi-stress creep and recovery test

The multi-stress creep and recovery (MSCR) test is based on the creep and recovery test concept used to evaluate the rutting potential of the bituminous binder. The MSCR test was performed on unaged, short-term aged, and long-term aged samples of HMA and WMA binders at 60°C temperature using 25 mm geometry parallel plate. With the help of dynamic shear rheometer, the shear stresses such as 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, and 25.6 kPa were applied on HMA and WMA binder specimens for one second, and the load was removed immediately to observe recovery over 9 seconds. This is considered as one cycle of creep and recovery. The response of bituminous binder for one cycle of creep and recovery is shown in Figure 3.12. At each stress level, all the binders were subjected to 10 creep-recovery cycles. Simultaneously, the shear stress and unrecoverable shear strain data was recorded at 0.1 second interval in the creep cycle, and 0.45 second interval in the recovery cycle. The non-recoverable creep compliance (J_{nr}) of bituminous binder can be determined from Equations (3.2) to (3.3).

$$J_{nr}\ at\ 1st\ cycle = \frac{USS_{10}\ in\ 1st\ cycle}{Applied\ shear\ stress\ in\ 1st\ cycle} \quad \text{Eq. (3.2)}$$

$$J_{nr} = \frac{\sum_{i=1}^{10} J_{nri}}{10} \quad \text{Eq. (3.3)}$$

Where, USS_{10}, and J_{nri} are unrecoverable shear strain at the end of 10 s in the first cycle and non-recoverable compliance for the i^{th} cycle. Lower the J_{nr} value of bituminous binders indicates that the binder will have better resistance to permanent deformation (Singh and Kataware, 2016).

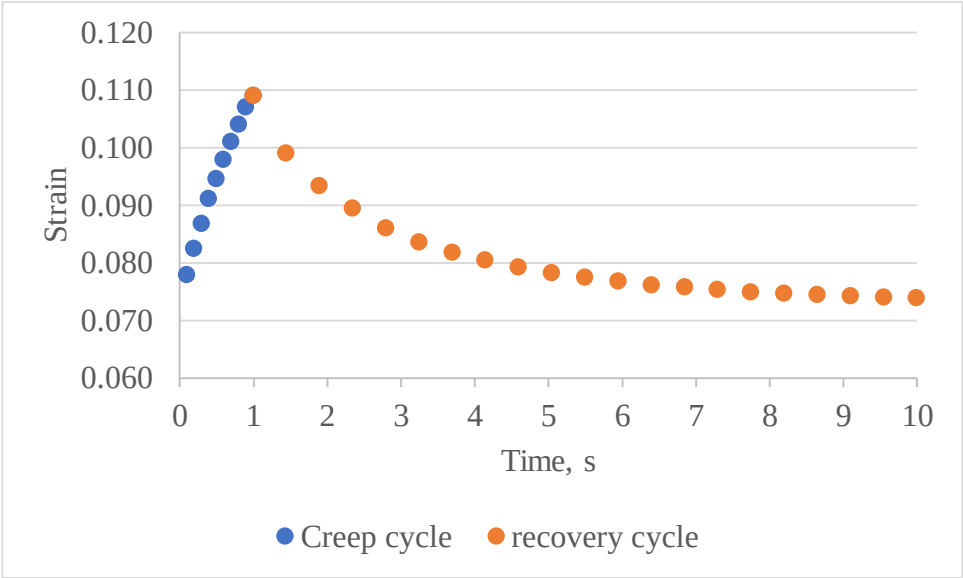


Fig. 3.12 Schematic diagram of multiple stress creep recovery test

3.7.5 Frequency temperature sweep test

The frequency temperature sweep test (FTST) is an oscillatory sweep test in which a wide range of temperatures and frequencies are varied over a period of time at constant strain as shown in Figure 3.13. FTST was performed for unaged, and short-term aged samples of HMA and WMA binders using 25 mm geometry with 1 mm gap setting at temperatures from 52 to 100ºC in increment of 6ºC, frequencies from 2 to 20 rad/s in increments of 2 rad/s, 12% strain for unaged, and 10% strain for short-term aged samples. Subsequently, zero-shear viscosity and low-shear viscosity were determined, and master curves were developed at a reference temperature of 60°C. Further, FTST was also performed on long-term aged samples of HMA and WMA binders using 8 mm geometry with a 2 mm gap setting at frequencies from 2 to 20 rad/s in increments of 2 rad/s, and temperature from 10 to 34°C in increments of 6°C to develop fatigue parameter master curves.

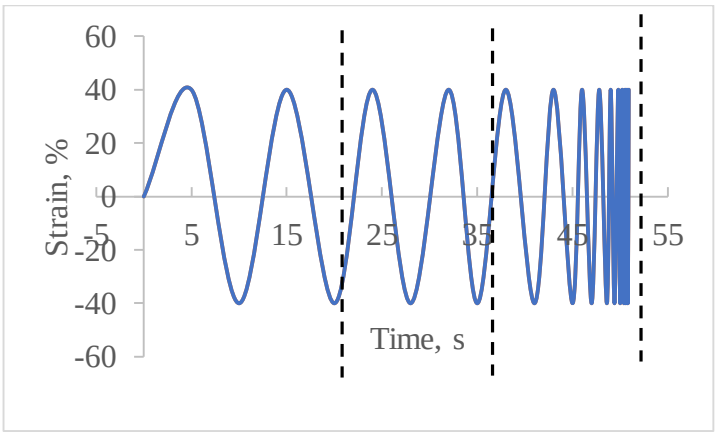


Fig. 3.13 Schematic diagram of frequency sweep test

3.7.6 Master curve for superpave rutting and fatigue parameters

The Master curve was developed by shifting the superpave rutting parameter and fatigue parameter data at reference temperatures of 60°C and 25°C respectively using William-Landel-Ferry (WLF) Equation (Williams et al., 1955) with the sigmoidal model (Biswas and Pellian, 2007), and modified sigmoidal model (Yang & You, 2015) was used to fit the data to obtain sigmoidal parameter using solver function in Microsoft Excel. The WLF equation, sigmoidal, and modified sigmoidal model are shown respectively by Equations (3.4) to (3.6).

$$\log f_{red} - \log f = \log \alpha_t = -\frac{C_1(T-T_{ref})}{(C_2+T-T_{ref})} \quad \text{Eq. (3.4)}$$

$$\log|G^*| = \Delta + \frac{\alpha}{1+e^{\beta-\gamma \log f_{red}}} \quad \text{Eq. (3.5)}$$

$$\delta = c\frac{\pi}{2}\frac{\alpha\gamma}{\left(1+e^{\beta-\gamma \log f_{red}}\right)^2} e^{\beta-\gamma \log f_{red}} \quad \text{Eq. (3.6)}$$

Where, f_{red} is reduced frequency in rad/s, f is loading frequency in rad/s, α_t is shift factor, C_1 and C_2 are empirical constants, T is test temperature, and T_{ref} is reference temperature at which the master curve needs to be developed, Δ is the minimum complex modulus, $\Delta+\alpha$ is the maximum modulus or span of the data, β and γ are the locations and slope steepness of the sigmoidal curve, and δ is phase angle.

3.7.7 Linear amplitude sweep test

Linear amplitude sweep (LAS) test was used to characterize the fatigue behaviour of bituminous binders at long-term aged condition. The schematic diagram of the LAS test is shown in the Figure 3.14. LAS test was carried out on long-term aged samples of HMA and WMA binders at a temperature of 25°C in two stages: frequency sweep test followed by amplitude sweep. In the first stage, frequency sweep test was performed on the sample at frequencies from 0.2 to 30 Hz at 0.1% strain to determine the rheological property of the bituminous binder. In the second stage, the amplitude sweep test was carried out on the same sample at 0.1%, and 1% to 30% with 1% increment of strain at 10 Hz frequency to characterize the damage characteristics of bituminous binder (AASHTO TP101, 2015). The fatigue life (N_f) of HMA and WMA binders was determined using Equations (3.7) to (3.12).

$$N_f = A * (\gamma_{max})^{-B} \quad \text{Eq. (3.7)}$$

Where, γ_{max} is the maximum expected strain in bitumen, and A, B are fatigue law coefficients. The parameter B was determined using Equations (3.8) and (3.9) on frequency sweep test data. The parameter A was determined using viscoelastic continuum damage analysis on amplitude sweep data as shown in Equations (3.8) to (3.12).

$$B = 2 * \alpha \quad \text{Eq. (3.8)}$$

$$\alpha = 1 + \frac{1}{m} \quad \text{Eq. (3.9)}$$

$$A = \frac{f*(D_f)^k}{K*(\pi C_1 C_2)^\alpha} \quad \text{Eq. (3.10)}$$

$$D_f = \left(\frac{C_0 - C \text{ at peak stress}}{C_1}\right)^{1/C_2} \quad \text{Eq. (3.11)}$$

$$log([C_0 - C(t)]) = \log(C_1) + C_2 \log[D(t)] \quad \text{Eq. (3.12)}$$

Where, α is the undamaged bitumen binder property and m is the slope of the plot between log ω on the x-axis and G′(ω) on the y-axis, ω is frequency, C_o is equal to 1 at an initial value of C, C is binder integrity parameter, C_1 and C_2 are coefficients of Equation (3.12).

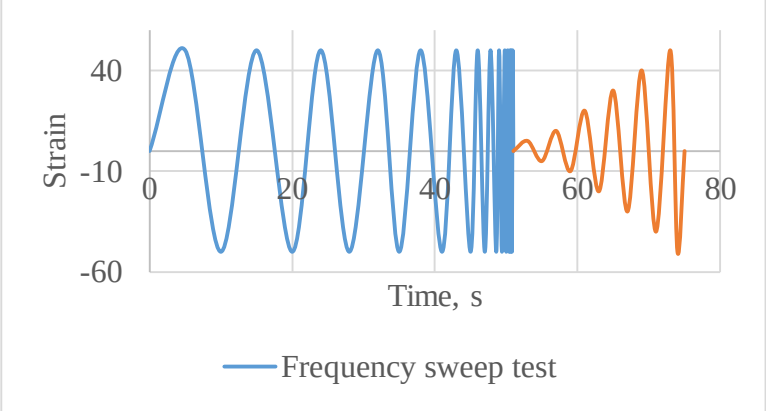


Fig. 3.14 Schematic diagram of linear amplitude sweep test

3.7.8 Glover-Rowe parameter

The cracking susceptibility of long-term aged HMA and WMA binders was evaluated using the Glower-Rowe parameter. All the short-term aged binders were oxidized at various aging levels of 10 h, 25 h, 40 h, and 65 h using a pressure aging vessel. Using a dynamic shear rheometer, two frequency temperature sweeps were performed in succession on the same sample. In the first sequence, the frequency temperature sweep test was performed within a temperature range of 40°C to 10°C in increments of 10°C, 2% strain, 2 mm gap setting, and frequencies ranging from 1 to 20 rad/s. This was followed by a second sequence in which a frequency temperature sweep was performed at temperatures of 50°C and 60°C, 5% strain, 1 mm gap setting, and frequencies ranging from 1 to 20 rad/s. The target strain and gap setting were changed in order to maintain a minimum torque limit of 250 µNm for the DSR apparatus used in the current study. The data was recorded and exported for dynamic modulus and phase angle corresponding to the temperature and frequency. The master curves were used in order to estimate dynamic modulus and phase angle at temperature of 15°C and frequency of 0.005 rad/s. The dynamic modulus and phase angle data was fitted with sigmoidal model and modified sigmoidal, and

shifted to the reference temperature using WLF equation. All the model parameters were estimated using the solver function in Microsoft Excel. Finally, Glower-Rowe parameter was estimated using Equation (3.13).

$$G - R = \frac{G^*(\cos\delta)^2}{\sin\delta} \quad \text{Eq. (3.13)}$$

Where, G^* and δ are dynamic modulus and phase angle estimated at a reference temperature of 15°C and frequency of 0.005 rad/s.

3.8 BITUMINOUS MIXTURE CHARACTERISATION

In India, Bituminous Concrete (BC) mixtures are widely used for the construction of surface courses. Indian Roads Congress (IRC) recommends BC mixture with a modified binder for the surface course for design traffic volumes exceeding 50 million standard axles (msa). Further, BC mixture is also recommended for design traffic volumes ranging from 20 to 50 msa, and even for design traffic of 5 to 20 msa (IRC 37, 2018). Hence, for the current research work, bituminous concrete mixture with mid-aggregate gradation 2 was selected as per the specifications of the Ministry of Road Transport and Highways (MoRTH, 2013).

3.8.1 Mixing and compaction temperatures

Mixing and compaction temperatures considered in the current study were determined based on the equiviscous condition in Asphalt Institute manual MS-2 (2014) for viscosity grade binders. A Brookfield rotational viscometer was used for shearing viscosity grade binders (VG20, VG40) at temperatures ranging from 120 to 170^{o}C in increments of 10^{o}C as per the standard test method for viscosity determination of asphalt at elevated temperatures using a rotational viscometer (ASTM D4402, 2015). Viscosity corresponding to 0.17 ± 0.02 Pa-s shall be taken as the mixing temperature, and corresponding to 0.28 ± 0.03 Pa-s shall be taken as the compaction temperature. For the modified binders (PMB40, CRMB60), the mixing and compaction temperatures were taken based on manufacturers' recommendation. For all the WMA mixtures, the mixing and compaction temperatures adopted were 25^{o}C lower than that of the mixing and compaction temperatures of the corresponding HMA mixtures.

3.8.2 Optimum binder content

Marshall mix design procedure outlined in the Asphalt Institute manual MS-2 (2014) was used to determine the optimum binder content of bituminous concrete mixtures. Mix design was performed for two combinations: control mixture without plastic coating (BC), and mix containing waste-plastic-coated coarse aggregate (LBC). The BC mixture was prepared by

mixing the whole fraction of aggregates with a bituminous binder at mixing temperature. For the LBC mixture, initially 6% LDPE-waste plastic was added by weight of bitumen as recommended by IRC:SP:98 (2013) to coat the preheated coarse aggregate, and these LDPE-coated-coarse aggregates (LCA) were subsequently added and mixed to the remaining fractions of fine aggregate maintained at the mixing temperature. Later, bituminous binders were poured into it and mixed uniformly to prepare the LBC mixtures. Both BC and LBC mixtures were short-term aged in a forced draft oven at the compaction temperature for 2 hours, in-order to simulate the short-term ageing of the mix during construction. For performing the mix design, 100 mm diameter Marshall specimens were prepared at different binder contents by weight of the total mix. 75 blows were applied on each face of the specimen. The bulk density of compacted specimens was determined as per the ASTM D6752 (2018) procedure. For performing volumetric analysis, the maximum specific gravity of the bituminous mix (G_{mm}) was determined using Corelok as per ASTM D6857 (2018) procedure. Marshall stability test was performed at 60°C, using a strain rate controlled loading frame at a loading rate of 51 mm/minute. The peak load at failure (Marshall stability value) and corresponding axial deformation (flow value) of the specimen along the diametrical loading axis was observed. Optimum binder content (OBC) was identified corresponding to the 4% air void criterion, and the volumetric properties at the identified binder content were analyzed for compliance with the MoRTH (2013) specifications.

3.8.3 Moisture induced damage test

The HMA and WMA mixtures prepared with and without LCA were subjected to short-term aging as per the procedure outlined in AASHTO T 283 (2014). Six specimens with target air voids of 4% and 7% were compacted for each type of mixture with help of a gyratory compactor. Another six compacted specimens with 4% air voids were long-term aged in the forced draft oven as per the procedure outlined in AASHTO R 30 (2015). Moisture conditioning of the specimens was carried out as per the procedure given in AASHTO T 283 (2014). Compacted specimens were placed in a vacuum container, and vacuum saturation was applied for 5 to 10 minutes at 67 kPa. After the specimens achieved a saturation level of 70 to 80%, the specimens were subjected to freezing at a temperature of -18 ± 3^{o}C for 16 hours followed by thawing at a temperature of 60^{o}C for 24 hours. The specimens after thawing were conditioned at 25^{o}C for 2 hours in a different water bath as shown in Figure 3.15.

(a)

(b)

(c)

(d)

(e)

Fig. 3.15 Moisture-induced damage test: (a) dry conditioning, (b) ITS testing, (c) saturation, (d) freezing, and (e) thawing

The moisture conditioned and unconditioned specimens were tested using the Marshall loading frame. The indirect tensile strength was determined using Equation (3.14).

$$S_t = \frac{2P}{\pi t D} \qquad \text{Eq. (3.14)}$$

Where, S_t is indirect tensile strength in kPa, P is peak load at failure in kN, t is the thickness of the specimen in mm, D is the diameter of the specimen in mm. The tensile strength ratio (TSR) was estimated for the all bituminous mixtures used in this research work using Equation (3.15).

$$TSR = \frac{S_{td}}{S_{tw}} \times 100 \quad \text{Eq. (3.15)}$$

Where, S_{td}, and S_{tw} are dry and wet indirect tensile strengths of the bituminous mixtures, respectively.

3.8.4 Dry wheel tracking test

The resistance to permanent deformation was evaluated using a dry wheel tracking machine confirming to EN 12697-22 (2013) as shown in Figure 3.16. The HMA and WMA mixtures were prepared with and without LCA using HMA and WMA binders at their respective mixing temperatures. All the HMA mixtures were subjected to short-term aging as per the procedure outlined in the AASHTO R 30 (2015) whereas the short-term aging of WMA mixtures was reduced by 25ºC compared to the short-term aging temperature of the HMA mixtures. All the HMA and WMA specimens were compacted using a gyratory compactor to target air voids of 4% and 7%. Another set of specimens compacted to target air voids of 4% were long-term aged in the forced draft oven as per the procedure outlined in AASHTO R 30 (2015). The dry wheel tracking test was carried out at 60ºC which refers to the average maximum pavement temperature prevalent in most of the regions in India. The test records the progression of accumulated permanent deformation of the specimen using a LVDT, along the wheel path. Two cylindrical specimens with 150 mm diameter and 100 mm height were used for the test. The vertical faces of the specimen were trimmed, in-order to fit into the confining rigid mould. The table holding the specimen move to and fro, along the center of the specimen, and had a total travel length of 230 mm, at a speed of 25 load cycles per minute. One two and fro movement of the table is considered as one cycle or two passes. The test applied a wheel load of 700 N over a contact surface of 1000 mm^2. The specimens were conditioned for a period of 2 hours at the test temperature before the start of the test. The test termination criteria selected were 10,000 cycles (20,000 passes), or an accumulated permanent deformation of 15 mm, whichever was reached earlier.

Fig. 3.16 Sample preparation for wheel tracking test

3.9 SUMMARY

In this chapter, the detailed methodology adopted to fulfil the study objectives is described in detail. The materials used for the current study and equipment used to perform tests on bituminous binders, bituminous mixtures, and aging of bituminous binders and bituminous mixtures are presented. Subsequently, the sample preparation process for FTIR spectroscopy and DSR are discussed along with the relevant test protocols and analysis procedures. Finally, the test protocols relevant to bituminous mixture characterization in terms of resistance to moisture damage and rutting are discussed in detail. The next chapter deals with the rheological characterization of bituminous binders.

CHAPTER 4

CHEMICAL CHARACTERIZATION OF BITUMINOUS BINDERS

4.1 GENERAL

Most of the pavements around the world are constructed with bituminous mixtures using Hot Mix Asphalt (HMA) technology where the bitumen binders and mixtures are subjected to very high temperatures of about 148ºC to 178ºC (Corrigan, 2016). During the production, mixing, transporting, laying, and compaction operations, the HMA mixtures undergo short-term aging whereas during the service life of pavements, bituminous layers undergo long-term aging. As high temperatures are involved, evaporation of lighter fractions occurs during short-term aging. During service life of HMA pavement, the oxygen reacts with the top surface of bituminous layer resulting in stiffening of the binder. In order to reduce production and compaction temperatures of HMA mixtures, the construction industry around the world is practicing and adopting WMA technology. During the short-term and long-term aging of HMA and WMA mixtures, the binders undergo aging differently, and very few studies have attempted to quantify the formation of aging compounds during the production process of WMA binders. Hence, the present research work selected the most widely used chemical WMA additive, Evotherm, due to its surfactant nature. During the short-term aging and long-term aging of mixtures, the two most important compounds formed are: carbonyl and sulfoxides. These two compounds are mostly used to quantify aging of bituminous binders using Fourier Transform Infrared (FTIR) spectroscopy.

The present chapter is focused on the evaluation and quantification of aging compounds formed during production, short-term aging, and long-term aging of HMA and WMA binders using FTIR spectroscopy. The following section discusses about the production of Evotherm-modified binders, short-term and long-term aging protocols, FTIR testing, spectra analysis, and quantification of aging compounds.

4.2 PRODUCTION OF EVOTHERM-MODIFIED BINDERS

Two unmodified binders and two modified binders are used in this study. The unmodified binders of grade VG20 and VG40 as per IS 73 (2018) and the modified binders such as PMB40 as per IS 15462 (2019) and CRMB60 as per IS 17079 (2019) are used. All these binders were further modified with the WMA additive i.e., Evotherm and the Evotherm-modified binders are

referred as EVG20, EVG40, EPMB40, and ECRMB60. The Evotherm dosages, mixing time, mixing rate, and mixing duration adopted for the preparation of WMA binders were discussed in Chapter 3.

4.3 AGING OF HMA AND WMA BINDERS

The HMA and WMA binders were short-term aged at a reference temperature of 163^{o}C using rolling thin film oven whereas long-term aging of HMA and WMA binders was performed at a reference temperature of 100^{o}C. The detailed procedure for short-term aging and long-term aging of HMA and WMA binders were discussed in Chapter 3.

4.4 FTIR SAMPLE PREPARATION

The solvent cast method was adopted for the preparation of pellets required for measuring spectra using FTIR spectrometer. The choice of the solvent and the concentration of the solvent defines the quality of the spectra measured. The details of the solvent used and the procedure for sample preparation were discussed in Chapter 3.

4.5 MEASUREMENT OF SPECTRA

The spectra are measured at unaged, short-term aged, and long-term aged conditions for HMA and WMA binders using PerkinElmer Spectrum 100 FTIR spectrometer in transmittance mode at room temperature. The procedure for measurement of spectra in the laboratory was discussed in detail in Chapter 3. The spectrum was recorded in the wavenumber range of 4000 to 400 cm^{-1}. The spectra obtained from the FTIR gives the percentage transmittance (T). The percentage transmittance is converted to absorbance (A) by using Equation (4.1).

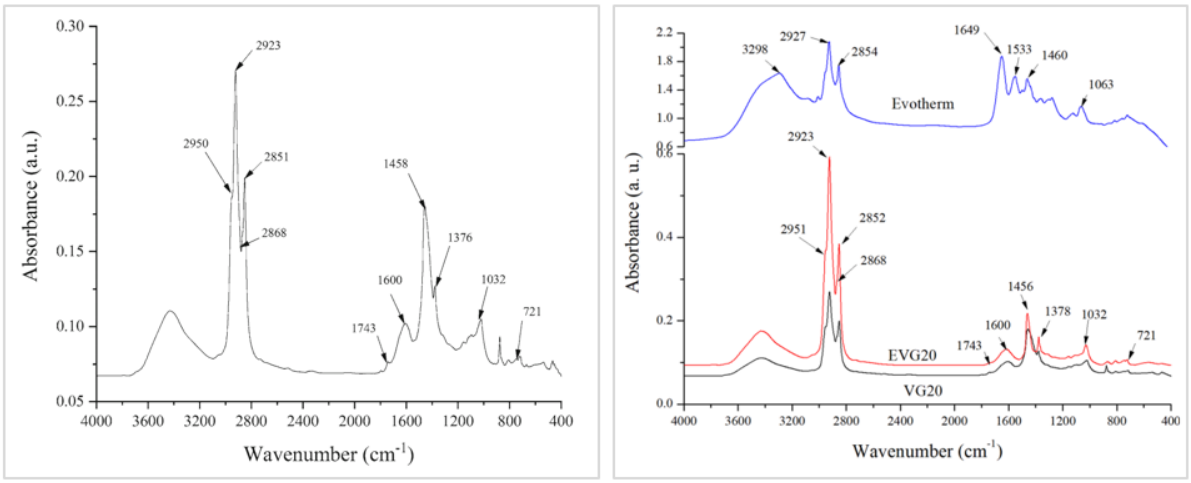
$$A = 2 - \log_e T \qquad \text{Eq. (4.1)}$$

Where, T is the transmittance in percentage, and A is the absorption in percentage.

4.6 INTERPRETATION OF SPECTRA DATA

A sample spectrum corresponding to VG20 binder at unaged condition with its significant peaks is shown in Figure 4.1(a), and their corresponding vibrations are listed in Table 4.1. Figure 4.1 (b) shows the spectra of VG20 and EVG20, and Evotherm additive from 4000 to 400 cm^{-1}. Similar spectral graphs are plotted and are shown in Appendix A.1 for VG40 and EVG40, PMB40 and EPMB40, CRMB and ECRMB60 binders. Figure 4.1(a) shows the prominent peaks present in bituminous binder. The sample spectrum shown corresponds to VG20. The peaks in the range of 2800 to 3200 cm^{-1} represent C-H stretching in CH_2 and CH_3. The bending vibrations of CH_2 and CH_3 can be seen at 1458 and 1376 cm^{-1}. The peak at 1600 cm^{-1}

corresponds to C=C vibrations in aromatics. The other peaks of interest are S=O and C=O at 1032 and 1743 cm^{-1} which represents the sulfoxide and the carbonyl present in the bitumen. The carbonyl and sulfoxide peaks are commonly used to characterize aging in bituminous binders (Petersen, 1986). Figure 4.1(b) shows the Evotherm spectra. The peaks in the Evotherm spectra at 2927 and 2854 cm^{-1} correspond to C–H stretching in CH_2 and CH_3, respectively. The peaks at 1649 cm^{-1} and 1460 cm^{-1} correspond to C=C vibrations and −CH2− scissor vibrations of a methylene group. The asymmetric N–O stretching of the nitro group is present at a wavenumber of 1533 cm^{-1}. The spectra of the Evotherm modified VG20 bitumen is also shown in Figure 4.2 (b).



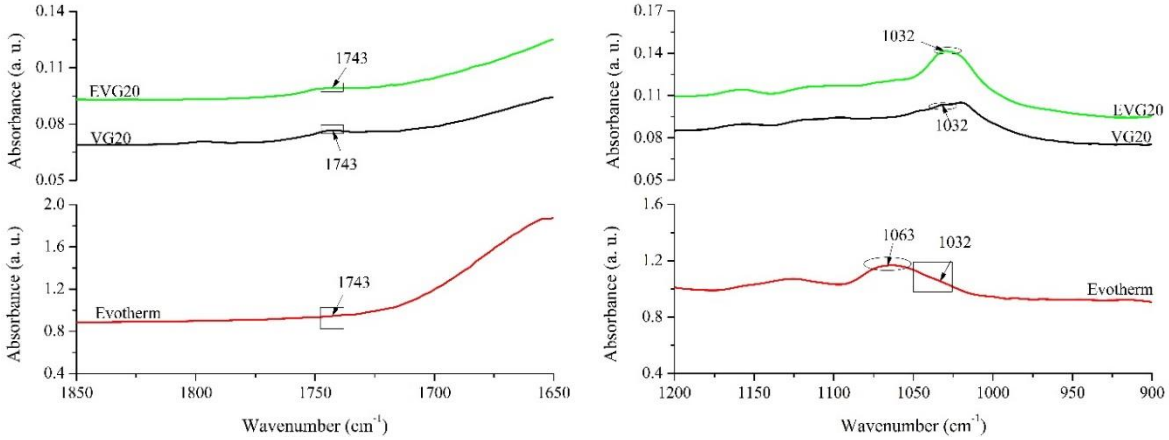
(a) (b)

Fig. 4.1 Spectra: (a) of VG20 binder at unaged condition, (b) comparison of VG20, EVG20, Evotherm

Table 4.1 Peak position and their corresponding vibrations

Peak position (cm^{-1})	**Vibration**
2851 and 2868	Symmetric stretching of C-H in CH2 and CH3, respectively
2923 and 2950	Asymmetric stretching of C-H in CH2 and CH3, respectively
1458 and 1376	Asymmetric and symmetric bending of CH3, respectively
1600	C=C stretching
1743	C=O stretching
1032	S=O stretching
721	$-CH_2$ rocking

The other prominent peaks in Evotherm are 3298 cm^{-1} and 1063 cm^{-1} representing the presence of amines and the sulfur-containing organics (Yu et al., 2017). Generally, the amine peaks are sharp. However, the peak at 3298 cm^{-1} is broad owing to the influence of the O–H group. The prominent peaks present in VG20 and EVG20 are identical, and their corresponding peak vibrations are shown in Table 4.1. The carbonyl and sulfoxide regions present in Figure 4.1 are examined closely in Figure 4.2.



(a) Carbonyl peaks (b) Sulfoxide peaks

Fig. 4.2 Carbonyl and sulfoxide regions in bitumen and Evotherm

Figure 4.2 shows the carbonyl and sulfoxide regions for the base binder, WMA binder, and Evotherm. There is scarcely any peak observed in the carbonyl region in the spectra of Evotherm. Hence, when Evotherm is added to the VG20 binder, no change in peak position was observed at 1743 cm^{-1} peak corresponding to the carbonyl region (Figure 4.2(a)). Similar responses are also observed in the case of other binders. The addition of Evotherm to the base binders only shows physical interaction. In the sulfoxide region (Figure 4.2(b)), for VG20 and EVG20, one can observe a peak at 1032 cm^{-1} corresponding to the sulfoxide present in bitumen. In EVG20, this peak is observed with a higher intensity and area. This can be attributed to the sulfur-containing organics present in Evotherm (Yu et al., 2017). The sulfur peak is, however, present at 1063 cm^{-1} in Evotherm. The sulfoxide vibrations in FTIR spectra range from 1030 to 1070 cm^{-1}. The vibrations of phenyl methyl sulfoxide or cyclohexyl methyl sulfoxide occur at 1055 cm^{-1}, the upper end of the sulfoxide region (Silverstein and Webster, 2005). It is understood that the nature of sulfoxide in bitumen and Evotherm is not similar. However, only preliminary information is available related to the interaction of Evotherm with bitumen to comment about the possible shift of the sulfoxide peak from 1063 cm^{-1} in Evotherm to 1032 cm^{-1} in Evotherm-modified binders.

4.7 CALCULATION OF SPECTRAL INDICES

The various chemical functional groups considered for the analysis of spectra are: carbonyl, sulfoxide, aliphaticity, aromaticity, and long-chain group. Carbonyl, sulfoxide, aliphaticity, aromaticity, and long-chain group can be identified at the wavenumber range shown in Table 4.2 (Petersen, 2009; Pieri et al., 1996). The area under the peak position of these functional groups was calculated with Spectrograph 1.2 software using baseline method. The areas of the peak within the 95% confidence interval are accepted and the rest are rejected. The

average of the areas accepted for each peak is used for further analysis of the spectra. To quantify aging, the effect of adding Evotherm in the control binders was evaluated with help of these indices at all aging conditions. These indices were calculated using Equations (4.2) to (4.6). Among all these indices, the carbonyl and sulfoxide indices are used to evaluate aging in bituminous binders in the current study.

Table 4.2 Functional groups and corresponding wavenumbers

Functional group	Wavenumber, cm^{-1}
Carbonyl	1660-1800
Sulphoxide	1010-1050
Aliphaticity	1350-1510
Aromaticity	1560-1660
Long chain	715-713

$$Carbonyl\ index = \frac{A_{1660-1800}}{A_{1660-1800}+A_{1010-1050}+A_{1350-1510}+A_{1560-1660}+A_{715-713}} \quad \text{Eq. (4.2)}$$

$$Sulfoxide\ index = \frac{A_{1010-1050}}{A_{1660-1800}+A_{1010-1050}+A_{1350-1510}+A_{1560-1660}+A_{715-713}} \quad \text{Eq. (4.3)}$$

$$Aliphaticity\ index = \frac{A_{1350-1510}}{A_{1660-1800}+A_{1010-1050}+A_{1350-1510}+A_{1560-1660}+A_{715-713}} \quad \text{Eq. (4.4)}$$

$$Aromaticty\ index = \frac{A_{1560-1660}}{A_{1660-1800}+A_{1010-1050}+A_{1350-1510}+A_{1560-1660}+A_{715-713}} \quad \text{Eq. (4.5)}$$

$$Long-chain\ index = \frac{A_{715-713}}{A_{1660-1800}+A_{1010-1050}+A_{1350-1510}+A_{1560-1660}+A_{715-713}} \quad \text{Eq. (4.6)}$$

4.8 QUANTIFICATION OF AGING COMPOUNDS

To evaluate the aging in HMA and WMA binders, the carbonyl and the sulfoxide functional groups are studied. The carbonyl index, and sulfoxide index are estimated as discussed in Section 4.7 and the data was compiled for all the binders at all aging conditions. Later, the bar chart was plotted in order to critically study the effect of Evotherm additive during production process and also its effect when subjected to short-term aging and long-term aging.

4.8.1 Influence of production process on aging compounds

To quantify aging of bitumen during the production process of WMA binder, the carbonyl and sulfoxide indices for HMA and WMA binders are compared for unaged binders as shown in Figure 4.3 and Figure 4.4, respectively. It is observed that the carbonyl index for WMA binders are higher compared to the carbonyl index for HMA binders. The reason for this increase in the

carbonyl index can be attributed to the effect of oxidation during the production of WMA binder as the binders are heated to about 150–165°C in the presence of oxygen for 30 minutes. It is observed that the increase in carbonyl index is highest in the case of PMB40 and least in the case of VG20. Since considerable aging is likely to occur during the production process of PMB40 and CRMB60, one cannot compare VG20 and VG40 base binder with the PMB 40 and CRMB base binder. The absolute variations of carbonyl index and sulfoxide index are estimated between HMA and WMA binders at production condition, and are listed in Table 4.3. It is observed that the absolute varitions are dissimilar and varies for binder type even though same Evotherm additive is used for the production of WMA binders. The increase in carbonyl index is lowest in the case of VG20 and is higher in the case of PMB40.

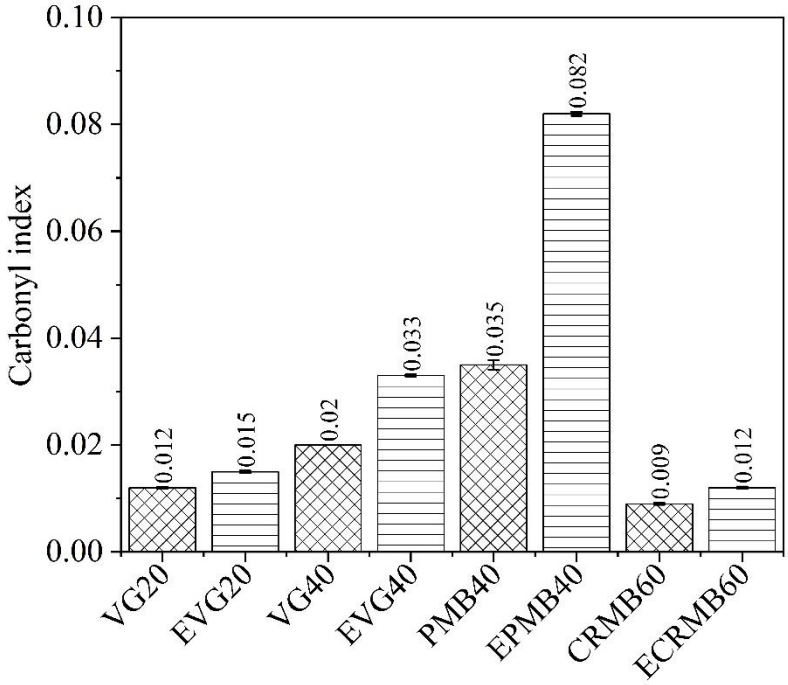


Fig. 4.3 Carbonyl after the production of WMA binders

The increase in sulfoxide index for EVG20 is seen to be about three times compared to that of VG20. This can be partly attributed to the sulfoxide formation during WMA binder production process and partly to the sulfur-containing organics present in the Evotherm (Yu et al., 2017). The sulfoxides formed are mainly due to the elemental sulfur or sulfides that can readily get oxidized due to the presence of the oxygen during the production process. Crumb rubber in CRMB also contains sulfur due to the vulcanization of the rubber. In the case of PMB40, the presence of sulfur from its manufacturing stage and the sulfur containing organics present in the Evotherm lead to increase in sulfoxide index by 274%. The lesser formation of sulfoxide compounds in CRMB60 compared to PMB40 is due to the presence of sulfur in the non oxidizable form (Nivitha et al., 2016). The resistance to aging in the case of CRMB60 is evident

as the polymer chains from the rubber network hinder the penetration of oxygen into the bitumen (Wang et al., 2020).

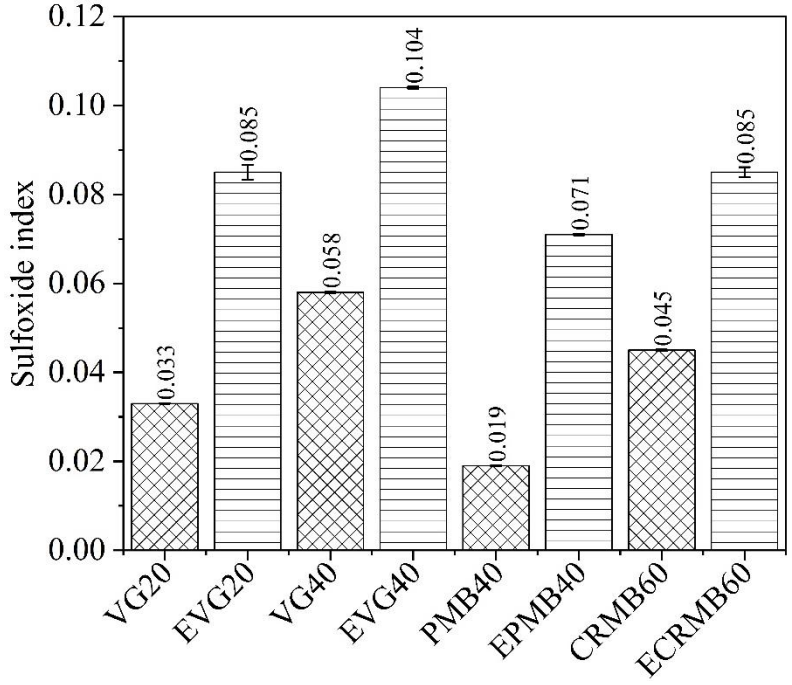


Fig. 4.4 Sulfoxide index after the production of WMA binders

Table 4.3 Absolute variations of aging indices in HMA and WMA binders

Binders	Absolute variations of indices, %	
	Carbonyl index	Sulfoxide index
VG20 and EVG20	27	155
VG40 and EVG40	65	78
PMB40 and EPMB40	133	274
CRMB60 and ECRMB60	31	89

4.8.2 Influence of Evotherm additive on the aging process

To compare aging in HMA and WMA binders, when aged at identical conditions, the HMA and WMA binders subjected to short-term aging are considered here. The indices in the short-term and long-term aging conditions are normalized with respect to the unaged condition. Figure 4.5 and Figure 4.6 shows the normalized carbonyl and sulfoxide indices as a function of aging. In the long-term aged condition, the carbonyl formation for HMA binders is highest in VG20 and lowest in PMB40. Compared to the base binders, the formation of carbonyl compounds is lower (about one-half) in WMA binders when aged at identical temperatures. The formation of sulfoxides exhibits different behavior depending on the type of material. Sulfoxide formation in bitumen during aging exhibits two types of mechanism, i.e., both formation of sulfoxides and decomposition of sulfoxides co-occur (Branthaver et al., 1993). The increase or decrease in the sulfoxide index upon aging depends on the mechanism that is dominant

(Branthaver et al., 1993). This can be a reason for the reduced magnitude of sulfoxide formation in WMA binders upon long-term aging.

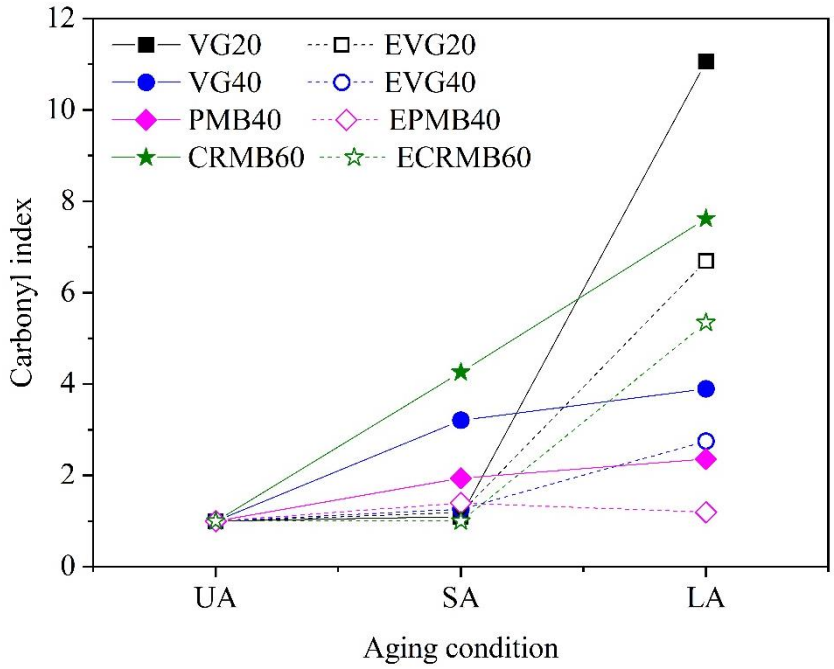


Fig. 4.5 Normalized variation of carbonyl index with aging

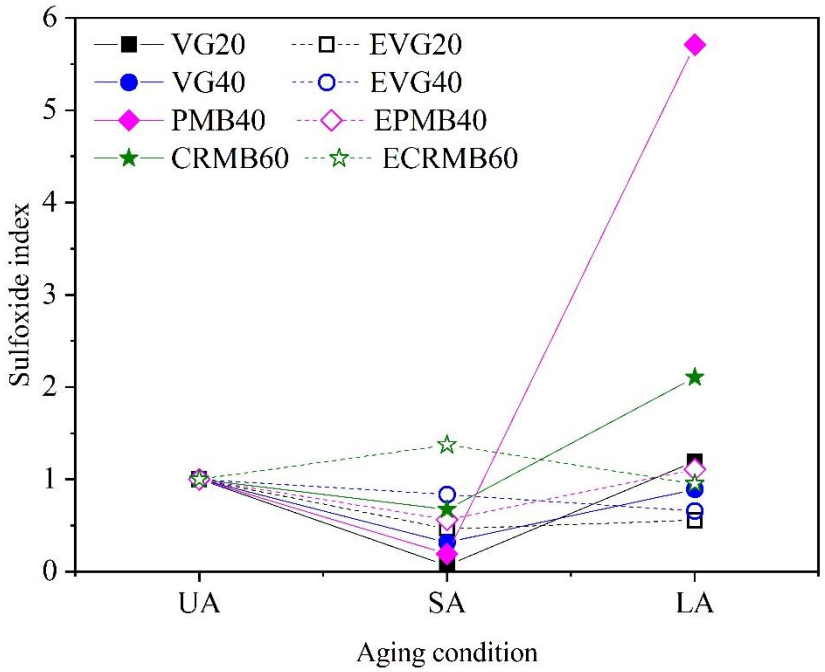


Fig. 4.6 Normalized variation of sulfoxide index with aging

For the HMA binders, the sulfoxide formation is seen to be the predominant mechanism in the long-term aged condition. In contrast to the carbonyl index, the sulfoxide formation in PMB40 is seen to be higher followed by CRMB60, VG20, and VG40. The sulfoxide index is highest in PMB40 due to addition of sulfur during the production process of polymer modified bitumen.

Even though sulfur content in crumb rubber is 2% which is much higher than that in PMB40, the sulfoxide index of CRMB60 is lower than that of PMB40 which is in line with that reported by Nivitha et al. (2016). Nivitha et al. (2016) proposed that the sulfur present in crumb rubber was mainly in the form of S–S which is expected to undergo oxidation only at temperatures of about 250°C.

4.9 SUMMARY

In this chapter, the results obtained through comprehensive investigations on aging compounds in HMA and WMA binders in-terms of carbonyl and sulfoxide indices are presented and discussed in detail. The next chapter deals with rheological characterisation of bituminous binders wherein various rutting parameters and fatigue parameters are presented.

CHAPTER 5
RHEOLOGICAL CHARACTERISATION OF BITUMINOUS BINDERS

5.1 INTRODUCTION

The primary focus of pavement industries around the world is on reducing the production and laying temperatures of bituminous mixtures using various WMA technologies without affecting the performance of bituminous mixtures. This ensures better working conditions for the workers at the construction site apart from minimizing the air pollution and savings in energy consumption. Among various WMA technologies, Evotherm additive is widely used around the world due to its chemical surfactant nature. This chapter presents the results obtained through a comprehensive evaluation of rheological performance of HMA and WMA binders from the perspective of rutting resistance and fatigue resistance. Further, the influence of adding Evotherm additive in control binders was also studied in detail for thermal equilibrium time at unaged, short-term aged, and long-term aged conditions. Master curves developed for superpave rutting parameter and fatigue parameter are also discussed in detail in this chapter. The following sections provide a detailed discussion on the analysis procedures and results obtained based on thermal equilibrium time, amplitude sweep test, frequency temperature sweep test, MSCR test, linear amplitude sweep test, and testing for the Glower-Rowe parameter at various aging conditions.

