

# **Evaluation of Modified Binders and Mixes with Warm Mix Asphalt (WMA) Additives**

*Thesis submitted in Partial Fulfilment of the  
Requirements for the Degree of*

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in Civil Engineering

by

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# Certificate

This is to certify that the thesis titled “*Evaluation of Modified Binders and Mixes with Warm Mix Asphalt (WMA) Additives*” submitted by *Ashok Julaganti* to Indian Institute of Technology Guwahati, for the award of the degree of Doctor of Philosophy is a record of bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy.

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# Declaration

I declare that this written submission represents my ideas in my own words and where others ideas and 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 misinterpreted or fabricated or falsified any idea/ data/ fact/ source in my submission. This thesis, in any way, does not purport to endorse any proprietary products or technologies.

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# Abstract

Road transportation sector plays a major role for socio-economic growth of any country. At present, India has the third largest road network in the world, with over 5.472 million km of roadways spread across the country. In India, majority of the pavements are of flexible type that are surfaced with hot mix asphalt (HMA). HMA is a mixture of different sizes of aggregates, uniformly mixed and coated with bitumen at temperatures greater than 150°C. These high production temperatures consume large amount of energy/fuel and release greenhouse emissions into the atmosphere.

Rising fuel prices and increasing environmental awareness have motivated researchers to look for new technologies that can reduce energy requirements and emissions associated with HMA production. Warm mix asphalt (WMA) is a technology aimed at reducing the mixing and compaction temperatures by 20–40°C with performance equivalent to that of HMA. Reduced production temperatures help to bring down fuel consumption and emissions during asphalt mix production.

Meanwhile, the benefits of modified asphalt binders to cater for increasing traffic, severe axle loads, and unanticipated variations in pavement temperatures, are increasingly being recognised. Binder modification is reported to improve the performance of asphalt mixtures in terms of resistance to rutting, fatigue, thermal cracking, and oxidative ageing. Polymer- and crumb rubber-modified binders (PMB and CRMB) are commonly used binders under this category in India. However, modified binders require higher mixing and compaction temperatures during production of asphalt mixes. Integrating WMA technologies with modified binders appears to be a synergistic combination that will help in reducing the mixing and compaction temperatures of modified binders while utilising their benefits.

The current study sets out to evaluate the influence of WMA additives on rheological properties of modified asphalt binders as well as on the performance of bituminous concrete mixes containing modified binders. Experimental variables in the present research include modified binder type (PMB and CRMB), WMA additive type and its content (Evotherm: 0.5%, 0.6%; and Sasobit: 1%, 2%, 3% by weight of binder), and reductions in mix production temperatures (0°C, 20°C, 30°C, and 40°C). Warm binders were evaluated for rheological properties through different tests: viscosity, temperature and frequency sweeps, high performance grade, repeated creep recovery, and multiple stress creep and recovery. Warm mixes as well as control mixes (without WMA additives, and prepared at standard temperatures) were evaluated for volumetric and Marshall parameters, followed by assessment of their performance characteristics in terms of moisture susceptibility, resilient modulus, rutting, and fatigue.

Rheological results showed that addition of Evotherm had no appreciable effect on the rheology of PMB and CRMB binders, whereas the addition of Sasobit improved stiffness and elastic properties of both binders at high pavement service temperatures. While studying ageing characteristics at lower short-term ageing temperatures, results showed that there was decrease in the high performance grade, complex modulus, elastic modulus, and viscous modulus of warm asphalt binders containing Sasobit on being aged at lower temperatures. However, with increase in Sasobit content rheological parameters of binders with Sasobit aged at 143°C and 123°C compared well with control binders aged at standard temperature (163°C).

Bituminous concrete mix evaluation results showed that the addition of WMA additive (either Evotherm or Sasobit) showed comparable volumetrics, Marshall, and moisture damage resistance with control mixes in the range of 20–30°C temperature reductions. Performance properties of warm mixes (produced with 30°C reduction) in terms of resilient modulus, creep, and fracture life were comparable to control mixes. Overall, findings of this study indicate that a reduction of 30°C in the production temperatures can be achieved with both PMB and CRMB binders and selected WMA additives (Evotherm and Sasobit). From rheological evaluation and mix properties, it is recommended to use a dosage rate of 0.6% for Evotherm and 2% for Sasobit.

**Keywords:** Warm mix asphalt, polymer modified bitumen, crumb rubber modified bitumen, Sasobit, Evotherm.

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अज्ञानतिमिरान्धस्य ज्ञानांजनशलाकया ।  
चक्षुरुन्मीलितं येन तस्मै श्रीगुरवे नमः ॥

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# List of Abbreviations

<b>AASHTO</b>	.. American Association of State Highway and Transportation Officials
<b>AI</b>	..... Ageing Index
<b>ANOVA</b>	.... Analysis of Variance
<b>ASTM</b>	..... American Society for Testing and Materials
<b>AV</b>	..... Air Voids
<b>AVR</b>	..... Air Void Ratio
<b>BBR</b>	..... Bending Beam Rheometer
<b>BC</b>	..... Bituminous Concrete
<b>BS</b>	..... British Standard
<b>CO</b>	..... Carbon Monoxide
<b>COC</b>	..... Cleveland Open Cup Apparatus
<b>CEI</b>	..... Compaction Energy Index
<b>CR</b>	..... Crumb Rubber
<b>CRMB</b>	.... Crumb Rubber Modified Bitumen/Binder
<b>DSR</b>	..... Dynamic Shear Rheometer
<b>EN</b>	..... European Committee for Standardization,
<b>EVA</b>	..... Ethylene Vinyl Acetate
<b>ETP</b>	..... Ethylene Terpolymer

**F-T** ..... Fischer-Tropsch

**GPC** ..... Gel Permeation Chromatography

**HMA** ..... Hot Mix Asphalt

**HWMA** ... Half Warm Mix Asphalt

**IIT** ..... Indian Institute of Technology

**IRC** ..... Indian Roads Congress

**IS** ..... Indian Standard

**ITS** ..... Indirect Tensile Strength

**ITFT** ..... Indirect Tensile Fatigue Test

**LEA** ..... Low Energy Asphalt

**LMS** ..... Large Molecular Size

**LVDT** ..... Linear Variable Differential Transducer

**MoRTH** ... Ministry of Road Transport and Highways

**MSCR** .... Multiple Stress Creep and Recovery

**NAPA** ..... National Asphalt Paving Association

**NMAS** .... Nominal Maximum Aggregate Size

**OBC** ..... Optimum Binder Content

**PATTI** .... Pneumatic Adhesion Tensile Testing Instrument

**PAV** ..... Pressure Ageing Vessel

**PG** ..... Performance Grade

**PI** ..... Penetration Index

**PMA** ..... Polymer Modified Asphalt

**PMB** ..... Polymer Modified Bitumen/Binder

<b>R&amp;B</b> .....	Ring and Ball Apparatus
<b>RAP</b> .....	Reclaimed Asphalt Pavement
<b>RMS</b> .....	Retained Marshall Stability
<b>RPT</b> .....	Reduction in Production Temperature
<b>RSM</b> .....	Response Surface Methodology
<b>RTFO</b> .....	Rolling Thin Film Oven
<b>SBR</b> .....	Styrene Butadiene Rubber
<b>SBS</b> .....	Styrene Butadiene Styrene
<b>TDI</b> .....	Traffic Densification Index
<b>TSR</b> .....	Tensile Strength Ratio
<b>UTM</b> .....	Universal Testing Machine
<b>VFA</b> .....	Voids Filled with Asphalt
<b>VFB</b> .....	Voids Filled with Bitumen
<b>VG</b> .....	Viscosity Graded
<b>VMA</b> .....	Voids in Mineral Aggregates
<b>VOC</b> .....	Volatile Organic Compounds
<b>WMA</b> .....	Warm Mix Asphalt



# List of Symbols

$\overline{ITS}_c$ .....	Average Indirect Tensile Strength of Conditioned Specimens
$\overline{ITS}_u$ .....	Average Indirect Tensile Strength of Unconditioned Specimens
$\overline{MS}_c$ .....	Average Marshall Stability of Conditioned Specimens
$\overline{MS}_u$ .....	Average Marshall Stability of Unconditioned Specimens
$\sigma$ .....	Applied Stress Level
$\Delta h$ .....	Change in Height of Specimen
$G^*$ .....	Complex Modulus
$J$ .....	Compliance
$P$ .....	Compressive Load
$\theta$ .....	Deflection Angle
$df$ .....	Degree(s) of Freedom
$G'$ .....	Elastic Modulus
$H_0$ .....	Initial Height of Specimen
$T$ .....	Maximum Applied Torque
$\gamma_{max}$ .....	Maximum Resultant Strain
$\tau_{max}$ .....	Maximum Shear Stress
$G_{mm}$ .....	Maximum Specific Gravity
$J_{nr}$ .....	Non-recoverable Creep Compliance

$\epsilon_{nr}$  ..... Non-recoverable Strain

$\epsilon_p$  ..... Permanent Axial Strain

$\delta$  ..... Phase Angle

$\mu$  ..... Poisson's Ratio

**D** ..... Specimen Diameter

**h** ..... Specimen Height

**r** ..... Specimen Radius

**M<sub>R</sub>** ..... Resilient Modulus

**H<sub>r</sub>** ..... Total Recoverable Horizontal Deformation

**G''** ..... Viscous Modulus



# Chapter 1

## Introduction

### 1.1 General

Road transportation sector in India has expanded substantially in the last sixty years after independence, both in terms of capacity and dimensions. At present, India is having the third largest road network in the world, with over 5.472 million km of roadways spread across the country (MoRTH, 2016). Currently, majority of the Indian roads are flexible pavements, which are surfaced with hot mix asphalt (HMA). HMA has been continuously evolving over the last 130 years and is recognised as a quality engineered paving material to produce durable pavements. It is produced from a combination of well-graded aggregates and bitumen<sup>1</sup> mixed together at high temperatures ranging from 150°C to 170°C. HMA is produced either in a batch mix plant or a drum mix plant through a sequential procedure that involves drying of aggregates, heating of bitumen, mixing of aggregates and bitumen, and finally storage of the mix in silos.

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<sup>1</sup>Bitumen and asphalt are synonyms of each other and both terms have been used interchangeably in this thesis. Similarly, bituminous mixes and asphalt mixes are used interchangeably.

Performance of a bituminous mix is dependent mainly on: aggregate physical characteristics (strength, shape, hardness, toughness, adhesion with bitumen); binder properties (viscosity, resistance to permanent deformation, ageing, fatigue, low temperature cracking); and on bituminous mix properties (air voids, resistance to moisture-induced damage, fatigue life, permanent deformation resistance, and resistance to low temperature cracking). Aggregates are mainly obtained from natural deposits of rocks, which are crushed to obtain the desired shape and size. Aggregates constitute about 93–95% of bituminous mix by weight. Bituminous binder comprises 5–7% of the mix, and is the costliest component and plays an important role in the performance of mixes. Different methods of design and compaction are used to get the desired volumetrics of bituminous mixes to achieve the requisite strength, flexibility, and durability.

Asphalt binders are normally obtained through refining of crude petroleum. These are also known as straight-run or neat binders. However, with the increase in traffic, axle loads, and higher variations in service temperatures, bitumen modification is increasing day-by-day. Styrene butadiene styrene (SBS), styrene butadiene rubber (SBR), ethylene vinyl acetate (EVA), polyethylene and crumb rubber are some of the most common modifiers used for asphalt binder modification (Airey, 2004; Sengoz and Isikyakar, 2008). Binder modification has been reported to improve the performance properties of asphalt mixtures in terms of permanent deformation, fatigue, low temperature cracking, adhesion characteristics, wearing resistance, and resistance to ageing (Airey, 2003; Lu and Isacsson, 2000). Usually, modified asphalt binders are more viscous compared to straight-run (neat) binders as low molecular weight oil fraction present in binders get absorbed by polymers (Kim et al., 2012) and crumb rubber particles (Gaweł et al., 2011). The increase in viscosity of modified asphalt binders often

results in higher mixing and compaction temperatures (about 10–30°C higher compared to neat binders), which increases the fuel consumption during production of HMA and also subsequently leads to higher emissions.

One main concern associated with the high HMA mixing and compaction temperatures<sup>2</sup> is requirement of large amounts of energy and release of enormous amounts of emissions into the environment. For example, production of one lakh tonnes of HMA in a year through batch mix plant requires about 6.5 to 7.5 lakh litres of fuel and releases about 20 tons of carbon monoxide (CO), 0.7 tons of volatile organic compounds (VOC), 0.3 tons of sulphur oxides, 1.3 tons of nitrogen oxides and about 0.45 tons of total hazardous air pollutants into the atmosphere (USEPA, 2000). Stringent environmental regulations and the present demand to reduce fuel consumption and emissions have created need in the asphalt industry to look for alternative technologies that can reduce the energy required to produce HMA.

Warm mix asphalt (WMA) technology is one of the solutions. WMA is a generic term referring to technologies which allow reduction in mixing and compaction temperatures of asphalt mixes. This reduction in production temperatures is achieved either by lowering viscosity of asphalt binders, or by increasing volume of binder, or by reducing surface tension between the aggregates and the binder (Lee et al., 2009). Asphalt Institute in USA describes WMA as an HMA mix that is produced and compacted at temperatures 10–40°C lower than the conventional HMA mixes, whereas in Europe, the technologies used to reduce the mixing temperatures of bituminous mixtures by 20–40°C are called as WMA (Vaitkus et al., 2009). In India, the technologies which are capable

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<sup>2</sup>Mixing and compaction temperatures are collectively referred as production temperatures, and are used interchangeably in this thesis.

of reducing the mixing and compaction temperatures by at least 30°C are referred as WMA (IRC:SP-101, 2014).

Lower production temperatures with WMA help in reducing the fuel consumption and emissions from the asphalt mix plants by approximately 30% (Hurley and Prowell, 2005). WMA also offers additional benefits like longer hauling distances, reduced binder ageing, quicker turnover to traffic, cool weather paving, low plant wear and tear, improved workability, and better working environment for the paving crew.

## 1.2 Problem Statement

WMA technologies are recently developed with the aim to reduce the mixing and compaction temperatures of asphalt mixes. These technologies reduce the production temperatures either by reducing the viscosity of binder or by improving the workability at binder-aggregate interface or by increasing the volume of binder. Based on their working mechanisms, WMA technologies have been broadly classified into three categories: (i) based on organic additives, (ii) based on chemical additives, (iii) based on foaming techniques. Some common organic additives include Sasobit, Asphaltan B, Licomont BS 100, *etc.* Examples of some common chemical additives are Evotherm, Cecabase RT, *etc.*

Continual rise in traffic volume, axle loads, coupled with significant temperature variations will continue to support the use of modified binders for present-day asphalt pavements. Requirement of impractically high manufacturing temperatures for these binders has been a long-felt concern related to their widespread use. In this regard, it becomes imperative to investigate their performance in union with WMA additives—not only in terms

of rheological characterisation of the binders, but also in terms of properties of asphalt mixes made with such binders. In spite of many studies reported on the use of WMA additives with straight-run binders, only limited studies have evaluated performance of WMA additives with modified asphalt binders. While there have been improvements in properties of binders and mixes with the addition of WMA technologies, many studies have reported decline in the desirable attributes, especially in terms of moisture-induced damage resistance, fatigue resistance, and rutting behaviour. Under the category of organic additives, Sasobit has been reported in many studies, while Evotherm has been the widely used chemical WMA additive. Both technologies/additives appear promising for future applications.

Moreover, in majority of the studies on WMA mixes, researchers have employed single content of selected WMA additive(s) for evaluating asphalt binder and mix properties. The proliferation in the number of WMA additives available commercially—each with distinct recommended dosage rate and the achievable reductions—has further created impetus for more in-depth studies taking into account the effect of additive dosages and reductions in production temperatures. This will help to further the understanding on behaviour of WMA additives and to derive meaningful conclusions related to their effects on binder and mix properties.

Implementation of WMA technology in India is in its emergence stage. The differences in aggregate gradations, binder type and production, mix type, as well as mix design and testing conditions followed in India further require specific studies to gain understanding and confidence on performance of WMA mixes. Under this perspective, this study evaluates the effect of WMA additives on rheological properties of modified asphalt binders as well as on performance

of bituminous concrete mixes containing modified asphalt binders. The present research incorporates different variables including: WMA additive type, WMA additive dosage, modified binder type, and different reductions in mix production temperatures. Modified binders incorporated with different dosages of WMA additives are examined for rheological characterisation through determination of viscosity, high temperature performance, creep and recovery response, temperature and frequency sweep tests. As for the mixes, the study evaluates the resistance to permanent deformation, resilient modulus, fatigue damage, and moisture susceptibility characteristics in addition to volumetric and Marshall properties. Control mixes (without WMA additive) are also prepared at standard production temperatures and tested for different performance properties for comparison with WMA mixes.

### **1.3 Objectives of the Study**

The primary aim of this research is to evaluate the properties of modified asphalt binders and mixes with different WMA additives. The study includes two WMA additives (Evotherm and Sasobit) each with different dosage rates, two modified binder types (PMB: polymer modified bitumen and CRMB: crumb rubber modified bitumen), and four reductions in mix production temperatures. The specific objectives under this research are the following:

1. Evaluation of rheological characteristics of modified binders with different dosages of selected WMA additives.
2. Evaluation of volumetric properties of warm asphalt mixes and comparison with control mixes.

3. Determination of moisture susceptibility characteristics of control and warm mixes.
4. Performance evaluation of control and warm mixes in terms of resilient modulus, fatigue damage, and resistance against permanent deformation.

## 1.4 Organisation of Thesis

The contents of this thesis have been organised in eight chapters. Chapter 1 presents an introduction to the research area, and highlights the research problem and objectives of the research work. An extensive review of literature related to this research and identification of research gaps is covered in Chapter 2. Chapter 3 presents the selection of materials, their characterisation, experimental programme, and test procedures used to achieve the framed objectives. Chapter 4 reports results of rheological characterisation of both modified binders under unaged and short-term ageing conditions containing different dosages of WMA additives. The results of Marshall mix design properties of bituminous mixtures with two WMA additives as a function of production temperature, dosage of each WMA additive, and binder type are presented in Chapter 5. Chapter 6 presents the moisture susceptibility characteristics of warm mixes prepared with the two WMA additives. The performance test results of both control and warm mixes are presented in Chapter 7. Finally, Chapter 8 summarises the study and presents the conclusions drawn from the results and analyses, and recommendations for future research.



## Chapter 2

### Review of Literature

#### 2.1 Introduction

WMA technologies are recently introduced technologies aimed at reducing the asphalt mix production temperatures. Researchers have been making continual efforts to evaluate the performance of mixes with different WMA additives and to compare them with conventional HMA mixes as control. This chapter presents a comprehensive review of literature on WMA technologies that encompasses the historical timeline of WMA, classification of WMA technologies, and their potential benefits. This is followed by the review of leading studies conducted to evaluate the influence of WMA technologies on the properties of asphalt binders and asphalt mixes.

#### 2.2 WMA: Historical Timeline

The idea of reducing emissions and energy requirements in asphalt industry is not new. Dr. Ladis H. Csanyi, a Professor in Iowa State University, in 1956,

realised the potential of foamed bitumen for the production of cold mix asphalt. Since then, foamed bitumen technology continued to gain popularity and has been successfully used in many countries. The original process for the preparation of foamed bitumen involved injection of steam into hot bitumen. In 1968, Mobil Oil Australia acquired the rights for Csanyi's invention and modified the process by adding cold water instead of steam.

In 1995, Maccarone studied the developments in cold mix asphalt with foamed bitumen and high binder content emulsions (Maccarrone, 1995). In 1997, a new technology called warm mix asphalt (WMA) was introduced by the pavement associations in European countries. Jenkins et al. (1999) introduced a new process called half warm mix asphalt (HWMA) that involved heating the aggregates at temperatures below 100°C and above the ambient temperatures.

The journey of WMA started in the year 1997 with German Bitumen Forum, organised in response to Kyoto protocol, aimed at reducing the emissions of greenhouse gases associated with HMA production. The use of WMA was first reported by Harrison and Christodulaki in 2000 at the First International Conference of Asphalt Pavements in Sydney. In the USA, WMA was first introduced in 2002 as a result of a sponsored technology scanning tour to Europe conducted by the National Asphalt Pavement Association (NAPA) (D'Angelo et al., 2008). Since then, WMA has continued to garner interest among the construction agencies and pavement researchers, and has led to the development of many additives/technologies (Cao and Ji, 2011). It is worth mentioning that more than 20 WMA additives/technologies are now available commercially.

## 2.3 Classification of WMA Technologies

The similarities involved in processes that reduce the manufacturing and paving temperatures of asphalt mixes have given rise to various classifications of WMA technologies. One way of classification is on the basis of production temperatures and energy savings as shown in Figure 2.1 (D'Angelo et al., 2008; Zaumanis, 2010). Warm mixes are prepared over a wide range of temperatures, ranging from 10°C lower than the HMA temperatures to the temperatures above 100°C (D'Angelo et al., 2008; Rubio et al., 2012).

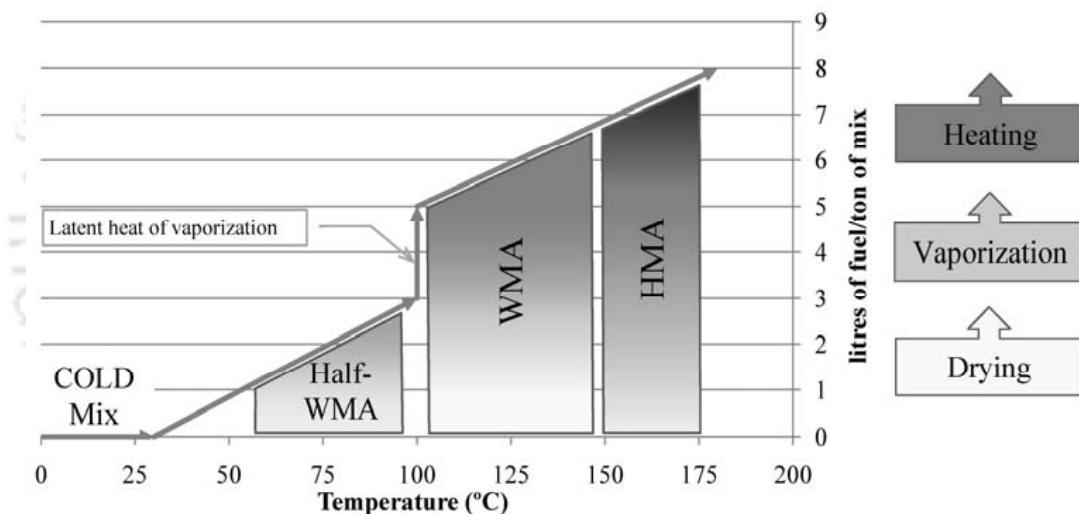


Figure 2.1: Classification of WMA technologies based on temperatures (Silva et al., 2010)

Another classification of WMA technologies is based on the similarities involved in processes/technologies. Researchers have grouped the warm mix technologies into three broad categories (D'Angelo et al., 2008; Zaumanis, 2010; Rubio et al., 2012; Xu et al., 2017):

1. Use of Foaming Technologies
2. Use of Organic Additives

### 3. Use of Chemical Additives

#### 2.3.1 Use of Foaming Technologies

In this WMA technology, small amounts of water is either injected into the hot binder or directly introduced in the mixing chamber. When water is added to the hot bitumen at high temperatures, it causes water to evaporate and get encapsulated in the bitumen. This foaming action of the hot liquid binder acts as temporary asphalt volume extender and mixture lubricant, and enables the aggregate particles to coat rapidly and improves workability and compactability of the mix at lower temperatures (Chowdhury and Button, 2008). Care has to be taken while adding water into the mixing chamber or hot binder, as excess amount of water may lead to stripping problems. Typically, the water is added at a rate of 0.5% (by weight of binder) into the hot bitumen just before mixing with the aggregates (Zaumanis, 2010).

Although the basic process remains same for most foaming technologies, the way in which the water is added to the binder may vary. Based on the method of addition of water, foaming process is sub-divided into two groups (Zaumanis, 2010):

1. Water-based technologies (Direct method)
2. Water-containing technologies (Indirect method)

#### Water-based Technologies

Water-based technologies use water in a direct way. In this method, the water required to produce the foaming effect is injected directly into the hot binder

through special nozzles. The injected water evaporates rapidly when coming in contact with hot bitumen and produces a large volume of foam. This category may be subdivided into the types of product used to make the mix (Rubio et al., 2012):

**a) Double Barrel Green System, Ultrafoam GX, and Aquablack WMA**

In all these WMA processes, water is directly injected into the hot asphalt binder stream through special types of nozzles. Each WMA process uses equipment developed by individual company. The nozzles are controlled by the computer to adjust the foaming rate. A picture of Astec Inc. foaming nozzle and multi-nozzle foaming device is shown in Figures 2.2 and 2.3 respectively.

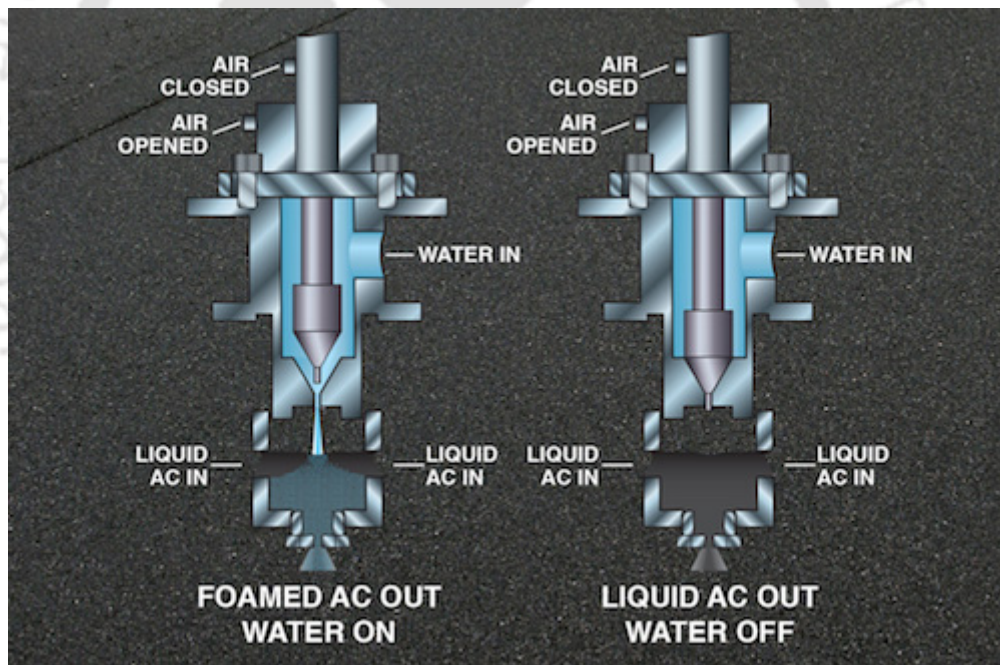


Figure 2.2: Astec Inc. foaming nozzle (Astec Inc., 2014)  
Note: AC–Asphalt cement

**b) WAM-Foam**

WAM-Foam (Warm Asphalt Mixes with Foam) process is developed jointly by Shell Global Solutions and Koko Veidekke in Norway (Larsen et al., 2004). It is a

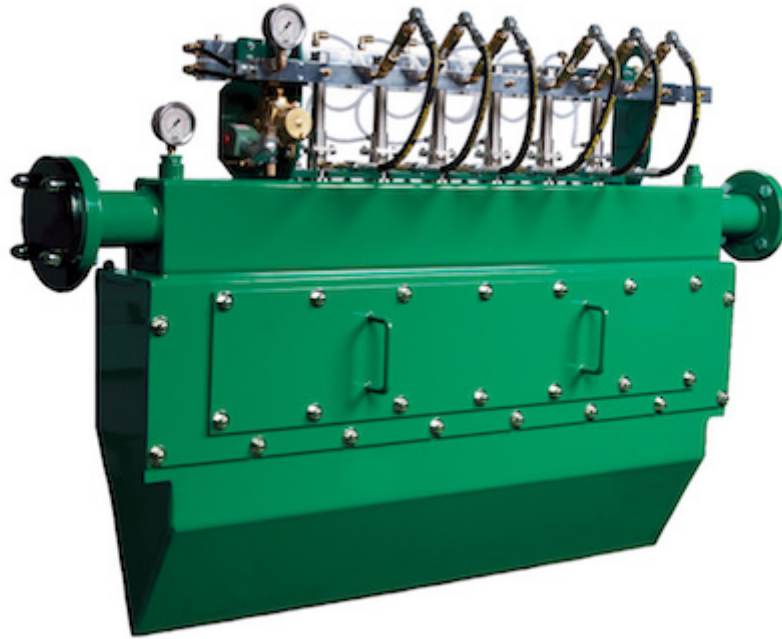


Figure 2.3: Astec Inc. multinozzle foaming manifold (Astec Inc., 2014)

two component binder system (also known as two-phase method) that introduces a soft binder and a hard-foamed binder at different times in the mixing cycle during asphalt mix production. In this system, an extremely soft binder is first mixed with the aggregate to precoat at a temperature of 98–120°C. Then the hard binder is foamed by injecting the cold water in the range of 2 to 5% by the mass of hard binder. The foamed hard binder is mixed with the precoated aggregate mix. Typically, hard binder represents 70 to 80% of total binder content. However, blend ratio of soft and hard binder components is determined based on the penetration level required for final binder. This process provides necessary workability and allows the mixture to be placed and compacted at 80–90°C (Larsen et al., 2004; Kristjansdottir, 2006; D'Angelo et al., 2008; Chowdhury and Button, 2008; Rubio et al., 2012). Typical process of Shell WAM foam process is shown in Figure 2.4.

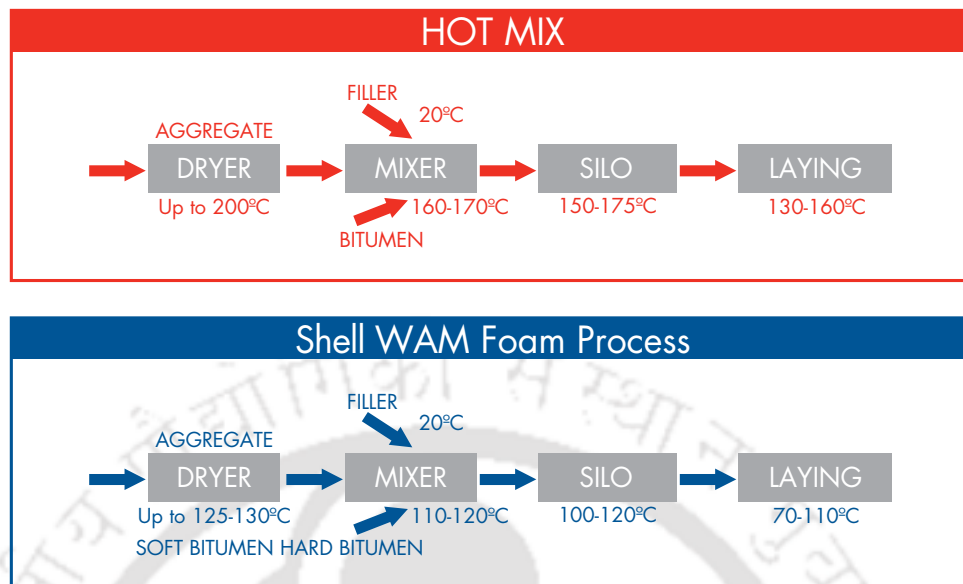


Figure 2.4: Shell WMA Foam process (Shell Bitumen, 2014)

### c) Low Energy Asphalt

Low energy asphalt (LEA) is a sequential process in which the aggregate is first mixed with a chemical added asphalt binder at a temperature of 140°C, followed by the introduction of wet sand at ambient temperatures. Moisture in wet sand helps in creating the foaming action. The wet sand fraction, which could be as high as 40% of the total mixture, is unheated in this process as shown in Figure 2.5. Asphalt mix prepared with LEA process is normally discharged at temperatures less than 90°C (Button et al., 2007).

### Water-Containing Additives

Water-containing or water-bearing additives are finely powdered synthetic zeolites that produce foaming action. Zeolites have a porous structure that can accommodate, absorb, and lose the water without damaging their crystalline structure. The zeolites are hydro-thermally crystallised that contain water

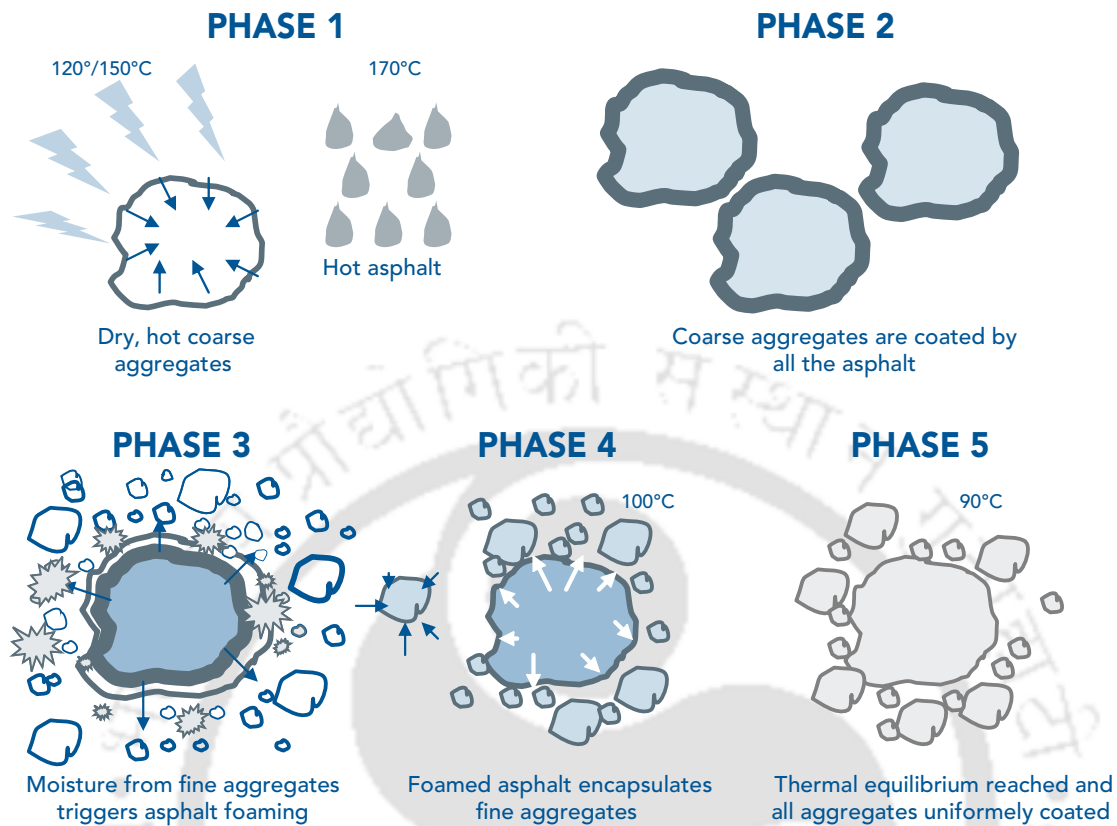


Figure 2.5: LEA process (Button et al., 2007)

approximately 21% by mass. The water is released from the zeolite structure as the temperature rises above 85°C (Zaumanis, 2010). This causes a micro-foaming effect in the asphalt mix, which provides improved workability and compactability to the mix for about 6–7 h (D'Angelo et al., 2008; European Asphalt Pavement Association, 2010; Rubio et al., 2012). Typically, 0.3% zeolite by weight of mixture is added to the mixture at the same time as binder. Aspha-min, Advera, and natural zeolites are examples of water containing additives. A picture of Aspha-min in granule form is shown Figure 2.6.



Figure 2.6: Aspha-min in granule form

### **2.3.2 Organic Additives**

Organic additives achieve the temperature reduction by reducing the binder viscosity at typical mix production temperatures. These additives have high molecular weight hydrocarbon chains with a melting point of 80–120°C. When these additives are added to binder, reduction in viscosity of binder is observed at temperatures beyond their melting point. As the additive-binder blend cools down to below the melting point, these additives solidify into microscopically small and uniformly distributed particles. This has the effect of increase in binder stiffness and resistance against deformation in the same way as fiber-reinforced materials (Zaumanis, 2010; Rubio et al., 2012). While selecting the organic additives, it needs to be ensured that the melting point of additives should be higher than expected pavement service temperatures. The right choice of organic additive also minimises embrittlement of asphalt at low

temperatures (European Asphalt Pavement Association, 2010; Zaumanis, 2010). These additives are often referred as *intelligent fillers*. Organic additives can be added directly either to the asphalt binder or to the asphalt mixture. Generally, the dosage of organic additive ranges from 2–4% by total mass of binder. Some examples of commercially available organic additives are: Sasobit<sup>®</sup>, Asphaltan B, and Licomont BS 100.

#### **a) Sasobit**

Sasobit is produced by Fischer–Tropsch (F–T) process where coal or natural gas is partially oxidised with carbon monoxide, which is subsequently reacted with hydrogen under catalytic conditions producing a mixture of hydrocarbons. The end product consists of fine crystalline structure with aliphatic polymethylene hydrocarbons having a chain length of C<sub>40</sub> to C<sub>115</sub> plus (Sasobit Product Information 124, 2017). Sasobit has melting point in the range of 85°C to 115°C and is completely soluble in the binder at temperatures above 115°C. It reduces viscosity of bitumen above its melting point, and below its melting point, it imparts additional stability to the binder by forming a crystalline network structure (Sasobit Product Information 124, 2017; Hurley and Prowell, 2005; Akisetty et al., 2009a, 2010a; Kim et al., 2010; Kumar et al., 2016).

#### **b) Asphaltan B**

Asphaltan B is a refined Montan wax produced by Romonta GmbH, Germany. Montan wax is a combination of non-glyceride long-chain carboxylic acid esters, free long-chain organic acids, long-chain alcohols, ketones, hydrocarbons and resins (D'Angelo et al., 2008). Montan wax is also known as lignite wax, and is used in making car and shoe polishes, paints, lubricants for moulding process, paper, and plastics. Romonta recommends dosage of Asphaltan B at 2 to 4% by mass of binder. It can be added to the mixture or directly to the asphalt binder.

The melting point of Asphaltan B is about 82–95°C. It also acts as an asphalt flow improver like F–T waxes, which results in reduced mix production temperatures.

**c) Licomont BS 100**

Licomont BS 100 is a fatty acid amide. Fatty acid amides are produced by reacting amines with fatty acids. Melting point of these fatty acid amides is in the range of 141°C and 145°C (Zaumanis, 2010). Similar products have been used as viscosity modifiers in asphalt for a number of years and are available in various forms. Fatty acid amides have been used in roofing asphalt since the late 1970s to early 1980s (D'Angelo et al., 2008).

### **2.3.3 Chemical Additives**

Chemical additives are relatively new and emerging group of warm mix additives. Unlike foaming techniques and organic additives, these products do not depend on increasing the volume of binder or reducing its viscosity for lowering production and placement temperatures of asphalt mixes. They generally include a combination of emulsification agents, surfactants, polymers, and additives to improve coating, mix workability, and compaction (Zaumanis, 2010; Rubio et al., 2012). These additives improve the workability of binder during mixing and compaction of the asphalt mix by regulating the interfacial frictional forces between the asphalt coated aggregate particles (European Asphalt Pavement Association, 2010). The amount of additive and temperature reduction depends on the specific product used. These additives are used either in the form of an emulsion or are added to hot bitumen during the production process and then mixed with hot aggregates. Evotherm<sup>®</sup>, Cecabase RT<sup>®</sup>, and Rediset WMX are the examples of chemical additives.

**a) Evotherm**

Evotherm was developed in the USA by MeadWestvaco (MWV) Asphalt Innovations, Charleston, South Carolina. It is a patented formulation of specialty surfactants, formulated to allow the binder to fully wet and coat the aggregates at reduced temperatures, and to lower the high-shear viscosity of binder so that workability and compactability are improved at low temperatures. They also improve the bitumen-aggregate adhesion in the finished pavement. MWV supplies Evotherm in three forms: Evotherm Emulsion Technology (Evotherm ET), Evotherm Dispersed Asphalt Technology (Evotherm DAT) and Evotherm 3<sup>rd</sup> Generation (Evotherm 3G).

Evotherm ET (Emulsion Technology) was introduced in 2005. It uses a chemical package of emulsification agents and anti-stripping agents to improve aggregate coating, mixture workability and compaction. Evotherm ET is a binder-rich water-based emulsion that contains approximately 70% of asphalt residue (Hurley and Prowell, 2006; Arega et al., 2011). The water in the emulsion flashes off in the form of steam when it is mixed with hot aggregates leaving the residual asphalt and chemical additives (Hurley and Prowell, 2006; Kandhal, 2010; Bonaquist, 2011). This technology does not require plant modification and simply replaces the liquid asphalt in the HMA design (Estakhri et al., 2010).

Evotherm DAT was developed in 2006 and introduced in the field in 2007 (Kandhal, 2010; Maze et al., 2011). It is a mixture of water and a chemical that is injected directly into the asphalt binder supply line at the mix plant (Maze et al., 2011) as shown in Figure 2.7. Evotherm DAT uses the same chemical package as Evotherm ET. The main advantage of Evotherm DAT over Evotherm ET is that it uses less amount of water (Bonaquist, 2011). It decreases viscosity of binder at mixing temperatures, which leads to improved coating of aggregates. Use of

Evotherm DAT does not require any plant modifications except a separate pipe line to inject the additive (Kandhal, 2010). MWV suggests a dosage rate of 10 to 20% of Evotherm DAT by weight of binder. Evotherm DAT is available in two forms: Evotherm F6 and Evotherm H5.



Figure 2.7: Staking of Evotherm DAT line to bitumen line (Maze et al., 2011)

Evotherm 3G is the latest technology developed by MeadWestvaco Paragon Technical Services and Mathy Technology and Engineering (Nazzal and Abu-Qtaish, 2013). It is a water-free form that includes additives to improve coating and workability, surfactants to enhance aggregate-binder adhesion, and agents to promote workability and compaction (MWV, 2010). The main benefit of Evotherm 3G is that it can be mixed with the binder at a terminal and can be distributed to asphalt plants using normal binder distribution process (Bonaquist, 2011). It can also be added at the mix plant using a metering system as shown in Figure 2.8. Evotherm 3G is available in two different forms: Evotherm J1 and Evotherm M1.



Figure 2.8: Metering system for Evotherm line (Maze et al., 2011)

**b) Rediset WMX**

Rediset WMX is a product from Azko Nobel, Netherlands. It is a combination of cationic surfactants and additives to enhance the adhesion of binder to the aggregate. Surfactants improve the wetting ability of the asphalt binder for better coating with the aggregates, and the additives allow a reduction in viscosity of the binder providing a lubricating effect for easier coating and compaction (Sampath, 2010). Rediset WMX is available in a free-flowing pellet form as shown in Figure 2.9. Recommended percentage of Rediset WMX is 1.5-2.0% by weight of binder.

**c) Cecabase RT®**

Cecabase RT® is a patented chemical WMA additive developed by CECA Chemicals, a part of Arkema Group, France. It consists of surface-active agents,



Figure 2.9: Rediset (Sampath, 2010)

which are made up by at least 50% renewable raw materials. The recommended dosage of Cecabase RT<sup>®</sup> is 0.3-0.5% by weight of the binder (Vaitkus et al., 2009).

## 2.4 Benefits of WMA Technologies

WMA technologies are reported to offer several benefits over conventional HMA. The specific benefits and the degree of benefits depend upon WMA process used. Some of the advantages associated with the use of WMA technologies are:

1. **Energy Savings:** The most important benefit from WMA is the reduction in the consumption of fuel used for heating of the aggregates and bitumen. Many studies have reported that the energy savings of about 35% can be achieved due to reduction in the production temperatures (Kandhal, 2010; Sampath, 2010).
2. **Decreased Emissions:** Use of WMA technologies lead to decrease in the emissions of gaseous pollutants (CO<sub>2</sub>, CO, SO<sub>2</sub>, and NO<sub>x</sub>). This permits the

asphalt industries to install asphalt mixing plants in and around non-attainment areas.

3. **Decreased Fumes and Odour:** WMA produces lower fumes and odour at both plant and paving sites compared to traditional HMA. This provides safer working conditions for the paving personnel.
4. **Less Binder Ageing:** Lesser binder ageing takes place due to lower production temperatures of WMA, thus improving the longevity of pavement.
5. **Extended Paving Season:** By producing WMA at normal HMA temperatures, it is possible to extend the paving season to the colder months of the year since the WMA acts as a compaction aid.
6. **Longer Haul Distance:** As the difference between production temperatures and ambient temperature is smaller for WMA compared to that of HMA, the drop in temperature with time is less for WMA allowing a longer time/hauling distance for paving and compaction operations.

## 2.5 Effect of WMA Additives on Binder Rheology

Working mechanism of several WMA technologies is based on changing the properties of the asphalt binder to achieve desired degree of reduction in production temperatures. Therefore, it is essential to understand the effect of WMA additive type and content on rheology of different binders. Review of studies conducted to evaluate the effect of WMA technologies on asphalt binder rheology are discussed further.

Kanitpong et al. (2007) investigated the effect of Sasobit on the properties of two asphalt binders: a virgin binder (AC 60/70), and a polymer-modified asphalt (PMA) binder modified with 5% SBS. Warm asphalt binders were prepared by adding 3% Sasobit (by weight of binder) directly to the binders at a temperature of 130°C. Warm asphalt binders were evaluated for viscosity, storage modulus ( $G'$ ), loss modulus ( $G''$ ), and creep recovery tests. Addition of Sasobit reduced the viscosity of both binders, and the effect was minimal for AC 60/70 binder.  $G'$  and  $G''$  of both binders increased with the addition of Sasobit in temperature range of 16°C to 60°C, and the increase was profound at higher temperatures (50°C to 60°C). Creep and recovery test results revealed that addition of Sasobit resulted in lower accumulated strain for both AC and PMA binders as shown in Table 2.1.

Table 2.1: Creep and recovery test results of binders (Kanitpong et al., 2007)

<b>Binder</b>	<b>Strain at 50 cycles (mm/mm)</b>	<b>Rate of strain accumulation</b>
AC 60/70	37.2	$7.5 \times 10^{-2}$
AC 60/70 + 3% Sasobit	0.587	$1.0 \times 10^{-3}$
PMA	0.251	$3.0 \times 10^{-4}$
PMA + 3% Sasobit	0.016	$2.0 \times 10^{-5}$

You and Goh (2008) evaluated the rheological properties of neat asphalt binder with two percentages of a synthetic zeolite. Warm asphalt binders were prepared with 0.3% and 0.5% (by weight of binder) synthetic zeolite and were tested for Superpave properties. Viscosity of binder reduced with the addition of synthetic zeolite, however the addition of synthetic zeolite had no significant effect on viscosity results. Resistance of binder towards rutting decreased in both unaged and aged conditions. Addition of additive bumped down the grade of binder by one performance grade (PG 64 to PG 58). DSR and BBR results

revealed that binders with synthetic zeolite had lower fatigue resistance compared to neat binders.

In one of the studies by Akisetty et al. (2009b), high temperature properties of rubberised binders with two WMA additives (Sasobit and Aspha-min) were studied. PG 64–22 asphalt binders from five different sources were used in this study. Rubberised binders were prepared by adding 10% crumb rubber particles by weight of binder. Warm rubberised asphalt binders were prepared using 0.3% (by weight of binder) of Aspha-min and 1.5% (by weight of binder) of Sasobit. Binders were tested for viscosity in unaged condition at 135°C and 120°C, and for failure temperatures before and after short-term ageing using DSR. The effect of time on viscosity of binders after adding WMA additives was also measured. Addition of Aspha-min increased the viscosity of binder, whereas Sasobit reduced the viscosity. Addition of WMA additives increased the viscosity of binder with time. Both additives increased the failure temperature of binders. It was reported that the binder source significantly affected the high temperature rheological properties of rubberised binders.

The ageing characteristics of asphalt binders with WMA additives was studied by Gandhi et al. (2009) with PG 64–22 binders (three sources) and two WMA additives (Aspha-min and Sasobit). Warm asphalt binders were prepared by adding Aspha-min and Sasobit to the binders. Rolling thin film oven (RTFO) and pressure ageing vessel (PAV) were respectively used to simulate the short-term and long-term ageing of the binders. As the warm asphalt is produced at lower temperatures, the short-term ageing of warm asphalt binder was conducted at a lower temperature. Binder from sources 1 and 3 were RTFO aged at 130°C; and Binder 2 at 140°C, in addition to the standard testing

temperature whereas for the long term ageing, the same traditional method was followed. The significant findings of the study were:

- RTFO aged binders containing Aspha-min had higher viscosities and binders containing Sasobit had lower viscosities compared to unmodified binders.
- Ageing index values (determined as the ratio of viscosity to RTFO aged binder to that of unaged binder) of binders aged at a lower temperature were less than the binders aged at the standard temperature of 163°C.
- RTFO aged binders containing Aspha-min and Sasobit had higher  $G^*/\sin\delta$  values compared to unmodified binders.
- Addition of Aspha-min or Sasobit did not influence fatigue resistance ( $G^*\cdot\sin\delta$ ) of binders.
- Addition of Aspha-min or Sasobit reduced  $m$ -values of binders aged at 163°C, whereas  $m$ -values of warm asphalt binders aged at 130/140°C were greater than the warm asphalt binders aged at 163°C.
- It was reported that binder source had no significant effect on viscosity, anti-rutting factor, fatigue resistance, and creep stiffness.

Biro et al. (2009) evaluated the rheological properties of asphalt binders with WMA additives at midrange temperatures. Warm asphalt binders was prepared using two additives (Aspha-Min and Sasobit) and neat PG 64–24 binders (from five sources). Dosage rate of Aspha-Min and Sasobit was 0.3% (by weight of mixture) and 1.5% (by weight of the binder) respectively. Rheological tests such as viscosity, performance grade, creep, and creep recovery, temperature sweep, and frequency sweep were performed. All virgin binders from different sources

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exhibited Newtonian behaviour at 60°C. Addition of WMA additive Aspha-Min did not influence the nature of binders, whereas addition of Sasobit exhibited shear thinning behaviour. Addition of WMA additives increased stiffness of binders in the frequency range of 0.01 to 100 Hz, and lowered the compliance values in both creep and creep recovery tests. Temperature sweep test results showed that WMA additives did not affect complex modulus ( $G^*$ ) in the temperature range of 25–80°C, but the addition Sasobit decreased the phase angle of binders. Overall, it was reported that the binders containing Sasobit performed well in frequency sweep, creep, creep recovery, and temperature sweep tests than binders containing Aspha-min.

Doh et al. (2010) evaluated the effectiveness of two WMA additives as a replacement of rejuvenators in recycled mixes. WMA additives: Sasobit and Evotherm were used in this study. In order to evaluate the rejuvenating effect with the two WMA additives, asphalt binder was recovered from different reclaimed asphalt pavement (RAP) sources using Abson method. Two neat performance grade (PG) binders *viz.* PG 58–22 and PG 64–22 were used. Recycled binder was prepared by incorporating 20% and 30% recovered binder into the virgin binder. Dosage rate of Sasobit and Evotherm was 2% and 0.5% by weight of binders. Addition of WMA additives reduced kinematic viscosity of the binders at 135°C. Gel permeation chromatography (GPC) results showed that addition of Evotherm reduced the large molecular size (LMS) percentage in the recycled binder compared to recycled binders containing Sasobit. It was reported that WMA additive Evotherm was better than Sasobit for reducing viscosity and stiffness of the recycled binder. It was concluded that the Evotherm can be used to incorporate 30% of recovered binder into the virgin binder without use of any other rejuvenator. Sasobit, on the other hand, was found to be better for reducing the viscosity of normal binder.

Kim et al. (2010) studied the effect of WMA additives on performance properties of polymer modified asphalt (PMA) binders. Two WMA additives *viz.*, Sasobit, and Aspha-min, and PG 76–22 PMA binders from three different sources were used in this study. Warm PMA binders were prepared by adding Aspha-min at 0.3% by weight of mixture and Sasobit at 1.5% by weight of binder to the PMA binders. Superpave tests were conducted on warm PMA binders at unaged, RTFO aged, and PAV aged conditions. Viscosity of PMA binders decreased with the addition of Sasobit and increased with the addition of Aspha-min. Anti-rutting parameter ( $G^*/\sin \delta$ ) increased with the addition of WMA additives regardless of ageing state and binder source. Warm PMA binders were less resistant towards fatigue cracking at intermediate temperatures and thermal cracking at low temperatures.

Akisetty et al. (2010a) investigated the long-term performance properties of crumb rubber modified (CRM) binders with two WMA additives: Sasobit and Aspha-min. Virgin PG 64–22 asphalt binders from five sources were used in this study. CRM binders were prepared in the laboratory by adding one source and one percentage of CR (10% by weight of binder). Rubberised warm asphalt binders were produced by adding Sasobit at 1.5% by weight of binder and Aspha-min at 0.3% by weight of mixture (assuming 6% binder content in the mixture). Warm asphalt binders were tested for the long-term performance through different Superpave tests like viscosity at 135°C before and after RTFO ageing, fatigue cracking at 25°C, and cracking property at -12°C on RTFO+PAV residual. The main conclusions of the study were:

- Ageing index values of binders increased due to addition of warm mix additives.

- Warm asphalt binders were less resistant to fatigue cracking than control binders.
- Addition of Sasobit to rubberised binder increased the stiffness and decreased the  $m$ -value at  $-12^{\circ}\text{C}$  representing less resistance towards low temperature cracking, whereas addition of Aspha-min increased the stiffness and  $m$ -value at  $-12^{\circ}\text{C}$ .

Akisetty et al. (2010b) investigated unaged CRM binders through rheological properties like viscosity, creep recovery, and repeated creep recovery at  $60^{\circ}\text{C}$ . It was found that addition of WMA additives increased the viscosity of binders at  $60^{\circ}\text{C}$  irrespective of binder source. All the binders with and without WMA additives exhibited shear thinning behaviour. Binders with Sasobit had lower compliance values in both creep recovery and repeated creep recovery tests than with Aspha-min and unmodified CRM binders. CRM binders with Sasobit had lower phase angle at lower temperatures and at lower frequencies suggesting improved elasticity at lower temperatures.

Carter et al. (2010) evaluated rheological characteristics of three PG binders (PG 58–28, PG 64–34, and PG 64–34 with crumb rubber) with varying dosages of Sasobit. Results showed that reduction in viscosity with Sasobit was most effective with PG 64–34 binder. On the other hand, addition of Sasobit did not have significant effect on the viscosity of crumb rubber modified binder. A dosage of 2% Sasobit increased the high PG temperature of PG 64–34 binder to  $70.8^{\circ}\text{C}$ . However, addition of Sasobit had negative effect on the low temperature grades.

Wei et al. (2010) studied the rheological properties of two base asphalt binders with varying dosages of wax additive Sasobit. Two straight run binders

(PG 64–16 and PG 70–22) and four dosage rates of Sasobit (0.5%, 1%, 1.5%, and 2% by weight of binder) were used for the preparation of warm asphalt binders. Fourier transform infrared (FTIR) spectroscopy was used to investigate the chemical changes in the asphalt binder before and after addition of Sasobit. Rheological tests showed that addition of Sasobit increased the complex modulus and elastic properties of asphalt binders. Moreover, it was reported that degree of influence of Sasobit depended on the original asphalt binder. FTIR results showed that addition of Sasobit increased the absorbance of methylene absorption bands ( $680\text{--}750\text{ cm}^{-1}$ ), however, there was no significant effect on the sulfoxide ( $1030\text{ cm}^{-1}$ ) and carbonyl ( $1075\text{ cm}^{-1}$ ) compounds. Surface free energy analysis showed that the addition of Sasobit increased the hydrophobicity of asphalt binders and wettability of asphalt binders on the aggregate surfaces.

Cao and Ji (2011) studied rheological properties of neat asphalt binder and polymer modified binder (PMB) with different percentages of Sasobit. Pen 60/80 and SBS modified PMB binder were selected for this study. Warm asphalt binders were prepared by adding four different percentages of Sasobit (2%, 3%, 4%, and 5%) by mass of binder into the base binder. Penetration at  $25^{\circ}\text{C}$ , viscosity at both  $135^{\circ}\text{C}$  and  $163^{\circ}\text{C}$ , and ductility values were reduced, while softening point increased with the increase in Sasobit dosage. Increase in Sasobit dosage increased rutting resistance ( $G^*/\sin\delta$ ) and reduced fatigue resistance ( $G^*\cdot\sin\delta$ ) and low temperature properties of both binders. Based on the investigation, 3% Sasobit content was suggested as the optimum Sasobit content.

Mogawer et al. (2011) evaluated adhesion characteristics of the asphalt binders with four different WMA technologies through bitumen bond strength (BBS) test. WMA additives: Advera, Sasobit, SonneWarmix and Evotherm were

used. Dosage rate of Advera was 0.25% by weight of mix and remaining additives were dosed by weight of binder as: Sasobit at 1.5%, SonneWarmix at 1.0% and Evotherm M1 at 0.5%. BBS test was conducted for warm asphalt binders in both dry and wet (after 24 h moisture conditioning at 40°C) conditions using pneumatic adhesion tensile testing instrument (PATTI). Asphalt binder modified with Sasobit had highest pull off tensile strength in both dry and wet conditions indicating better adhesion. However, the drop of dry tensile strength after moisture conditioning was lower for control binder followed by binder modified with SonneWarmmix, Sasobit, Advera, Evotherm. It was reported that the addition of WMA additives had no negative effect on adhesion characteristics of asphalt binders.

Morea et al. (2012) evaluated the rheological properties of extracted asphalt binders from three different mixes *viz.* HMA, WMA (without additive), and WMA with two different tensoactive additives. Two chemical additives, generically referred as A and B were used, in which, “A” additive consisted of surface-active agents (added at a rate of 0.4% by mass of binder) and “B” contained resins, polymers, and adhesive agents (added at a rate of 2% by mass of binder). HMA mixes with 70/100 pen-grade binder and PMB were mixed at 152°C and 194°C and compacted at 140°C and 184°C respectively. WMA mixes with 70/100 binder and PMB were mixed and compacted at 30°C and 35-40°C lower temperatures, respectively. Asphalt binders were extracted directly from the mixes using Abson method. Multiple stress creep and recovery (MSCR) tests on the extracted binders showed that reduction in production temperatures increased the permanent strain irrespective of binder used, and this effect was more pronounced in case of PMB binder. Reduction in production temperature decreased the elastic response of the binder. The addition of chemical additives into PMB binder improved the elastic response of binder, and reduced the

permanent strain, whereas it did not alter the properties of pen 70/100 binders as shown in Figure 2.10 and 2.11.

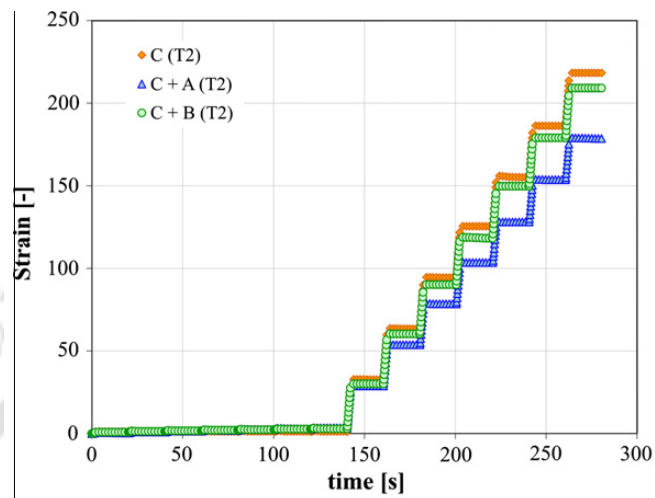


Figure 2.10: MSCR test results of warm 70/100 binders (Morea et al., 2012)

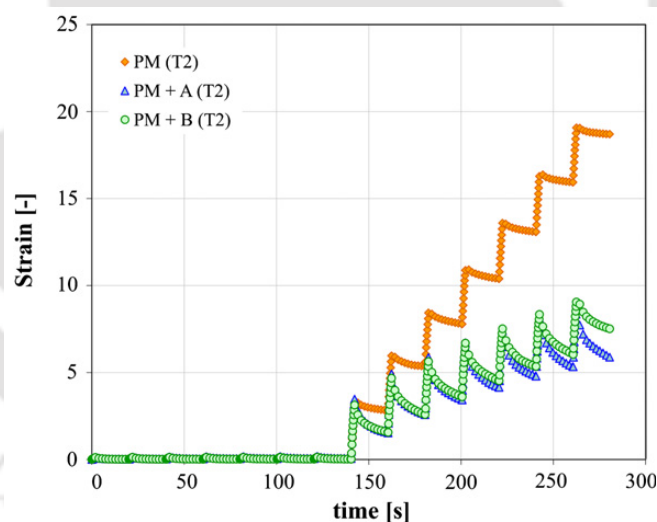


Figure 2.11: MSCR test results of warm PMB binders (Morea et al., 2012)

In one of the studies undertaken by Yi-qiu et al. (2012), the viscoelastic properties of asphalt binders were investigated with WMA additive Sasobit. Neat asphalt binders LH-70, LH-90 and KLMY-90 were selected for this study. Three percentages of Sasobit (2%, 3% and 4% by weight of binder) were used. Properties like penetration, softening point, viscosity, and rutting parameter

were determined. Increase in Sasobit dosage increased softening point, complex modulus, complex viscosity (at  $<70^{\circ}\text{C}$ ), and anti-rutting parameter ( $G^*/\sin\delta$ ). It also decreased the penetration, viscosity (at  $>110^{\circ}\text{C}$ ), and phase angle of the binders. It was reported that the increment rate of softening point and reduction rate of penetration was slow when the Sasobit content was higher than 2%. Mixing and compaction temperatures from the viscosity-temperature relationship were lowered by  $5^{\circ}\text{C}$  for all the binders with the addition of 3% Sasobit.

Wang et al. (2012) examined the effect of WMA additives on high temperature properties of CRM binders in both unaged and short-term aged conditions. WMA additives: Sasobit (2%), RH (4%), and Advera (5%) by weight of binder were used in this study. CRM binders were prepared by adding different concentrations of CR (10%, 15%, 20%, and 25% by weight of binder) to PG 64–22 binder. Addition of WMA additives decreased complex modulus ( $G^*$ ) values with increase in test temperature irrespective of CR concentration at both unaged and short-term aged conditions. However, the increase in concentration of CR increased  $G^*$  values at each temperature. Phase angle ( $\delta$ ) increased with increase in test temperature and decreased with increase in CR concentration at both unaged and aged conditions. Among all additives, CR binders with RH additive had higher rutting resistance in unaged condition and CR binders with Sasobit in short-term aged condition.

Rodríguez-Alloza et al. (2013) studied the effect of four organic additives on rheological properties of neat and CRM binders. CRM binder was prepared by adding 15% crumb rubber (by weight of bitumen) to the base binder B 50/70. Four organic WMA additives Sasobit, Asphaltan A, Asphaltan B, and Licomont were used. Warm asphalt binders were prepared by adding WMA additives at a

rate of 2% and 4% by weight of binder. Rheological properties like viscosity, penetration, ductility, elastic recovery, and softening point were evaluated. The effect of additives on the mixing and compaction temperatures was assessed. Viscosity of both neat and CRM binders were reduced with the addition of WMA additives. The increase in the WMA additive dosage further reduced the viscosity of both binders. Addition of WMA additives increased the softening point temperature and reduced the penetration values of binders. It was reported that there was no clear trend in the elastic recovery and ductility results of both binders with the addition of WMA additives.

Hossain et al. (2012) evaluated the effect of WMA additives on the chemical composition of asphalt binders. Straight run binder (PG 64-22) and two WMA additives (Sasobit and Aspha-min) were used. Spectroscopy techniques including FTIR, nuclear magnetic resonance (NMR), and elemental analysis were used for chemical characterization. NMR spectroscopy results showed that addition of Sasobit increased the aliphatic content of asphalt binders that improved the binders' elastic component. Addition of Aspha-min did not change the aliphatic component of base asphalt binder. FTIR spectroscopy results showed that absorbance peaks of base asphalt binder shifted to left side with the addition of Sasobit or Aspha-min. It was also reported that asphalt binders with Sasobit and Aspha-min had higher contents of carbon and nitrogen compared to base asphalt binder, which improved the complex modulus of asphalt binder.

Topal et al. (2014) evaluated the rheological characteristics of neat binder (50/70) with two types of zeolite (natural and synthetic). Dosage rate of both types of zeolite was 5% by weight of bitumen. Rheological properties such as, penetration, softening point, penetration index (PI), viscosity were evaluated.

Addition of synthetic and natural zeolite decreased the penetration and increased the softening point making the WMA asphalt less susceptible to rutting. Addition of zeolite also resulted in higher PI indicating lower temperature susceptibility and higher resistance to low temperature cracking. Addition of natural and synthetic zeolites reduced the viscosity of binder (at 135°C) by 21% and 24% respectively.

Zhang et al. (2015) conducted a study on the viscosity-temperature characteristics of warm mix asphalt binder with Sasobit. Two penetration grade binders (70# and 90#) and five doses of Sasobit (1%, 2%, 3%, 4% and 5% per unit weight of the asphalt binder) were used in this study. Rheological properties such as penetration, softening point, ductility, dynamic viscosity (at 60°C) and apparent viscosity (in the range of 110°C to 160°C) were evaluated. Increase in Sasobit content decreased the penetration value and increased the softening point for both grades of bitumen. However, a decrease in ductility was observed with the increase in Sasobit dosage, making it susceptible to low temperature failures. Dynamic viscosity increased with the increase in Sasobit dosage. Apparent viscosity results concluded that the addition of Sasobit would reduce the viscosity of both binders during the construction stage to improve the workability and thereby reduce the compaction temperature.

Kheradmand et al. (2015) investigated the rheological properties of asphalt binders modified with Sasobit. One 60-70 penetration grade bitumen and two dosages of Sasobit (1.5% and 3% by weight of binder) were used. Warm asphalt binders were tested for rheological properties including penetration, softening point, viscosity (at 135°C and 165°C), frequency sweep and temperature susceptibility. FTIR analysis was conducted to understand to effect of Sasobit on chemical characteristics of binders. Addition of Sasobit decreased the

penetration, and viscosity at 135°C and 165°C. Elastic properties, complex modulus, and softening point of bitumen were found to increase with the addition of Sasobit. It was reported that addition of Sasobit had slight effect on carbonyl index (C=O), which measures the degree of oxidation. However, it was reported that there was no significant effect on the FTIR results of asphalt binder with the addition of Sasobit.

Yu et al. (2016) studied the effect of non-foaming WMA additives on rheological and chemical characteristics of asphalt rubber binders. One asphalt rubber binder and three non-foaming WMA additives (Evotherm DAT, Sasobit, and 56# paraffin wax) were used in the study for the preparation of three types of warm asphalt binders. Additionally, fourth warm asphalt binder was prepared with the combination of Evotherm DAT and Sasobit). Penetration, softening point, FTIR, and Superpave tests were conducted on the warm asphalt binders. Sasobit enhanced the high-temperature properties of asphalt rubber binder and had slightly negative influence on its resistance to fatigue and cracking. Evotherm DAT reduced both rutting and fatigue resistance of asphalt binder, but had no significant effect on the low temperature properties. Addition of paraffin wax showed slightly negative effects on the Superpave properties. Moreover, it was reported that the use of combination of WMA additives did not improve rheological properties of asphalt binder and was not a viable option for reducing the production temperatures. FTIR results showed that all binders had similar absorption peaks at similar wavenumbers. It was concluded that addition of WMA additives had no significant effect on chemical properties of asphalt binders.

Kataware and Singh (2017) determined the effectiveness of different types of WMA additives on rheological properties of SBS polymer modified binder

(PMB). Three WMA additives: Sasobit (1%, 2% and 3%), Rediset (1%, 2% and 3%), and Zeolite (4%, 6% and 8%) were selected in this study. Addition of Sasobit and Rediset reduced the viscosity of PMB, while addition of Zeolite increased the viscosity. There was enhancement in the rutting and fatigue resistance of PMB binder by the addition of Sasobit, however the addition of Rediset reduced the rutting and fatigue performance and deteriorated the performance grade of PMB. Addition of Zeolite had negligible effect on rutting and fatigue performance of PMB. Based on the viscosity and other rheological properties, it was concluded that the optimum Sasobit dosage for PMB was 2% by weight of binder.

Kumar et al. (2017) evaluated the effect of three WMA additives (Evotherm, Sasobit, and Rediset) on the flow and creep behaviour of virgin and polymer modified binders. Addition of WMA additives reduced mixing and compaction temperatures of virgin binder by 15–20°C and polymer modified binder by 10–20°C. Binders containing Sasobit had lowest compliance values followed by Evotherm and Rediset. Addition of Rediset reduced the rutting resistance of both binders. It was reported that the effect of Sasobit additive was more prominent for virgin binder compared to the polymer modified binder.

## **2.6 Effect of WMA Additives on Mixture Properties**

Working mechanism of several WMA technologies is based on changing the properties of the asphalt binder, and hence influence its rheology. Changes in rheology will eventually translate into changes in the properties of mixes. On the other hand, some technologies work at the binder-aggregate interface to improve the workability of asphalt mix to reduce the production temperatures.

Therefore, it is essential to understand the effect of WMA additive type and content on the properties of asphalt mixtures. Review of studies conducted to evaluate the effect of WMA technologies on asphalt mix properties are discussed further.

Kanitpong et al. (2007) measured the workability, compactability, and moisture susceptibility resistance of warm mixes with Sasobit. Control mixes and warm mixes were prepared at three different mixing temperatures with AC 60/70 binder (150°C, 130°C, and 110°C) and PMA (170°C, 150°C, and 130°C). Compaction temperature was kept 15°C below the mixing temperature. Compaction energy index (CEI) and traffic densification index (TDI) were used for evaluating the workability and compactability characteristics of the mixes. Results showed that the addition of Sasobit improved the compactability of mixes and the resistance to densification under traffic loads. Moisture susceptibility of mixes (with and without Sasobit) decreased with the reduction in the mixing temperature. Addition of Sasobit did not improve the moisture susceptibility resistance of asphalt mixes compacted at lower mixing temperatures. However, the addition of Sasobit had a neutral effect on the moisture damage resistance of asphalt mixes at high mixing temperatures.

You and Goh (2008) evaluated the dynamic modulus of asphalt mixes with two percentages of synthetic zeolite (0.3% and 0.5% by weight mixture). Warm mixes were compacted at 120 and 100°C, whereas control mixes were compacted at 142°C. Warm mixtures with 0.5% synthetic zeolite compacted at 120°C had higher dynamic modulus value ( $E^*$ ) than other mixtures. All WMA mixtures had higher dynamic modulus than the control mix.

Mallick et al. (2008) investigated the feasibility of using Sasobit H8 in recycling of HMA with higher RAP content (75% of the mix). In this study, five

## 2.6. Effect of WMA Additives on Mixture Properties

types of mixes were prepared including HMA mix with PG 64–28 using extracted aggregates at 150°C, HMA mix with PG 52–28 at 135°C, HMA mix with PG 42–42 at 125°C, two WMA mixes with two different binders *viz.* PG 52–28 and PG 42–42 at 125°C. Sasobit H8 content of 1.5% by weight of total binder was used for preparation of WMA mixes. Air voids of WMA mixes compacted at lower temperature were similar to the HMA mixes as shown in Figure 2.12. Among all the mixes, WMA mix with lower grade of binder (PG 42–42) showed comparable performance with respect to control HMA mix (with PG 64–28) in terms of modulus and rut depth. It was concluded that higher RAP percentages of around 75% can be used to produce the mixes at lower temperatures using Sasobit.

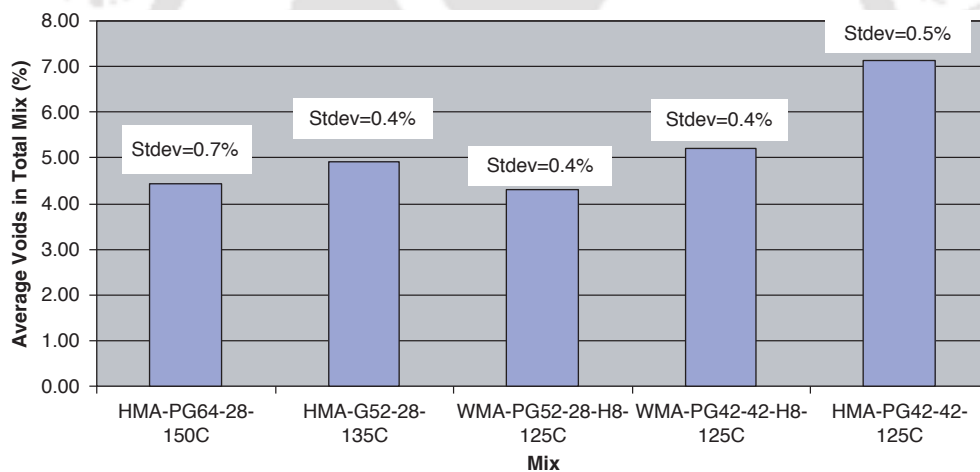


Figure 2.12: Air voids of different mixes (Mallick et al., 2008)

Akisetty et al. (2009a) investigated the effect of compaction temperature on volumetric properties of rubberised mixes containing Sasobit and Aspha-min. Superpave gyratory compactor was used to compact the bituminous mixes at four temperatures: 154°C, 135°C, 116°C, and 97°C. Reduction in compaction temperature increased the air voids content of rubberised warm mixes. Statistical analysis results showed that the reduction in compaction temperature significantly affected the air void content of rubberised mixes. Volumetric

parameters such as voids filled with asphalt (VFA) increased and voids in mineral aggregates (VMA) decreased with the addition of WMA additives at the same compaction temperature. It was concluded that the addition of WMA additives can decrease the compaction temperatures of CRM mixtures while maintaining the target air void content ( $4\pm 1\%$ ).

Su et al. (2009) evaluated the engineering properties of WMA mixtures with three different gradations (fine (B), medium (M) and coarse (A)) as shown in Figure 2.13. Synthetic wax (3.5% by weight of binder) was used as the WMA additive. Control mixes were prepared with gradation (M) at  $173^{\circ}\text{C}$  and compacted at  $163^{\circ}\text{C}$ , whereas WMA mixtures were prepared with three gradations at  $30^{\circ}\text{C}$  and  $50^{\circ}\text{C}$  lower than the control mixes. Marshall mix design results showed similar volumetric properties between control and warm mixes with a slight decrease in stability values at lower production temperatures. WMA mixes showed poor resistance to moisture damage than control mixes as presented in Figure 2.14. Rutting depth and raveling susceptibility of WMA mixes were greater than the control mix except in case of WMA-B (containing fine gradation) prepared at  $30^{\circ}\text{C}$ . WMA mixes showed a lower fatigue life than HMA mixes by 27% to 33% approximately, when the production temperature was lowered by  $50^{\circ}\text{C}$ . It was concluded that the WMA containing fine gradation (B) produced at  $30^{\circ}\text{C}$  showed a similar or slightly lower performance than the HMA control mix.

Gandhi et al. (2010) evaluated the ageing characteristics of bituminous mixes with WMA additives Aspha-min and Sasobit. Dosage rate of Aspha-min and Sasobit was 0.3% (by weight of mixture) and 1.5% (by weight of binder). HMA samples were prepared and compacted at  $150^{\circ}\text{C}$  and  $145^{\circ}\text{C}$  respectively. WMA samples were prepared and compacted at  $30^{\circ}\text{C}$  lower than HMA. Both HMA and

2.6. Effect of WMA Additives on Mixture Properties

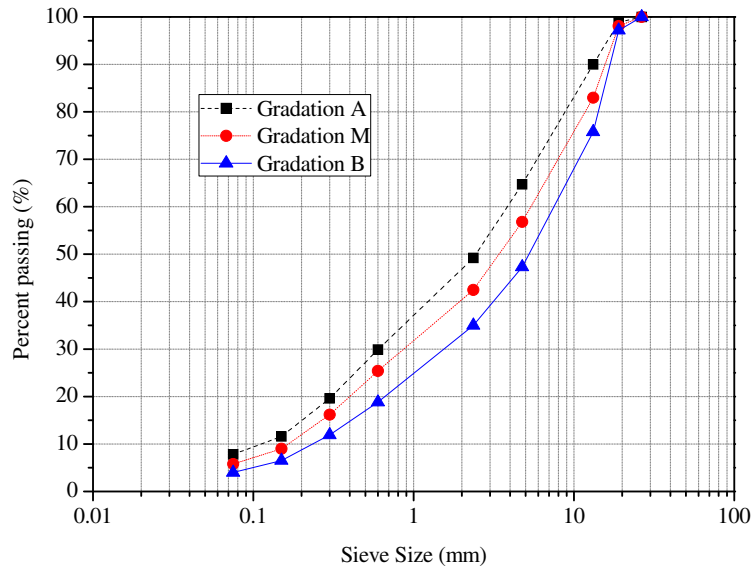


Figure 2.13: Aggregate gradation curves (Su et al., 2009)

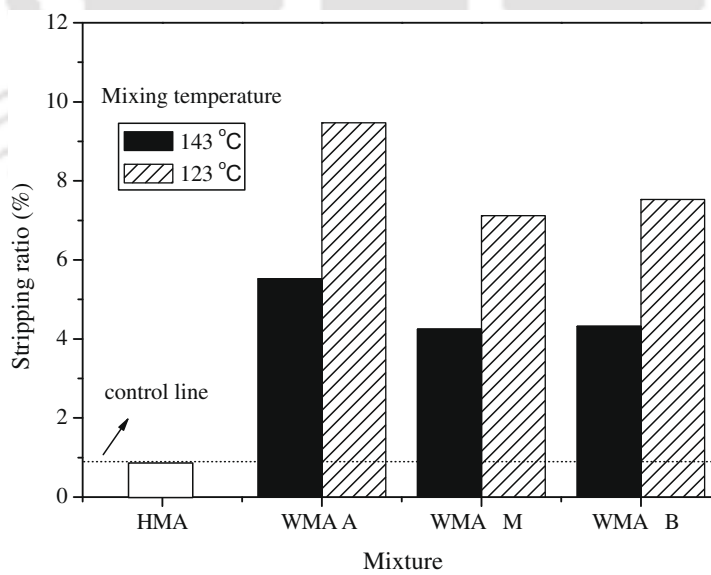


Figure 2.14: Moisture susceptibility of mixes (Su et al., 2009)

WMA mixes were long term aged by conditioning the compacted samples in a forced draft oven for 120 h at a temperature of 85°C. Resilient modulus ( $M_R$ ) test results showed that addition of Sasobit had no significant effect on  $M_R$  values at all test temperatures (5°C, 25°C, and 40°C) in case of unaged samples, whereas the addition of Aspha-min had significantly lowered the  $M_R$  values at two test temperatures (25°C and 40°C) than control unaged mixes. Addition of WMA additives had no significant effect on  $M_R$  values of aged mixes. WMA additives improved the moisture resistance in unaged mixes, but the addition of Sasobit decreased the moisture resistance significantly in aged mixes. Both unaged and aged mixes containing Sasobit significantly reduced the rut depth compared to control mixes. It was also concluded that the binder source did not have any significant effect on the resilient modulus, moisture susceptibility, and rutting resistance of both unaged and aged mixes.

Nazzal et al. (2010) evaluated performance of WMA mixes containing 15% RAP. Three WMA and one HMA test sections were constructed at reduced mixing and compaction temperatures shown in Table 2.2. WMA additives Sasobit (1.5% by mass of binder), Aspha-min (0.3% by total weight of mix), and Evotherm (5.3% by total weight of mix) were used in this study. All test sections were laid with polymer modified bitumen (SBS modified). WMA mixes produced and compacted at lower temperatures achieved better densities than HMA mix. Three WMA sections exhibited highest rutting rate in the initial stages compared to HMA, later the rutting rate of WMA sections were similar than to the HMA section. Stack emissions monitored during the production of HMA and WMA mixes are shown in Table 2.3. The emissions of  $SO_2$  and VOCs reduced by 83% and 50%, respectively, during production of mixes with Aspha-min and Sasobit in comparison to HMA.

Table 2.2: Production temperatures of asphalt mixtures (Nazzal et al., 2010)

<b>Mixture</b>	<b>Production temperature, °C</b>	<b>Compaction temperature, °C</b>
Control HMA	154–166	149–162
Aspha-min	132–137	121–127
Sasobit	127–137	118–129
Evotherm	115–127	104–116

Table 2.3: Results of stack emissions tests (Nazzal et al., 2010)

<b>Emittant</b>	<b>Mixture</b>			
	<b>Control HMA</b>	<b>Evotherm</b>	<b>Aspha-min</b>	<b>Sasobit</b>
SO <sub>2</sub> , lb/h	0.24	0.37	0.04	0.04
Change from HMA	—	+ 54.20%	– 83.30%	– 83.30%
NO <sub>x</sub> , lb/h	5.2	5.1	3.6	4.1
Change from HMA	—	– 1.92%	– 30.80%	– 21.20%
CO, lb/h	63.1	50.3	24	23.2
Change from HMA	—	– 20.30%	– 62.00%	– 63.20%
VOC, lb/h	7.8	20.2	2.9	3.8
Change from HMA	—	+ 159%	– 62.80%	– 51.30%

Xiao et al. (2010a) investigated the influence of WMA additive, hydrated lime, and moisture content of aggregates on the mix rutting resistance using asphalt pavement analyzer (APA). Mixes were prepared with combination of two aggregate moisture contents (0% and 0.5% by weight of the dry mass of aggregates), two lime contents (1% and 2% by weight of dry aggregates), three WMA additives (Aspha-min, Sasobit, and Evotherm), and three aggregate sources (granite-I, schist and granite-II) and one binder grade (PG 64–22). WMA mixes were prepared at a mixing temperature range of 121°C to 127°C and compaction temperature range of 115°C to 121°C. Mixes containing Sasobit had lowest rut depth when compared to mixes containing Evotherm and Aspha-min in both dry and wet conditions. Increase in lime content did not significantly affect the rutting resistance of WMA mixes. Rut depth of the WMA mixes containing moist aggregates was insignificant. WMA mixes with schist aggregate had lowest rut depth compared to the mixes with granite-I and granite -II. It was concluded that aggregate type significantly affects the rutting resistance regardless of the WMA additive, lime content, and moisture content.

Xiao et al. (2010b) studied the influence of anti-stripping additives on moisture susceptibility of WMA mixtures. In this study, three type of aggregates (designated as A, B and C), two types of WMA additives (Aspha-min and Sasobit), three anti-stripping additives (lime and two liquid anti-stripping agents), and one binder grade (PG 64–22) were used. HMA mixes were compacted in the temperature range of 132–137°C. WMA mixes were compacted 17°C lower than the HMA mixes. Both dry and wet ITS values of the mixtures without WMA additives (*i.e.* control mix) were higher than the mixtures containing Aspha-min and Sasobit regardless of aggregate type and anti-stripping agent type. Mixes containing hydrated lime had high wet ITS, high toughness, and high tensile strength ratio (TSR) compared to mixes containing

liquid anti-stripping additives. Mixes containing aggregate C exhibited significant stripping damage in boiling water test.

Behl et al. (2011) investigated the applicability of WMA to paving operations and the environmental conditions prevailing in India. Paving grade bitumen (VG 30), quartzite aggregates, and a chemical WMA additive (0.5% by weight of the bitumen) were used in this study. Control HMA mixes were prepared at a mixing temperature of 155°C to 160°C. Warm mixes were prepared at four different temperature ranges (125°C–130°C, 115°C–120°C, 105°C–110°C, and 95°C–100°C). Warm mixes had higher TSR values than control mixes for the warm mixes prepared at 125°C–130°C and 115°C–120°C. Warm mixes prepared at 95°C–100°C temperature failed specification limit of TSR (minimum 80%). Retained Marshall stability values of all mixes satisfied the specification limit (minimum 75%). Warm mixes prepared at 120°C had better resistance towards rutting than control HMA mixes.

Sanchez-Alonso et al. (2011) studied the influence of mixing and compaction temperatures on compactability and mechanical properties of bituminous mixes with different WMA additives. Table 2.4 shows the labels and percentages of six WMA additives used in this study. HMA and WMA mixes were prepared at three temperatures: 160°C, 140°C, and 120°C. CEI results showed that WMA additives improved the workability of bituminous mixes at lower manufacturing temperatures. Optimal manufacturing temperatures based on CEI and TDI values of mixes was 120°C for A2 and A4 additives, and 140°C for remaining additives. TSR and stiffness modulus of mixes decreased with the decrease in manufacturing temperatures. Warm mixes showed higher resistance to moisture damage and stiffness modulus compared to R mix produced at same

temperature. TSR values of warm mixes with A5 additive produced at three production temperatures satisfied the minimum requirement of 85%.

Table 2.4: WMA additives and their percentages (Sanchez-Alonso et al., 2011)

Terminology	Classification	Chemical composition	Additive dosage
R	—	—	0
A1	Chemical	Surfactant of amino nature	0.4% w/b <sup>1</sup>
A2	Chemical	Mix of surfactants	0.3% w/b
A3	Chemical	Mix of surfactants, waxes, polymers, etc.	3% w/b
A4	—	Surfactant phosphoric nature	0.3% w/b
A5	Organic	Paraffin wax	3% w/b
A6	Foam	Synthetic zeolite	0.3% w/m <sup>2</sup>

<sup>1</sup> w/b: by weight of binder

<sup>2</sup> w/m: by weight of mix

Mogawer et al. (2011) investigated the effect of ageing times and ageing temperatures on moisture susceptibility of WMA mixes using Hamburg wheel tracking device (HWTd). WMA additives: Advera, Sasobit, SonneWarmix, and Evotherm were used for the evaluation. Dosage rate of Advera was 0.25% by weight of mix, and remaining were dosed by weight of binder as: Sasobit at 1.5%, SonneWarmix at 1.0% and Evotherm M1 at 0.5%. Control and WMA mixes were prepared with a combination of three levels of ageing temperatures (146°C, 129°C and 113°C) and ageing times (2h, 4h, and 8h). Mixes failed in HWTd testing were repeated by adding a liquid anti-stripping agent named ArrMaz Custom Chemicals XL9000 (0.5% by weight of binder) and hydrated lime (1% by weight of aggregate). Both control and WMA mixes with longer times and higher ageing temperatures showed higher resistance to moisture induced damage.

## 2.6. Effect of WMA Additives on Mixture Properties

Out of all WMA additives, Evotherm and Sasobit showed similar or better performance than the control mixes. It was reported that addition of liquid anti-strip or hydrated lime in HMA and WMA mixes had positive effect on moisture susceptibility resistance.

Kakade et al. (2011) evaluated the performance of WMA and half warm mix asphalt (HWMA) using foaming chemical additive. VG 30 grade bitumen and a chemical additive developed in Indian Institute of Technology Kharagpur was used to prepare dense-graded bituminous concrete (BC) mixes. WMA mixes were prepared by only using chemical additive, whereas HWMA was prepared by adding 6% of water along with the chemical agent. Manufacturing process of HMA, WMA, and HWMA is shown in Figure 2.15. WMA and HWMA mixes showed higher ITS, TSR, and resilient modulus compared to HMA mixes. Energy savings of 13.5% and 52.5% was observed for WMA and HWMA respectively, when compared with HMA.

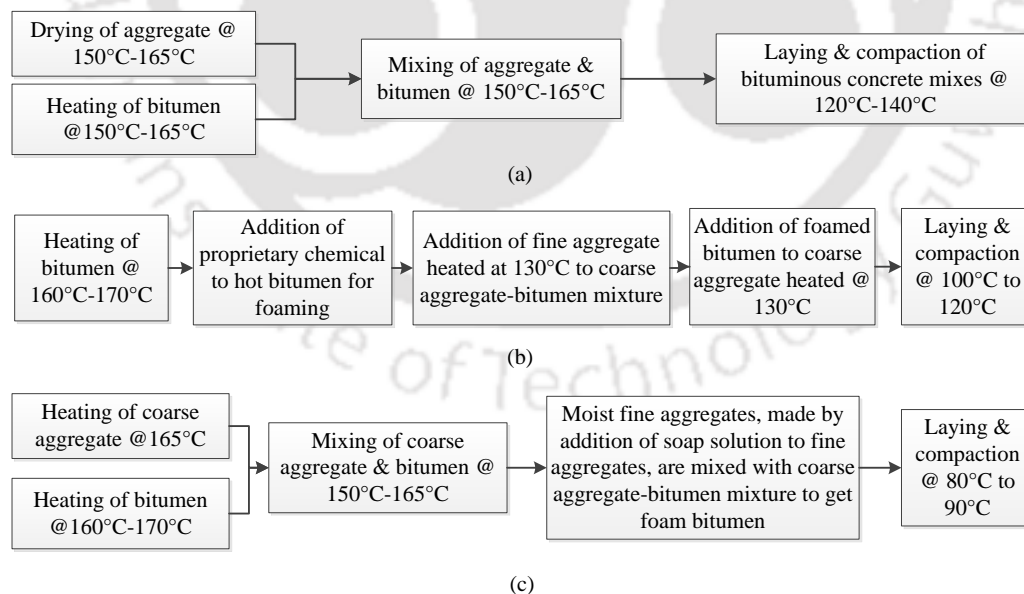


Figure 2.15: Manufacturing process of (a) HMA, (b) WMA, (c) HWMA (Kakade et al., 2011)

Kim et al. (2012) evaluated the effect of WMA additives on engineering properties of PMA mixtures. Twelve PMA mixtures (four control PMA mixtures and eight warm PMA mixtures) were prepared by using two additives (Aspha-min and Sasobit), two binder sources, and two aggregate types. Warm-PMA mixes were prepared at 10°C lower than the control PMA mixes. ITS values and TSR values of both control and warm-PMA mixes were greater than the minimum requirement of 445 kPa and 85% respectively. Rutting resistance of mixes increased with the addition of Sasobit, whereas Aspha-min did not show any effect on the rutting potential. For mixes (with and without WMA additives), rut depth measured from APA test was less than 3 mm. Resilient modulus test results showed an increase in the temperature sensitivity of PMA mixes on addition of WMA additives. The percentage change in resilient modulus values and ranking of PMA mixes are shown in Table 2.5. It was also reported that the source of aggregate had significant effect on moisture susceptibility, rutting resistance, and resilient modulus of both control and warm-PMA mixes.

Table 2.5: Percentage change in resilient modulus (Kim et al., 2012)

	Aggregate type A						Aggregate type B					
	Binder I			Binder II			Binder I			Binder II		
	C	A	S	C	A	S	C	A	S	C	A	S
5 → 25°C	76	66	62	81	79	74	62	70	54	63	67	68
5 → 40°C	90	86	86	94	93	91	83	81	77	79	87	86
Rank	7	5	5	10	9	8	4	3	1	2	6	5

Kanitpong et al. (2012) investigated the effect of aggregate type and aggregate gradation on moisture susceptibility and rutting resistance of WMA mixes using dynamic creep test. Two aggregate types (granite and slag), two aggregate gradations (coarse and fine), and one WMA additive (Sasobit, 1% by weight of

binder) were used. HMA and WMA mixes were prepared at 150°C and 110°C respectively. WMA mixes had greater resistance towards rutting than control HMA mixes from the dynamic creep test results. Coarse graded mixes with granite aggregates had lower resistance towards rutting than the fine graded mixes. A reverse trend was observed in case of slag aggregates. From the flow number ratio (FNR) and permanent deformation ratio (PDR) values, it was observed that warm mixes were more sensitive towards moisture damage than HMA mixes. Mixes with fine gradation had greater resistance to moisture susceptibility than mixes with coarse gradation irrespective of the aggregate type.

Morea et al. (2012) studied rutting and moisture susceptibility characteristics of WMA mixes with chemical tensoactive additives. HMA mixes with 70/100 binder and PMB were mixed at 152°C and 194°C and compacted at 140°C and 184°C respectively. WMA mixes with 70/100 binder and PMB were prepared at 30°C and 35–40°C lower temperatures respectively. Reduction in manufacturing temperatures lowered the rutting and moisture susceptibility resistance of asphalt mixtures with 70/100 binder. In contrast, either addition of WMA additives or reduction in temperatures did not have any significant effect on rutting behaviour of PMB mixes. Moisture damage resistance of WMA mixes increased with the addition of WMA additives even after reduction in the production temperatures by 35–40°C.

Mo et al. (2012) investigated compactability and performance characteristics of warm mixes. Chemical WMA additive Rediset WMA-8017, 2% by weight of binder, was used. HMA and WMA mixes were prepared at different mixing and compaction temperatures with virgin bitumen and SBS modified bitumen for evaluating the compactability characteristics. Addition of chemical additive

improved the compaction of mixes irrespective of binder used. Warm mix with neat binder compacted at 105°C showed compactability similar to the HMA mix compacted at 115°C. In case of modified binder, warm mix compacted at 130°C showed a slightly higher compactability than HMA mix compacted at 170°C. Warm mixes were prepared with base bitumen and SBS modified bitumen and compacted at 20°C and 40°C lower temperatures than HMA mixes for evaluating the rutting resistance. Warm mixes showed very low resistance towards rutting compared to HMA mixes, irrespective of the binder used as shown in Figure 2.16. Mixes with modified bitumen showed better performance than mixes with base bitumen.

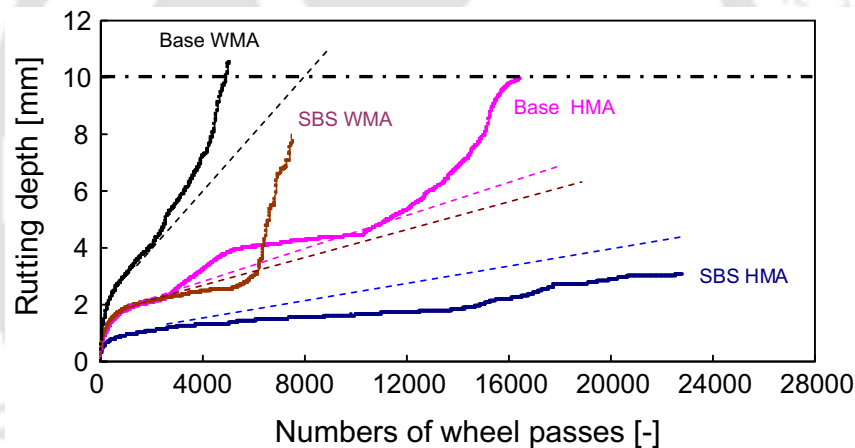


Figure 2.16: Rutting performance of WMA and HMA mixes (Mo et al., 2012)

Sanchez-Alonso et al. (2012) investigated the effect of impact and gyratory compaction on the mechanical properties of WMA mixes. Labels and percentages of six WMA additives used in the study are shown in Table 2.6. HMA and WMA mixes were prepared at three temperatures: 160°C, 140°C, and 120°C. Samples prepared with gyratory compaction showed higher TSR values and lower stiffness modulus values compared to those prepared with impact compaction. TSR and stiffness values of both control and warm mixes decreased with reduction in the production temperature irrespective of the compaction

## 2.6. Effect of WMA Additives on Mixture Properties

method used. WMA additives improved the moisture damage resistance with respect to control mix produced at same temperature. Statistical analysis showed that production temperature plays a significant role in both moisture sensitivity and stiffness modulus results, whereas type of WMA additive significantly affects the stiffness modulus. Production temperature was found to be a highly sensitive variable in Marshall method, whereas both variables (type of mix and production temperatures) were equally sensitive in Superpave gyratory method.

Table 2.6: WMA additives and their percentages (Sanchez-Alonso et al., 2012)

Terminology	Classification	Chemical composition	Additive dosage
R	—	—	0
A1	Chemical	Surfactant of amino nature	0.4% w/b <sup>1</sup>
A2	Chemical	Mix of surfactants	0.3% w/b
A3	Chemical	Mix of surfactants, waxes, polymers, etc.	3% w/b
A4	—	Surfactant phosphoric nature	0.3% w/b
A5	Organic	Paraffin wax	3% w/b
A6	Foam	Synthetic zeolite	0.3% w/m <sup>2</sup>

<sup>1</sup> w/b: by weight of binder

<sup>2</sup> w/m: by weight of mix

Xie et al. (2013) studied the effect of aggregate type and binder type on the mechanical properties of warm mixes. Experimental design consisted of two binder types (unmodified and SBS modified), two types of aggregate (basalt and limestone), and three WMA additives (Sasobit, Evotherm, and Rediset). Dosage rates of Sasobit, Evotherm, and Rediset were 2%, 0.6%, and 2% by weight of binder respectively. HMA mixes with neat binder were mixed and compacted at

155°C and 145°C and with modified binder at 165°C and 155°C. WMA mixes were mixed and compacted at 25°C lower than the HMA mixes. It was reported that WMA mixes with limestone aggregate were easier to compact than the ones with basalt aggregate. All three WMA additives showed similar effect on air voids. WMA mixes with Sasobit had higher Marshall stability, indirect tensile strength, and rutting resistance compared to other mixes. Rediset was more effective in bending failure strain when basalt aggregate was used, and Sasobit and Evotherm were more effective when limestone aggregate was used. Mixes with basalt aggregates had higher Marshall stability, rutting resistance, and cracking resistance compared to mixes with limestone aggregates.

Kavussi et al. (2014) studied the effects of aggregate gradation, lime content, and WMA additive Sasobit content on the moisture susceptibility characteristics of warm mix asphalt using response surface methodology (RSM). Experimental matrix included 60/70 penetration grade bitumen, three aggregate gradations from one aggregate source containing 85%, 70%, and 55% passing 4.75 mm sieve, three lime contents (0%, 1.5%, and 3%) and three Sasobit contents (0.5%, 1.5%, and 2.5% by weight of binder). Optimum binder content of mixes containing three gradations were determined using Marshall mix design and employed to prepare the warm mixes at 125°C. Using RSM, three polynomial regression models were generated for dry ITS, wet ITS, and TSR. RSM results showed that the TSR values were greater than 80% when the lime content ranged from 1.1% to 2.5%, Sasobit content from 0.5% to 2.5%, and percent passing 4.75 mm sieve from 66% to 74%. It was reported that the maximum TSR could be achieved with the combination of 1.7% lime, 2.5% Sasobit content, and 69.8% of the aggregates passing 4.75 mm sieve in the mix.

Topal et al. (2014) evaluated the performance characteristics of warm mixes containing two types of zeolite additive. Neat bitumen (50/70 penetration grade) and two types of zeolites (natural and synthetic zeolites) at dosage rate of 5% by weight of bitumen were used. Indirect tensile stiffness modulus (ITSM) results showed that the utilisation of zeolites enhanced the mixture stiffness at three test temperatures (20°C, 25°C, and 30°C). Addition of zeolites enhanced the resistance to fatigue and rutting thereby increasing the mixture rigidity. In regard to zeolite type, synthetic zeolite showed better fatigue resistance and rutting performance compared to natural zeolite. Finally, it was concluded that natural zeolite and synthetic zeolite exhibit similar mechanical characteristics. The natural zeolite can be considered as an better alternative to the commercial synthetic zeolite.

Ghuzlan and Ar'ar (2016) compared the performance of WMA mixes with control (HMA) mixes. Neat bitumen (60-70 penetration grade) and WMA additive Sasobit (1.5% by weight of binder) were used in this study. Control mixes were prepared and compacted at 163°C and 150°C respectively. Warm mixes were prepared and compacted at 130°C. Dynamic creep test results showed that warm mixes had better rutting resistance over control mixes at test temperatures of 25°C and 40°C. Fatigue resistance of warm mixes were higher than the control mixes at both test temperatures of 20°C and 30°C.

Khedmati et al. (2017) studied the moisture susceptibility characteristics of stone matrix warm mix asphalt using RSM. Experimental design used in the study included three aggregate gradations (fine, medium, and coarse), three bitumen contents (5.5%, 6.5% and 7.5%), three Zycosoil contents (0%, 0.1%, and 0.2%), three Sasobit contents (0.5%, 1.5%, and 2.5%), and three mixing temperature (100°C, 120°C, and 140°C). Warm mixes were prepared and tested for ITS and TSR. Using RMS, three polynomial regression model were generated

for  $ITS_{dry}$ ,  $ITS_{wet}$  and TSR. RSM results showed that maximum TSR was achieved at medium aggregate gradation, 0.1% Zycosoil content, 6.5% bitumen content, 1.5% Sasobit content, and at mix temperature of 120°C. Moreover, the interactions between the different parameters showed that the TSR values were more influenced by Zycosoil content and gradation than bitumen content, Sasobit content, and mixing temperatures.

## 2.7 Summary

This chapter presented review of the literature on the brief history of warm mix asphalt (WMA) development, classification of WMA technologies, and advantages with the use of WMA. Furthermore, a comprehensive literature review was presented on the influence of WMA additives on rheological properties of asphalt binders as well as on volumetric, mechanical, and performance properties of asphalt mixes.

Review of different studies indicate that differences do exist between performance of asphalt binders and mixes with and without WMA additives. While there have been improvements in properties of binders and mixes with addition of WMA technologies, many studies have reported decline in the desirable attributes, especially in terms of moisture-induced damage resistance, fatigue resistance, and rutting behaviour. In some cases, the performance was also found to be influenced by the source and type of aggregate and binder. Both straight-run (unmodified) and modified asphalt binders have been researched. Further, type and content of a WMA additive have significant influence on asphalt binder properties, workability of mix, and properties of asphalt mixes. Under the category of organic additives, Sasobit has been reported in many

studies, while Evotherm has been the widely used chemical WMA additive. Both technologies/additives appear promising for future applications.

Researchers have used different reduced production temperatures to prepare WMA mixes. Generally, temperature reductions ranging from 10–40°C have been reported for producing the WMA mixes. Reduction in production temperatures affects binder ageing characteristics and workability of mixes, and hence plays a major role in achieving the desired volumetric properties, performance, and durability of the asphalt mixes. It was also observed that production temperature is very sensitive in Marshall compaction compared to Superpave gyratory compaction. Marshall method of mix design is also currently followed in India.

As of now, it is not yet possible to offer definitive conclusions in regard to the effect of WMA technologies on properties of asphalt binders and mixtures. However, it cannot be denied that the technology is rapidly gaining widespread acceptance among the highway agencies worldwide. The technology is still in its infancy in India. For these reasons, more in-depth research studies are needed with WMA technologies to assess their potential for use in India. Under this perspective, the present research effort considers holistic examination of two WMA additives (Evotherm and Sasobit), each with varying dosage rates, on the properties of two modified binders (polymer- and crumb rubber-modified binders), and bituminous concrete mixtures made with combinations of these binders and additives at different reductions in production temperatures.

## Chapter 3

### Materials and Experimental Programme

#### 3.1 Introduction

This chapter provides description of materials used in the research, which include bituminous binders, mineral aggregates, and WMA additives. This is followed by discussion of experimental programme to accomplish the objectives framed for the research. The test methods adopted for rheological characterisation of warm asphalt binders are highlighted. The chapter further provides the details pertaining to the design of bituminous concrete (control) mixes and their volumetric and Marshall parameters, followed by preparation and evaluation of warm mixes. The chapter concludes with the presentation of test procedures to investigate the performance of warm asphalt mixes in terms of moisture susceptibility, permanent deformation, fatigue, and resilient modulus.

## 3.2 Materials

### 3.2.1 Bitumen

Bitumen is the most important ingredient in bituminous mixes, which acts as an adhesive or binding agent. Bituminous mixtures with conventional (neat/virgin) binders are not able to perform adequately under the influence of increase in vehicular traffic, vehicle axle count, and adverse climatic conditions (Airey, 1997). Hence, the use of modified binders (binders containing certain additives like polymers, crumb-rubber *etc.*) is increasing all around the world to meet these demands. Many studies reported that modified binders increase resistance to rutting and fatigue as well as provide better adhesion between aggregates and binder (Airey, 2003, 2004; Lee et al., 2007).

Two types of modified binders *viz.*, polymer modified bitumen grade 40 (PMB 40) and crumb rubber modified bitumen grade 60 (CRMB 60) were selected for the study. Grades of PMB and CRMB were selected as per IRC:111 (2009) specifications for the regions having maximum and minimum daily mean air temperatures greater than 35°C and -10°C respectively. Both modified binders were supplied by TikiTar Industries, Gujarat and were manufactured through wet process by modifying the base bitumen (VG 30) with ethylene terpolymer (ETP) and crumb rubber particles respectively in the bitumen modification plant.

Physical properties of both modified binders (PMB 40 and CRMB 60) were tested as per IS 15462 (2004) specifications and the test results are presented in Tables 3.1 and 3.2. The equivalent high performance grade of two modified binders were also determined according to Superpave tests and the results are

presented in Table 3.3. In the present study, mixing and compaction temperatures for modified binders presented in Table 3.4 were used based on the manufacturer recommendations.

Table 3.1: Physical properties of PMB 40

Tests	Requirements	Results
Penetration at 25°C. 0.1 mm, 100 g, 5 s	30 to 50	39
Softening point, (R&B), °C	Min. 60	64.5
Ductility at 27°C, cm	Min. 50	61.6
Flash point, by COC, °C	Min. 220	300
Elastic recovery of half thread in ductilometer at 15°C, %	Min. 75	76.5
Separation difference in softening point, (R&B), °C	Max. 3	1.9
Viscosity at 150°C, poise	3 to 9	8.58
Thin Film Oven Test (TFOT)		
Loss in weight, %	Max. 1.0	0.62
Increase in softening point, °C	Max. 5	4.1
Reduction in penetration of residue, 25°C, %	Max. 35	33
Elastic recovery of half thread in ductilometer at 25°C, %	Min. 50	58

### 3.2.2 Aggregates

Aggregates were collected from different stone crusher plants located nearby IIT Guwahati. Physical characteristics of these aggregates in terms of hardness, toughness, shape, soundness, and adhesion with bitumen were evaluated and compared with the requirements stipulated by Ministry of Road Transport and

Table 3.2: Physical properties of CRMB 60

Tests	Requirements	Results
Penetration at 25°C, 0.1 mm, 100 g, 5 s	<50	35
Softening point, (R&B), °C	Min. 60	64.5
Flash point, by COC, °C	Min. 220	320
Elastic recovery of half thread in ductilometer at 15°C, %	Min. 50	68
Separation difference in softening point, (R&B), °C	Max. 4	2.9
Viscosity at 150°C, poise	3 to 9	8.90
Thin Film Oven Test (TFOT)		
Loss in weight, %	Max. 1.0	0.56
Increase in softening point, °C	Max. 5	3.5
Reduction in penetration of residue, 25°C, %	Max. 40	31.4
Elastic recovery of half thread in ductilometer at 25°C, %	Min. 35	48

Table 3.3: Superpave properties of modified binders

Ageing states	Test properties	PMB 40	CRMB 60
Unaged	Viscosity at 135°C (Pa·s)	1.93	2.09
	Failure temperature (°C)	78.7	81.6
	$G^*/\sin\delta$ at 76°C, kPa	1.34	1.56
RTFO aged	Failure temperature (°C)	81.8	82.3
	$G^*/\sin\delta$ at 76°C, kPa	3.96	4.16
RTFO + PAV aged	$G^*\cdot\sin\delta$ at 31°C, kPa	3830	4100

Table 3.4: Mixing and compaction temperatures of modified binders

<b>Binder</b>	<b>Mixing temperature, °C</b>	<b>Compaction temperature, °C</b>
PMB 40	170	160
CRMB 60	175	165

Highways specifications (MoRTH, 2013). Aggregate source located in Deuduwar village, which is about 25 km from IIT Guwahati, met all the requirements and this source was finally selected for the study. Physical requirements as per MoRTH (2013), and test results of the selected aggregate source are shown in Table 3.5.

Aggregate gradation conforming to bituminous concrete (BC) with nominal maximum aggregate size (NMAS) of 13.2 mm was selected for preparation of bituminous mixes. Bituminous concrete (BC) is most commonly used wearing course gradation on national highways and expressways in India. Mid-range values adopted for the study are presented in Table 3.6 along with recommended range as per IRC:111 (2009) and MoRTH (2013) specifications.

Table 3.5: Physical properties of aggregates

<b>Test</b>	<b>Specification</b>	<b>Result</b>
Grain size analysis	Max. 5% passing 0.075mm sieve	1.6%
Flakiness and elongation index	Max. 35% (combined)	29.7%
Los Angeles abrasion value	Max. 30%	27.0%
Aggregate impact value	Max. 24%	21.3%
Water absorption	Max. 2%	1.3%
Stripping test	Min. retained coating 95%	100%

Table 3.6: Aggregate gradation for BC

IS sieve size (mm)	Recommended range MoRTH (2013)	Gradation used
19	100 – 100	100
13.2	90 – 100	95
9.5	70 – 88	79
4.75	53 – 71	62
2.36	42 – 58	50
1.18	34 – 48	41
0.6	26 – 38	32
0.3	18 – 28	23
0.15	12 – 20	16
0.075	4 – 10	7

### 3.2.3 WMA Additives and Dosage Rates

WMA allows lowering the mixing and compaction temperatures of asphalt mixtures by 20–40°C with the help of different technologies: foaming, organic, and chemical. Two WMA additives, namely Sasobit (an organic WMA additive) and Evotherm (a chemical WMA additive) were selected for preparation of warm mixes with both PMB and CRMB binders. The working mechanisms of both additives are explained in detail in the following sections.

#### Sasobit

Sasobit is an organic type WMA additive manufactured by Sasol Wax, South Africa. It is also known as Fischer–Tropsch (F–T) wax or synthetic wax or an

asphalt flow improver. Sasobit has melting point range of approximately 85°C–115°C and is completely soluble in bituminous binder at temperatures above 115°C. It forms a homogenous solution with binder above its melting point and reduces the viscosity of binder at typical mixing and compaction temperatures of asphalt mixes. Sasobit is usually available in pellets or flakes or powdered form. Sasobit used in the study was provided by KPL International Limited, India, in prills form as shown in Figure 3.1. Sasol wax recommends the Sasobit dosage in the range of 0.8% to 4% by weight of binder (Sasobit Product Information 124, 2017). In the present study, three percentages of Sasobit (*viz.* 1%, 2%, and 3%) by weight of binder were selected.



Figure 3.1: Sasobit in pellet form

### **Evotherm**

Evotherm is a chemical warm mix additive developed in the USA by MeadWestvaco (MWV) Asphalt Innovations, Charleston, South Carolina. Evotherm helps to achieve better asphalt coating and workability of mix through the formation of micelles, which are agglomeration of surfactant molecules present in Evotherm having polar heads and non-polar tails. Polar heads are attracted to polar minerals of the aggregates, and the non-polar tails attract the asphalt. This helps to achieve better coating of asphalt over aggregates with lesser requirement of heat energy. Furthermore, the micelles also act as slip planes allowing asphalt coated aggregates to slip past each other, and thus improve workability to acquire the required density at lower temperatures (MWV, 2013). Evotherm is available in three different forms: Evotherm Emulsion Technology (Evotherm ET), Evotherm Dispersed Asphalt Technology (Evotherm DAT) and Evotherm 3<sup>rd</sup> Generation (Evotherm 3G).

Evotherm 3G is the latest technology developed by MeadWestvaco Paragon Technical Services and Mathy Technology and Engineering (Nazzal and Abu-Qtaish, 2013). It is a water-free form that includes additives to improve coating and workability, surfactants to enhance aggregate-binder adhesion, and agents to promote workability and compaction (MWV, 2010). In this study, Evotherm J1, one form of Evotherm 3G was used. Manufacturer recommended dosages of Evotherm J1 range from 0.30% to 0.75% by weight of binder for modified binders. For the present study two doses of Evotherm (0.5% and 0.6%) by weight of binder were selected. Evotherm J1 in liquid form (Figure 3.2) was provided by MWV.



Figure 3.2: Evotherm J1 in liquid form

### **3.3 Experimental Plan**

The objectives of this study were grouped together into four independent tasks. The tasks are outlined in the following sections. Each task was carried out separately to fulfil the specific objectives of the study.

#### **3.3.1 Task 1: Rheological Evaluation of Warm Asphalt Binders**

Task 1 of the study was conducted to evaluate rheological characteristics of modified binders with different doses of the two WMA additives in both unaged and short-term aged conditions. Binders were short-term aged using a rolling thin film oven (RTFO). Rheological tests were performed to assess the effects of WMA additives on viscosity and failure temperature of the binders; and also to

predict response of binders to different stress levels, different loading frequencies, and different temperatures in both unaged and short-term aged conditions. Figure 3.3 shows the experimental plan followed to evaluate the rheological properties of modified binders with different doses of WMA additives. The following sections briefly describe the process for preparing the warm asphalt binders, operation principle of Brookfield rotational viscometer and dynamic shear rheometer (DSR), and the test methods used for rheological evaluation of warm asphalt binders.

#### **3.3.1.1 Preparation of Warm Asphalt Binders**

Warm asphalt binders were prepared using wet process. A standard procedure was followed for blending WMA additives with modified binders. The procedure involved preheating PMB and CRMB to a temperature of about 120°C in a temperature controlled oven, followed by adding the required dosage of WMA additive and finally mixing the blend thoroughly for 15 min using a mechanical stirrer to achieve a homogeneity. These warm asphalt binders were subsequently used for rheological testing and for preparation of warm mixes.

#### **3.3.1.2 Operation Principle of Testing Instruments**

##### ***Brookfield Rotational Viscometer***

Viscosity is a property of the fluid which measures its resistance to flow. It is defined as a ratio of applied shear stress to the rate of shear strain, and is measured in terms of pascal seconds, millipascal seconds, or centipoise. Viscosity is a fundamental property of an asphalt binder that helps to understand its behaviour at a given temperature and/or over a temperature

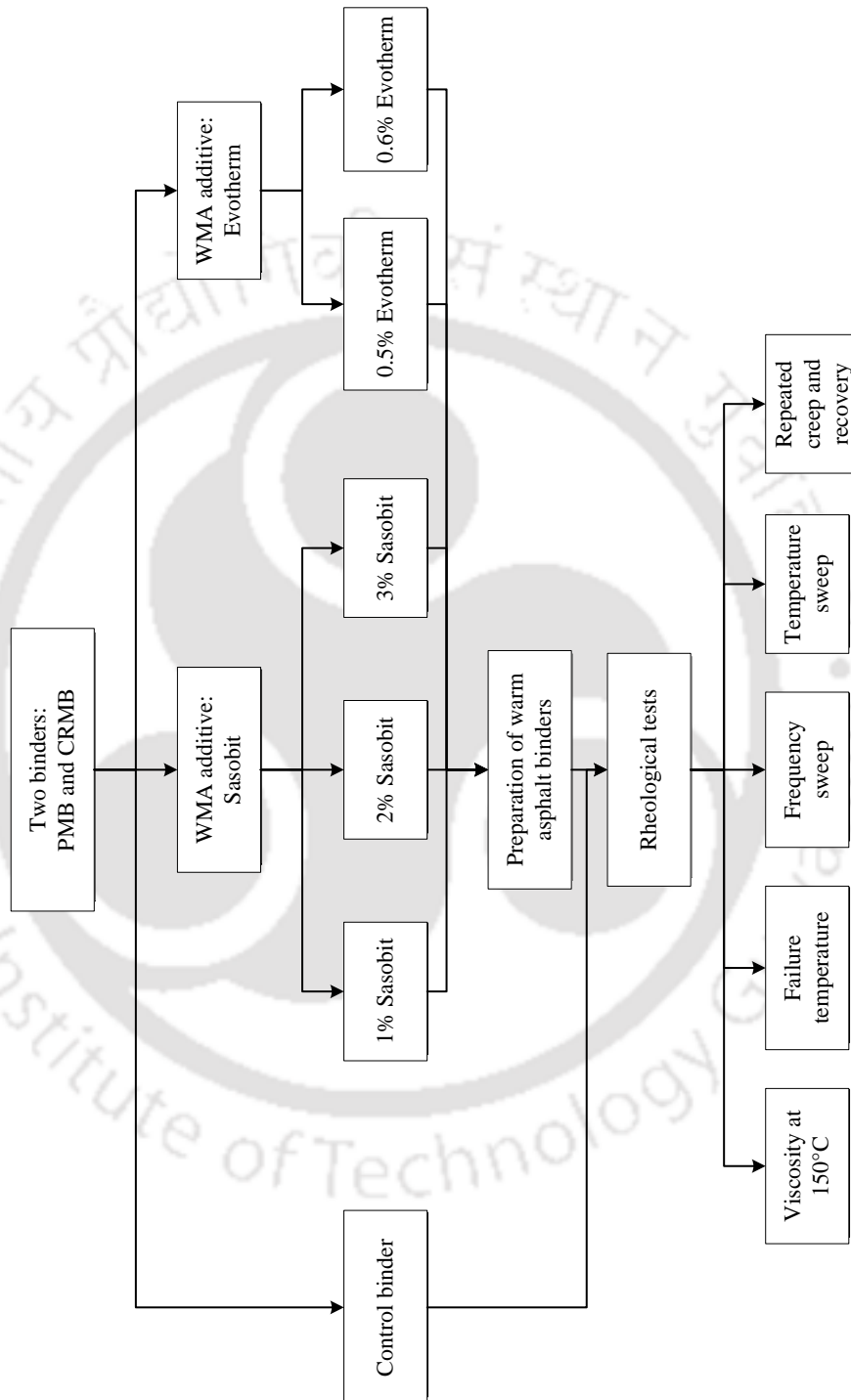


Figure 3.3: Experimental plan for Task 1 at unaged condition

### 3.3. Experimental Plan

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range. Viscosity determination of asphalt also helps to determine the mixing and compaction temperatures for preparation of asphalt mixtures.

Brookfield rotational viscometer RVDV-II+ Pro was used for measuring the viscosity of binders as per ASTM D4402/D4402M (2015). Figure 3.4 shows the Brookfield rotational viscometer and Thermocel system. Brookfield rotational viscometer consists of a cylinder rotating coaxially inside a static cylinder containing the asphalt binder sample. The entire assembly is placed in Thermocel for maintaining the desired test temperature. The torque required to rotate the spindle is used to measure the relative resistance to rotation of the asphalt at a particular temperature and shear rate. The torque value obtained is converted to viscosity by the instrument software with the use of in-built calibration factors.