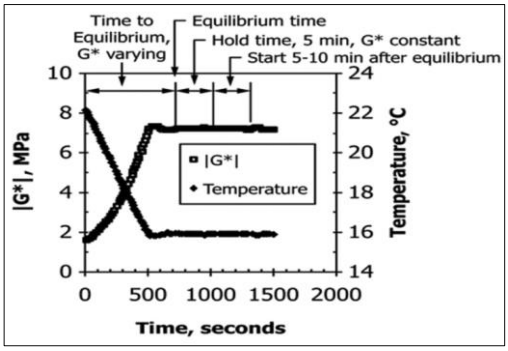


Fig. 5.1 Variation of |G*| with temperature (ASTM D7175, 2015)

5.2 THERMAL EQUILIBRIUM TIME

Thermal equilibrium is defined as the condition at which heat transfer does not happen further between any two materials which are in physical contact with each other. The test protocol adopted to determine the thermal equilibrium time of HMA and WMA binders was discussed in Chapter 3 for unaged and short-term aged conditions at various temperatures (40, 55, and 65^{o}C), and long-term aged condition at 60^{o}C. As shown in Figure 5.1 (ASTM D7175, 2015),

the bitumen sample attains a thermal equilibrium when $|G^*|$ reaches a constant value. The variation of $|G^*|$ was recorded at regular intervals of 30 s. The raw $|G^*|$ data was smoothened using a five-point moving average method and the smoothened $|G^*|$ data was plotted as a function of time. For reference, the variation of complex modulus with time at 65°C for unaged PMB40 binder is shown in Figure 5.2. However, before starting the test, a certain time is needed for the trimming of the sample. The sample spread and trimming time for the unaged and short-term aged conditions, for both HMA and WMA binders at different temperatures is shown in Table 5.1. The time at which complex modulus ($|G^*|$) stabilises was determined for all binder types and at all the test temperatures.

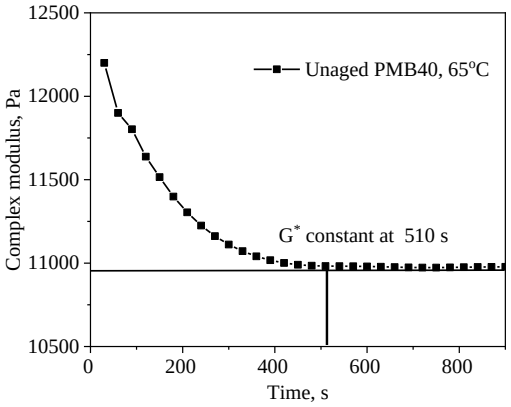


Fig. 5.2 Variation of complex modulus with time for unaged PMB40 binder at 65ºC

Table 5.1 Spread and trimming times of HMA and WMA binders at various aging conditions

Binder	Sample spread and trimming time, s						
	Unaged			Short-term aged			Long-term aged
	40°C	55°C	65°C	40°C	55°C	65°C	60ºC
VG20, EVG20	125	95	63	130	98	65	70
VG40, EVG40	210	156	122	215	160	128	135
PMB40, EPMB40	290	165	130	300	165	130	138
CRMB60, ECRMB60	220	165	125	540	330	240	255

Table 5.2 Stabilization time for complex modulus as function of temperature for HMA and WMA binders at various aging conditions

Temp., ºC	VG 20	EVG 20	VG 40	EVG 40	PMB40	EPMB40	CRMB60	ECRMB60
Unaged Condition								
40	960	900	1230	1260	1530	1590	1290	1440
55	690	570	810	780	700	900	810	840
65	270	240	570	480	510	600	600	660
Short-term aged condition								
40	1290	1590	1560	1620	1710	1620	1650	1500
55	870	900	1170	1020	1050	1050	1260	1110
65	630	570	810	750	840	780	900	750
Long-term aged condition								
60	1570	1390	2760	1875	2418	2088	2715	2325

Table 5.3 Linear fit parameters for HMA and WMA binders at unaged and short-term aged condition

Parameter	VG20	EVG20	VG40	EVG40	PMB40	EPMB40	CRMB60	ECRMB60
Unaged condition								
a	2296.2	2184.1	2635	2858	3695	3713.42	2762.63	3053.15
b	-29.28	-28.49	-30.5	-34.78	-48.5	-46.5	-31.73	-35.68
Short-term aged condition								
a	2579.1	3452.3	3117	3362	3665	3530.8	3871.6	3721.6
b	-29.08	-43.77	-33.2	-38.71	-42.5	-40.92	-41.84	-41.84

Table 5.4 Final thermal equilibrium time (s) of HMA and WMA binders at unaged and short-term aged conditions after adding 300 s

Temp., °C	VG20	EVG20	VG40	EVG40	PMB40	EPMB40	CRMB60	ECRMB60
Unaged condition								
40	1425	1344	1733	1767	2055	2147	1793	1926
45	1278	1202	1583	1593	1813	1914	1635	1748
50	1132	1060	1433	1419	1570	1681	1476	1569
55	986	917	1282	1245	1328	1448	1317	1391
60	839	775	1132	1071	1085	1214	1159	1212
65	693	632	982	897	843	981	1000	1034
Short-term aged Condition								
40	1720	2020	2075	2135	2310	2220	2490	2340
45	1571	1783	1924	1920	2053	1989	2289	2139
50	1425	1564	1758	1726	1840	1785	2080	1930
55	1268	1298	1630	1480	1515	1515	1890	1740
60	1134	1126	1426	1339	1415	1376	1661	1511
65	995	935	1238	1178	1270	1210	1440	1290

Table 5.2 shows the time at which $|G^*|$ of HMA and WMA binders at various aging conditions stabilises to a constant value. The thermal equilibrium times obtained at 40, 55, and 65°C, after the addition of spread and trimming time, were used and a best-fit curve was generated. The best fit indicated that the data followed a linear trend. This procedure was repeated for all the binder types. For reference, the linear curve fit at 65°C for the unaged EPMB40 binder is shown in Figure 5.3. The expression for the linear curve fit is shown in Equation (5.1). The parameters of the linear fit for the unaged and short-term aged conditions for both HMA and WMA binders are shown in Table 5.3.

$$y = a + b \times x \qquad \text{Eq. (5.1)}$$

Where, x is temperature, y is thermal equilibrium time, and a, and b are linear fit parameters. The parameters from the linear fit were used to determine thermal equilibrium times at all six test temperatures and for all the binders. Finally, an additional time of 300 s was added to the thermal equilibrium time to arrive at final thermal equilibrium time as shown in Table 5.4. The time for thermal equilibrium for both HMA and WMA binders at various aging conditions is shown in Appendix B.1.

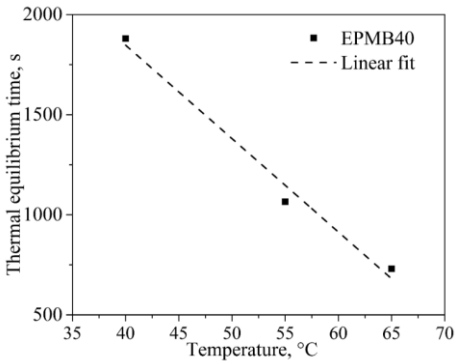


Fig. 5.3 Linear curve fit for unaged Evotherm-modified PMB40

The influence of Evotherm on thermal equilibrium time for HMA and WMA binders are evaluated at unaged, short-term aged, and long-term aged conditions. The comparison plots of thermal equilibrium time between HMA and WMA binders at unaged and short-term aged conditions are presented in Appendix B.3 and Appendix B.4. From Figure B.3(a) and Figure B.3(b), it is observed that in unaged condition, the thermal equilibrium times for EVG20 and EVG40 bitumen are comparatively lower than VG20 and VG40 binders except for EVG40 bitumen at 40 and 45°C. This might be due to possible physical interaction between Evotherm and unmodified binders rather than a chemical interaction (Ferrotti et al., 2017). Further, the WMA additive gets homogeneously dispersed in the base binder (Abdullah et al., 2016). From Figure B.3(c) it is observed that there is an increase in the thermal equilibrium time for the

unaged EPMB40 bitumen when compared with unaged PMB40 bitumen. The addition of a chemical WMA additive changes the morphology of PMB (Ferrotti et al., 2017). This change in morphology might explain the higher thermal equilibrium times for the EPMB40 binder when compared with the PMB40 binder at all test temperatures. From Figure B.3(d), the thermal equilibrium time of the unaged ECRMB60 binder is observed to be higher than the unaged CRMB60 binder at all the test temperatures. Due to the addition of Evotherm to the base CRMB60 binder, a chemical interaction occurs between the base CRMB60 binder and the Evotherm additive. Because of this chemical interaction, the Evotherm additive surrounds the crumb rubber particles in the ECRMB60 binder (Yu et al., 2017). This chemical interaction can be the reason for the increase in the thermal equilibrium time of the ERCMB60 binders when compared to the CRMB60 binder.

From Figure B.4(a) and B.4(b) of Appendix B.4, the thermal equilibrium time for short-term aged EVG20 and EVG40 is lower than short-term aged control binders at higher temperatures, whereas a reverse trend is observed at lower temperatures. The presence of Evotherm additive and reduced short-term aging temperature of WMA binders reduces the formation of aging compounds in Evotherm-blended short-term aged binders resulting in stiffness reduction. From Figure B.6(c), it is seen that short-term aged EPMB40 exhibited lower thermal equilibrium time compared to short-term aged PMB40. The reason for this can be attributed to the presence of Evotherm which reduces the binder aging (Abdullah et al., 2016) resulting in lower thermal equilibrium time for short-term aged EPMB40 compared to short-term aged PMB40. From Figure B.4(d), thermal equilibrium time for short-term aged ECRMB60 is lower compared to short-term aged CRMB60 at all the test temperatures. As Evotherm results in reduced formation of carbonyl and sulphoxide compounds in short-term aged CRMB60 (Xiao et al., 2012), this can be the reason for reduction in stiffness of short-term aged ECRMB60 and thereby decreasing the thermal equilibrium time. From Table 5.2, it is observed that the equilibrium time of long-term aged WMA binders is lower compared to the equilibrium time of long-term aged HMA binders. This can be due to the presence of Evotherm additive which results in lower formation of aging compounds (carbonyl and sulfoxide functionalities) (Roja et al., 2016; Behl and Chandra, 2017).

From Appendix B1and Appendix B2, it can be seen that thermal equilibrium time is very much dependent on the test temperature and binder type. At lower temperatures, higher thermal equilibrium time is observed as the binders exhibit higher stiffness at lower temperatures. Time taken by modified binders to equilibrate is higher than that of unmodified binders. Determining the thermal equilibrium time is a time consuming procedure. It is logical to develop a regression

model for thermal equilibrium time considering test temperature and a simple physical parameter indicating the stiffness of the binder. Softening point is a parameter indicating the temperature at which a solid-like response changes to a fluid-like response which is an indirect measure of the stiffness of the binder. The softening points all the HMA and WMA binders is shown in Table 5.5 for unaged and short-term aged condition. A linear regression model is developed to predict the thermal equilibrium time based on test temperature and softening point as shown in Equation (5.2).

$$TET = 1889.44 - 37.71 * TT + 25.18 * SP \quad \text{Eq. (5.2)}$$

Where, *TET* is the thermal equilibrium time in seconds, *TT* and *SP* are the test temperature and softening point, respectively in °C. The adjusted R^2 value of the model is 0.86. The plots for observed and predicted equilibrium time, residuals at various test temperatures, and residuals at various softening points of the binders used in the current study are shown in Figure B.5(a), Figure B.5(b), Figure B.5(c), respectively of Appendix B.5. From Figure B.5(b) and Figure B.5(c), the random spread of data is observed around the horizontal axis which indicates the appropriateness of linear regression model for thermal equilibrium.

Table 5.5 Softening points of HMA and WMA binders

	Softening point, ℃	
	Unaged	**Short-term aged**
VG20	52	57
VG40	54	63
PMB40	70	76
CRMB60	64	74
EVG20	51	54
EVG40	53	59
EPMB40	65	67
ECRMB60	65	71

5.3 AMPLITUDE SWEEP TEST

An amplitude sweep test was performed on HMA and WMA binders as per the procedure mentioned in Chapter 3 for unaged, short-term, and long-term aged conditions. The data was continuously recorded in Rheoplus software for complex modulus (G^*), phase angle (δ), and rutting parameter ($G^*/\text{Sin } \delta$). Later, this data is tabulated at 12% strain for unaged, and 10% strain for short-term and long-term aged conditions. Subsequently, a bar chart was plotted for HMA and WMA binders at all aging conditions. From Fig. 5.4, it is observed that in unaged condition, the Superpave rutting parameter of EVG20 binder is less compared to that of VG20 binder. As shown in Appendix B.6, a similar trend is also observed between VG40 and EVG40

binders in unaged condition, whereas a marginal increase is seen for modified binders consisting of Evotherm when compared to modified binders without Evotherm. Further, it is observed from Fig. 5.4 that the superpave rutting parameter for EVG20 binder is less compared to that of VG20 binder at both short-term and long-term aged conditions. Likewise, as shown in Appendix B.6, a similar trend is observed in the Superpave rutting parameter for remaining three binders at both the short-term aged and long-term aged conditions. The reason for decrease in the Superpave rutting parameter is essentially due to reduction in internal friction in the base binders due to the addition of the Evotherm additive (Bairgi et al., 2019).

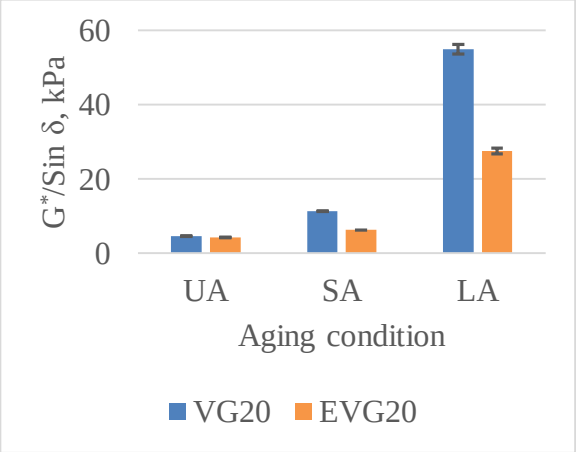


Fig. 5.4 Superpave rutting parameter for VG20 and EVG20 binders

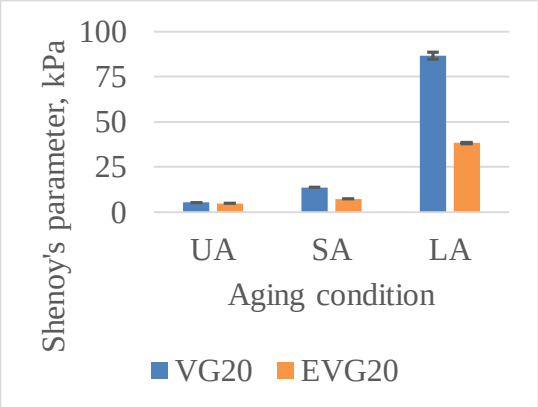


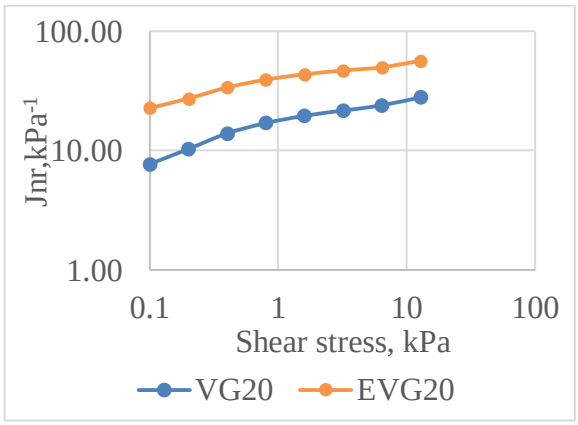
Fig. 5.5 Shenoy's parameter for VG20 and EVG20 binders

5.4 SHENOY'S PARAMETER

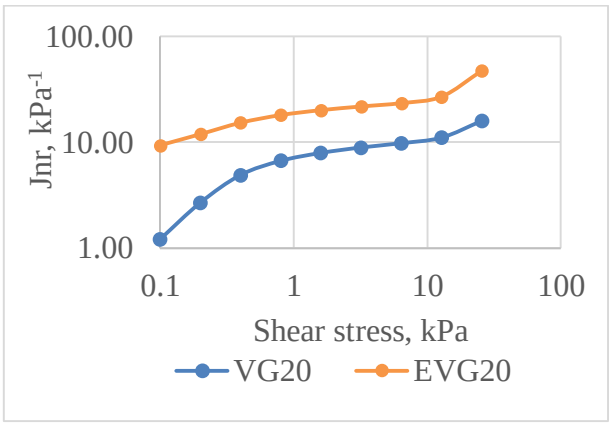
Shenonoy's parameter was calculated using Equation (5.3) from the amplitude sweep test data (complex modulus and phase angle) of HMA and WMA binders at 12% strain for unaged, and 10% strain for short-term aged and long-term aged conditions.

$$Shenoy'sparameter = \frac{G^*}{\left(1-\frac{1}{\tan\delta \sin\delta}\right)} \qquad \text{Eq. (5.3)}$$

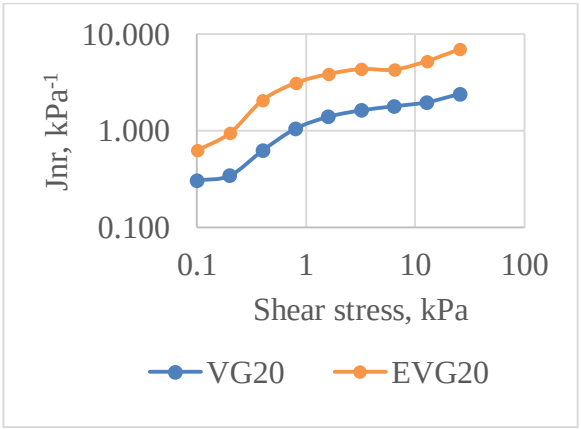
Where, G^* is the complex modulus, and δ is the phase angle. Shenoy's parameters were then estimated and a bar chart was plotted for HMA and WMA binders at all aging conditions. From Fig. 5.5, it is observed that Shenoy's parameter of EVG20 binder is more or less equal to that of VG20 binder at unaged conditions. At short-term aged and long-term aged conditions, the Shenoy's parameter for EVG20 binder is lower compared to that of VG20 binder. Likewise, as shown in Appendix B.7, a similar trend is observed in the Shenoy's parameter for remaining three binders at all the aging conditions. This indicates that addition of Evotherm additive to the control binders decreases the rutting resistance due to the formation of lower aging compounds in WMA binders compared to HMA binders (Roja et al., 2016).



(a) UA



(b) SA



(c) LA

Fig. 5.6 Non-recoverable creep compliance for VG20 and EVG20 binders at unaged (UA), short-term aged (SA), and long-term aged (LA) conditions

5.5 MULTI-STRESS CREEP AND RECOVERY TEST

Multi-stress creep and recovery test was performed on HMA and WMA binders at all aging conditions as per the procedure discussed in Chapter 3 at a reference temperature of 60°C. The data was continuously recorded for shear stress and unrecoverable shear strain for each cycle

of creep and recovery loading, and non-recoverable compliance (J_{nr}) were estimated using Equations (3.2) and (3.3). Lower J_{nr} value indicates that the binder will have better resistance to permanent deformation. Semi-log graph was plotted for HMA and WMA binders at all aging conditions. From Fig. 5.6, it is observed that the non-recoverable creep compliance of EVG20 was higher compared to VG20 at all aging conditions. This implies that the addition of Evotherm to the base binder decreases the rutting resistance due to reduction in internal friction (Bairgi et al., 2019), and also due to the lower formation of carbonyl and sulfoxide compounds in Evotherm-modified binders compared to control binders at both short-term and long-term aging conditions(Kumar et al., 2019). Likewise, as shown in Appendix B.8 to B.10, a similar trend for non-recoverable creep compliance is observed for remaining three binders at all aging conditions.

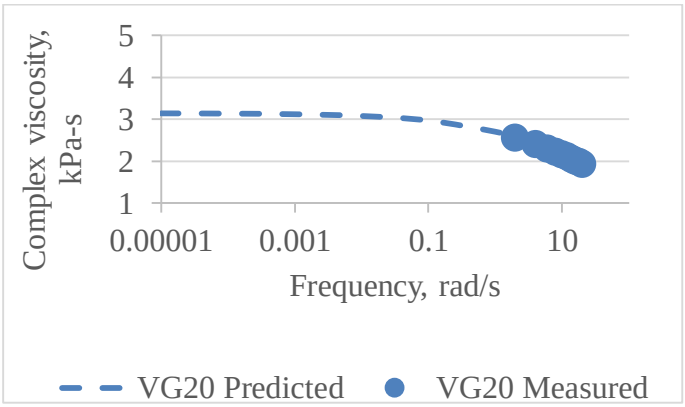


Fig. 5.7 Modeling of frequency sweep test

5.6 FREQUENCY TEMPERATURE SWEEP TEST

Frequency temperature sweep test was performed as per the test procedure discussed in Chapter 3 on HMA and WMA binders at unaged and short-term aged conditions to evaluate the zero-shear viscosity and low-shear viscosity at a reference temperature of 60°C. The data was continuously recorded for complex viscosity at each test temperature for all binders using Rheoplus software. The data was extracted and a line graph was plotted for a complex viscosity versus frequency for unaged VG20 binder as shown in Figure 5.7. Subsequently, Cross model (Biro et al., 2009) as shown in Equation (5.4) was fitted to this line graph in the Matlab software, and model parameters were obtained. With the help of these model parameters, zero shear viscosity was determined, and low shear viscosity was estimated at a frequency of 0.01, 0.001, and 0.0001 rad/s. The data analysis was repeated for determining zero shear viscosity and low shear viscosity for HMA and WMA binders at unaged and short-term aged conditions.

$$\eta^* = \frac{\eta_0}{1+(K\omega)^m} \qquad \text{Eq. (5.4)}$$

Where, η^* is complex viscosity, η_o is zero shear viscosity, ω is frequency, and K and m are model parameters. A bar chart was plotted for zero shear viscosity of VG20 and EVG20 binders at unaged and short-term aged conditions as shown in Figure 5.8. It is observed that the zero shear viscosity of EVG20 binder is lower than that of VG20 binder at unaged condition. This indicates that the addition of Evotherm additive to VG20 binder increases the rutting potential due to reduction in frictional force (Bairgi et al., 2019). Additionally, it is also observed that at the short-term aged condition, the zero shear viscosity of EVG20 binder is lower than that of VG20 binder. This indicates that the addition of Evotherm to VG20 binder increases the rutting potential due to lower aging compounds in WMA binders compared to HMA binders (Roja et al., 2016; Behl et al., 2017). Likewise, as shown in Appendix B.11, a similar trend for zero shear viscosity is observed for remaining three binders at unaged and short-term aged conditions.

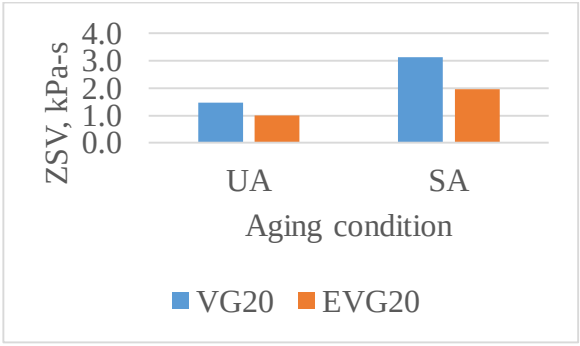
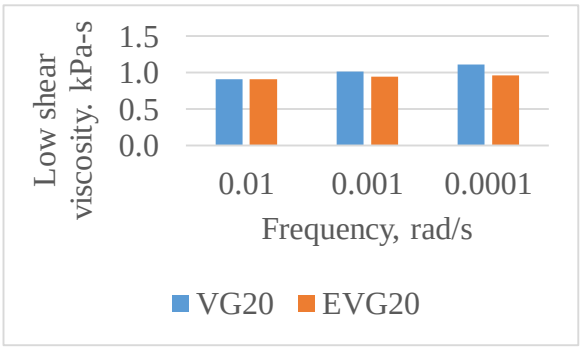
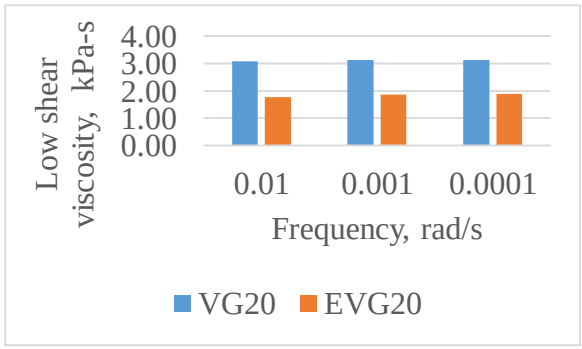


Fig. 5.8 Zero shear viscosity for VG20 and EVG20 binders at the unaged and short-term aged conditions



(a) UA



(b) SA

Fig. 5.9 (a) Low shear viscosity at unaged condition, and (b) low shear viscosity at short-term aged condition for VG20 and EVG20 binders

A bar chart was plotted for low-shear viscosity at three frequencies (0.0001, 0.001, 0.01 rad/s) as shown in Figure 5.9 at unaged and short-term aged conditions for VG20 and EVG20 binders. It is observed that irrespective of frequencies, EVG20 binder exhibited reduced low-shear viscosity compared to VG20 binder at unaged condition. This indicates that the addition of Evotherm additive to VG20 binder decreases the rutting resistance. Further, it is also observed

that at short-term aged condition, EVG20 binder exhibited reduced low-shear viscosity compared to VG20 binder. This indicates that the addition of Evotherm additive to VG20 binder decreases the rutting resistance due to lower formation of carbonyl and sulfoxide functionalities in EVG20 binder. Likewise, as shown in Appendix B.12 and B.13, a similar trend for low-shear viscosity is observed for remaining three binders at unaged and short-term aged conditions.

5.7 RANKING OF BINDERS BASED ON RUTTING PARAMETERS

In this study, various rutting parameters such as the superpave rutting parameter ($G^*/\text{Sin }\delta$), Shenoy's parameter, non-recoverable creep compliance (J_{nr}), zero shear viscosity (ZSV), and low shear viscosity are determined for HMA and WMA binders at short-term aged condition. Based on these parameters all the binders were ranked and shown in Table 5.6. It is observed that the performance towards rutting resistance of CRMB60 binder is the best and EVG20 binder is the least. Thus, the rutting resistance of bituminous binders is decreasing in the order of CRMB60, ECRMB60, PMB40, VG40, EPMB40, VG20, EVG40, and EVG20.

Table 5.6 Ranking of HMA and WMA binders evaluated at 60°C

S. No.	Binders	$G^*/\text{Sin }\delta$	Shenoy's parameter	J_{nr}	ZSV	LSV		
						0.1	0.01	0.0001
1	VG20	6	6	6	6	6	6	6
2	VG40	4	4	4	5	4	4	4
3	PMB40	3	3	2	2	3	3	3
4	CRMB60	1	1	1	1	1	1	1
5	EVG20	8	8	8	8	8	8	8
6	EVG40	7	7	7	7	7	7	7
7	EPMB40	5	5	5	4	5	5	5
8	ECRMB60	2	2	3	3	2	2	2

5.8 MASTER CURVE FOR SUPERPAVE RUTTING PARAMETER AND FATIGUE PARAMETER

The frequency temperature sweep test was performed on short-term aged, and long-term aged samples of HMA and WMA binders as per the procedure discussed in Chapter 3. Master curves were plotted for the superpave rutting parameter ($G^*/\sin\delta$) at a reference temperature of 60°C and the superpave fatigue parameter at 25°C. The Master curve was developed by shifting the Superpave rutting parameter and fatigue parameter data to a reference temperature of 60°C and 25°C, respectively using William-Landel-Ferry (WLF) Equation (Williams et al., 1955) with the sigmoidal model (Biswas and Pellian, 2007), and modified sigmoidal model (Yang and You, 2015) was used to fit the data to obtain sigmoidal parameter using the solver function in Microsoft Excel. The WLF equation, sigmoidal, and modified sigmoidal model are respectively shown in Equations (5.5) to (5.7).

$$\log f_{red} - \log f = \log \alpha_t = -\frac{C_1(T-T_{ref})}{(C_2+T-T_{ref})} \quad \text{Eq. (5.5)}$$

$$\log|G^*| = \Delta + \frac{\alpha}{1+e^{\beta-\gamma \log f_{red}}} \quad \text{Eq. (5.6)}$$

$$\delta = c\frac{\pi}{2}\frac{\alpha\gamma}{\left(1+e^{\beta-\gamma \log f_{red}}\right)^2} e^{\beta-\gamma \log f_{red}} \quad \text{Eq. (5.7)}$$

Where, f_{red} is reduced frequency in rad/s, f is loading frequency in rad/s, α_t is shift factor, C_1 and C_2 are empirical constants, T is test temperature, T_{ref} is reference temperature at which the master curve needs to be developed, Δ is the minimum complex modulus, $\Delta+\alpha$ is the maximum modulus or span of the data, β and γ are the locations and slope steepness of the sigmoidal curve, and δ is the phase angle. The model parameters obtained for the HMA and WMA binders at short-term aged and long-term aged conditions are shown in Tables 5.7 to 5.10.

Table 5.7 Sigmoidal parameter for HMA binders at short-term aged condition

Parameters	VG20	VG40	PMB40	CRMB60
C1	10.04	20.73	10.42	37.01
C2	152.34	289.40	156.84	570.83
α	5.51	9.08	7.70	8.36
β	0.001	0.02	0.001	0.001
γ	0.72	0.36	0.42	0.36
δ	1.34	0.15	0.64	0.62
SSE	0.08	0.16	0.07	0.19

Table 5.8 Sigmoidal parameter for WMA binders at short-term aged condition

Parameters	EVG20	EVG40	EPMB40	ECRMB60
C1	9.36	9.56	9.85	10.91
C2	137.74	142.37	155.86	165.56
α	7.31	6.95	6.17	6.81
β	0.02	0.001	0.01	0.001
γ	0.51	0.53	0.51	0.51
δ	0.27	0.64	1.10	1.08
SSE	0.01	0.02	0.02	0.17

Table 5.9 Sigmoidal parameter for HMA binders at long-term aged condition

Parameters	VG20	VG40	PMB40	CRMB60
C1	11.32	10.20	8.75	9.35
C2	167.39	163.71	173.19	177.00
α	2.82	2.74	2.71	2.81
β	0.001	0.33	0.52	0.28
γ	0.59	0.54	0.65	0.63
δ	5.23	5.62	5.66	5.23
SSE	0.07	0.08	0.10	0.05

Table 5.10 Sigmoidal parameter for WMA binders at long-term aged condition

Parameters	EVG20	EVG40	EPMB40	ECRMB60
C1	10.13	10.35	10.69	9.80
C2	176.71	176.03	169.06	171.00
α	2.85	2.86	2.86	2.79
β	0.12	0.001	0.001	0.28
γ	0.67	0.64	0.67	0.63
δ	5.13	5.17	5.12	5.23
SSE	0.06	0.05	0.03	0.06

The master curves for rutting and fatigue parameters are shown in Figure 5.10 and Figure 5.11, respectively for VG20 and EVG20 binders at short-term aged, and long-term aged conditions. From Figure 5.10, it is observed that for a wide range of frequencies the rutting parameter is lower for EVG20 binder compared to VG20 binder. This indicates that the addition of Evotherm additive to VG20 binder decreases the rutting resistance. Likewise, as shown in Appendix B.14, a similar trend for Superpave rutting parameter is observed for remaining three binders over wide range of frequencies. From Figure 5.11, it is observed that the fatigue parameter is lower for the EVG20 binder compared to VG20 binder. This indicates that the addition of Evotherm additive to VG20 binder improves the fatigue resistance. Likewise, as shown in Appendix B.15, a similar trend for Superpave fatigue parameter is observed for remaining three binders over wide range of frequencies. This shows that addition of Evotherm additive to the base binder decreases the rutting resistance whereas it improves the resistance towards fatigue cracking due to formation of lower aging compounds in WMA binders compared to HMA binders (Roja et al., 2016, Behl et al., 2017).

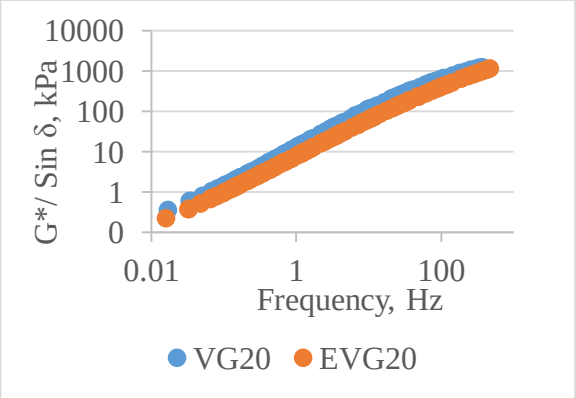


Fig. 5.10 Superpave rutting parameter master curve for VG20 and EVG20 binders

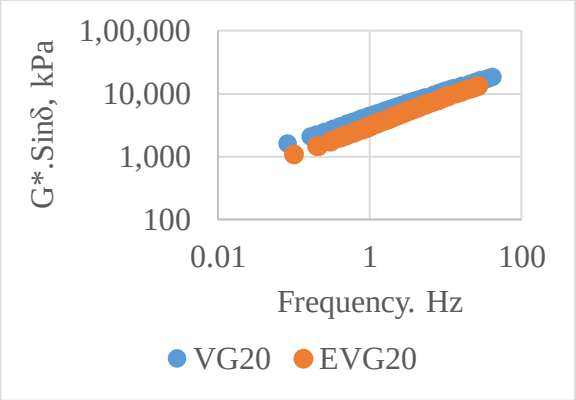


Fig. 5.11 Fatigue parameter master curve for VG20 and EVG20 binders

5.9 LINEAR AMPLITUDE SWEEP TEST

Linear amplitude sweep test was carried out on long-term aged samples of HMA and WMA binders as per the procedure detailed in Chapter 3 at a reference temperature of 25°C for fatigue performance evaluation. The data from the frequency sweep test was continuously recorded for frequency, complex modulus, phase angle, and storage modulus. Later, this data was extracted to determine the undamaged material property "α", and fatigue law parameter "B" using Equations (5.8) and (5.9). Subsequently, the data was continuously recorded for complex modulus, shear stress, shear strain, time, and phase angle from the amplitude sweep test. The data was extracted, and viscoelastic continuum damage analysis was carried to determine fatigue law parameter "A". This parameter was estimated using Equations (5.10) to (5.12).

$$B = 2 * \alpha \quad \text{Eq. (5.8)}$$

$$\alpha = 1 + \frac{1}{m} \quad \text{Eq. (5.9)}$$

$$A = \frac{f*(D_f)^k}{K*(\pi C_1 C_2)^\alpha} \quad \text{Eq. (5.10)}$$

$$D_f = \left(\frac{C_0 - C \text{ at peak stress}}{C_1}\right)^{1/C_2} \quad \text{Eq. (5.11)}$$

$$log([C_0 - C(t)]) = \log(C_1) + C_2 \log[D(t)] \quad \text{Eq. (5.12)}$$

Where, α is the undamaged bitumen binder property and m is the slope of the plot between log ω on the x-axis and G′(ω) on the Y axis, ω is frequency, C_o is equal to 1 at an initial value of C, C is binder integrity parameter, C_1 and C_2 are coefficients of Equation (5.12). The fatigue life (N_f) of the HMA and WMA binders was determined using Equation (5.13).

$$N_f = A * (\gamma_{max})^{-B} \quad \text{Eq. (5.13)}$$

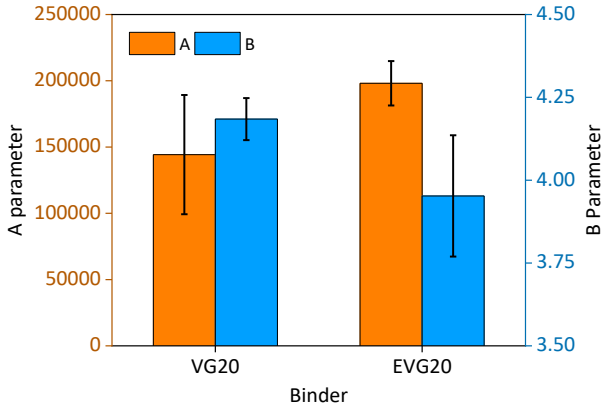


Fig. 5.12 Fatigue law parameters for VG20 and EVG20 binders

Where, γ_{max} is the maximum expected strain in bitumen, and *A*, *B* are fatigue law coefficients. The fatigue law parameters and fatigue life of long-term aged samples of HMA and WMA binders were compiled and bar graphs are plotted. Figure 5.12 presents a bar chart of fatigue law parameters for long-term aged samples of VG20 and EVG20 binder. It is observed that the *A* and *B* parameters are higher and lower, respectively for EVG20 binder compared to VG20 binder. This shows that addition of Evotherm additive to VG20 binder improves the fatigue life. Likewise, as shown in Appendix B.16, a similar trend for fatigue law parameters is observed for remaining three binders.

Figure 5.13 presents the bar chart for the fatigue life of long-term aged VG20 and EVG20 binders at 2.5% and 5% strain. It is observed that the fatigue life of EVG20 binder is higher compared to VG20 binder at 2.5% and 5% strain. This indicates that the addition of Evotherm additive to VG20 binder improves the fatigue life due to formation of lower aging compounds in WMA binders compared to HMA binders (Roja et al., 2016; Bhel et al. 2017). Likewise, as shown in Appendix B.17, a similar trend for fatigue life is observed for remaining three binders.

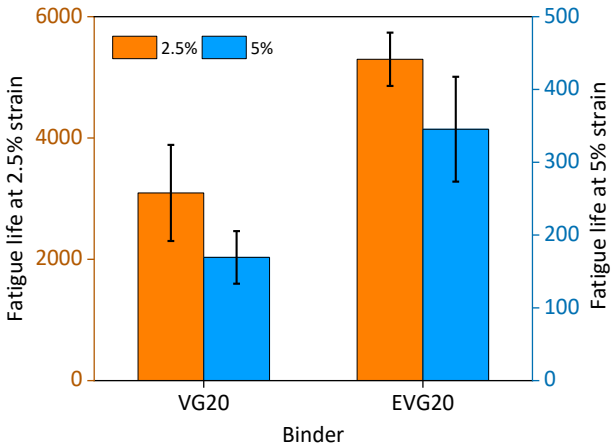


Fig. 5.13 Fatigue life for VG20 and EVG20 binders

5.10 RANKING OF BINDERS BASED ON FATIGUE PARAMETER

In this study, the fatigue parameters and fatigue life of HMA and WMA binders are determined at long-term aged condition. Based on these parameters all the binders are ranked and shown in Table 5.11. It is observed that the performance towards fatigue resistance of ECRMB60 binder is the best and VG20 binder is the least. Thus, the fatigue resistance of bituminous binders is decreasing in the order of ECRMB60, CRMB60, EPMB40, PMB40, EVG40, EVG20, VG40, VG20.

Table 5.11 Ranking of HMA and WMA binders based on fatigue parameters

S. No.	Binders	G*.Sin δ	N_f at 2.5%	N_f at 5%
1	VG20	6	8	8
2	VG40	8	6	7
3	PMB40	7	4	4
4	CRMB60	2	2	5
5	EVG20	3	7	6
6	EVG40	5	5	3
7	EPMB40	4	3	1
8	ECRMB60	1	1	2

5.11 GLOVER-ROWE PARAMETER

Two frequency temperature sweep tests were carried out on the long-term aged samples of HMA and WMA binders in succession using the procedure detailed in Chapter 3 to determine the Glower-Rowe parameter $[(G^*(\cos\delta)^2)/(\sin\delta)]$ at a reference temperature of 15°C and frequency of 0.005 rad/s. The data was recorded and exported for dynamic modulus and phase angle corresponding to the reference temperature of 15°C and frequency of 0.005 rad/s. Master curves were plotted at a reference temperature of 15°C by curve fitting the sigmoidal model (Biswas and Pellian, 2007) to dynamic modulus data, and modified sigmoidal (Yang and You, 2015) model to phase angle data. All the measured data points were shifted to a reference temperature by using William Landel Ferry equation. Data obtained from the frequency temperature test was analysed using the solver function in Microsoft Excel to obtain C_1, C_2, α, β, γ, and Δ model parameter values. By using these model parameter values, the dynamic modulus and phase angle were determined at 15°C reference temperature and 0.005 rad/s frequency. Later, the Glover-Rowe parameter was estimated for HMA and WMA binders at all long-term aged conditions using Equation (3.13) and a bar chart was plotted as shown in Figure 5.14. It is observed that the Glover-Rowe parameter for EVG20 binder is lower compared to VG20 binder at all the long-term aging duration considered in the current study. This indicates that the addition of Evotherm additive to V20 binder improves the resistance

towards fatigue cracking. Likewise, a similar trend is observed for EVG40 binder as shown in Appendix B.18(a). From Appendix B.18(b), it is also observed that the EPMB40 binder has a lower G-R parameter compared to the PMB binder at 10 h and 25 h long-term aging whereas at 40 h and 65 h long-term aging, the reverse trend is observed. From Appendix B.18(c), it is observed that ECRMB60 binder has a slight increase in G-R parameter compared to CRMB60 binder at 10 h and 25 h long-term aging whereas it decreased at 40 h and 65 h long-term aging.

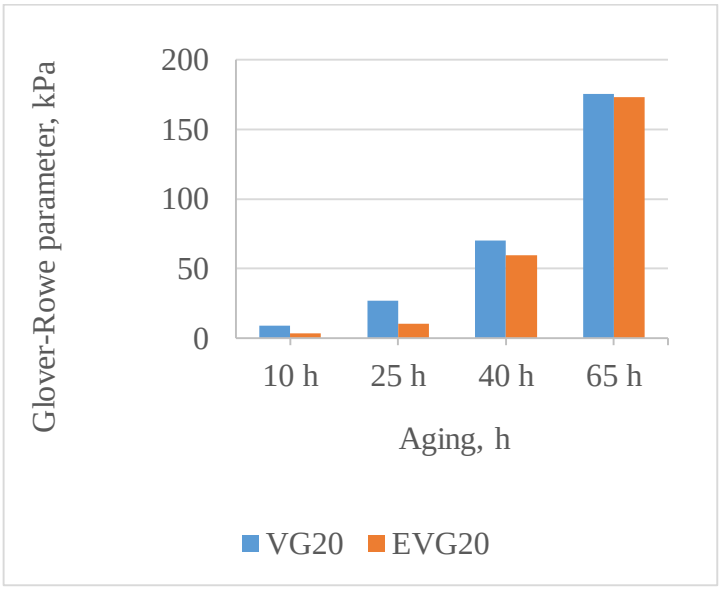


Fig. 5.14 Glover-Rowe parameter for VG20 and EVG20 binders at various long-term aging durations

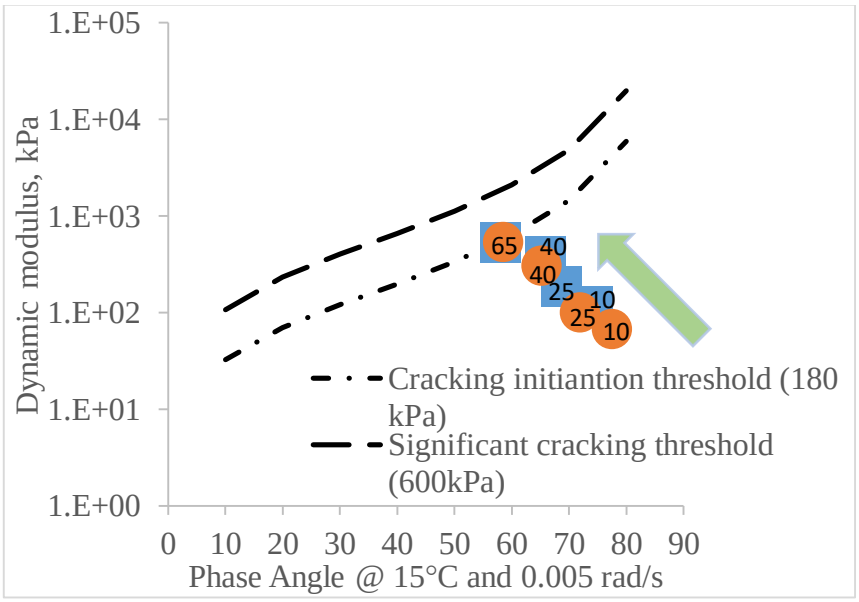


Fig. 5.15 Black space diagram for VG20 and EVG20 binders

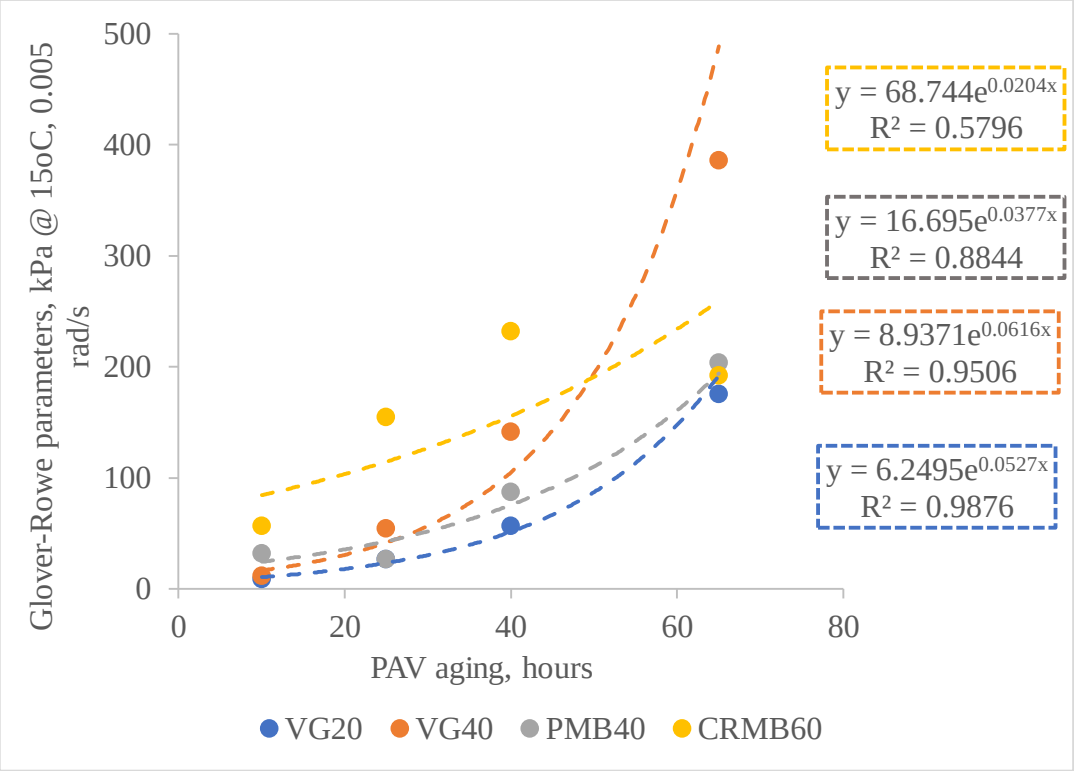


Fig. 5.16 Progression of G-R parameter with aging duration for HMA binders

A graph drawn between dynamic modulus versus phase angle is known as a black space diagram. A G-R black space diagram is plotted as shown in Figure 5.15 between dynamic modulus and phase angle at 15ºC and 0.005 rad/s for VG20 and EVG20 binders at various levels of aging. The dashed line indicates the threshold value for significant cracking (600 kPa) whereas the dash-dot indicates the threshold value for crack initiation (180 kPa). An arrow shown in the Figure 5.15 represents the increase in dynamic modulus and decrease in phase angle as long-term aging duration increases wherein the data points approach the threshold level of cracking. It is observed that the data points of the EVG20 binder are lying below the data points of VG20 in the G-R space diagram at all aging durations. This indicates that the addition of Evotherm additive to VG20 binder improves the cracking resistance. Likewise, as shown in Appendix B.19 to B.21, a similar trend is observed for the remaining three binders.