Figure 3.4: Brookfield rotational viscometer

### Dynamic Shear Rheometer

Dynamic Shear Rheometer (DSR) is used to measure the rheological properties of control and warm asphalt binders at high and intermediate pavement service temperatures. Rheological measurements were carried out as per ASTM D7175 (2015) using the DSR (Make: Anton Paar, Model: MCR 102). During the testing on DSR, bituminous binder sample is sandwiched between a fixed plate and an oscillating plate. As shown in Figure 3.5, the upper plate is caused to oscillate sinusoidally at selected frequencies and torque amplitude while the base plate is fixed during testing. The upper plate oscillates about its own axis such that it moves from point A to point B, then moves back from point B to point C, and returns to point A from point C. This entire movement comprises one cycle. Frequency is expressed as the number of cycles traversed by the oscillating plate in one second.

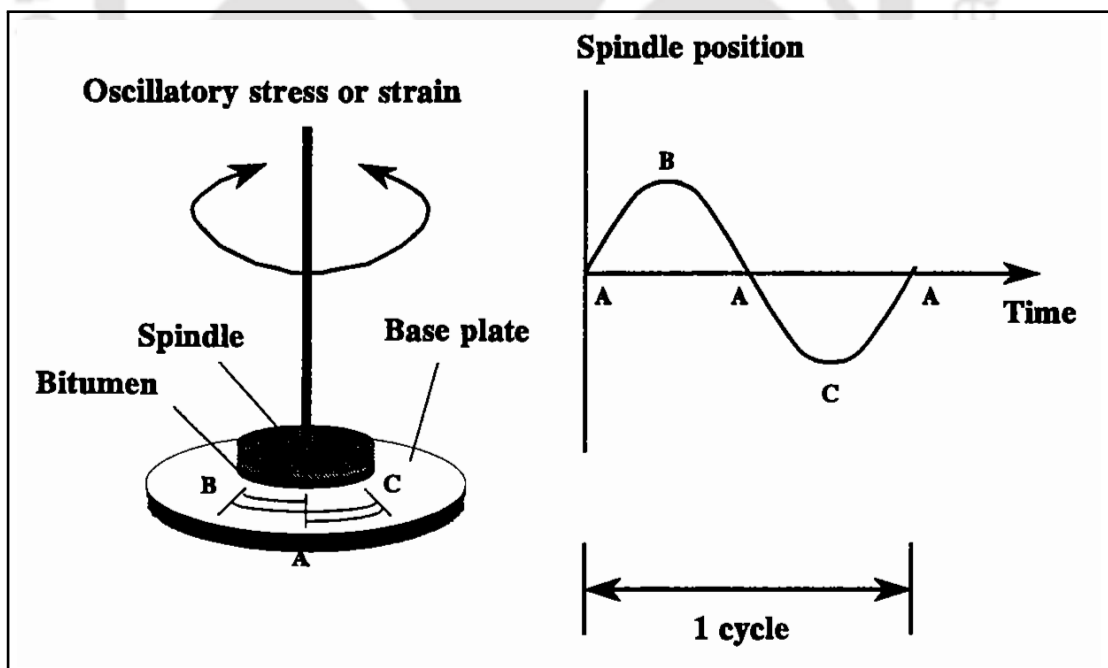


Figure 3.5: Principle of dynamic shear rheometer (Airey, 1997)

In this test, the thickness of binder sample sandwiched between the two parallel plates depends on the test temperature. Low test temperatures in the range of 4 to 40°C require a gap of 2 mm (2000 microns) and high test temperatures (greater than 46°C) require a gap of 1 mm (1000 microns). Also, two types of spindles are used: 25-mm diameter parallel plate for high temperatures and 8-mm diameter parallel plate for low temperatures (Roberts et al., 1996). After the bitumen sample is sandwiched, DSR measures the strain/stress by applying a torque to a bituminous specimen in response to the known applied stress/strain. The calculation of the shear stress and shear strain are determined by Equation 3.1 and Equation 3.2:

$$\tau_{\max} = \frac{2T}{\pi r^3} \quad (3.1)$$

$$\gamma_{\max} = \frac{\theta r}{h} \quad (3.2)$$

where,

$\tau_{\max}$  = maximum applied stress

$\gamma_{\max}$  = maximum resultant strain

T = maximum applied torque

r = specimen radius (either 4 or 12.5 mm)

$\theta$  = deflection (rotation) angle (in radians)

h = specimen height (either 1 or 2 mm).

Using the above equations, complex shear modulus ( $G^*$ ) is determined as the ratio of maximum shear stress ( $\tau_{\max}$ ) to maximum shear strain ( $\gamma_{\max}$ ). The time lag between the applied stress and the resulting strain is referred as the phase angle ( $\delta$ ).  $G^*$  is a measure of the total resistance of a material to deformation when

the binder is subjected to shear loading repeatedly. It consists of two parts: elastic component (storage modulus) and viscous component (loss modulus). Storage modulus ( $G'$ ) relates to the energy stored, whereas loss modulus ( $G''$ ) relates to energy lost through flow or deformation during a test cycle (Roberts et al., 1996). The phase angle ( $\delta$ ) is an indicator of the relative amounts of recoverable and non-recoverable deformations.

For a perfectly elastic material, there is an instant response and therefore, the time lag between the applied stress and the resulting strain, or  $\delta$  is zero. When a viscous liquid such as hot asphalt binder is tested, the time lag is large and  $\delta$  approaches 90 degrees. However, asphalt binders display a stress-strain response between these two extremes at the pavement service temperatures, and hence the phase angle varies between 0 to 90 degrees.

### 3.3.1.3 Test Procedures

#### *Viscosity*

Viscosity is the property of a fluid which measures its internal friction that causes resistance to flow. Viscosity of asphalt binders was measured using Brookfield rotational viscometer according to ASTM D4402/D4402M (2015). In this test, about 10 g of asphalt binder sample was taken in a cylinder and the viscosity was measured at 150°C using cylindrical spindle (SC4–21) at 20 rpm.

#### *Failure Temperature*

Failure temperature/continuous performance grade of asphalt binders was determined at unaged and short-term aged conditions according to Superpave anti-rutting criterion ( $G^*/\sin\delta$ ) through the DSR. Failure temperature is the

temperature at which  $G^*/\sin\delta$  has a maximum value of 1 kPa for unaged binders and 2.2 kPa for short-term aged binders. This test was performed at 12% controlled linear strain for unaged binders and 10% controlled linear strain for short-term aged binders with 1 mm gap between 25 mm diameter parallel plates. The angular frequency of 10 rad/s was maintained during the test. Higher failure temperature is a desirable attribute for a binder from the standpoint of resistance against permanent deformation at high pavement service temperatures.

#### ***Frequency Sweep Test***

Frequency sweep test was conducted to determine the structural response of asphalt binders subjected to small-deformation oscillations over a range of frequencies. Higher frequencies resemble higher traffic speeds and vice versa. The test was performed over four frequency decades: 0.01–0.1, 0.1–1, 1–10, and 10–100 Hz at a constant temperature (60°C) and constant amplitude within the linear viscoelastic domain. Elastic modulus ( $G'$ ) and viscous modulus ( $G''$ ) of the binders were measured during the test.

#### ***Temperature Sweep Test***

Temperature sweep test provides an idea on the dependence of rheological parameters of binders over a wide range of temperatures. It was performed through DSR over a temperature range of 25°C to 80°C at a constant strain amplitude and frequency (10 rad/s) within the linear viscoelastic domain. Complex modulus ( $G^*$ ) and phase angle ( $\delta$ ) of the binders were measured during the test.

### ***Creep Test***

Creep is defined as the slow and permanent deformation under the influence of constant shear stress. This test simulates the situation where the stress levels are maintained for a longer duration of time. In this test, binders were subjected to constant stress loading of 10 Pa for 300 seconds at 60°C and strain was monitored over the time period. As the strains induced in the binder are dependent on the applied stress level, the results are presented in terms of compliance (J). Compliance is defined as the ratio of total strain to the applied stress. A low compliance value at a given stress level reflects higher rutting resistance.

### ***Repeated Creep Recovery Test***

Repeated creep recovery test, which represents the dynamic behaviour of traffic, was performed on warm asphalt binders. In this test, shear stress of 10 Pa was applied repeatedly 52 times with a loading time of 1 s in total cycle length of 10 s. Binder deformation was monitored continuously over the test duration and the results are reported in terms of compliance.

### ***Multiple Stress and Creep Recovery Test***

Multiple stress and creep recovery (MSCR) test was carried out as per ASTM D7405-10a (2010). MSCR test has better correlation with mixture rutting than Superpave binder criteria ( $G^*/\sin\delta$ ) (D'Angelo, 2009). In this test, the warm asphalt binders were subjected to a haversine shear load of 1 s creep loading within a total cycle length of 10 s. Ten cycles were applied on the asphalt sample with a creep stress of 0.1 kPa immediately followed by ten load cycles at 3.2 kPa.

Strain was monitored over the test duration to determine the non-recoverable creep compliance ( $J_{nr}$ ) as given in Equation 3.3.

$$J_{nr} = \frac{\epsilon_{nr}}{\sigma} \quad (3.3)$$

where,

$J_{nr}$  = non-recoverable creep compliance, Pa<sup>-1</sup>

$\epsilon_{nr}$  = non-recoverable strain

$\sigma$  = stress level, Pa

### 3.3.2 Task 2: Evaluation of Marshall Mix Design Parameters of Warm Mixes

Task 2 of this research was carried out to evaluate the effect of WMA additives and their dosage rates on the volumetric elements and Marshall parameters of bituminous mixes prepared with PMB and CRMB at different reductions in production temperatures. The experimental variables for mix preparation included two binder types (PMB and CRMB), two WMA additives (Evotherm and Sasobit), different dosages of each WMA additive (Sasobit: 1%, 2%, and 3%, and Evotherm: 0.5% and 0.6% by weight of binder), and four reductions in the production temperatures (0°C, 20°C, 30°C, and 40°C). The prepared mixes were tested for mix volumetric elements: bulk density, air voids, voids in mineral aggregates (VMA), and voids filled with bitumen (VFB), and Marshall parameters: Marshall stability, and Marshall flow. The experimental flow chart to achieve this objective is shown in Figure 3.6.

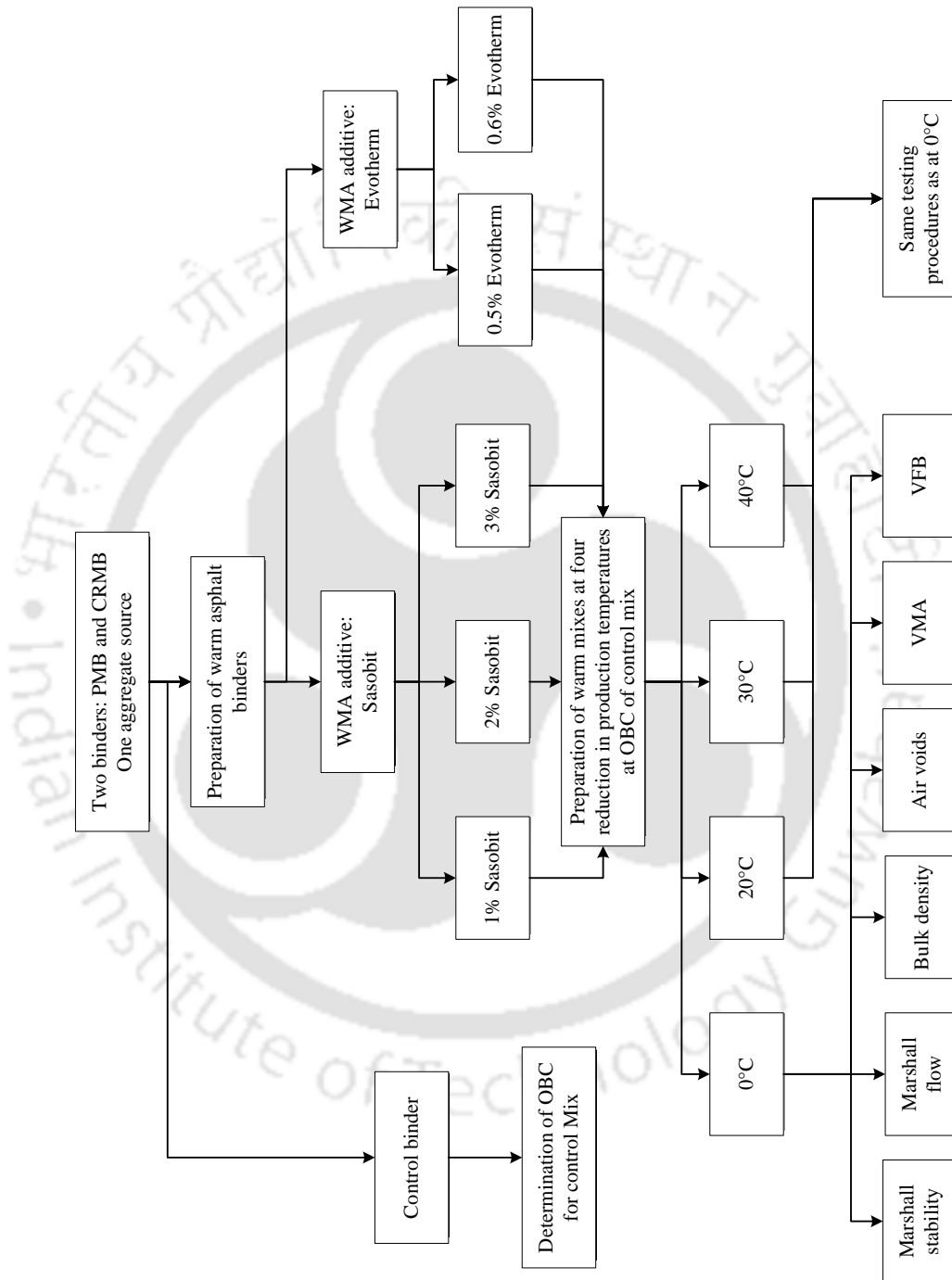


Figure 3.6: Experimental plan for Task 2

### 3.3.2.1 Design of Bituminous Concrete Mixes

Bituminous concrete (BC) is most commonly used wearing course on national highways and expressways in India. Selected aggregate gradation and the specified gradation limits for BC mix as per MoRTH (2013) specifications is shown in Figure 3.7. Standard Marshall method of mix design was adopted in this study as specified in MoRTH (2013) specifications. Marshall samples were prepared and tested as per the guidelines stated in ASTM D1559 (1989).

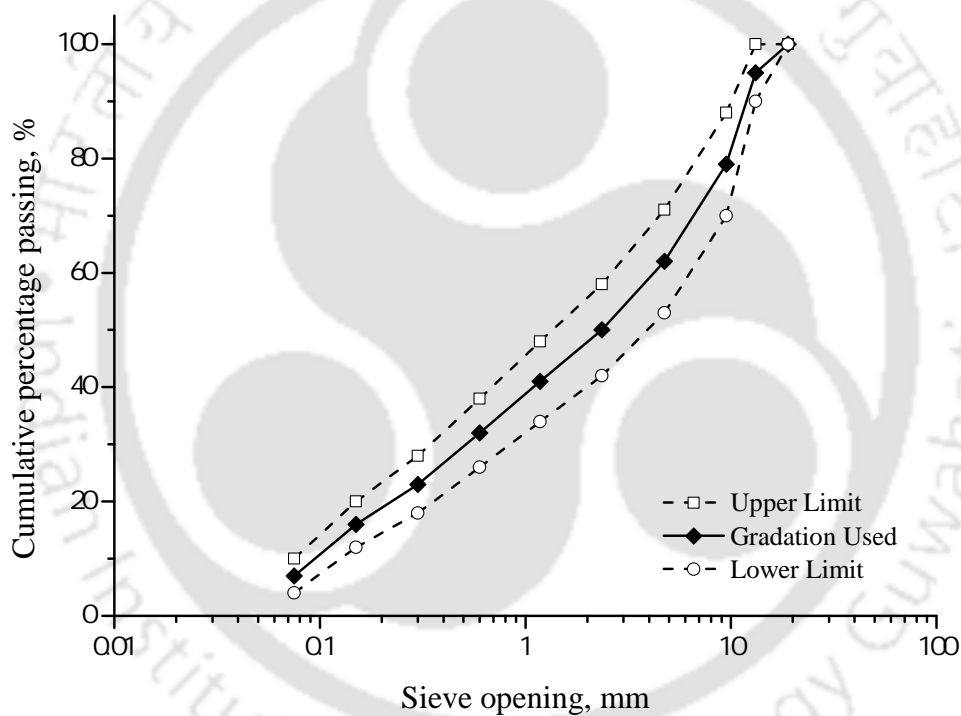


Figure 3.7: Aggregate gradation selected for BC mixes

For preparing Marshall samples, the following recipe was followed. According to the selected gradation, the aggregates were batched as shown in Figure 3.8. The batched aggregate samples were kept in temperature controlled oven for a minimum of 4 h at a temperature 10°C higher than the mixing temperature for drying and heating. Modified binders were also heated in oven to attain the desired mixing temperature. Bituminous mixes were prepared by

mixing the batched aggregates and specified amount of binder in temperature controlled crater for 30 to 40 s at the mixing temperature as shown in Figure 3.9. The prepared mix was transferred into a rectangular aluminium pan and placed in an oven equipped with circulating fan at the compaction temperature for 2 h  $\pm$  5 min (Figure 3.10) for short-term ageing as specified in AASHTO R 30-02 (2006). Short-term ageing represents the ageing of binder that takes place during transportation of mix to the paving site (Behera et al., 2013; Asphalt Institute, 1997) and also allows the bitumen to get absorbed into aggregate pores (Roberts et al., 1996; Asphalt Institute, 1997). The conditioned samples were transferred into Marshall moulds and compacted with an energy level of 75 blows on each face of the cylindrical specimen using an automatic Marshall impact compactor having a weight of 4.54 kg and a free fall of 45.7 cm.



Figure 3.8: Batched aggregates

### 3.3. Experimental Plan

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Figure 3.9: Mixing of batched aggregates and bitumen



Figure 3.10: Conditioning of loose bituminous mixes at compaction temperature

Three Marshall samples were prepared at each binder content varying from 5.5% to 7.0% (by weight of mix) with an increment of 0.5%. Marshall samples were left to cool at the room temperature for overnight and then extracted from the moulds. Additional three mixes were prepared in loose condition at each binder content to determine the maximum specific gravity ( $G_{mm}$ ). CoreLok™ equipment (manufactured by InstronTek Inc.) was used to determine maximum specific gravity of bituminous mixes as shown in Figure 3.11 according to ASTM D6857/D6857M (2011).



Figure 3.11: Determination of  $G_{mm}$  for loose mixes using Corelok™ instrument

Extracted Marshall samples prepared at different bitumen contents were subjected to the two principal features of Marshall Method of mix design: density-void analysis and stability-flow test. Bulk density determination of the samples was performed in accordance with ASTM D2726/D2726M (2014). Marshall samples were then conditioned in hot water bath for 30 to 40 min at  $60 \pm 1^\circ\text{C}$  and then subjected to testing to determine Marshall stability and flow.

### 3.3. Experimental Plan

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Marshall stability testing was performed using Matest 50 kN UTM II digitalized Marshall stability testing machine shown in Figure 3.12 in accordance with ASTM D1559 (1989).



Figure 3.12: Testing of Marshall Samples for Marshall stability

After the completion of testing on samples, density-voids analysis was performed to determine VMA, AV, and VFB of the compacted samples. Test results that were apparently erratic were discarded before averaging the bulk density values of bituminous mixes as per the criteria given in ASTM D2726/D2726M (2014). The average values of bulk density, Marshall stability, flow, AV, VMA, and VFB were plotted separately against the bitumen content as shown in Figure 3.13 and 3.14 for bituminous mixes with PMB and CRMB binders respectively.

Optimum binder content (OBC) was determined at 4% air void content as per the guidelines stated in the Asphalt Institute Manual Series No 2 (Asphalt

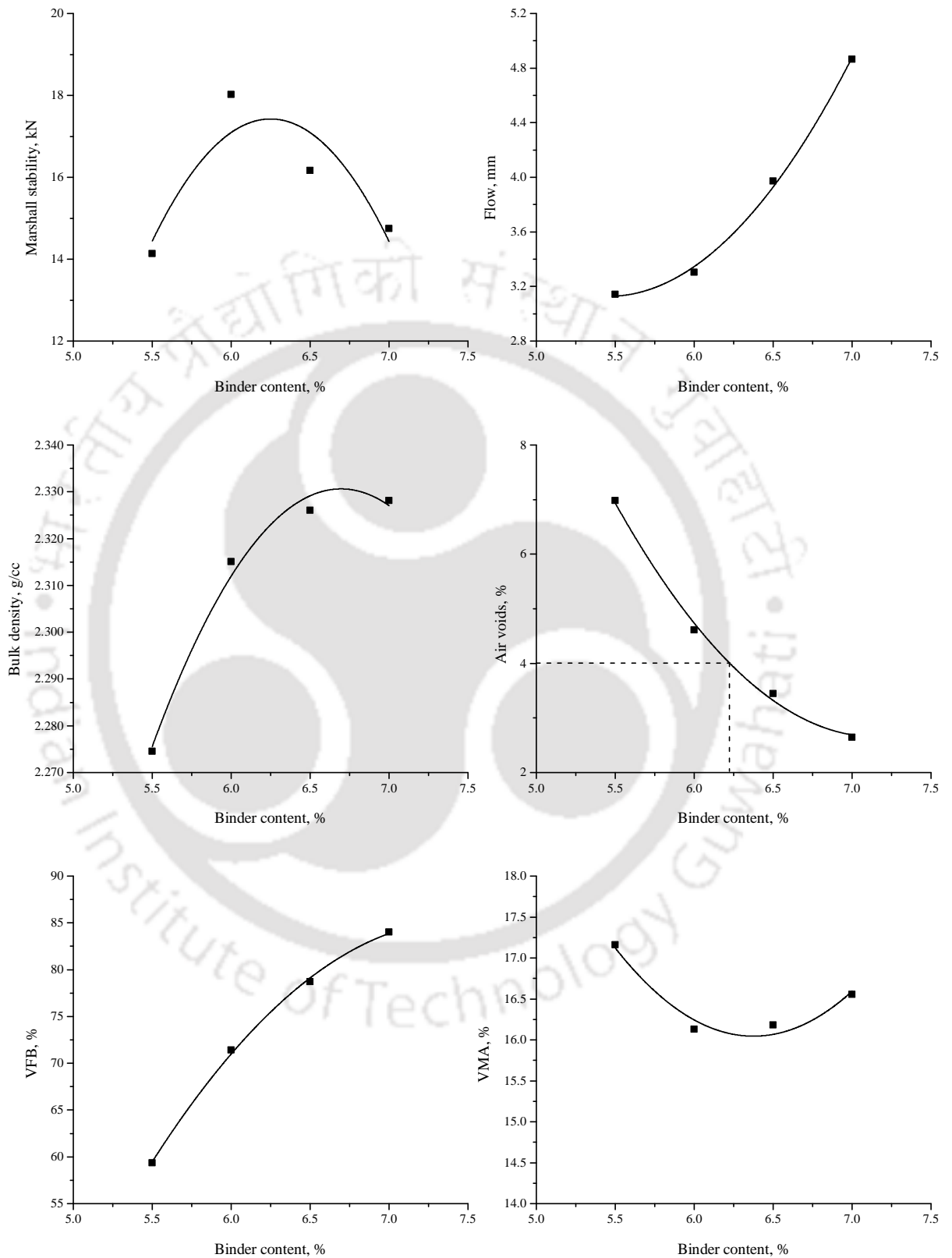


Figure 3.13: Marshall and volumetric results of PMB control mixes

### 3.3. Experimental Plan

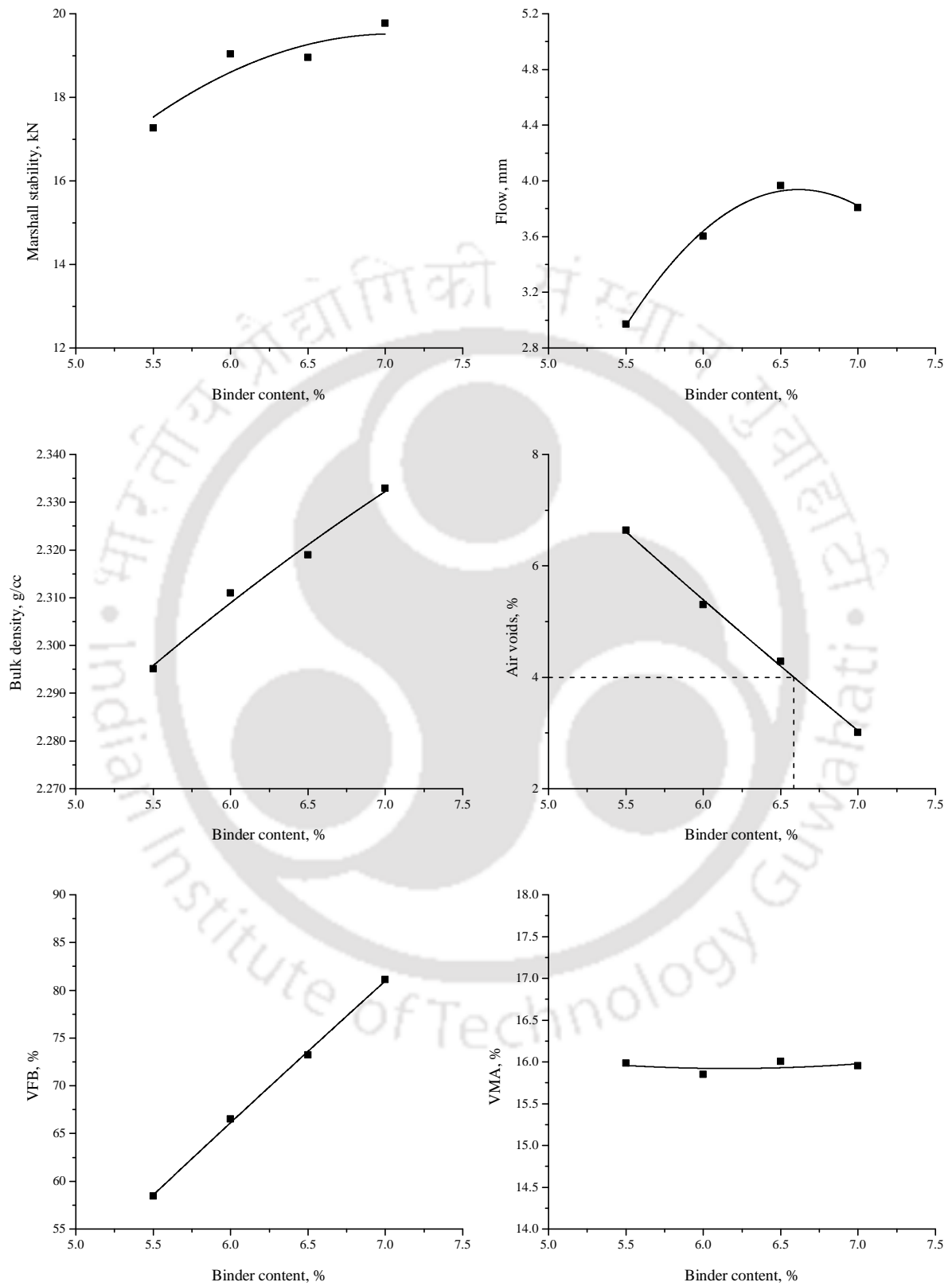


Figure 3.14: Marshall and volumetric results of CRMB control mixes

Institute, 1997), which is also the median of the required air voids limits (3 to 5%) as specified in MoRTH (2013) specifications. All the mix properties at this binder content were determined and compared with the mix design criteria listed in Table 3.7 as stipulated by MoRTH (2013).

Table 3.7: Mix design requirements as per MoRTH (2013)

Property	Requirement
Marshall stability at 60°C, kN	Min. 12
Marshall flow, mm	2.5 – 4.0
Air voids (AV), %	3.0 – 5.0
Voids filled with bitumen (VFB), %	65 – 75
Voids in mineral aggregate (VMA), %	Min. 14

OBCs achieved for BC mixes at 4% air void content with PMB and CRMB binders were 6.2% and 6.6% (by weight of mix), respectively. These mixes were referred as control mixes. Various parameters like Marshall stability, Marshall flow, AV, VMA, and VFB for control mixes at OBC are summarised in Table 3.8. OBC for BC mixes with CRMB is found to be higher than those with PMB. This may be attributed to the formation of thicker film of CRMB over the aggregates due to the presence of crumb rubber particles (Akisetty et al., 2009a). Marshall stability values of CRMB mixes are higher than PMB mixes at OBC by approximately 14.2%. The increase in Marshall stability may be due to higher viscosity of CRMB than PMB.

### 3.3.2.2 Preparation of Warm Mixes

WMA additives help to reduce the production temperatures of bituminous mixes. Sasol Wax claims that the blending of Sasobit additive in bituminous

Table 3.8: Marshall parameters of BC mixes at OBC

Property	Results	
	PMB 40	CRMB 60
Optimum binder content (OBC), %	6.2	6.6
Marshall stability at 60°C, kN	16.9	19.3
Marshall flow, mm	3.5	3.9
Voids filled with bitumen (VFB), %	73.9	74.6
Air voids (AV), %	4.0	4.0
Voids in mineral aggregate (VMA), %	15.6	15.7
Bulk density, g/cc	2.321	2.325

mixes can reduce the production temperatures by 10–30°C (Sasobit Product Information 124, 2017). MWV, the manufacturer of Evotherm, claims that the mixing and compaction temperature of bituminous mixes can be reduced by 50–100°F (10–38°C). From standard mixing and compaction temperatures used for control HMA mixes (shown in Table 3.4), three reductions in production temperatures (20°C, 30°C, and 40°C) were chosen for preparing warm mixes. These reductions fall in the designated range of temperature reductions as specified by the manufacturer of each additive.

Warm mixes were prepared using warm asphalt binders with the desired percentage of WMA additive (either Sasobit or Evotherm). Warm mixes were prepared similar to control mixes using standard Marshall mix design as explained in Section 3.3.2.1. These mixes were prepared by lowering the mixing and compaction temperatures by 0°C, 20°C, 30°C, and 40°C from the standard mixing and compaction temperatures. It should be emphasised here that the warm mixes were also prepared at standard mixing and compaction temperatures (*i.e.* 0°C reduction) to facilitate comparison with the control mixes

at the same production temperatures. Various mixing and compaction temperatures used for preparation of WMA mixes with modified binders are summarised in Table 3.9.

Table 3.9: Mixing and compaction temperatures for preparation of warm mixes

<b>Binder type</b>	<b>Mixing temperature, (°C)</b>	<b>Compaction temperature, (°C)</b>	<b>Reduction in mixing and compaction temperature, (°C)</b>
PMB	170	160	0
	150	140	20
	140	130	30
	130	120	40
CRMB	175	165	0
	155	145	20
	145	135	30
	135	125	40

### 3.3.3 Task 3: Moisture Susceptibility Characteristics of Warm Mixes

Task 3 included the objective of determining the moisture susceptibility resistance of warm mixes. Warm mixes were prepared with different combinations of binder type, WMA additive type, percentage of WMA additive, and production temperature. All combinations were tested for moisture susceptibility characteristics using modified Lottman test (as per AASHTO T 283 (2003)) and retained Marshall stability test (as per MoRTH (2013)). The detailed testing procedures of modified Lottman and retained Marshall stability are

presented in the following sections. The experimental plan followed to achieve this objective is shown in Figure 3.15.

#### 3.3.3.1 Test Procedures

##### ***Modified Lottman Test***

Modified Lottman test is commonly used for determining the moisture susceptibility characteristics of bituminous mixes (Alam et al., 1998; Airey and Choi, 2002; Hicks et al., 2003; Brown et al., 2001; Mogawer et al., 2011). This test procedure was piloted by Lottman in 1978, at the University of Idaho (Hunter and Ksaibati, 2002). In early 1980, Tunnicliff and Root altered and presented their version of Lottman procedure. Later, the Lottman method was modified and standardized as AASHTO T 283, *Resistance of Compacted Bituminous Mixture to Moisture Induced Damage*, in 1985. Modified Lottman test method shelters the good features of both Lottman test and Tunnicliff and Root test (Roberts et al., 1996; Hunter and Ksaibati, 2002; Airey and Choi, 2002).

In this study, modified Lottman test was performed according to the guidelines stipulated in AASHTO T 283 (2003). Six Marshall samples of 101.6 mm diameter × 63.5 mm (approx.) height were prepared at an air void content of  $7\pm 0.5\%$ . This air void content was achieved by reducing the compaction energy. Prepared Marshall samples were divided into two sets. One set of samples was tested in the dry condition for indirect tensile strength (ITS). The other set of samples was subjected to partial saturation and moisture conditioning with a freeze-thaw cycle before testing the samples for ITS.

Group one samples, termed as unconditioned samples, were kept at the room temperature. For the group two samples, termed as conditioned samples,

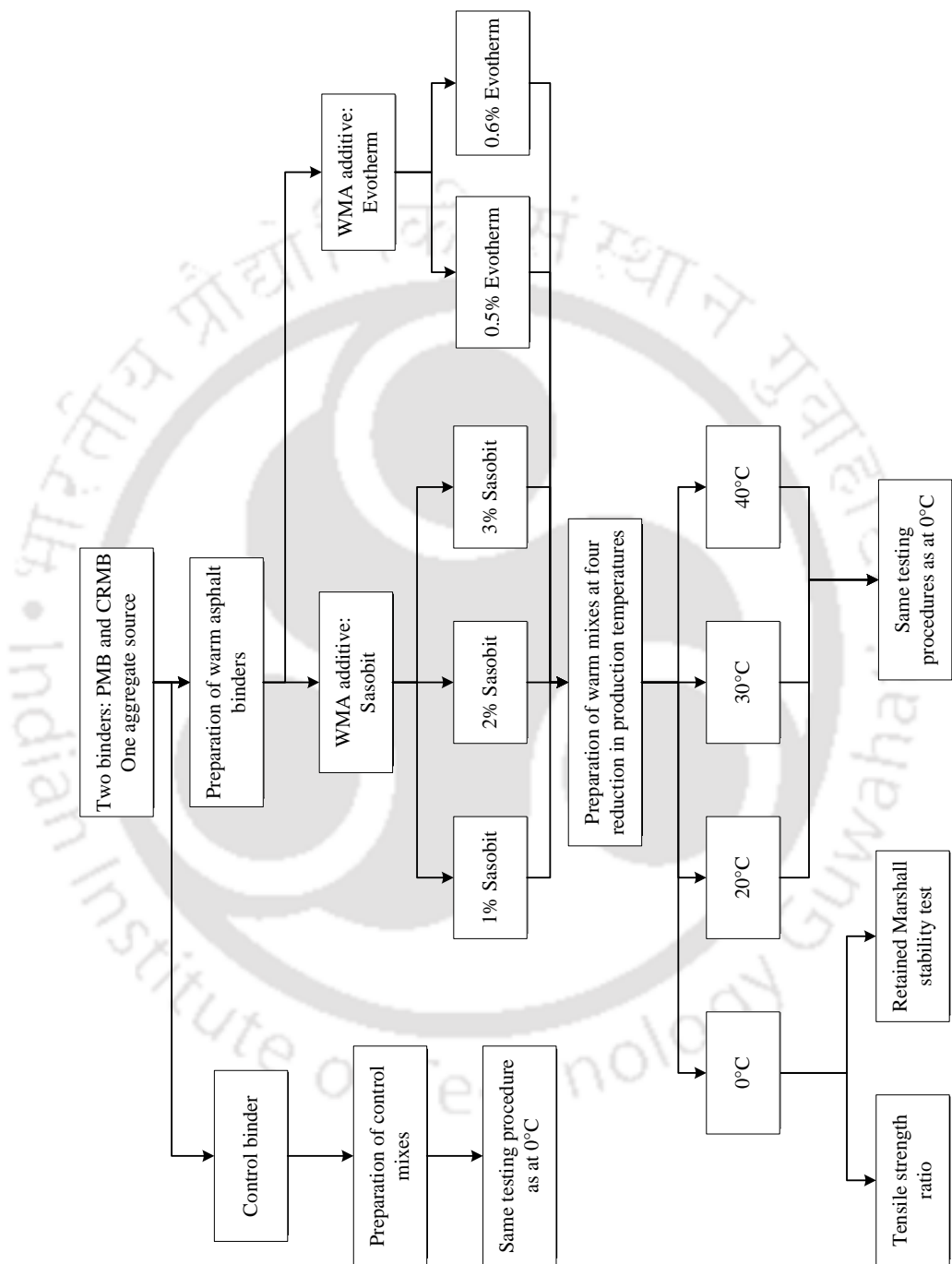


Figure 3.15: Experimental plan for Task 3

### 3.3. Experimental Plan

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each sample was first subjected to partial vacuum saturation to attain the degree of saturation of 70 to 80%. The saturated samples were placed in a plastic bag containing  $10 \pm 0.5$  ml water and were then sealed. The samples were moved into a freezer at a temperature of  $18 \pm 3^\circ\text{C}$  for 16 h followed by thaw cycle in the water bath at a temperature of  $60 \pm 1^\circ\text{C}$  for 24 h. Vacuum saturation of samples reflects the field performance up to 4 years, while vacuum saturation along with freeze-thaw cycle represents the field performance from 4 to 12 years (Roberts et al., 1996; Airey and Choi, 2002). Both unconditioned and conditioned specimens were placed in a water bath at  $25 \pm 0.5^\circ\text{C}$  for 2 h before measuring the ITS. Pictorial form of vacuum saturation, freezing, and thawing are shown in Figures 3.16, 3.17, and 3.18 respectively.



Figure 3.16: Vacuum saturation of group 2 samples

Both unconditioned and conditioned samples were tested to determine the ITS at  $25 \pm 0.5^\circ\text{C}$  as per ASTM D6931-12 (2012). The samples were placed between the two loading strips as shown in Figure 3.19. A compressive load was



Figure 3.17: Freezing of group 2 samples



Figure 3.18: Thawing of group 2 samples

### 3.3. Experimental Plan

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applied to cylindrical specimen at a constant deformation rate of 50 mm/min through two diametrically opposed rigid platens to induce tensile stress along the vertical diametral plane of the test specimen. The load was continuously applied until failure of the sample. The peak compressive load was recorded and used to calculate the tensile strength of the specimen using Equation 3.4:

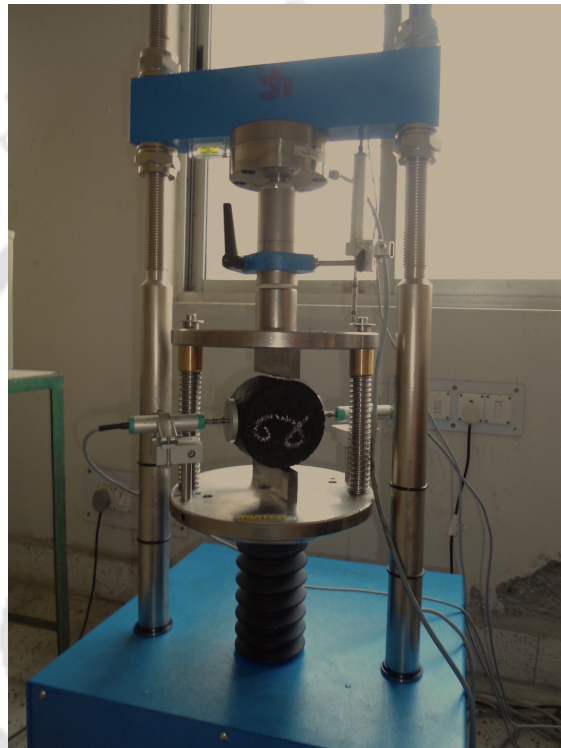


Figure 3.19: Indirect tensile testing

$$ITS = \frac{2000P}{\pi Dh} \quad (3.4)$$

where,

ITS = indirect tensile strength, kPa

P = peak compressive load, N

D = diameter of the specimen, mm

h = thickness of the specimen, mm

Moisture susceptibility was determined as a numerical index in terms of tensile strength ratio (TSR), expressed as a ratio of average indirect tensile strength of conditioned specimens to the average indirect tensile strength of unconditioned specimens. TSR of each mixture was determined using the Equation 3.5:

$$\text{TSR} = \frac{\overline{\text{ITS}}_c}{\overline{\text{ITS}}_u} \times 100 \quad (3.5)$$

where,

TSR = tensile strength ratio, %

$\overline{\text{ITS}}_u$  = average indirect tensile strength of unconditioned specimens, kPa

$\overline{\text{ITS}}_c$  = average indirect tensile strength of conditioned specimens, kPa

#### ***Retained Marshall Stability Test***

Retained Marshall stability is a measure of loss of compressive strength resulting from the action of water on bituminous mixes. The test was performed as per the guidelines specified in MoRTH (2013). A similar procedure is also proposed by *Saskatchewan Highways and Transportation* in Standard Test Procedure Manual (STP 204-22), *American Military Standard* (MIL-STD-620A), and *Standard test Method for Measurement of Reduction in Marshall Stability of Bituminous Mixtures Caused by Immersion in Water* (U.S. Army Corps of Engineers, CRD-C 652-95).

As per the test protocol cited in MoRTH (2013), six standard Marshall specimens of 101.6 mm diameter × 63.5 mm height were prepared at approximately 6% air void content by reducing the number of compaction blows. These six samples were divided into two subsets having similar bulk

density or an air void content. Subset 1 specimens, referred as unconditioned specimens, were kept in water bath for 30 min at 60°C before Marshall stability testing. Subset 2 specimens, referred as conditioned specimens, were kept in a water bath for 24 h at 60°C prior to Marshall stability testing. Retained Marshall stability was determined as a ratio of average Marshall stability of conditioned specimens to that of average Marshall stability of unconditioned specimens, as given in Equation 3.6. RMS was used as an indicator moisture susceptibility resistance of bituminous mixes.

$$\text{RMS} = \frac{\overline{\text{MS}}_c}{\overline{\text{MS}}_u} \times 100 \quad (3.6)$$

where,

RMS = retained Marshall stability, %

$\overline{\text{MS}}_u$  = average Marshall stability of unconditioned specimens, kN

$\overline{\text{MS}}_c$  = average Marshall stability of conditioned specimens, kN

#### 3.3.4 Task 4: Performance Characteristics of Warm Mixes

Task 4 of this study was conducted to evaluate the performance characteristics of warm mixes in terms of resilient modulus, permanent deformation, and fatigue damage. Experimental plan shown in Figure 3.20 was used to accomplish this task. Warm mixes were prepared using the aforementioned experimental variables and subjected to performance testing. Resilient modulus, dynamic creep, and indirect tensile fatigue tests were performed according to AASHTO TP 31 (1996), BS DD 226 (1996), and EN 12697 – 24 (2012) respectively. All the tests were carried out using Cooper 14 kN universal testing machine (UTM). The test results achieved for warm mixes were compared with the corresponding control

HMA mixes. The experimental test procedures of resilient modulus, dynamic creep, and indirect tensile fatigue are explained in detail in the subsequent sections.

### 3.3.4.1 Test Procedures

#### *Resilient Modulus Test*

Resilient modulus ( $M_R$ ) test is used to predict the response of a bituminous material to a repeated impulse or moving loads that may be imposed by a traffic/vehicle tires on a road surface. Resilient modulus is defined as the ratio of applied stress to the recoverable strain (resilient strain). It is considered as an important design input parameter to calculate the optimum thickness of a new pavement or to estimate the remaining life of an existing pavement. Resilient modulus test has gained popularity after the implementation as a stiffness property for bituminous mixes in AASHTO 1993 Pavement Design Guide (Brown et al., 2009). Resilient modulus at low temperatures (5°C) gives an indication of thermal cracking resistance of bituminous mixtures (Gandhi et al., 2010; Kim et al., 2012). A low resilient modulus at low temperatures is a desirable attribute from the standpoint of resistance to thermal cracking and a high resilient modulus at high temperatures is desired for the elastic property (Kim et al., 2012; Masoudi et al., 2017).

Resilient modulus test was performed at temperatures of 5°C, 25°C, and 40°C in accordance with AASHTO TP 31 (1996). As per the test protocol, four Marshall samples were prepared for each individual set. To determine repetitive load level, one of the four Marshall samples was tested for ITS at 25°C as per ASTM D6931-12 (2012) using Matest 50 kN UTM II digitalized Marshall stability testing

### 3.3. Experimental Plan

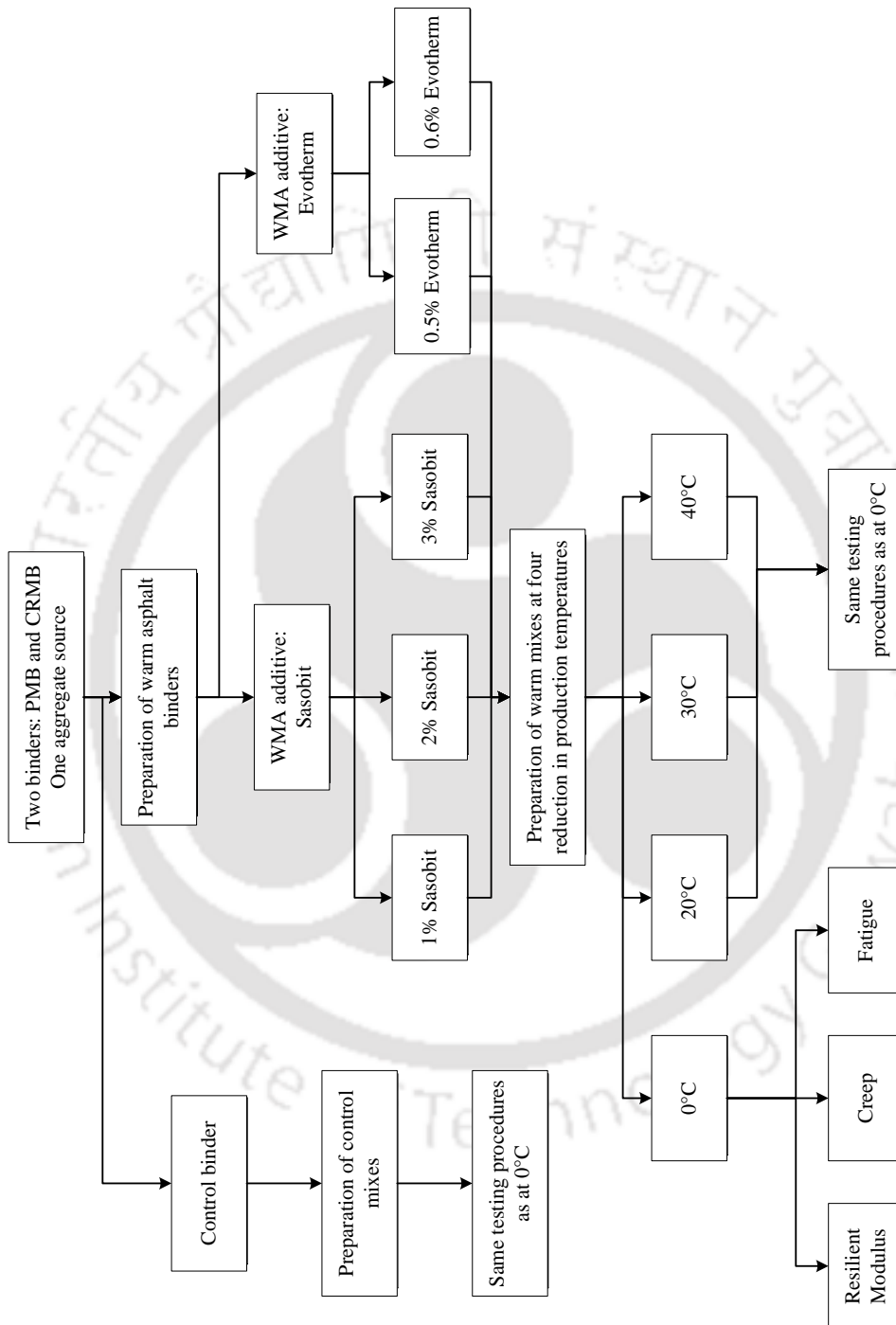


Figure 3.20: Experimental plan for Task 4

machine. Prior to resilient modulus testing, Marshall samples and testing jig along with necessary accessories were pre-conditioned in the controlled environmental chamber. Repeated load levels of 30%, 15%, and 5% of ITS were used respectively at test temperatures of 5°C, 25°C, and 40°C. A compressive repetitive load was applied on vertical diametric plane of cylindrical specimen in the form of haversine wave with a loading time of 0.1 s in a total cycle length of 1 s. Linear variable differential transducers (LVDTs) were used for measuring both horizontal and vertical deformation responses. At each test temperature, the Marshall specimens were subjected to 100 repetitive load pulses for conditioning and 5 repetitive load pulses for calculating resilient modulus. Resilient modulus was calculated using Equation 3.7. After completing the test, the sample was rotated by  $(90 \pm 10)^\circ$  and second set of loading was applied perpendicular to the direction of the first set. Finally, the average of resilient moduli of two sets was reported as the resilient modulus of a particular bituminous mix sample. Poisson's ratio was taken as 0.25, 0.35, and 0.40 at the test temperatures of 5°C, 25°C, and 40°C respectively (Roberts et al., 1996). The test setup for determining the resilient modulus is shown in Figure 3.21.

$$M_R = \frac{P(\mu + 0.27)}{H_r h} \quad (3.7)$$

where,

$M_R$  = resilient modulus, MPa

$P$  = repeated vertical load, N

$H_r$  = total recoverable horizontal deformation, mm

$h$  = mean thickness of specimen, mm

$\mu$  = Poisson's ratio

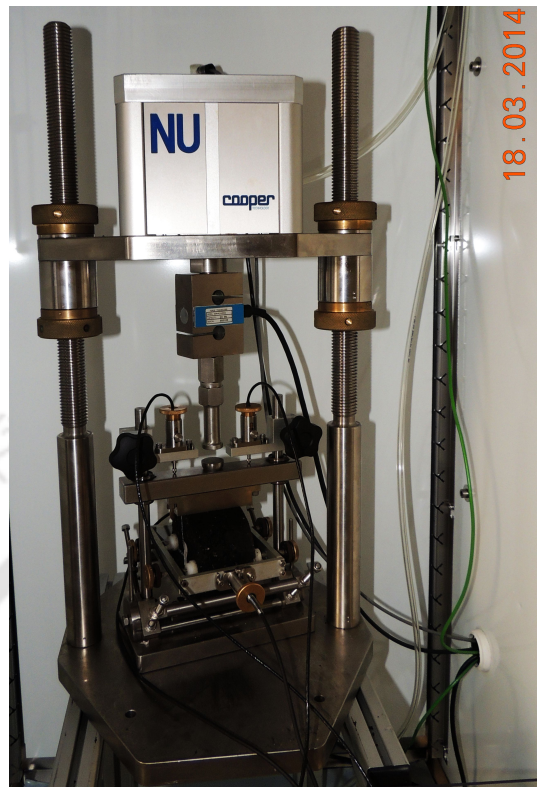


Figure 3.21: Resilient modulus test setup

#### ***Dynamic Creep Test***

Dynamic creep test measures the resistance to permanent deformation of the bituminous mixes, caused due to repeated traffic loadings. Rutting typically appears as a surface depression under the wheel path accompanied by small upheavals at the sides. Rutting, in most cases, is caused by consolidation or densification of the pavements layers or shear flow in the HMA layer or a combination of both. It reduces the structural and functional performance of the pavement.

Since many years, creep test has been used to estimate the rutting potential of bituminous mixes. In this study, uniaxial repeated load test was used to determine the rutting characteristics of warm mixes at 40°C in accordance with BS DD 226 (1996). In this test, loading on the specimens was uniaxial and

dynamic that represents the repeated application of axle loads on pavement structure. Three identical Marshall specimens were prepared using Marshall impact compactor. The end faces of test samples were smoothed to minimise the friction between the loading platens. Marshall specimens and the loading platens were pre-conditioned in a controlled temperature environment for about 6 h to establish uniform temperature. A pre-conditioning load of 10 kPa was applied for a period of  $600 \pm 6$  s. After the pre-conditioning period, a cyclic axial stress of 100 kPa was applied in a square waveform with a frequency of 0.5 Hz on the horizontal diametric plane of cylindrical specimen. A total of 1800 cycles were applied with a loading period of 1 s and a rest period of 1 s. Two LVDTs were placed to monitor axial deformations of the test specimen throughout the test duration. Axial strain of test sample was determined at the end of the rest period immediately after completion of test using Equation 3.8. Figure 3.22 shows the test assembly of uniaxial repeated load test.

$$\epsilon_p = \frac{\Delta h}{H_0} \quad (3.8)$$

where,

$\epsilon_p$  = permanent axial strain

$\Delta h$  = change in the height of the specimen, mm

$H_0$  = initial height of the specimen, mm

### ***Fatigue Test***

According to ASTM E1823-13 (2013), fatigue is defined as a process of progressive localised permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some



Figure 3.22: Uniaxial repeated load test assembly

point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations. In asphalt pavements, fatigue is considered as one of the major distress associated with repetitive stresses and strains caused by both traffic loading and environmental factors. The repetitive action of cyclic loading and unloading causes fatigue damage and appears in the form of longitudinal cracks along the wheel path on the pavement surface and propagates into alligator cracking over the time. The progress of fatigue cracking reduces both structural and functional performance of the pavement.

In this study, indirect tensile fatigue test (ITFT) was used to evaluate the fatigue characteristics of the warm mixes. This test was performed as per the guidelines stated in EN 12697 – 24 (2012). In order to evaluate the fatigue life of warm and control mixes, Marshall samples were prepared and then placed in a controlled temperature environment at test temperature of 20°C along with

other testing accessories for a minimum of 4 h prior to testing. Test was conducted by applying a repeated compressive load of 500 kPa with a haversine load signal through the vertical diametric plane of cylinder-shaped test specimen. This loading develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametrical plane, which causes the specimen to fail by splitting along the central part of the vertical diameter. The repetitive load was applied at a frequency of 2 Hz with a loading time of 0.1 s and rest time of 0.4 s. LVDTs were mounted horizontally to the test specimen to monitor the deformations. The loading was applied continuously until the specimen failed by splitting along the central part of the vertical diameter. Fracture life of the specimen was reported as the total number of load applications that caused complete fracture of the specimen. Figure 3.23 shows the test set up while performing the test and Figure 3.24 shows a failed sample at the end of ITFT test.

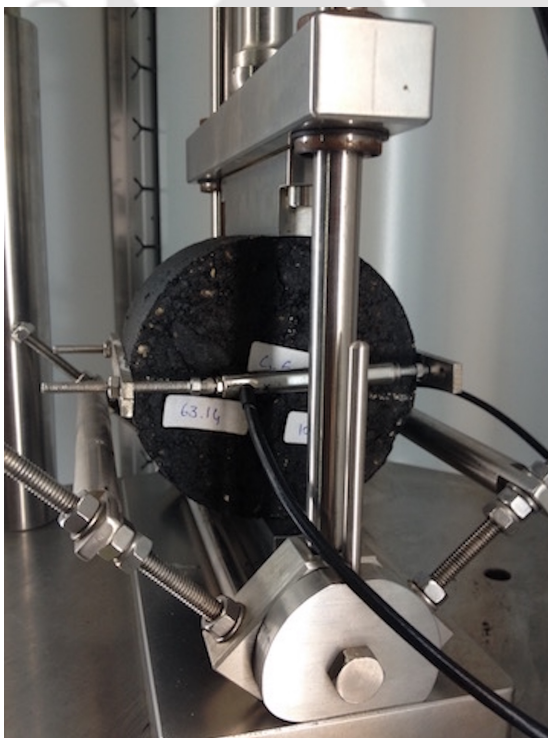


Figure 3.23: ITFT set up

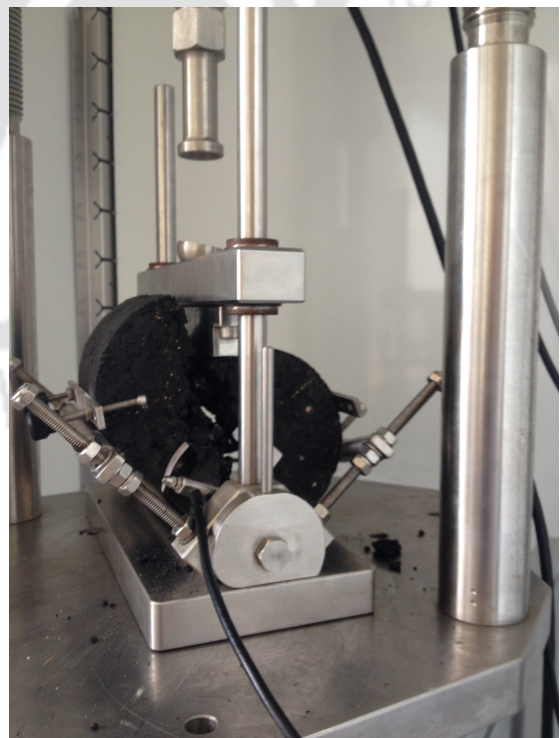


Figure 3.24: Failure of sample

### 3.4 Summary

The details of materials selected in the study including bituminous binders, mineral aggregates, and WMA additives were discussed in this chapter. The experimental programme to achieve the objectives of the study was presented and discussed. Various test procedures for evaluating the rheological properties of warm asphalt binders were explained. Methodologies for preparation of warm mixes at different production temperatures and their evaluation for volumetric and Marshall parameters, moisture susceptibility, resilient modulus, permanent deformation, and fatigue characteristics were also presented in this chapter.



## Chapter 4

# Rheological Characteristics of Warm Asphalt Binders

### 4.1 Introduction

Asphalt binder is a thermoplastic, viscoelastic substance that behaves as a glass-like elastic solid at lower temperatures and/or during rapid loading (short loading times or high loading frequencies) and as a viscous fluid at high temperatures and/or during slow loading (long loading times or low loading frequencies) (Airey, 1997). Therefore, response of the binder to stress is dependent on temperature and loading time. Consequently, its rheology is defined by stress-strain-time-temperature response.

Rheology is a fundamental interdisciplinary science that deals with the flow and deformation of materials in response to the imposed stresses. It describes the interrelations between force, deformation, and time. The rheological properties of the asphalt binder exert strong influence on the performance of asphalt pavements, even though it shares only 5 to 7% by total weight of the mix.

Changes in the properties of asphalt binders under the influence of WMA additives can be understood from the study of rheology of binders containing these additives. Furthermore, the rheology of binder is not only a function of type of WMA additive, but it is also likely to be significantly influenced by the additive dosage. A range of dosages are typically recommended for use by the manufacturers of these additives. Too less or too much of additive dosage may have undesirable effects on the rheology of binders, and also on the performance of asphalt mixes produced with such binders. In other words, binders may exhibit different properties (perform differently) with different doses of WMA additives. Hence, there is a need to evaluate the rheological characteristics of binders with varying doses of WMA additives.