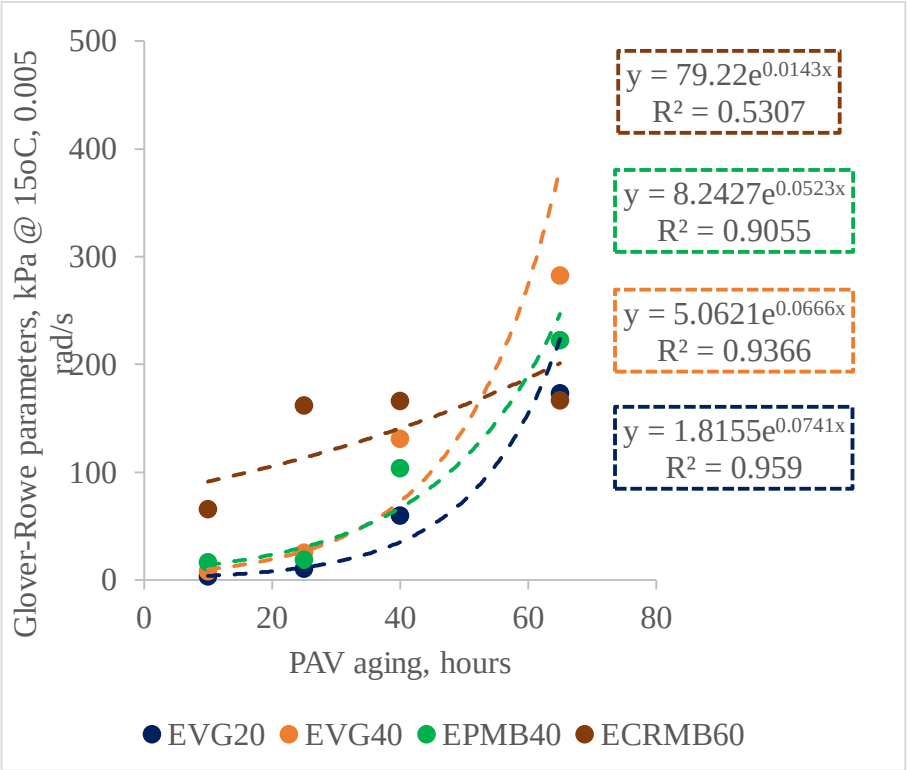


Fig. 5.17 Progression of G-R parameter with aging duration for WMA binders

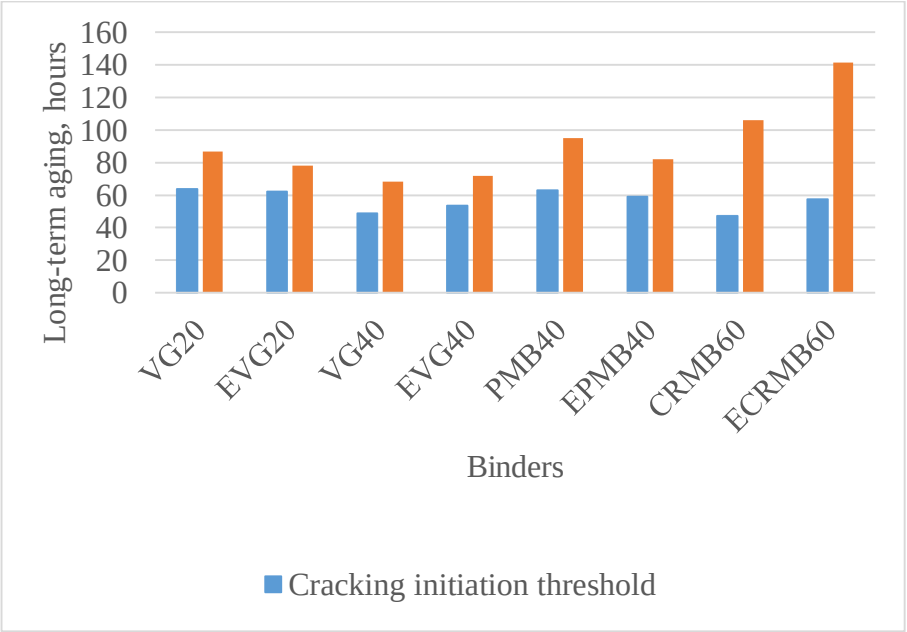


Fig. 5.18 Required long-term aging hours for cracking initiation and significant cracking threshold for HMA and WMA binders

A line graph is plotted for the G-R parameter versus aging duration for HMA and WMA binders as shown in Figure 5.16 and Figure 5.17, respectively. The progression of G-R parameters with respect to aging duration was fitted exponentially and the corresponding equations are shown in the respective figures. With the help of these equations and threshold values (180 kPa and

600 kPa) for cracking, the required long-term aging hours for cracking initiation threshold, and significant cracking threshold were estimated. Subsequently, a bar is plotted as shown in Figure 5.18. It is observed that the required long-term aging hours of aging for significant cracking threshold is highest for ECRMB60 and lowest for VG40.

5.12 SUMMARY

In this chapter, the results obtained through comprehensive rheological investigations on HMA and WMA binders in-term of various rutting parameters and fatigue parameters are presented and discussed in the detail. The next chapter deals with the performance evaluation of bituminous mixtures.

CHAPTER 6

PERFORMANCE EVALUATION OF BITUMINOUS MIXTURES

6.1 INTRODUCTION

Depending on the grade of the unmodified bitumen, bituminous mixtures are produced at relatively higher temperatures ranging from 140 to 170°C. The production temperatures of bituminous mixtures with modified binders are much higher. These higher production temperatures require relatively higher energy which subsequently leads to environmental pollution due to the emission of gases. To minimize energy consumption and emission of gases at higher production temperatures, Warm Mix Asphalt (WMA) technology has been introduced. The WMA technology became very popular across the world due to the lower production and laying temperatures of bituminous mixtures. However, reduction in these temperatures reduces the aging of the binder resulting in bituminous mixtures with lower stiffness thereby making the bituminous mixtures less rut resistant (A. Banerjee et al., 2012; Roja et al., 2015; Wu et al., 2017). Addition of waste plastic to bituminous mixtures is expected address these issues. Thus, the current chapter evaluates the performance of HMA and WMA mixtures containing LDPE-waste-plastic-coated-coarse aggregate (LCA) in terms of moisture resistance and rutting resistance. Moisture resistance of these mixtures was evaluated by carrying out tensile strength tests on unconditioned and moisture-conditioned specimens thereby tensile strength ratio or retained tensile strength was calculated. The rut resistance of HMA and WMA mixtures was determined by running a dry wheel tracking test on bituminous mixture specimens. The following sections provide a detailed discussion on the results obtained from moisture damage tests and wheel tracking tests.

6.2 BITUMINOUS MIXTURES

Bituminous pavement generally consists of a bituminous surface course and a binder course. Bituminous concrete is a dense mix and is widely used in India for the construction of surface course for all high-volume roads where the design traffic is above 5 msa. Hence, mid-gradation of bituminous concrete (BC) grading 2 confirming to the specifications of the Ministry of Road Transport and Highway (MoRTH, 2013) has been selected. Low-density-polyethylene-plastic-coated-coarse aggregates (LCA) fractions of size 13.2 mm, 9.5 mm, and 4.75 mm were used to

prepare HMA and WMA mixtures. For the current study, four types of bituminous mixtures have been used which include BC (control mixture), LBC (containing LCA), EBC (containing Evotherm-modified binder), and LEBC (containing both LCA and Evotherm-modified binder). In this chapter, BC and LBC bituminous mixtures are termed as HMA mixtures, whereas EBC and LEBC bituminous mixtures are termed as WMA mixtures. Four different types of bitumen (VG20, VG40, PMB40, CRMB60) have been blended with Evotherm additive (EVG20, EVG40, EPMB40, ECRMB60). The binders without WMA additive are termed as HMA binders whereas the binders with Evotherm additive are termed as WMA binders.

6.3 MIXING AND COMPACTION TEMPERATURES

Mixing and compaction temperatures for viscosity grade binders (VG20, VG40) were determined as per ASTM D4402 (2015). The detailed procedure for determining mixing and compaction temperatures is presented in Chapter 3. The apparent viscosity data was collected at different temperatures and semi-logarithm graphs are plotted as shown in Figures 6.1 and 6.2 for VG20 and VG40 binders, respectively. The mixing and compaction temperatures for VG20 binder are 150^{o}C and 140^{o}C, respectively. Similarly, the mixing and compaction temperatures for VG40 binder are 165^{o}C and 150^{o}C, respectively. For modified binders (PMB40, CRMB60), the mixing and compaction temperatures are selected based on recommendations of the manufacturer. The mixing temperature of 175^{o}C was selected so that modified bitumen uniformly coats the aggregates (Hensley and Palmer, 1998). Further, the mixing and compaction temperatures for Evotherm-modified binders was reduced by 25^{o}C because WMA mixtures are produced and compacted at a relatively lower temperatures in the range of 20-40^{o}C (Rubio et al., 2012) compared to the HMA mixtures. The mixing and compaction temperatures of HMA and WMA binders are shown in Table 6.1.

Table 6.1 Mixing and compaction temperatures of HMA and WMA binders

Binders	**Mixing temperature, ^{o}C**	**Compaction temperature, ^{o}C**
VG20	150	140
VG40	165	150
PMB40	175	165
CRMB60	175	170
EVG20	125	115
EVG40	140	125
EPMB40	150	140
ECRMB60	150	145

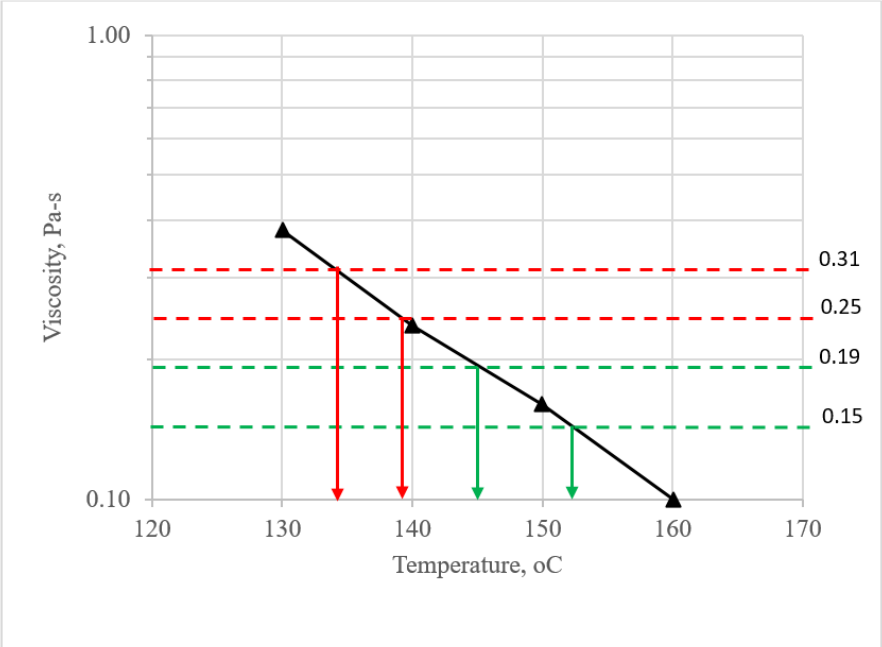


Fig. 6.1 Mixing and compaction temperatures for VG20 binder

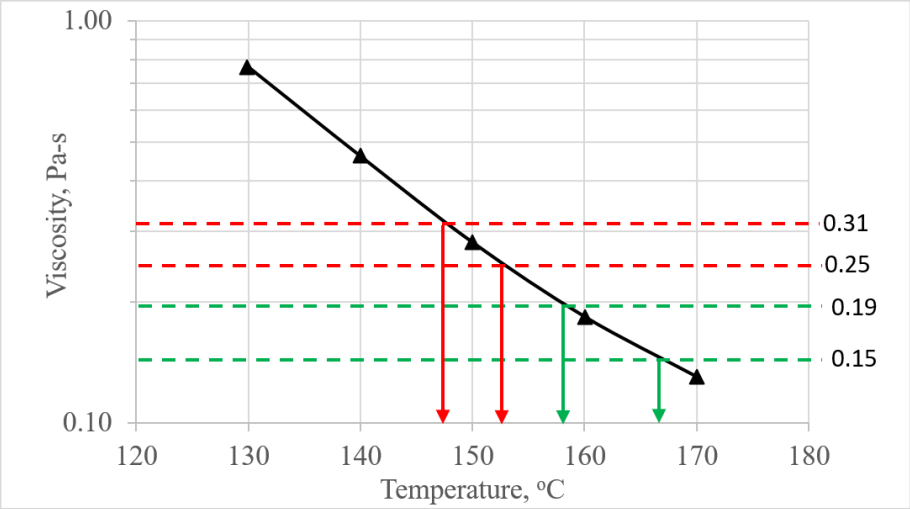


Fig. 6.2 Mixing and compaction temperatures for VG40 binder

6.4 BINDER CONTENT

Marshall mix design for BC and LBC mixtures was carried out in the laboratory as per the Asphalt Institute manual MS-2 (2014). Marshall specimens for BC mixtures were prepared by mixing preheated aggregates with bitumen followed by compaction of the mix. The Marshall specimens for LBC mixtures were prepared using an enhanced process where prepared LCA was initially mixed with the pre-heated fine aggregates. Hot binder was poured in the resulting aggregate followed by compaction of the mix as shown in Figure 6.3. Subsequently, the volumetric data was compiled at design air voids of 4% for each type of mixture for optimum binder content, maximum specific gravity of the mix (G_{mm}), bulk specific gravity of the mix (G_{mb}), stability, flow, voids in mineral aggregates (VMA), and voids filled with bitumen (VFB).

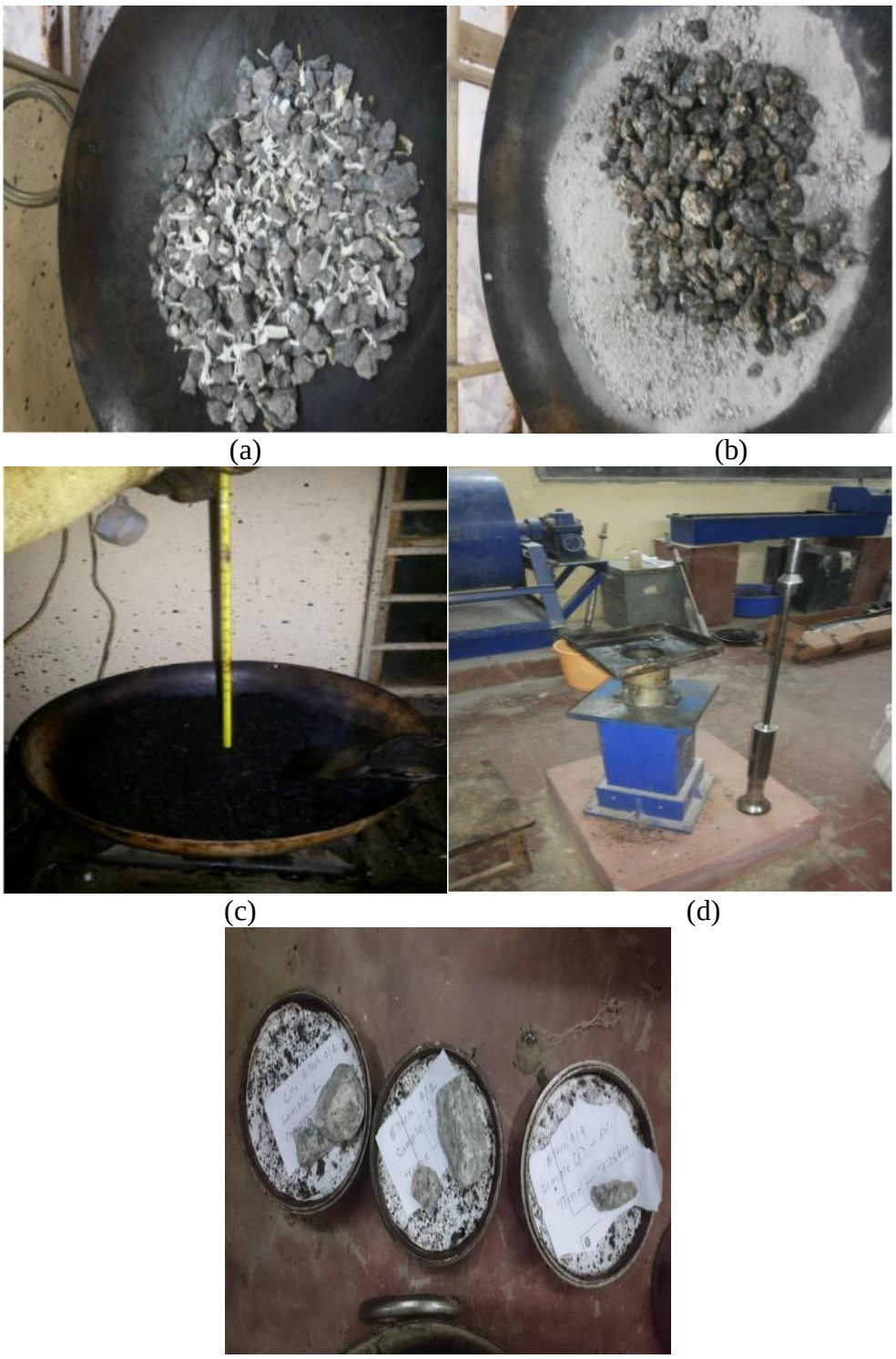


Fig. 6.3 Specimen preparation process for LBC mixtures: (a) preparation of LCA, (b) mixing of LCA with fine aggregate, (c) mixture preparation, (d) Marshall specimen compaction, and (e) compacted Marshall specimens

The volumetric and strength properties of BC and LBC mixtures prepared using HMA binders are listed in Table 6.2 and Table 6.3, respectively. It is observed that the addition of LDPE-waste plastic reduced the binder content by 0.2% for unmodified binders and 0.3% for modified

binders, respectively. At the same time, the addition of LDPE-waste plastic increased the stability of bituminous mixtures. This shows that addition of LDPE-waste plastic improves the stiffness of the bituminous mixtures. The binder contents obtained for the respective HMA mixtures were also used for the corresponding WMA mixtures.

Table 6.2 Properties of BC mixtures for unmodified binders

Parameters	**VG20**		**VG40**		**Specification (MoRTH, 2013)**
Mixture type	BC	LBC	BC	LBC	
Binder content, %	5.7	5.5	5.7	5.5	Min. 5.4
G_{mm}	2.448	2.444	2.441	2.450	N/A
G_{mb}	2.349	2.346	2.339	2.34	N/A
Air voids, %	4.04	4.04	4.21	4.09	3 to 5
Stability, kN	13.1	14.5	16.3	17.30	Min. 12
Flow, mm	3.7	3.65	3.05	3	2 to 4
VMA, %	16.21	15.86	16.29	15.94	Min. 14
VFB, %	74.8	74.72	74.3	74.08	65 to 75

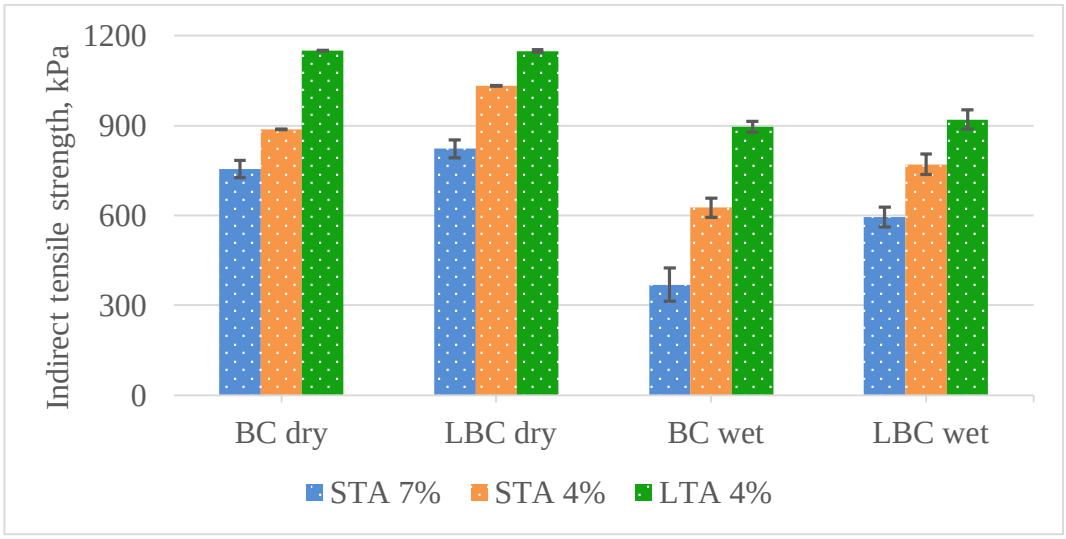
Table 6.3 Properties of BC mixtures for modified binders

Parameters	**PMB40**		**CRMB60**		**Specification (MoRTH, 2013)**
Mixture type	BC	LBC	BC	LBC	
Binder content, %	6.0	5.7	5.5	5.2	Min. 5.4
G_{mm}	2.436	2.440	2.467	2.469	N/A
G_{mb}	2.334	2.337	2.362	2.366	N/A
Air voids, %	4.2	4.2	4.3	4.2	3 to 5
Stability, kN	12.2	13.6	23.2	24.2	Min. 12
Flow, mm	2.8	2.86	2.2	2.1	2 to 4
VMA, %	16.74	16.36	15.3	14.9	Min. 14
VFB, %	75	74.2	72.2	72.0	65 to 75

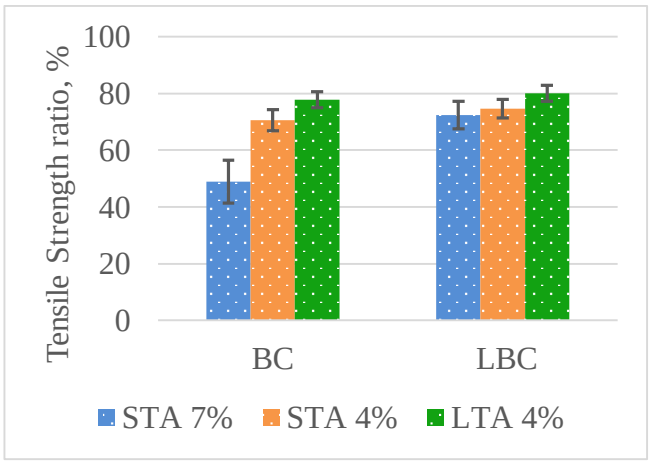
6.5 MOISTURE DAMAGE RESISTANCE OF HMA MIXTURES

Moisture damage test was performed on HMA mixture (BC, LBC) specimens prepared with HMA binders at a reference temperature of 25^{o}C as per AASHTO T 283 (2015). The moisture damage test was performed on BC and LBC specimens using the procedure detailed in Chapter 3. The specimens were compacted to target air voids of 4% and 7% for short-term aged condition, and target air voids of 4% for long-term aged condition. To evaluate the moisture resistance of bituminous mixtures, the failure load in Indirect Tensile Strength (ITS) test was noted for wet and dry scenarios. Later, dry as well as wet indirect tensile strengths were used to compute the Tensile Strength Ratio (TSR). Finally, bar charts were plotted to evaluate the effect

of air voids and aging on the performance of BC and LBC mixtures in terms of resistance to moisture damage. Further, the addition of LDPE-waste plastic to the BC mixtures was also evaluated for resistance to moisture damage.



(a)



(b)

Fig. 6.4 (a) Dry and wet indirect tensile strength, and (b) TSR of BC and LBC mixtures prepared with VG20 binder

6.5.1 Effect of air voids and aging on ITS and TSR

The bar chart for dry ITS and wet ITS, and the tensile strength ratio of BC and LBC mixtures prepared with VG20 binder are shown in Figure 6.4 at all air voids and aging conditions. It is observed that with a reduction in air voids from 7% to 4% at the short-term aged condition, the dry ITS, wet ITS, and TSR values increased for both the BC and LBC mixtures prepared with VG20 binder. This indicates that both BC and LBC mixtures exhibit improved internal resistance due to densification of the specimen. It is also observed that with increase in aging level from short-term to long-term at the same 4% air voids, the dry ITS, wet ITS, and TSR

values increased for both the BC and LBC mixtures prepared with VG20 binder. This indicates that both BC and LBC mixtures exhibit improved internal resistance due to stiffening of the binder. Likewise, as shown in Appendix C.1 to C.3, a similar trend for dry ITS, wet ITS, and TSR is observed for the remaining three binders.

6.5.2 Effect of LDPE-waste plastic on ITS and TSR

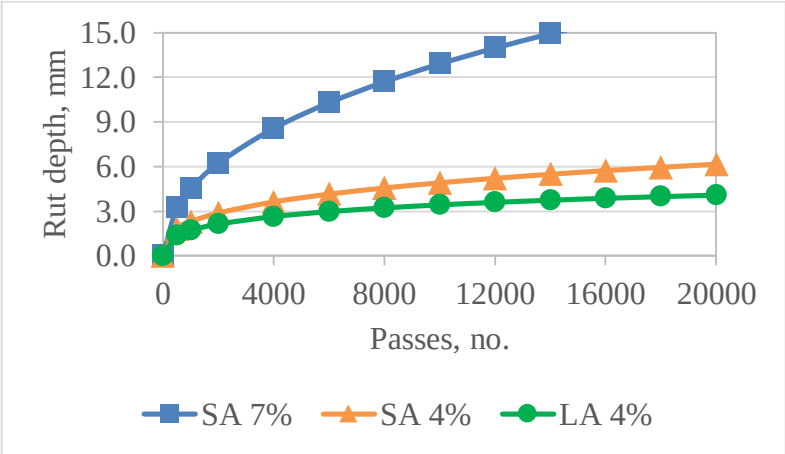
From Figure 6.4(a), it is observed that the dry ITS and wet ITS of LBC mixtures is higher compared to that of BC mixtures prepared with VG20 binder at all aging conditions. This indicates that the addition of LDPE waste plastic to BC mixture improves both the dry ITS and wet ITS. The addition of LDPE waste plastic to bituminous mixtures improves the adhesion bond between bitumen and plastic-coated aggregate (Vasudevan et al., 2012; Rajasekaran et al., 2013;). Further, it is also observed from Figure 6.4(b) that TSR of LBC mixtures is higher compared to that of the BC mixtures. This is due to the higher wet ITS of LBC mixtures compared to wet ITS of BC mixtures. Further, the addition of LDPE waste plastic increases the adhesion bond between bitumen and aggregate (Rajasekaran et al., 2013). Likewise, as shown in Appendix C.1 to C.3, a similar trend for dry ITS, wet ITS, and TSR is observed for the remaining three binders.

6.6 RUTTING RESISTANCE OF HMA MIXTURES

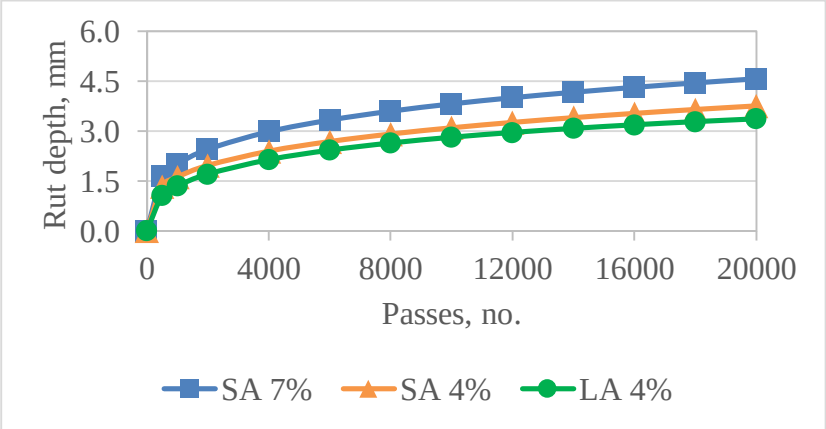
A dry wheel tracking test was performed on HMA mixture (BC, LBC) specimens prepared with HMA binders at a reference temperature of 60^{o}C. The wheel tracking test was performed on BC and LBC specimens by adopting the procedure detailed in Chapter 3. The specimens were compacted to target air voids of 4% and 7% for short-term aged condition, and target air voids of 4% for long-term aged condition to evaluate the influence of air voids and aging on rutting performance of BC and LBC mixtures. Further, the influence of adding LDPE-waste plastic to the BC mixtures was also evaluated for rutting performance. The progression of rut depth was continuously recorded for a number of cycles. The rut data was extracted, analyzed, and the progression of rut depth was plotted as a function of number of passes for both BC and LBC mixtures at both 7% and 4% air voids for both short-term and long-term aged conditions. The following sub-sections provide a detailed discussion on the effect of air voids, aging, and presence of LDPE-waste plastic in bituminous mixtures on resistance to permanent deformation.

6.6.1 Effect of air voids and aging on rutting resistance

The rut depth progression of BC and LBC mixtures prepared with VG20 binder is presented in Figure 6.5 at all air voids and aging conditions. It is observed that with a reduction in air voids from 7% to 4% at the short-term aged condition, the rut resistance increased for both the BC and LBC mixtures prepared with VG20 binder. This indicates that both BC and LBC mixtures exhibit improved internal resistance due to densification of the specimen. It is also observed that with increase in aging level from short-term to long-term at the same 4% air voids, the rut resistance increased for both the BC and LBC mixtures prepared with VG20 binder. This indicates that both BC and LBC mixtures exhibit improved internal resistance due to stiffening of the binder. The increase in stiffness of the binder is due to increase in formation of aging compounds (carbonyl and sulfoxide functionalities) upon changing the aging condition from short-term to long-term (Roja et al., 2015; Behl et al., 2017). Likewise, as shown in Appendix C.4 to C.5, a similar trend for rut resistance is observed for the remaining three binders.

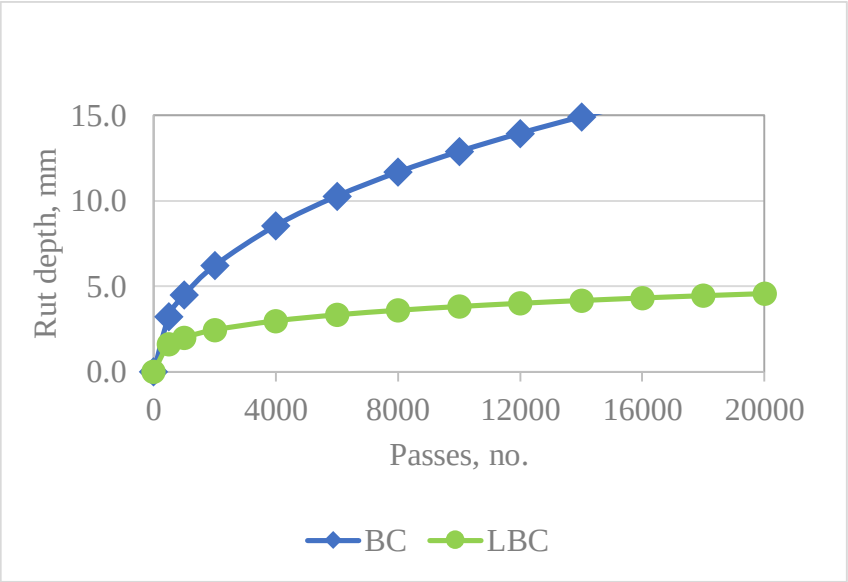


(a) BC

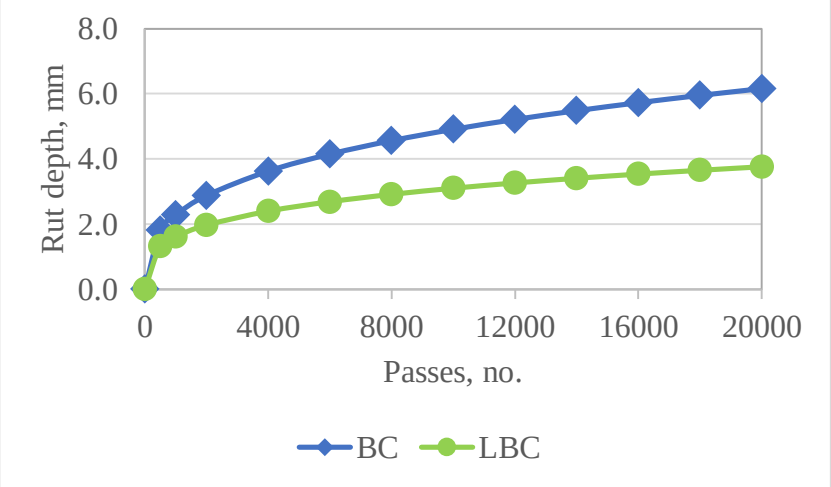


(b) LBC

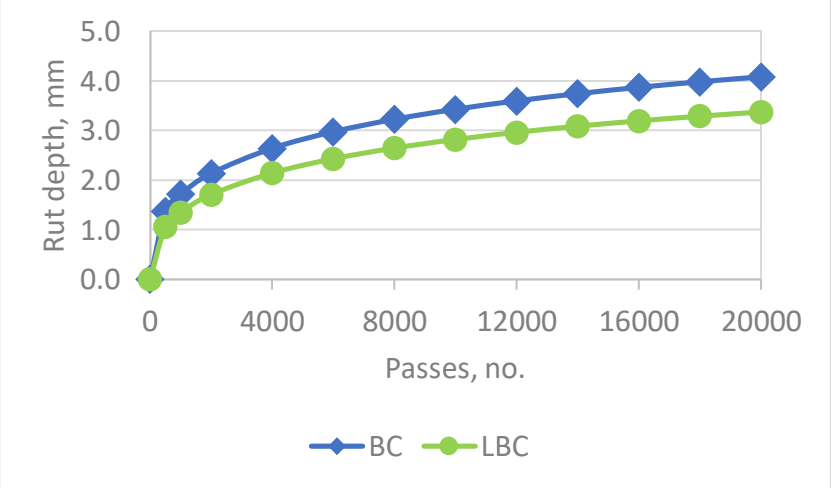
Fig. 6.5 Rut depth progression of BC and LBC mixtures prepared with VG20 binder at various aging conditions



(a) STA 7%



(b) STA 4%



(c) LTA 4%

Fig. 6.6 Rut depth progression of BC and LBC mixtures prepared with VG20 binder at various aging conditions

6.6.2 Effect of LDPE-waste plastic on rutting resistance

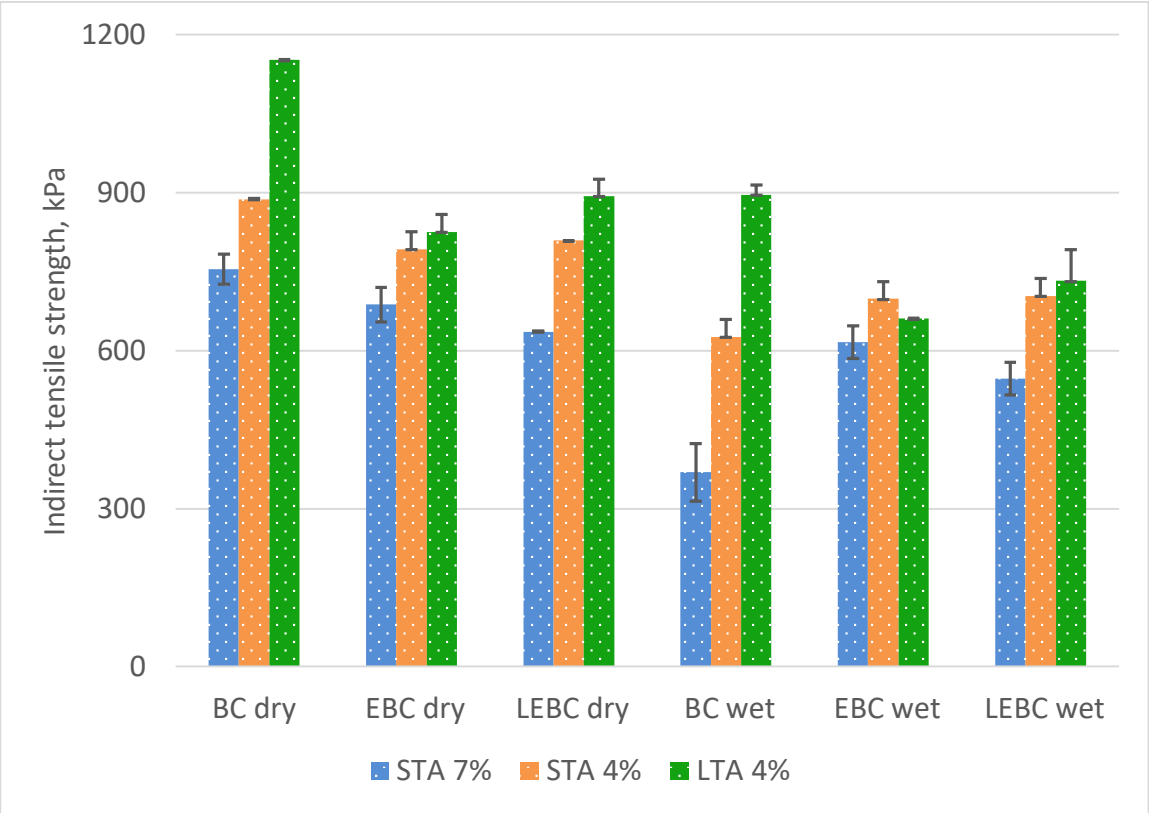
The rut depth progression of BC and LBC mixtures prepared with VG20 binder is compared in Figure 6.6 at all air voids and aging conditions. It is observed that the rut resistance of LBC mixtures is higher compared to that of BC mixtures prepared with VG20 binder at all aging conditions. This indicates that the addition of LDPE waste plastic to BC mixture improves the rut resistance due to increase in stiffness of bituminous mixtures (Radeef et al., 2021). Likewise, as shown in Appendix C.6 to C.8, a similar trend for rut resistance is observed for the remaining three binders.

6.7 MOISTURE DAMAGE RESISTANCE OF WMA MIXTURES

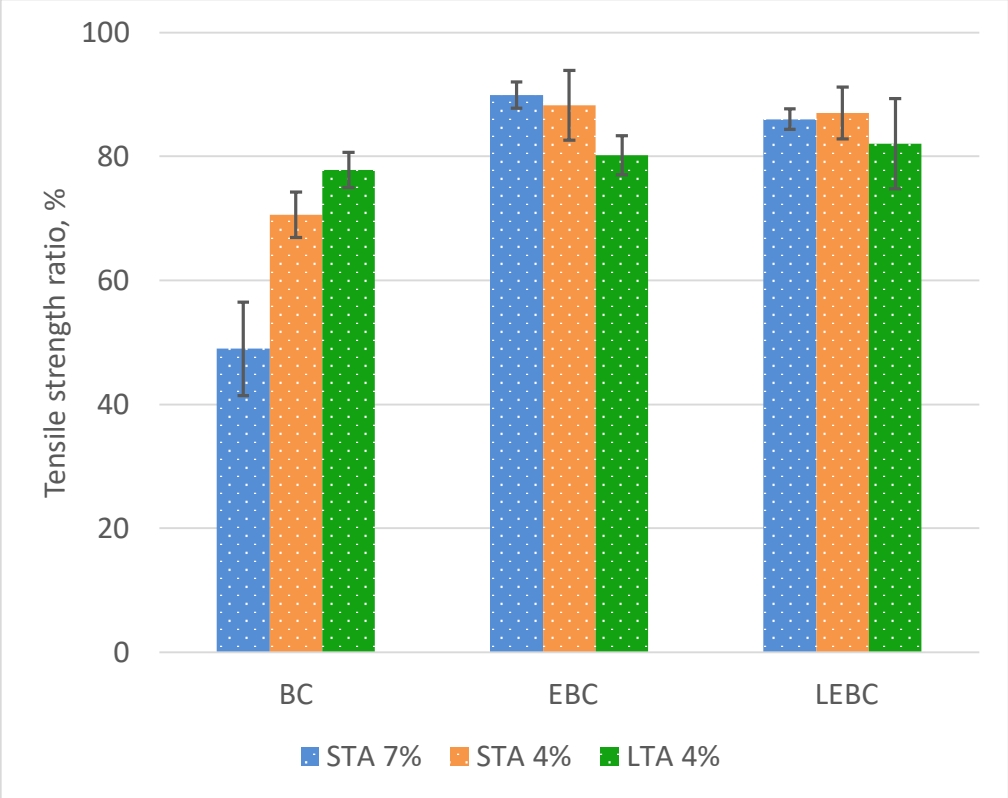
Moisture damage test was performed on WMA mixture (EBC, ELBC) specimens prepared with WMA binders at a reference temperature of 25^{o}C as per AASHTO T 283 (2015). The moisture damage test was performed on EBC and ELBC specimens using the procedure detailed in Chapter 3. The specimens were compacted to target air voids of 4% and 7% for short-term aged condition, and target air voids of 4% for long-term aged condition. The dry ITS, wet ITS, and TSR data was compiled for all WMA mixtures with and without LDPE-waste plastic to evaluate the effect of air voids, aging, and the addition of LDPE waste plastic in WMA mixtures in terms of resistance to moisture damage. Further, the effect Evotherm additive on the performance of BC mixtures was also evaluated in terms of the resistance to moisture damage.

6.7.1 Effect of air voids and aging on ITS and TSR

The bar chart for dry ITS and wet ITS, and the tensile strength ratio of BC mixtures prepared with VG20 bitumen, EBC and LEBC mixtures prepared with EVG20 binder are shown in Figure 6.7 at all air voids and aging conditions. It is observed that with a reduction in air voids from 7% to 4% at the short-term aged condition, the dry ITS, wet ITS, and TSR values increased for BC, EBC, and LEBC mixtures with an exception to TSR of EBC mixtures. It is also observed that with increase in aging level from short-term to long-term at the same 4% air voids, the dry ITS, wet ITS, and TSR values increased for both BC, EBC, and LEBC mixtures with an exception to wet ITS of EBC mixtures, TSR of EBC mixtures, and TSR of LEBC mixtures. Likewise, as shown in Appendix C.9 to C.11, a similar trend for dry ITS, wet ITS, and TSR is observed for the remaining three binders with an exception to TSR of EBC mixtures prepared with EPMB40 binder.



(a)



(b)

Fig. 6.7 (a) Dry and wet indirect tensile strength, and (b) TSR of BC mixtures prepared with VG20 binder, EBC and LEBC mixtures prepared with EVG20 binder

6.7.2 Effect of Evotherm and LDPE-waste plastic on ITS and TSR

From Figure 6.7, it is observed that the dry ITS of EBC mixtures is less compared to that of BC mixtures. This indicates that the addition of WMA additive to BC mixtures reduces the dry indirect tensile strength. The wet ITS of EBC mixtures at short-term aging condition is higher compared to that of BC mixtures whereas a reverse trend is observed at long-term aging condition. Further, the TSR at all aging conditions for EBC mixtures is higher compared to that of BC mixtures. The presence of Evotherm increases the total surface energy and work of adhesion and reduces the work of debonding, indicating a better asphalt-aggregate bond and lower moisture susceptibility (Ghabchi et al., 2013). It is also observed that the performance of LEBC mixtures is lower than that of EBC mixtures at all aging conditions. Even though the usage of Evotherm additive alone or LDPE waste plastic alone in bituminous mixtures in general improved the resistance to moisture damage, the benefits achieved due to the combined usage of Evotherm and LDPE waste plastic in bituminous mixtures is not that significant in terms of the resistance to moisture damage. Likewise, as shown in Appendix C.9 to C.11, a similar trend in moisture damage resistance is observed for the remaining three binders.