This chapter presents the results of rheological tests, *viz.*, temperature sweep, frequency sweep, creep, and repeated creep recovery, conducted on modified binders containing different dosages of two WMA additives: Evotherm and Sasobit. Failure temperature of warm asphalt binders were also determined. Tests were performed using Anton Paar MCR 102 dynamic shear rheometer (DSR). Viscosity of warm asphalt binders was also determined at 150°C using Brookfield rotational viscometer DV II Pro. Rheological properties of both PMB and CRMB binders with WMA additive Sasobit were also assessed under different short-term ageing temperatures (163°C, 143°C, and 123°C).

## **4.2 Effect of Evotherm on Rheological Properties of Modified Binders**

Two dosages of WMA additive Evotherm (0.5%, and 0.6% by weight of binder) were used. Binders without Evotherm (*i.e.* 0% dosage) are referred as control

binders. Two modified binders: polymer modified binder (PMB) and crumb rubber modified binder (CRMB), were used as the base binders. Preparation of additive-binder blend consisted of first heating the base binders to about 120°C and then introducing the desired quantity of additive, followed by a thorough stirring to achieve homogeneity. The following sections discuss the effects of varying dosages of Evotherm on the rheological characteristics of PMB and CRMB binders.

### ***Viscosity at 150°C***

Viscosity is a measure of consistency of asphalt binder, and reflects the internal resistance of the binder when it flows. Viscosity of both PMB and CRMB binders was measured with and without Evotherm using Brookfield rotational viscometer at 150°C and the results are shown in Figures 4.1 and 4.2. It is observed that viscosity of warm asphalt binders with Evotherm is slightly lower than the control binders. An addition of 0.6% Evotherm reduces the viscosity of PMB and CRMB binders by about 9%. WMA additive Evotherm, which was obtained and added in liquid form during the preparation of warm binders, lead to slight reduction in the viscosity of PMB and CRMB binders.

### ***Failure Temperature***

Failure temperature of an original (unaged) asphalt binder corresponds to the temperature at which the Superpave rutting parameter ( $G^*/\sin\delta$ ) attains a value of 1.0 kPa. Failure temperatures of PMB and CRMB binders with and without Evotherm are presented in Figures 4.3 and 4.4 respectively. It is observed that addition of Evotherm decreases the failure temperatures of both binders, suggesting a decrease in binder stiffness. Decrease in failure temperature is

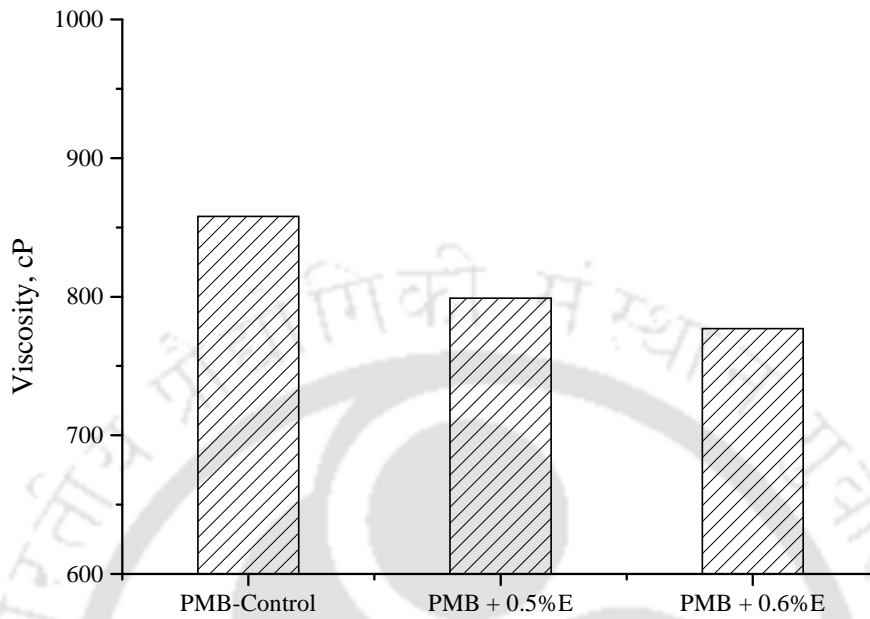


Figure 4.1: Viscosity results of PMB warm asphalt binders with Evotherm

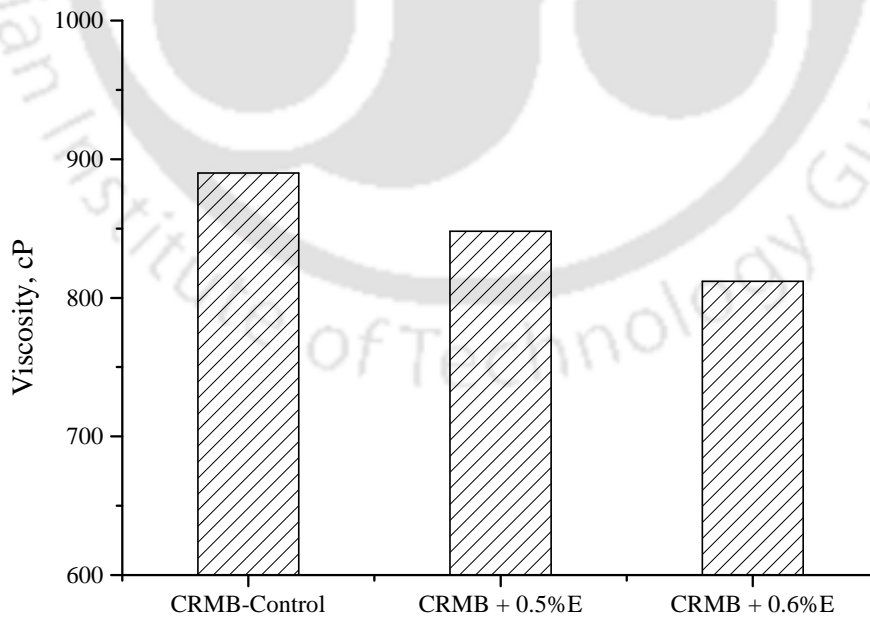


Figure 4.2: Viscosity results of CRMB warm asphalt binders with Evotherm

slightly higher in case of CRMB binders compared to PMB binders. A maximum decrease of 1.8°C and 4.1°C in the failure temperature is observed, respectively, for PMB and CRMB on addition of 0.6% Evotherm. However, there is no change in the performance grade (PG 76) of both base binders on addition of Evotherm.

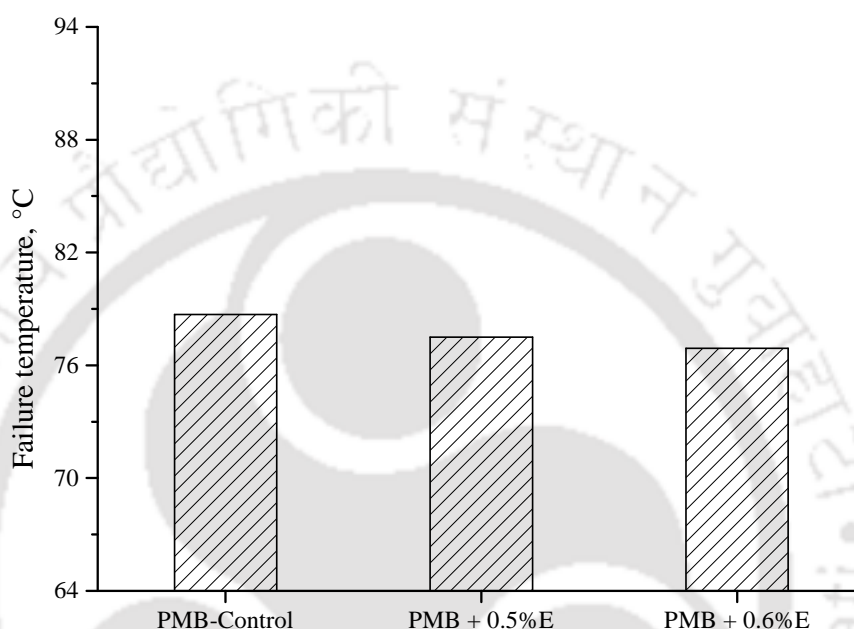


Figure 4.3: Failure temperature of PMB warm asphalt binders with Evotherm

### **Frequency Sweep Test**

Frequency sweep test allows evaluation of rheological response of asphalt binders over wide range of frequencies, while the amplitude of the deformation remains constant. Response at low frequencies describes the behaviour at slow changes of stress, whereas the higher frequencies divulge the behaviour at fast moving loads. Figures 4.5 and 4.6 respectively show the elastic ( $G'$ ) and viscous ( $G''$ ) moduli of PMB and CRMB warm asphalt binders as a function of frequency from 0.01 to 100 Hz. Results show that the elastic and viscous moduli increase with the increase in test frequency. Both elastic and viscous moduli of PMB and CRMB binders decrease slightly on addition of Evotherm over the frequency

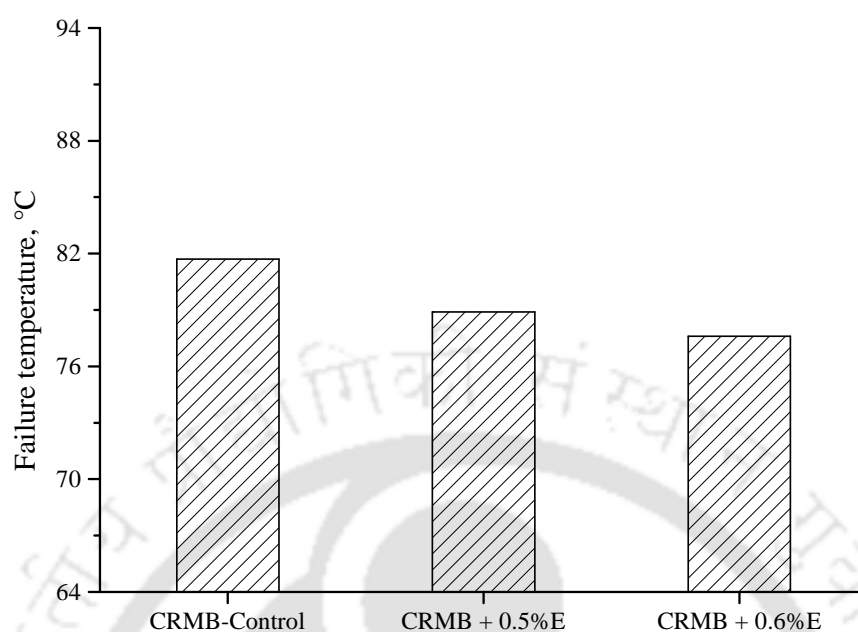


Figure 4.4: Failure temperature of CRMB warm asphalt binders with Evotherm range used. Further, an increase in Evotherm content from 0.5% to 0.6% slightly reduces the elastic and viscous modulus of both binders. However, this reduction becomes insignificant at higher test frequencies, indicating that increase in dosage does not produce appreciable changes in the elastic nature of PMB and CRMB binders.

#### **Temperature Sweep Test**

Temperature sweep test provides an idea about the rheological changes in the asphalt binders at varying temperatures experienced by the pavement during its service life. The test was performed over the temperature range of 25–80°C, and the two fundamental rheological parameters, namely the complex modulus ( $G^*$ ) and the phase angle ( $\delta$ ), were reported for the modified binders (PMB and CRMB) under varying Evotherm dosages. Figures 4.7 and 4.8 present the results. Introducing Evotherm into the binders does not show any significant effect on

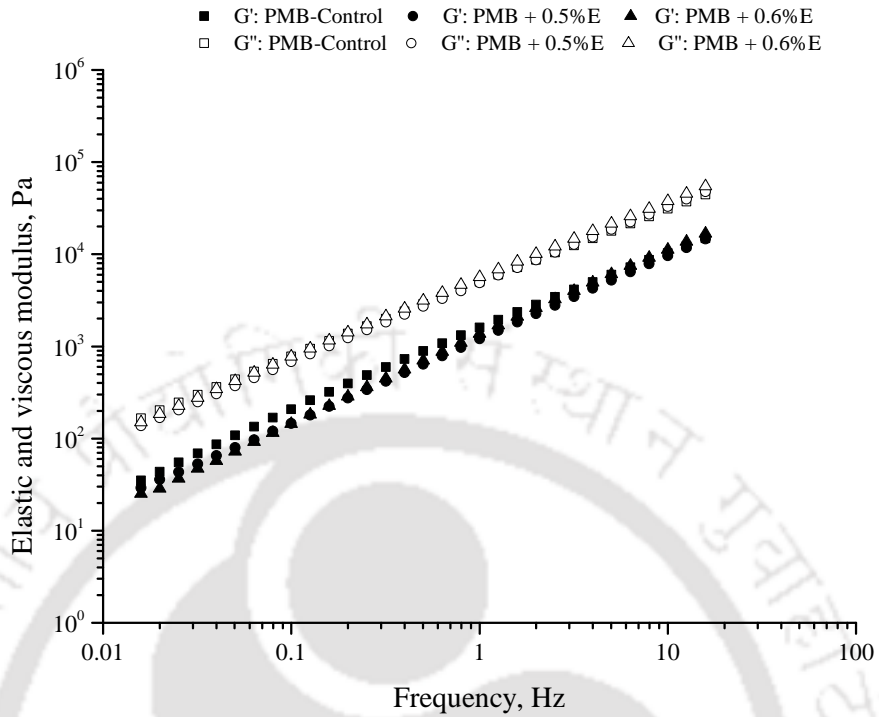


Figure 4.5: Frequency sweep results of PMB warm asphalt binders with Evotherm

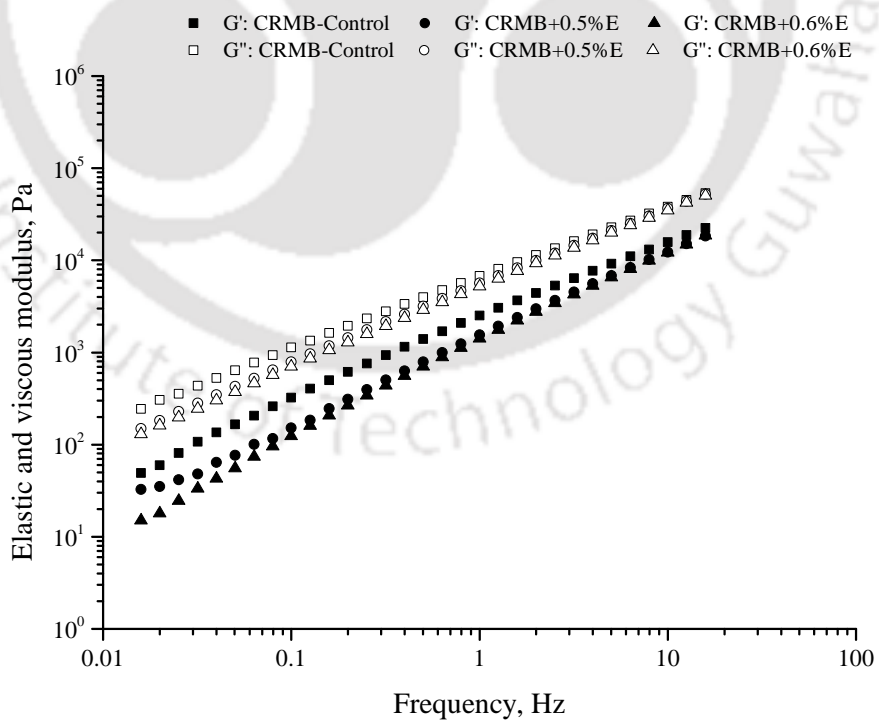


Figure 4.6: Frequency sweep results of CRMB warm asphalt binders with Evotherm

the complex modulus of both binders. A slight increase in phase angle is observed on addition of Evotherm at test temperatures greater than 50°C. Increase in Evotherm dosage from 0.5% to 0.6% did not show any significant effect on complex modulus and phase angle of both PMB and CRMB binders.

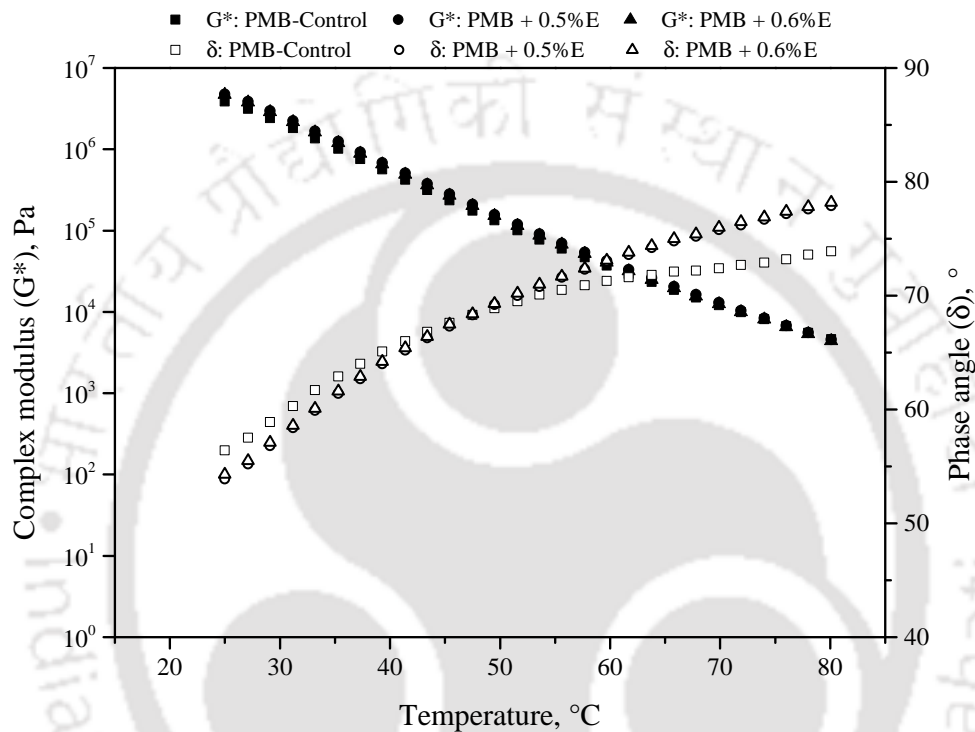


Figure 4.7: Temperature sweep results of PMB warm mixes with Evotherm

### Creep Test

Creep test measures the strain response of binders under a constant shear stress (10 Pa in this study) maintained for a predetermined time (300 s in this study). The test was performed at 60°C for all binders. The results are reported in terms of compliance, a parameter expressed as the ratio of strain undergone by the binder to the applied stress. The compliance is used as a measure of deformation; higher values denoting higher deformation. Figures 4.9 and 4.10 respectively illustrate the compliance (calculated at conclusion of the test at 300

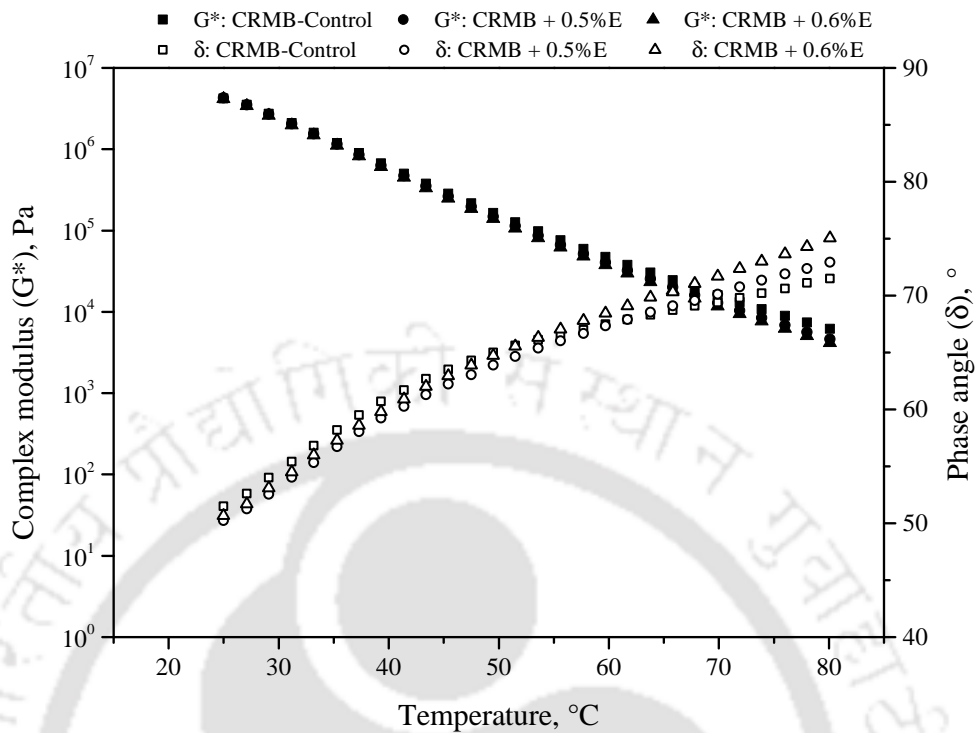


Figure 4.8: Temperature sweep results of CRMB warm mixes with Evotherm

s) for PMB and CRMB warm asphalt binders. There is a slight decrease in the compliance values of both PMB and CRMB binders on addition of Evotherm. Addition of 0.6% Evotherm increases the compliance values by 7% and 5%, respectively, for PMB and CRMB binders. Results show that addition of Evotherm does not show any significant change in the resistance to deformation of both binders under a constantly applied stress.

#### **Repeated Creep Recovery Test**

Repeated creep recovery test involves application of a fixed shear stress for a short time followed by removal of the stress (allowing the binder to recover the deformation), and finally replicating the load-unload cycle for a preset number of times. Results are reported in terms of compliance measured over the complete test duration. In the present study, the test consisted of repeated

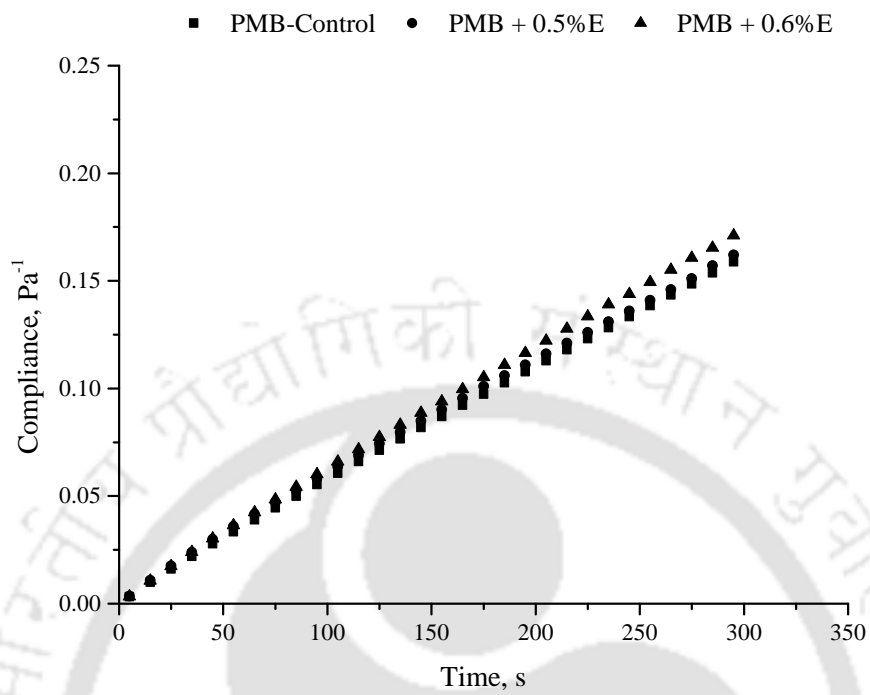


Figure 4.9: Creep results of PMB warm asphalt binders with Evotherm

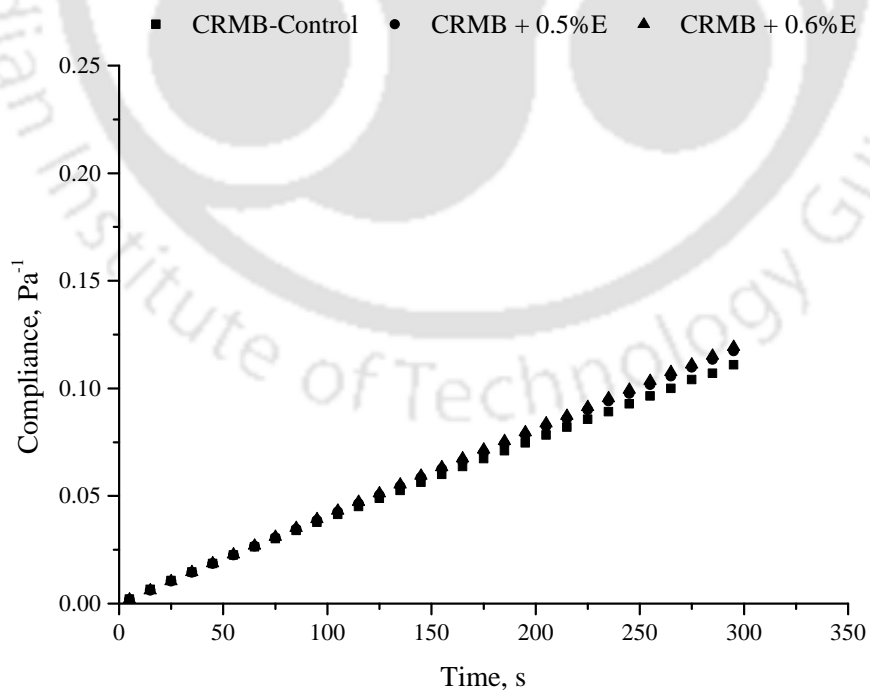


Figure 4.10: Creep results of CRMB warm asphalt binders with Evotherm

applications of 10 Pa shear stress over 52 cycles, with each cycle comprising of 1 s loading time and 9 s rest time. Compliance values of PMB and CRMB warm asphalt binders are shown in Figures 4.11 and 4.12 respectively. Addition of Evotherm leads to only a slight increase in the compliance values with both PMB and CRMB binders. An addition of 0.6% Evotherm caused a meagre decrease of 5% and 7% in compliance of PMB and CRMB binders (computed in terms of the compliance at the end of the test). The findings from this test are in agreement with those from failure temperature, temperature sweep, and creep tests. These results show that addition of Evotherm had no appreciable effect on the rheological characteristics of both PMB and CRMB binders, as this additive is designed to work at the aggregate and binder interface rather than influencing the binders' rheology.

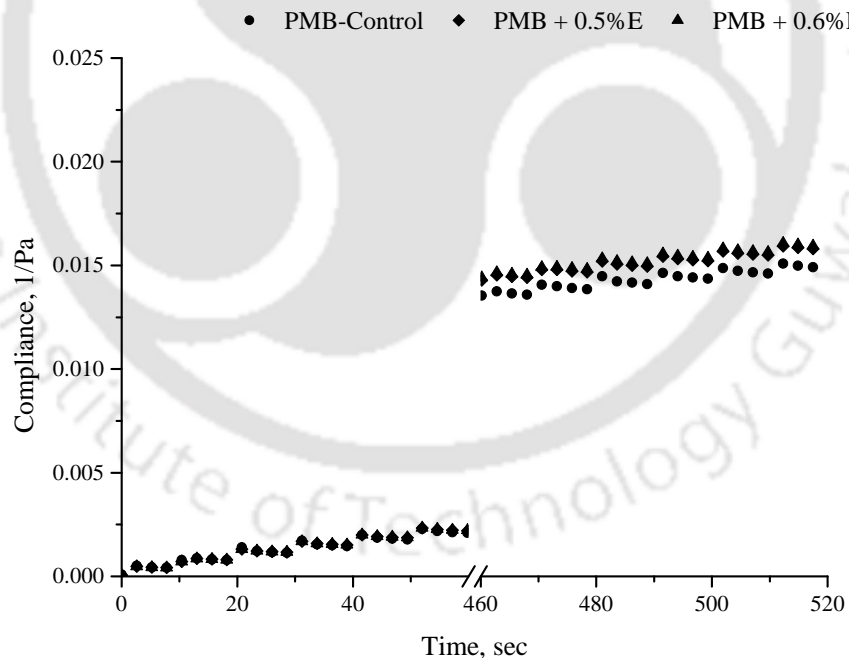


Figure 4.11: Repeated creep recovery results of PMB warm asphalt binders with Evotherm

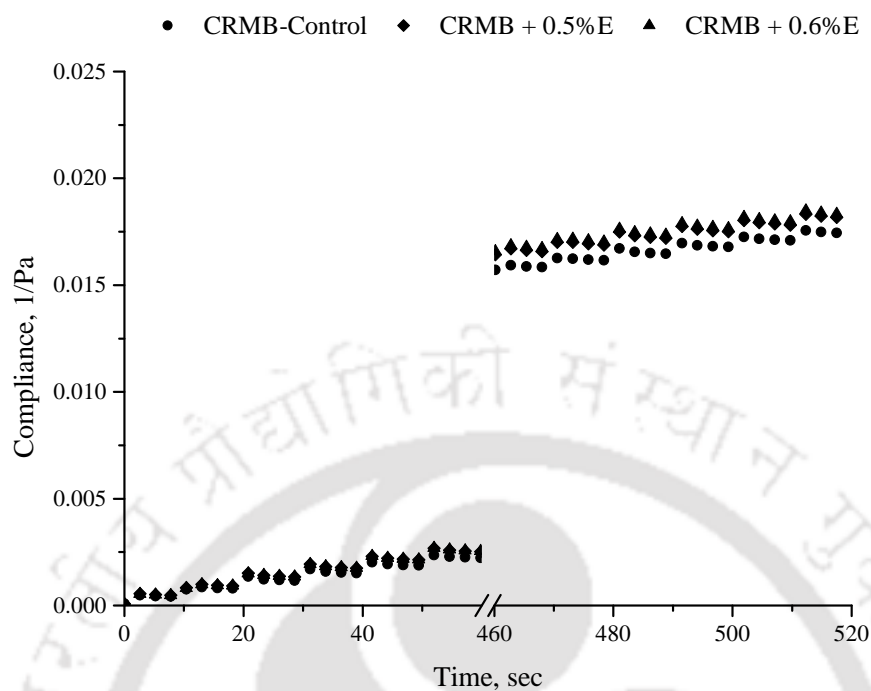


Figure 4.12: Repeated creep recovery results of CRMB warm asphalt binders with Evotherm

### 4.3 Effect of Sasobit on Rheological Properties of Modified Binders

This phase of the rheological characterisation involved use of WMA additive Sasobit with three dosages: 1%, 2%, and 3% by weight of binder. Binders without Sasobit (*i.e.* 0% dosage) are referred as control binders. The two modified binders: polymer modified binder (PMB) and crumb rubber modified binder (CRMB), were used as the base binders. Preparation of additive-binder blend consisted of first heating the base binders to about 120°C and then introducing the desired quantity of the additive, followed by a thorough stirring to achieve homogeneity. It needs to be emphasised here that the temperature of 120°C is well above the melting point of Sasobit (85°C–115°C), and was selected to ensure proper dispersion of the additive in the binders. The sections that

follow discuss the effects of varying dosages of Sasobit on the rheological characteristics of PMB and CRMB binders.

### **Viscosity at 150°C**

Viscosity results of control PMB and CRMB binders along with warm binders measured at 150°C through rotational viscometer are shown in Figures 4.13 and 4.14 respectively. Addition of Sasobit reduces the viscosity of both PMB and CRMB binders at 150°C, and thus will assist in reducing the mix production temperatures by achieving the desired viscosity at lower production temperatures. With the addition of 3% Sasobit, a decrease of about 15–25% in viscosity values is observed for both PMB and CRMB binders.

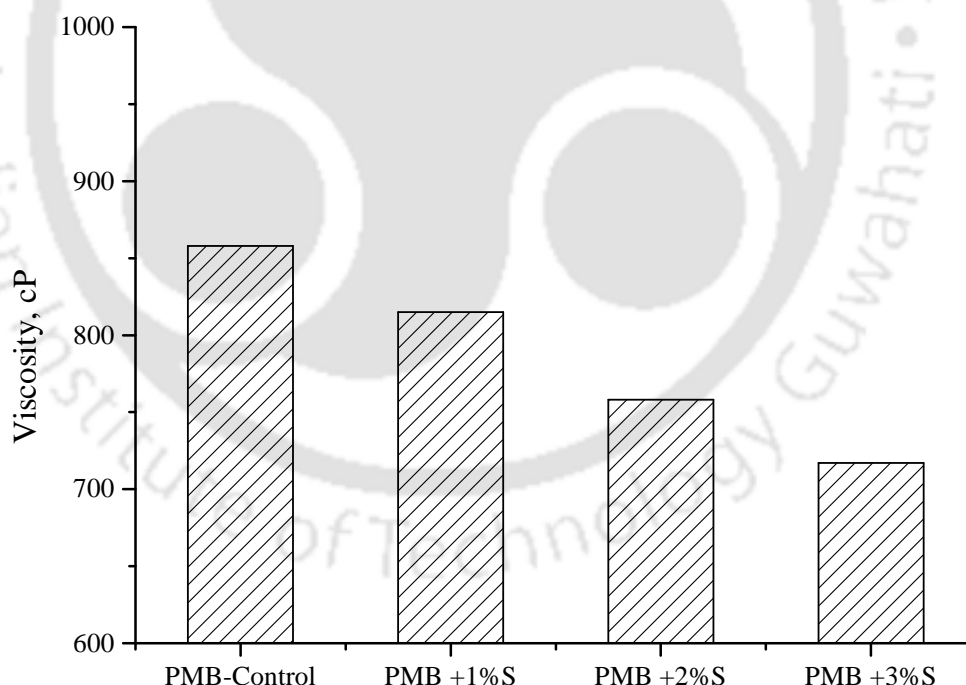


Figure 4.13: Viscosity results of PMB warm asphalt binders with Sasobit

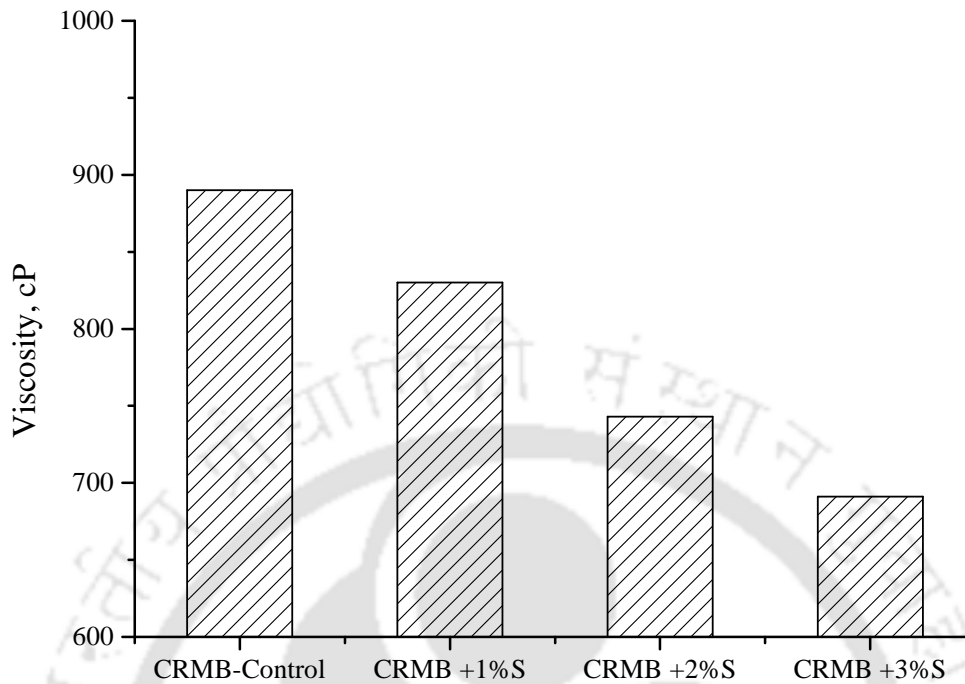


Figure 4.14: Viscosity results of CRMB warm asphalt binders with Sasobit

### **Failure Temperature**

Failure temperature of an unaged asphalt binder is determined as the temperature at which the Superpave rutting parameter ( $G^*/\sin\delta$ ) reaches a value of 1.0 kPa when tested on a dynamic shear rheometer (DSR) at 12% strain amplitude. Higher temperatures are indicative of better deformation resistance of the binder at high service temperatures. Failure temperature of PMB and CRMB warm binders is presented in Figures 4.15 and 4.16 respectively. Addition of Sasobit increases the failure temperatures of both base binders. Sasobit enhances the stiffness by forming a crystalline network structure below its melting point and thereby increases the failure temperature. A higher increase in the failure temperature is observed with increase in Sasobit content from 1% to 2% for PMB and 0% to 1% for CRMB binder. Addition of 3% Sasobit shifted the high temperature grade of both binders from PG 76 to PG 88 through an increase

in the failure temperature by about 10.9° and 6.7°C for PMB and CRMB respectively.

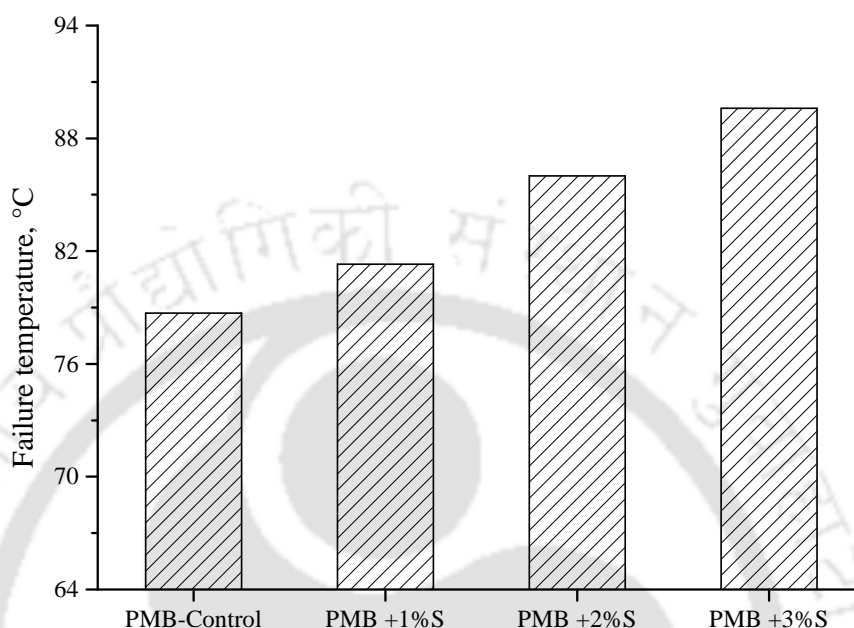


Figure 4.15: Failure temperature of PMB warm asphalt binders with Sasobit

### ***Frequency Sweep Test***

Frequency sweep test was performed at 60°C to evaluate the effect of Sasobit dosage on rheology of binders under different frequencies. Results are reported in terms of the elastic modulus ( $G'$ ) and the viscous modulus ( $G''$ ) over frequencies ranging from 0.01 to 100 Hz. Figures 4.17 and 4.18 present the results, respectively, for PMB and CRMB binders. Addition of Sasobit enhances the elastic and viscous moduli of both binders at all frequencies, which shows that the resistance to permanent deformation is improved due to additional stiffness provided by Sasobit. Furthermore, with the increase in Sasobit dosage, the improvements become more pronounced.

4.3. Effect of Sasobit on Rheological Properties of Modified Binders

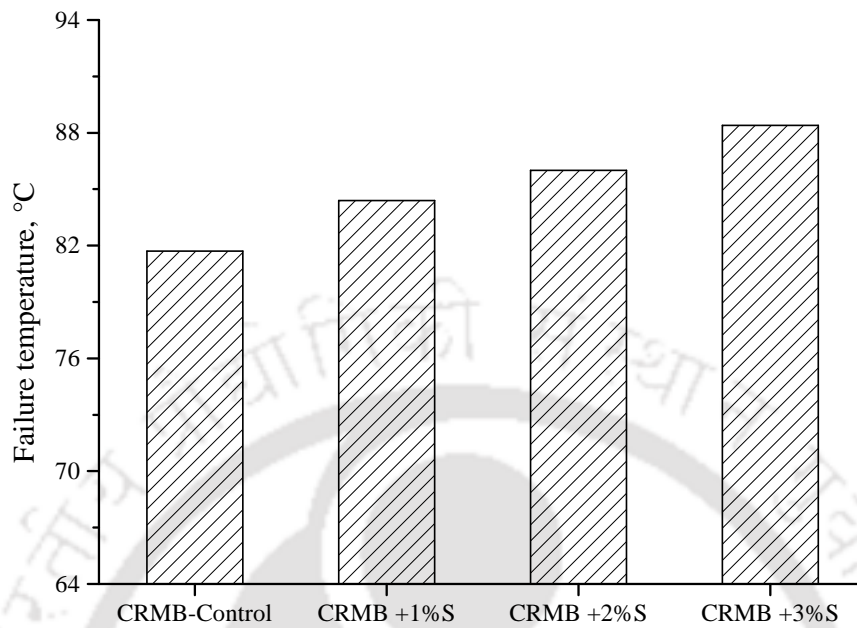


Figure 4.16: Failure temperature of CRMB warm asphalt binders with Sasobit

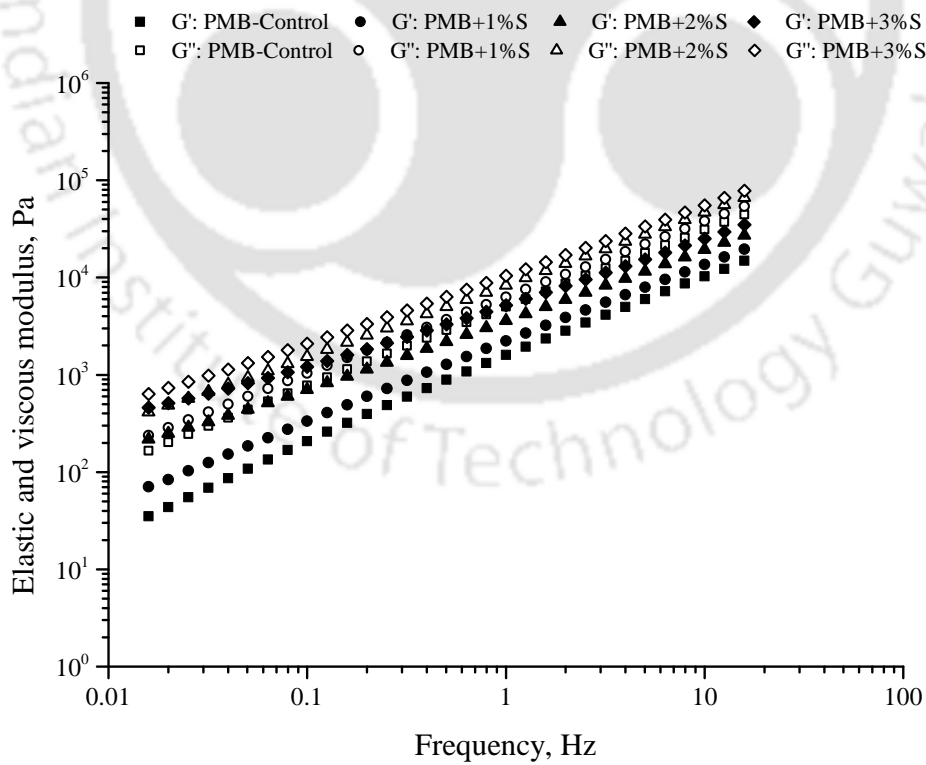


Figure 4.17: Frequency sweep results of PMB warm asphalt binders with Sasobit

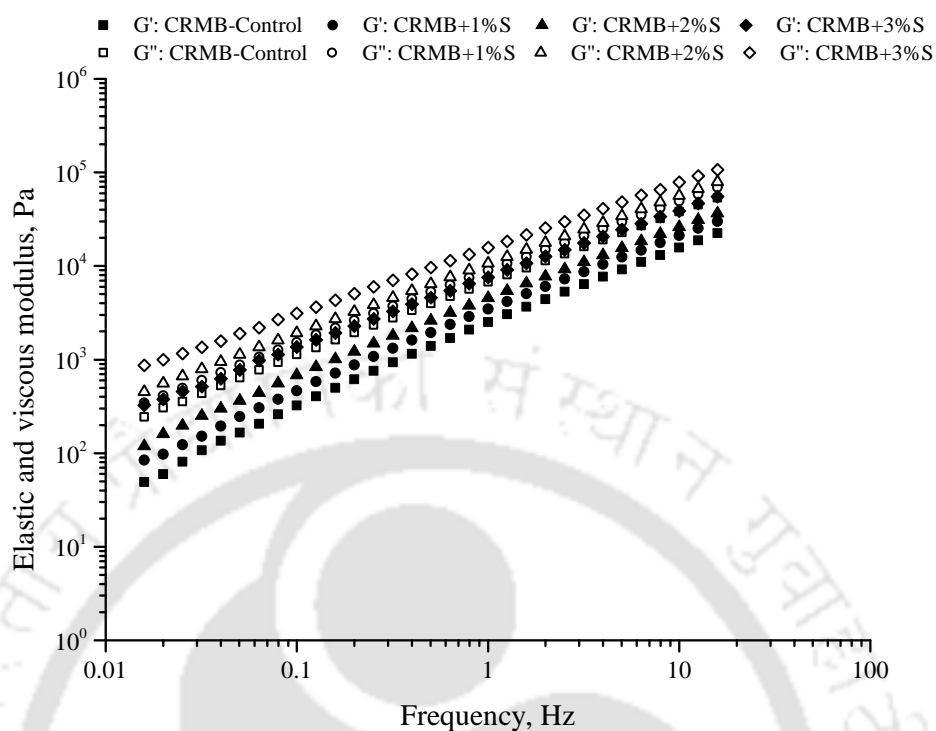


Figure 4.18: Frequency sweep results of CRMB warm asphalt binders with Sasobit

### Temperature Sweep Test

Temperature sweep test was conducted to evaluate the effect of Sasobit dosage on temperature dependence of complex modulus ( $G^*$ ) and phase angle ( $\delta$ ) of modified binders over a temperature range of 25°C to 80°C. Figures 4.19 and 4.20 present temperature sweep results of PMB and CRMB warm binders respectively. Addition of Sasobit increases the complex modulus and decreases the phase angle, indicating an increase in the stiffness and elastic nature of both PMB and CRMB binders. Reduction in phase angle on adding Sasobit is slightly higher in case of PMB binders. However, as expected, the complex modulus of both binders decreases and the phase angle increases with increase in the test temperatures.

4.3. Effect of Sasobit on Rheological Properties of Modified Binders

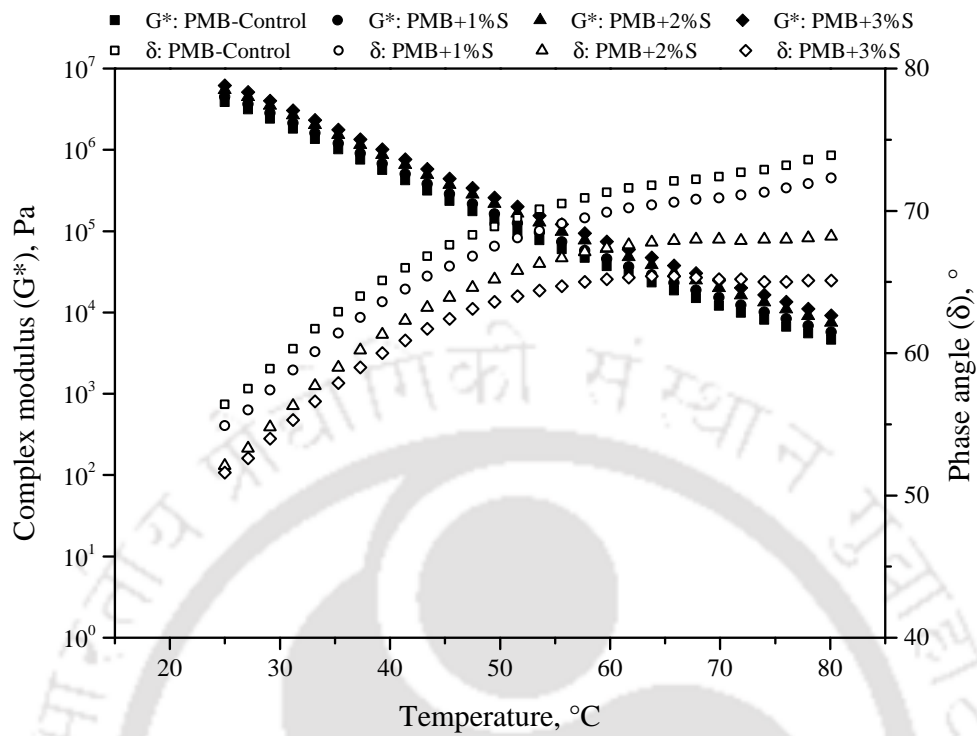


Figure 4.19: Temperature sweep results of PMB warm asphalt binders with Sasobit

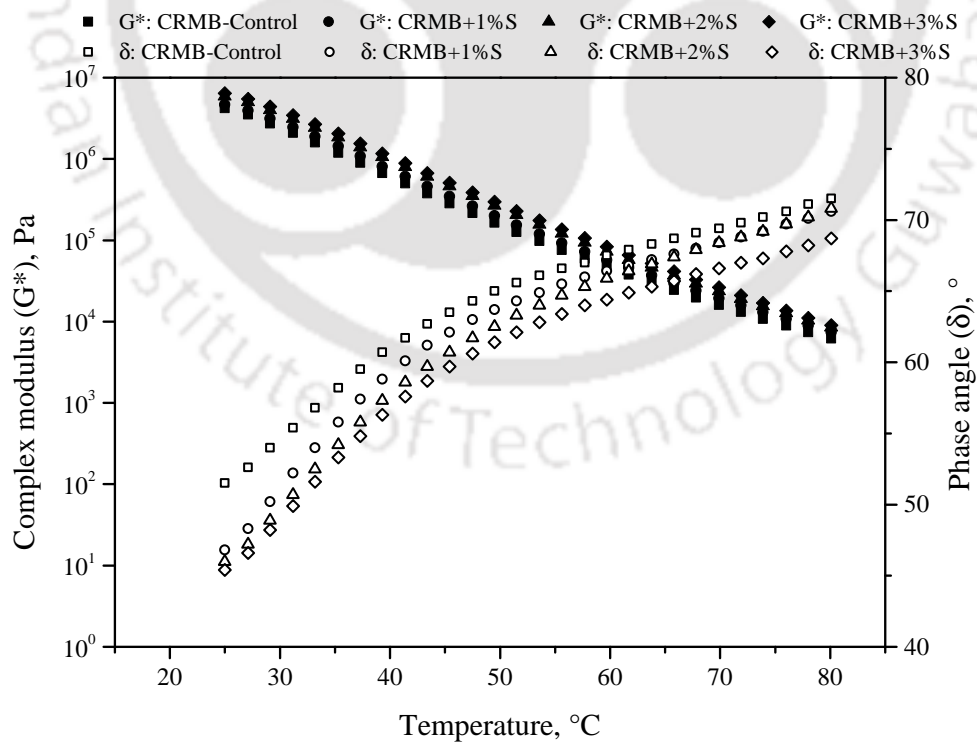


Figure 4.20: Temperature sweep results of CRMB warm asphalt binders with Sasobit

### ***Creep Test***

Creep test measures the deformation undergone by an asphalt binder under a sustained load for a fixed duration of time. Deformation (in terms of strain) was evaluated under a fixed shear stress of 10 Pa for a duration of 300 s. Results are expressed in terms of creep compliance, defined as the ratio of strain to the applied stress. Creep compliance values of PMB and CRMB warm binders with different percentages of Sasobit are shown in Figures 4.21 and 4.22 respectively. Addition of Sasobit leads to a significant reduction in compliance values. This clearly indicates that the addition of Sasobit improves the rutting resistance of both PMB and CRMB binders, which is attributed to the additional stability imparted by the crystalline network structure formed due to presence of Sasobit.

Compliance values of modified binders obtained at 300 s and percent change in compliance values with different Sasobit doses are also presented in Table 4.1. It is observed that addition of 2% Sasobit remarkably decreased the compliance values by about 83% in case of PMB and 60% for CRMB binder. An addition of 3% Sasobit further decreased the compliance by 92.5% and 76.5% respectively for PMB and CRMB binders. Overall, increase in Sasobit dosage has positive effect on the stiffness and resistance to permanent deformation of PMB and CRMB binders.

### ***Repeated Creep Recovery Test***

The repeated creep recovery test incorporates multiple cycles consisting of loading and rest periods. The rest periods allow the binder to recover a part of the deformation. Test conditions for this test were: 1 s loading period, 9 s rest period, a total of 52 cycles (each of 10 s duration), and test temperature of 60°C.

#### 4.3. Effect of Sasobit on Rheological Properties of Modified Binders

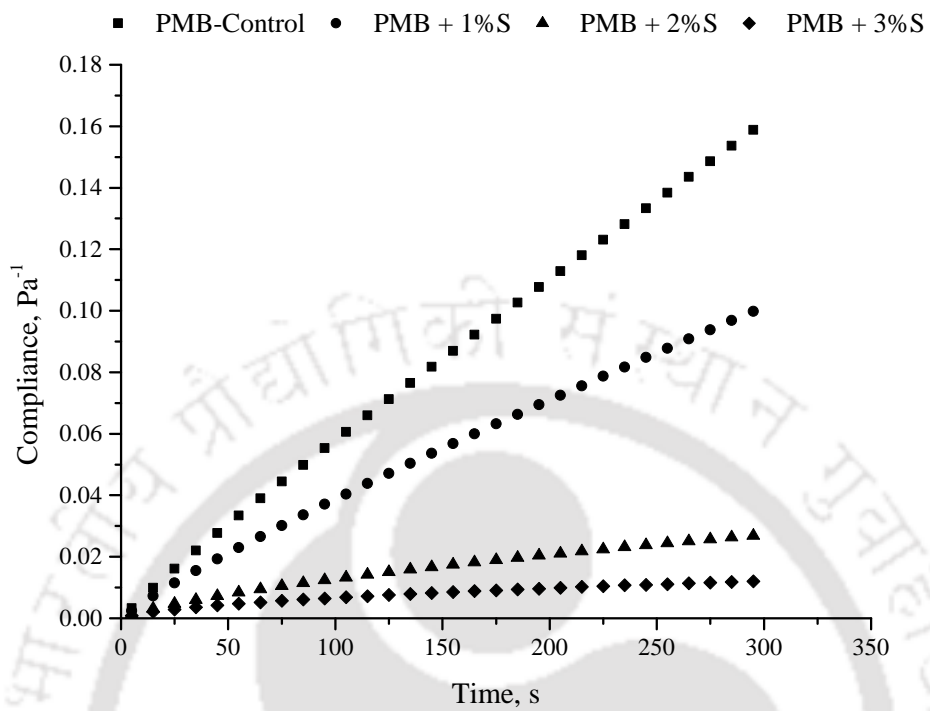


Figure 4.21: Creep results of PMB warm asphalt binders with Sasobit

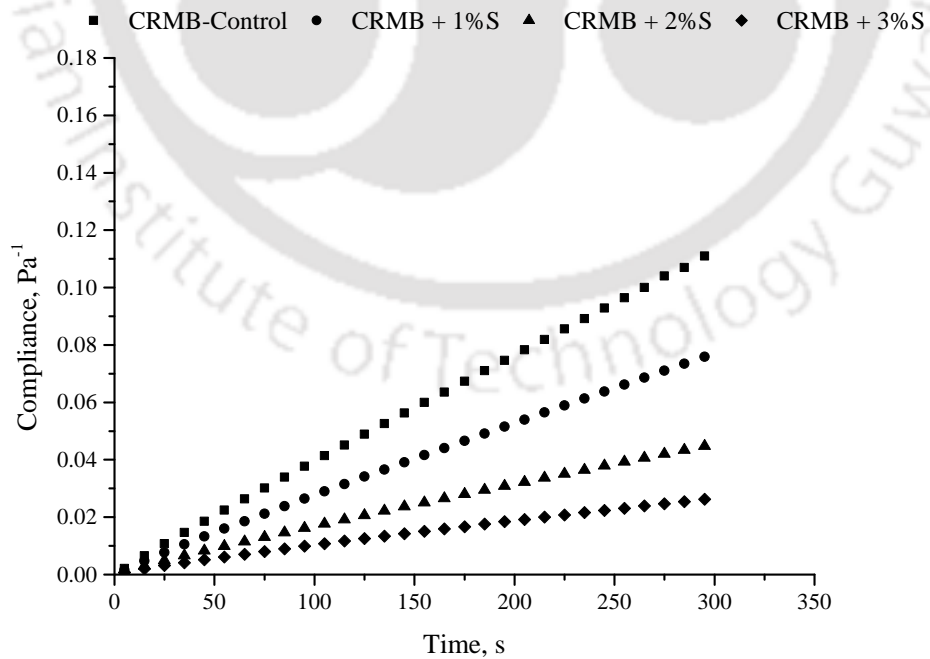


Figure 4.22: Creep results of CRMB warm asphalt binders with Sasobit

Table 4.1: Compliance and percent change in compliance of warm asphalt binders

Binder type	Sasobit content by wt. of binder	Compliance at 300 s, 1/Pa	Decrease in compliance in terms of %
PMB	0% S	0.1613	0
PMB	1% S	0.101	37.4
PMB	2% S	0.0272	83.1
PMB	3% S	0.0121	92.5
CRMB	0% S	0.113	0
CRMB	1% S	0.0771	31.8
CRMB	2% S	0.0455	59.7
CRMB	3% S	0.0265	76.5

Similar to the creep test, the results are reported in terms of compliance. Figures 4.23 and 4.24 respectively show the results of repeated creep recovery test performed on PMB and CRMB warm asphalt binders. It is observed that addition of Sasobit decreases the compliance values of both warm asphalt binders. The trends are similar to those observed from creep tests. Overall, a significant increase in the permanent deformation resistance of both PMB and CRMB binders is found on addition of Sasobit. This improvement is more pronounced upto 2% Sasobit content for both PMB and CRMB binders.

4.3. Effect of Sasobit on Rheological Properties of Modified Binders

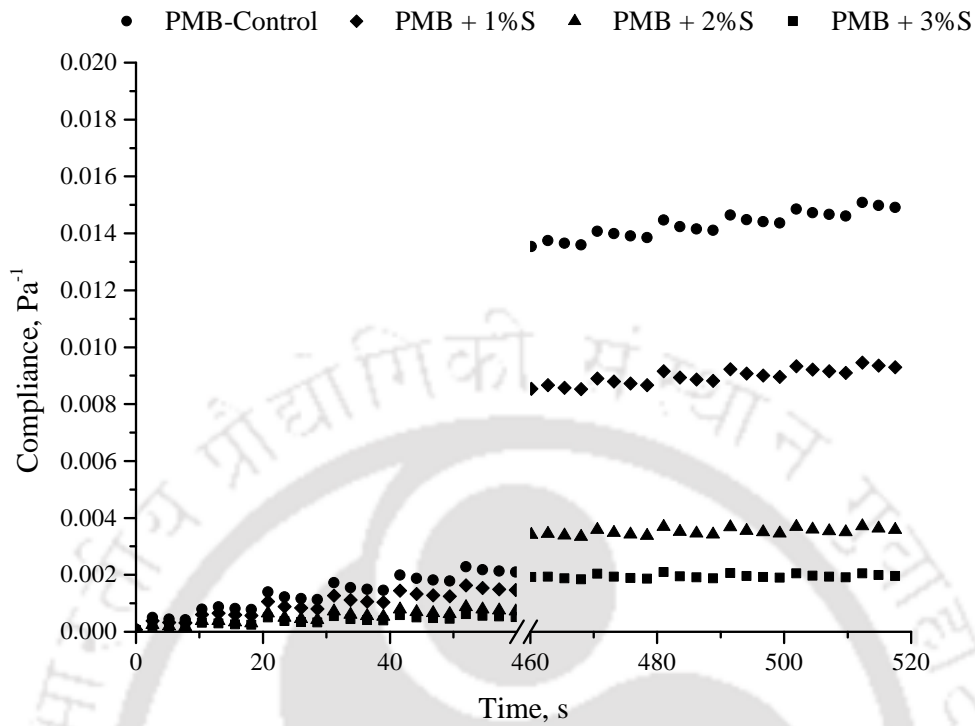


Figure 4.23: Repeated creep recovery results of PMB warm asphalt binders with Sasobit

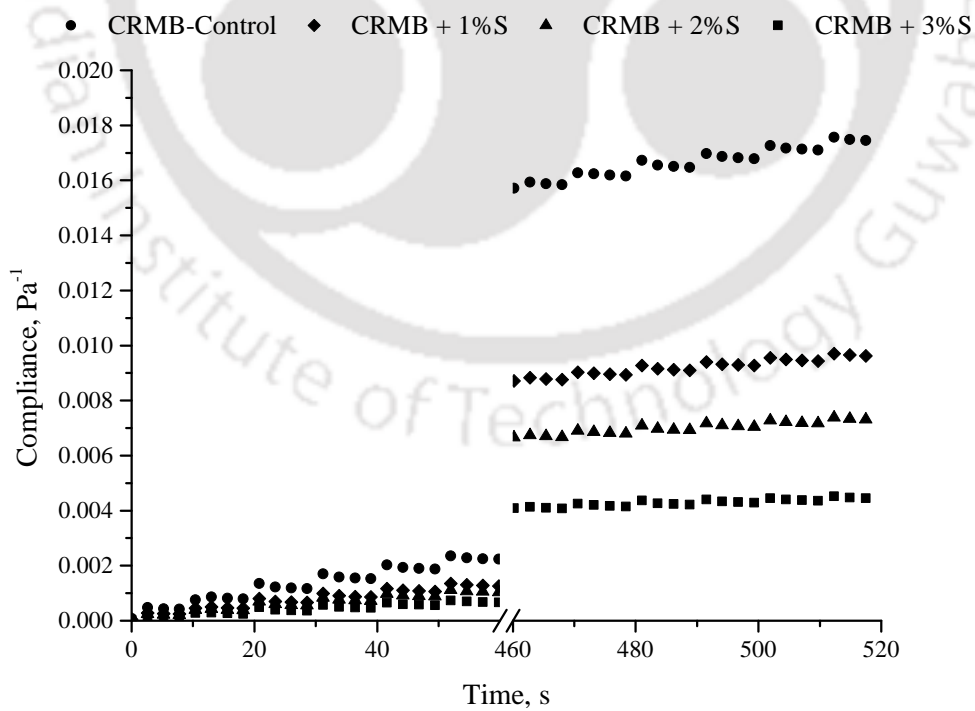


Figure 4.24: Repeated creep recovery results of CRMB warm asphalt binders with Sasobit

## 4.4 Rheological Properties of Warm Binders with Sasobit under different Short-term Ageing Temperatures

Asphalt binder ageing, which reflects its hardening and stiffening, is one of the major factors responsible for deterioration of desirable asphalt performance properties (Lu and Isacsson, 2002; Kim et al., 2013). Ageing phenomena of asphalt occurs in two phases: (i) short-term ageing— occurs during production to construction phase of asphalt mix, and (ii) long-term ageing— occurs during the service life of asphalt pavement. The effect of ageing on asphalt properties during short-term and long-term stages depends on various factors like asphalt physicochemical characteristics, asphalt film thickness, nature of aggregates and particle size distribution, air void content of the mix, production related factors like type of mixer, production temperature, duration of mixing, etc. (Lu and Isacsson, 2002). A significant amount of asphalt ageing takes place during short-term stage due to presence of asphalt binder in thin films over the aggregates and its exposure to high production temperatures (Airey, 1997; Lamontagne et al., 2001; Singh et al., 2016). Moreover, the impact of ageing on asphalt binder properties doubles for every 10°C increase in the mixing temperature above 100°C (Read and Whiteoak, 2003).

In general, changes in properties of asphalt binders caused due to high mixing and compaction temperatures practiced in the field (short-term stage) are simulated in laboratory using rolling thin film oven (RTFO) at an ageing temperature of 163°C according to ASTM D2872-12e1 (2012). As the fuel and energy savings from WMA technologies can only be realised by reducing the mix

production temperatures, it becomes evident that short-term ageing of warm asphalt binders occurs at lower temperatures when compared to conventional binders. Hence, the use of traditional RTFO ageing protocol for evaluating short-term ageing characteristics may not be applicable for warm binders.

It, therefore, becomes important to evaluate the effect of short-term ageing temperature on the rheological properties of binders with different dosages of WMA additives. From the section 4.2, it was observed that the addition of Evotherm had marginal effect on the rheological properties of both modified binders, for the likely reason that Evotherm works at the aggregate-binder interface rather than altering the properties of the binder. For this reason, the effect of short-term ageing temperatures on properties of modified binders (PMB and CRMB) was evaluated only with WMA additive Sasobit.

The effect of reduced short-term ageing temperatures on rheological properties were determined at three short-term ageing temperatures: 163°C (standard temperature), 143°C (20°C reduction from standard temperature), and 123°C (40°C reduction from standard temperature). Warm asphalt binders with Sasobit as well as control binders (without Sasobit) were both short-term aged using an RTFO for 85 min according to ASTM D2872-12e1 (2012) at different temperatures. These short-term aged binders were then characterised from the results of viscosity, failure temperature, temperature sweep, frequency sweep, and multiple stress creep and recovery (MSCR) tests. The sections that follow present the results of each rheological test.

#### ***Viscosity at 150°C***

Viscosity of short-term aged PMB and CRMB warm and control binders were tested using rotational viscometer at 150°C and the results are shown in Figures

4.25 and 4.26. The decrease in RTFO ageing temperatures decreases viscosity of both PMB and CRMB binders, indicating a reduction in stiffness of the binders on being aged at lower temperatures. Addition of Sasobit reduces the viscosity of both binders at all ageing temperatures. This is due to Sasobit's nature as it liquefies above its melting point (85°C–115°C) and thereby reduces the viscosity. Furthermore, increase in Sasobit dosage results in further decrease in the viscosity of both modified binders. For instance, compared to warm binder with 1% Sasobit, addition of 3% Sasobit decreases the viscosity of PMB by 15%, 19%, and 25%, respectively at 163°C, 143°C, and 123°C ageing temperatures. In case of CRMB, a reduction of 21%, 24%, and 20% in the viscosity values is observed with increase in Sasobit content from 1% to 3% at 163°C, 143°C, and 123°C ageing temperatures, respectively. This shows that the behaviour of Sasobit does not change even when warm asphalt binders are short-term aged at lower temperatures.

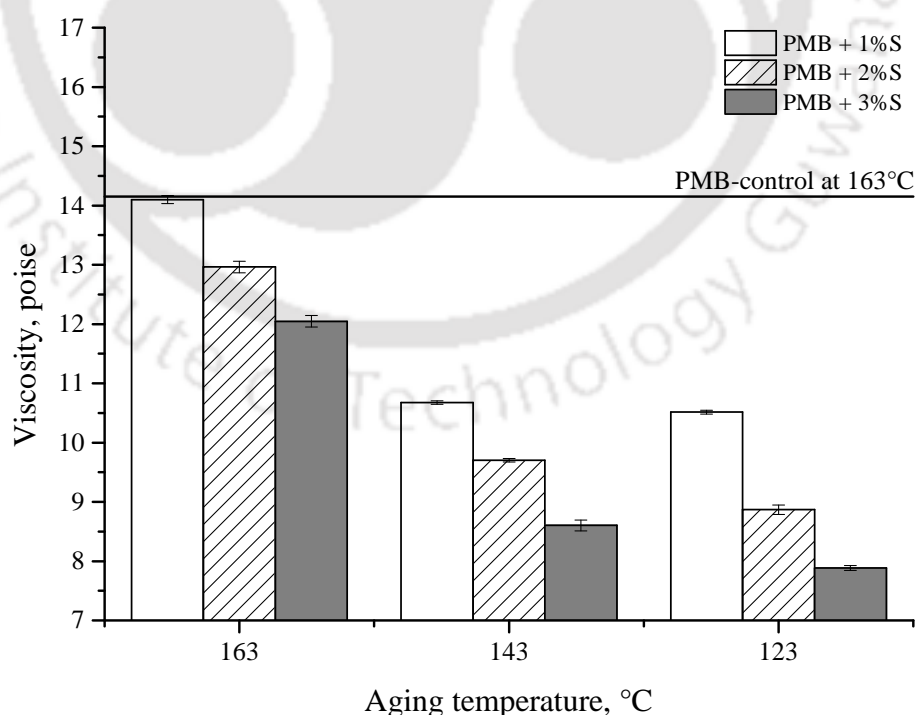


Figure 4.25: Viscosity results of PMB warm asphalt binders

#### 4.4. Rheological Properties of Warm Binders with Sasobit under different Short-term Ageing Temperatures

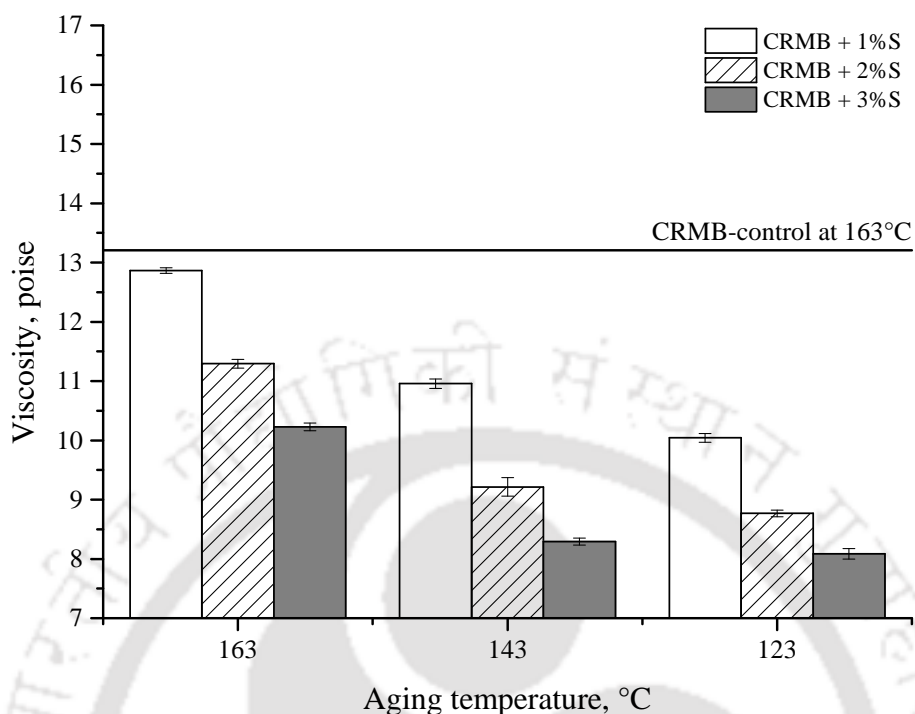


Figure 4.26: Viscosity results of CRMB warm asphalt binders

The extent of hardening of both control and warm asphalt binders at different RTFO ageing temperatures is also determined using ageing index (AI). AI is defined as ratio of average viscosity of short-term aged binder to the average viscosity of corresponding unaged binder (Equation 4.1):

$$AI = \frac{\text{Viscosity of aged binder}}{\text{Viscosity of unaged binder}} \quad (4.1)$$

AI values obtained for PMB and CRMB binders are shown in Figures 4.27 and 4.28 respectively. It is observed that reduction in RTFO ageing temperature decreases AI values of warm asphalt binders. The decrease in AI values indicates that binders aged at lower temperatures show better resistance towards physical and chemical changes in the asphalt binder that occur during ageing. At 163°C, there is a marginal increase in AI values on addition of Sasobit for both PMB and CRMB binders. Further, the increase in Sasobit content decreases the AI values

at all RTFO ageing temperatures. AI values for PMB and CRMB warm asphalt binders at 143°C and 123°C ageing temperatures are significantly lower than the values of corresponding control binders aged at 163°C. This shows that warm asphalt binders will have better ageing resistance compared to control binders and will therefore help to improve durability of the binders.

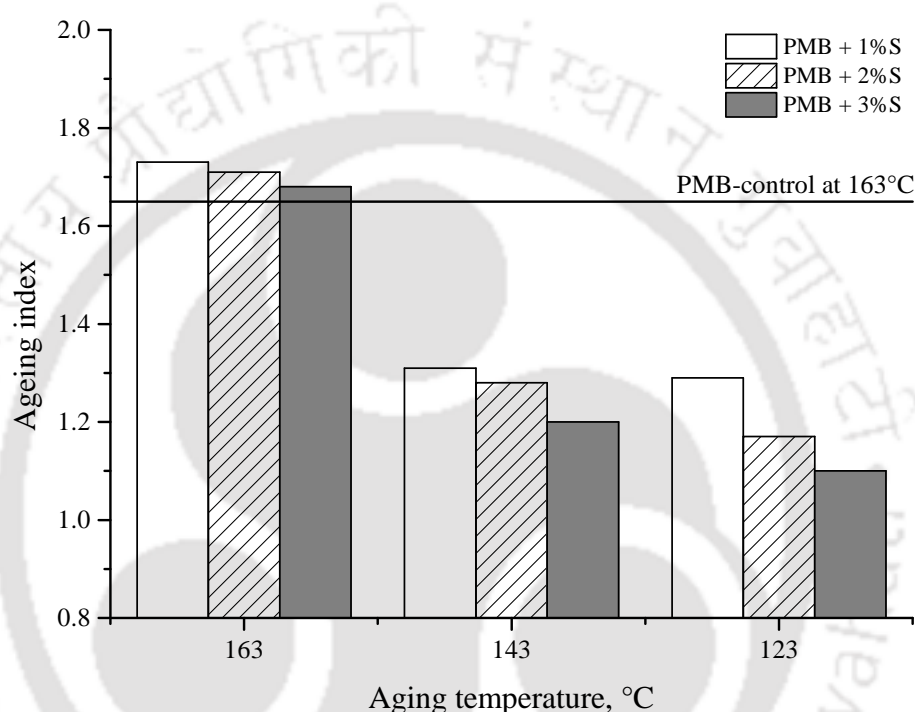


Figure 4.27: Ageing index results of PMB warm asphalt binders

### **Failure Temperature**

Failure temperature, determined as the maximum temperature for which  $G^*/\sin\delta$  has a value of 2.2 kPa (tested at 10% strain and 10 rad/s frequency) after short-term ageing, was used to evaluate high-temperature performance of short-term aged binders. Figures 4.29 and 4.30 present the failure temperature of short-term aged PMB and CRMB binders respectively. As expected, decrease in the short-term ageing temperature decreases the failure temperature of both PMB and CRMB warm asphalt binders. A decrease of 40°C in the RTFO ageing

#### 4.4. Rheological Properties of Warm Binders with Sasobit under different Short-term Ageing Temperatures

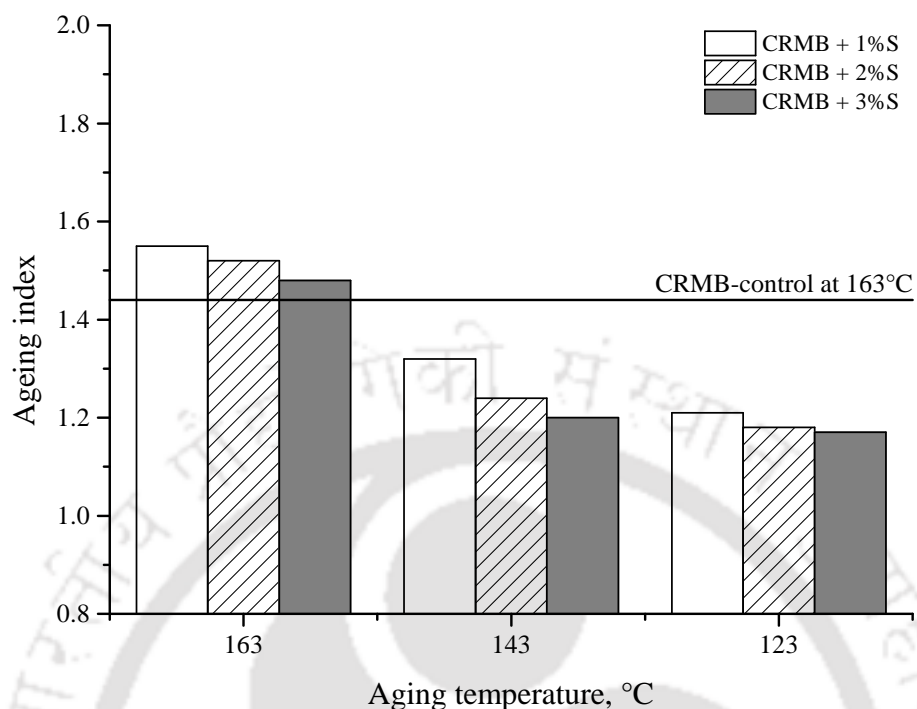


Figure 4.28: Ageing index results of CRMB warm asphalt binders

temperature (from 163°C to 123°C), decreased the failure temperature of PMB warm asphalt binders with 1%, 2%, and 3% Sasobit by 4.0°C, 2.6°C, and 4.9°C respectively; whereas in case of CRMB warm asphalt binders, the reductions are 2.3°C, 2.2°C, and 1.5°C respectively. All PMB and CRMB warm asphalt binders aged at 163°C have higher failure temperatures compared to their respective control binders aged at 163°C due to additional stiffness provided by crystalline network structure of Sasobit in the binder.

Failure temperature of PMB binder is found to be lower than CRMB binder at all RTFO ageing temperatures and Sasobit dosages. Failure temperature of PMB + 3% Sasobit and CRMB + 1% Sasobit warm asphalt binders at 123°C (40°C lower) RTFO ageing temperature is respectively similar to the failure temperature of control PMB and CRMB aged at 163°C. This indicates that reduction in failure temperatures expected due to lower production temperatures will be compensated through the addition of WMA additive Sasobit.

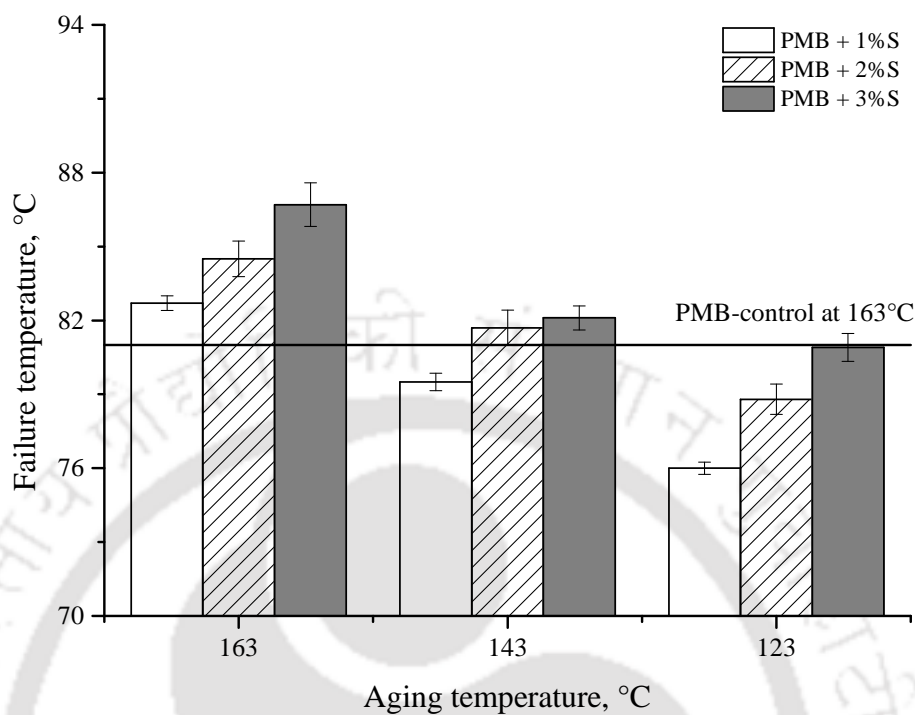


Figure 4.29: Failure temperature results of PMB warm asphalt binders

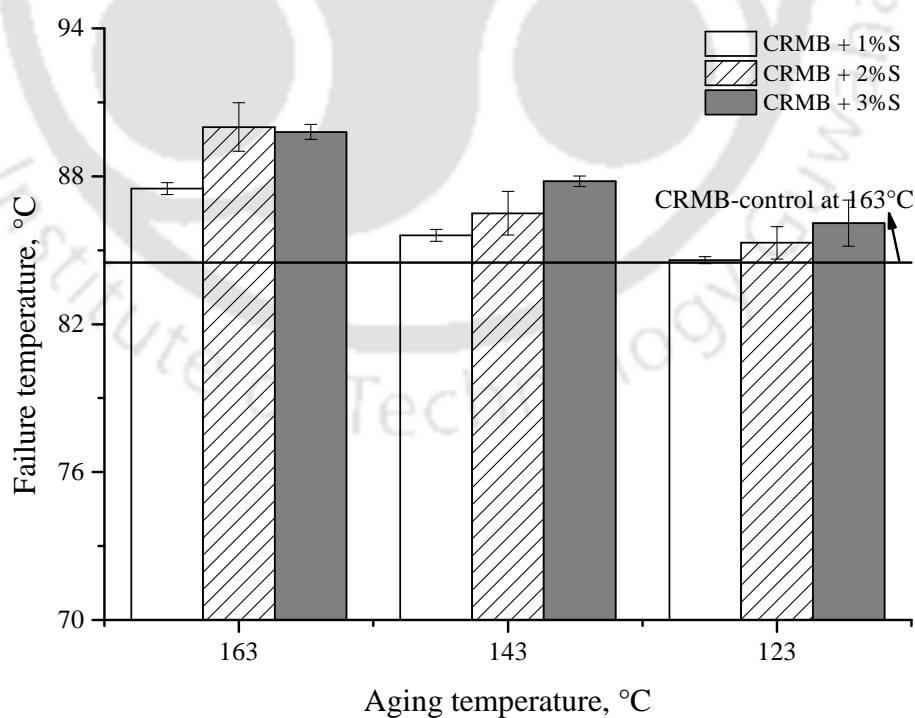


Figure 4.30: Failure temperature results of CRMB warm asphalt binders

### Frequency Sweep Test

Frequency sweep test was performed over four frequency decades (0.01–0.1 Hz, 0.1–1 Hz, 1–10 Hz, and 10–100 Hz) at 60°C to evaluate the rheological response of the binders when subjected to small-deformation oscillations. Frequency sweep results are presented in terms of elastic modulus ( $G'$ ) and viscous modulus ( $G''$ ) of the binders as a function of frequency. Figures 4.31 — 4.36 presents the results of frequency sweep test to show the effect of Sasobit content on binders at different RTFO ageing temperatures.

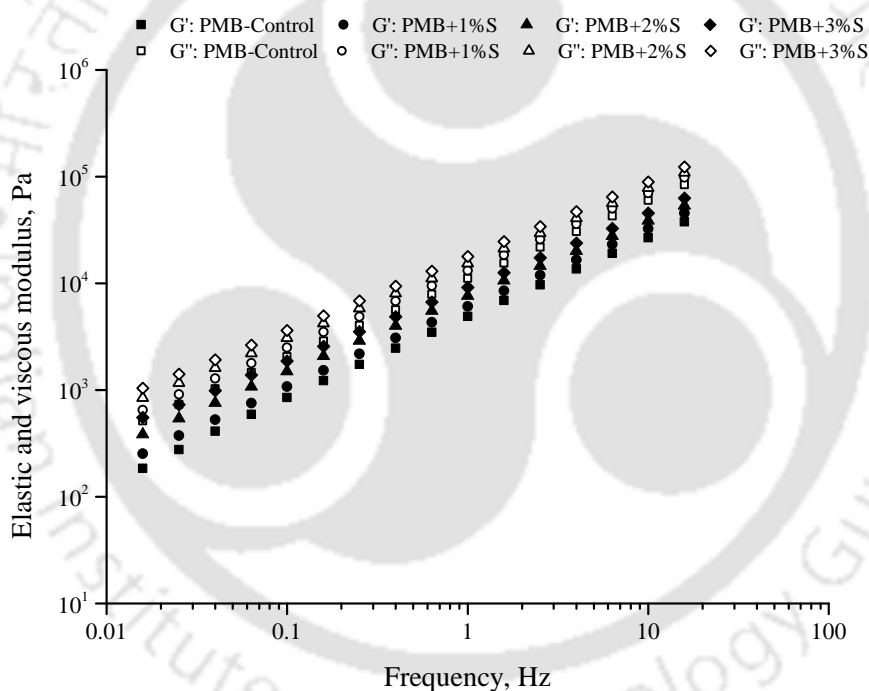


Figure 4.31: Frequency sweep results of PMB warm asphalt binders at 163°C RTFO ageing temperature

In general, an increase in frequency increases elastic and viscous moduli of both binders at all ageing temperatures and Sasobit contents. Addition of Sasobit increases the elastic and viscous moduli of both binders at all RTFO ageing temperatures within the test frequency range. This further shows that resistance to permanent deformation of warm asphalt binders enhanced due to

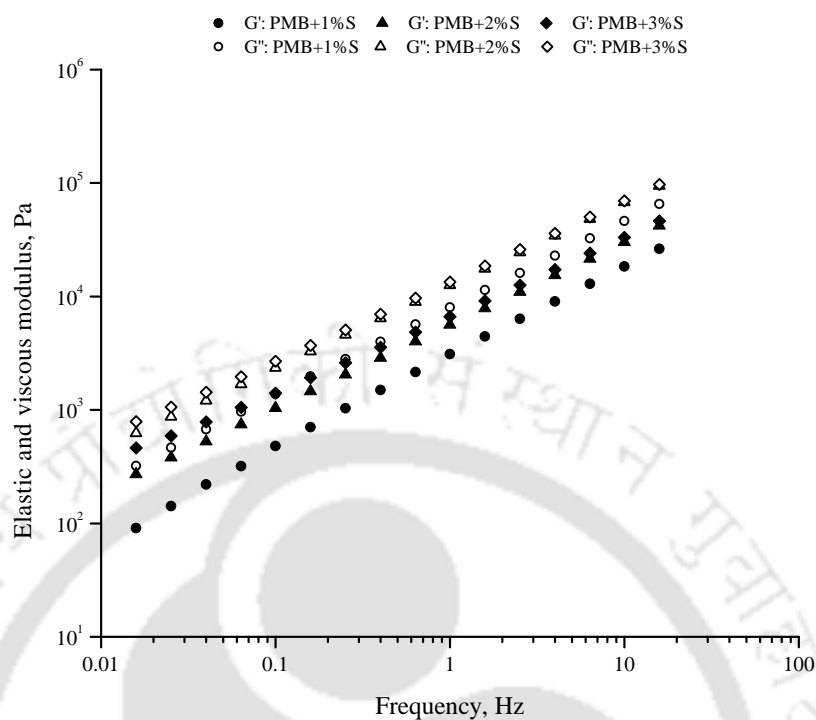


Figure 4.32: Frequency sweep results of PMB warm asphalt binders at 143°C RTFO ageing temperature

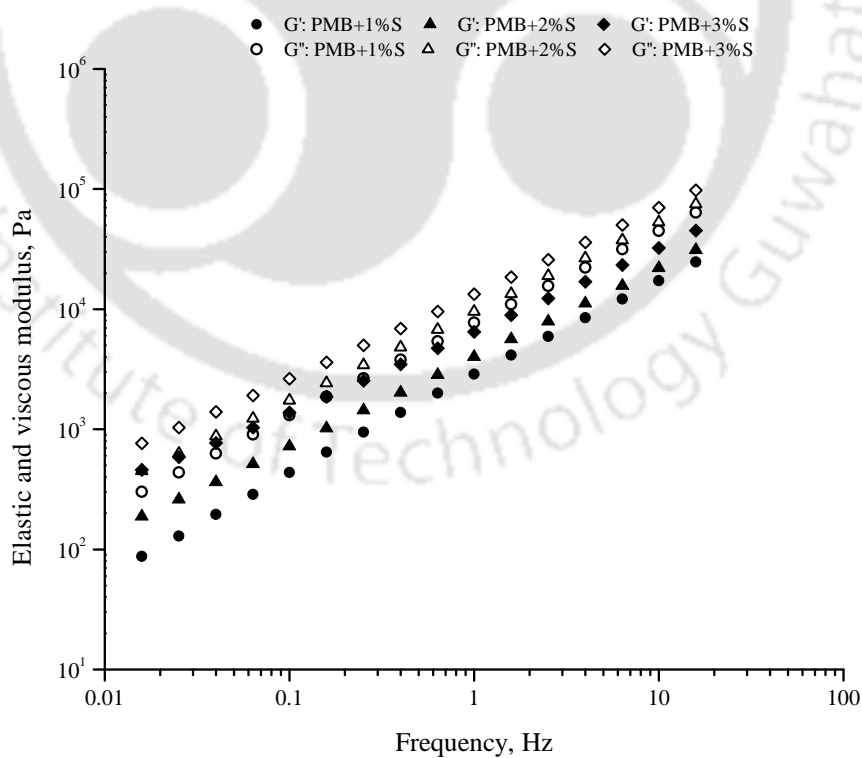


Figure 4.33: Frequency sweep results of PMB warm asphalt binders at 123°C RTFO ageing temperature

4.4. Rheological Properties of Warm Binders with Sasobit under different Short-term Ageing Temperatures

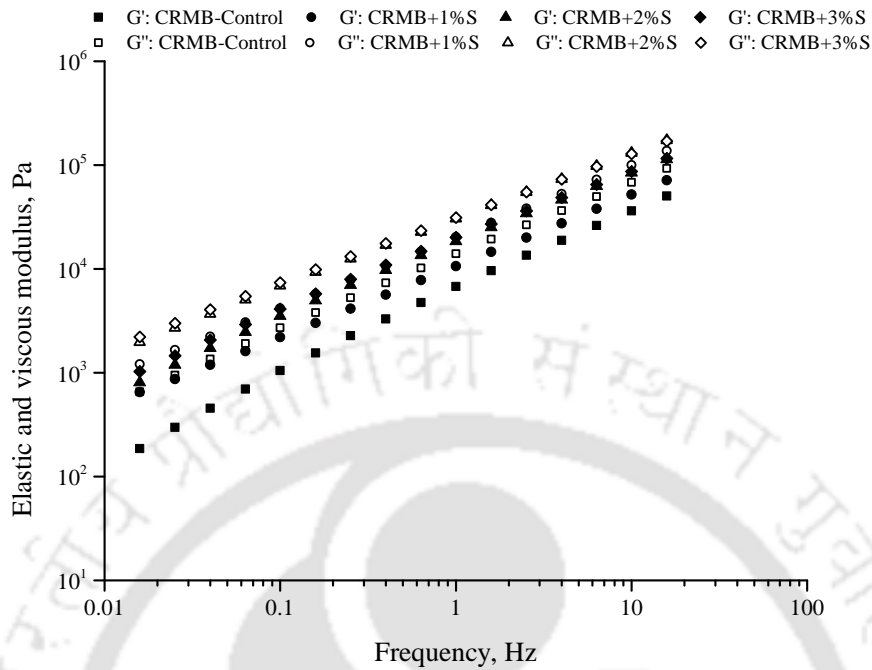


Figure 4.34: Frequency sweep results of CRMB warm asphalt binders at 163°C RTFO ageing temperature

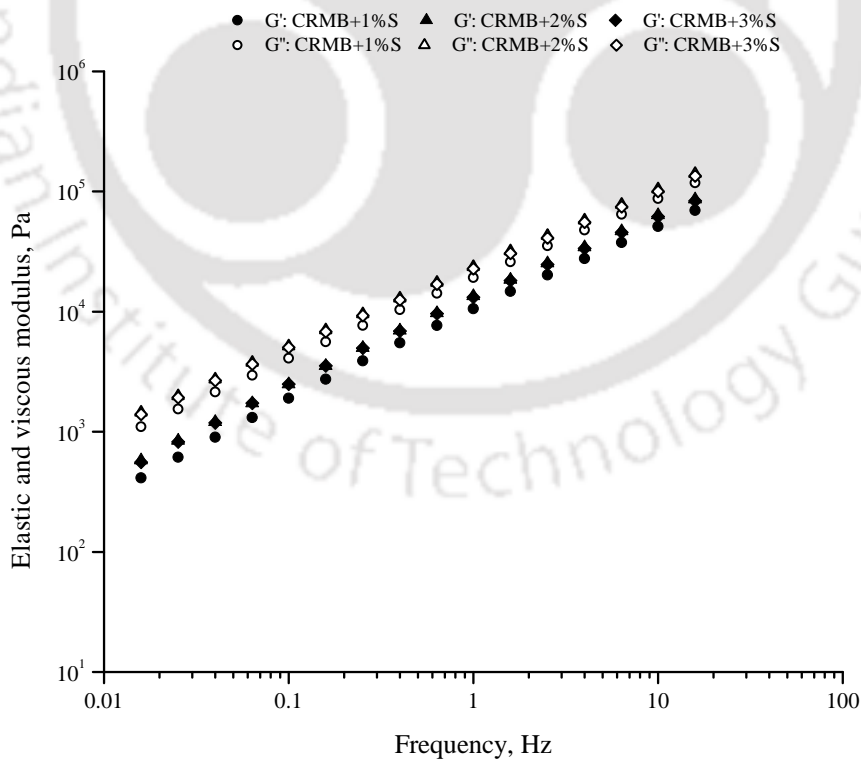


Figure 4.35: Frequency sweep results of CRMB warm asphalt binders at 143°C RTFO ageing temperature

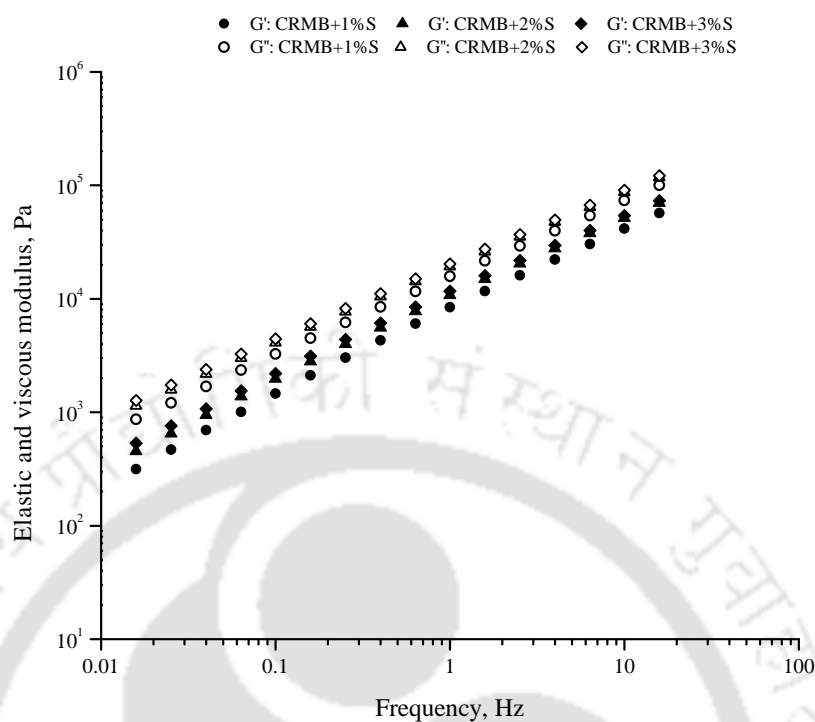


Figure 4.36: Frequency sweep results of CRMB warm asphalt binders at 123°C RTFO ageing temperature

additional stiffness provided by Sasobit, and with increase in Sasobit dosage, the improvements became more pronounced.

In order to understand the effects of RTFO ageing temperature and Sasobit content more clearly, elastic and viscous moduli of warm asphalt binders are extracted from frequency sweep results at a frequency of 1.59 Hz (10 rad/s) and shown in Tables 4.2 and 4.3 respectively for PMB and CRMB warm asphalt binders. It is observed that addition of Sasobit increases both elastic and viscous moduli of PMB and CRMB binders even at lower ageing temperatures compared to their respective control binders. Addition of Sasobit causes higher increase in the elastic modulus compared to viscous modulus. For instance, elastic modulus of PMB + 3%S aged 123°C is 1.29 times higher than PMB–control aged at 163°C, whereas the increase in viscous modulus is only 1.19 times higher. This shows

4.4. Rheological Properties of Warm Binders with Sasobit under different Short-term Ageing Temperatures

that addition of Sasobit improves the binders' rutting resistance even at lower production temperatures.

Table 4.2: Frequency sweep results of PMB warm asphalt binders at 1.59 Hz

RTFO ageing temperature, °C	PMB-Control	PMB + 1%S	PMB + 2%S	PMB + 3%S
163	6900 <sup>1</sup>	8480	10600	12600
	15500 <sup>2</sup>	18500	21300	24700
143	—	4440	7860	9130
	—	11400	17600	18600
123	—	4140	5650	8900
	—	11000	13400	18500

<sup>1</sup> Elastic modulus (top value in each row)

<sup>2</sup> Viscous modulus (bottom value in each row)

**Temperature Sweep Test**

Temperature sweep test was performed at lowest possible strain in the temperature range of 25–80°C. Results of temperature sweep test to evaluate the effect of Sasobit content on asphalt binders at different RTFO ageing temperatures are presented in Figures 4.37 — 4.42. Increase in Sasobit content increases complex modulus and reduces phase angle of both PMB and CRMB binders at all RTFO ageing temperatures, indicating that the addition of Sasobit improves the stiffness and elastic nature of both binders.

In order to clearly interpret the temperature sweep results, complex modulus and phase angle values obtained at a temperature of 60°C are reproduced in Tables 4.4 and 4.5 respectively for PMB and CRMB warm asphalt binders. From the table, it is observed that CRMB + 2% Sasobit even when aged at 123°C has

Table 4.3: Frequency sweep results of CRMB warm asphalt binders at 1.59 Hz

RTFO ageing temperature, °C	CRMB-Control	CRMB + 1%S	CRMB + 2%S	CRMB + 3%S
163	10700 <sup>1</sup>	14600	25200	27000
	19700 <sup>2</sup>	27800	41000	41300
143	—	14700	18500	18100
	—	26000	31900	30600
123	—	11700	14900	16000
	—	21600	26100	27400

<sup>1</sup> Elastic modulus (top value in each row)

<sup>2</sup> Viscous modulus (bottom value in each row)

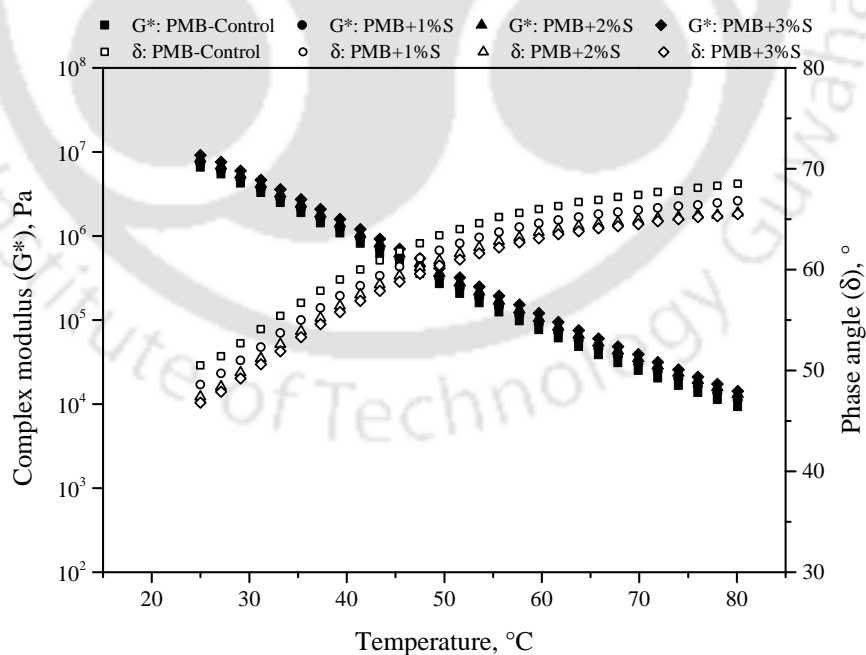


Figure 4.37: Temperature sweep results of PMB warm asphalt binders at 163°C RTFO ageing temperature

4.4. Rheological Properties of Warm Binders with Sasobit under different Short-term Ageing Temperatures

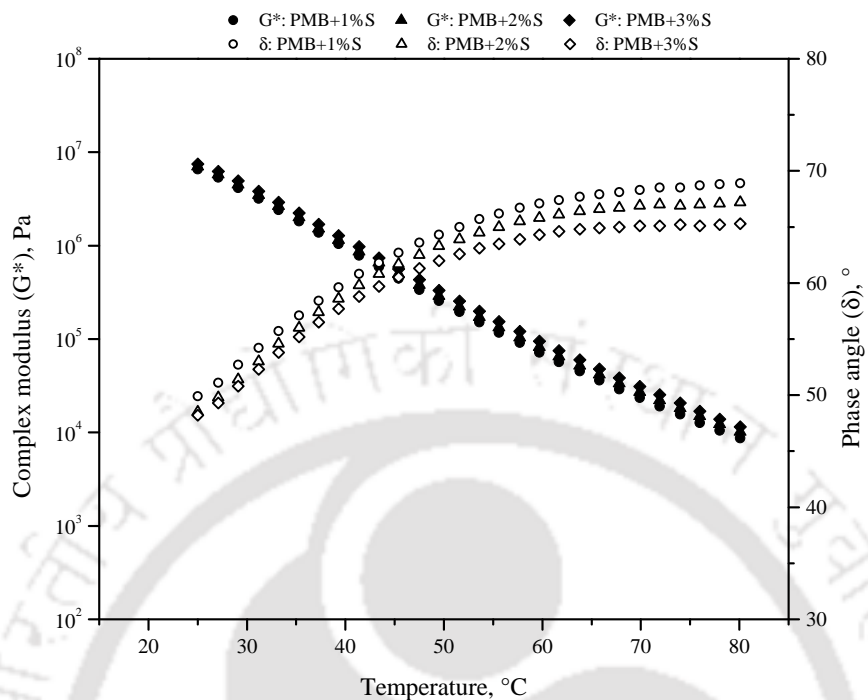


Figure 4.38: Temperature sweep results of PMB warm asphalt binders at 143°C RTFO ageing temperature

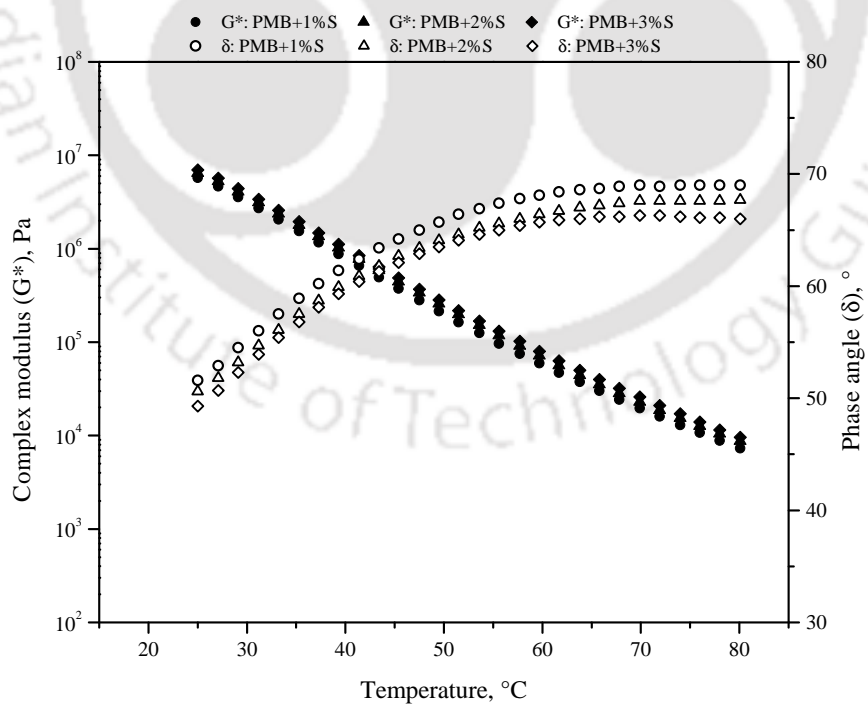


Figure 4.39: Temperature sweep results of PMB warm asphalt binders at 123°C RTFO ageing temperature

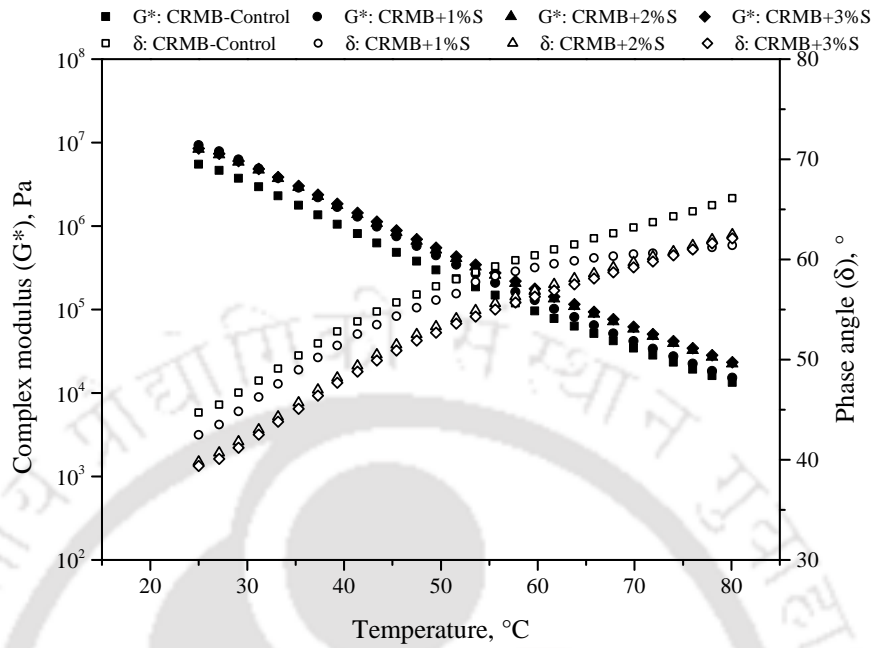


Figure 4.40: Temperature sweep results of CRMB warm asphalt binders at 163°C RTFO ageing temperature

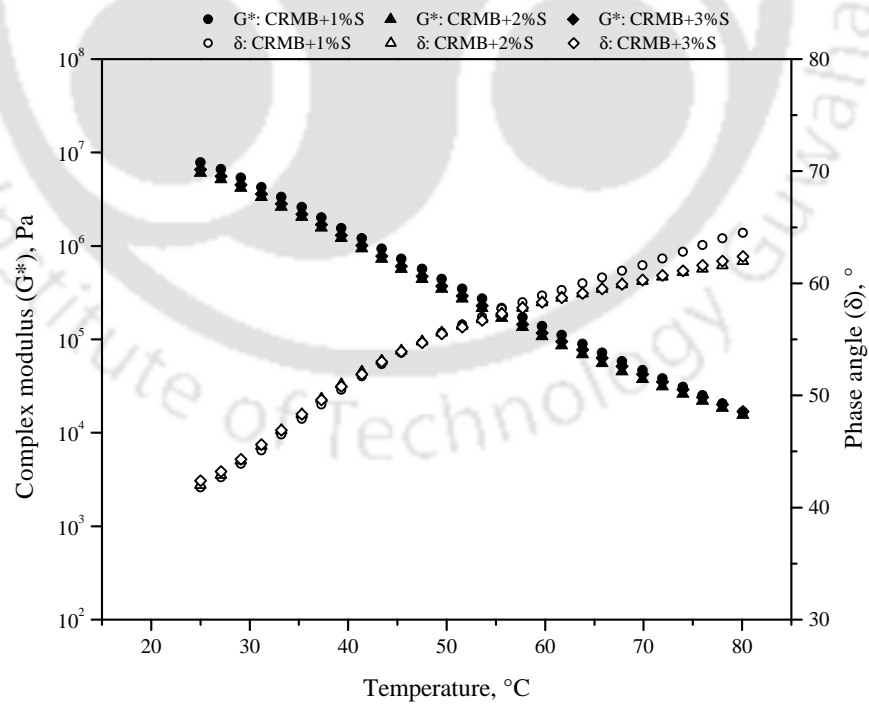


Figure 4.41: Temperature sweep results of CRMB warm asphalt binders at 143°C RTFO ageing temperature

#### 4.4. Rheological Properties of Warm Binders with Sasobit under different Short-term Ageing Temperatures

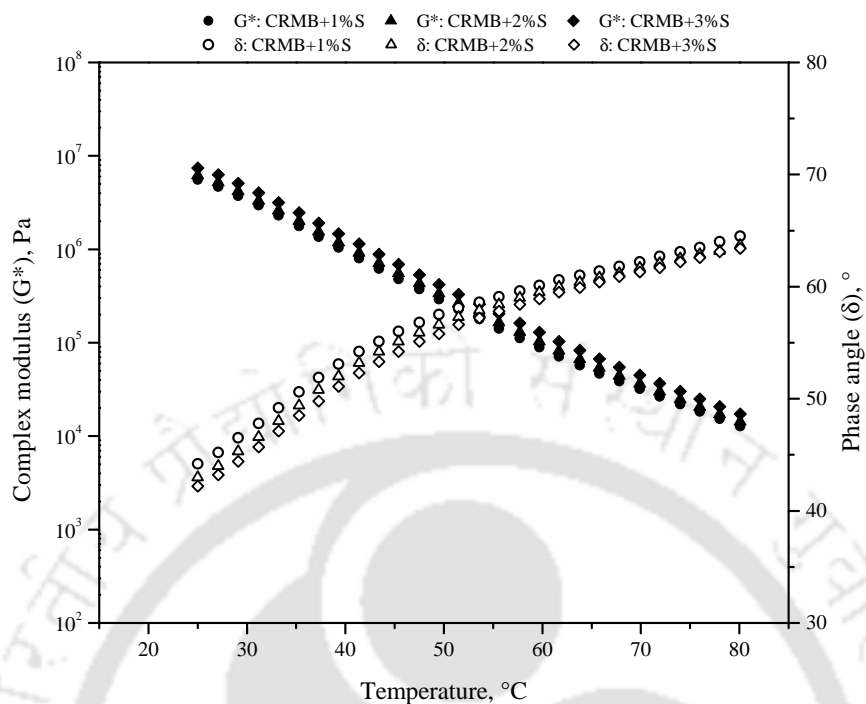


Figure 4.42: Temperature sweep results of CRMB warm asphalt binders at 123°C RTFO ageing temperature

higher complex modulus and lower phase angle compared to the control binder aged at 163°C. This indicates that warm asphalt binders even when aged at lower temperatures have higher resistance towards permanent deformation and elastic nature compared to the control binder aged at standard temperature of 163°C.

#### **Multiple Stress and Creep Recovery Test**

MSCR test is used to evaluate the permanent deformation resistance of asphalt binders under different stress levels. This test is used as an advancement over the Superpave rutting parameter ( $G^*/\sin\delta$ ) specification. Use of a low (0.1 kPa) and a high (3.2 kPa) stress level in the test allows complete mobilisation of the modifiers and thus helps to assess stress dependency of the modified asphalt binders. The MSCR was carried out as per ASTM D7405-10a (2010)

Table 4.4: Temperature sweep results of PMB warm asphalt binders at 60°C

RTFO ageing temperature, °C	PMB-Control	PMB + 1%S	PMB + 2%S	PMB + 3%S
163	68300 <sup>1</sup>	80200	93400	107000
	66.2 <sup>2</sup>	64.8	63.8	63.3
143	—	63900	73100	84400
	—	67.2	66	64.4
123	—	52700	63500	71100
	—	68.2	66.5	65.8

<sup>1</sup> Complex modulus (top value in each row)

<sup>2</sup> Phase angle (bottom value in each row)

Table 4.5: Temperature sweep results of CRMB warm asphalt binders at 60°C

RTFO ageing temperature, °C	CRMB-Control	CRMB + 1%S	CRMB + 2%S	CRMB + 3%S
163	86500 <sup>1</sup>	12300	150000	159000
	60 <sup>2</sup>	59.2	57.2	56.7
143	—	91000	96100	105000
	—	59.4	58.5	58.2
123	—	79600	92000	115000
	—	60.3	59.7	59.2

<sup>1</sup> Complex modulus (top value in each row)

<sup>2</sup> Phase angle (bottom value in each row)

4.4. Rheological Properties of Warm Binders with Sasobit under different Short-term Ageing Temperatures

specifications at 76°C, which is the high temperature performance grade of both PMB and CRMB control binders. Compliance values of both PMB and CRMB binders at a stress level of 3.2 kPa are shown in Figures 4.43 and 4.44 respectively.

As expected, the lower ageing temperatures increase the compliance values of warm binders. However, addition of Sasobit helps the warm asphalt binders to have lower compliance values, signifying that the addition of Sasobit improves resistance towards permanent deformation of the binders. Compliance values of control PMB and CRMB binder at 163°C ageing temperature are found to be lower than the PMB and CRMB warm asphalt binders at 123°C ageing temperature (40°C reduction from the standard temperature) on addition of 3% Sasobit with both binders.

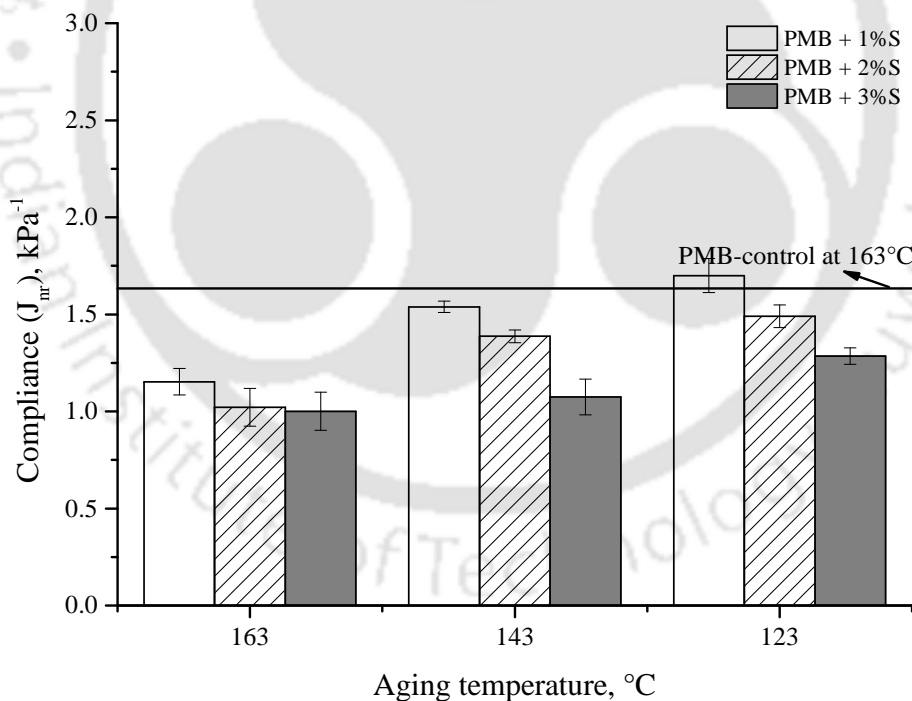


Figure 4.43: MSCR results of PMB warm asphalt binders

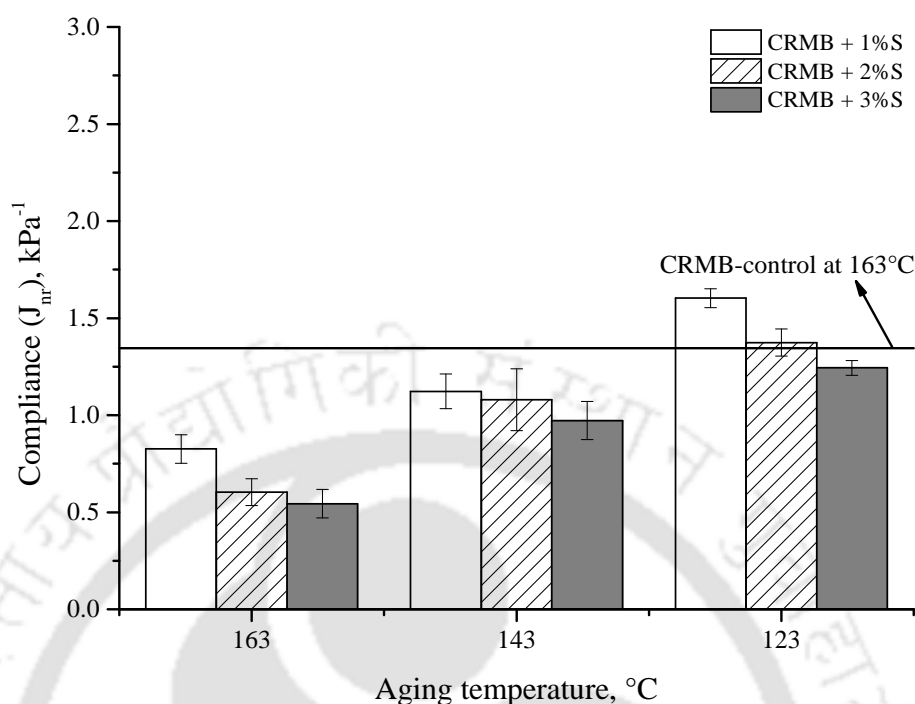


Figure 4.44: MSCR results of CRMB warm asphalt binders

## 4.5 Summary

This chapter described rheological characterisation of binders with varying dosage rates of WMA additives: Evotherm and Sasobit. Warm asphalt binders were prepared by adding Evotherm (0.5%, and 0.6%) and Sasobit (1%, 2%, and 3%) to two modified binders (PMB and CRMB). Results of rheological tests, including viscosity, failure temperature, frequency sweep, temperature sweep, creep, and repeated creep recovery were discussed in this chapter.