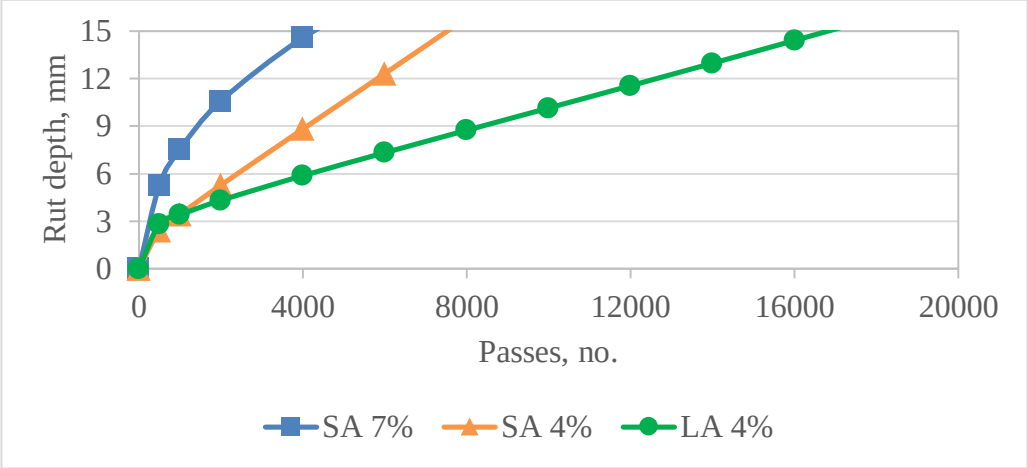
6.8 RUTTING RESISTANCE OF WMA MIXTURES

A dry wheel tracking test was performed on WMA mixture (EBC, LEBC) specimens prepared with WMA binders at a reference temperature of 60^{o}C. The wheel tracking test was performed on EBC and LEBC specimens by adopting the procedure detailed in Chapter 3. The specimens were compacted to target air voids of 4% and 7% for short-term aged condition, and target air voids of 4% for long-term aged condition to evaluate the influence of air voids and aging on rutting performance of EBC and LEBC mixtures. Further, the influence of adding Evotherm additive and combined usage of Evotherm additive and LDPE-waste plastic in BC mixtures was also evaluated for rutting performance. The following sub-sections provide a detailed discussion on the effect of air voids, aging, presence of Evotherm, and combined presence Evotherm and LDPE-waste plastic in bituminous mixtures on resistance to permanent deformation.

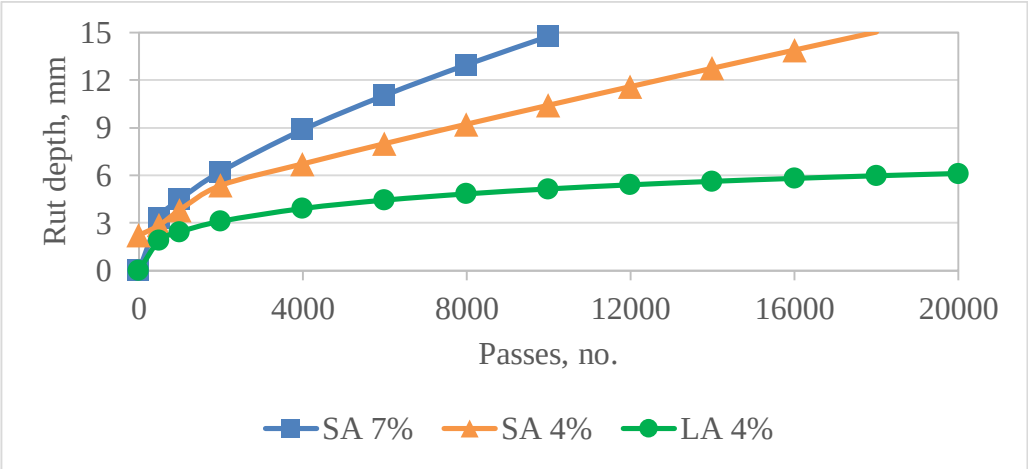
6.8.1 Effect of air voids and aging on rutting resistance

The rut depth progression of EBC and LEBC mixtures prepared with EVG20 binder is presented in Figure 6.8 at all air voids and aging conditions. It is observed that with a reduction in air voids from 7% to 4% at the short-term aged condition, the rut resistance increased for both the EBC and LEBC mixtures prepared with EVG20 binder. This indicates that both EBC and LEBC mixtures exhibit improved internal resistance due to densification of the specimen. It is also

observed that with increase in aging level from short-term to long-term at the same 4% air voids, the rut resistance increased for both the EBC and LEBC mixtures prepared with EVG20 binder. This indicates that both EBC and LEBC mixtures exhibit improved internal resistance due to stiffening of the binder due to long-term aging. Likewise, as shown in Appendix C.12 to C.13, a similar trend for rut resistance is observed for the remaining three binders.



(a) EBC



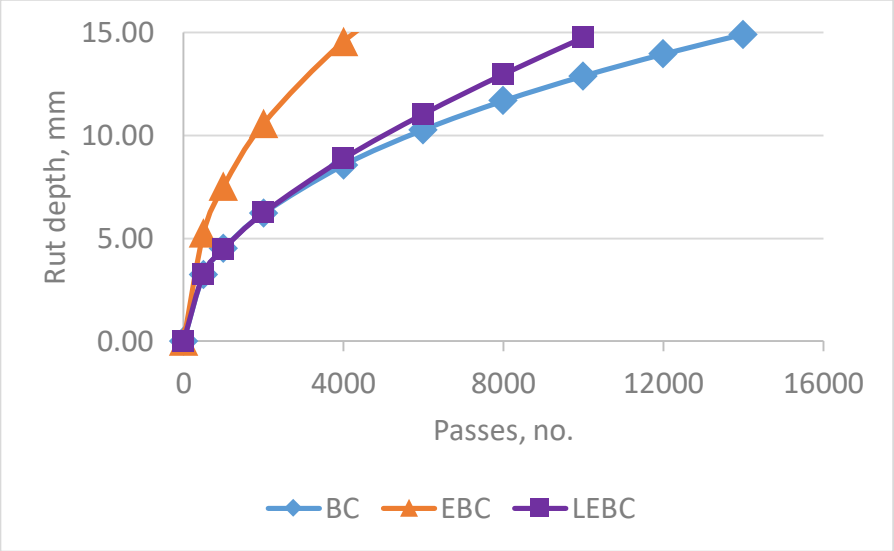
(b) LEBC

Fig. 6.8 Rut depth progression of EBC and LEBC mixtures prepared with EVG20 binder

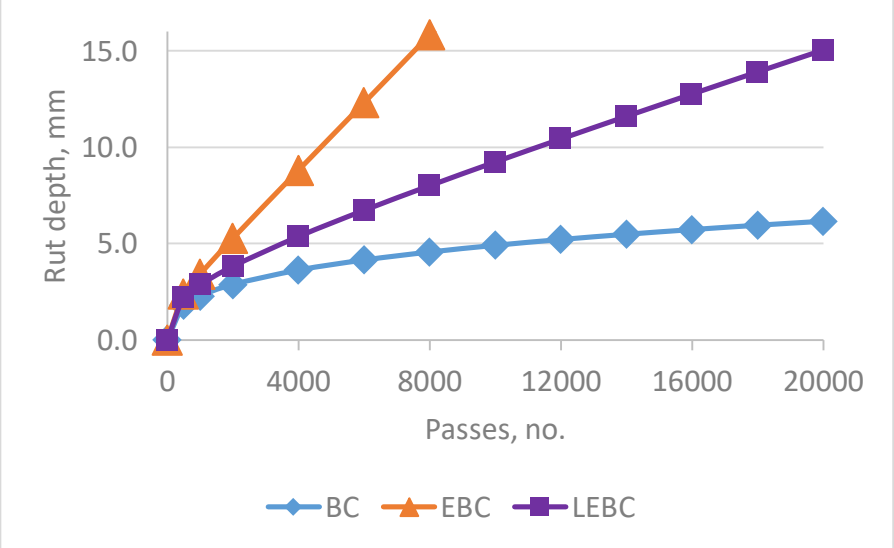
6.8.2 Effect of Evotherm and LDPE plastic on rutting resistance

The rut depth progression of BC mixtures prepared with VG20 binder, EBC and LEBC mixtures prepared with EVG20 binder is compared in Figure 6.9 at all air voids and aging conditions. It is observed that the rut resistance of BC mixtures is higher compared to that of EBC mixtures prepared with EVG20 binder at all aging conditions. This indicates that the addition of Evotherm additive to BC mixtures degrades the rutting resistance due to the lower stiffness of WMA binders and mixtures compared to the stiffness of HMA binders and mixtures. Further, it is also observed that the rut resistance LEBC mixtures is higher compared to that of EBC

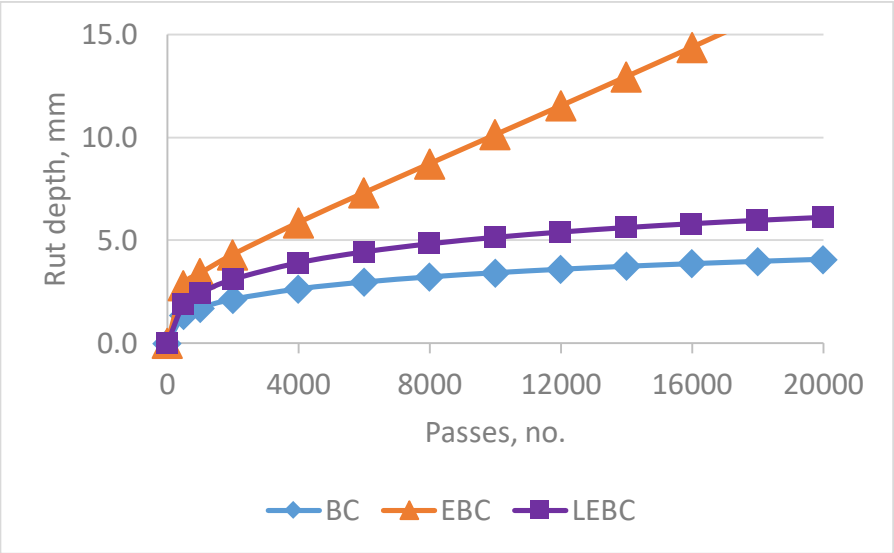
mixtures at all aging conditions indicating the addition of LDPE-waste plastic in the EBC mixture improves the rut performance. Even though addition of Evotherm additive to BC mixtures degrades the performance in terms of resistance to rutting, the addition of LDPE-waste plastic to EBC mixtures enhances its resistance to rutting. Likewise, as shown in Appendix C.14 to C.16, a similar trend for rut resistance is observed for the remaining three binders.



(a) STA 7%



(b) STA 4%



(c) LTA 4%

Fig. 6.9 Rut depth progression of BC, EBC, and LEBC mixtures at various aging conditions

6.9 CORRELATIONS BETWEEN BITUMINOUS MIXTURE RUT DEPTH AND BINDER RUTTING PARAMETERS

Figure 6.10 to Figure 6.14 shows the correlation plots between rut depth and all the binder rutting parameters. It is observed that among all plots, the plot between rut depth and low shear viscosity is strongly correlated compared to the remaining binder rutting parameters.

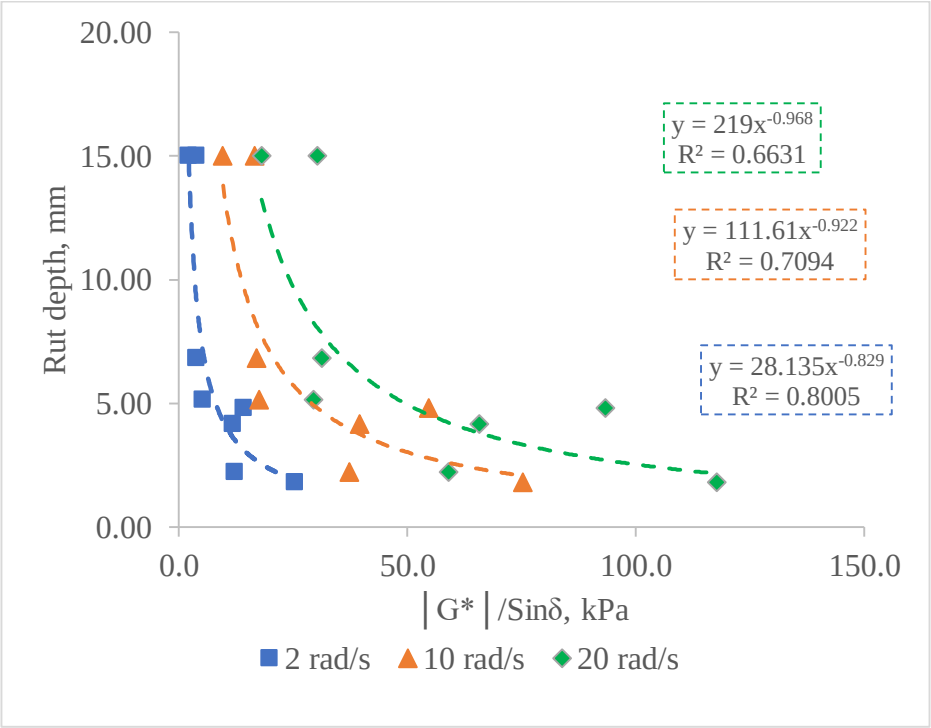


Fig. 6.10 Rut depth vs rutting parameter (all binders)

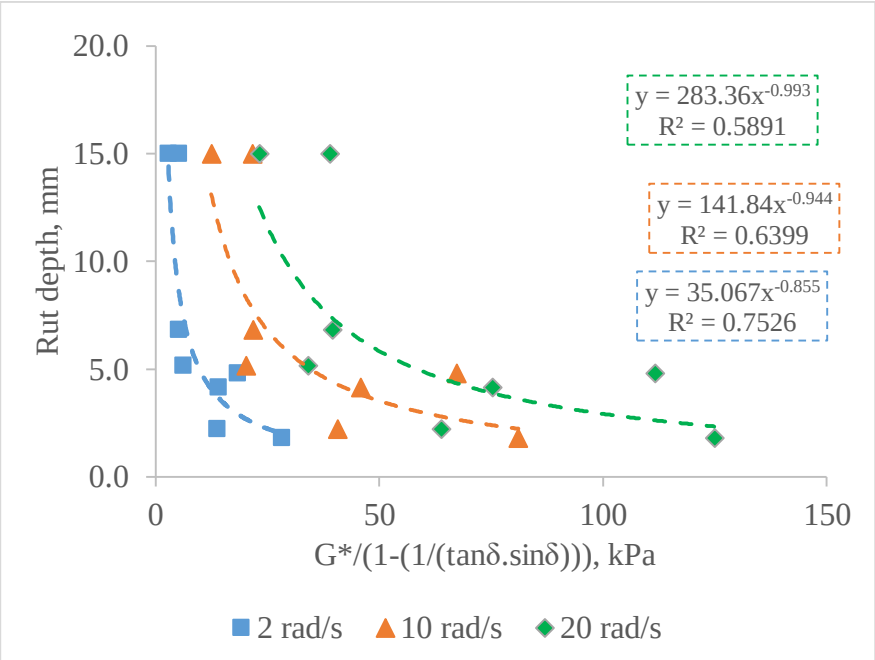


Fig. 6.11 Rut depth vs Shenoy's parameter (all binders)

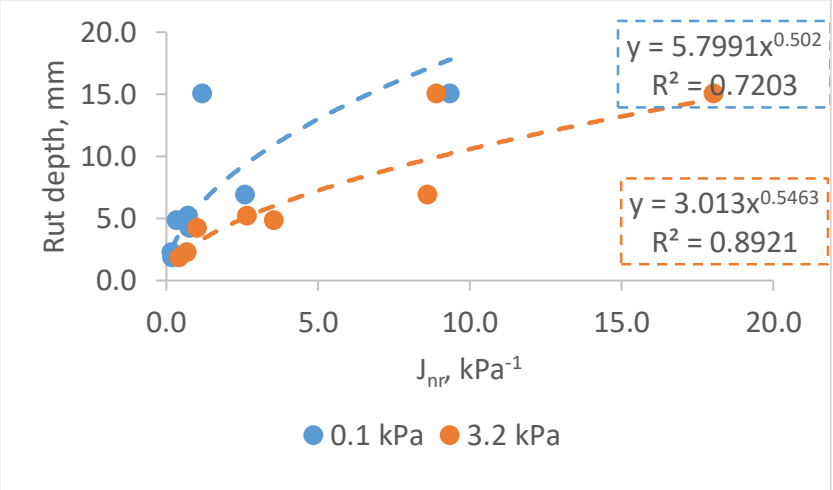


Fig. 6.12 Rut depth vs non-recoverable creep compliance (all binders)

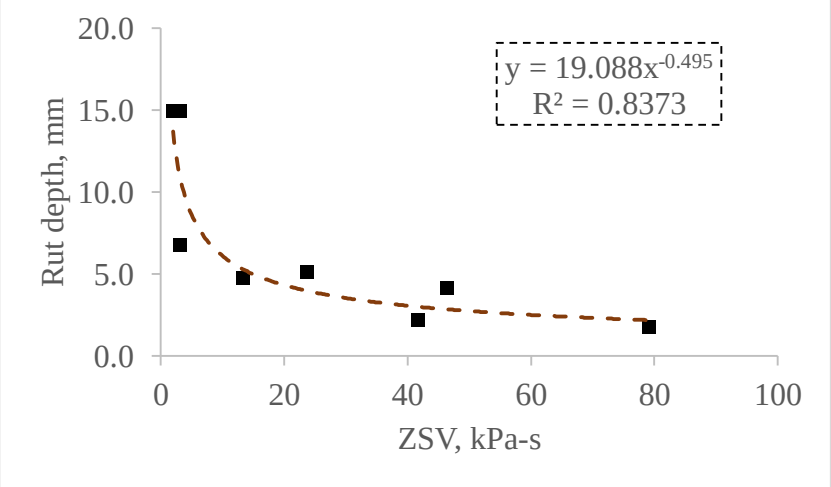


Fig. 6.13 Rut depth vs zero shear viscosity (all binders)

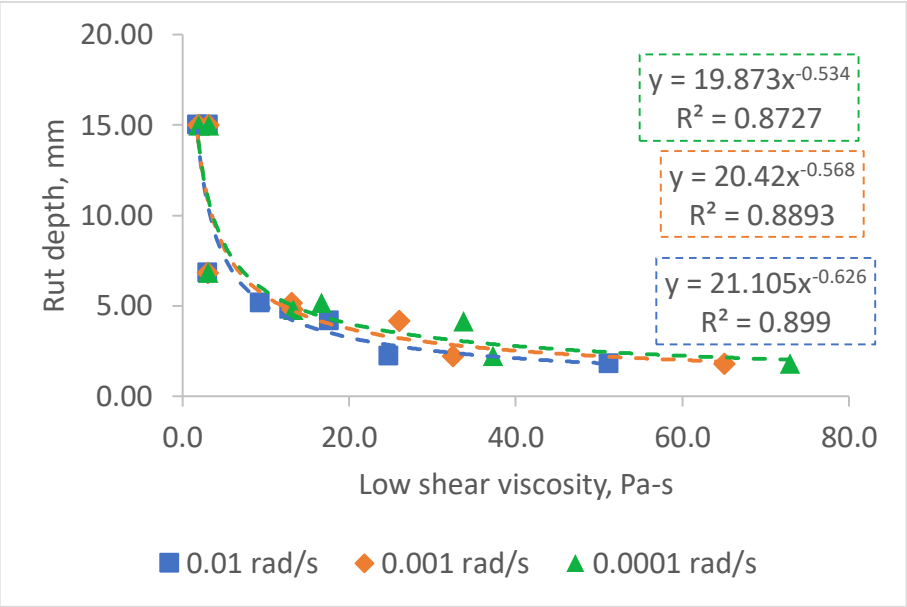


Fig. 6.14 Rut depth vs low shear viscosity (all binders)

It was observed that irrespective of the frequency, the low shear viscosity exhibited a stronger correlation with the rut depth. However, rutting parameters such as $|G^*|/Sin\delta$ and Shenoy's parameter resulted in correlations that were observed to be frequency dependent. Similarly, the non-recoverable creep compliance resulted in correlations that were observed to be stress dependent. The low shear viscosity resulted in best correlation with rut depth that was observed to be independent of frequency unlike other rutting parameters that were observed to be dependent on frequency or applied stress levels. Thus, the low shear viscosity is recommended as the best rutting performance indicator for the bituminous mixtures selected in the current study. Further, the correlations developed in this study are independent of the type of binder.

6.10 SUMMARY

This chapter comprehensively evaluated the resistance to moisture damage and rutting of both HMA and WMA mixtures with and without LDPE-waste plastic at two different air voids and two aging conditions. Further, correlations have been developed between bituminous mixture rut depth and the binder rutting parameters. The next chapter presents the conclusions drawn from the current study apart from the scope for future research work.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 SUMMARY

The experimental investigation for the present work was carried out in three phases. In the first phase, HMA and WMA binder aging was quantified in terms of carbonyl and sulfoxide indices, and rheological properties were evaluated for HMA and WMA binders at unaged, short-term aged, and long-term aged conditions. The spectra measured using Fourier Transform Infrared spectrometer was analyzed using spectrograph 1.2 software by adopting the baseline method and subsequently the influence of Evotherm additive during the WMA binder production process was evaluated along with the effect of Evotherm on the binder aging process. For the rheological investigation, a dynamic shear rheometer was used to perform various tests such as amplitude sweep test, frequency sweep test, multiple stress creep and recovery test, frequency-temperature sweep test, and linear amplitude sweep test in the laboratory to evaluate the effect of adding Evotherm to the base binders for thermal equilibrium time, Superpave rutting parameter, Shenoy's fatigue parameter, non-recoverable creep compliance, zero shear viscosity, low-shear viscosity, fatigue life, Glover-Rowe parameter, cracking initiation and significant cracking thresholds at various aging conditions. In the second phase, the performance of bituminous concrete mixtures containing control and low-density-polyethylene waste plastic coated coarse aggregate with and without Evotherm additive in the base binders was evaluated for permanent deformation and moisture-induced damage resistance. The permanent deformation resistance of HMA and WMA mixtures was evaluated with the help of the wheel tracking test whereas moisture-induced damage resistance was evaluated with the help of the indirect tensile strength test. In the third phase, bituminous binder rheological parameters were correlated with the bituminous mixture test results in terms of rut depth. The analysis of these test results from the current research study resulted in a set of conclusions which are presented in the next section.

7.2 CONCLUSIONS

The following conclusions are drawn from this study:

1. In the unaged condition, a considerable increase (average 64%) in carbonyl index was observed for the WMA binders compared to the HMA binders, and this can be attributed to the aging during the production of WMA binders as the binders are heated to about 150 to 165°C in the presence of oxygen for 30 minutes. The increase in sulfoxide index for WMA binder is substantial (average 149%) which can be partly attributed to the sulfur-containing organics present in Evotherm and partly due to the sulfoxide formation during the production process of WMA binder.
2. The magnitude of increase in carbonyl index for the HMA and WMA binders during short-term and long-term aging is specific to the type of binder. The carbonyl formation during the long-term aging is highest for VG20 binder and lowest for PMB40 binder. The sulfoxide index in PMB40 is higher followed by CRMB60, VG20, and VG40. This is due to addition of sulfur during the production process of polymer modified bitumen. The increase or decrease in sulfoxide index during aging for a given binder depends on the relative dominance of formation or decomposition of sulfoxides.
3. For identical aging temperatures, the formation of carbonyl compounds in WMA binders was seen to be less (average 0.55, about one-half) than that observed in HMA binders for both unmodified and modified binders. This can be attributed to either the presence of certain compounds in Evotherm or the nature of the interaction of Evotherm with the base binder. Thus, the WMA binders are expected to exhibit increased resistance to aging resulting in lower binder stiffness to resist rutting. At the same time, the fatigue resistance is expected to increase.
4. The thermal equilibrium time is observed to depend on the type of binder. In unaged condition, the presence of Evotherm increased the thermal equilibrium times for polymer modified bitumen and crumb rubber modified bitumen due to possible interactions between Evotherm and the respective modifiers (polymer and crumb rubber). Short-term aging increased the thermal equilibrium time of bituminous binders due to increase in binder stiffness which can be corroborated with the formation of aging compounds upon short-term aging. At the same time, addition of Evotherm to the base binders in short-term aged condition reduced the thermal equilibrium times due to reduction in formation of aging compounds resulting from lower short-term aging temperatures of Evotherm binders. The linear regression model developed in this study can be used to determine the thermal equilibrium time by knowing the softening point and test temperature at which

rheological characterization is to be made for a given asphalt binder. This linear regression model could save a lot of time for asphalt engineers and academicians involved in the characterization of asphalt binders at a particular test temperature.

5. The various rutting parameters such as Superpave rutting parameter, Shenoy's parameter, zero shear viscosity, and low-shear viscosity of WMA binders are lower compared to HMA binders. Similarly, the non-recoverable creep compliance of WMA binders is higher at all stress levels compared to HMA binders. This indicates that WMA binders are more susceptible to rutting. Among all the eight binders, CRMB60 is more rut resistant and EVG20 is least rut resistant. Further, Superpave rutting parameter-master curve was developed at 60°C for short-term aged HMA and WMA binders. Over a wide range of frequencies, the master curve of WMA binders is lower compared to HMA binders. This shows that WMA binders are more susceptible to rutting compared to HMA binders.
6. Fatigue-parameter-master-curve was developed at 25°C temperature for long-term aged HMA and WMA binders. Over a wide range of frequencies, the master curve of WMA binders is lower compared to HMA binders. This shows that WMA binders are more resistant to fatigue cracking compared to HMA binders. Based on the ranking of fatigue parameters for long-term aged binders, ECRMB60 is more fatigue resistant and VG20 is least fatigue resistant.
7. From the results of the linear amplitude sweep test, and Glover-Rowe parameter, it can be concluded that WMA binders are more resistant to fatigue cracking compared to HMA binders. With increasing durations of long-term aging, even though all data points are approaching towards the cracking line, the WMA binders are observed to be more resistant to cracking compared to the HMA binders.
8. From the volumetric mix design results of HMA mixtures with and without LDPE-coated aggregates, the presence of LDPE-coated aggregates reduced the binder content by 0.2% for unmodified binders and 0.3% for modified binders.
9. The presence of LDPE-coated coarse aggregate (LCA) in HMA mixtures improved dry indirect tensile strength (ITS), wet ITS, and tensile strength ratio (TSR) at all aging conditions. Thus, HMA mixtures consisting of LCA are more resistant towards moisture damage. The presence of LCA in HMA mixtures also improved the resistance towards permanent deformation.
10. Even though the dry ITS of WMA mixtures is less, there is an increase in wet ITS and TSR at all aging conditions. This shows that WMA mixtures are more resistant towards

moisture damage. However, the WMA mixtures are more susceptible to permanent deformation owing to lower aging potential of WMA binders.

11. The presence of LCA in WMA mixtures had no significant change as the performance of WMA mixtures with LCA is similar to the WMA mixtures without LCA in terms of moisture damage. However, the presence of LCA in WMA mixtures improved the resistance towards permanent deformation.
12. Among all rutting parameters, the low shear viscosity showed stronger and better correlation with rut depth of bituminous mixtures.

7.3 RECOMMENDATIONS

Based on the experimental results obtained from the current study, the following recommendations are made:

- Even though there was an increase in formation of carbonyl and sulfoxide compounds during the production process of warm mix asphalt binders, the increase in binder stiffness of warm mix asphalt binders is lower than that of the hot mix asphalt binders. Thus, it is recommended to adopted 30 minutes mixing time during the production process of warm mix asphalt binders.

- The performance of CRMB60 and ECRMB60 binders are superior in terms of resistance towards rutting and fatigue cracking, respectively followed by PMB40 binders. Thus, CRMB60 binder is recommended for bituminous wearing courses consisting of bituminous concrete mixtures. For lowering the production temperatures at bituminous mixing plants and to achieve better performance of bituminous mixtures, it is recommended to use CRMB60 binder blended with Evotherm additive.

- The addition of waste plastic in dry process to whole fraction of preheated aggregates results in formation of small lumps which lead to underperformance of bituminous mixtures. Thus, it is recommended to initially introduce the shredded waste plastic to preheated coarse aggregates followed by the addition of fine aggregates and the binder. The presence of LDPE waste plastic coated coarse aggregate in the bituminous mixtures along with Evotherm additive improves the resistance towards moisture damage and rutting. This in turn also reduces the required binder content by 0.2% for unmodified binders and 0.3% for modified binders. Thus, for better performance of wearing courses consisting of bituminous concrete mixtures, it is recommended to use LDPE waste plastic coated coarse aggregate and CRMB60 binder blended with Evotherm additive.

- The low shear viscosity resulted in best correlation with rut depth that was observed to be independent of frequency unlike other rutting parameters that were observed to be dependent on frequency or applied stress levels. Thus, the low shear viscosity is recommended as the best rutting performance indicator for the selection of a particular type of bituminous binder.

7.4 SCOPE FOR FURTHER STUDY

The current study can be extended further by taking into account the following points:

- In the entire experimental work, bituminous mixture specimens were prepared using granite aggregates sourced from a single location with one single gradation of aggregates. The performance characteristics of bituminous mixtures vary with the source of aggregates and there is a need to evaluate other types of aggregates that are widely used for construction of bituminous layers in India. Similarly, there is a need to evaluate the performance of bituminous mixtures with other gradations such as gap-gradation, and open-gradation with different filler types and proportions.

- Only LDPE waste plastic was used in this study. The use of other compatible waste plastics such as HDPE can be explored for further performance and durability studies. Only one chemical warm mix additive was used in this study. The influence of other types of warm mix technologies such as foaming technologies and organic additives can be explored for future studies. At the same time, the performance of WMA mixtures consisting of aggregates coated with other compatible waste plastics can be explored. Further, there is a need to evaluate the influence of production parameters (mixing temperature, mixing rate, mixing duration) on the relative performance and chemical changes in WMA binders. Further, usage of RAP materials with different characteristics in WMA mixtures can be compared with plastic incorporated WMA mixtures.

- The binder rheological parameters were correlated with permanent deformation in bituminous mixtures. Similarly, there is a need to correlate the rheological properties of binders with its chemical properties. The recovered binders from differently aged WMA mixtures can have different performance characteristics compared to direct WMA binder aging and there is a need to relate the performance characteristics of such binders. Further, there is a need to evaluate the performance of binders extracted from HMA and WMA mixtures containing waste plastics to explore the possible interactions between waste plastic and bituminous binders.

APPENDIX A

A.1 Spectra at unaged condition

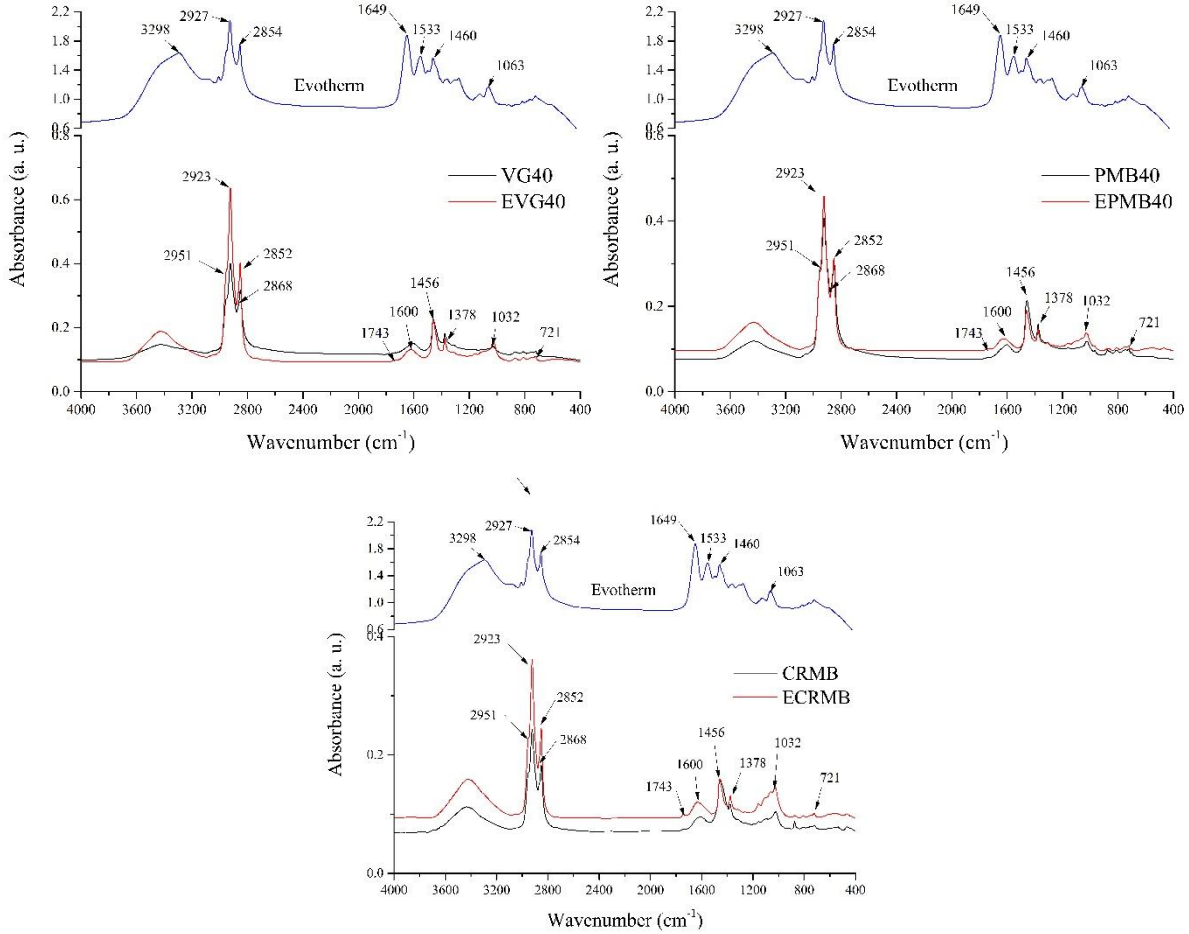
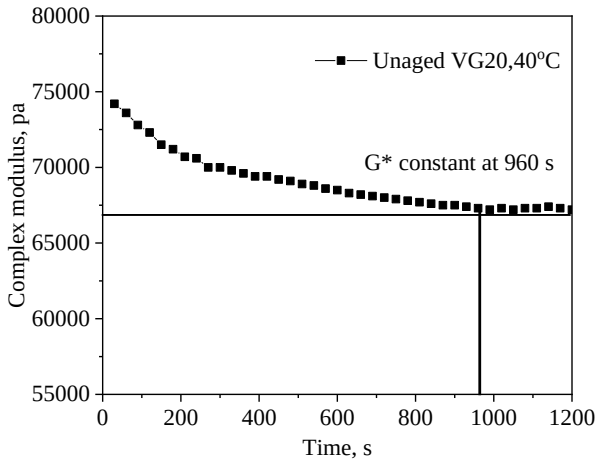
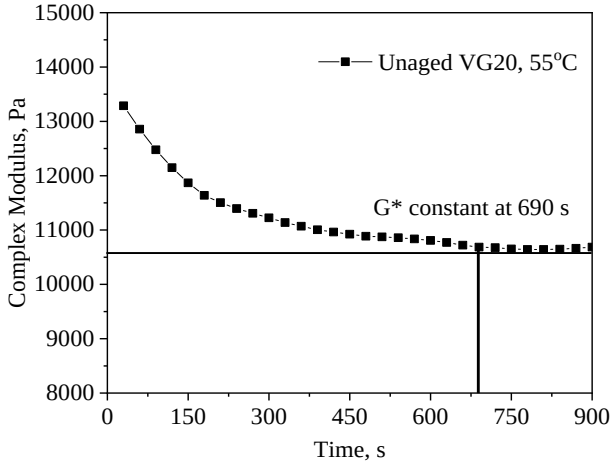


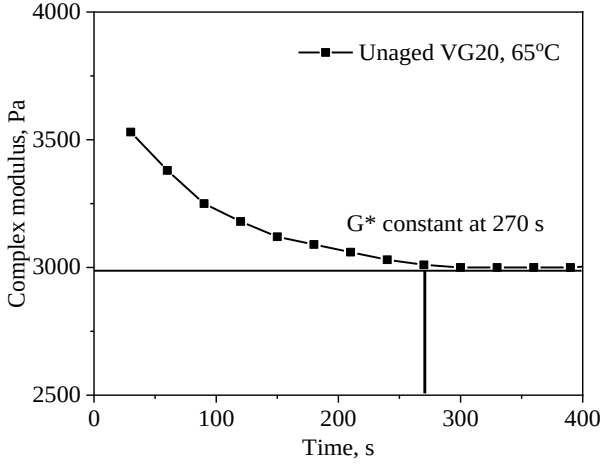
Fig. A.1 Spectra of HMA and WMA binders at unaged condition

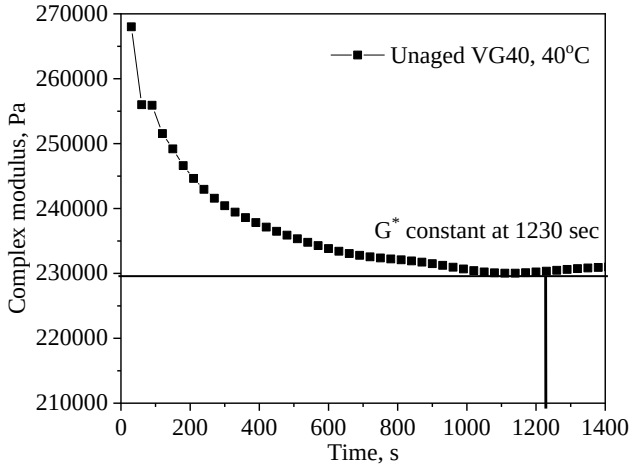
APPENDIX B

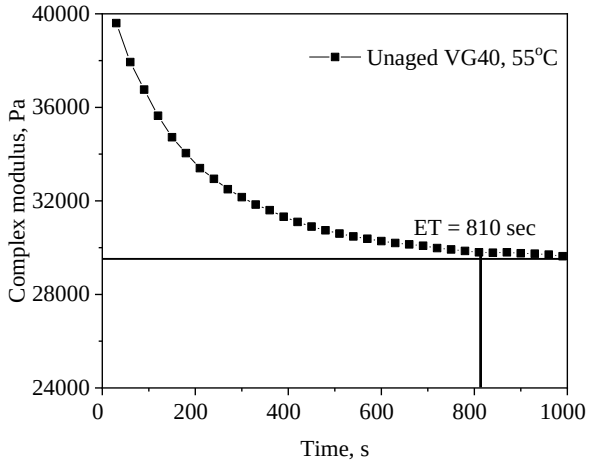
B.1 Time for thermal equilibrium control binders

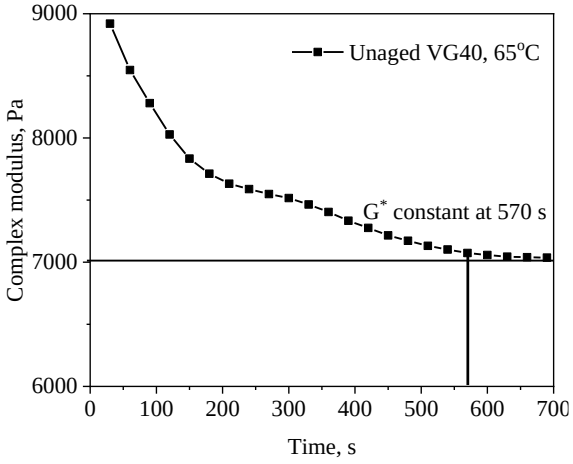


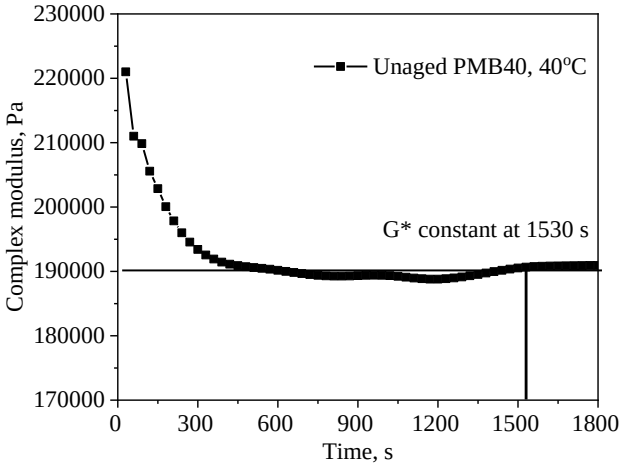


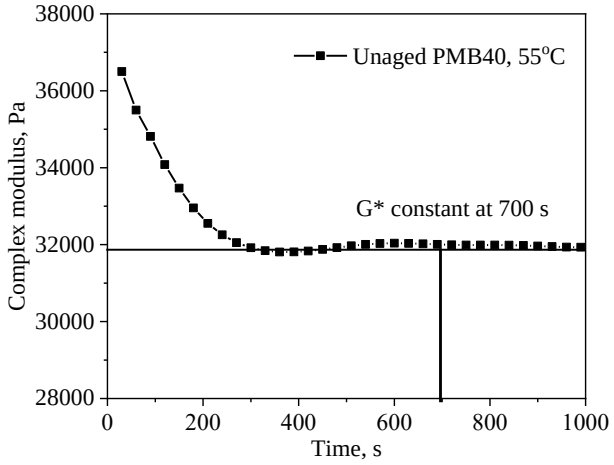


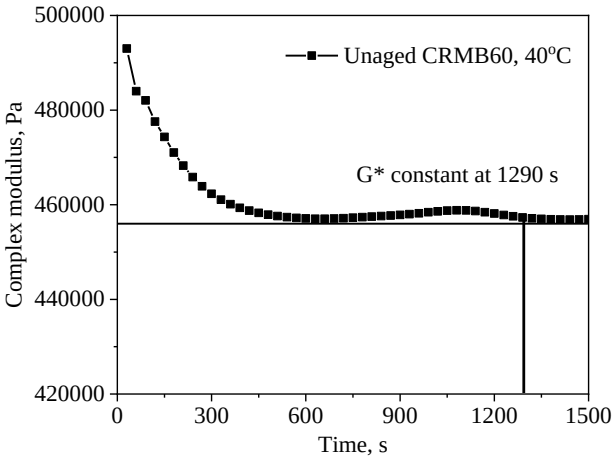


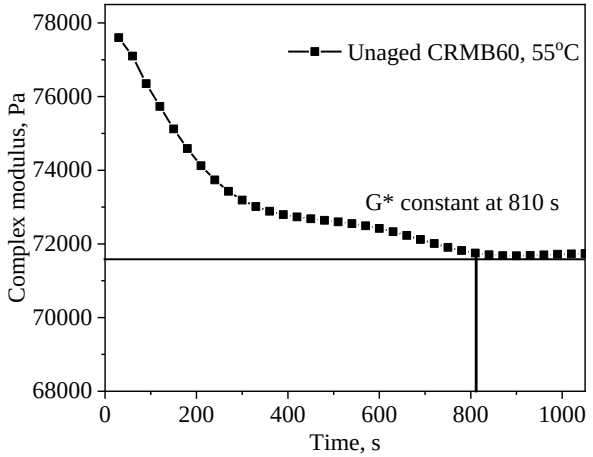


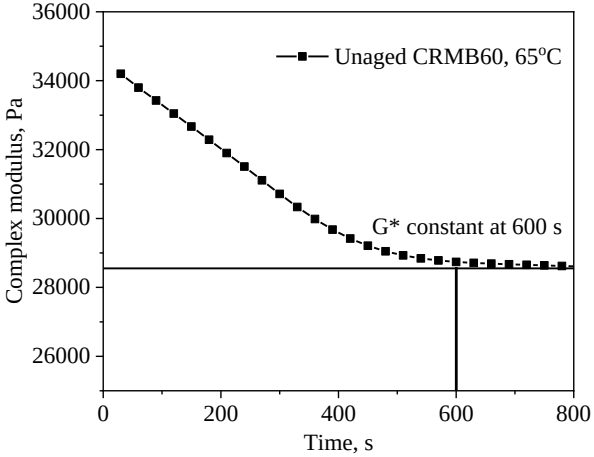


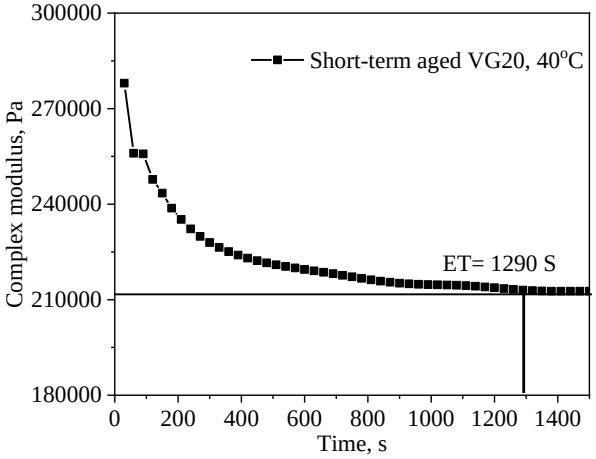

Unaged PMB40, 40°C
G* constant at 1530 s
Complex modulus, Pa
Time, s

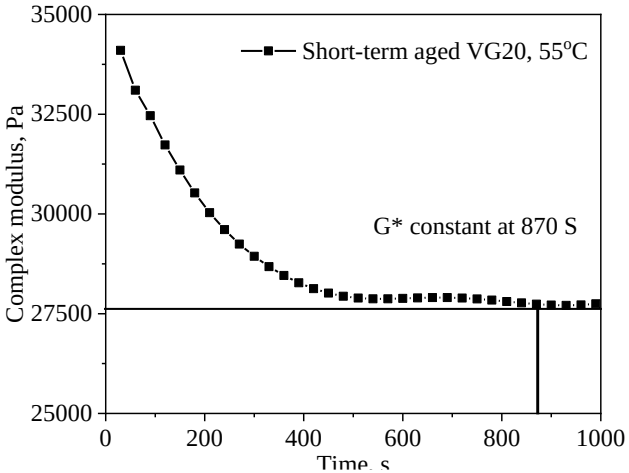

Unaged PMB40, 55°C
G* constant at 700 s
Complex modulus, Pa
Time, s

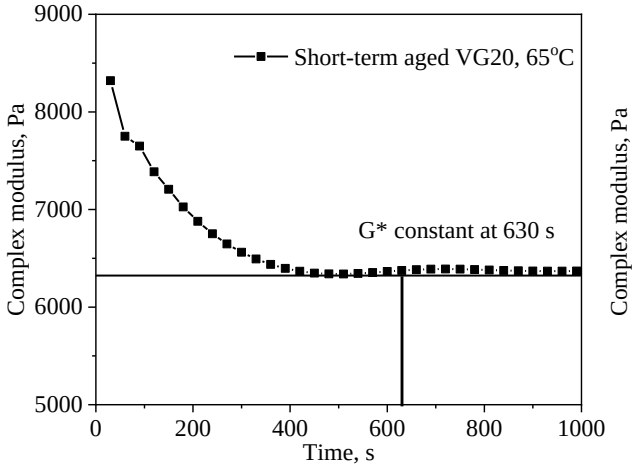

Unaged CRMB60, 40°C
G* constant at 1290 s
Complex modulus, Pa
Time, s

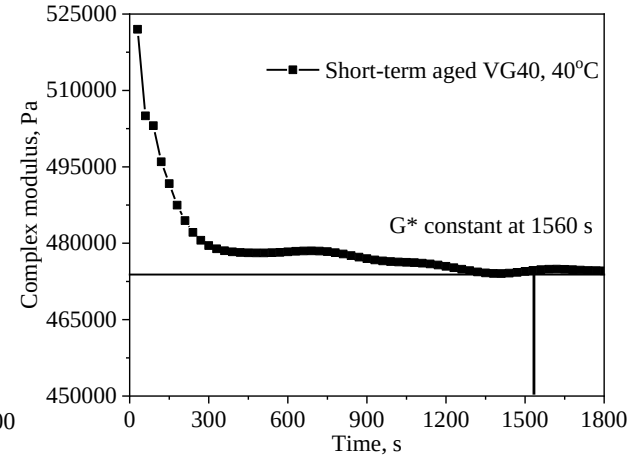

Unaged CRMB60, 55°C
G* constant at 810 s
Complex modulus, Pa
Time, s

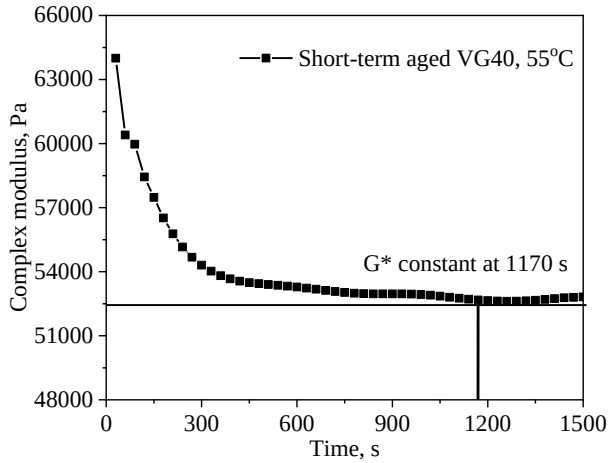

Unaged CRMB60, 65°C
G* constant at 600 s
Complex modulus, Pa
Time, s

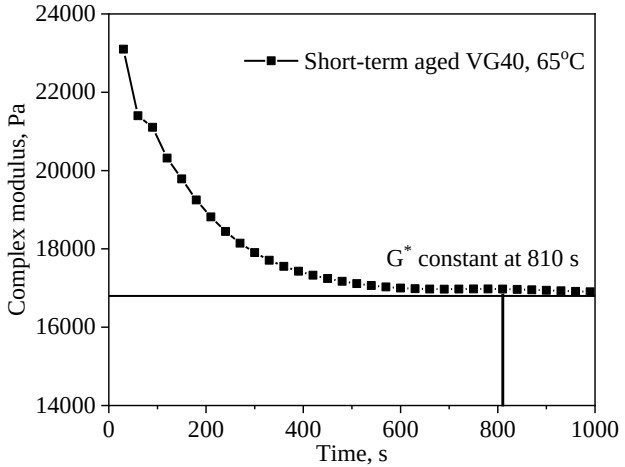

Short-term aged VG20, 40°C
ET= 1290 S
Complex modulus, Pa
Time, s

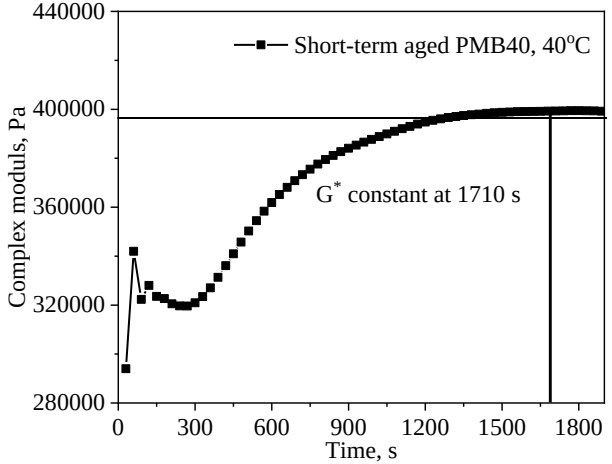

Short-term aged VG20, 55°C
G* constant at 870 S
Complex modulus, Pa
Time, s

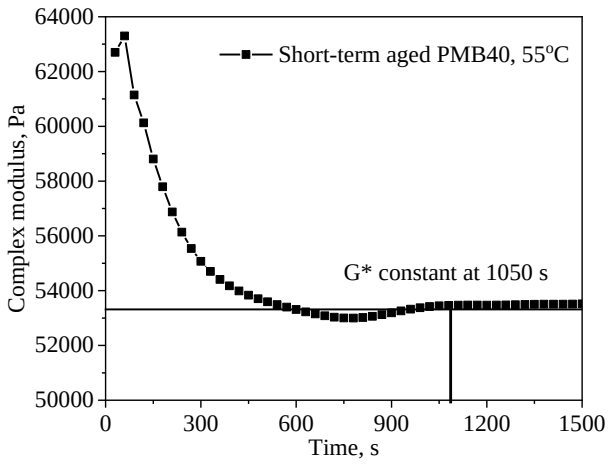

Short-term aged VG20, 65°C
G* constant at 630 s
Complex modulus, Pa
Time, s

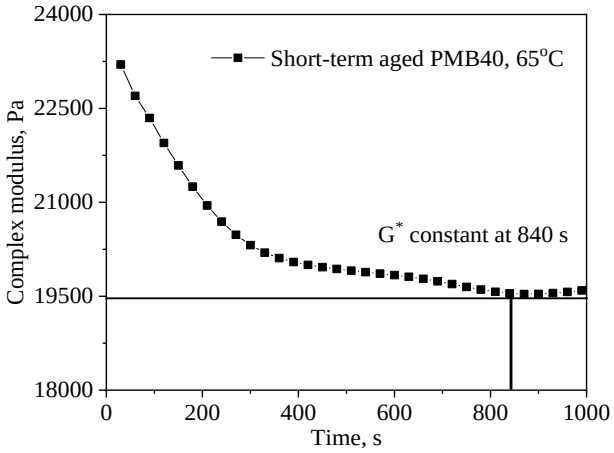

Short-term aged VG40, 40°C
G* constant at 1560 s
Complex modulus, Pa
Time, s

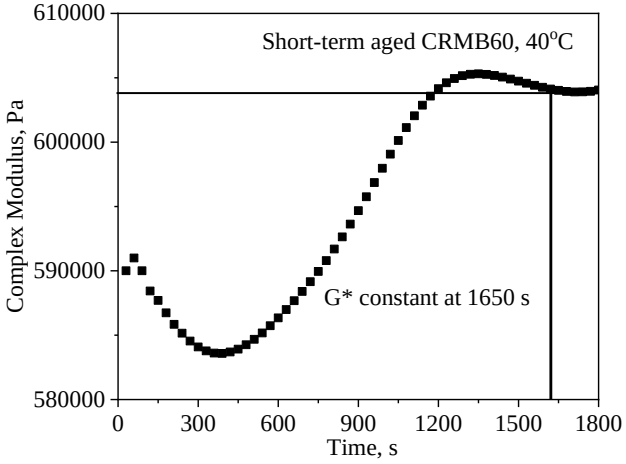

Short-term aged VG40, 55°C
G* constant at 1170 s
Complex modulus, Pa
Time, s

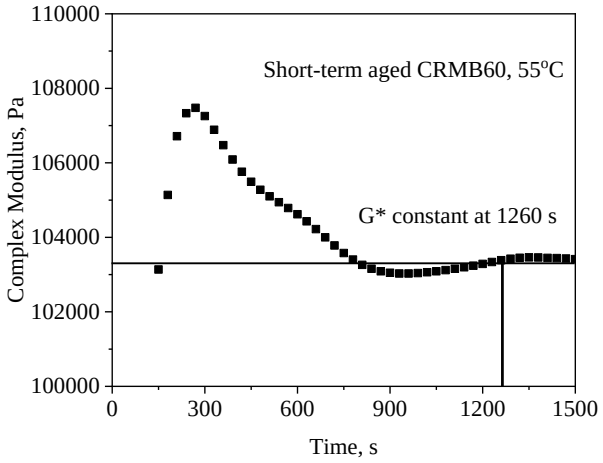

Short-term aged VG40, 65°C
G* constant at 810 s
Complex modulus, Pa
Time, s

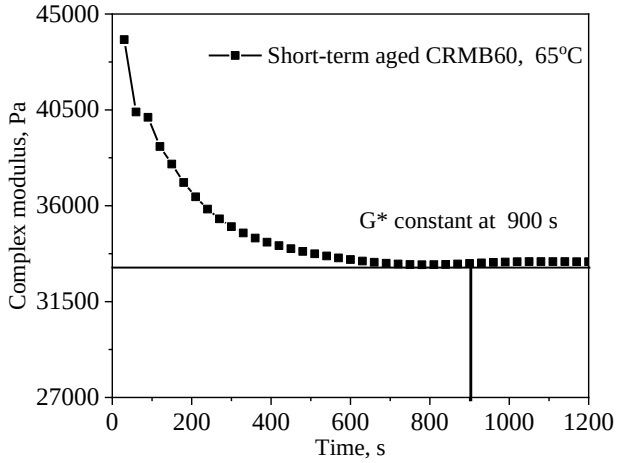

Short-term aged PMB40, 40°C
G* constant at 1710 s
Complex moduls, Pa
Time, s

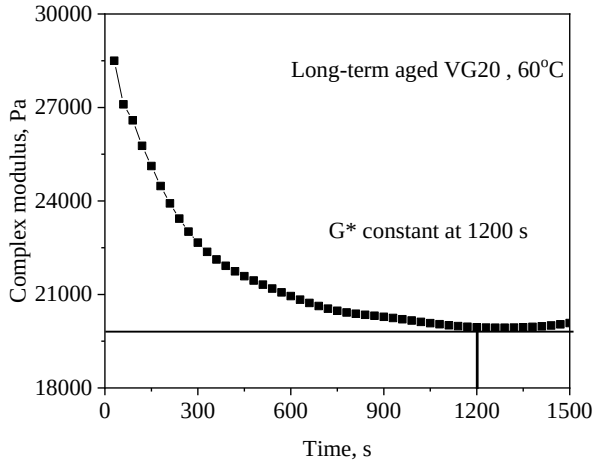

Short-term aged PMB40, 55°C
G* constant at 1050 s
Complex modulus, Pa
Time, s

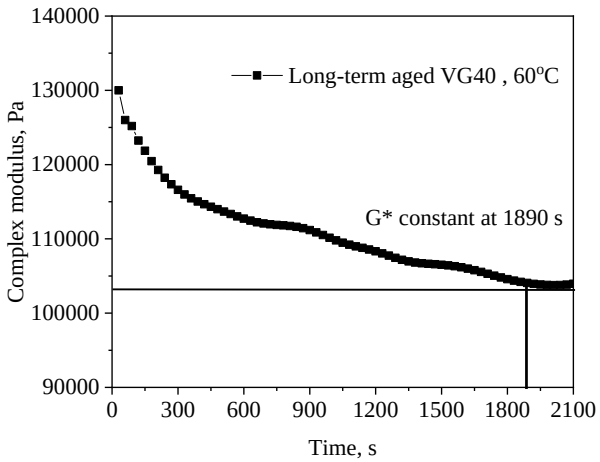

Short-term aged PMB40, 65°C
G* constant at 840 s
Complex modulus, Pa
Time, s

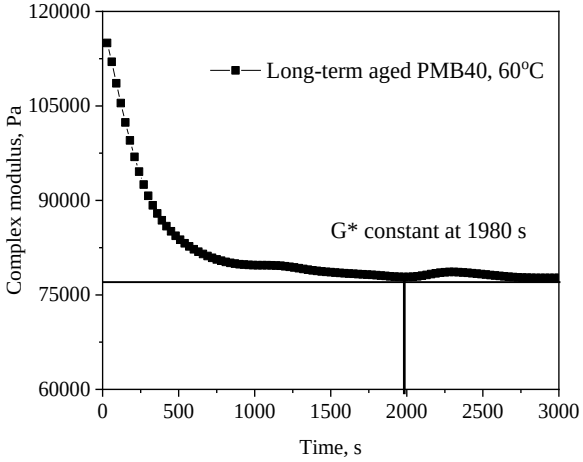

Short-term aged CRMB60, 40°C
G* constant at 1650 s
Complex Modulus, Pa
Time, s

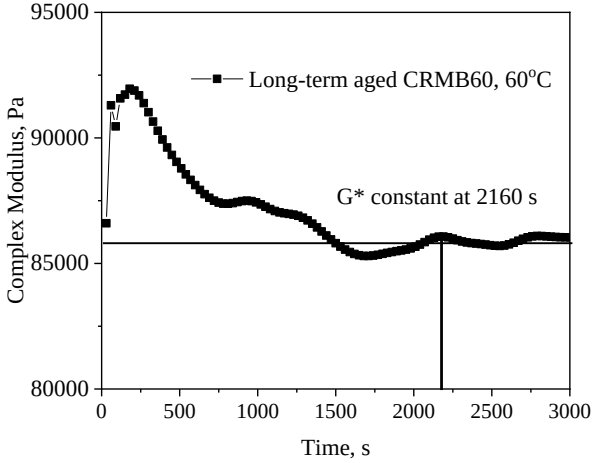

Short-term aged CRMB60, 55°C
G* constant at 1260 s
Complex Modulus, Pa
Time, s


Short-term aged CRMB60, 65°C
G* constant at 900 s
Complex modulus, Pa
Time, s

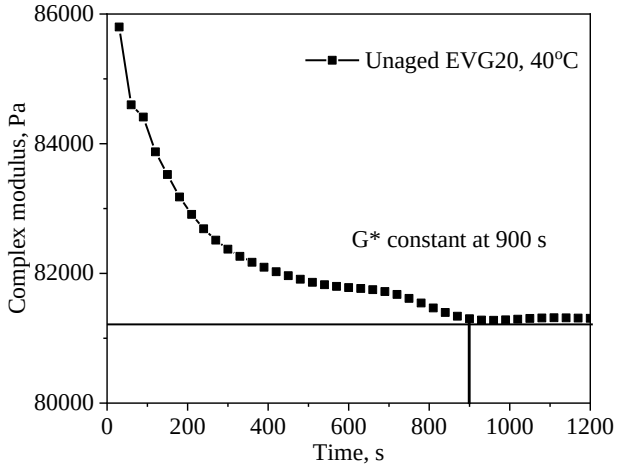

Long-term aged VG20 , 60°C
G* constant at 1200 s
Complex modulus, Pa
Time, s

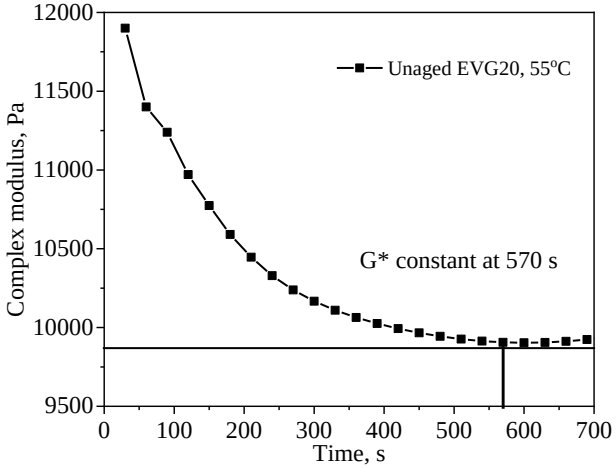


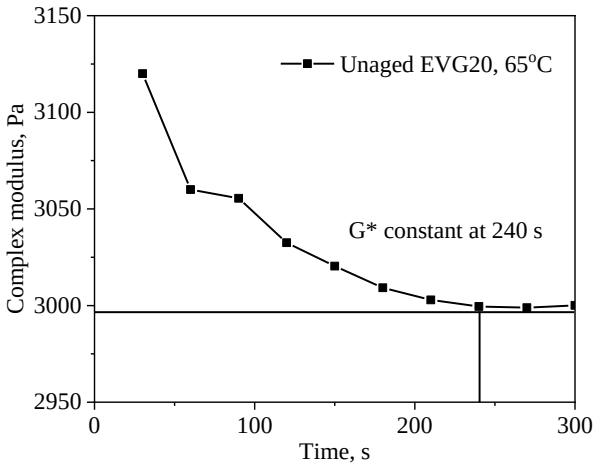


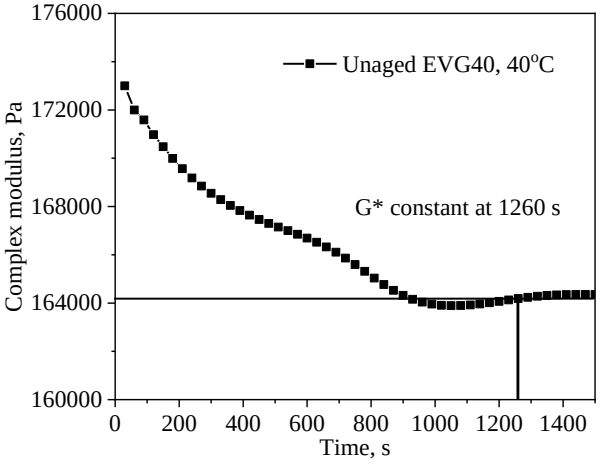


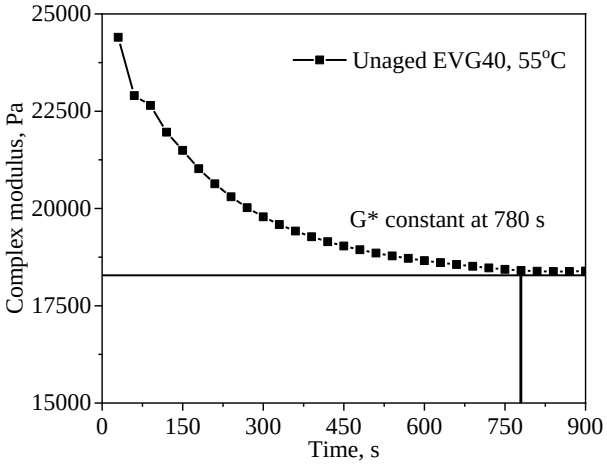
B.2 Time for thermal equilibrium for Evotherm-modified binders

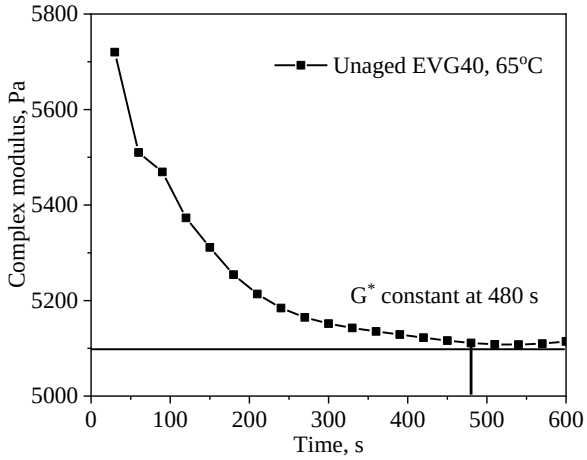


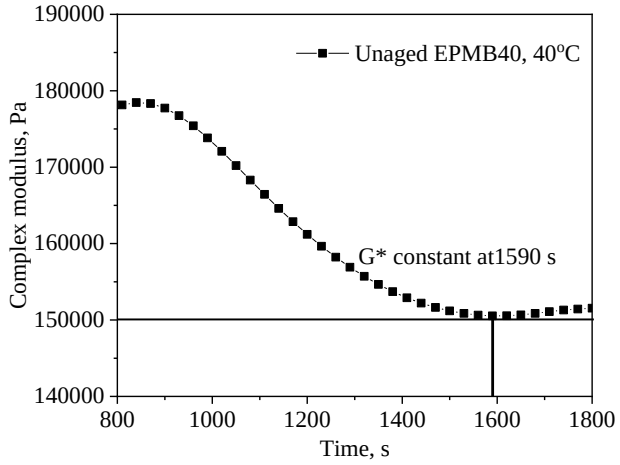


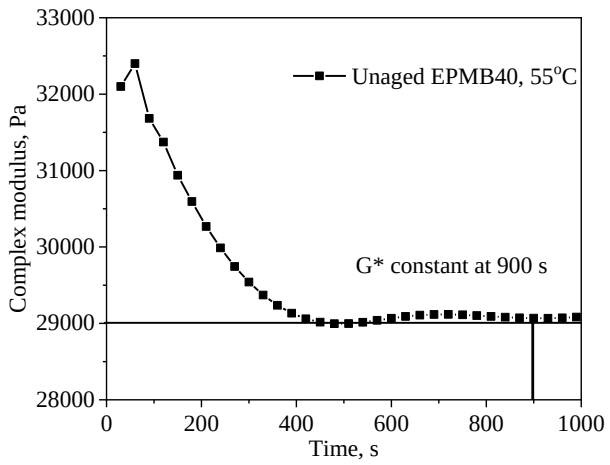


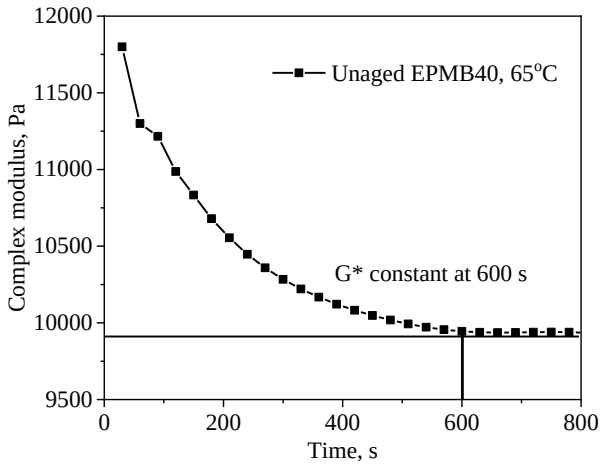

Unaged EVG40, 40°C
G* constant at 1260 s
Complex modulus, Pa
Time, s

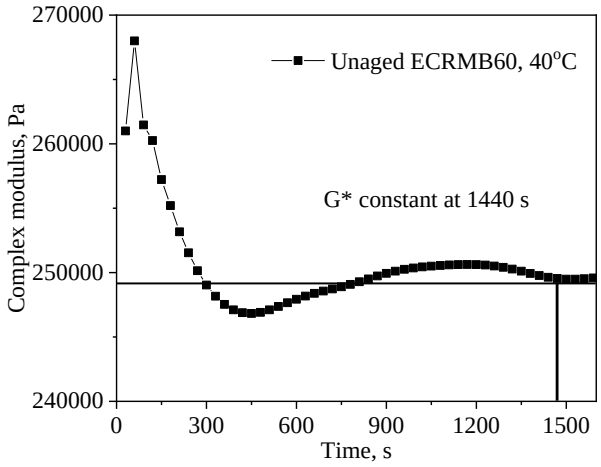

Unaged EVG40, 55°C
G* constant at 780 s
Complex modulus, Pa
Time, s

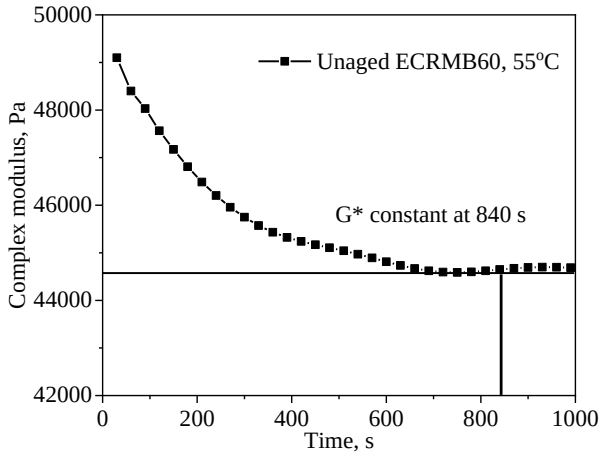

Unaged EVG40, 65°C
G* constant at 480 s
Complex modulus, Pa
Time, s

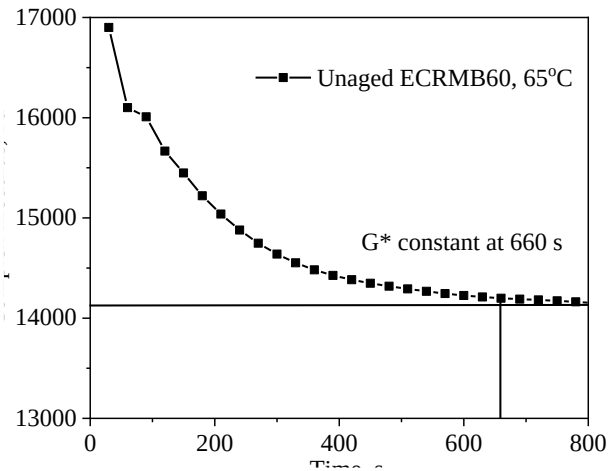

Unaged EPMB40, 40°C
G* constant at1590 s
Complex modulus, Pa
Time, s

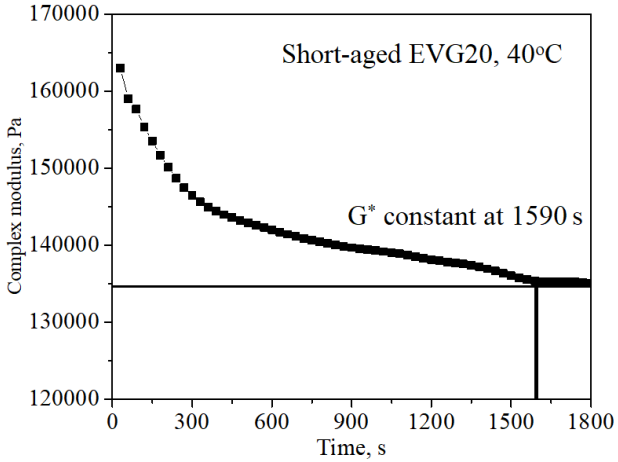

Unaged EPMB40, 55°C
G* constant at 900 s
Complex modulus, Pa
Time, s

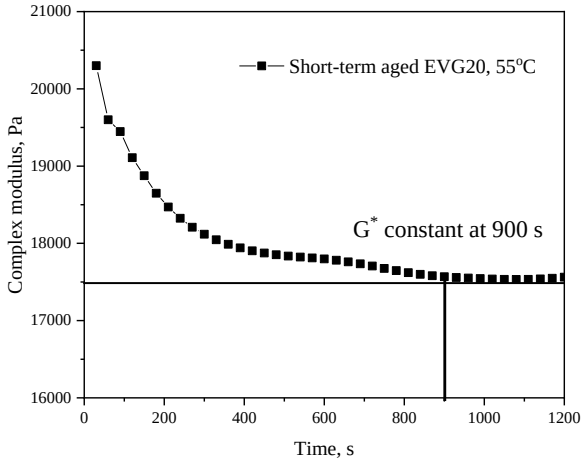

Unaged EPMB40, 65°C
G* constant at 600 s
Complex modulus, Pa
Time, s

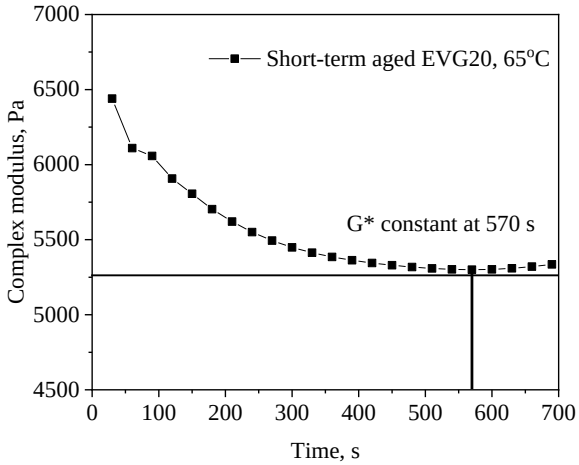

Unaged ECRMB60, 40°C
G* constant at 1440 s
Complex modulus, Pa
Time, s

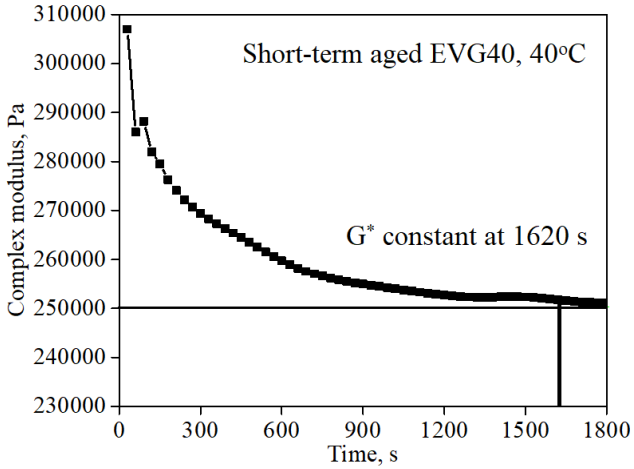

Unaged ECRMB60, 55°C
G* constant at 840 s
Complex modulus, Pa
Time, s

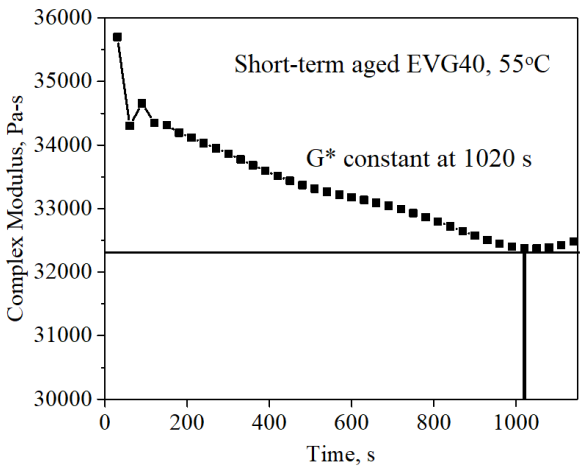

Unaged ECRMB60, 65°C
G* constant at 660 s

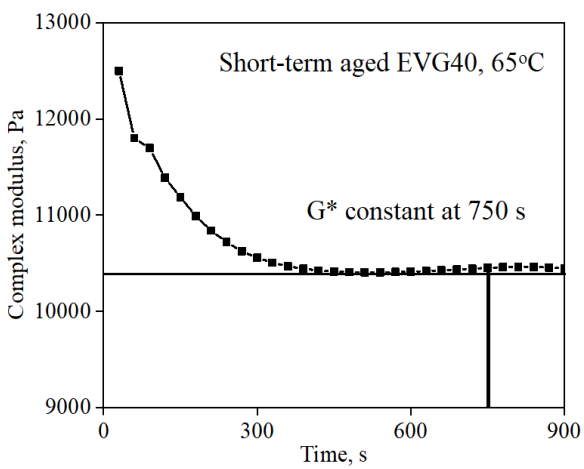

Short-aged EVG20, 40°C
G* constant at 1590 s
Complex modulus, Pa
Time, s

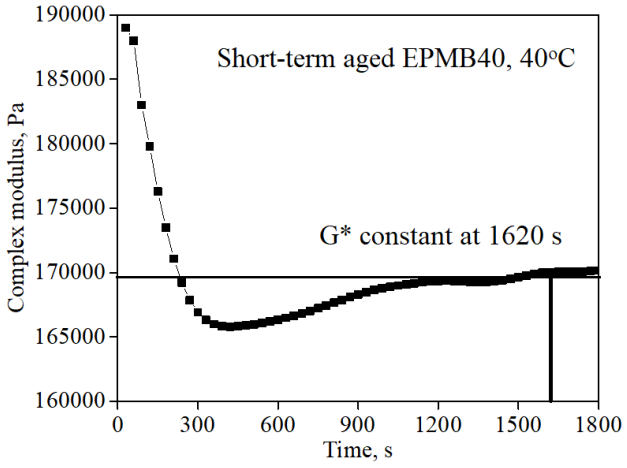

Short-term aged EVG20, 55°C
G* constant at 900 s
Complex modulus, Pa
Time, s

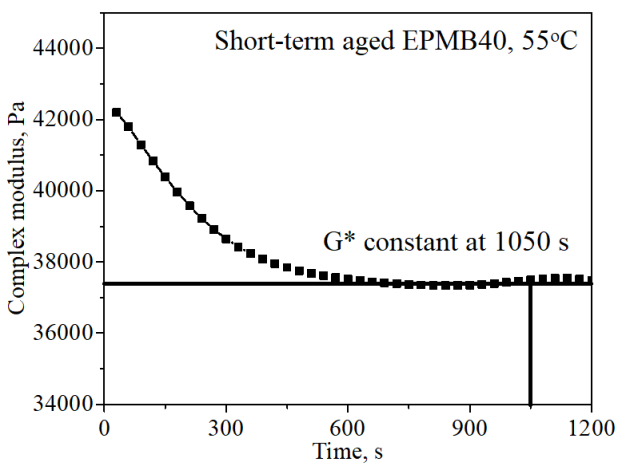

Short-term aged EVG20, 65°C
G* constant at 570 s
Complex modulus, Pa
Time, s

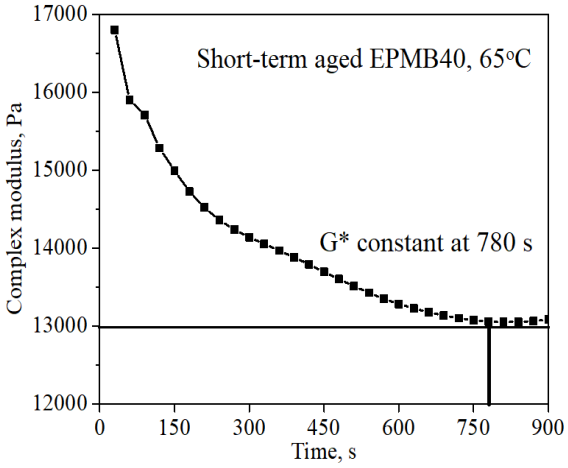

Short-term aged EVG40, 40°C
G* constant at 1620 s
Complex modulus, Pa
Time, s

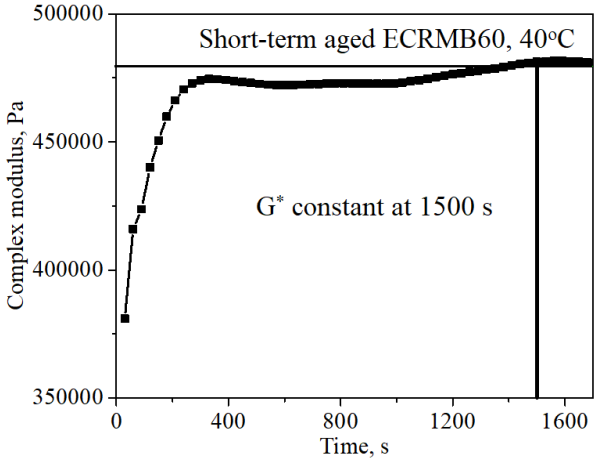

Short-term aged EVG40, 55°C
G* constant at 1020 s
Complex Modulus, Pa-s
Time, s

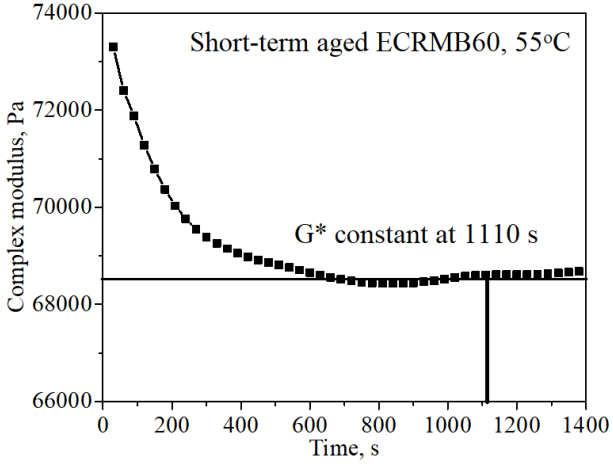

Short-term aged EVG40, 65°C
G* constant at 750 s
Complex modulus, Pa
Time, s

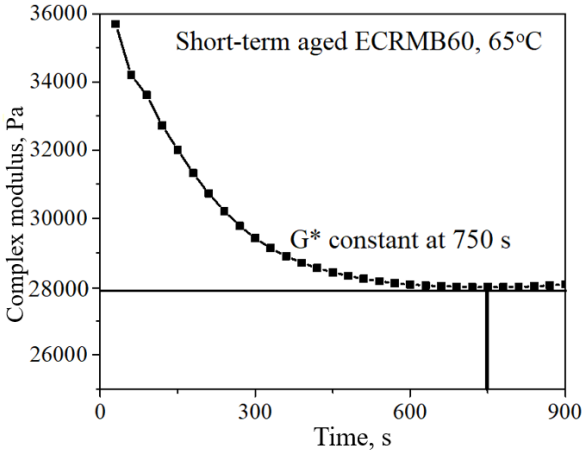

Short-term aged EPMB40, 40°C
G* constant at 1620 s
Complex modulus, Pa
Time, s

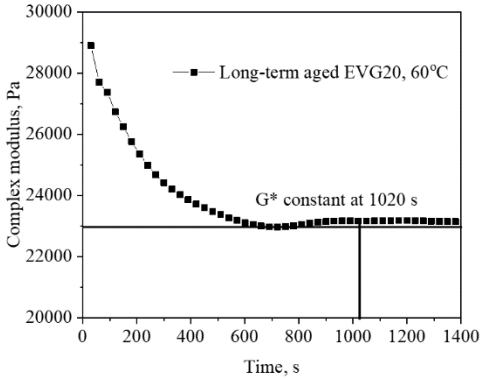

Short-term aged EPMB40, 55°C
G* constant at 1050 s
Complex modulus, Pa
Time, s

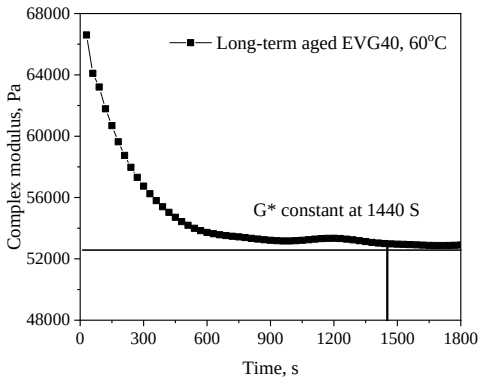

Short-term aged EPMB40, 65°C
G* constant at 780 s
Complex modulus, Pa
Time, s

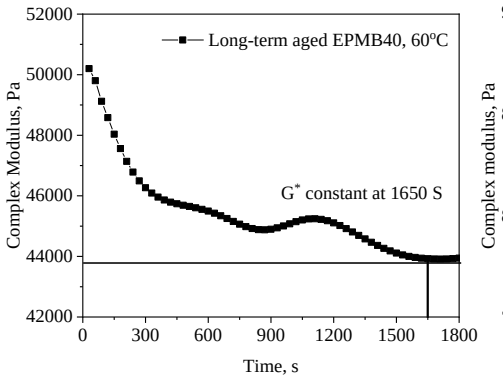

Short-term aged ECRMB60, 40°C
G* constant at 1500 s
Complex modulus, Pa
Time, s

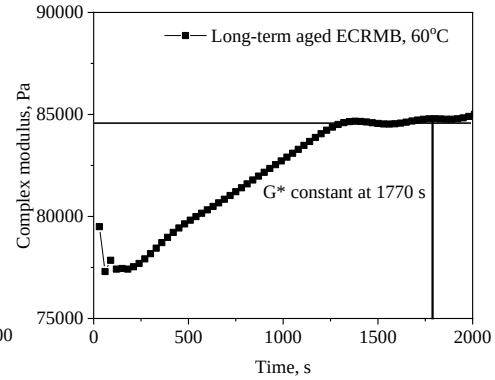

Short-term aged ECRMB60, 55°C
G* constant at 1110 s
Complex modulus, Pa
Time, s


Short-term aged ECRMB60, 65°C
G* constant at 750 s
Complex modulus, Pa
Time, s


Long-term aged EVG20, 60°C
G* constant at 1020 s
Complex modulus, Pa
Time, s


Long-term aged EVG40, 60°C
G* constant at 1440 S
Complex modulus, Pa
Time, s


Long-term aged EPMB40, 60°C
G* constant at 1650 S
Complex Modulus, Pa
Time, s


Long-term aged ECRMB, 60°C
G* constant at 1770 s
Complex modulus, Pa
Time, s

B.3 Influence of Evotherm on thermal Equilibrium time at unaged condition

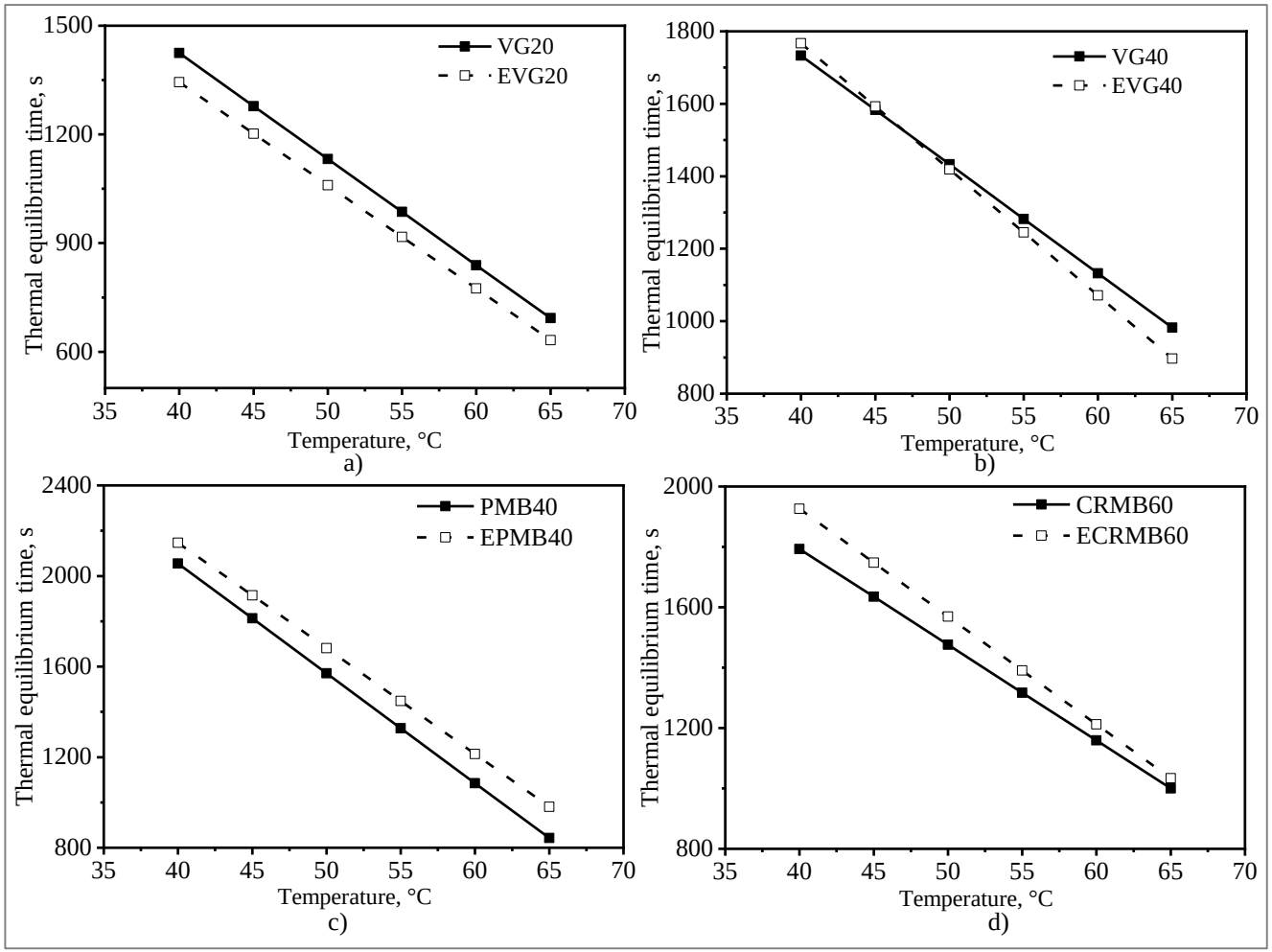


Fig. B.3 Variation of thermal equilibrium time as function of temperature between control and Evotherm modified binders at unaged condition