Rheological investigation with Evotherm revealed that its addition slightly reduced the viscosities and failure temperatures of both PMB and CRMB binders. From frequency and temperature sweep tests, it was observed that addition of Evotherm slightly reduced the elastic and viscous moduli of both

binders. Overall, the effect of Evotherm dosage on the rheological aspects of the binders was not appreciable.

With the addition of Sasobit, viscosities of both PMB and CRMB binders at 150°C showed significant reductions. This indicated the possibility to attain desired workability for proper mixing and coating at lower production temperatures. Failure temperatures of both binders increased with the increase in Sasobit dosage. Frequency and temperature sweep results showed that addition of Sasobit had positive effect on the elastic properties of both binders. Compliance obtained from creep and repeated creep recovery tests appreciably reduced for both binders under varying Sasobit contents.

Rheological aspects of Sasobit warm binders were further investigated under different short-term ageing temperatures. The short-term ageing was carried out using a rolling thin film oven at three temperatures (163°C, 143°C, and 123°C). Viscosity, failure temperature, complex modulus, elastic modulus, and viscous modulus of both binders decreased with the decrease in ageing temperature. The phase angle and compliance values increased with the decrease in ageing temperature. The addition of Sasobit compensated the effects of reduced ageing as rheological parameters of Sasobit warm binders aged at 143°C and 123°C compared well with the control binders aged at standard ageing temperature (163°C).

## Chapter 5

# Volumetric and Marshall Parameters of Warm Mixes

### 5.1 Introduction

Volumetric parameters of asphalt mixes *viz.*, air voids, voids in mineral aggregates, bulk density, and voids filled with bitumen play a major role in ensuring durability and performance of asphalt pavements. Mixing and compaction temperatures (collectively referred as production temperatures) play a significant role in achieving the desired volumetric properties and workability. Mixing temperature is the temperature at which the binder viscosity allows complete coating of aggregates during the preparation of mixes, whereas compaction temperature is the one required to achieve the desired workability and *in-situ* density. Excessively high mixing temperature may result in lean mixes while low mixing temperature may negatively affect bitumen coating around the aggregates (Mo et al., 2012). Similarly, high compaction temperature leads to tender mixes, excess absorption of bitumen in some aggregate types (leading to low effective bitumen content), and drain down of the asphalt binder

in some coarser mixes; whereas low compaction temperature leads to poor compaction and inadequate densities (Stuart, 2002; Asphalt Institute, 2011).

Mixing and compaction temperatures for neat (unmodified) asphalt binders are respectively determined at viscosities of  $170\pm 20$  cSt and  $280\pm 30$  cSt, as per the Asphalt Institute Manual Series No.2 (Asphalt Institute, 1997) guidelines (also used in India). These viscosity ranges do not hold equally good for modified binders, and often result in unreasonably high mixing and compaction temperatures ( $>190^\circ\text{C}$ ), which may eventually result in modifier damage, binder damage, construction problems, and fume production (Yildirim et al., 2000; Tang and Haddock, 2006). The high production temperatures associated with modified binders may also lead to difficulties in achieving the desired mix design and volumetric parameters for bituminous mixes (Lee et al., 2007; Akisetty et al., 2009a). Incorporation of WMA technologies with modified binders should help to reduce the mixing and compaction temperatures that are generally higher than in case of unmodified binders without sacrificing the volumetric and design parameters of bituminous mixes.

Therefore, the volumetric and Marshall parameters of bituminous concrete (BC) mixes with two WMA additives (Evotherm and Sasobit) are studied as function of production temperature, dosage/content of each WMA additive, and binder type and the results are presented in this chapter. Warm mixes were produced at four reductions in production temperatures ( $0^\circ\text{C}$ ,  $20^\circ\text{C}$ ,  $30^\circ\text{C}$ , and  $40^\circ\text{C}$ ) with different dosages of two additives (Evotherm: 0.5%, 0.6%, and Sasobit: 1%, 2%, 3%). Detailed experimental flowchart for this phase of the study is shown in Figure 3.6. Results of volumetric and Marshall parameters of warm mixes with Evotherm and Sasobit *vis-à-vis* control mixes (without WMA additives) are presented and discussed in the chapter. An attempt is also made

to determine the optimum reduction in production temperatures achievable for WMA mixes while satisfying the stipulated requirements of all mix volumetric elements and Marshall characteristics.

## 5.2 Marshall Mix Design Parameters of Warm Mixes with Evotherm

### *Bulk Density*

Bulk density values of warm mixes with Evotherm obtained at different production temperatures are depicted in Figures 5.1 and 5.2. Bulk density of warm mixes are found to be higher than the control mixes even after 20°C reduction in production temperatures. Addition of Evotherm reduces the shear forces between the coated aggregates particles, which enhances the workability and results in an increase in bulk density even at lower production temperatures. However, bulk density of warm mixes decreases with reduction in production temperatures, which is likely due to decrease in the workability at low production temperatures. Bulk density of warm mixes increases with the increase in Evotherm dosage (from 0.5% to 0.6%). Bulk densities of CRMB warm mixes are slightly higher than the PMB warm mixes indicating a better compactability of CRMB warm mixes with Evotherm.

Table 5.3 presents results of analysis of variance (ANOVA) conducted on bulk density values of warm mixes (at 5% significance level) wherein binder type, Evotherm content, and reduction in production temperature (RPT) are factors and bulk density is the response variable. The results show that all main effects (binder type, Evotherm content, and RPT) are significant. Two-way interaction

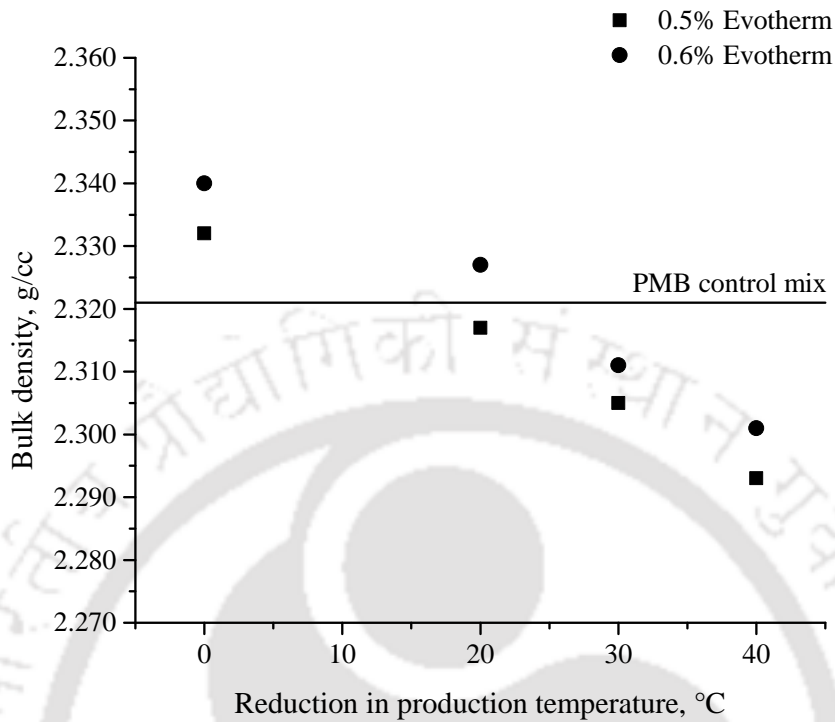


Figure 5.1: Bulk density of PMB warm mixes with Evotherm

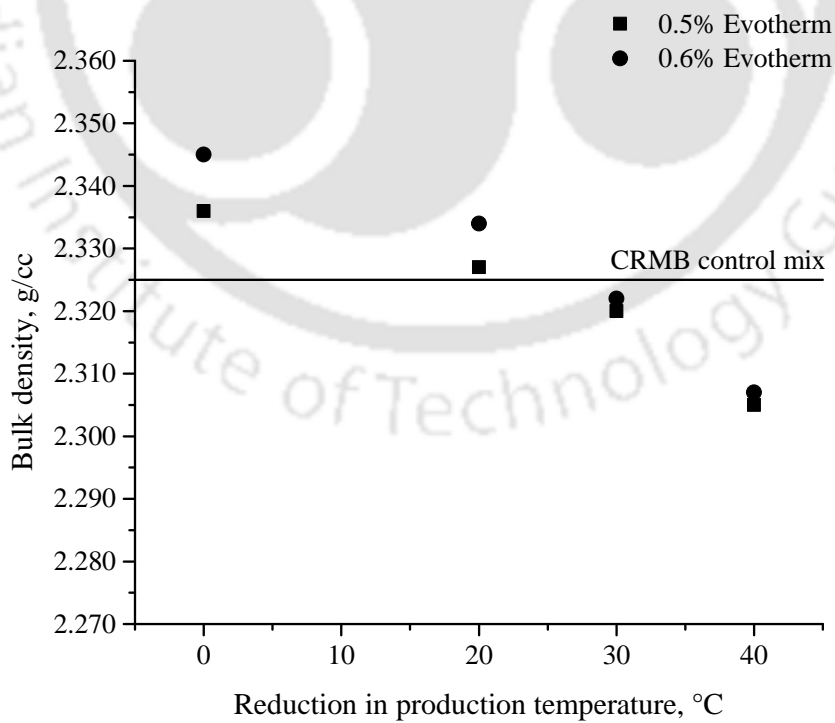


Figure 5.2: Bulk density of CRMB warm mixes with Evotherm

between binder type and RPT is also found to be significant. This shows that the effect of binder type on bulk density values is governed by the level of reduction in production temperature considered.

Table 5.1: ANOVA results for bulk density of warm mixes containing Evotherm

Source	df	F-statistic	p-value	Significant?
Binder type	1	49.843	0.000	Yes
Evotherm content	1	20.074	0.000	Yes
RPT <sup>1</sup>	3	165.982	0.000	Yes
Binder type * Evotherm content	1	1.843	0.184	No
Binder type * RPT	3	4.015	0.016	Yes
Evotherm content * RPT	3	0.267	0.848	No
Binder type * Evotherm content * RPT	3	0.581	0.632	No
Error	32			
Total	48			

<sup>1</sup> RPT: Reduction in production temperature

### **Air Voids**

Effect of reduction in production temperatures on air void content of PMB and CRMB warm mixes are shown in Figures 5.3 and 5.4 respectively. Air void contents of warm mixes with PMB and CRMB decreased to 3.6% and 3.3%, respectively, on addition of 0.5% Evotherm at 0°C reduction in production temperature as compared to control mixes designed at 4%. This shows that addition of Evotherm helps in enhancing the compactability of mixes at the same compaction effort. An increasing trend of air voids is observed with decrease in the production temperatures. This is anticipated as increase in viscosity of binder due to lower production temperatures will reduce

compactability of mixes. A similar finding was observed by Akisetty et al. (2009a) and Lee et al. (2007) for air voids of mixes with reduction in production temperatures. Figures 5.3 and 5.4 illustrate that for the warm mixes, the design air void content (*i.e.*, 4%) is achieved at reductions in the production temperatures in between 20 to 30°C.

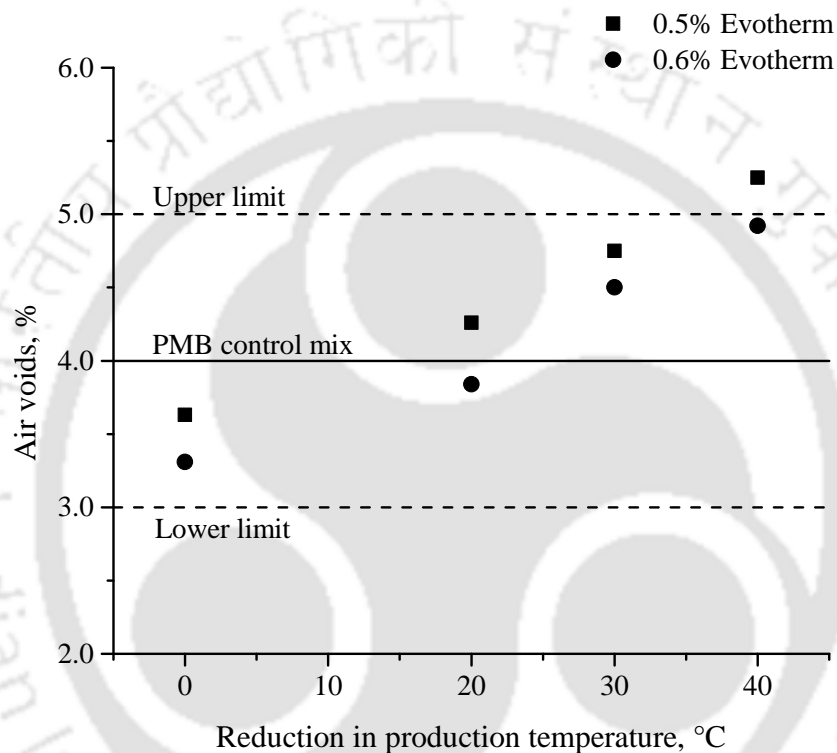


Figure 5.3: Air voids of PMB warm mixes with Evotherm

Increase in Evotherm content from 0.5% to 0.6% reduced the air void content of PMB and CRMB warm mixes due to improved compatibility with higher Evotherm dosage. All warm mixes are able to satisfy the requirement of air void content (3–5%) according to MoRTH (2013) specifications, except for PMB warm mix produced with 0.5% Evotherm at 40°C reduction in production temperature.

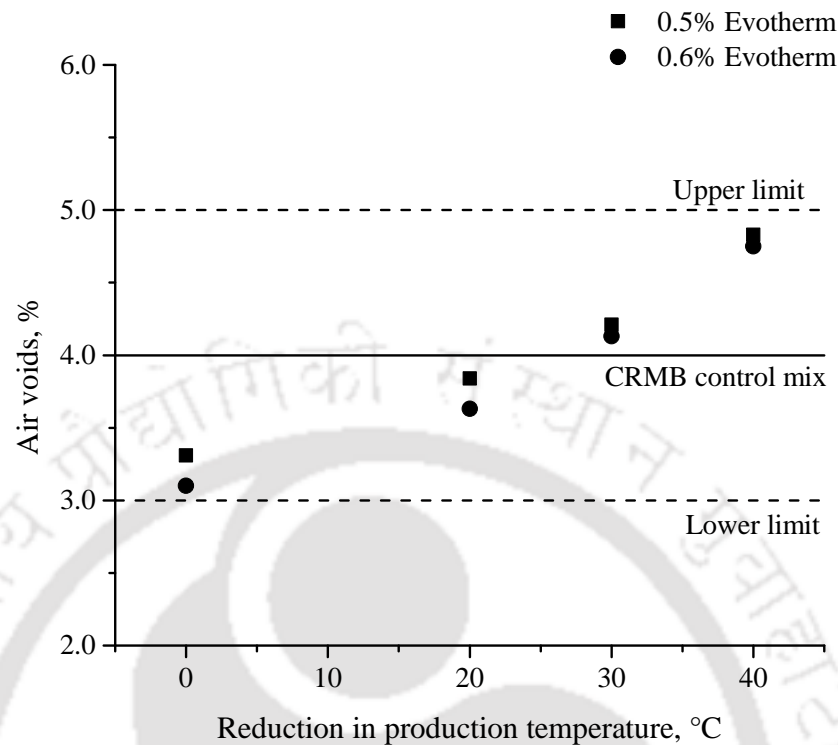


Figure 5.4: Air voids of CRMB warm mixes with Evotherm

### **Marshall Stability**

Marshall stability is defined as the maximum load carried by a compacted bituminous mix loaded diametrically at a standard test temperature of 60°C (Roberts et al., 1996). It was determined using Matest 50 kN UTM II digitalised Marshall stability testing machine with a loading rate of 50.8 mm/min. Marshall stability results of PMB and CRMB warm mixes produced at different production temperatures are illustrated in Figures 5.5 and 5.6 respectively. Marshall stability of both PMB and CRMB warm mixes increases on addition of Evotherm and is found to be comparable to control mixes even at 20°C to 30°C reduction in production temperatures. Marshall stability values of warm mixes with 0.6% Evotherm content are higher than those with 0.5% Evotherm content, apparently due to their higher bulk density. In regard to binder type, Marshall

stability of CRMB warm mixes are higher than those of PMB warm mixes. This might be attributed to higher bulk density of CRMB warm mixes.

Marshall stability values of warm mixes are found to decrease with reduction in production temperature. The reduction in bulk density, shown in Figures 5.1 and 5.2, also justifies the reduction in stability with decrease in production temperatures. Lower production temperatures decrease the ageing of binder and therefore result in lower Marshall stability of warm mixes due to reduced binder stiffness. However, both PMB and CRMB warm mixes are able to meet the minimum requirement of 12 kN specified for BC mixes with modified binders (MoRTH, 2013) even upto 40°C reduction in the production temperatures.

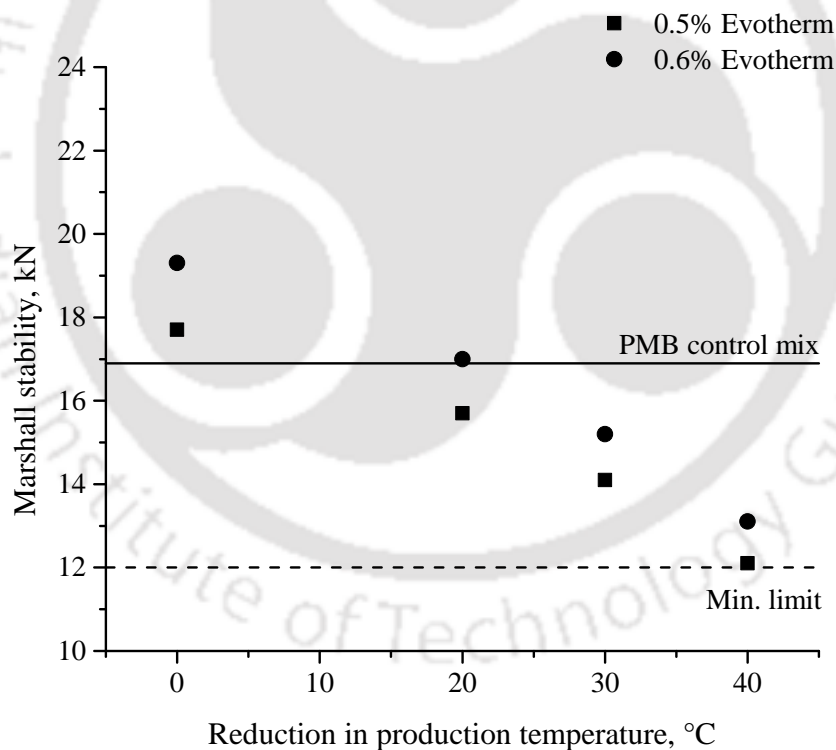


Figure 5.5: Marshall stability of PMB warm mixes with Evotherm

Results of ANOVA performed on Marshall stability are presented in Table 5.2. Results show that main effects of all factors significantly influence the Marshall stability of warm mixes. The two-way and three-way interactions are found to

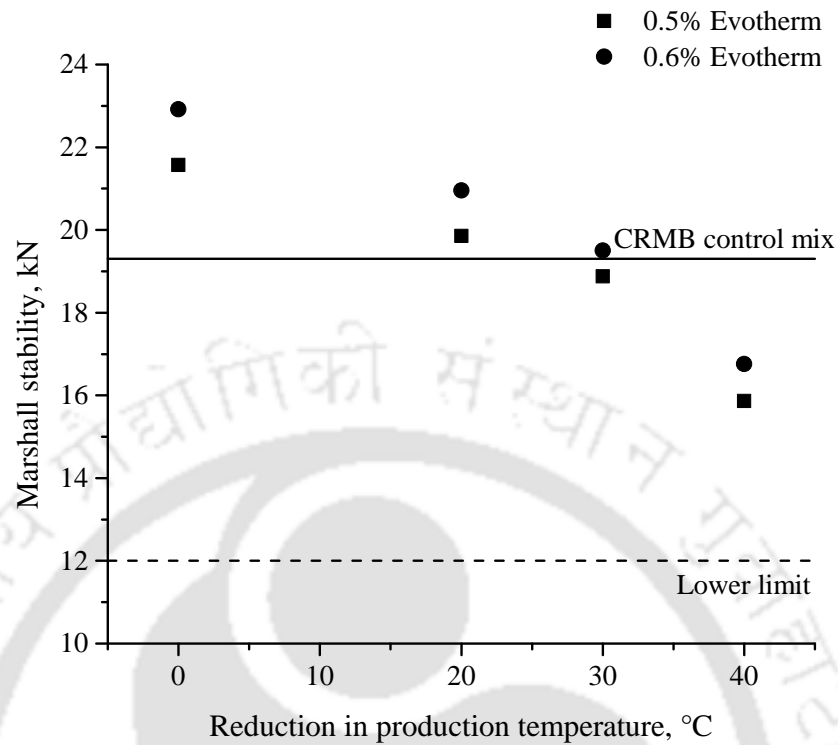


Figure 5.6: Marshall stability of CRMB warm mixes with Evotherm

have non-significant effect on Marshall stability of warm mixes, indicating that the effect of one factor on Marshall stability is same regardless of level of the other factor.

#### ***Voids in Mineral Aggregates and Voids Filled with Bitumen***

Figures 5.7, 5.8, 5.9, and 5.10 present trends of voids in mineral aggregates (VMA) and voids filled with bitumen (VFB) of warm mixes prepared at different mixing and compaction temperatures. It is observed that VMA of warm mixes increases with decrease in production temperatures, whereas VFB decreases with reduction in temperatures irrespective of Evotherm content and binder type. This observation is in good agreement with the findings of other researchers (Akisetty et al., 2009a; Lee et al., 2007). At 30°C and 40°C reduction in the production temperatures, both PMB and CRMB warm mixes are able to

Table 5.2: ANOVA results for Marshall stability of warm mixes containing Evotherm

Source	df	F-statistic	p-value	Significant?
Binder type	1	400.290	0.000	Yes
Evotherm content	1	39.587	0.000	Yes
RPT	3	130.487	0.000	Yes
Binder type * Evotherm content	1	0.76	0.785	No
Binder type * RPT	3	1.248	0.309	No
Evotherm content * RPT	3	2.243	0.102	No
Binder type * Evotherm content* RPT	3	1.184	0.331	No
Error	48			
Total	72			

meet the VMA (minimum of 14%) and VFB (65–75%) requirements as per MoRTH (2013) specifications. However, it should be noted that many researchers suggest VFB as a redundant parameter if VMA and air void requirements are satisfied (Roberts et al., 1996; Kandhal, 2016).

### 5.3 Marshall Mix Design Parameters of Warm Mixes with Sasobit

#### *Bulk Density*

Figures 5.11 and 5.12 respectively present the variation of bulk density of PMB and CRMB warm mixes produced with different percentages of Sasobit. Addition of Sasobit increases bulk densities of both PMB and CRMB warm mixes. This shows that Sasobit helps to increase the workability of mix by

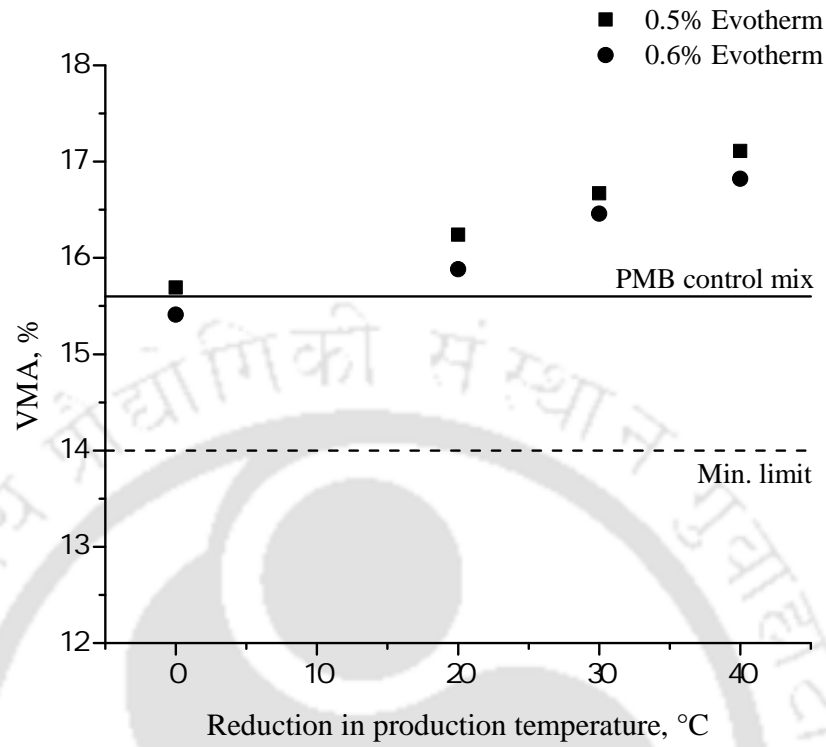


Figure 5.7: VMA of PMB warm mixes with Evotherm

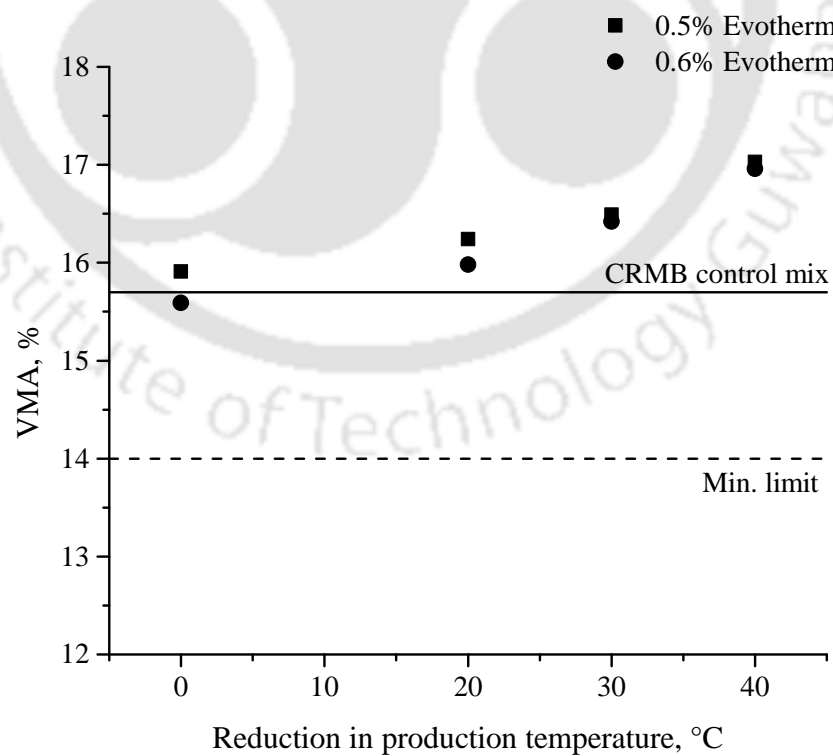


Figure 5.8: VMA of CRMB warm mixes with Evotherm

5.3. Marshall Mix Design Parameters of Warm Mixes with Sasobit

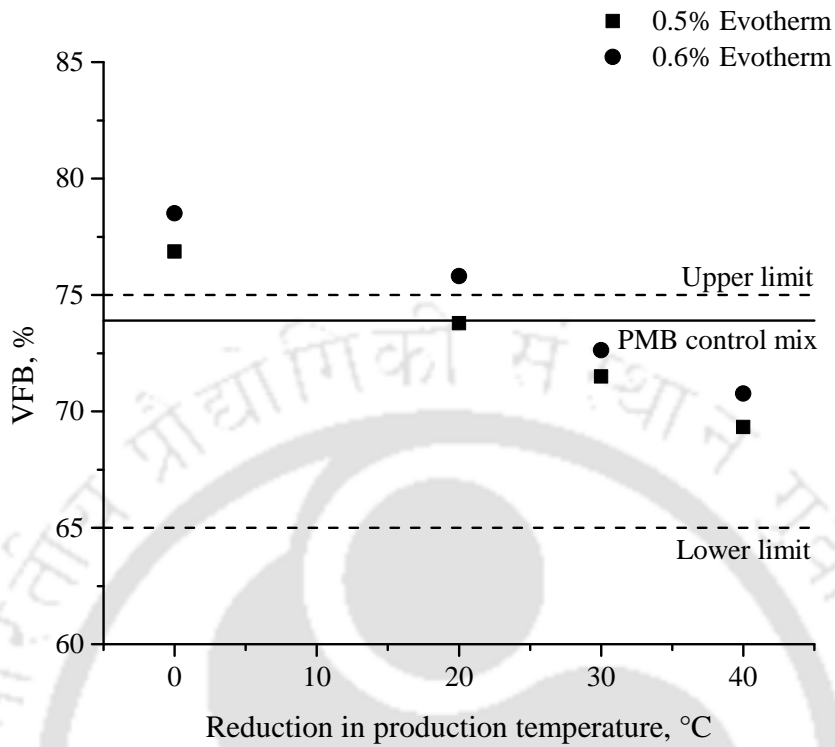


Figure 5.9: VFB of PMB warm mixes with Evotherm

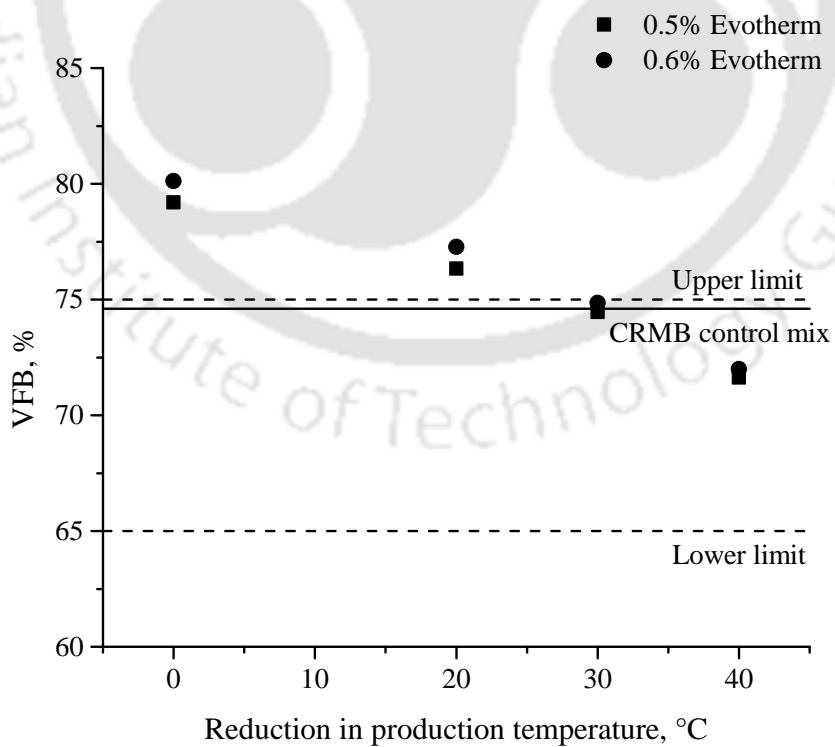


Figure 5.10: VFB of CRMB warm mixes with Evotherm

reducing the viscosity of the binder at typical production temperatures of HMA. However, as production temperature decreases, the workability of warm mixes also decreases due to increase in viscosity of binder, which results in lower bulk densities. Bulk density of PMB and CRMB warm mixes with 2% and 3% Sasobit at 20°C reduction in production temperature are greater than those of control mixes at standard production temperature (0°C reduction). Hence, it can be inferred that BC mixes with two modified binders can achieve desired density even at lower production temperatures on addition of Sasobit.

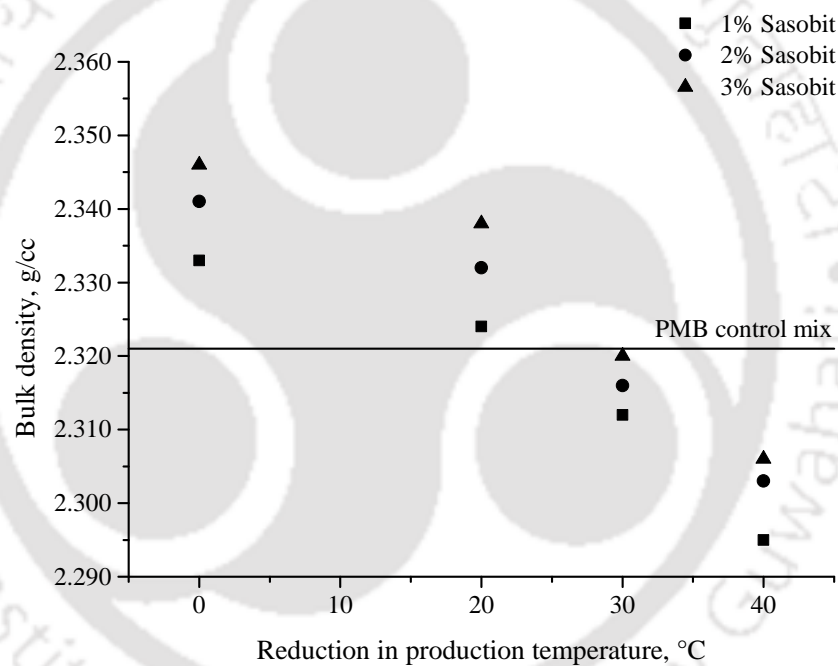


Figure 5.11: Bulk density of PMB warm mixes with Sasobit

Further, it is observed that increase in Sasobit dosage improves bulk density at all production temperatures. An increase in Sasobit content from 1% to 2% exhibits greater improvement in bulk density values as compared to increase in Sasobit content from 2% to 3%. The effect of increase in Sasobit dosage on bulk density values is found to be more pronounced at higher reductions in production temperatures (30°C and 40°C).

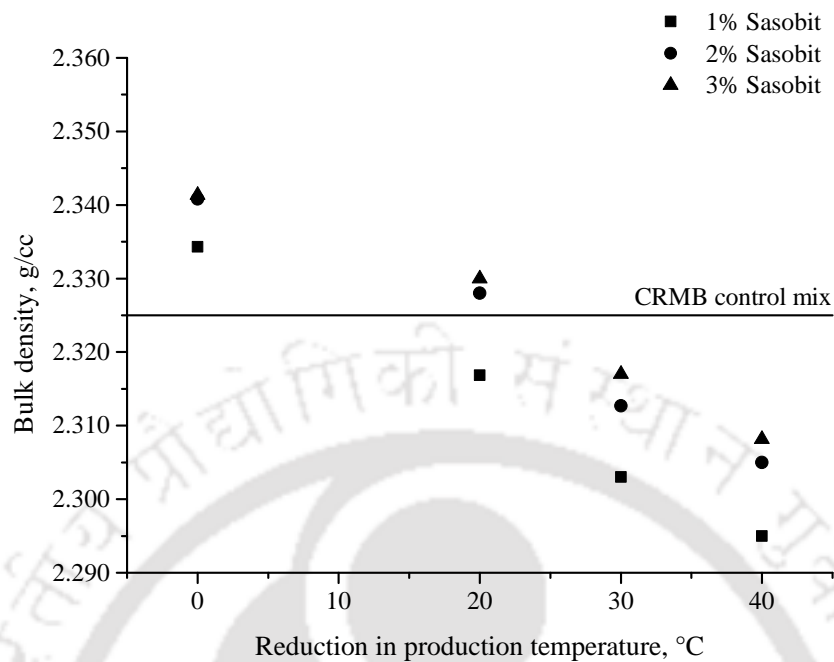


Figure 5.12: Bulk density of CRMB warm mixes with Sasobit

Results of statistical analysis performed on bulk density values using ANOVA are presented in Table 5.3. ANOVA results indicate that all three individual factors and two-way interactions between binder type and RPT have statistically significant influence on bulk density of warm mixes at 5% significance level. Insignificant two-way interactions of the factors binder type and RPT with Sasobit content show that the effect of Sasobit dosage remains the same for both binders at all reductions.

### **Air Voids**

Variation of air void content observed for both PMB and CRMB on addition of mixes with Sasobit is shown in Figures 5.13 and 5.14 respectively. Air void content of warm mixes decreases with increase in Sasobit content. This shows that addition of Sasobit helps in enhancing the compactability of mixes with the same compaction effort even at lower production temperatures. However, air

Table 5.3: ANOVA results for bulk density of warm mixes containing Sasobit

Source	df	F-statistic	p-value	Significant?
Binder type	1	5.861	0.019	Yes
Sasobit content	2	74.773	0.000	Yes
RPT	3	485.444	0.000	Yes
Binder type * Sasobit content	2	1.313	0.278	No
Binder type * RPT	3	5.475	0.003	Yes
Sasobit content * RPT	6	0.887	0.512	No
Binder type * Sasobit content * RPT	6	1.080	0.388	No
Error	48			
Total	72			

void content of warm mixes increases with decrease in production temperature. This is likely because increase in viscosity of binder at reduced production temperatures would reduce the compactability of mixes. A similar trend was observed by Akisetty et al. (2009a) for the air voids of warm mixes containing 1.5% Sasobit. All warm mixes with Sasobit meet the criteria of 3–5% air voids as per MoRTH (2013) requirements, except the warm mixes produced with 1% Sasobit at 40°C reduction in production temperature. Air void contents of 4% (as for control mixes) are achieved for warm mixes with 2% and 3% Sasobit for reduction in production temperatures in the range of 20°C to 30°C.

### ***Marshall Stability***

Marshall stability is defined as a resistance to plastic flow of a compacted bituminous mix specimen. It was determined at 60°C using Matest 50 kN UTM II digitalised Marshall stability testing machine. Marshall stability values of PMB

5.3. Marshall Mix Design Parameters of Warm Mixes with Sasobit

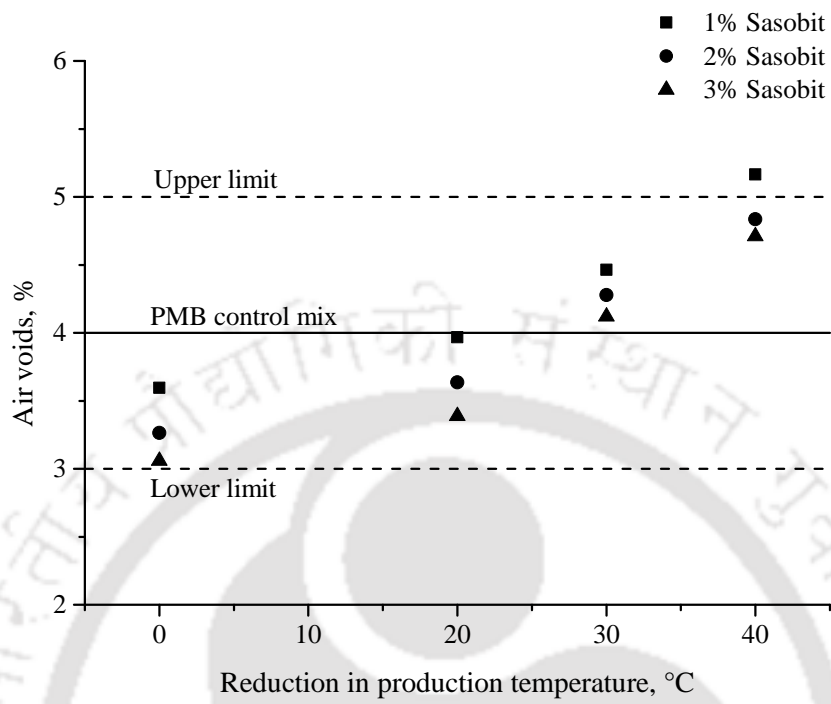


Figure 5.13: Air voids of PMB warm mixes with Sasobit

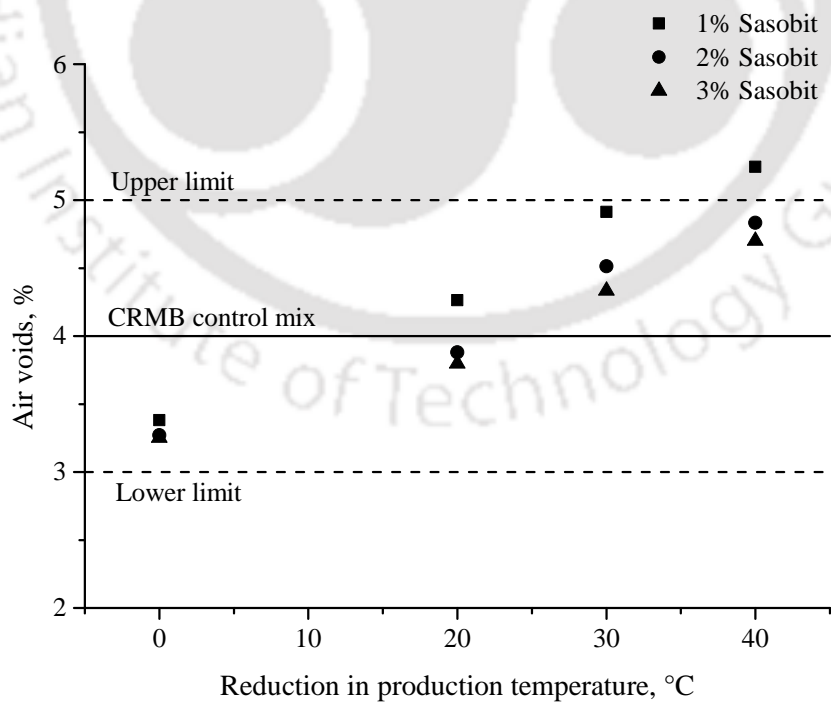


Figure 5.14: Air voids of CRMB warm mixes with Sasobit

and CRMB warm mixes found at different dosages of Sasobit and production temperatures are shown in Figures 5.15 and 5.16 respectively. In general, it is observed that Marshall stability of warm mixes increases with increase in Sasobit dosage and decreases with decrease in production temperatures. Marshall stability values of CRMB warm mixes are greater than PMB warm mixes due to higher viscous nature of CRMB binder. In addition, Figures 5.15 and 5.16 indicate that Marshall stability of all warm mixes satisfy the minimum requirement of 12 kN set forth by MoRTH (2013) for BC mixes with modified binders even at 40°C reduction in production temperatures. The decrease in Marshall stability with reduction in the production temperature can be explained by weakening of mass viscosity of aggregate-bitumen mix due to reduced ageing of binder at lower production temperatures, and due to reduction in bulk density of mixes as observed from Figures 5.11 and 5.12.

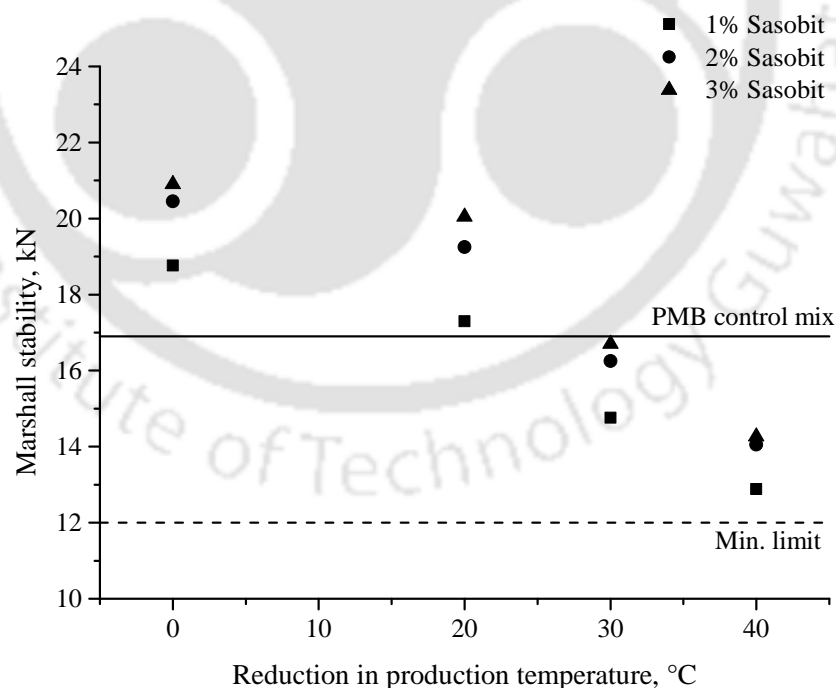


Figure 5.15: Marshall stability of PMB warm mixes with Sasobit

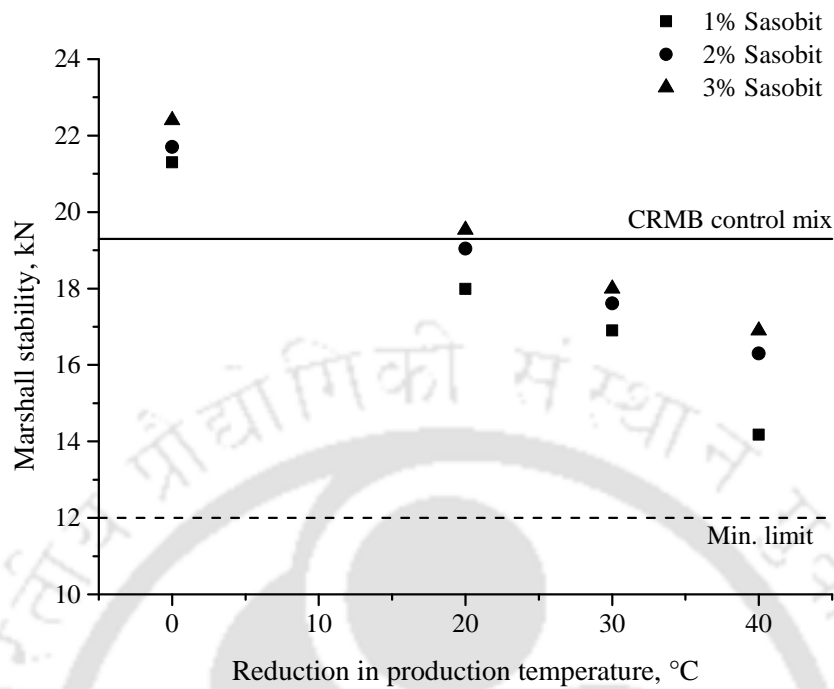


Figure 5.16: Marshall stability of CRMB warm mixes with Sasobit

Marshall stability of warm mixes with both binders are found to increase with increase in Sasobit dosage. An increase in Sasobit content from 1% to 3% increases the Marshall stability of PMB and CRMB warm mixes by 11% and 19% respectively even after a reduction of 40°C production temperature. This increase in stability is achieved due to the formation of crystalline lattice structure inside the binder, which helps to increase the stiffness of binder and finally the stability of the mix.

ANOVA results shown in Table 5.4 indicate that main effect of all factors considered in the study has statistically significant effect on Marshall stability. Among all interactions, two-way interaction between binder type and RPT is found to have significant influence on Marshall stability of warm mixes.

Table 5.4: ANOVA results for Marshall stability of warm mixes containing Sasobit

Source	df	F-statistic	p-value	Significant?
Binder type	1	112.154	0.000	Yes
Sasobit content	2	72.873	0.000	Yes
RPT	3	431.155	0.000	Yes
Binder type * Sasobit content	2	1.386	0.260	No
Binder type * RPT	3	13.709	0.000	Yes
Sasobit content * RPT	6	1.149	0.349	No
Binder type * Sasobit content * RPT	6	2.136	0.066	No
Error	64			
Total	96			

#### ***Voids in Mineral Aggregates and Voids Filled with Bitumen***

Figures 5.17, 5.18, 5.19, and 5.20 explain the trends of VMA and VFB of PMB and CRMB warm mixes. It is observed that reduction in production temperature increases the VMA. However, VMA is found to reduce with increase in Sasobit dosage at any production temperature, due to improved compactability achieved and consequent denser configuration attained by the aggregates with the increase in Sasobit content. The minimum VMA requirement of 14% is met by all warm mixes. An increase in air voids with decrease in production temperatures (Figures 5.13 and 5.14) should decrease VFB, which is indeed observed in Figures 5.19 and 5.20. VFB values of warm mixes produced at 30°C and 40°C lie within the required range of 65–75%.

5.3. Marshall Mix Design Parameters of Warm Mixes with Sasobit

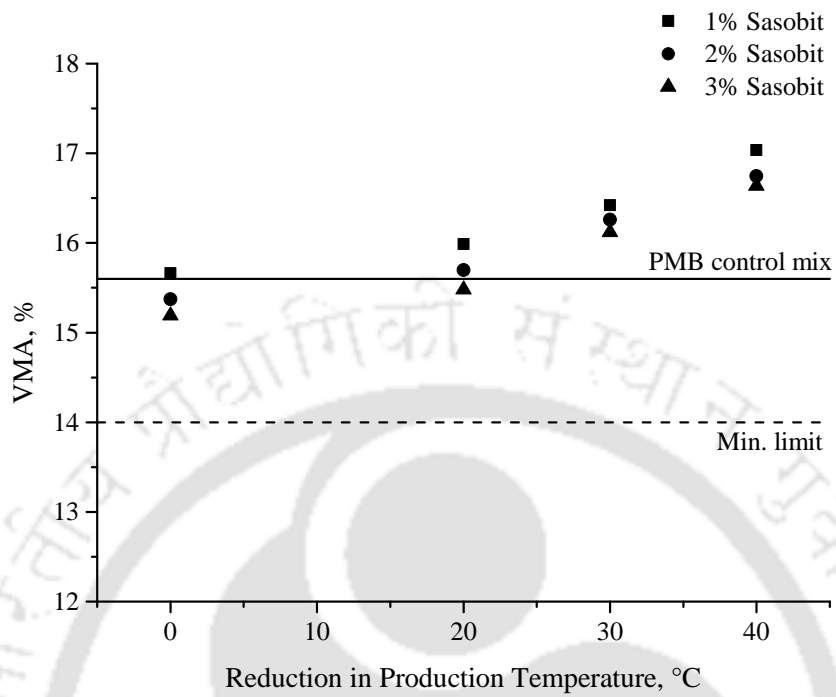


Figure 5.17: VMA of PMB warm mixes with Sasobit

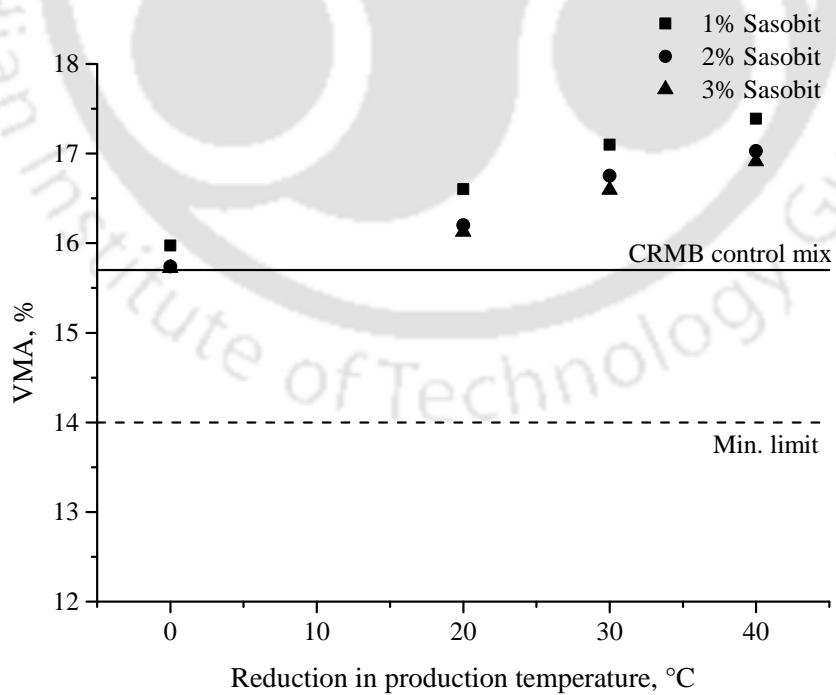


Figure 5.18: VMA of CRMB warm mixes with Sasobit

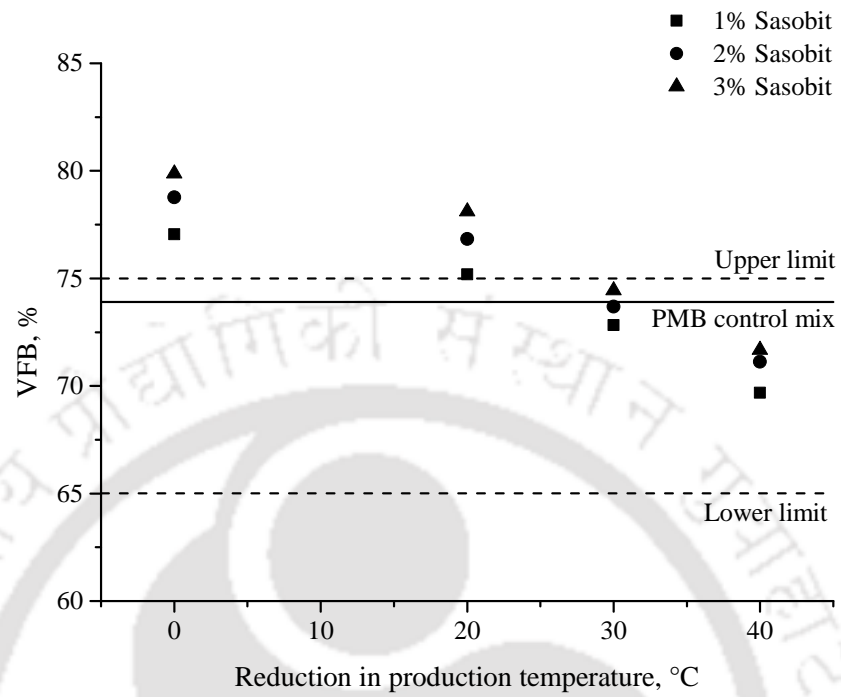


Figure 5.19: VFB of PMB warm mixes with Sasobit

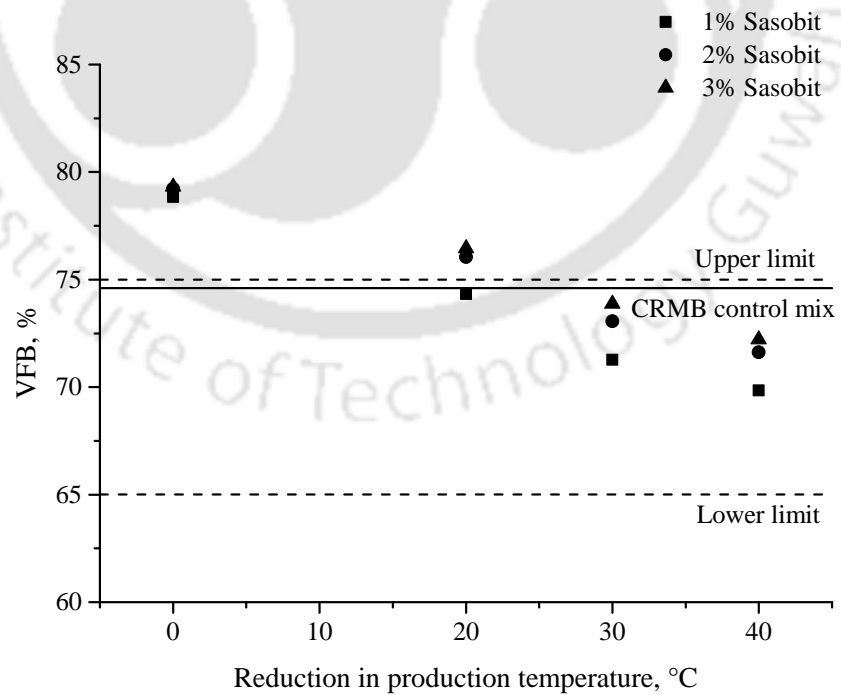


Figure 5.20: VFB of CRMB warm mixes with Sasobit

## 5.4 Determination of Optimum Range for Reduction in Production Temperature for Warm Mixes

An attempt is made in this study to identify the optimum range for reduction in production temperature achievable for each combination of binder type, additive type and its dosage based on Marshall mix design parameters. To find optimum range of reduction in production temperatures, a strip plot is constructed with all mix design parameters including Marshall stability, flow, AV, VMA, and VFB as function of reduction in production temperature. Based on the specified upper and/or lower limits of a design parameter, a region in the strip can be identified where the required specifications are met corresponding to the reductions (from 0 to 40°C). Similar strips can be constructed for all other design parameters. Finally, a window can be identified from all strips in which all mix design specifications as per MoRTH (2013) and IRC:111 (2009) (shown in Table 5.5) are conformed, thus finalising the optimum range for a given mix. Lower and upper limits of optimum ranges are thus obtained corresponding to each set of binder type and additive content. Not only the upper limit (indicating maximum achievable reduction in production temperature) is relevant for WMA mixes, the lower limit is also important so that the advantages associated with each WMA additive can be achieved while satisfying the mix design requirements set forth by MoRTH (2013) and IRC:111 (2009) for BC mixes with modified binders.

Strip plots for all warm mixes were constructed for determining the optimum range of reduction in production temperatures and are shown in Figures 5.21–5.30. Optimum reduction ranges for both PMB and CRMB mixes with different percentages of Evotherm and Sasobit determined from the strip plots

Table 5.5: Mix design requirements as per MoRTH (2013) and IRC:111 (2009)

Property	Requirement
Marshall stability at 60°C, kN	Min. 12
Marshall flow, mm	2.5 – 4.0
Air voids (AV), %	3.0 – 5.0
Voids filled with bitumen (VFB), %	65 – 75
Voids in mineral aggregate (VMA), %	Min. 14.0

are presented in column (4) of Table 5.6. It is observed that increase in WMA additive content allows higher reductions (upto 40°C) in production temperatures and also meets the requirements laid for control mixes. Lower limits of the optimum ranges shown in Table 5.6 (column (4)) point out that it is essential to lower the production temperatures on addition of WMA additive in order to fulfil mix design requirements.

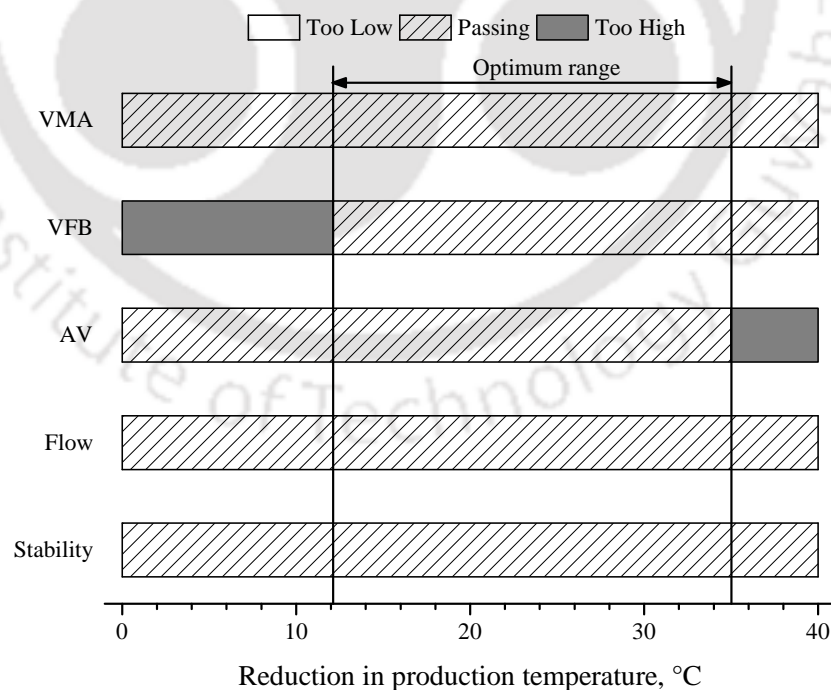


Figure 5.21: Optimum range for reduction in production temperature for PMB mixes with 0.5% Evotherm

5.4. Determination of Optimum Range for Reduction in Production Temperature for Warm Mixes

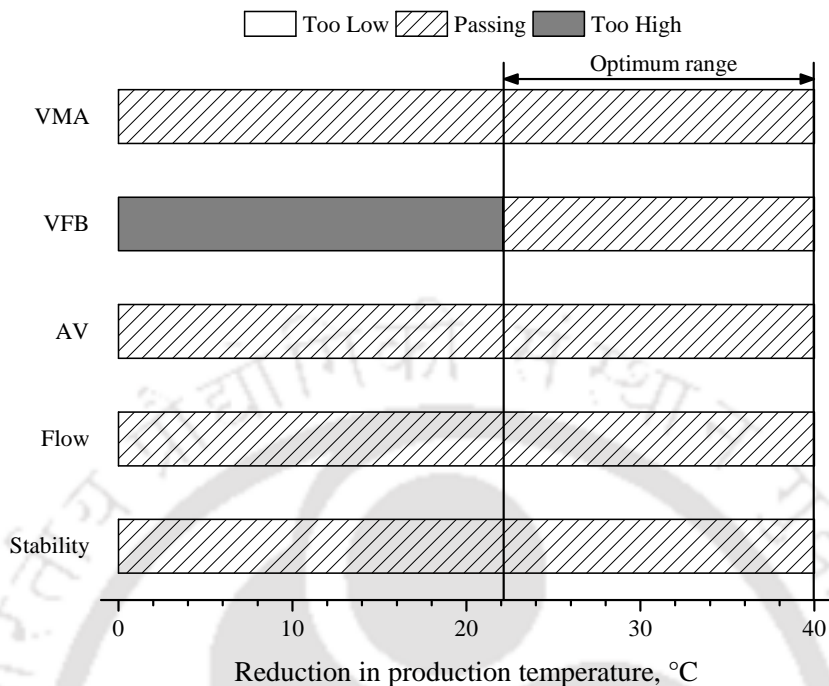


Figure 5.22: Optimum range for reduction in production temperature for PMB mixes with 0.6% Evotherm

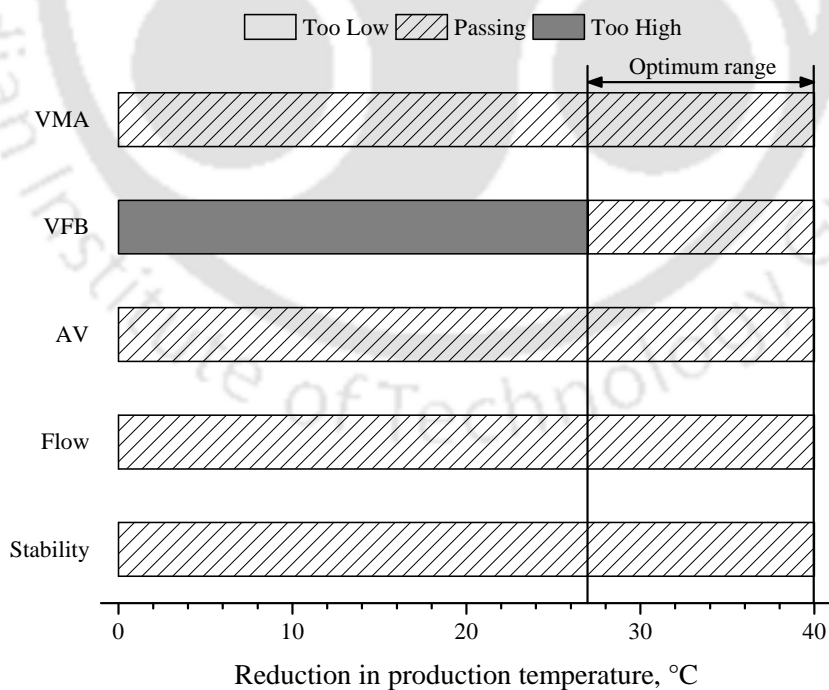


Figure 5.23: Optimum range for reduction in production temperature for CRMB mixes with 0.5% Evotherm

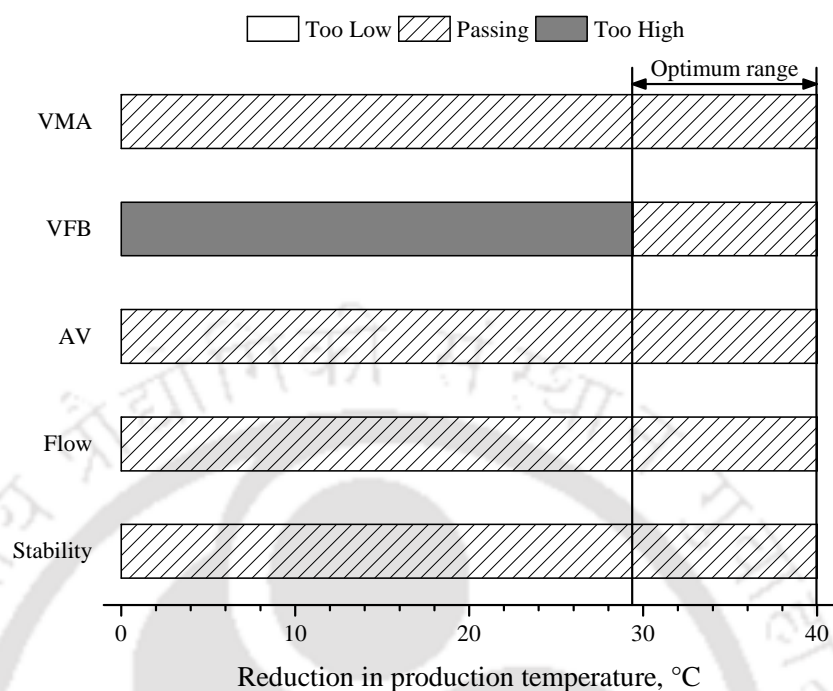


Figure 5.24: Optimum range for reduction in production temperature for CRMB mixes with 0.6% Evotherm

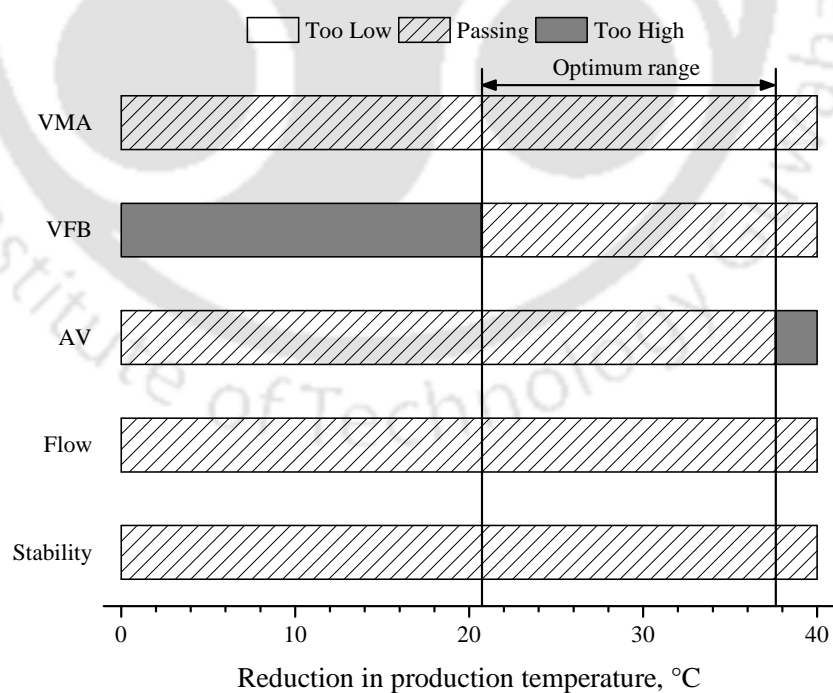


Figure 5.25: Optimum range for reduction in production temperature for PMB mixes with 1% Sasobit

5.4. Determination of Optimum Range for Reduction in Production Temperature for Warm Mixes

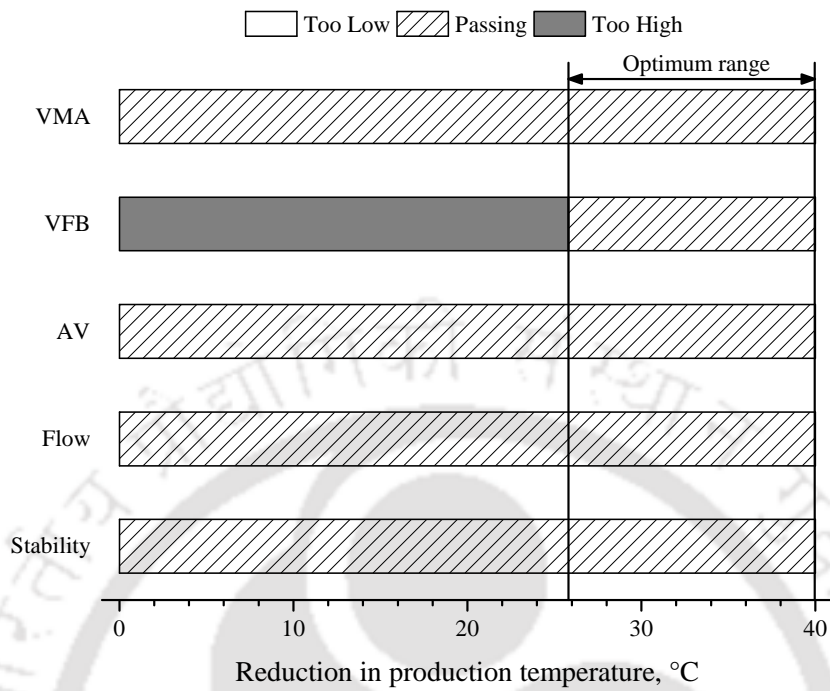


Figure 5.26: Optimum range for reduction in production temperature for PMB mixes with 2% Sasobit

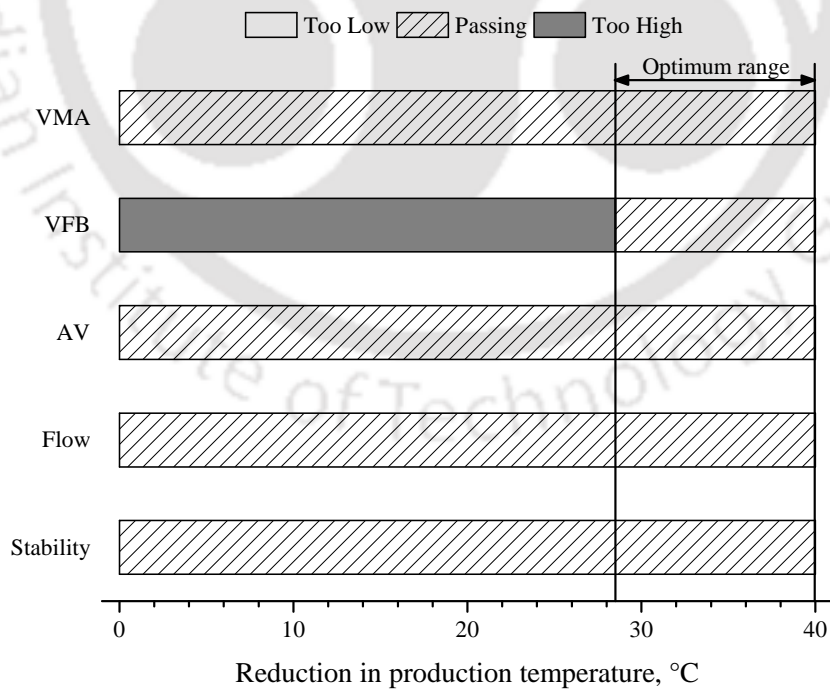


Figure 5.27: Optimum range for reduction in production temperature for PMB mixes with 3% Sasobit

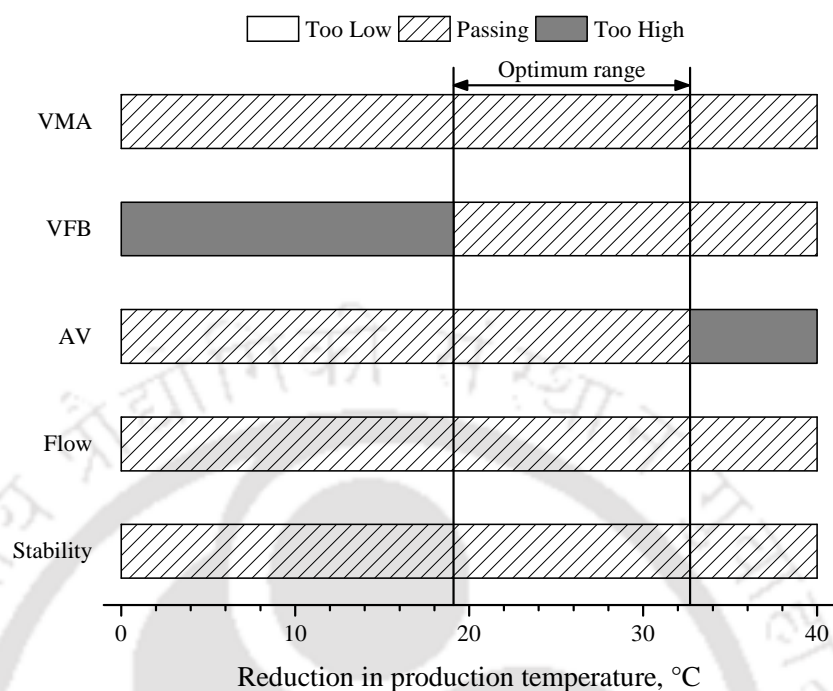


Figure 5.28: Optimum range for reduction in production temperature for CRMB mixes with 1% Sasobit

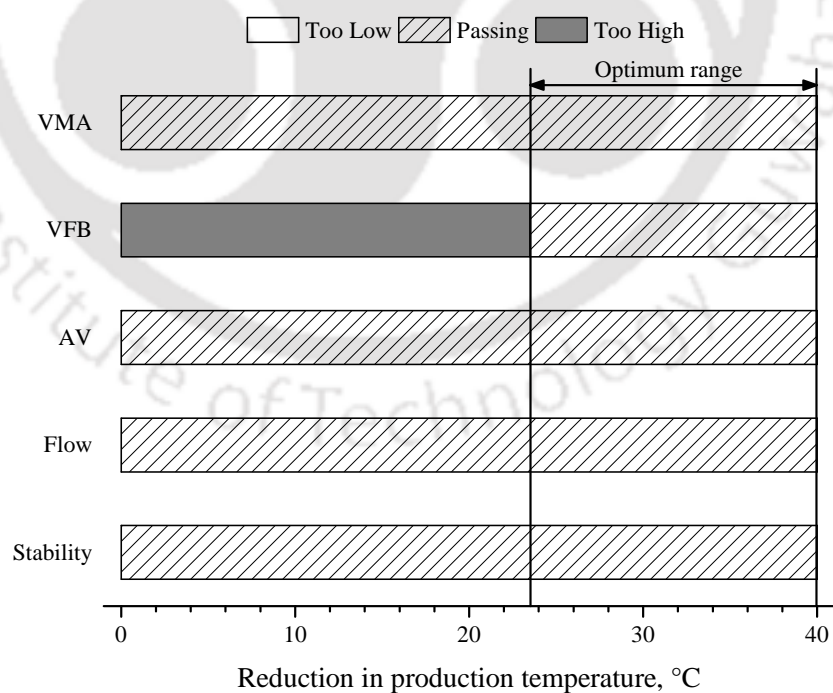


Figure 5.29: Optimum range for reduction in production temperature for CRMB mixes with 2% Sasobit

Table 5.6: Optimum range for reduction in production temperature for warm mixes

<b>Binder type</b>	<b>Additive type</b>	<b>Additive content</b>	<b>As per MoRTH (2013)</b>	<b>As per IRC: SP-101 (2014)</b>
<b>(1)</b>	<b>(2)</b>	<b>(3)</b>	<b>(4)</b>	<b>(5)</b>
PMB	Evotherm	0.5%	12 — 35°C	12 — 23°C
PMB	Evotherm	0.6%	22 — 40°C	22 — 25°C
CRMB	Evotherm	0.5%	27 — 40°C	27 — 33°C
CRMB	Evotherm	0.6%	30 — 40°C	30 — 34°C
PMB	Sasobit	1%	21 — 38°C	21 — 28°C
PMB	Sasobit	2%	25 — 40°C	26 — 32°C
PMB	Sasobit	3%	28 — 40°C	28 — 35°C
CRMB	Sasobit	1%	19 — 33°C	19 — 22°C
CRMB	Sasobit	2%	23 — 40°C	23 — 28°C
CRMB	Sasobit	3%	26 — 40°C	26 — 32°C

Recently published interim guidelines for warm mix asphalt by IRC (Indian Roads Congress) (IRC:SP-101, 2014) state that air void ratio (AVR) of a warm mix to control mix (Equation 5.1) should lie between 0.9 and 1.1 for the selection of production temperatures. The optimum range for reduction in production temperature was also determined as per the AVR requirement of the interim guidelines. For the purpose of determining the optimum ranges for warm mixes as per IRC:SP-101 (2014), AVR criterion was considered in lieu of air voids requirement (3–5%), while other criteria (*i.e.* Marshall stability, flow, VMA, and VFB) were retained as per MoRTH (2013) and IRC:111 (2009) for control BC mix.

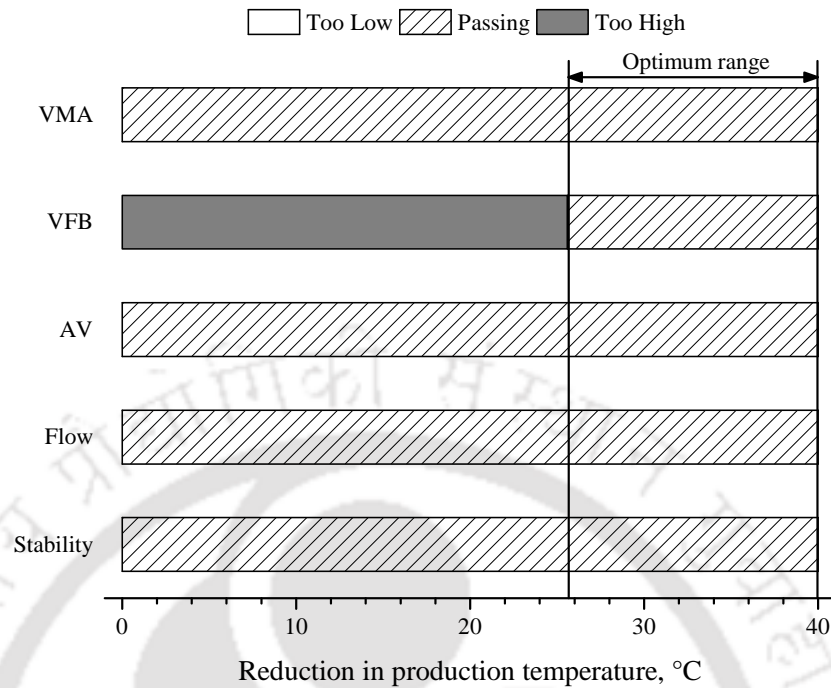


Figure 5.30: Optimum range for reduction in production temperature for CRMB mixes with 3% Sasobit

The obtained results are summarised in Table 5.6 in column (5).

$$AVR = \frac{\text{Air voids of warm mix at any production temperature}}{\text{Air voids of control mix at standard production temperature}} \quad (5.1)$$

In comparison to results obtained without imposing AVR criterion (column (4) of Table 5.6), it is observed that implementation of AVR criterion has narrowed down the optimum window with reduction in upper limits without appreciable change in lower limits. Hence, IRC:SP-101 (2014) guidelines appear to impose stringent requirements for WMA mixes despite the observation that these mixes are able to adequately meet the design standards stipulated by MoRTH (2013) and IRC:111 (2009) for conventional HMA mixes with higher permissible reduction in production temperatures.

## 5.5 Summary

Results of Marshall mix design parameters (in terms of bulk density, air voids, voids in mineral aggregates, voids filled with bitumen, and Marshall stability) of warm mixes prepared as a function of two modified binder types, two WMA additives, each with different dosage rates, and four reductions in production temperatures were discussed in this chapter. Bulk density and Marshall stability of both PMB and CRMB mixes increased on addition of Sasobit and Evotherm, and were found to be greater than the control mixes even after 20°C reduction in production temperatures. An increase in content of WMA additives improved the bulk density and Marshall stability of warm mixes at all production temperatures. Reduction in production temperatures reduced the bulk density and Marshall stability of warm mixes. Irrespective of the binder type, all warm mixes containing 0.6% Evotherm, 2% Sasobit, and 3% Sasobit were able to satisfy Marshall mix design requirements stipulated by MoRTH (2013) for BC mixes up to 40°C reduction in production temperatures. Statistical analysis showed that all the three factors considered (binder type, additive content, and reduction in production temperatures) had significant effect on bulk density and Marshall stability.

## Chapter 6

# Moisture Susceptibility Characteristics of Warm Mixes

### 6.1 Introduction

Moisture damage is one of the most common and complex phenomenon in asphalt pavements. It is defined as the loss of ability of the pavement to resist traffic induced stresses due to mechanical degradation of asphalt mix properties as a result of interaction with moisture. Adhesion failure and cohesion failure are the two main mechanisms that accelerate moisture damage in the asphalt pavements (Alam et al., 1998; Airey and Choi, 2002; Hicks et al., 2003; Cheng et al., 2003; Liu and Hao, 2006; Sebaaly et al., 2007; Wasiuddin et al., 2007; Al-Qadi et al., 2014). The loss of cohesion characteristics of binder that results in the loss of mixture stiffness is defined as cohesion failure. Adhesion failure (often referred as stripping) is caused due to loss of adhesive bond between the aggregate and the binder (*i.e.*, separation of binder from aggregate particles) with the interaction of water. Out of the two failures, adhesive failure is the most

common/dominant failure in the asphalt pavements (Hunter and Ksaibati, 2002; Caro et al., 2008b).

It is hypothesised that the reduced production temperatures of WMA mixes may lead to incomplete/ improper drying of aggregates, and thus increase their susceptibility towards moisture-induced damages. The residual moisture in the aggregate particles could adversely affect the adhesion characteristics at the aggregate-bitumen interface. Poor adhesion between aggregate and bitumen may result in stripping of binder from the aggregate surface leading to the moisture damage. The occurrence of stripping in the pavement may lead to initiation and propagation of various distresses such as rutting, corrugations, shoving, ravelling, and cracking (Alam et al., 1998; Brown et al., 2001; Hunter and Ksaibati, 2002; Sebaaly et al., 2003; Wasiuddin et al., 2007; Kringos et al., 2008a,b; Caro et al., 2008a; Xiao et al., 2009).

While some researchers have maintained that WMA mixes are not prone to moisture damage (Kanitpong et al., 2007; Mogawer et al., 2011; Yang et al., 2017), a few researchers still point towards inability of WMA to produce effectively coated aggregates, thereby rendering WMA mixes vulnerable to the effects of moisture (Hurley and Prowell, 2005; Wasiuddin et al., 2008; Sangsefidi et al., 2014).

This chapter presents the results and analyses of moisture susceptibility characteristics of warm mixes. Warm mixes were prepared with each combination of binder type (PMB and CRMB), WMA additive type (Evotherm and Sasobit), WMA additive content (Evotherm: 0.5%, 0.6%, and Sasobit: 1%, 2%, 3% by weight of binder) and four reductions in production temperatures (0°C, 20°C, 30°C, 40°C). These mixes were then tested for resistance to moisture damage through modified Lottman test (as per AASHTO T 283 (2003)) and retained Marshall stability test (as per MoRTH (2013)).

## 6.2 Moisture Susceptibility of Warm Mixes with Evotherm

### *Modified Lottman Test Results*

Modified Lottman test is one of the commonly used test for evaluating moisture susceptibility of bituminous mixes. This test measures reduction in indirect tensile strength (ITS) due to the effect of moisture conditioning and is expressed in terms of tensile strength ratio (TSR). TSR is the ratio of average ITS of moisture conditioned samples to the average ITS of unconditioned samples. Moisture conditioning of specimen includes vacuum saturation and a freeze-thaw cycle. Modified Lottman test was conducted as per the guidelines of AASHTO T 283 (2003). The minimum TSR requirement for BC mix is 80% (MoRTH, 2013).

TSR values of warm mixes produced with PMB and CRMB at different reductions in production temperature are shown in Figures 6.1 and 6.2 respectively. It is observed that the resistance of BC mixes to moisture susceptibility increases with the addition of Evotherm. Addition of 0.6% Evotherm at standard production temperatures increases the TSR values from 96.9% to 100.5% in case of PMB warm mixes, and from 94% to 99.8% in case of CRMB warm mixes. The increase in TSR values is likely due to improved adhesion between aggregate and binder because of the anti-stripping agents present in Evotherm (MWV, 2013). TSR values of warm mixes containing 0.6% Evotherm are higher than control mixes in case of both PMB and CRMB mixes even after 20°C reduction in production temperature.

## 6.2. Moisture Susceptibility of Warm Mixes with Evotherm

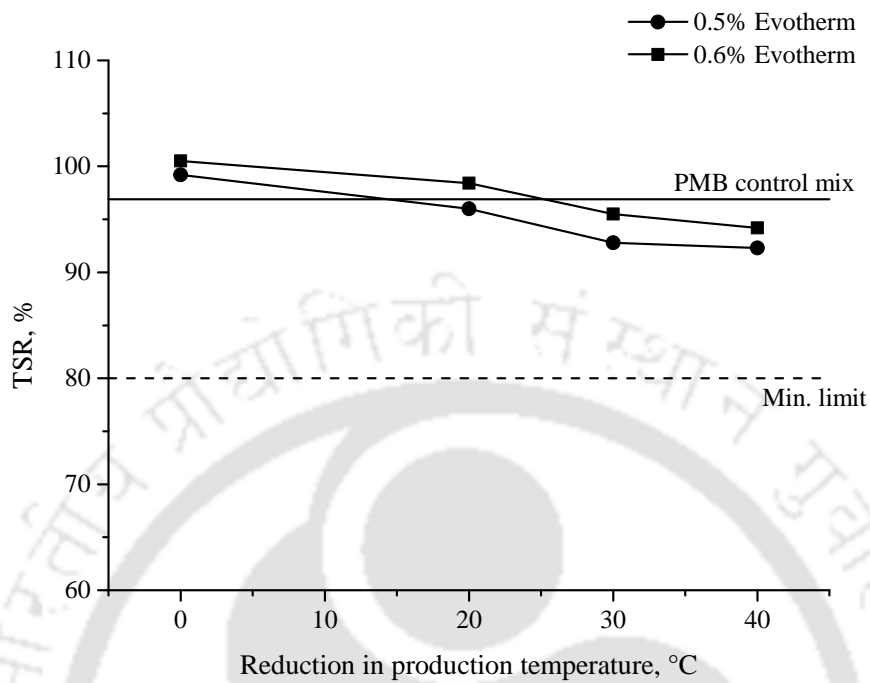


Figure 6.1: Modified Lottman test results of PMB warm mixes with Evotherm

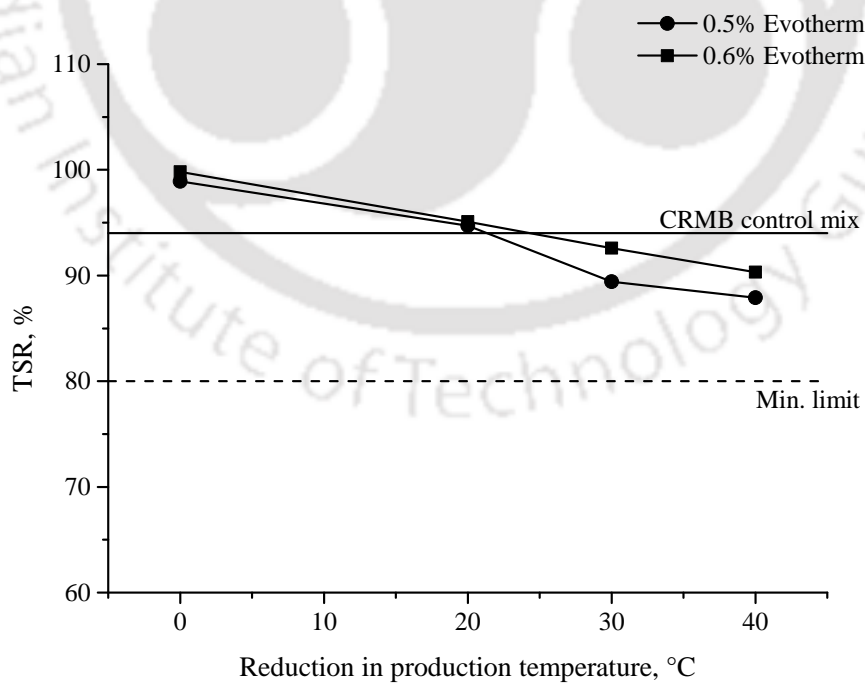


Figure 6.2: Modified Lottman test results of CRMB warm mixes with Evotherm

TSR value of warm mixes is observed to decrease with decrease in the production temperatures, likely due to reduced adhesion between aggregates and the binder at lower production temperatures. However, even after a reduction of 40°C in production temperature, the TSR values of warm mixes prepared with PMB and CRMB are about 90% and 85% respectively, which are greater than the minimum requirement of 80% set forth by the MoRTH (2013) specifications for HMA mixes. TSR values of warm mixes produced with PMB are found to be higher than the warm mixes prepared with CRMB.

An increase in Evotherm content increases the resistance of warm mixes towards moisture susceptibility and has a pronounced effect on TSR values at lower production temperatures (*i.e.* at 30°C and 40°C reduction in production temperature). Increase of 0.1% Evotherm content (from 0.5% to 0.6%) showed a maximum increase of 2.7% and 3.2% in the TSR values of PMB and CRMB warm mixes respectively at 30°C reduction in production temperature.

ANOVA was performed to identify the influence of investigated variables, namely binder type, Evotherm content, and reduction in production temperature on the TSR values and the results are shown in Table 6.1. The effects of all three individual factors are statistically significant at 5% significance level and this shows that these factors will have substantial impact on TSR values. All two-way interactions showed statistically non-significant effect on the TSR values of warm mixes.

### ***Retained Marshall Stability Test Results***

Retained Marshall stability (RMS) test measures the loss of compressive strength of bituminous mixes due to the action of water. RMS test compares Marshall stability of a moisture conditioned specimen (immersed in water bath at 60°C for

Table 6.1: ANOVA results for TSR values of warm mixes containing Evotherm

Source	df	F-statistic	p-value	Significant?
Binder type	1	20.959	0.000	Yes
Evotherm content	1	11.711	0.002	Yes
RPT	3	47.795	0.000	Yes
Binder type * Evotherm content	3	0.122	0.729	No
Binder type * RPT	3	2.013	0.132	No
Evotherm content * RPT	3	0.624	0.605	No
Binder type * Evotherm content * RPT	3	0.364	0.780	No
Error	32			
Total	48			

24 h) to that of unconditioned specimen (immersed in water bath at 60°C for 30 min). This test was performed according to MoRTH (2013) guidelines that specify a minimum RMS requirement of 75%.

RMS values of warm mixes with PMB and CRMB at different production temperatures are shown in Figures 6.3 and 6.4 respectively. It is observed that RMS values of warm mixes are higher than the control mixes at standard production temperature (*i.e.* at 0°C reduction) . A similar trend is also observed in modified Lottman testing. Even at 40°C reduction in production temperature, RMS values are about 95% and 85% for the warm mixes prepared with PMB and CRMB respectively, which are higher than the minimum requirement of 75% set forth by MoRTH (2013) specifications. RMS of warm mixes is also found to decrease with the decrease in production temperature. Moisture susceptibility resistance of warm mixes found through RMS test is higher compared to TSR test, which may be due to lower air void content (6% in RMS test compared to 7% in TSR test) and absence of a freezing cycle in case of RMS test.

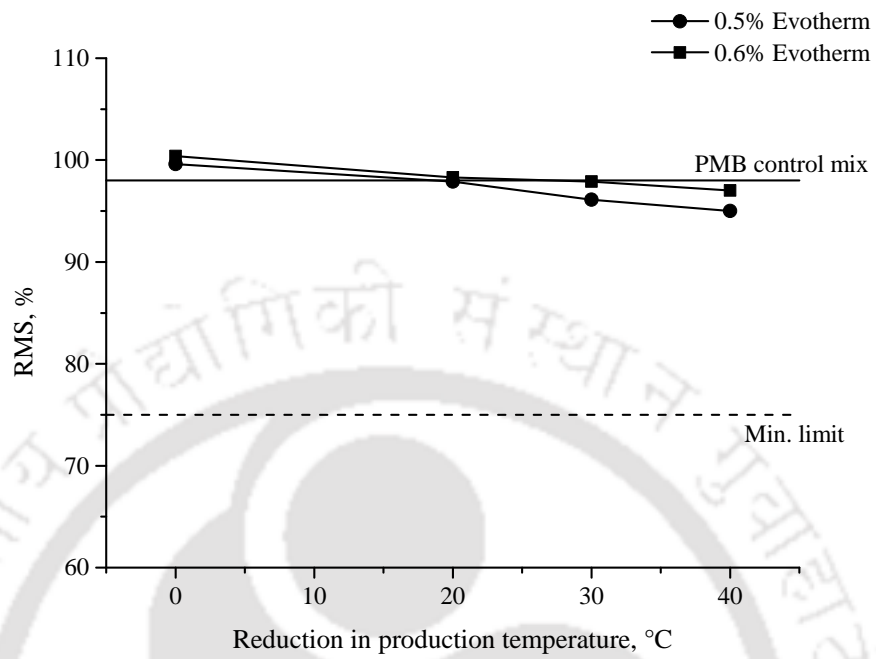


Figure 6.3: RMS test results of PMB warm mixes with Evotherm

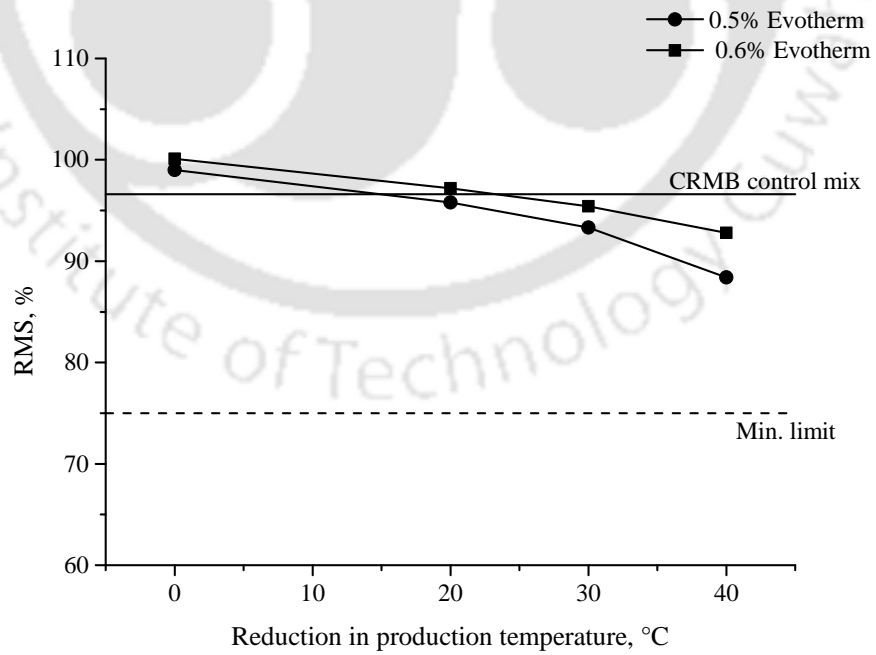


Figure 6.4: RMS test results of CRMB warm mixes with Evotherm

An increase in Evotherm content increases the moisture susceptibility resistance of warm mixes. Here also an increase in Evotherm content has shown more improvement in moisture damage resistance at lower production temperatures compared to higher production temperatures. A maximum increase of 2.0% and 4.4% in the RMS value of PMB and CRMB warm mixes respectively is observed at 40°C reduction in production temperature with the increase in Evotherm percentage from 0.5% to 0.6%. Warm mixes as well as control mixes produced with PMB are found to have higher RMS values compared to mixes prepared with CRMB.

Table 6.2 presents ANOVA results for RMS values wherein binder type, RPT, and Evotherm content are the factors and RMS is the response variable. Results of ANOVA showed that all main effects significantly influence RMS values. Among all interactions, the two-way interaction between binder type and reduction in production temperature shows significant effect on RMS values of warm mixes.

Table 6.2: ANOVA results for RMS values of warm mixes containing Evotherm

Source	df	F-statistic	p-value	Significant?
Binder type	1	27.243	0.000	Yes
Evotherm content	1	13.617	0.001	Yes
RPT	3	34.342	0.000	Yes
Binder type * Evotherm content	3	1.399	0.246	No
Binder type * RPT	3	4.480	0.007	Yes
Evotherm content * RPT	3	1.201	0.325	No
Binder type * Evotherm content * RPT	3	0.363	0.780	No
Error	32			
Total	48			

Also, strong statistical evidence in both ANOVA results of TSR values (p-value = 0.729) and RMS values (p-value = 0.246) shows that there is no interaction between binder type and Evotherm content. This shows that the effect of Evotherm content towards moisture damage is same regardless of the binder type used.

### **6.3 Moisture Susceptibility of Warm Mixes with Sasobit**

#### ***Modified Lottman Test Results***

Modified Lottman test measures the loss of tensile strength of an asphalt mixture due to the interaction with water and is expressed in terms of TSR. TSR is defined as a ratio of the ITS of conditioned specimen (subjected to vacuum saturation followed by freeze-thaw cycle) to the ITS of unconditioned specimen. This test was performed as per AASHTO T 283 (2003) specifications.

TSR results of PMB and CRMB warm mixes produced with three doses of Sasobit (1%, 2%, and 3%) at different reductions in production temperatures (0°C, 20°C, 30°C, and 40°C) are presented in Figures 6.5 and 6.6 respectively. TSR values of warm mixes prepared with PMB and CRMB with different percentages of Sasobit are found to be greater than the minimum requirement of 80% set forth by MoRTH (2013) specifications even at 40°C reduction in production temperature. However, the decrease in the production temperature reduced the TSR values of warm mixes regardless of binder type and Sasobit content. This might be attributed to incomplete drying of aggregates or lower adhesion between aggregate and binder at reduced mixing temperatures.

6.3. Moisture Susceptibility of Warm Mixes with Sasobit

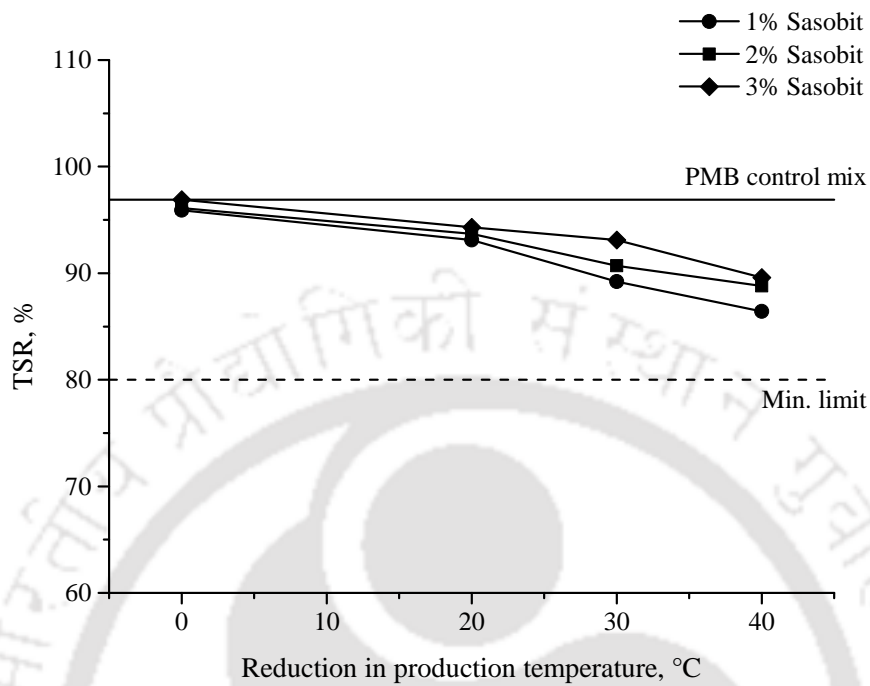


Figure 6.5: Modified Lottman test results of PMB warm mixes with Sasobit

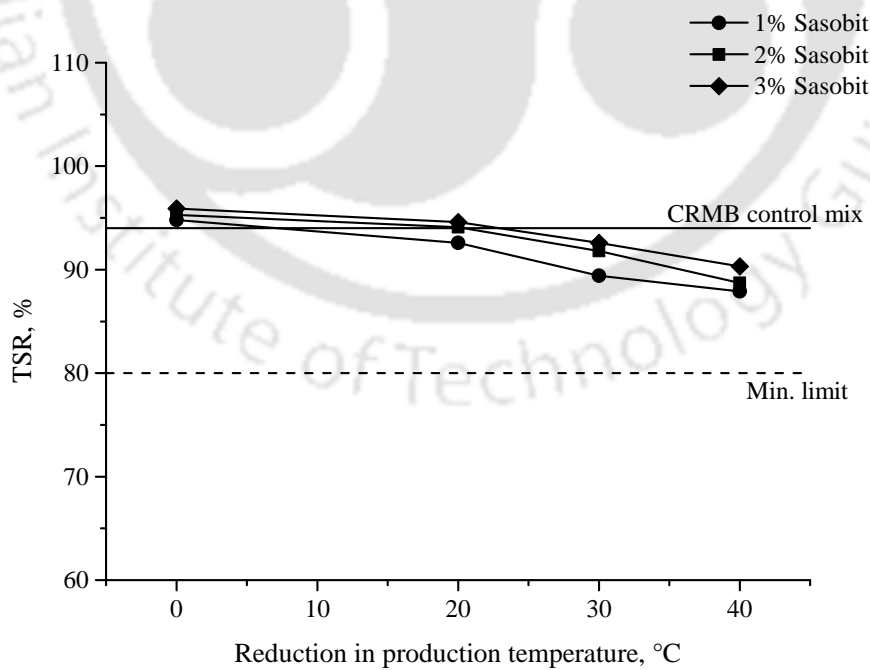


Figure 6.6: Modified Lottman test results of CRMB warm mixes with Sasobit

The results clearly indicate that increase in Sasobit dosage helps to improve moisture damage resistance. Addition of Sasobit increases the binder stiffness by forming a crystalline network structure in the binder, which has the effect of enhancing the ITS values of the mixes and thereby improving TSR. This observation is also in agreement with the findings of previous studies (Liu et al., 2011; Sangsefidi et al., 2014). A maximum increase of 2.4% is observed in the TSR values of both PMB and CRMB warm mixes with increase in the Sasobit content from 1% to 2% at 40°C and 30°C reduction in production temperatures respectively. In regard to binder type, both control and warm mixes prepared with PMB are found to have higher TSR values compared with CRMB irrespective of production temperature and additive content.

ANOVA results presented in Table 6.3 indicate that all main effects have significant effect on TSR values. All interactions are found to have statistically non-significant effect on the TSR values of warm mixes prepared with Sasobit. The non-significant nature of two-way interaction between two factors suggests that the effect of one factor on TSR values does not depend on the other factors considered in the study and vice-versa.

### ***Retained Marshall Stability Test Results***

RMS is expressed as ratio of Marshall stability of moisture conditioned specimen to that of unconditioned specimen and was conducted as per MoRTH (2013) specifications. RMS values of warm mixes prepared with PMB and CRMB at different production temperatures are shown in Figures 6.7 and 6.8 respectively. RMS values of warm mixes are found to be similar or slightly higher than control mixes produced at the standard mixing and compaction temperatures (*i.e.* 0°C reduction in production temperature). RMS values of warm mixes decrease with

Table 6.3: ANOVA results for TSR values of warm mixes containing Sasobit

Source	df	F-statistic	p-value	Significant?
Binder type	1	6.924	0.011	Yes
Sasobit content	2	13.459	0.000	Yes
RPT	3	78.413	0.000	Yes
Binder type * Sasobit content	2	0.079	0.924	No
Binder type * RPT	3	0.917	0.440	No
Sasobit content * RPT	6	0.891	0.509	No
Binder type * Sasobit content * RPT	6	0.305	0.931	No
Error	48			
Total	72			

the decrease in production temperatures irrespective of binder type and Sasobit content. RMS values of warm mixes produced at lower temperatures are smaller than those of control mixes. All warm mixes with different Sasobit percentages at four production temperatures meet the minimum requirement of 75% as per the MoRTH (2013) specifications.

An increase in the Sasobit percentage increases the moisture resistance of warm mixes at all production temperatures. A maximum increase of about 2% is observed in case of warm mixes prepared with both PMB and CRMB bindes on increase of Sasobit percentage from 1% to 2% and 2% to 3%.

Table 6.4 shows the results of ANOVA for RMS values of warm mixes. Results indicate that all main effects have significant effect on RMS values; while all interactions have non-significant effect on the RMS values of warm mixes. A similar observation is also perceived in the ANOVA results of TSR values.

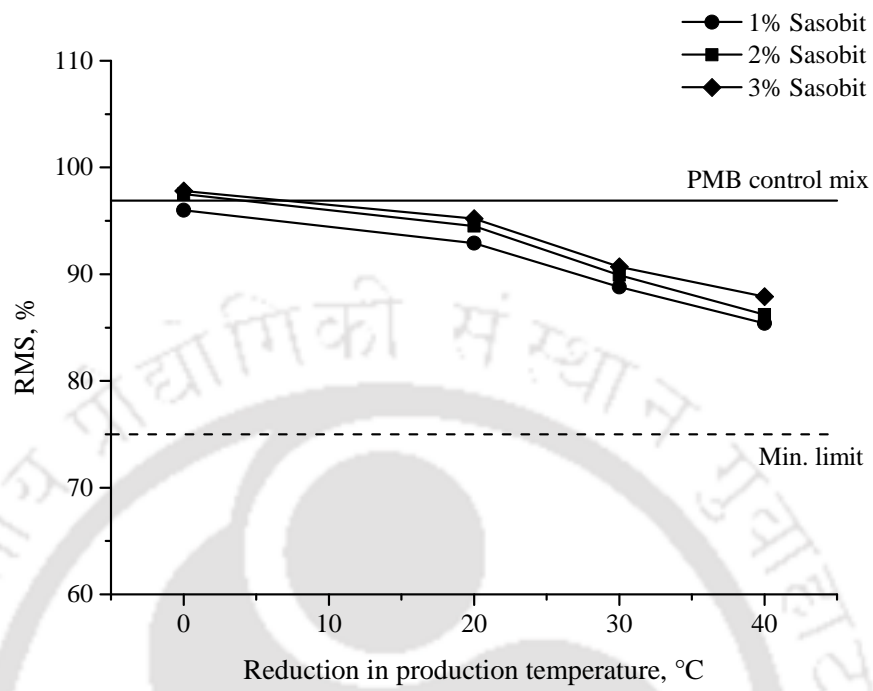


Figure 6.7: RMS test results of PMB warm mixes with Sasobit

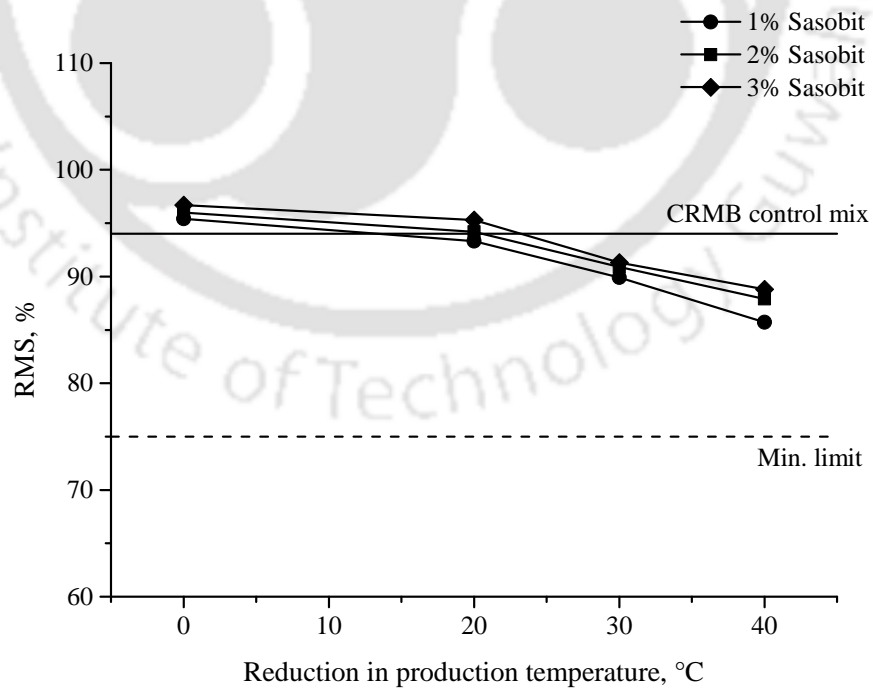


Figure 6.8: RMS test results of CRMB warm mixes with Sasobit

Table 6.4: ANOVA results for RMS values of warm mixes containing Sasobit

Source	df	F-statistic	p-value	Significant?
Binder type	1	9.924	0.000	Yes
Sasobit content	2	9.113	0.000	Yes
RPT	3	118.748	0.000	Yes
Binder type * Sasobit content	2	0.006	0.994	No
Binder type * RPT	3	1.592	0.204	No
Sasobit content * RPT	6	0.186	0.979	No
Binder type * Sasobit content * RPT	6	0.199	0.976	No
Error	48			
Total	72			

## 6.4 Summary

Moisture susceptibility characteristics of warm mixes prepared with different doses of the two WMA additives (Evotherm and Sasobit) at four reduced production temperatures were evaluated through modified Lottman and retained Marshall stability tests. The results of tensile strength ratio (TSR) and retained Marshall stability (RMS) tests were presented and discussed in this chapter. The increase in WMA additive content (either Sasobit or Evotherm) enhanced the moisture susceptibility resistance of warm mixes at all production temperatures. Addition of Evotherm showed a significant improvement in the resistance to moisture damage as observed through higher TSR and RMS. Furthermore, the increase in Evotherm content significantly improved the moisture susceptibility resistance of warm mixes at higher reductions in production temperatures (at 30°C and 40°C). With increase in Sasobit content, only slight improvement in moisture damage resistance was observed for mixes

with both PMB and CRMB binders. In general, warm mixes prepared with PMB showed higher moisture susceptibility resistance compared to mixes with CRMB. Resistance to moisture damage of warm mixes decreased with the reduction in production temperature. However, all warm mixes satisfied the minimum TSR and RMS requirement recommended by MoRTH (2013). ANOVA results showed that main effects (binder type, WMA additive content, and reduction in production temperature) had significant effect on both TSR and RMS test results.





## Chapter 7

# Performance Properties of Warm Mixes

### 7.1 Introduction

The main aim of WMA technologies is to achieve reduction in the mixing and compaction temperatures of asphalt mixes without reducing the mix performance. From Chapters 5 and 6, it is apparent that the WMA technologies/additives selected in the study are able to reduce the production temperatures without compromising the Marshall mix design parameters and resistance to moisture induced damage. The Indian specifications (MoRTH (2013) and IRC:111 (2009)) prescribe acceptability criteria for the design of asphalt mixtures in terms of volumetric properties (air voids, voids in mineral aggregates, and voids filled with bitumen), Marshall parameters (Marshall stability and flow), and moisture induced damage (tensile strength ratio and retained Marshall stability). However, mere conformity to the design specifications does not ensure that the constructed facility will perform adequately. It is important to take into consideration the laboratory evaluation of properties that closely resemble how the designed mixtures are going to

perform in the field. Hence, the present chapter reports evaluation of warm mixes in terms of their performance properties, which include resistance against permanent deformation, fatigue, and resilient characteristics.

Researchers have expressed two concerns related to performance of warm asphalt mixes that may arise on account of reduction in the production temperatures (Roja et al., 2016, 2017). First, the asphalt binder may undergo reduced ageing at lower production temperatures, and second, the performance characteristics may vary considerably with the type of WMA additive used. Reduced ageing of binder reduces its stiffness, which may increase susceptibility towards permanent deformation even though it may help in improving the resistance to raveling and fatigue cracking (Xiao et al., 2012). Furthermore, the type of WMA additive also has influence on the mix performance. For instance, organic WMA additives may enhance the resistance to rutting at high pavement temperatures while they may have negative effect on the fatigue and thermal cracking at low pavement service temperatures. Hence, it is essential to understand the effect of production temperatures and WMA additives and their contents on the performance of bituminous mixes.

This chapter presents the results of performance characterisation of warm mixes and further discusses the outcomes. The detailed experimental plan followed for this phase of the study is shown as Figure 3.20. In summary, two modified binders (PMB and CRMB), various doses of two additives (Evotherm: 0.5%, 0.6%; and Sasobit: 1%, 2%, 3%), and four reductions in production temperatures (0°C, 20°C, 30°C, and 40°C) were employed for the preparation of warm mixes for performance evaluation. Performance properties including resilient modulus (at 5°C, 25°C, and 40°C), rutting (at 40°C), and fatigue (at 20°C) were evaluated and the test results are presented and discussed.

## 7.2 Performance Properties of Warm Mixes with Evotherm

### *Resilient Modulus Test Results*

Resilient modulus ( $M_R$ ) is used to predict the response of a bituminous material to repeated moving loads imposed by traffic/vehicle tires on a road surface. It is also used as an input parameter in pavement design for estimating the thickness of pavement crust. Resilient modulus at low temperatures (5°C) is related to thermal cracking of asphalt mixtures to some extent (Gandhi et al., 2010). A low resilient modulus at lower temperatures (5°C) and a high resilient modulus at high temperatures (40°C) are the desirable attributes for the bituminous mixes to yield better performance. Resilient modulus is defined as the ratio of applied stress to the resilient strain. In this study, resilient modulus of warm mixes was determined using indirect tension test jig as per AASHTO TP 31 (1996) guidelines at three test temperatures of 5°C, 25°C, and 40°C.

Resilient modulus results of warm mixes with both modified binders at 5°C, 25°C, and 40°C test temperatures are presented in Figures 7.1 – 7.6. Warm mixes prepared at 0°C and 20°C reductions in production temperature show higher resilient modulus values compared to control mixes at all test temperatures. The resilient modulus values of warm mixes with both modified binders are found to decrease with reduction in the production temperature. This might be attributed to decrease in stiffness of the binder and increase in the air void content with reduction in the production temperatures. It is believed that higher air voids in the mixes lead to a situation where the coated aggregate particles are pushed away by the external forces imposed on the specimen during testing.

Moreover, reduced stiffness of the binder allows free movement of aggregate particles in the mix, which in turn, has negative effect on resilient modulus. Warm mixes containing Evotherm are found to have comparable performance at 30°C reduction in production temperature with respect to control mixes.

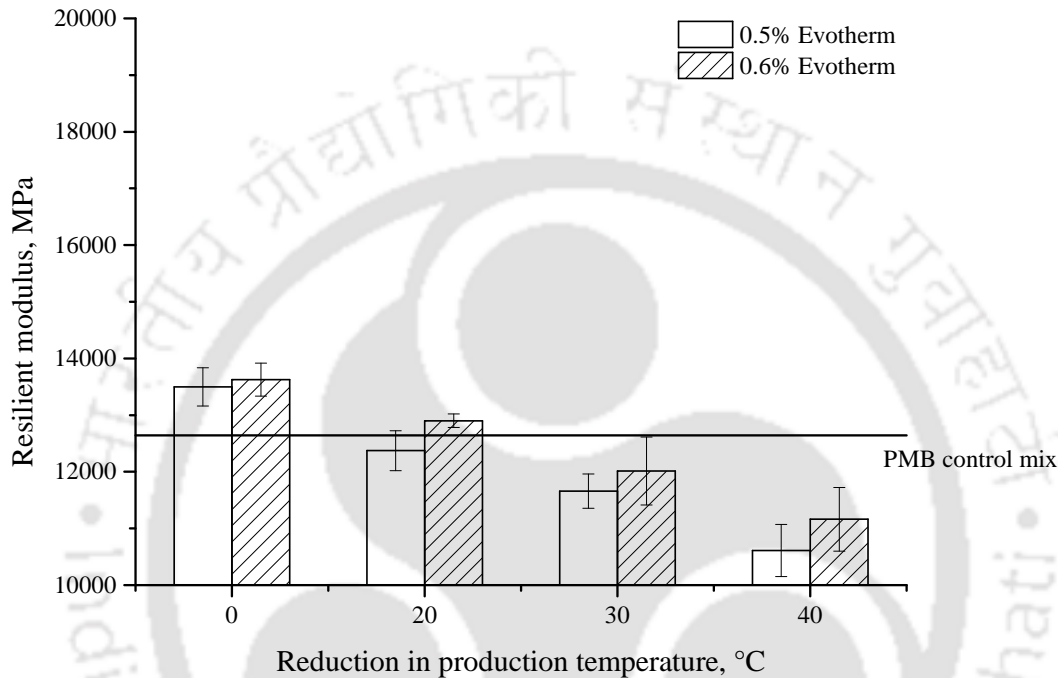


Figure 7.1: Resilient modulus of PMB warm mixes with Evotherm at 5°C

As expected, the increase in test temperature from 5°C to 25°C and 5°C to 40°C decreases the resilient modulus of warm mixes. The decrease in resilient modulus with the increase in test temperature is likely due to reduced stiffness of binder that allows free movement of aggregate particles in the mix. An average reduction of about 75% and 80% in the resilient modulus values of PMB and CRMB warm mixes, respectively, is observed with an increase in the test temperature from 5°C to 40°C; whereas the reduction for PMB and CRMB warm mixes is found to be 63% and 65% respectively with an increase in the test temperature from 5°C to 25°C. This shows that PMB warm mixes are slightly less temperature susceptible than CRMB warm mixes in terms of resilient modulus.