B.4 Influence of Evotherm on thermal Equilibrium time at Short-term aged condition

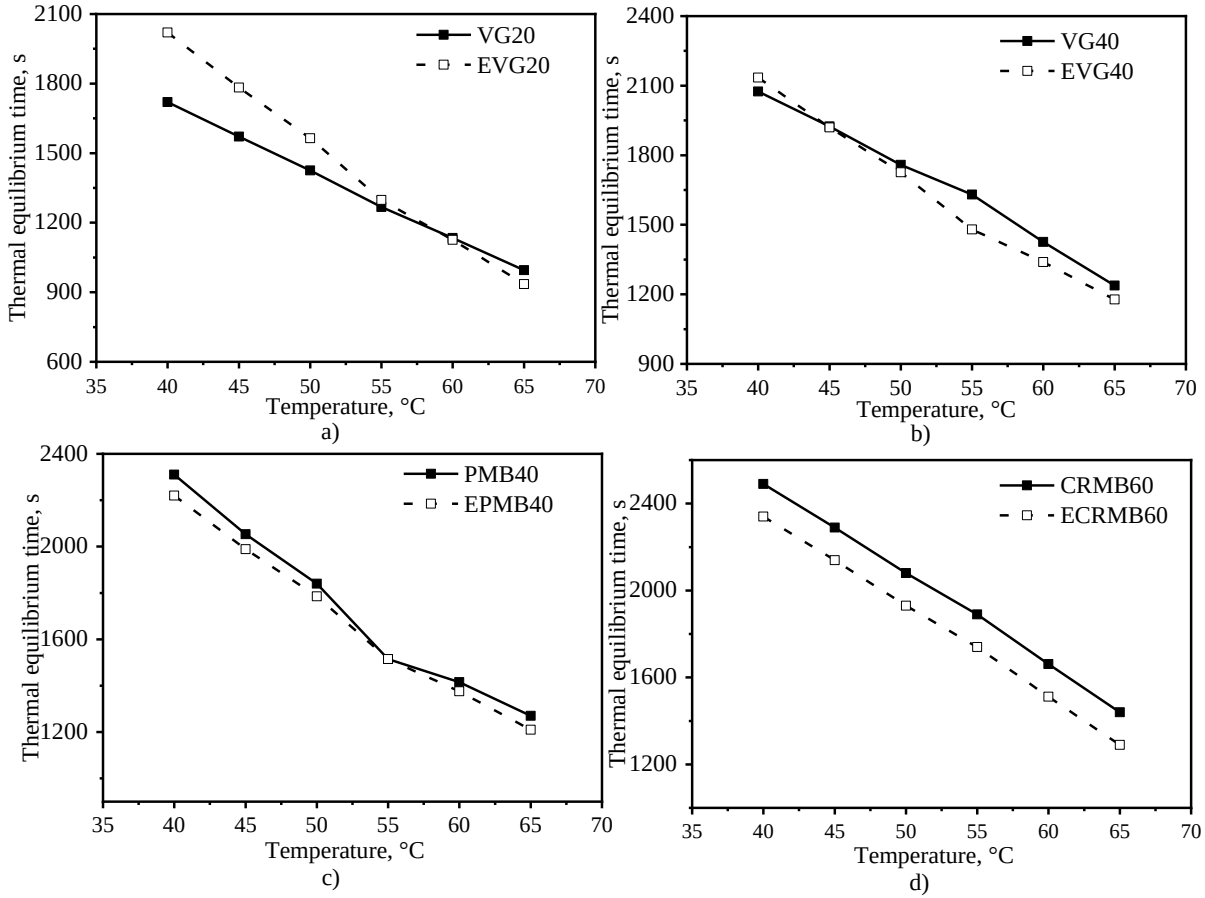
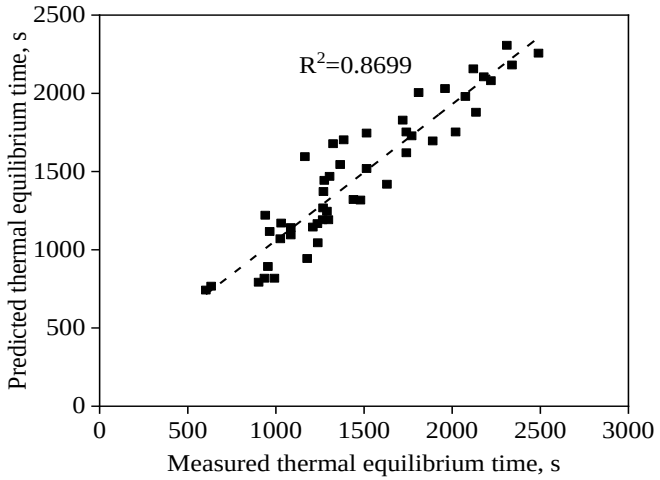
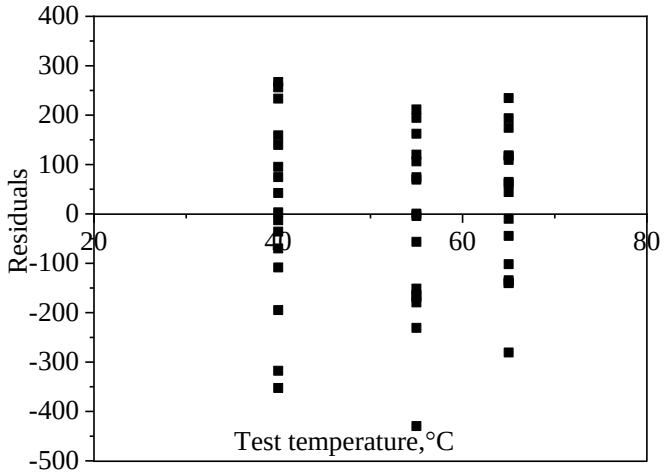


Fig. B.4 Influence of Evotherm on thermal equilibrium time on short-term aged control and Evotherm modified bituminous binders

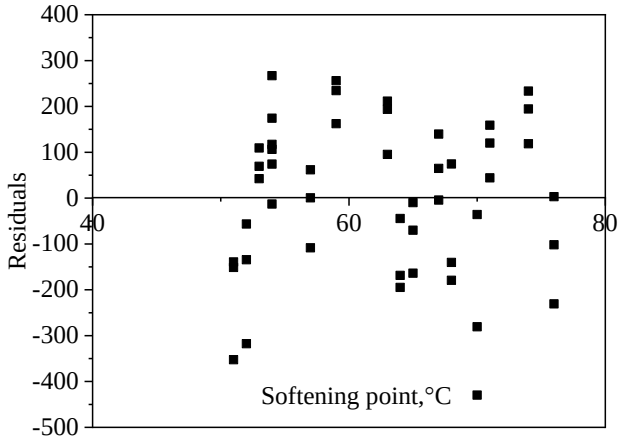
B.5 Development of model on equilibrium time



(a)



(b)



(c)

Fig. B.5 (a) Predicted thermal equilibrium time vs. measured thermal equilibrium time, (b) Residual plot for test temperature, and (c) Residual plot for softening point

B.6 Superpave rutting parameter

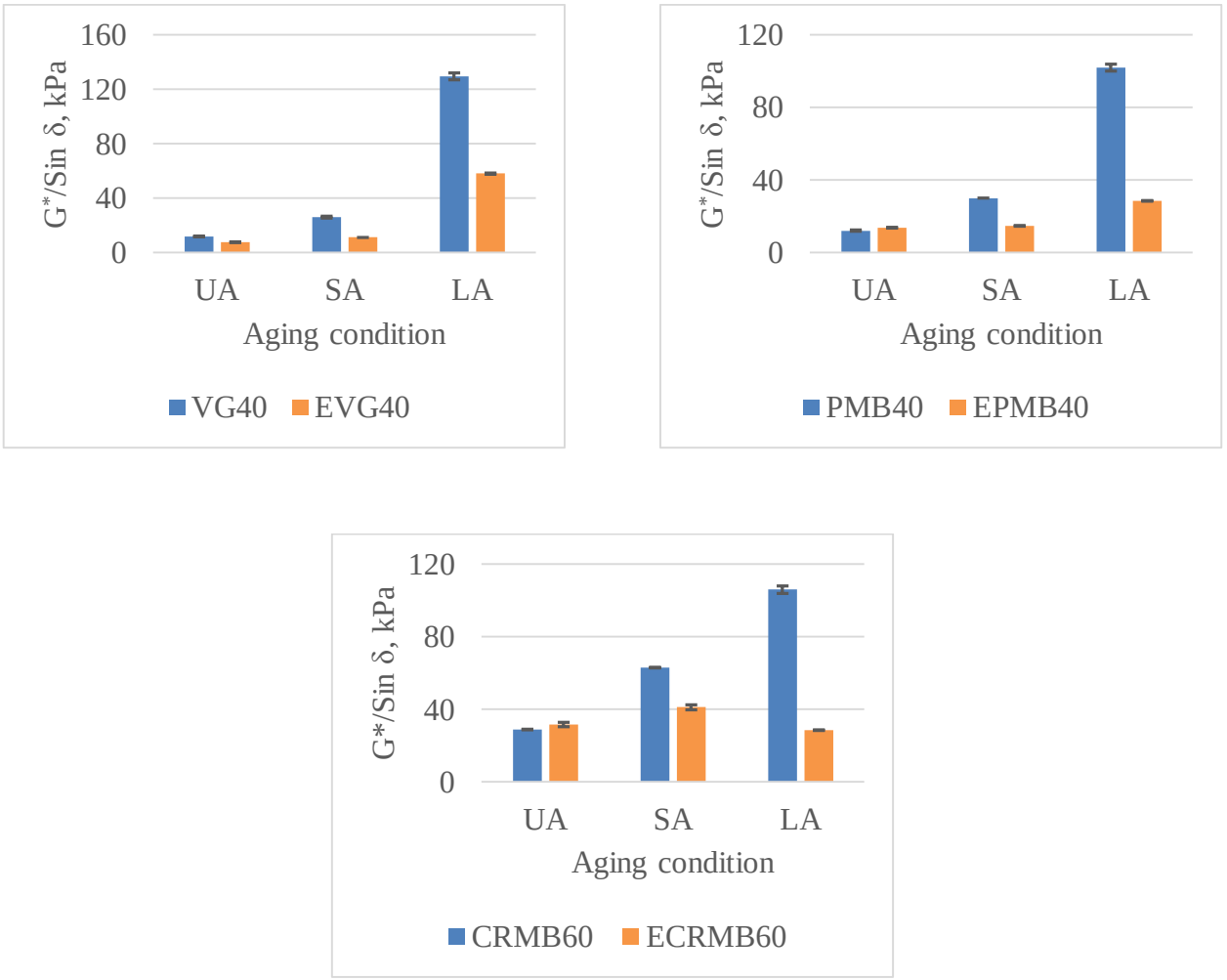


Fig. B.6 superpave rutting parameter of control and Evotherm-modified bituminous binders

B.7 Shenoy's parameter

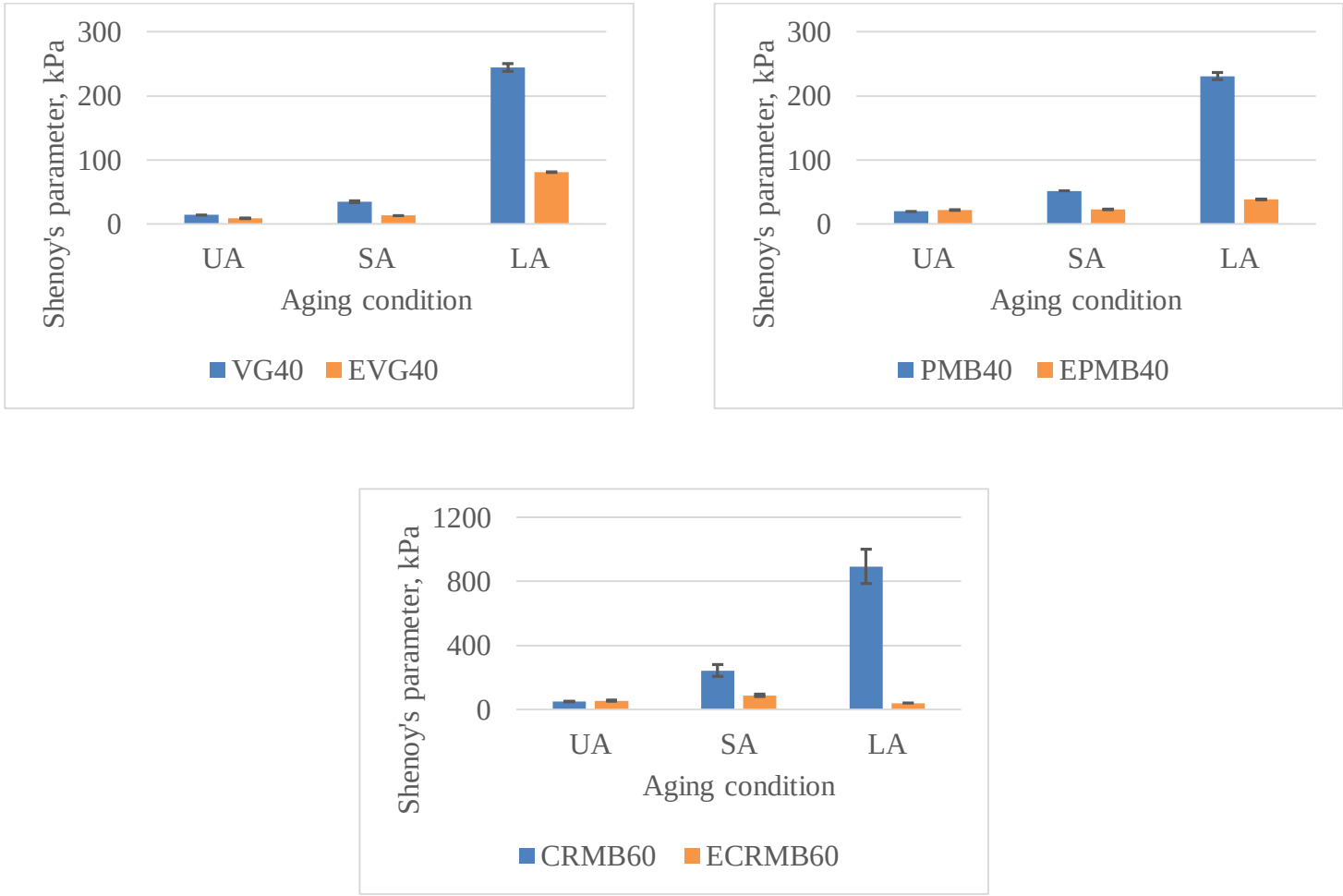


Fig. B.7 Shenoy's Parameter of control and Evotherm-modified bituminous binders

B.8 Non-recoverable creep compliance at unaged condition

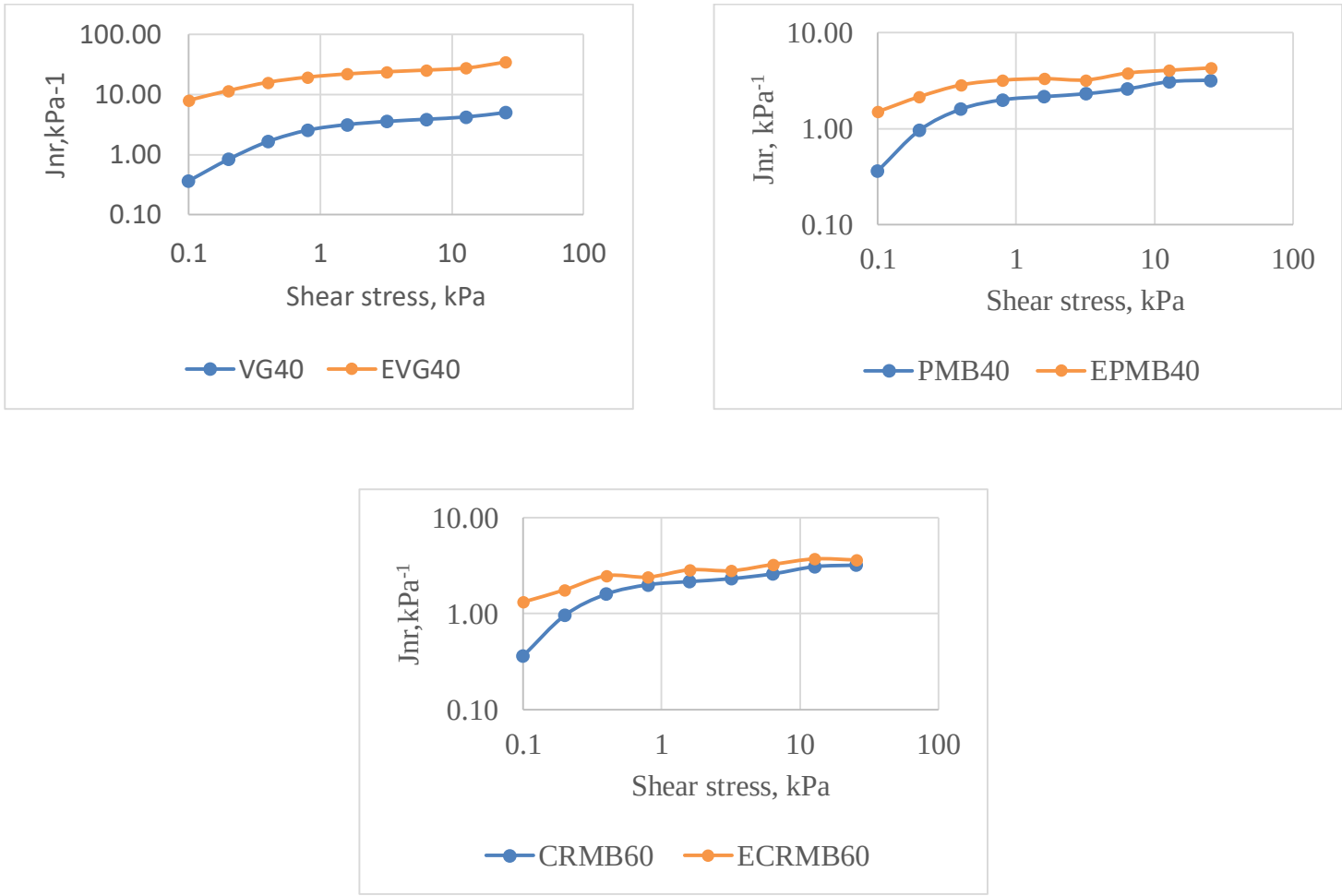
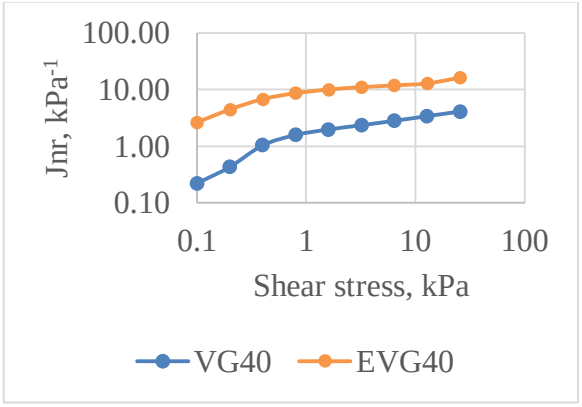
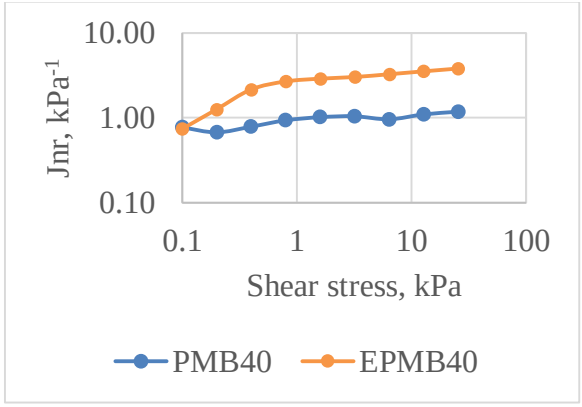


Fig. B.8 Non-recoverable creep compliance of control and Evotherm-modified bituminous binder at unaged condition

B.9 Non-recoverable creep compliance at Short-term aged condition





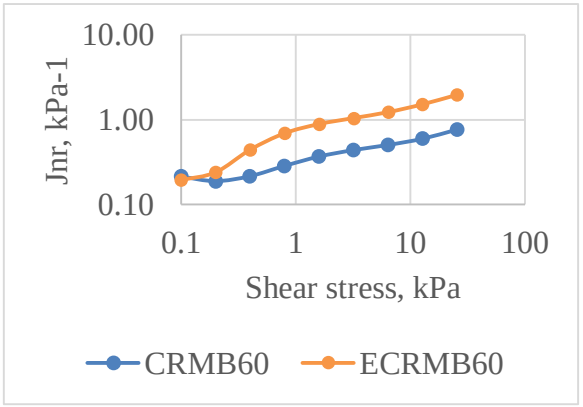


Fig. B.9 Non-recoverable creep compliance of control and Evotherm-modified bituminous binder at short-term aged condition

B.10 Non-recoverable creep compliance at Long-term aged condition

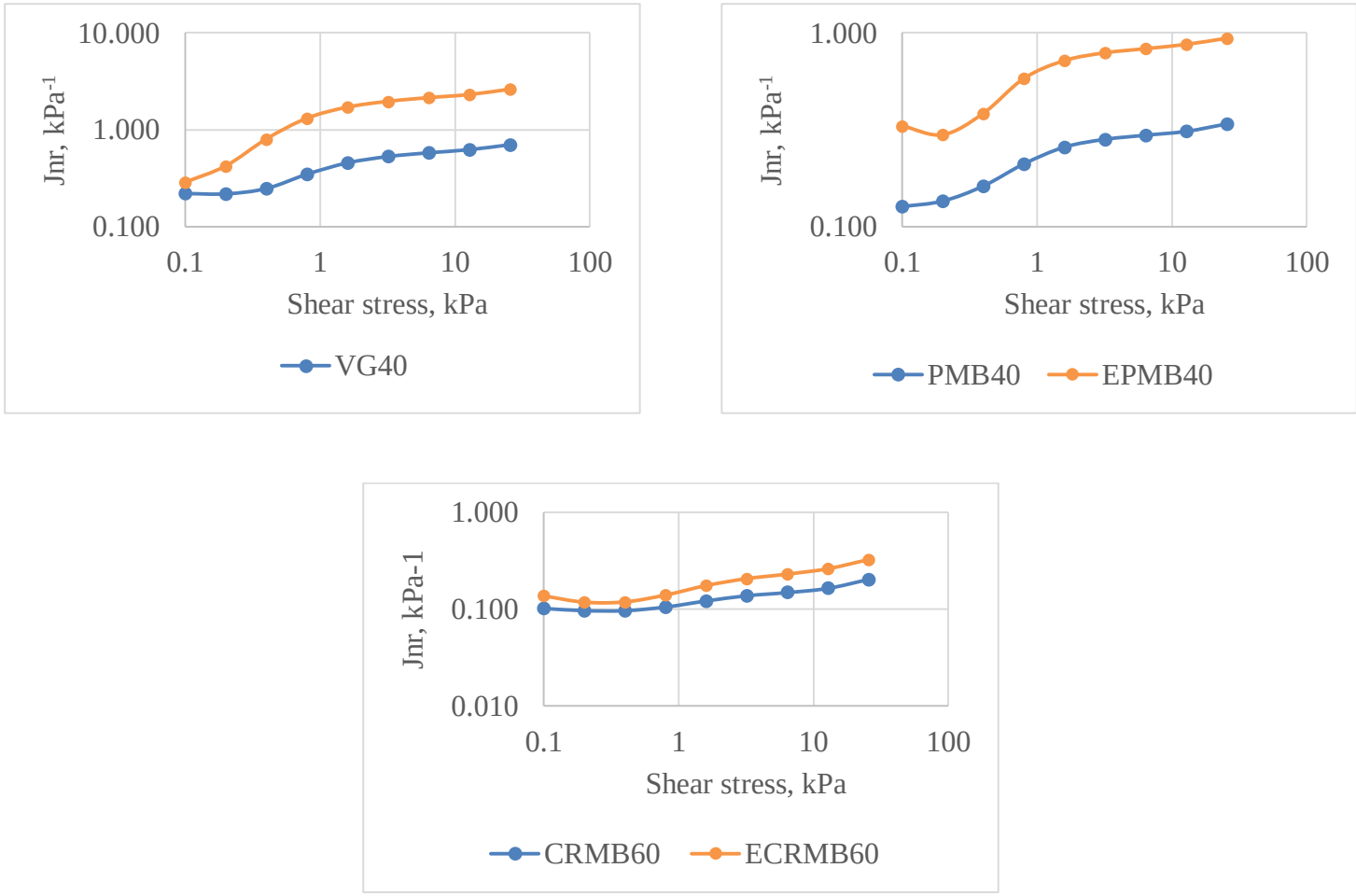


Fig. B.10 Non-recoverable creep compliance of control and Evotherm-modified bituminous binder at long-term aged condition

B.11 Zero shear Viscosity at unaged and short-term aged condition

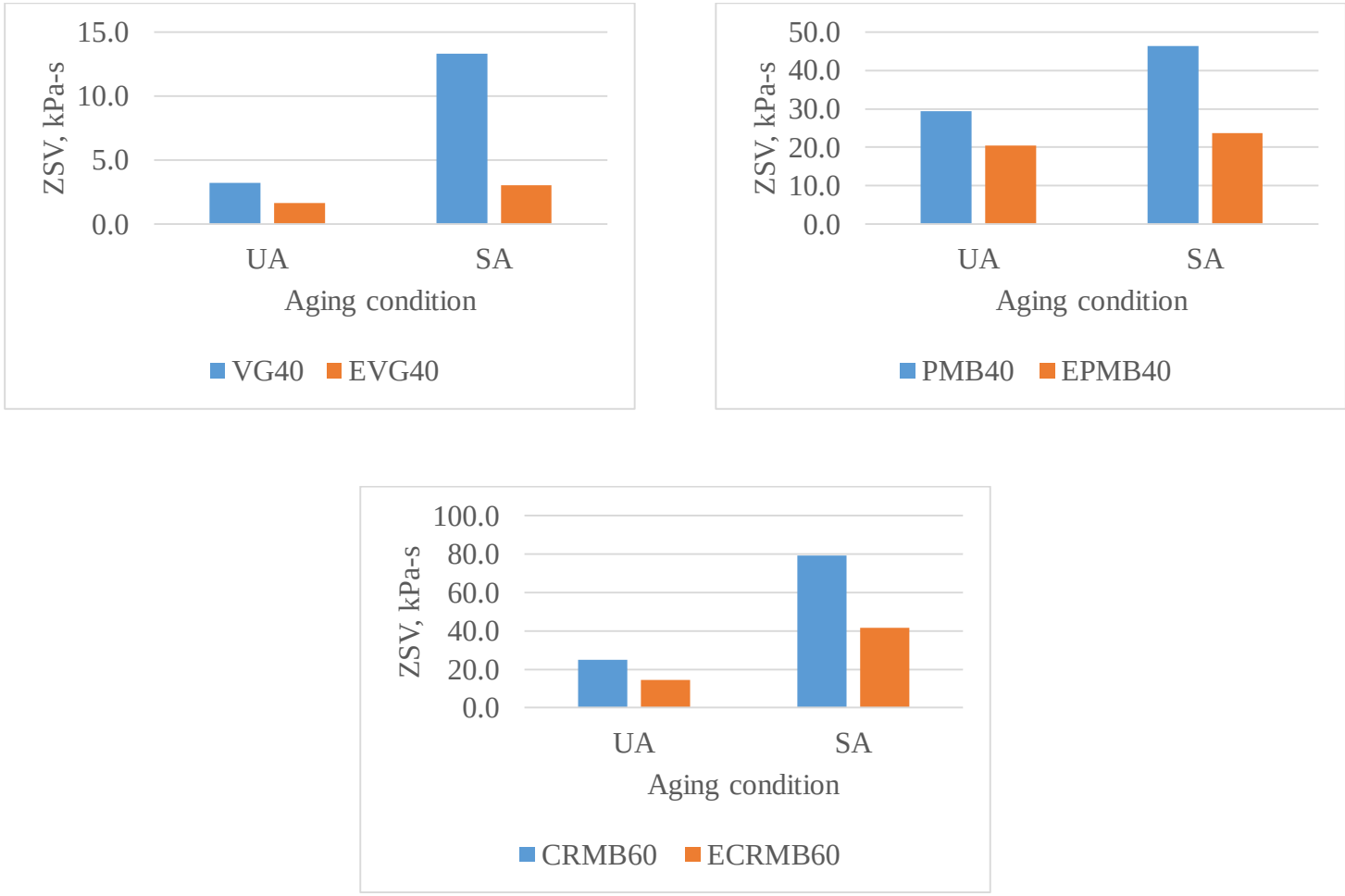


Fig. B.11 Zero shear viscosity of Control and Evotherm-modified bituminous binders at unaged and short-term aged condition

B.12 Low shear viscosity at unaged condition

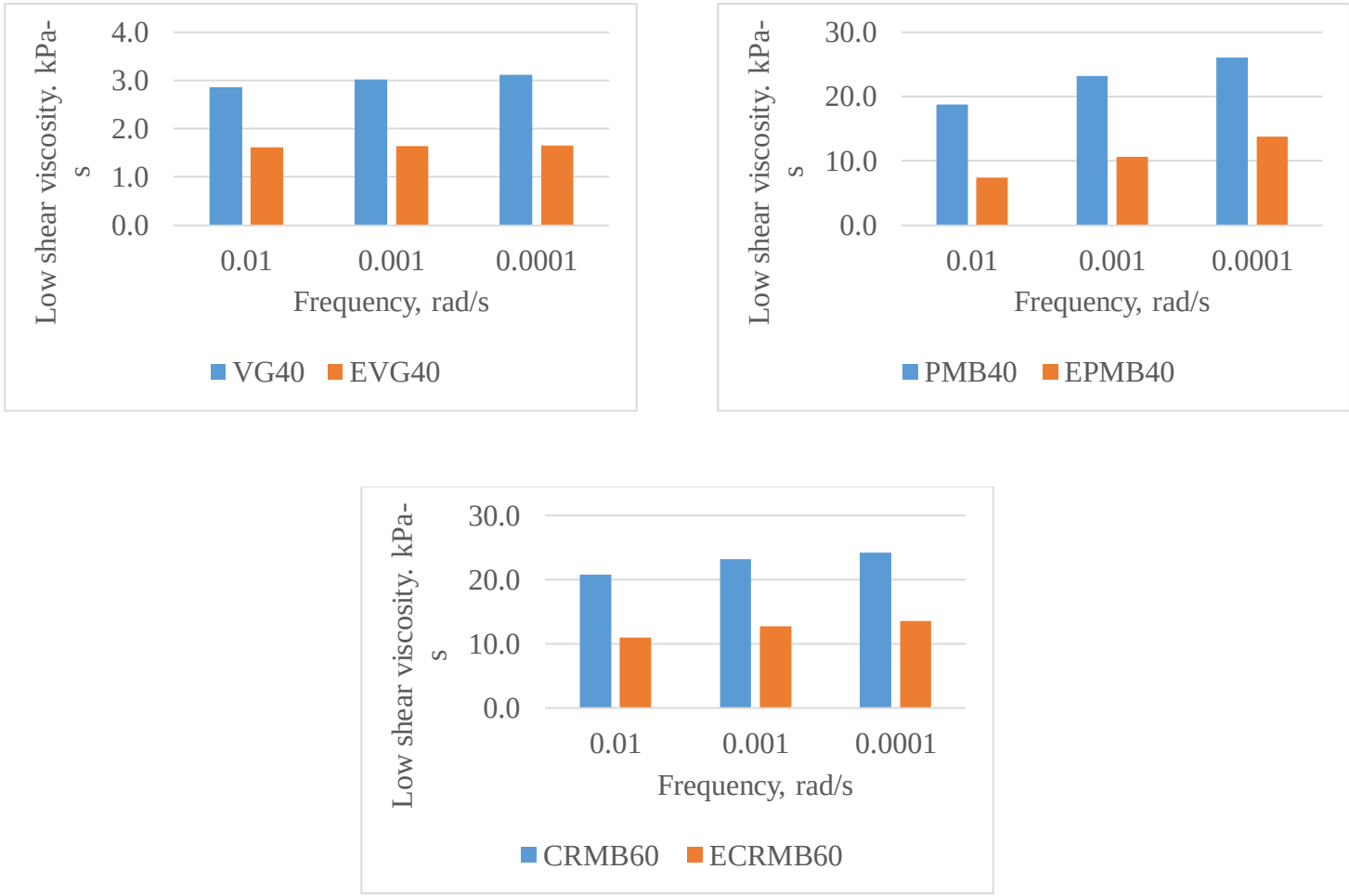


Fig. B.12 Low shear viscosity of control and Evotherm-modified bituminous binders at unaged condition

B.13 Low shear viscosity at short-term aged condition

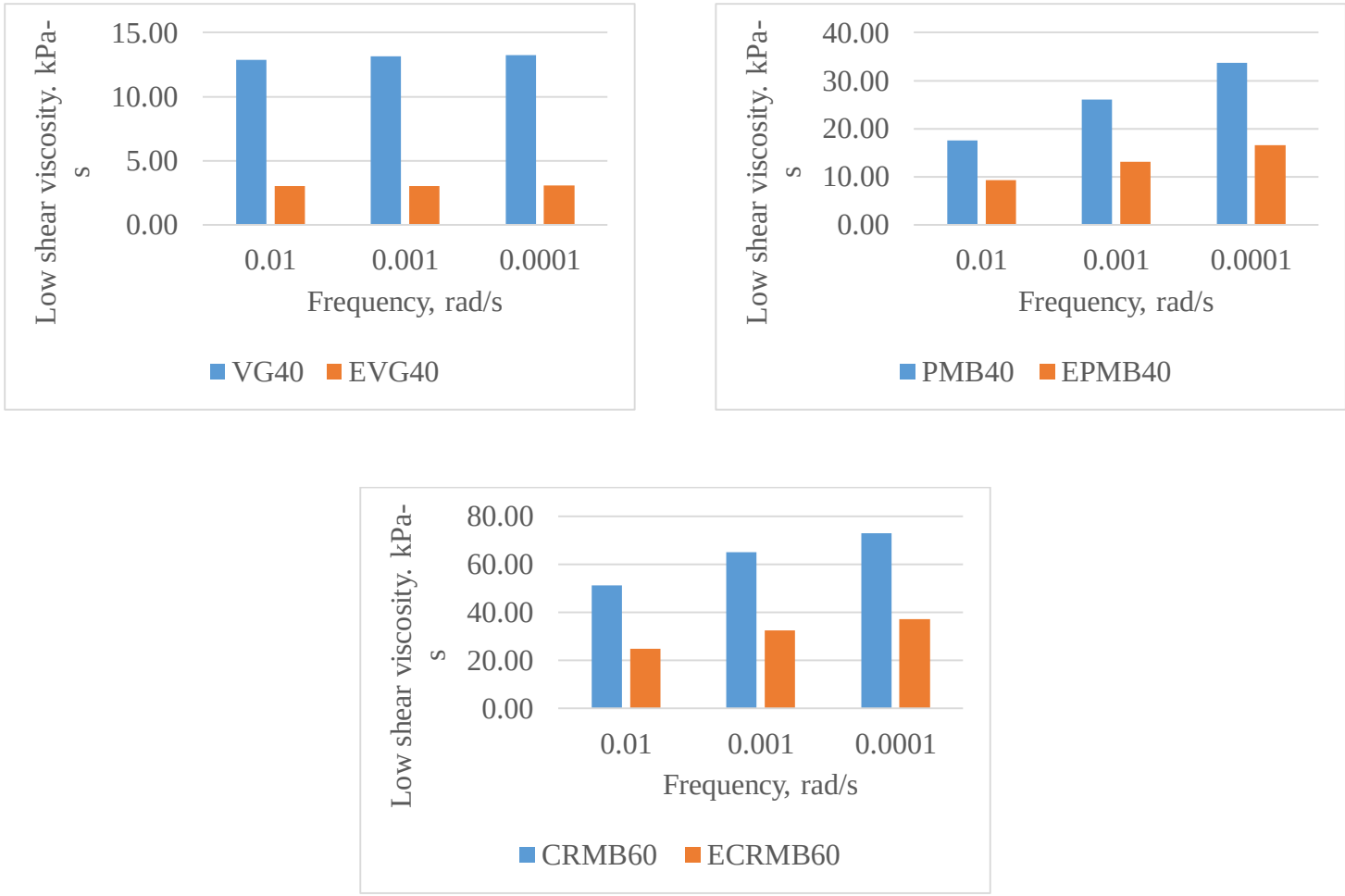


Fig. B.13 Low shear viscosity of Control and Evotherm-modified bituminous binders at short-term aged condition

B.14 Rutting parameter master curve

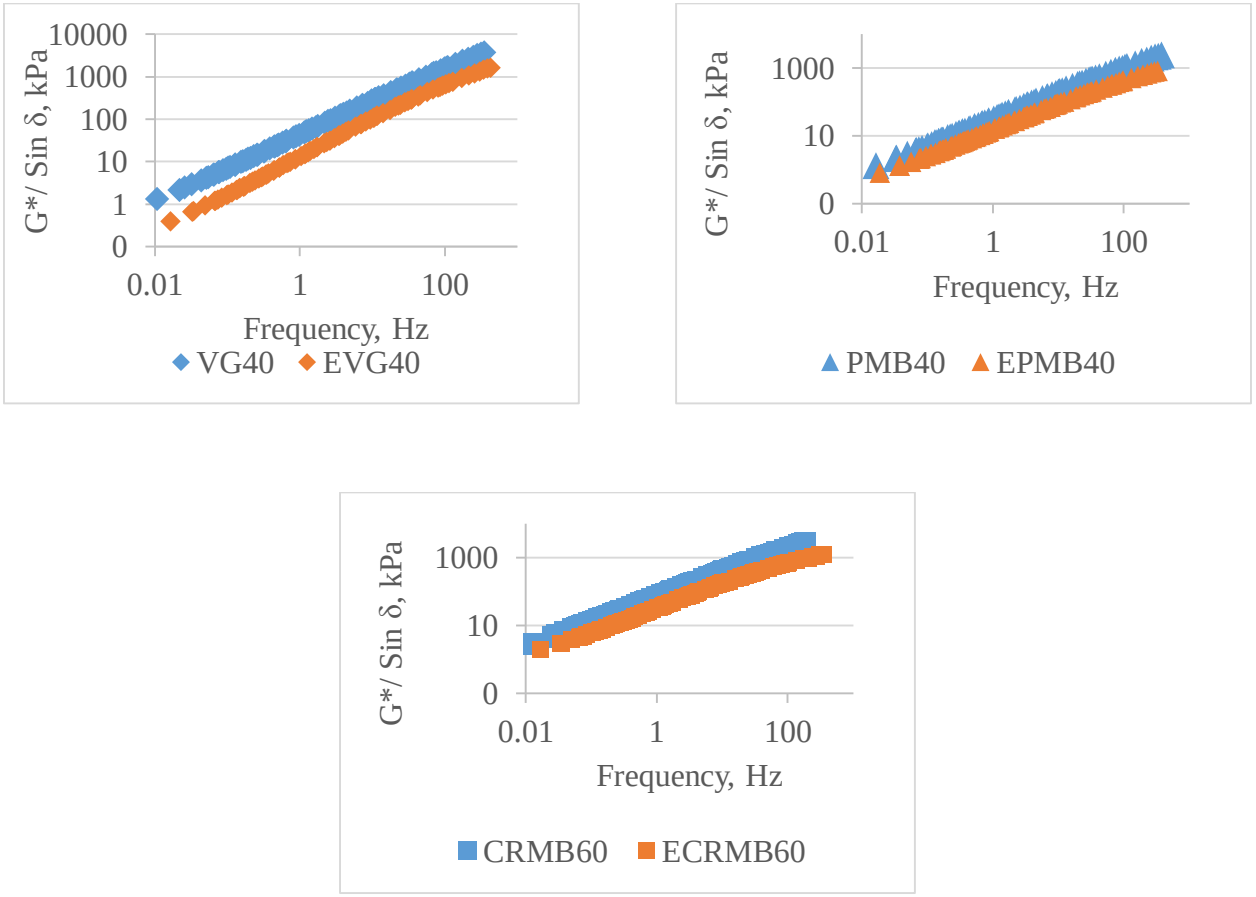


Fig. B.14 Rutting parameter master curve of control and Evotherm-modified bituminous binders

B.15 Fatigue parameter master curve

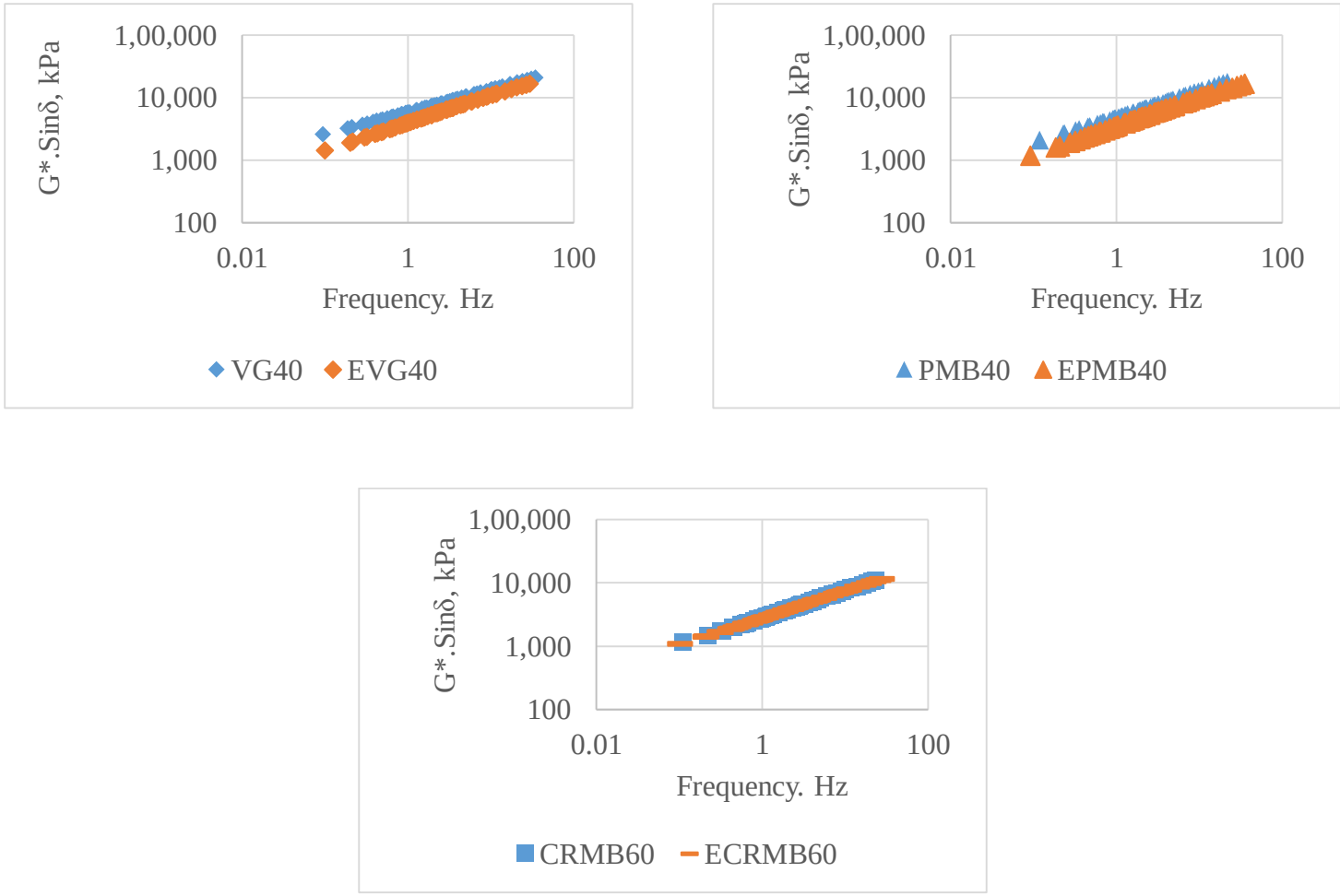


Fig. B.15 Fatigue parameter master curve for control and Evotherm-modified bituminous binders

B.16 Fatigue law parameters

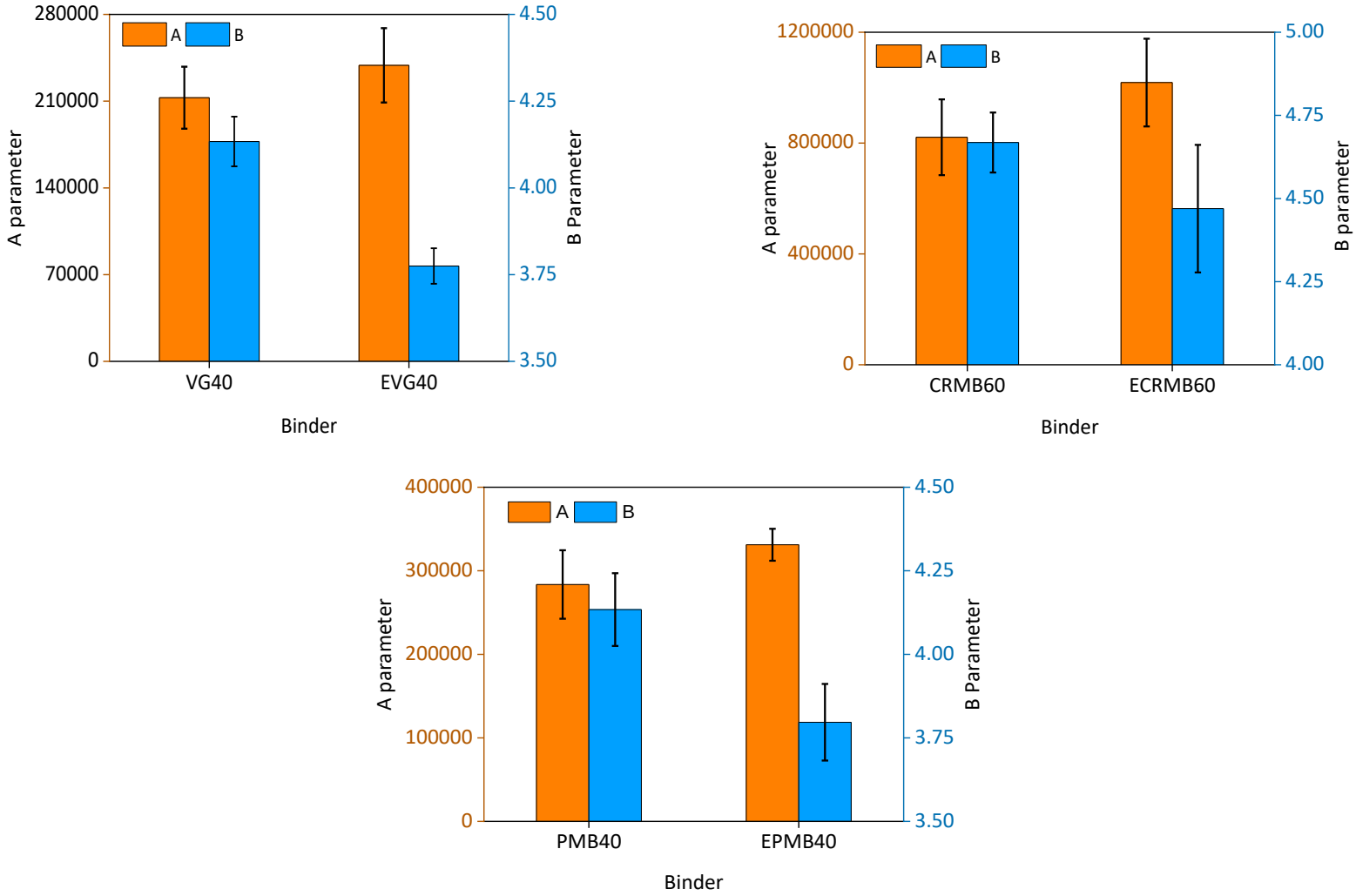


Fig. B.16 Fatigue law parameters of control and Evotherm-modified binders

B.17 Fatigue life

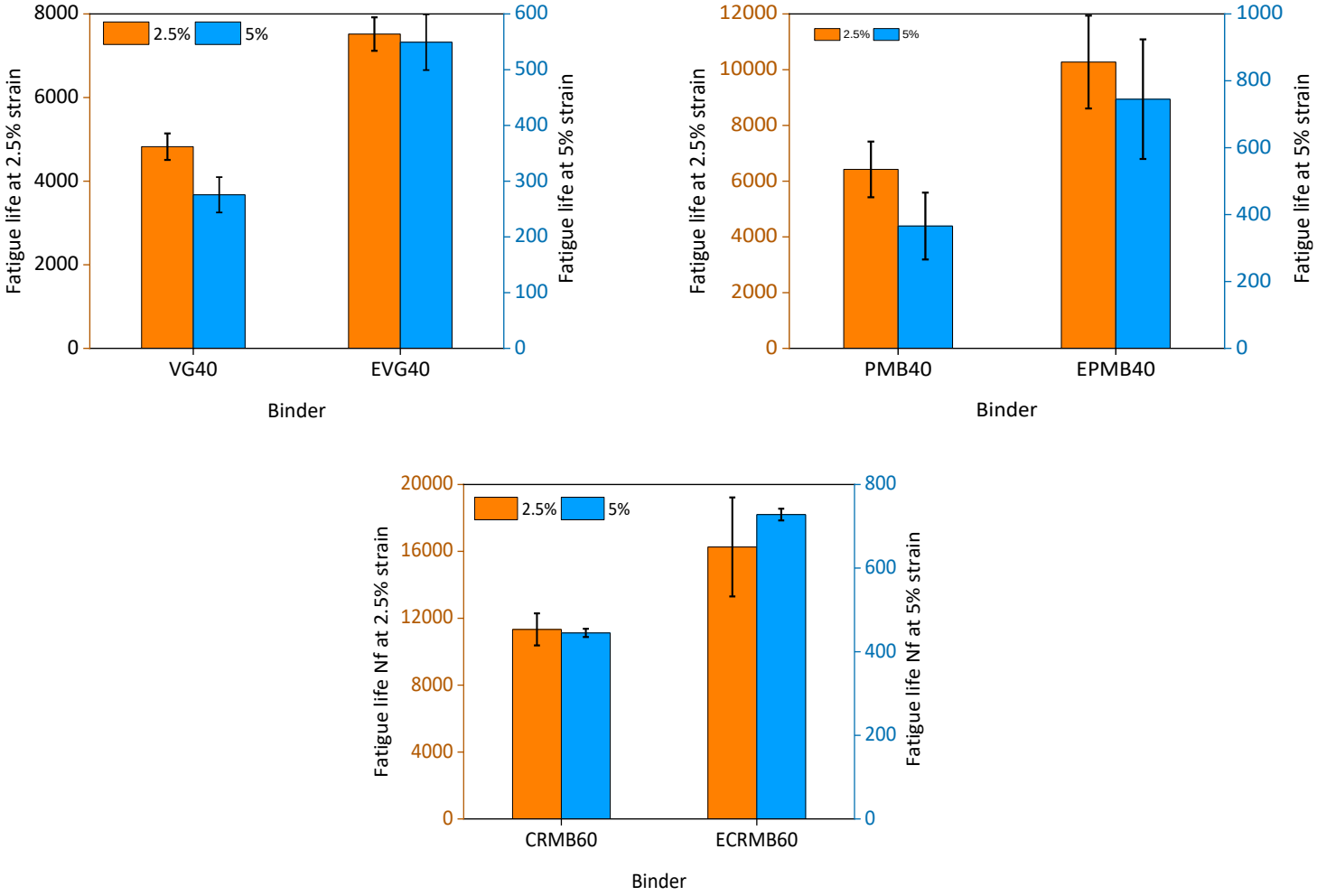


Fig. B.17 Fatigue life of control and Evotherm-modified binders

B.18 Glover-Rowe parameter

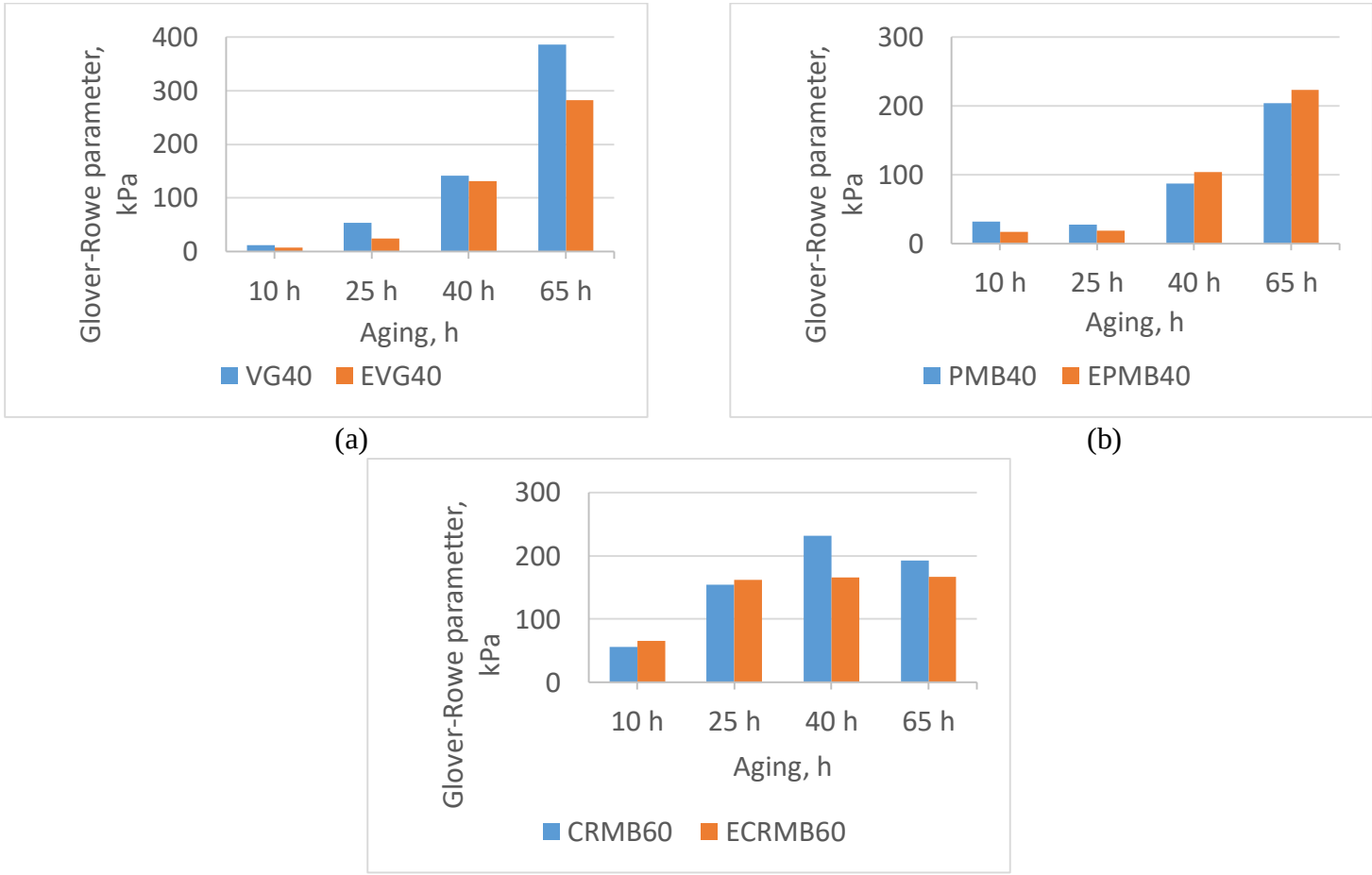


Fig. B.18 Glover-rower parameters of control and Evotherm-modified binders at various aging condition

B.19 Black space diagram VG40 and EVG40 binders

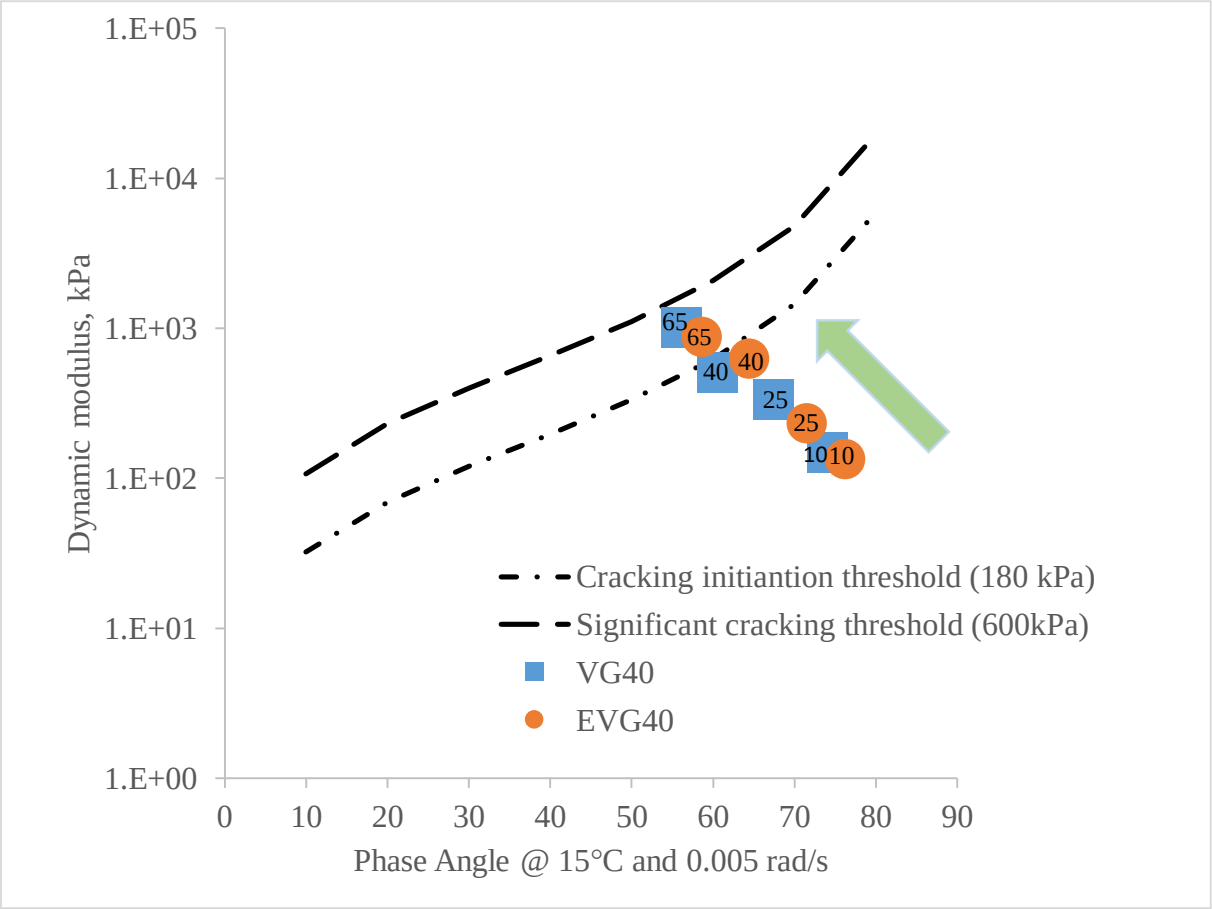


Fig. B.19 Black space diagram for VG40 and EVG40 binders

B.20 Black space diagram for PMB40 and EPMB40 binders

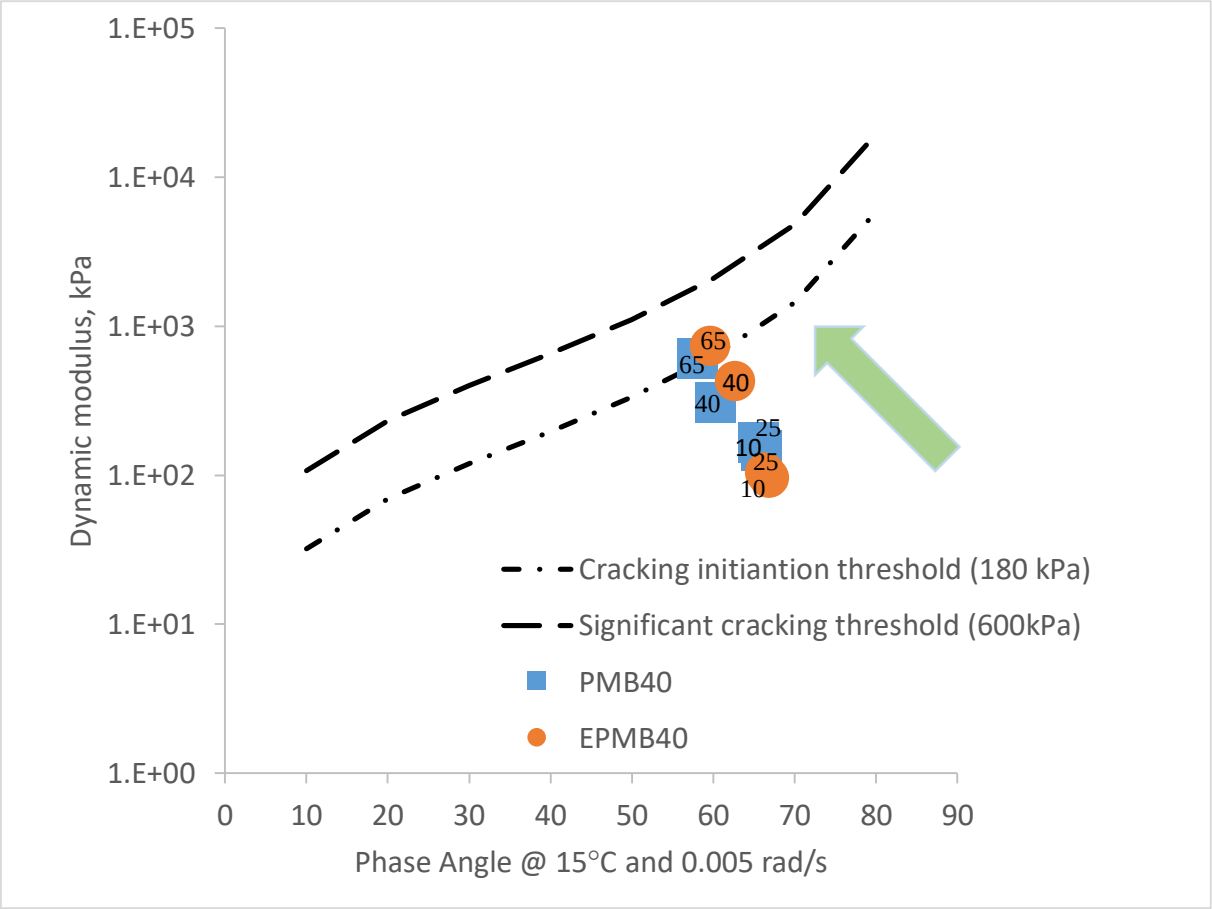


Fig. B.20 Black space diagram for PMB40 and EPMB40 binders

B.21 Black space diagram for CRMB60 and ECRMB60 binders

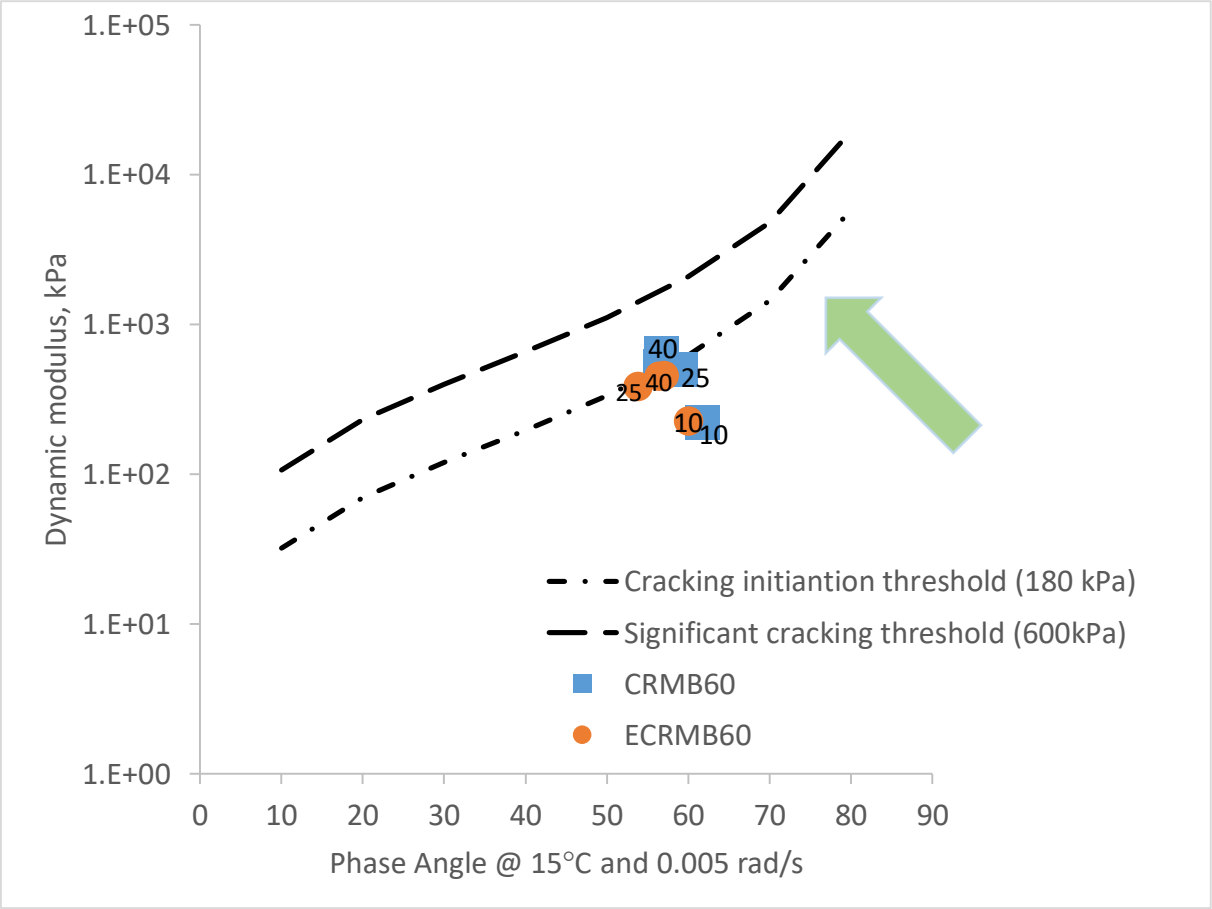
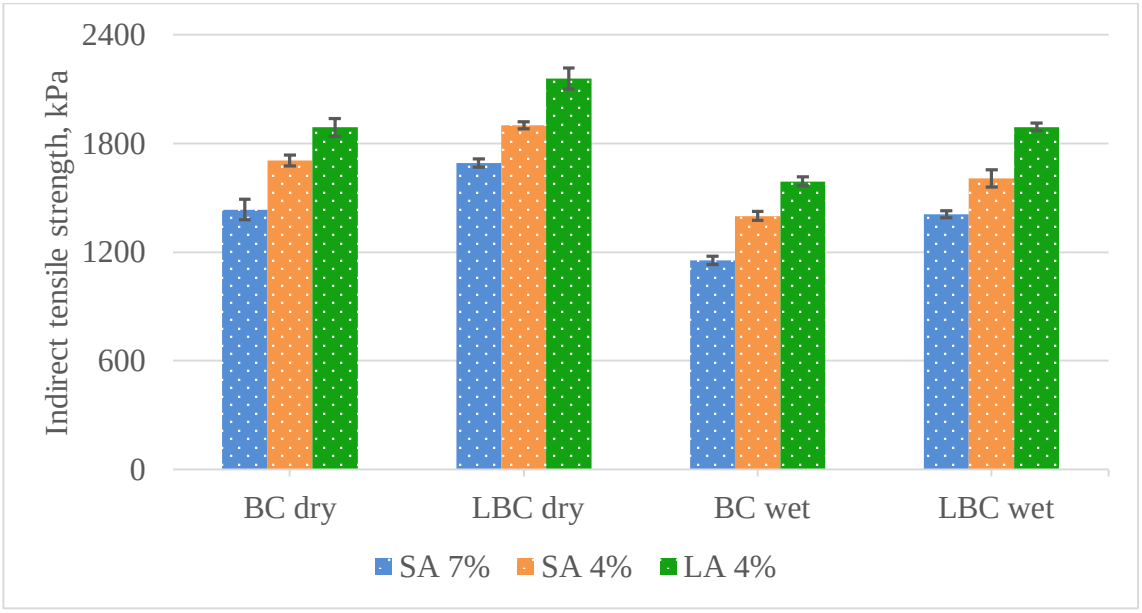


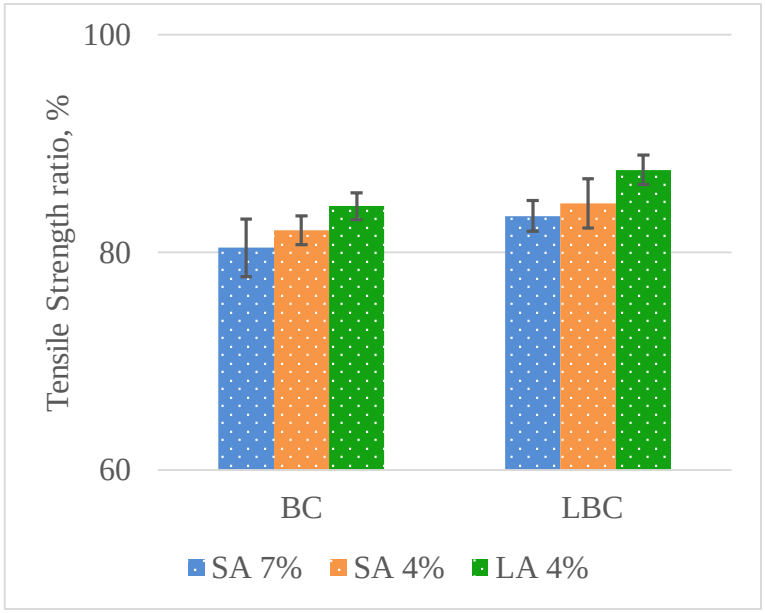
Fig. B.21 Black space diagram for CRMB60 and ECRMB60 binders

APPENDIX C

C.1 MID of BC and LBC with VG40 binder



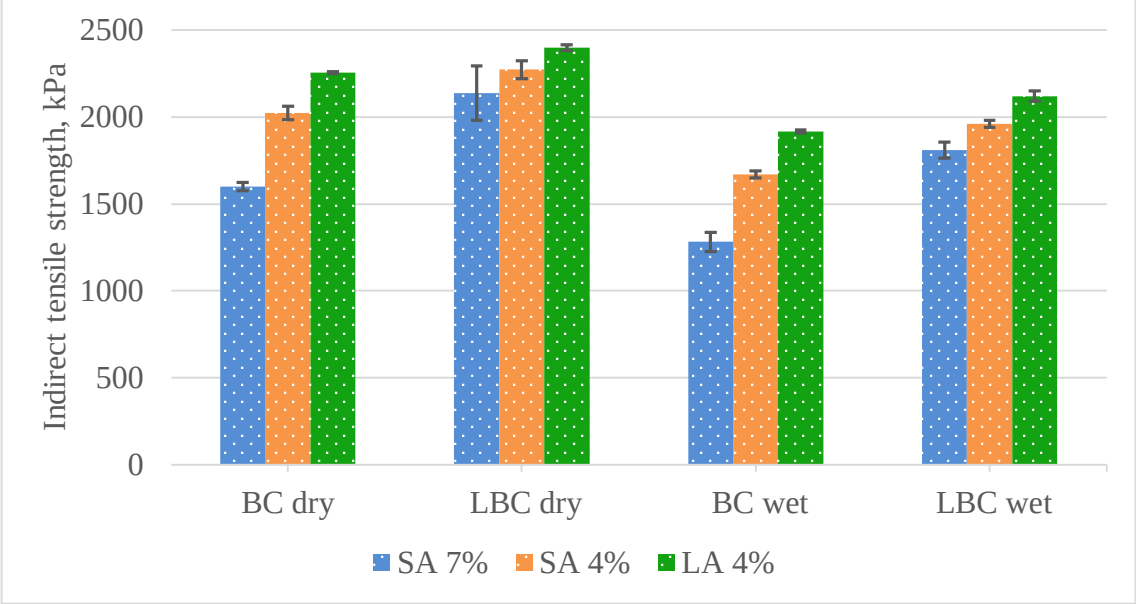
(a)



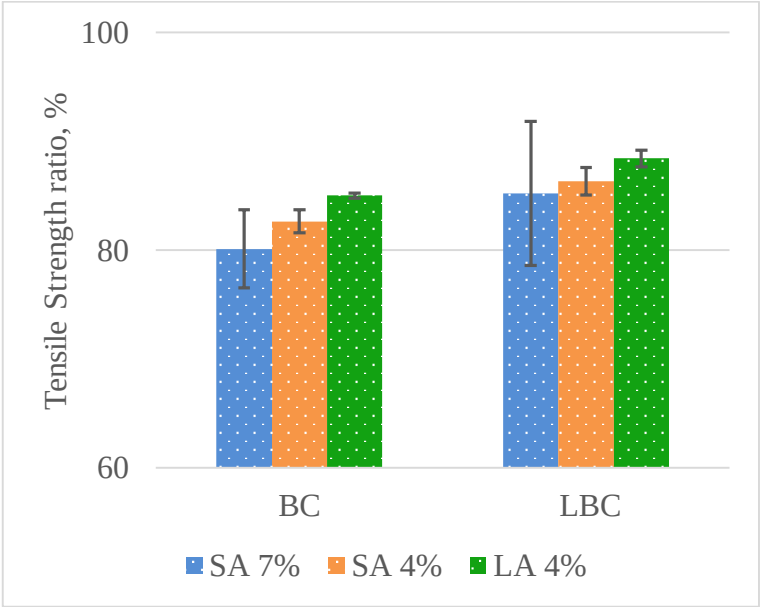
(b)

Fig. C.1 (a) Dry and Wet indirect tensile and (b) TSR of BCII and LBCII mixtures prepared with VG40 binder

C.2 MID of BC and LBC with PMB40 binder



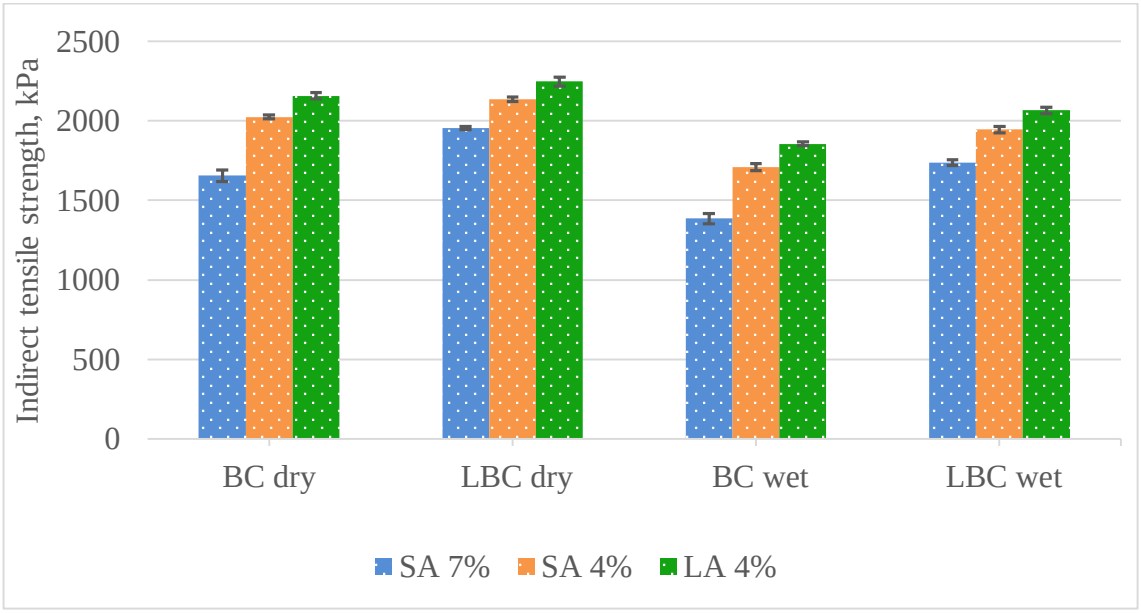
(a)



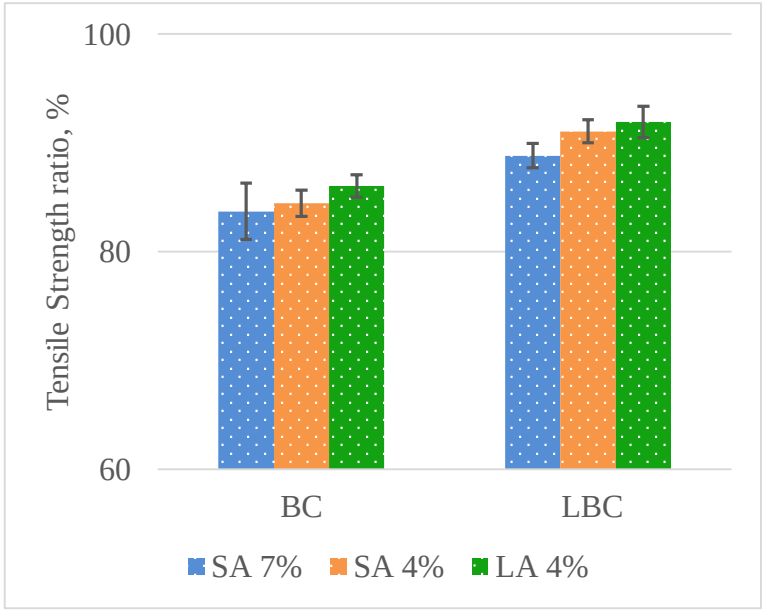
(b)

Fig. C.2 (a) Dry and Wet indirect tensile and (b) TSR of BC and LBC mixtures prepared with PMB40 binder

C.3 MID of BC and LBC with CRMB60 binder



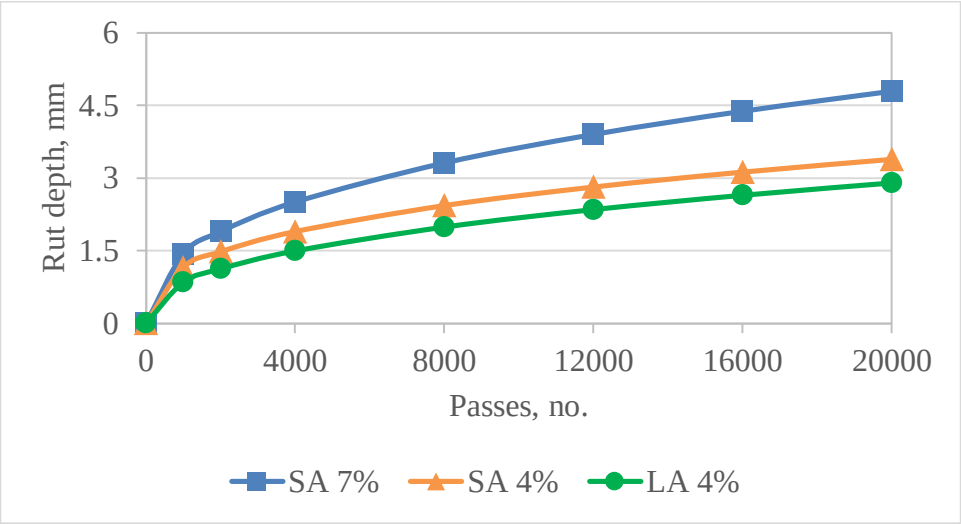
(a)



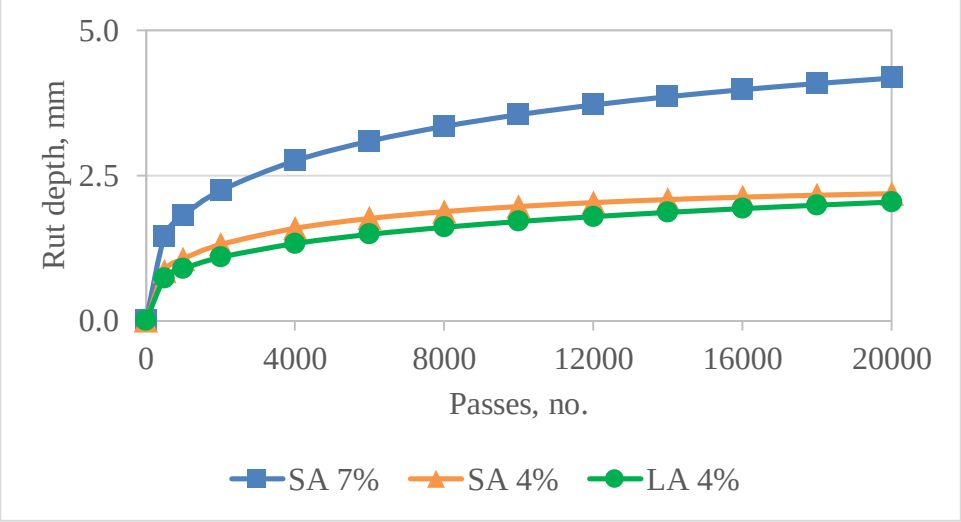
(b)

Fig. C.3 (a) Dry and Wet indirect tensile of BC II and LBCII and (b) TSR of BCII and LBCII mixtures prepared with CRMB60 binder

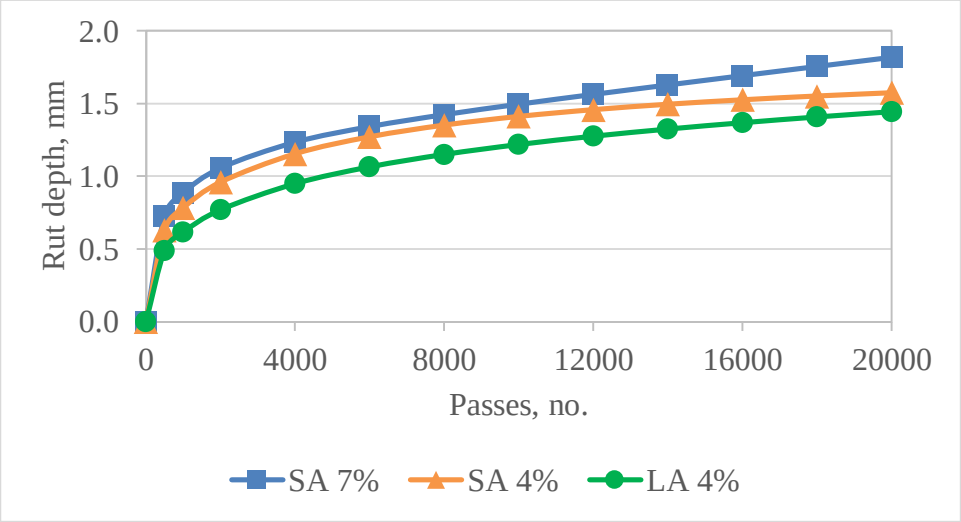
C.4 Rutting progression of BC mixture using control binders



(a) VG40



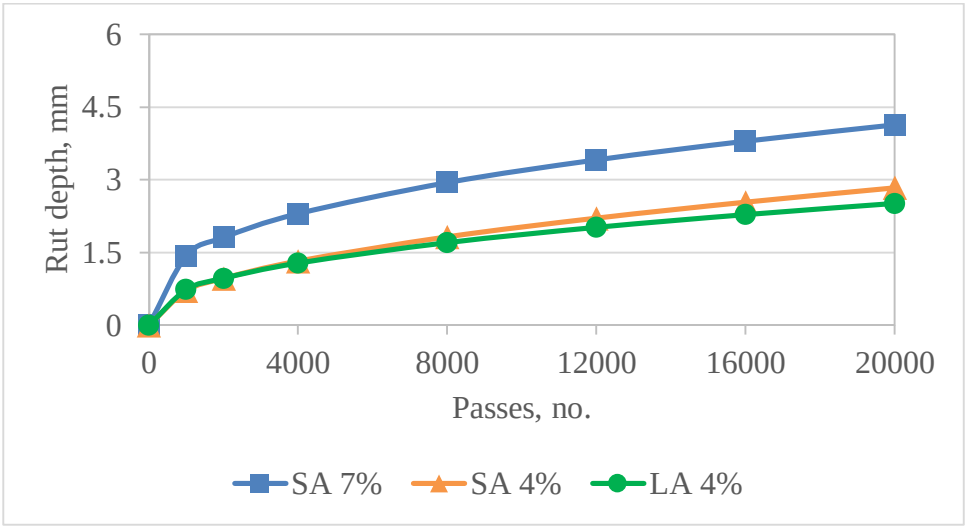
(b) PMB40

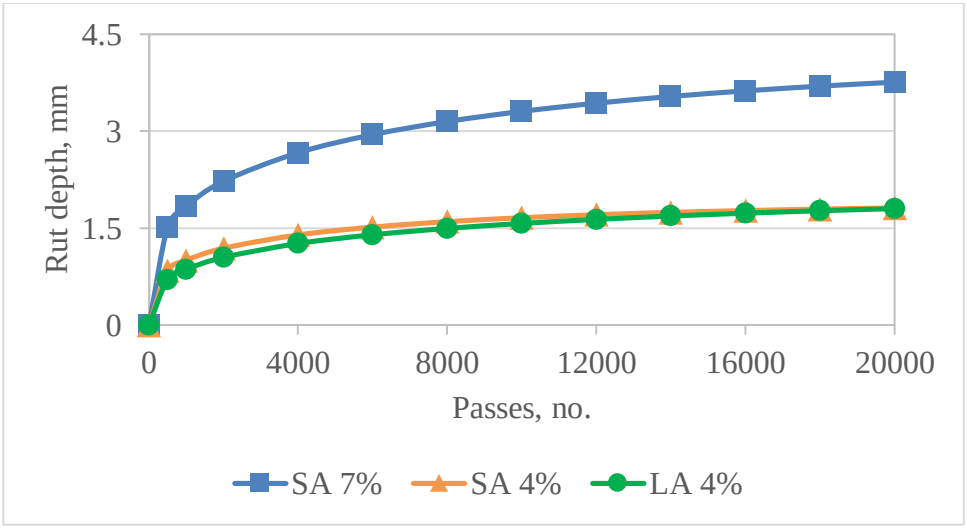


(c) CRMB60

Fig. C.4 Rutting progression of BC mixtures prepared with control binders.

C.5 Rutting progression of LBC mixture using control binders





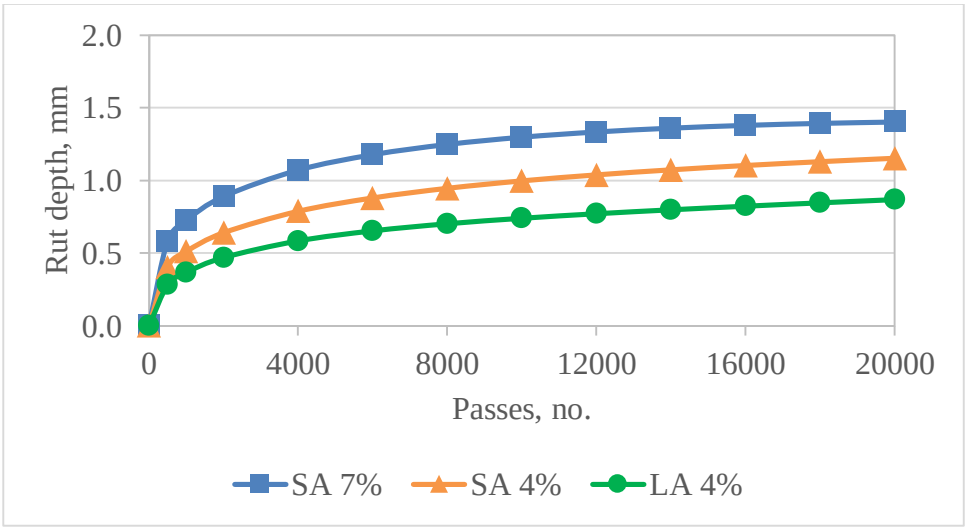
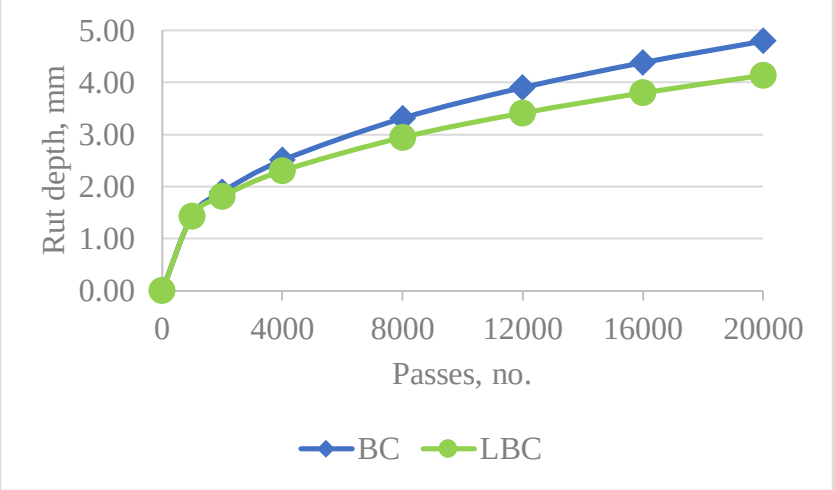
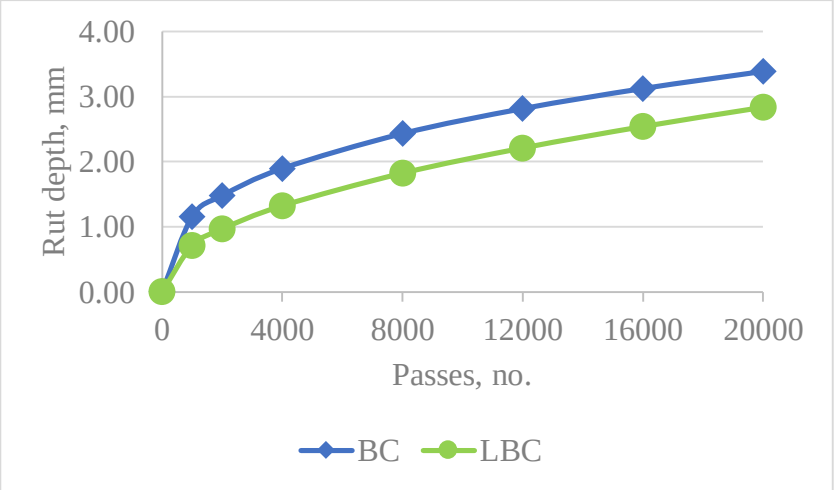


Fig. C.5 Rutting progression of LBC mixture using control binders

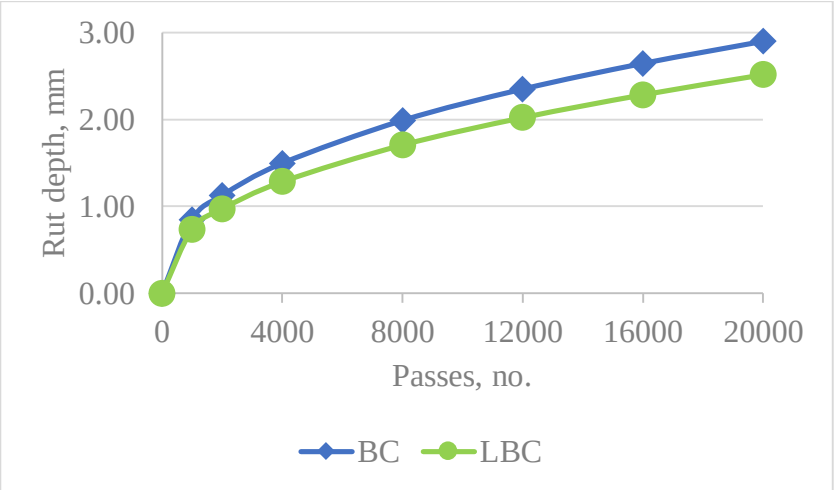
C.6 Rutting progression of BC and LBC with VG40 binder



(a) SA 7%



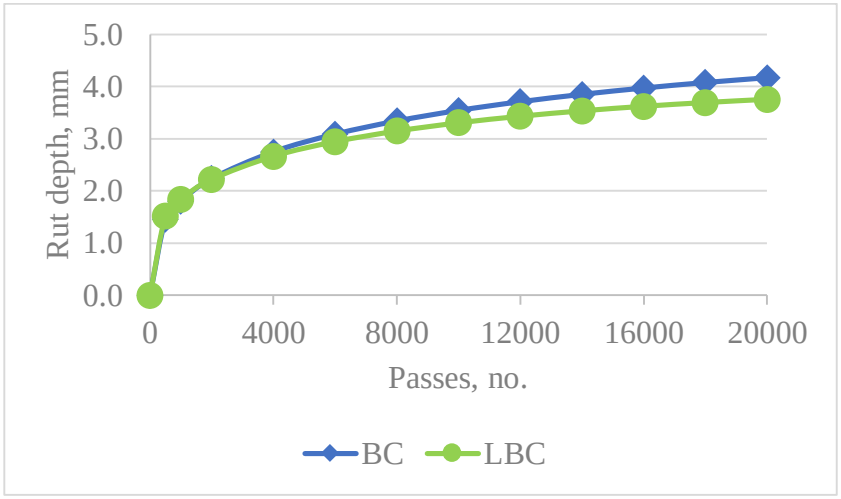
(b) SA 4%



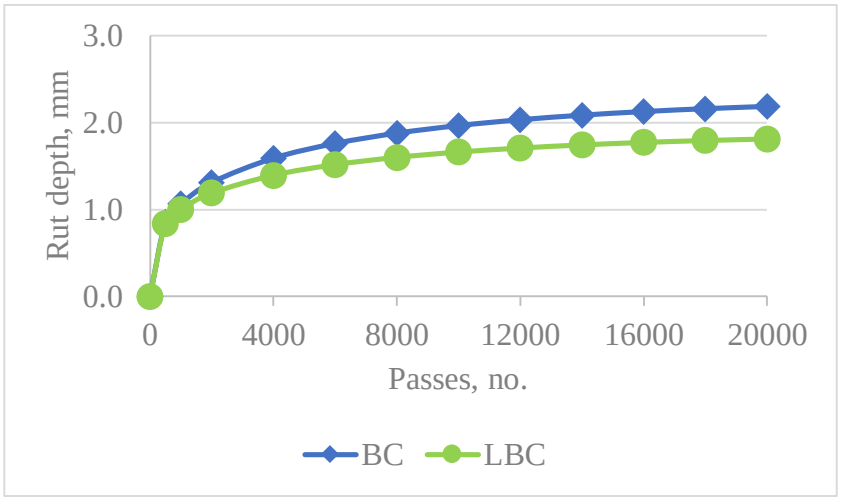
(c) LA 4%

Fig. C.6 Rut depth progression of BC and LBC mixtures prepared with VG40 binder

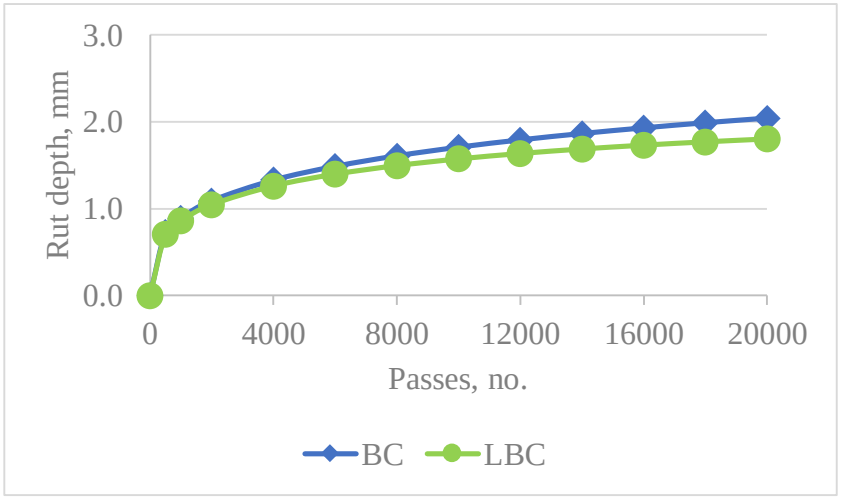
C.7 Rutting progression of BC and LBC with PMB40 binder



(a) SA 7%



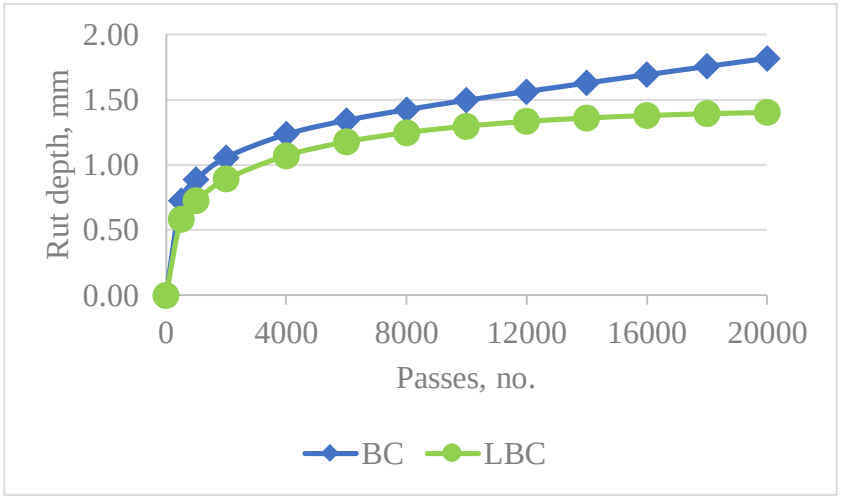
(b) SA 4%



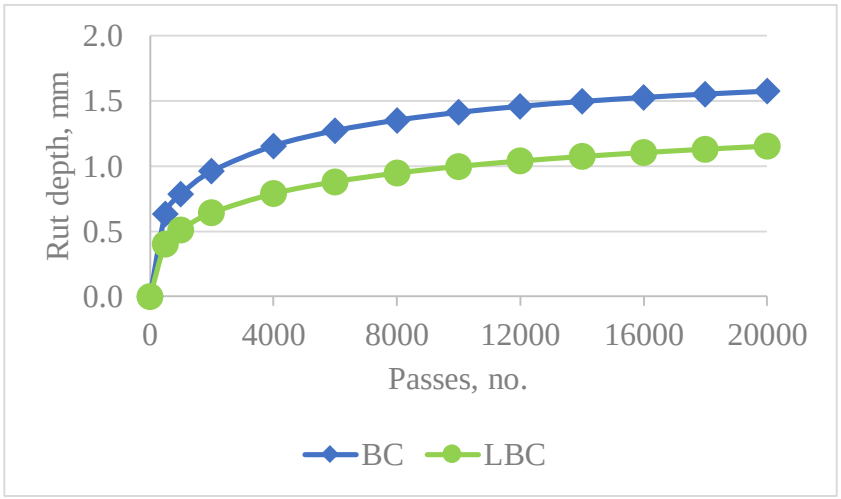
(c) LA 4%

Fig. C.7 Rut depth progression of BC and LBC mixtures prepared with PMB40 binder

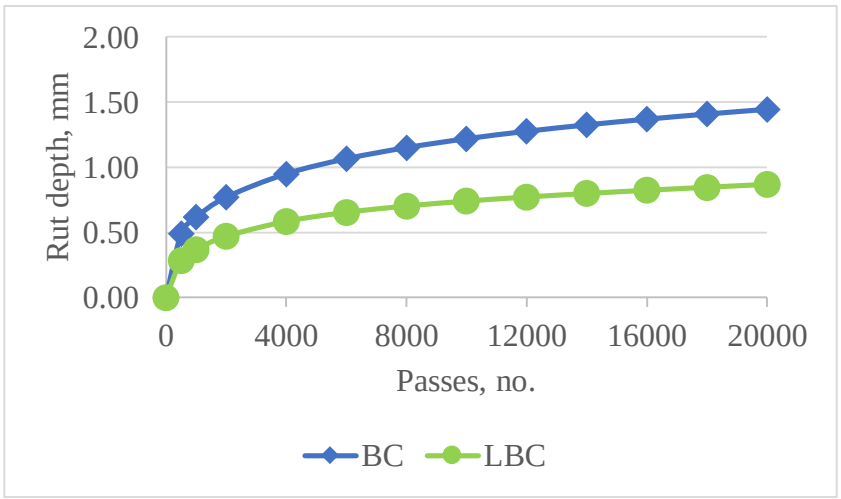
C.8 Rutting progression of BC and LBC with CRMB60 binder



(a) SA 7%



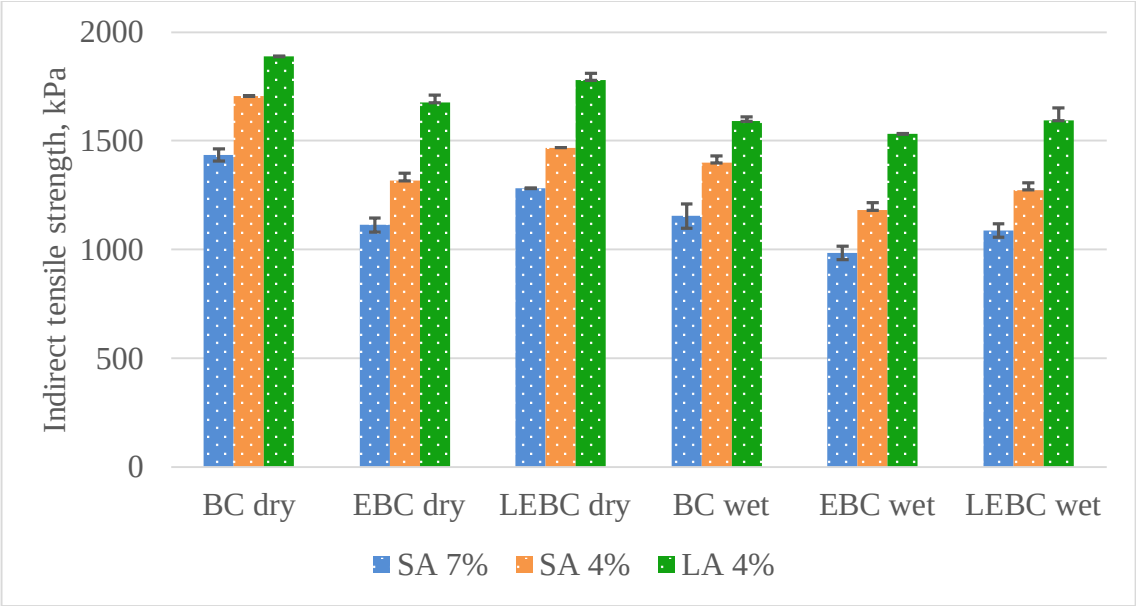
(b) SA 4%



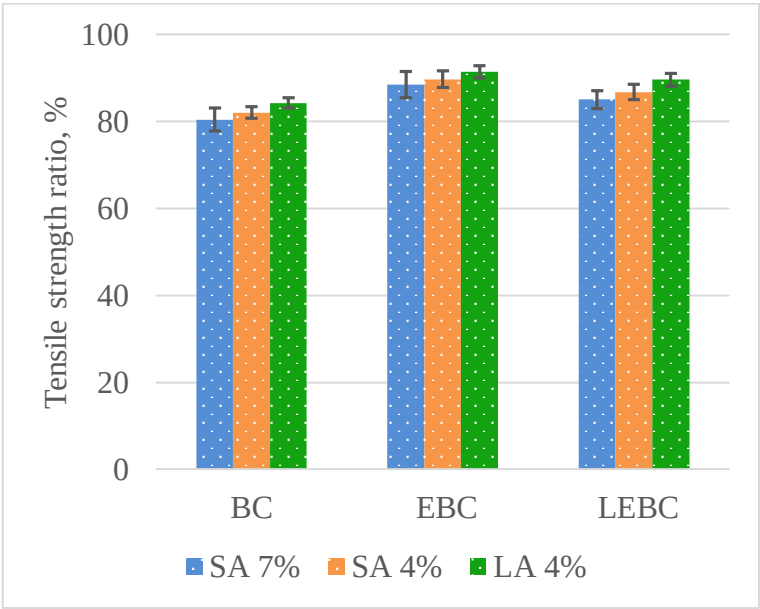
(c) LA 4%

Fig. C.8 Rut depth progression of BC and LBC mixtures prepared with CRMB60 binder

C.9 MID of BC, EBC, and LEBC with VG40 binder



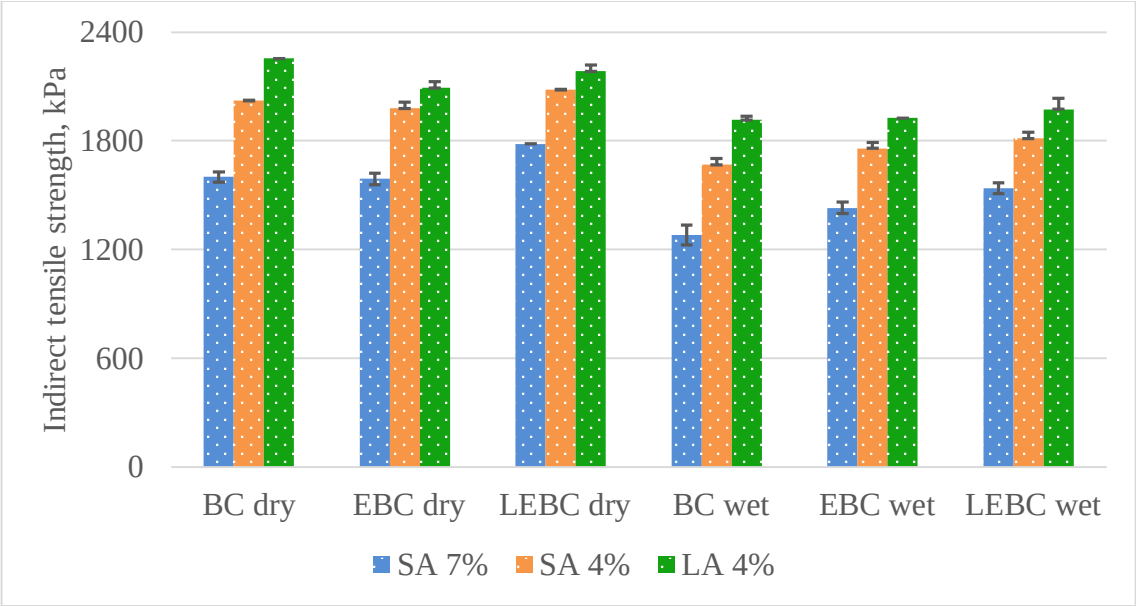
(a)



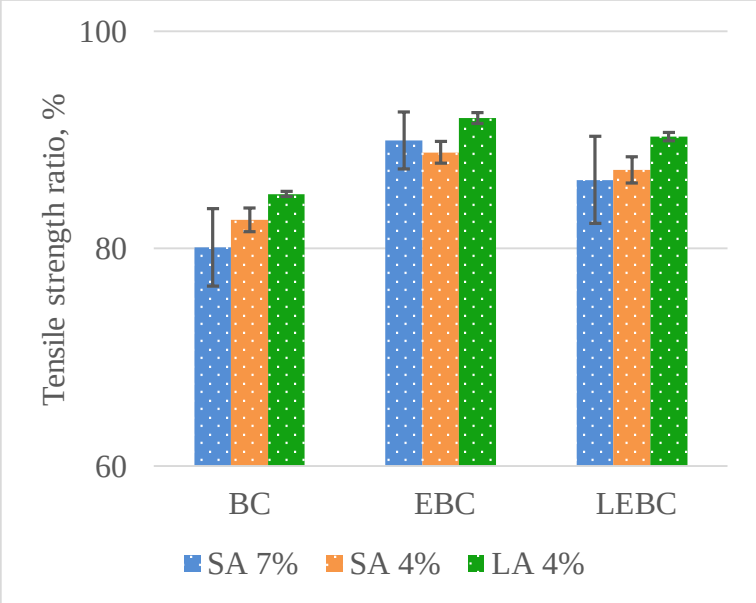
(b)

Fig. C.9 (a) Dry and Wet indirect tensile, and (b) TSR of BC, EBC, and LEBC mixtures prepared with VG40 binder

C.10 MID of BC, EBC, and LEBC with PMB40 binder



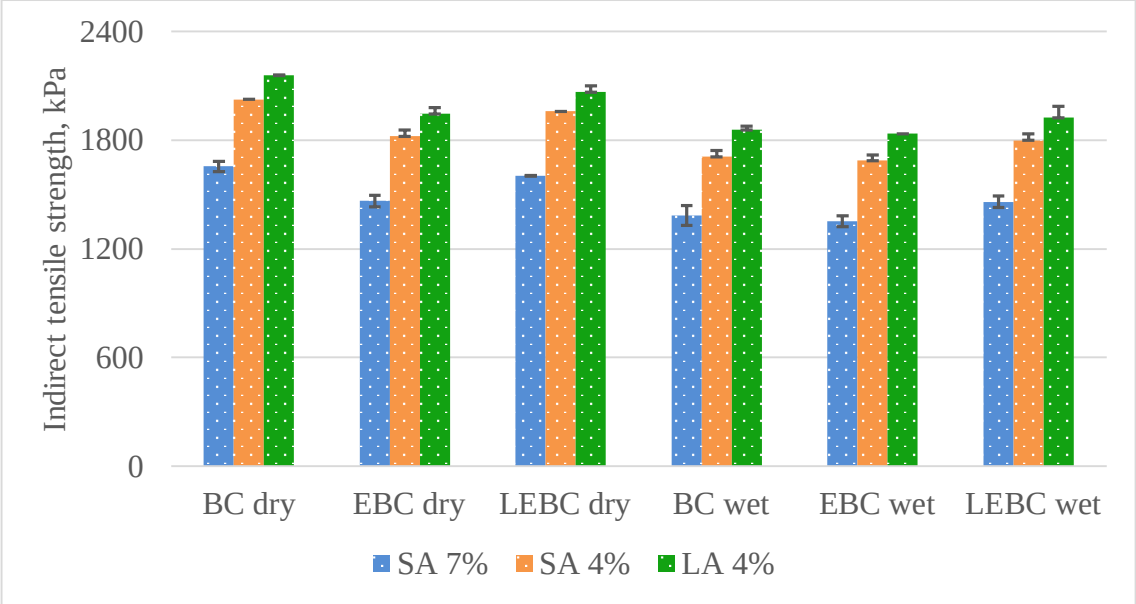
(a)



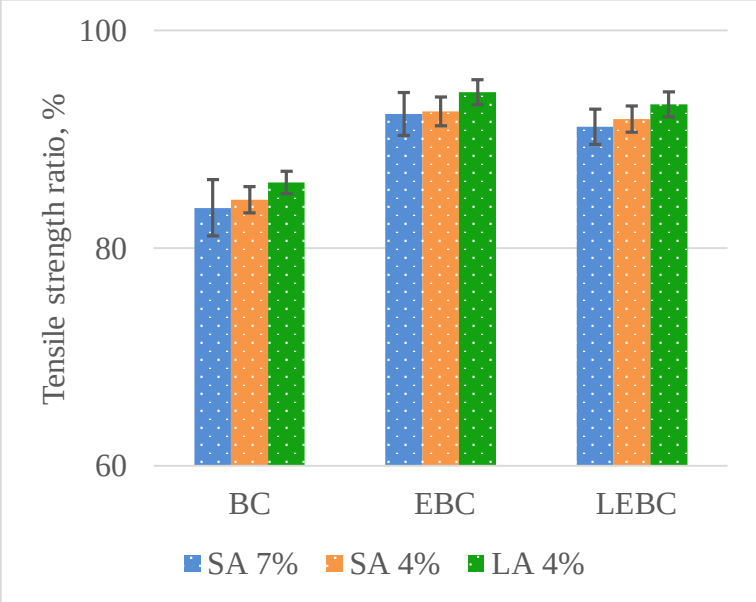
(b)

Fig. C.10 (a) Dry and Wet indirect tensile, and (b) TSR of BC, EBC, and LEBC mixtures prepared with PMB40 binder

C.11 MID of BC, EBC, and LEBC with CRMB60 binder



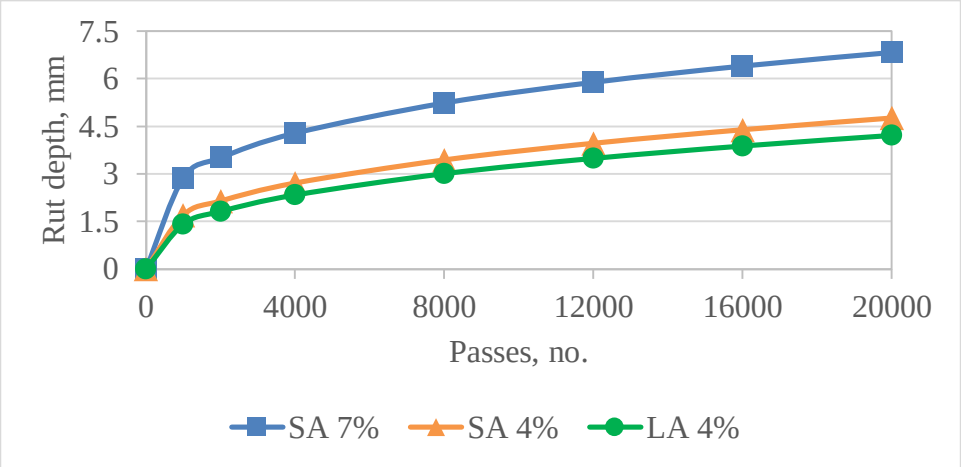
(a)



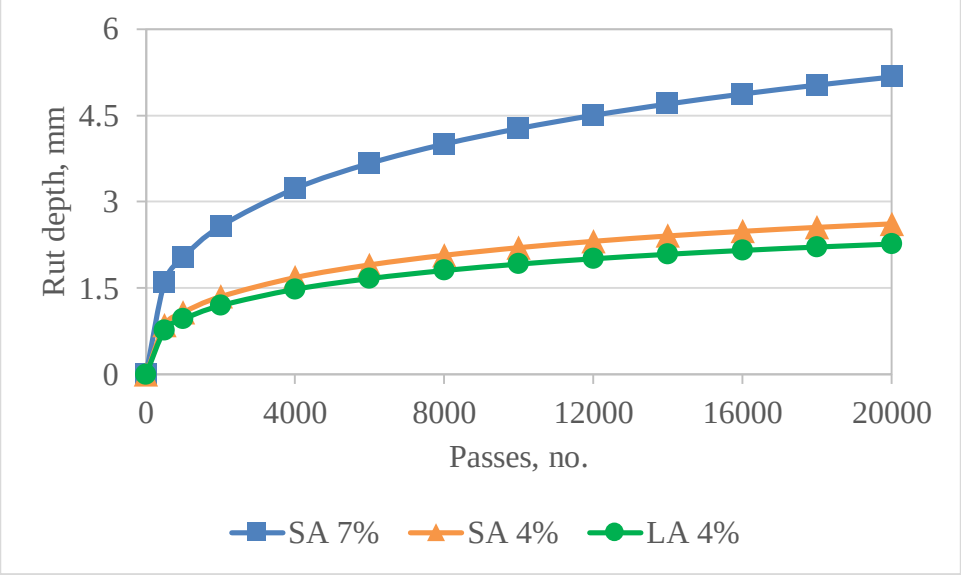
(b)

Fig. C.11 (a) Dry and Wet indirect tensile strength, and (b) TSR of BC, EBC, and LEBC mixtures prepared with CRMB60 binder

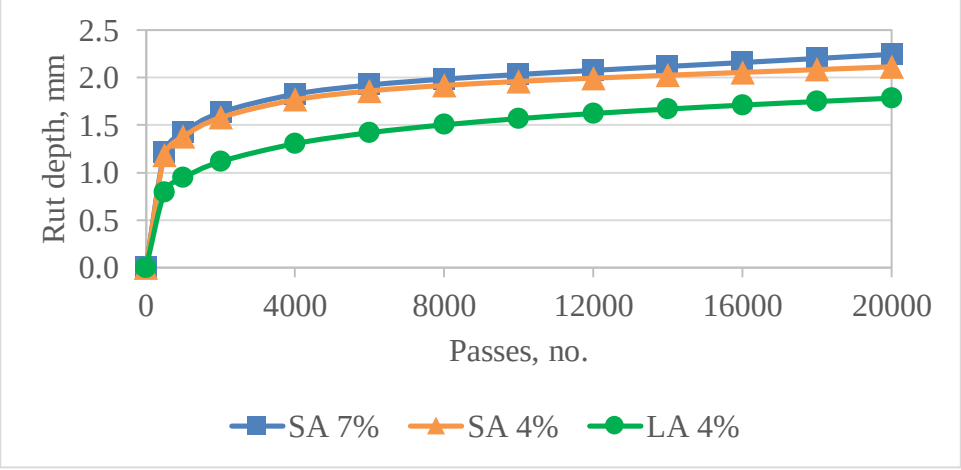
C.12 Rutting progression of EBC mixture for WMA binders



(a) EVG40



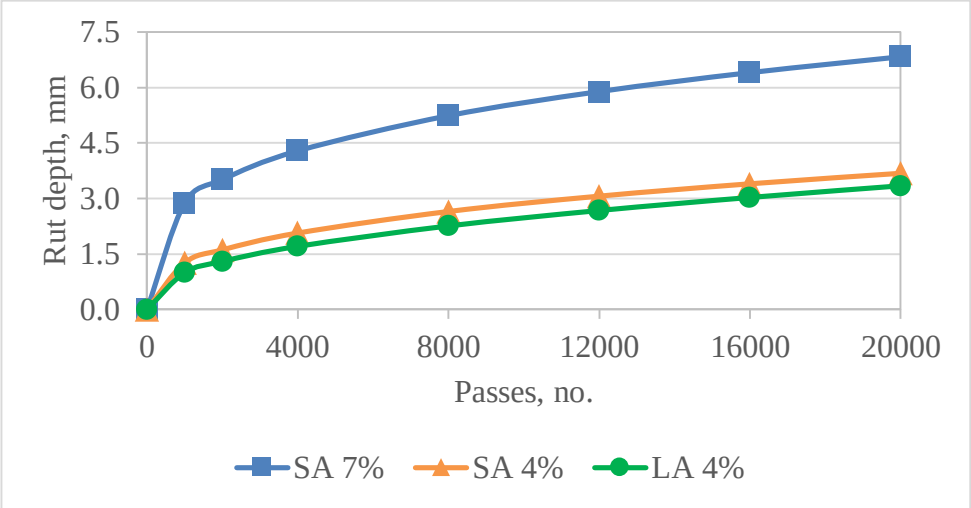
(b) EPMB



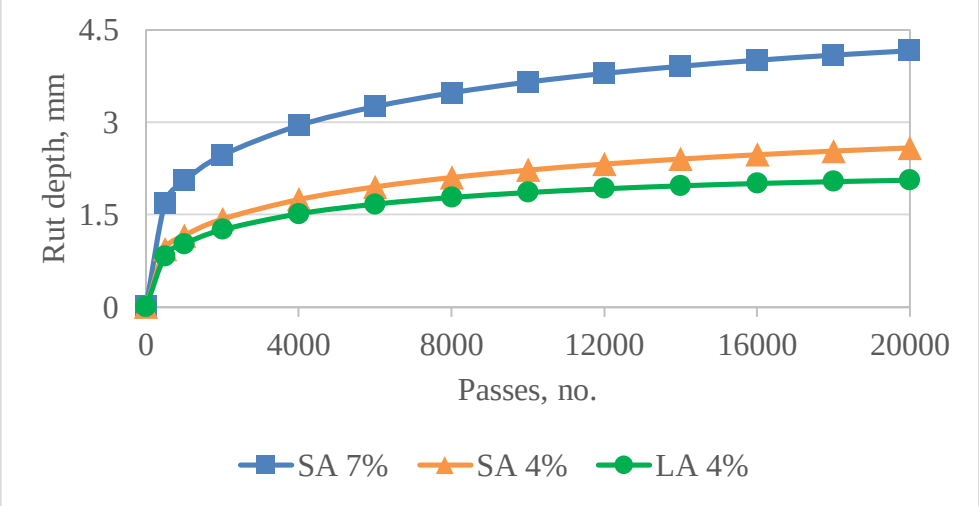
(c) ECRMB60

Fig. C.12 Rutting progression of EBC mixture for WMA binders

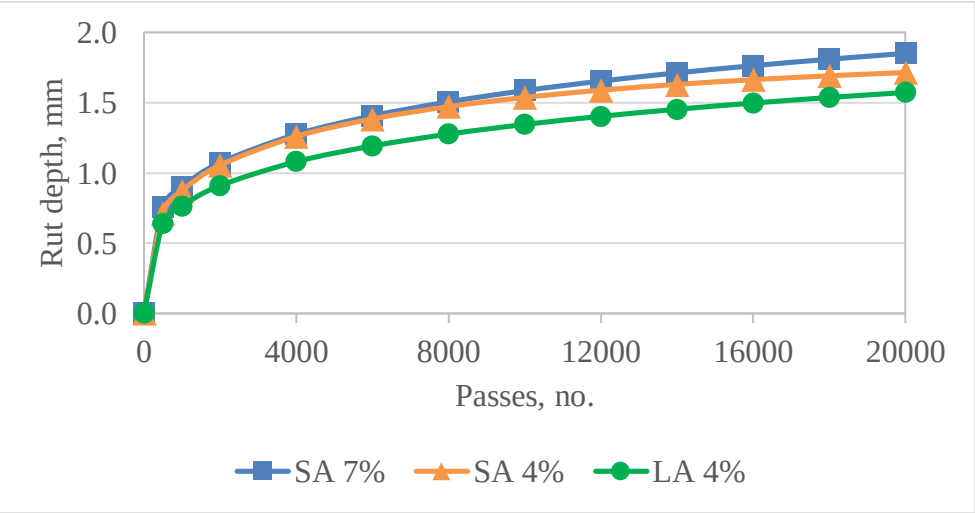
C.13 Rutting progression of LEBC mixture for WMA binders



(a) EVG40



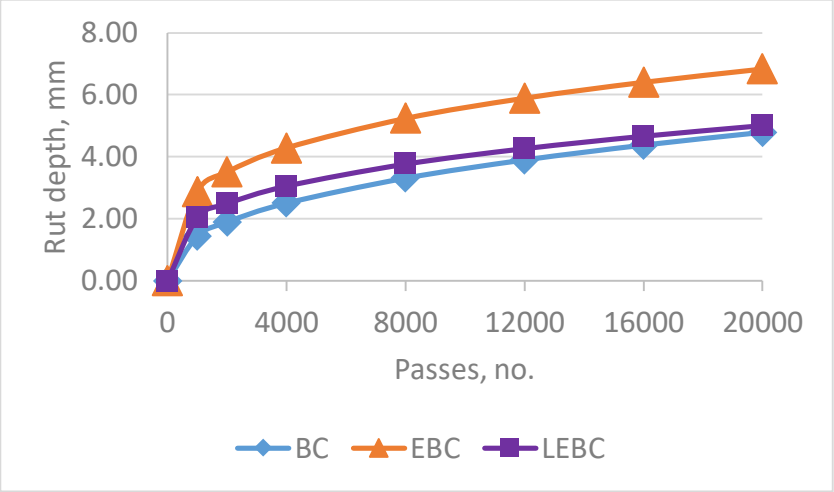
(b) EPMB40



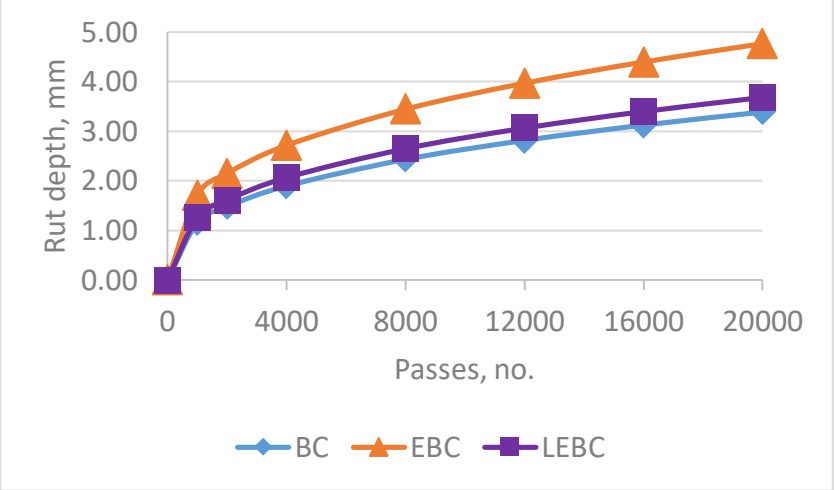
(c) ECRMB60

Fig. C.13 Rutting progression of LEBC mixture for WMA binders

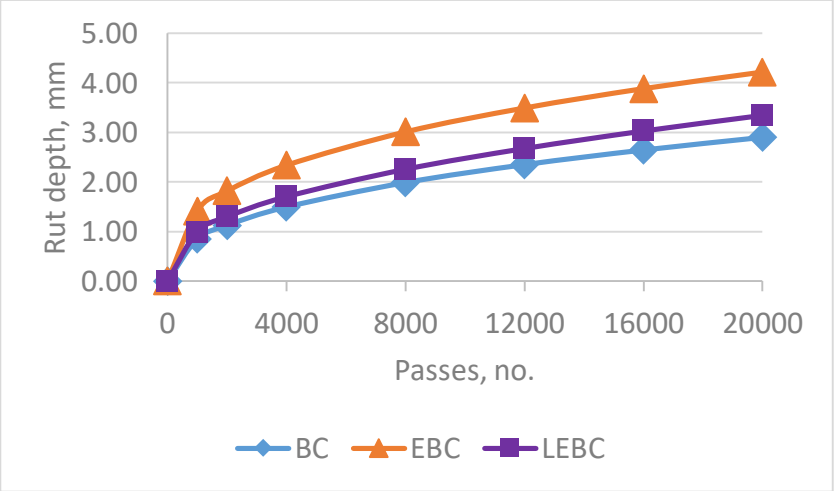
C.14 Rutting progression of BC, EBC and LEBC with VG40 binder



(a) SA 7%



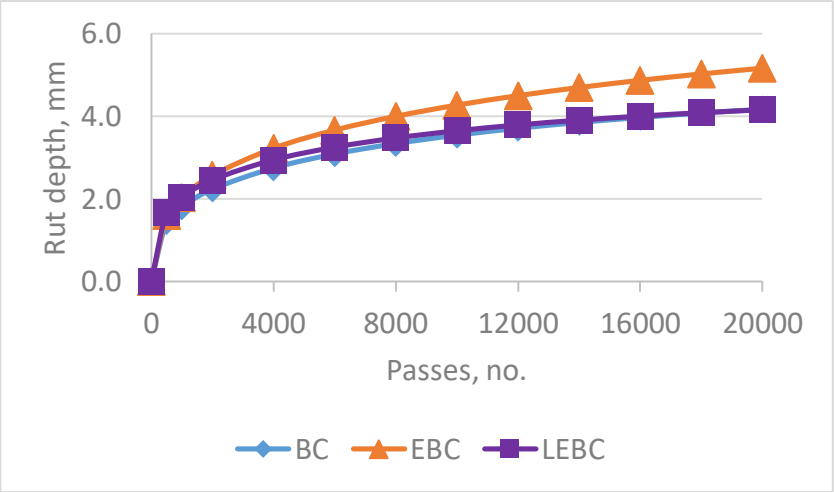
(b) SA 4%



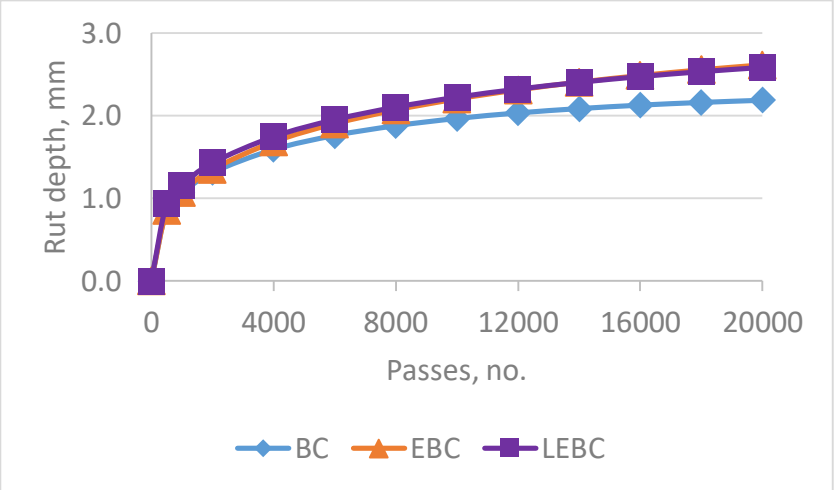
(c) LA 4%

Fig. C.14 Rut depth progression of BC, EBC, and LEBC mixtures prepared with VG40 binders

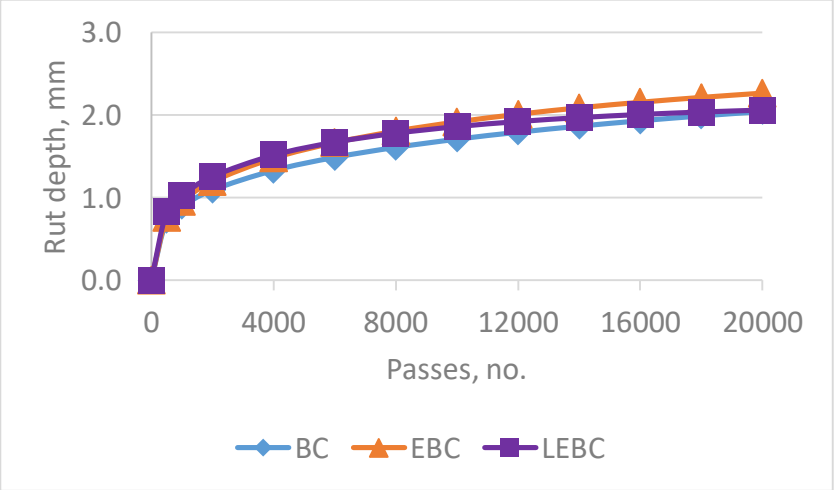
C.15 Rutting progression of BC, EBC and LEBC with PMB40 binder



(a) SA 7%



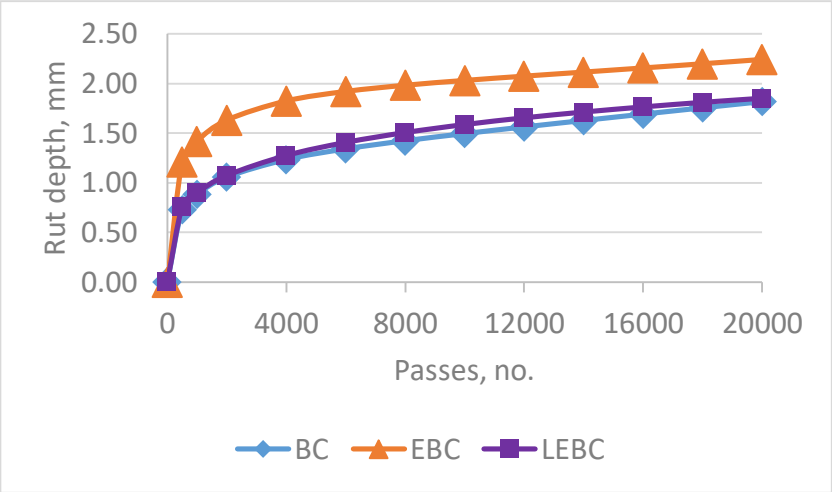
(b) SA 4%



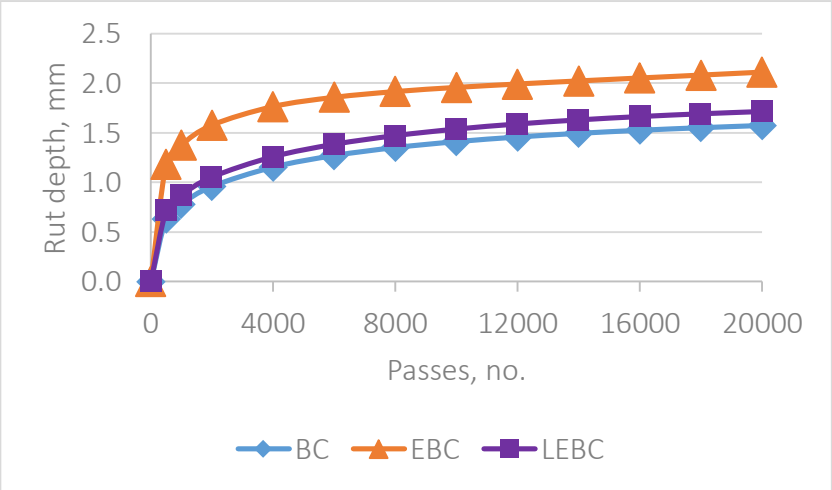
(c) LA 4%

Fig. C.15 Rut depth progression of BCII, EBCII, and LEBC mixtures prepared with PMB40 binders

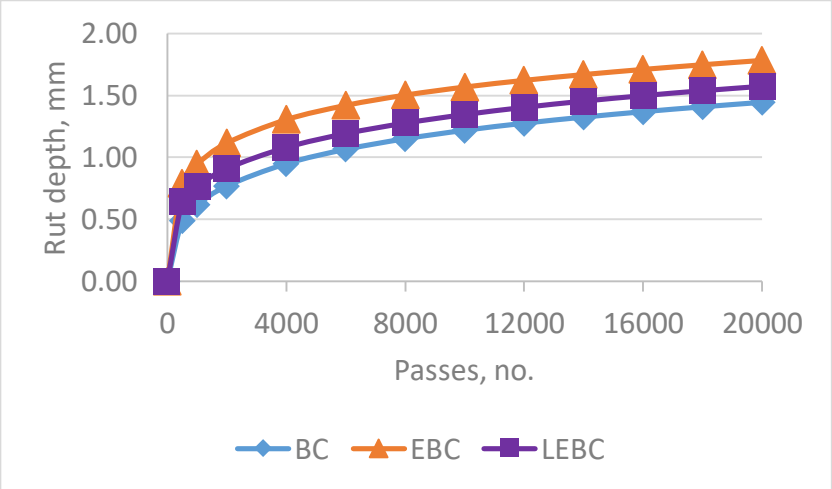
C.16 Rutting progression of BC, EBC and LEBC with PMB40 binder



(a) SA 7%



(b) SA 4%



(c) LA 4%Fig. C.16 Rut depth progression of BC, EBC, and LEBC mixtures prepared with CRMB60 binders

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LIST OF PUBLICATIONS

1. **Kumar, T. A**., Sandeep, I. J. S., Nivitha, M. R., Chowdary, V., and Krishnan, J. M. (2019). *"Quantification of Aging Compounds in Evotherm-Modified Warm-Mix Asphalt Binder Using Fourier Transform Infrared Spectroscopy."* Arabian Journal for Science and Engineering, 44, 8429-8437. (DOI: 10.1007/s13369-019-03965-w).
2. **Kumar, T.A., Arjun**, P.V., Mubashirhussain, S., Vishnu, R., Chowdary, V. and Asif, K. A. (2022). *"Influence of Evotherm on the Thermal Equilibrium Time of Unmodified and Modified Bituminous Binders."* Australian Journal of Civil Engineering.
3. **Kumar, T.A.,** Konda, B., and Chowdary, V. (2022). *"Influence of Waste Plastic Dosage on Bituminous Concrete Mix Design Properties."* International Journal of Transportation Engineering and Traffic System, 8(1), 33-39.