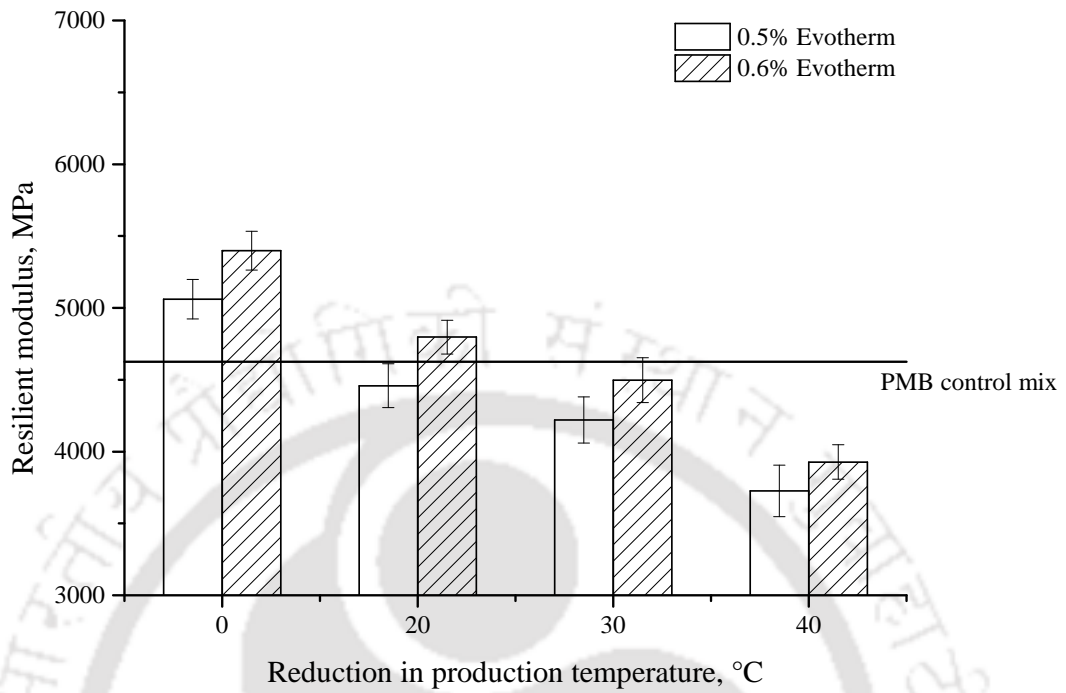


Figure 7.2: Resilient modulus of PMB warm mixes with Evotherm at 25°C

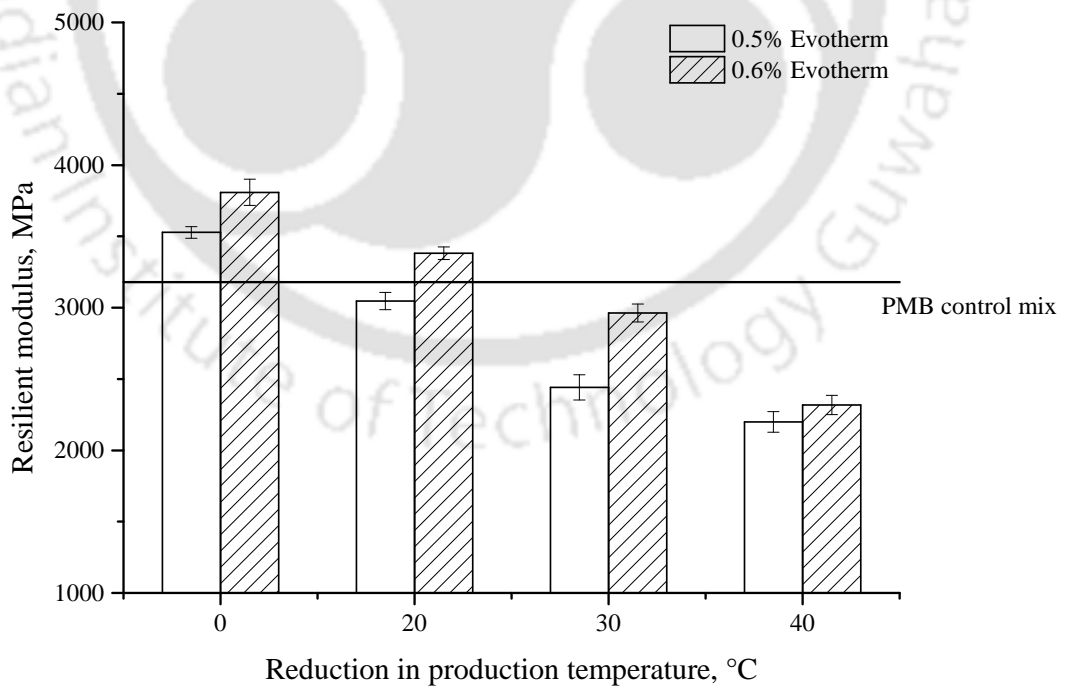


Figure 7.3: Resilient modulus of PMB warm mixes with Evotherm at 40°C

7.2. Performance Properties of Warm Mixes with Evotherm

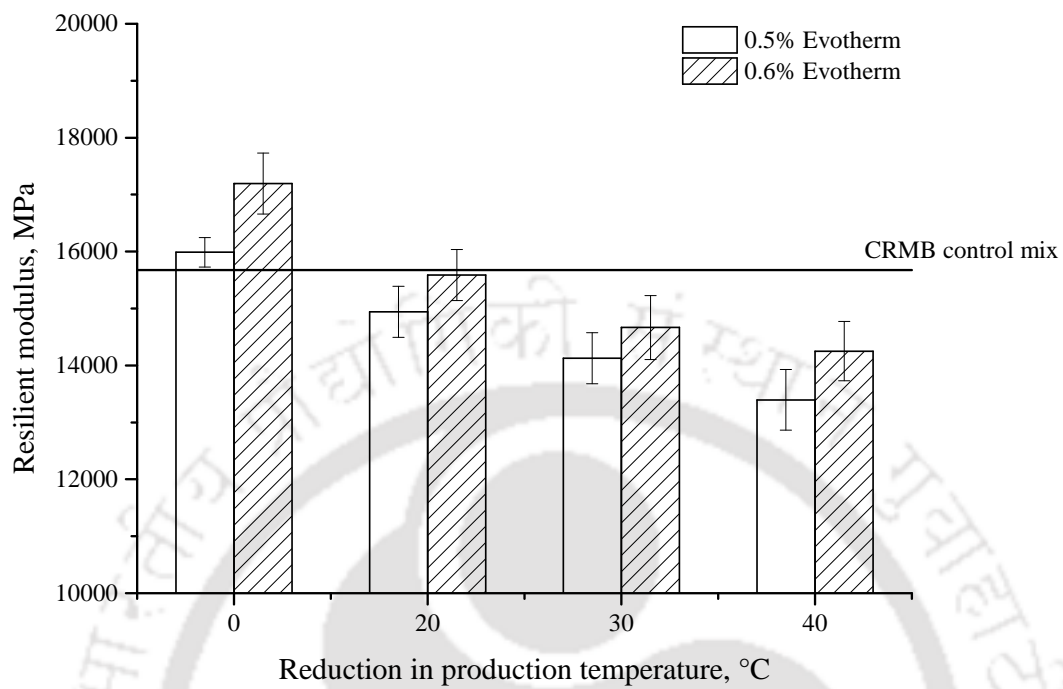


Figure 7.4: Resilient modulus of CRMB warm mixes with Evotherm at 5°C

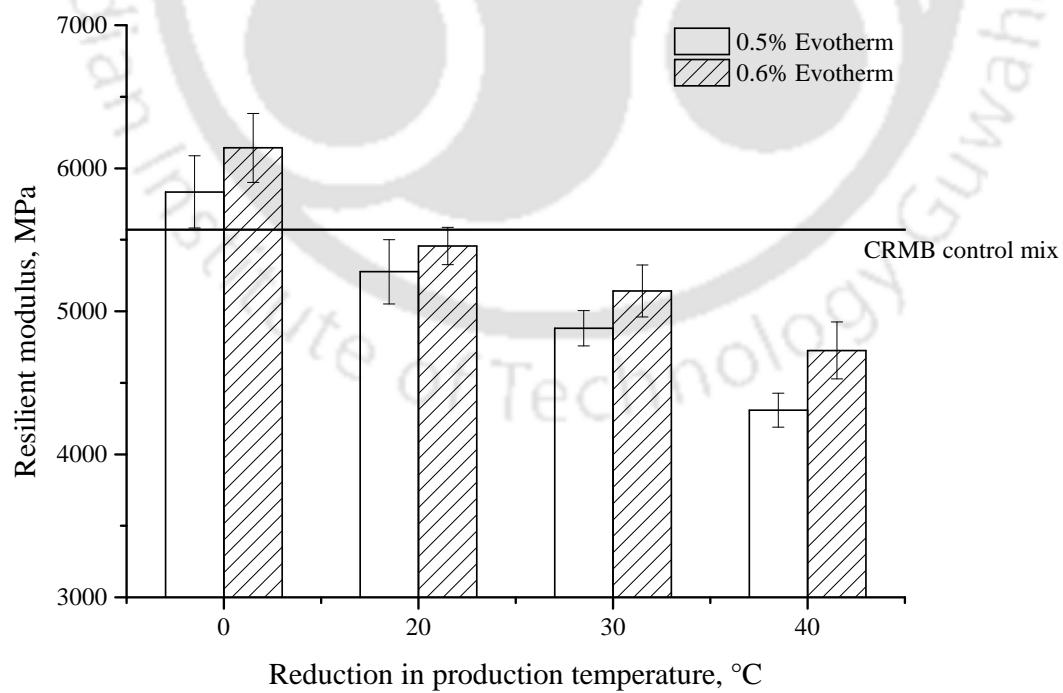


Figure 7.5: Resilient modulus of CRMB warm mixes with Evotherm at 25°C

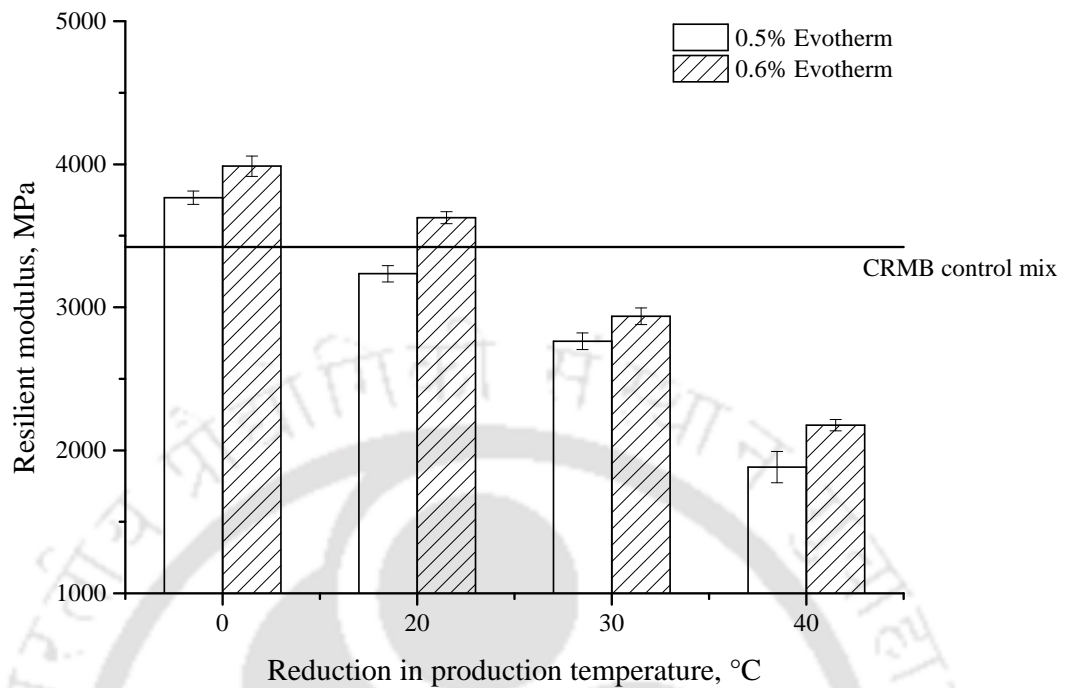


Figure 7.6: Resilient modulus of CRMB warm mixes with Evotherm at 40°C

An increase in Evotherm content from 0.5% to 0.6% increases the resilient modulus values of warm mixes at all test temperatures. This is in agreement with decrease in air voids of warm mixes with increase in Evotherm content. Moreover, increase in Evotherm content significantly improves the resilient modulus at a higher test temperature (40°C) compared to the improvement at lower test temperature (5°C). In regard to binder type, warm mixes with PMB show lower resilient modulus compared to mixes with CRMB at 5°C and 25°C irrespective of Sasobit content and production temperature. Whereas, at higher test temperature of 40°C the PMB mixes show higher resilient modulus compared to CRMB mixes.

ANOVA was performed on resilient modulus test results of warm mixes containing Evotherm at 5°C, 25°C, and 40°C and the results are shown in Tables 7.1 to 7.3. The results show that main effects of all factors (binder type, Evotherm content, and reduction in production temperature (RPT)) have significant effect

on resilient modulus of warm mixes at all three test temperatures. The interactions between binder type and RPT, and Evotherm content and RPT are significant only at the high test temperature (40°C).

Table 7.1: ANOVA results for  $M_R$  at 5°C of warm mixes containing Evotherm

Source	df	F-statistic	p-value	Significant?
Binder type	1	475.796	0.000	Yes
Evotherm content	1	22.135	0.000	Yes
RPT	3	83.269	0.000	Yes
Binder type * Evotherm content	3	2.717	0.109	No
Binder type * RPT	3	0.807	0.499	No
Evotherm content * RPT	3	0.197	0.898	No
Binder type * Evotherm content * RPT	3	0.761	0.525	No
Error	32			
Total	48			

### **Dynamic Creep Test Results**

Rutting (permanent deformation) in asphalt mixes is usually manifested as consolidation or lateral movement of the materials under vehicular loading. It generally occurs as depressions along the wheel path. Dynamic creep test was used to determine the rutting characteristics of warm mixes. This test was performed at 40°C according to BS DD 226 (1996) specifications.

Dynamic creep test results of PMB and CRMB warm mixes with Evotherm are shown in Figures 7.7 and 7.8 respectively. It is observed that warm mixes with Evotherm have lower axial strain compared to the control mixes even after 30°C reductions in production temperatures. Permanent axial strain values of both

Table 7.2: ANOVA results for  $M_R$  at 25°C of warm mixes containing Evotherm

Source	df	F-statistic	p-value	Significant?
Binder type	1	210.029	0.000	Yes
Evotherm content	1	34.990	0.000	Yes
RPT	3	150.173	0.000	Yes
Binder type * Evotherm content	3	0.001	0.976	No
Binder type * RPT	3	0.241	0.867	No
Evotherm content * RPT	3	0.095	0.962	No
Binder type * Evotherm content * RPT	3	0.633	0.599	No
Error	32			
Total	48			

Table 7.3: ANOVA results for  $M_R$  at 40°C of warm mixes containing Evotherm

Source	df	F-statistic	p-value	Significant?
Binder type	1	20.063	0.000	Yes
Evotherm content	1	234.011	0.000	Yes
RPT	3	1357.574	0.000	Yes
Binder type * Evotherm content	3	1.328	0.258	No
Binder type * RPT	3	30.785	0.000	Yes
Evotherm content * RPT	3	3.972	0.016	Yes
Binder type * Evotherm content * RPT	3	8.651	0.000	Yes
Error	32			
Total	48			

PMB and CRMB warm mixes containing 0.6% Evotherm at 30°C reduction in production temperature are about 20% lower than that of control mixes. This indicates higher resistance of warm mixes to permanent deformation, which is due to improved coating and cohesion characteristics with addition of Evotherm even at lower production temperatures. Rutting resistance of warm mixes is found to decrease with the decrease in production temperature, which is likely due to increase in the air void content and decrease in stiffness of binder at lower production temperatures.

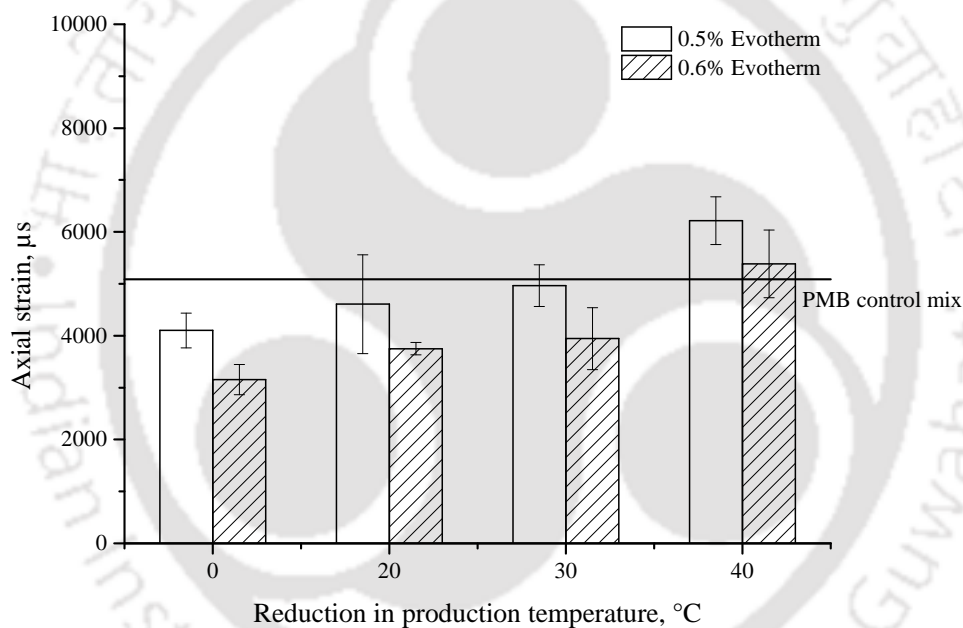


Figure 7.7: Permanent axial strain of PMB warm mixes with Evotherm

An increase in Evotherm content from 0.5% to 0.6% further decreases the axial strain, and therefore improves the resistance to deformation of warm mixes. With regard to binder type, the warm mixes prepared with PMB show higher rutting resistance compared to CRMB mixes at all reduction in production temperature (0°C, 20°C, 30°C, and 40°C). The same trend is also observed in case of control mixes. Results of ANOVA conducted on axial strain are presented in Table 7.4. The results show that main effects of all the three

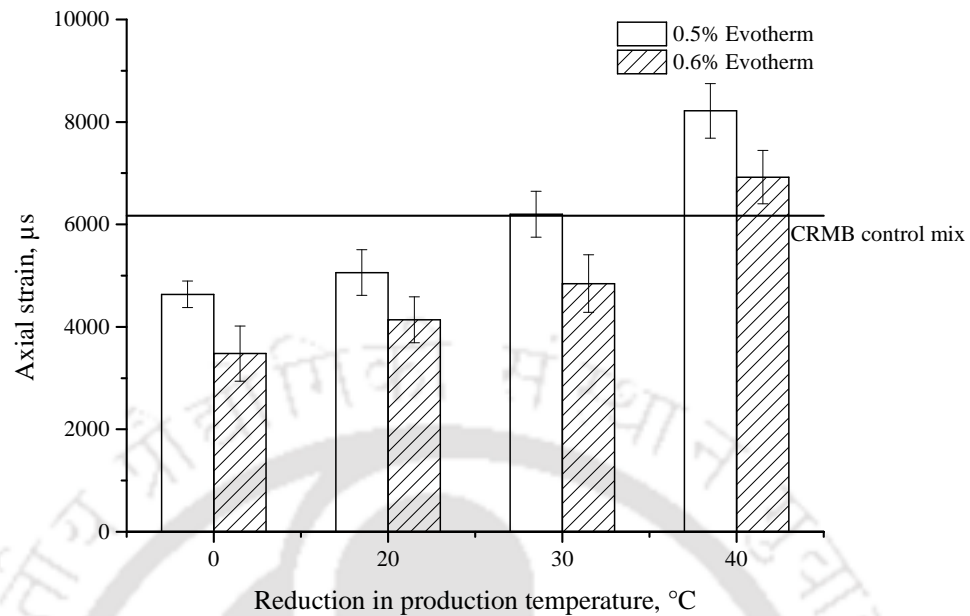


Figure 7.8: Permanent axial strain of CRMB warm mixes with Evotherm

factors are significant. Among all the interactions, interaction between binder type and RPT is found to have significant effect on the permanent axial strain of warm mixes containing Evotherm.

### ***Fatigue Test Results***

Fatigue cracking, associated with repeated traffic loading and other environmental factors, is considered as a major structural distress in bituminous pavements. Fatigue resistance of warm mixes was evaluated through the determination of their fracture life using indirect tensile fatigue test (ITFT) at 20°C as per EN 12697 – 24 (2012).

Fracture life of PMB and CRMB warm mixes prepared with Evotherm are shown in Figures 7.9 and 7.10, respectively. At standard production temperatures, fracture life of both PMB and CRMB warm mixes are higher than the respective control mixes. The increase in fracture life of warm mixes is

Table 7.4: ANOVA results for dynamic creep of warm mixes containing Evotherm

Source	df	F-statistic	p-value	Significant?
Binder type	1	35.554	0.000	Yes
Evotherm content	1	46.081	0.000	Yes
RPT	3	63.622	0.000	Yes
Binder type * Evotherm content	3	0.743	0.395	No
Binder type * RPT	3	4.305	0.012	Yes
Evotherm content * RPT	3	0.155	0.926	No
Binder type * Evotherm content * RPT	3	0.076	0.972	No
Error	32			
Total	48			

mainly due to decrease in air void content, as observed in Figures 5.3 and 5.4. According to Harvey et al. (1995), smaller air void content in the asphalt mixes likely has two effects that increases the fracture life of mixes. First, as air transmits little or no stress, replacing some of its volume with bitumen and aggregate reduces the stress level in these components. Second, a lower air void content in the mix results in a more homogenous structure with fewer, smaller, and better-distributed voids resulting in less stress concentration at the critical solid-air interfaces. Increase in reduction in production temperature reduces the fracture life of warm mixes due to increase in their air void content. However, the fracture life of PMB and CRMB warm mixes prepared at 30°C lower production temperatures are comparable to control mixes.

An increase in Evotherm content further improves the fracture life of both PMB and CRMB warm mixes. An increase in Evotherm content by 0.1% increases the fracture life by a maximum of 27% and 11% in case of PMB and CRMB respectively. In regard to binder type, the fracture life of PMB mixes are

found to be higher than the CRMB mixes at all production temperatures. This is likely due to lower fatigue resistance ( $G^* \cdot \sin \delta$ ) of CRMB compared to PMB observed during the rheological examination of binders (as shown in Table 3.3). ANOVA results performed on fracture life of warm mixes are shown in Table 7.5. The results indicate that only the main effects (binder type, Evotherm content, and RPT) have significant effect on the fracture life of warm mixes.

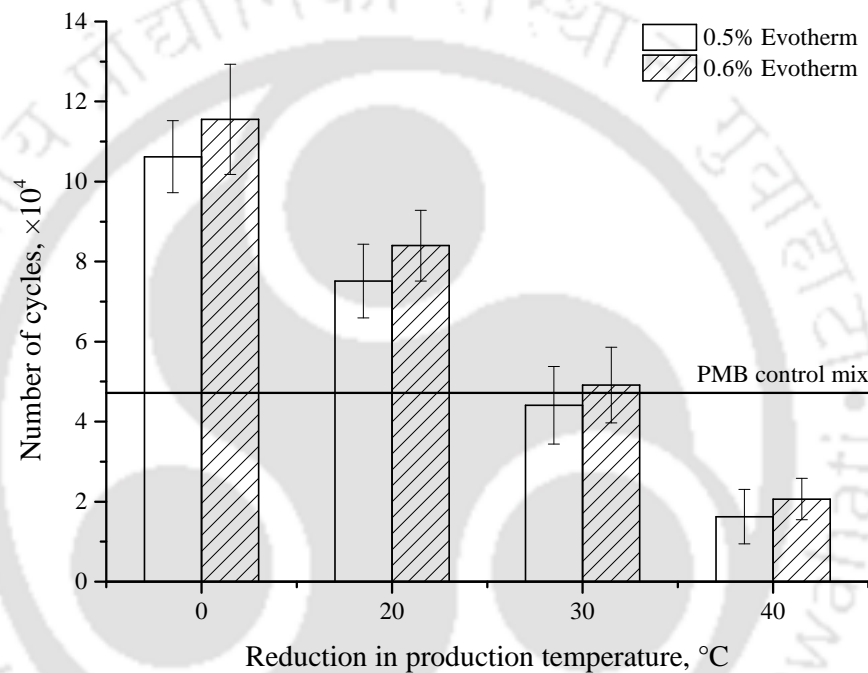


Figure 7.9: Fracture life of PMB warm mixes with Evotherm

### 7.3 Performance Properties of Warm Mixes with Sasobit

#### *Resilient Modulus Test Results*

Resilient modulus of warm mixes containing three doses of Sasobit (1%, 2%, and 3%) was evaluated as per AASHTO TP 31 (1996) at three test temperatures (5°C,

7.3. Performance Properties of Warm Mixes with Sasobit

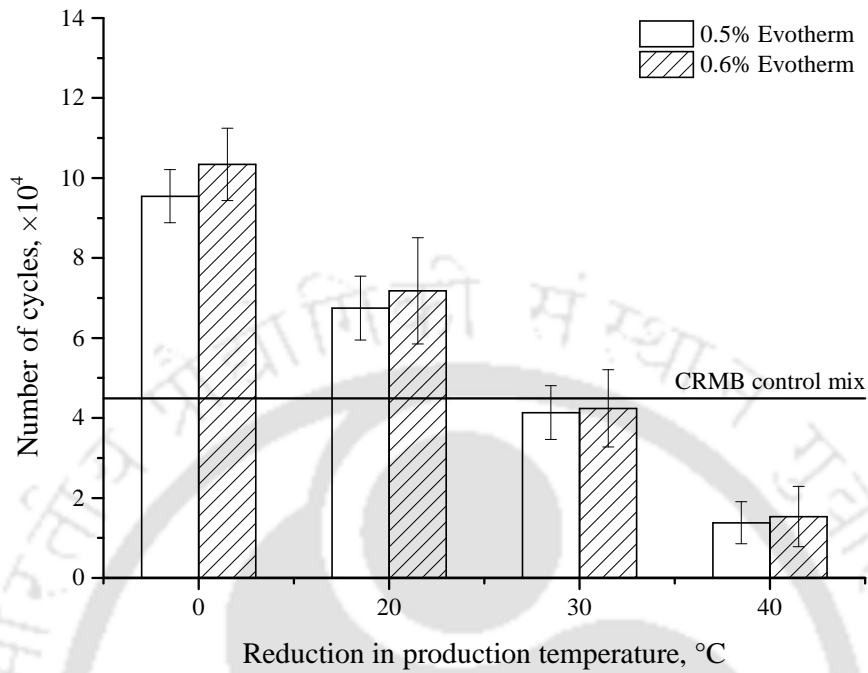


Figure 7.10: Fracture life of CRMB warm mixes with Evotherm

Table 7.5: ANOVA results for fracture life of warm mixes containing Evotherm

Source	df	F-statistic	p-value	Significant?
Binder type	1	17.993	0.000	Yes
Evotherm content	1	8.473	0.007	Yes
RPT	3	459.922	0.000	Yes
Binder type * Evotherm content	3	0.812	0.374	No
Binder type * RPT	3	1.110	0.359	No
Evotherm content * RPT	3	0.394	0.758	No
Binder type * Evotherm content * RPT	3	0.014	0.998	No
Error	32			
Total	48			

25°C, and 40°C). The results are presented in Figures 7.11 – 7.16 for warm mixes with PMB and CRMB binders. Warm mixes containing Sasobit prepared at 30°C reduction in production temperature have comparable resilient modulus values with control mixes. An increase in the Sasobit content improves the resilient modulus at all test temperatures. This may be mainly due to a well-distributed crystalline structure formed on addition of Sasobit in the binders. It is observed that the increment in resilient modulus with the increase in Sasobit content from 1% to 3% is found to be higher at 40°C test temperature compared to other test temperatures (5°C and 25°C). CRMB warm mixes showed slightly higher resilient modulus than PMB warm mixes.

Reduction in production temperatures decreases the resilient modulus values of warm mixes with both modified binders. This might be due to decrease in stiffness of binder and increase in air void content at lower production temperatures. A similar trend was also reported by Gandhi et al. (2009) and Akisetty et al. (2010b). ANOVA results performed on resilient modulus at 5°C, 25°C, and 40°C are shown in Tables 7.6–7.8. The results show that main effects of all factors (binder type, Sasobit content, and reduction in production temperature (RPT)) have significant effect on resilient modulus of warm mixes at all test temperatures. Only the interaction between binder type and RPT is found significant at 5°C and 40°C test temperatures.

### ***Dynamic Creep Test Results***

Rutting characteristics of warm mixes produced at different reductions in mixing and compaction temperatures were evaluated through the dynamic creep test at 40°C. Figures 7.17 and 7.18 respectively show the permanent axial strain of PMB and CRMB warm mixes containing Sasobit. Axial strain of warm

7.3. Performance Properties of Warm Mixes with Sasobit

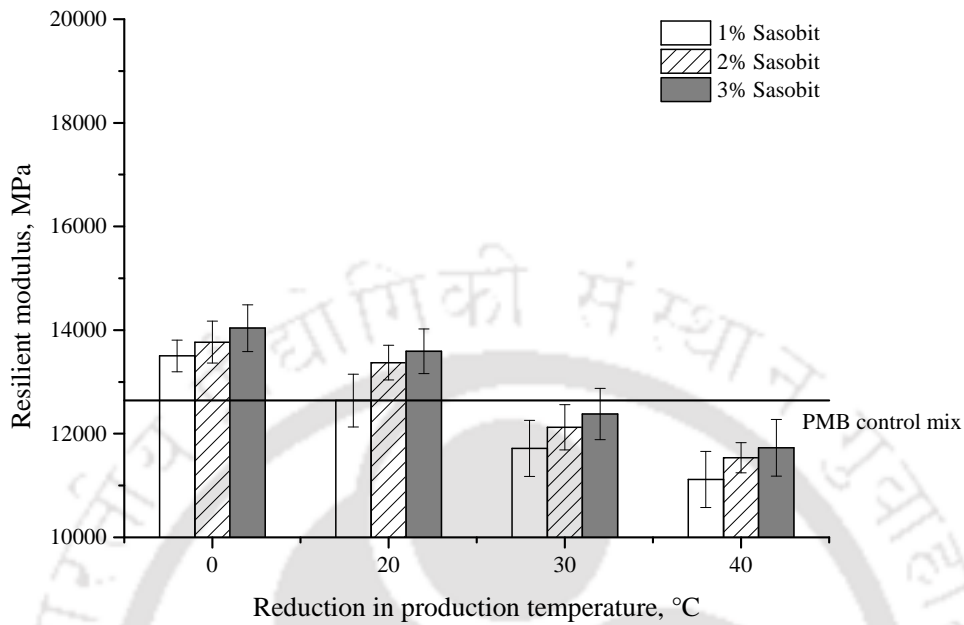


Figure 7.11: Resilient modulus of PMB warm mixes with Sasobit at 5°C

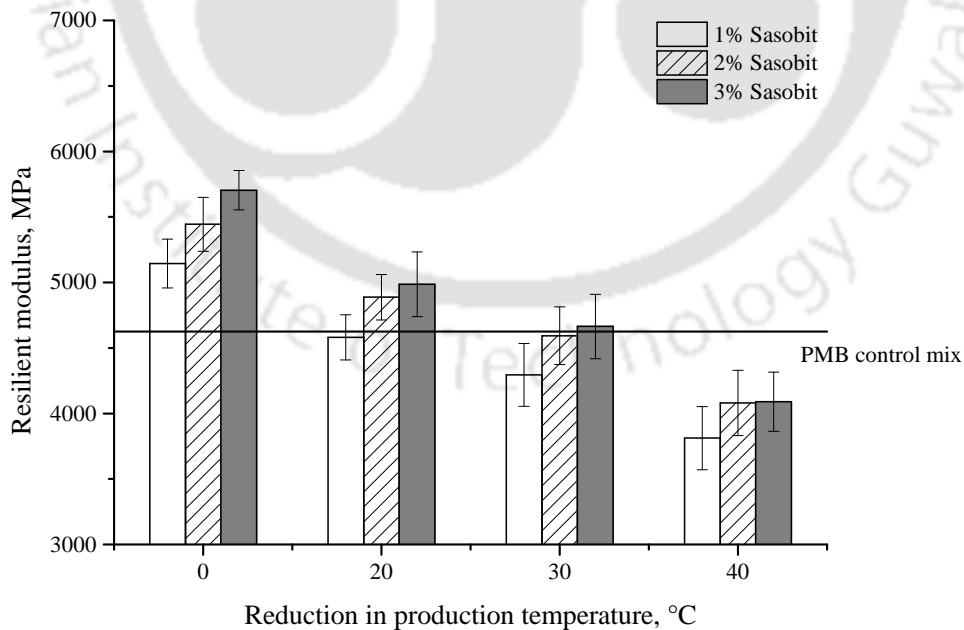


Figure 7.12: Resilient modulus of PMB warm mixes with Sasobit at 25°C

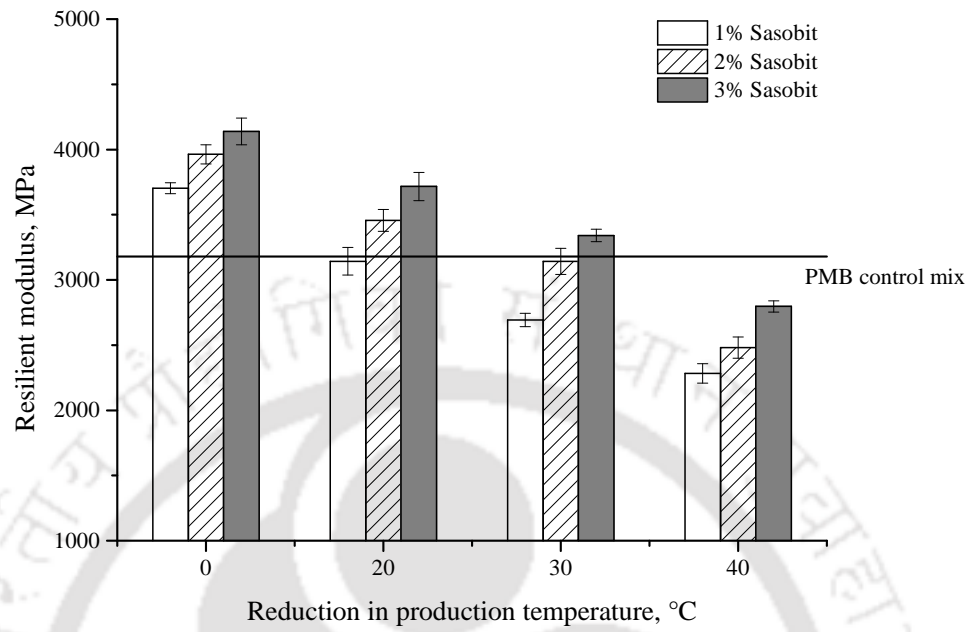


Figure 7.13: Resilient modulus of PMB warm mixes with Sasobit at 40°C

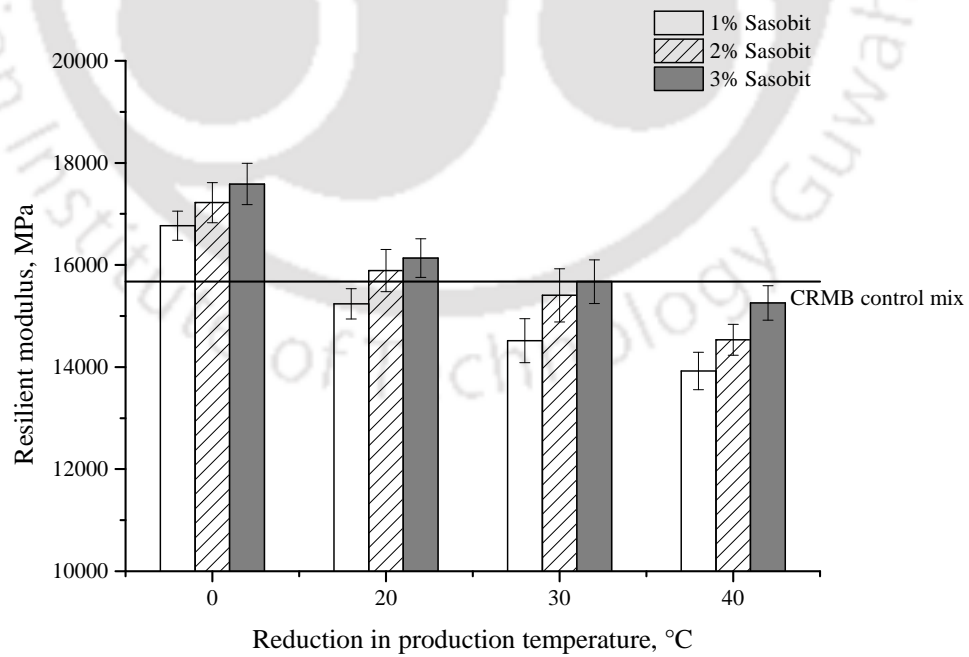


Figure 7.14: Resilient modulus of CRMB warm mixes with Sasobit at 5°C

7.3. Performance Properties of Warm Mixes with Sasobit

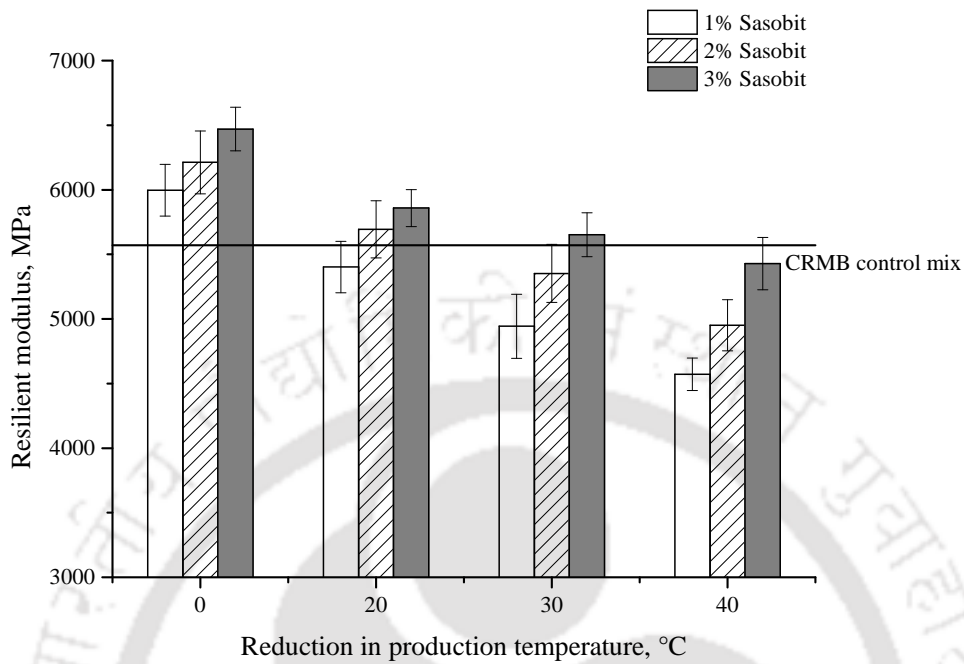


Figure 7.15: Resilient modulus of CRMB warm mixes with Sasobit at 25°C

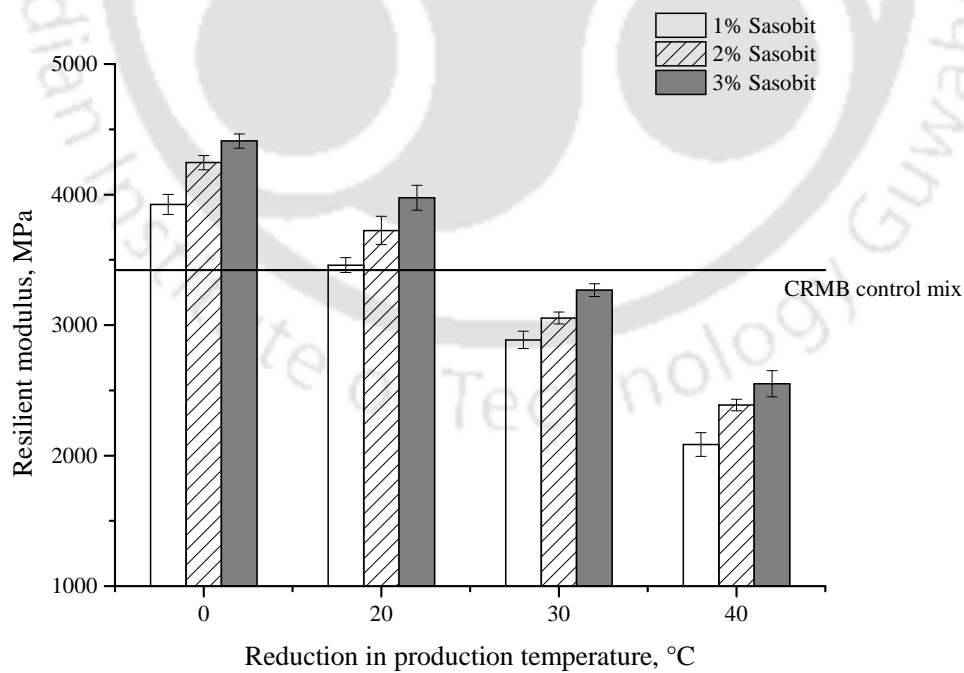


Figure 7.16: Resilient modulus of CRMB warm mixes with Sasobit at 40°C

Table 7.6: ANOVA results for  $M_R$  at 5°C of warm mixes containing Sasobit

Source	df	F-statistic	p-value	Significant?
Binder type	1	957.605	0.000	Yes
Sasobit content	2	26.599	0.000	Yes
RPT	3	117.516	0.000	Yes
Binder type * Sasobit content	2	1.111	0.338	No
Binder type * RPT	3	3.381	0.026	Yes
Sasobit content * RPT	6	0.288	0.940	No
Binder type * Sasobit content * RPT	6	0.321	0.923	No
Error	48			
Total	72			

Table 7.7: ANOVA results for  $M_R$  at 25°C of warm mixes containing Sasobit

Source	df	F-statistic	p-value	Significant?
Binder type	1	305.363	0.000	Yes
Sasobit content	2	37.206	0.000	Yes
RPT	3	133.130	0.000	Yes
Binder type * Sasobit content	2	1.991	0.148	No
Binder type * RPT	3	0.878	0.459	No
Sasobit content * RPT	6	0.201	0.975	No
Binder type * Sasobit content * RPT	6	0.820	0.560	No
Error	48			
Total	72			

Table 7.8: ANOVA results for  $M_R$  at 40°C of warm mixes containing Sasobit

Source	df	F-statistic	p-value	Significant?
Binder type	1	6218.578	0.000	Yes
Sasobit content	2	173.341	0.000	Yes
RPT	3	1218.323	0.000	Yes
Binder type * Sasobit content	2	2.553	0.088	No
Binder type * RPT	3	147.603	0.000	Yes
Sasobit content * RPT	6	0.806	0.570	No
Binder type * Sasobit content * RPT	6	1.279	0.285	No
Error	48			
Total	72			

mixes containing 2% and 3% Sasobit is found to be lower than the control mixes even after 30°C reduction in production temperature. This is attributed to the higher stiffness of binder imparted by the crystalline network structure formed in the binder with addition of Sasobit. Increase in Sasobit content further improves the resistance of warm mixes towards permanent deformation due to increased stiffness of the binder, which was also seen from the creep and repeated creep recovery results of warm asphalt binders (Figures 4.21–4.24). An increase in Sasobit content from 1% to 3% reduces the permanent axial strain by approximately 40% at 0°C reduction in production temperature and by approximately 30% at 40°C reduction in production temperature. The permanent axial strain is found to increase with decrease in the production temperatures. This might be due to increase in the air void content and decrease in stiffness of warm binders. The higher permanent strain at higher air void content is likely due to densification of mixes by the external loading. Further, it is well-recognised that mixes containing soft binder increase the susceptibility

toward permanent deformation. Warm mixes with PMB show higher resistance toward rutting in comparison to mixes with CRMB. ANOVA results presented in Table 7.9 show that all individual main effects and their interactions had significant effect on the axial strain of warm mixes.

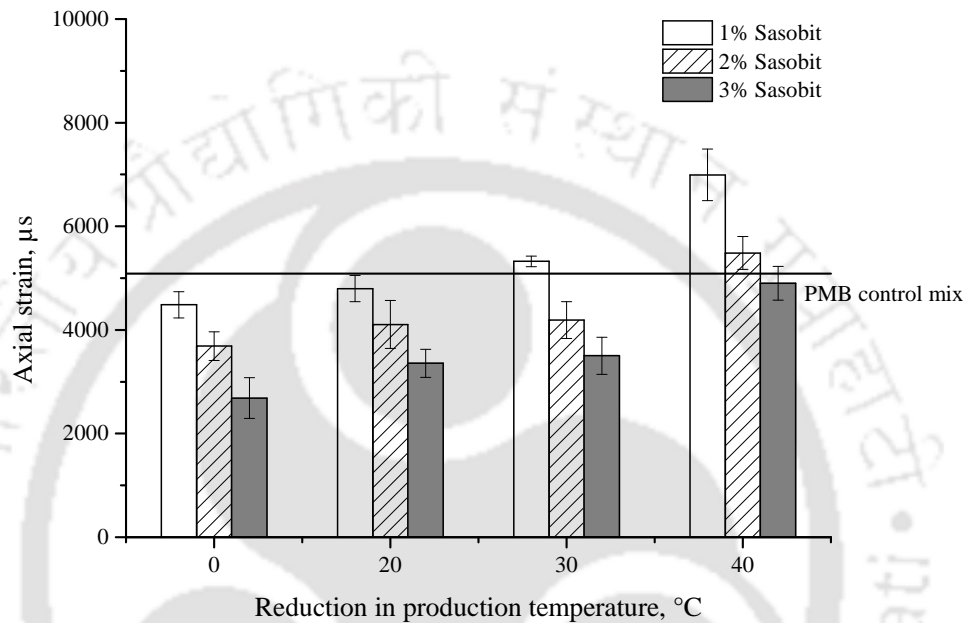


Figure 7.17: Permanent axial strain of PMB warm mixes with Sasobit

### ***Fatigue Test Results***

Indirect tensile fatigue test (ITFT) was conducted at 20°C to evaluate fatigue performance of warm mixes in terms of their fracture life (*i.e.* number of load cycles until complete failure of the specimen). Results of ITFT conducted for PMB and CRMB warm mixes with Sasobit are illustrated in Figures 7.19 and 7.20 respectively. Fracture life of warm mixes prepared with both PMB and CRMB binders are higher compared to their respective control mixes up to 20°C reduction in production temperatures. This improvement in the fracture life is due to reduction in air void content. Fracture life of warm mixes decreases with the reduction in production temperature. This might be attributed to the

### 7.3. Performance Properties of Warm Mixes with Sasobit

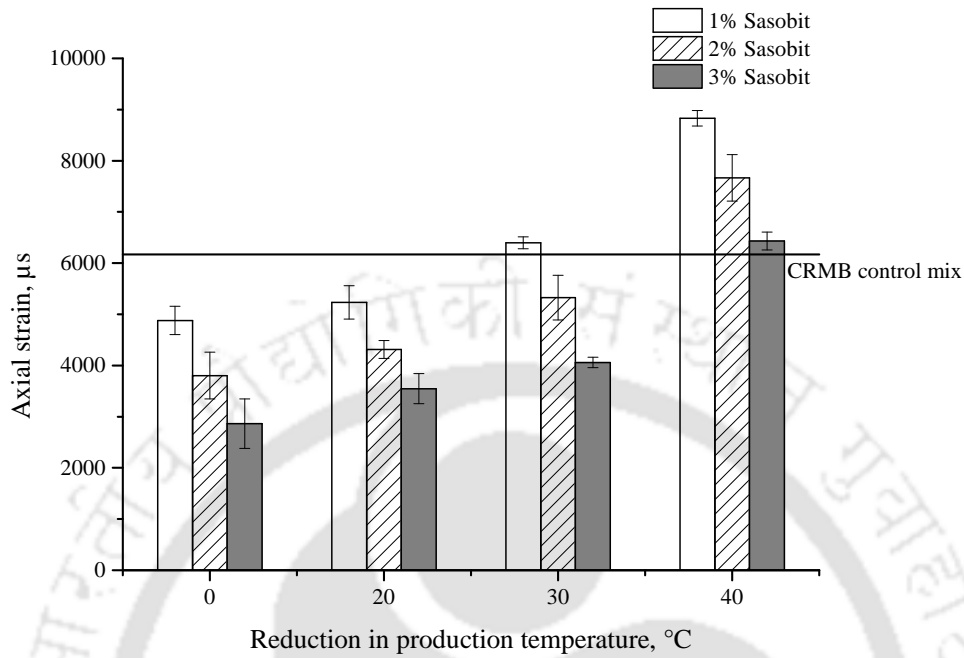


Figure 7.18: Permanent axial strain of CRMB warm mixes with Sasobit

Table 7.9: ANOVA results for dynamic creep of warm mixes containing Sasobit

Source	df	F-statistic	p-value	Significant?
Binder type	1	133.628	0.000	Yes
Sasobit content	2	214.205	0.000	Yes
RPT	3	255.580	0.000	Yes
Binder type * Sasobit content	2	3.836	0.028	Yes
Binder type * RPT	3	33.432	0.000	Yes
Sasobit content * RPT	6	3.102	0.012	Yes
Binder type * Sasobit content * RPT	6	2.496	0.035	Yes
Error	48			
Total	72			

increase in air void content, which generally leads to higher stress concentration and early failure because of abrupt changes in the geometry of voids in the specimen. Furthermore, reduction in fracture life may be also due to lower absorption of binder by aggregate at lower mixing and compaction temperatures which leads to reduction in adhesion between coated aggregate particles.

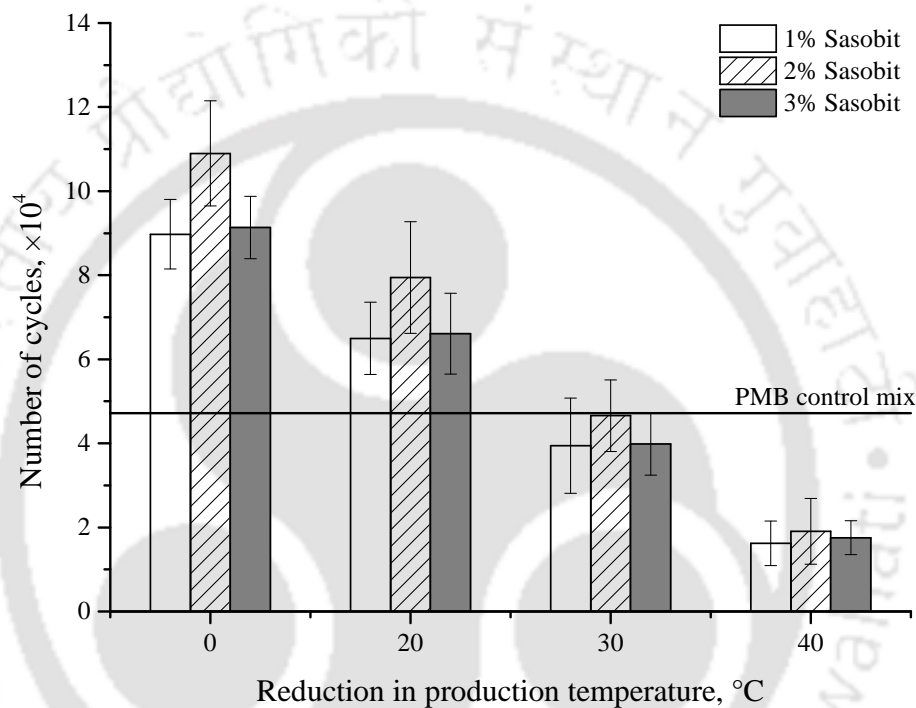


Figure 7.19: Fracture life of PMB warm mixes with Sasobit

An increase in Sasobit content from 1% to 2% increases the fracture life of both PMB and CRMB warm mixes. However, the fracture life of warm mixes decreases with further increase in Sasobit dosage from 2% to 3%. This might be due to excessive stiffening of binder at higher contents of Sasobit. In regard to binder type, warm mixes produced at different production temperatures with PMB show higher fracture life compared to CRMB, which can also be supported through lower fatigue resistance of CRMB binder compared to PMB binder in terms of  $G^* \cdot \sin \delta$  as presented in Table 3.3. ANOVA results for fracture life of

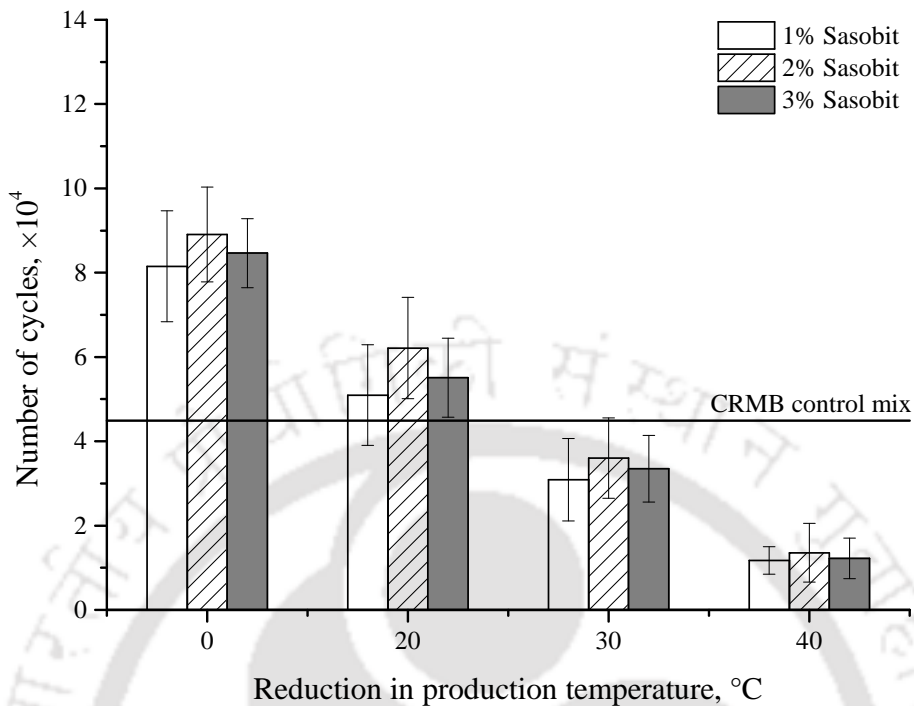


Figure 7.20: Fracture life of CRMB warm mixes with Sasobit

warm mixes presented in Table 7.10 show that all individual main effects are significant.

## 7.4 Summary

Performance characteristics of warm mixes, including resilient modulus ( $M_R$ ), rutting, and fatigue were evaluated through resilient modulus, dynamic creep, and indirect tensile fatigue tests, respectively. Results of these tests were analysed and discussed in this chapter. Both PMB and CRMB warm mixes prepared at 30°C reduction in production temperature showed comparable performance in terms of resilient modulus, rutting resistance, and fracture life in comparison to their respective control mixes. Resilient modulus and fracture life of warm mixes decreased with the reduction in production temperature.

Table 7.10: ANOVA results for fracture life of warm mixes containing Sasobit

Source	df	F-statistic	p-value	Significant?
Binder type	1	19.115	0.000	Yes
Sasobit content	2	5.514	0.007	Yes
RPT	3	211.597	0.000	Yes
Binder type * Sasobit content	2	0.637	0.533	No
Binder type * RPT	3	0.756	0.524	No
Sasobit content * RPT	6	0.552	0.766	No
Binder type * Sasobit content * RPT	6	0.155	0.987	No
Error	48			
Total	72			

Permanent axial strain of warm mixes increased with the reduction in production temperature. Increase in WMA additive content (either Evotherm or Sasobit) increased the resilient modulus (at all three test temperatures 5°C, 25°C, and 40°C), rutting resistance, and fracture life of warm mixes. Optimum fatigue performance for both PMB and CRMB warm mixes was found at 2% Sasobit dosage. In general, PMB warm mixes showed higher rutting and fatigue resistance compared to CRMB warm mixes. Statistical analysis showed that the all factors considered in the study (binder type, additive content, and reduction in production temperature) had significant effect on resilient modulus, rutting, and fatigue properties of warm mixes.



## Chapter 8

# Summary, Conclusions and Recommendations for Future Research

### 8.1 Summary

Warm mix asphalt (WMA) refers to the technologies meant for significantly reducing the mixing and compaction temperatures (collectively referred as production temperatures) of asphalt mixtures, and hence have the main advantages of cutting fuel consumption and decreasing the emissions of greenhouse gases. Meanwhile, the benefits of modified asphalt binders to cater for increasing traffic, severe axle loads, and unanticipated variations in pavement temperatures, are increasingly being recognised. However, increase in production temperatures associated with modified binders has been a long-felt concern related to their widespread use. The main objectives of this research were to: (1) characterise modified asphalt binders through evaluation of the rheology of binders with different dosages of selected WMA additives; (2) characterise bituminous concrete mixes through evaluation of the effect of WMA additive type, WMA additive dosage, and reductions in production temperatures

on volumetric and mix design parameters, and on performance properties including moisture-induced damage resistance, fatigue life, permanent deformation resistance, and resilient modulus.

To achieve the objectives, present study included two types of modified bitumen (polymer- and crumb rubber-modified bitumen), two types of WMA additives: Evotherm (chemical additive) and Sasobit (organic additive), various dosage rates of selected WMA additives (Evotherm: 0.5%, 0.6%, and Sasobit: 1%, 2%, 3% by weight of binder), and four reductions in production temperatures (0°C, 20°C, 30°C, and 40°C) from the standard production temperatures used for control HMA mixes. Warm asphalt binders were prepared with the combination of modified binder type, WMA additive type, and WMA additive dosage, and were evaluated for the rheological properties. Warm mixes were then prepared with the combination of modified binder type, WMA additive type, WMA dosage rate, and reductions in the production temperatures. Warm mixes were evaluated for volumetric, Marshall, moisture susceptibility, resilient modulus, rutting, and fatigue characteristics.

## 8.2 Conclusions

Based on the laboratory experimentation and statistical analyses, the following conclusions are derived:

- Rheological evaluation results showed that addition of Evotherm had no significant effect on the rheological characteristics of both PMB and CRMB binders, as it is designed to work at the interface between aggregate and binder rather than influencing binders' rheology. Addition of Sasobit, on the other hand, decreased the viscosity of both PMB and CRMB binders at

150°C by approximately 15–25%, thus allowing for adequate coating and workability at reduced production temperatures. Failure temperature, temperature sweep, frequency sweep, creep, and repeated creep recovery test results showed that the addition of Sasobit improved complex modulus and elastic properties of both PMB and CRMB binders at high pavement service temperatures.

- Warm PMB and CRMB binders containing Sasobit were further investigated for rheological properties under reduced short-term ageing temperatures. Ageing index of WMA binders declined on being aged at lower temperatures indicating improved resistance to the effects of ageing. The reduction in RTFO ageing temperature decreased the viscosity, failure temperature, complex modulus, elastic modulus, and viscous modulus of both PMB and CRMB binders with Sasobit. Decrease in stiffness of warm binders due to lower ageing temperatures was compensated by the crystalline network formed due to the presence of Sasobit as rheological parameters of Sasobit warm binders aged at 143°C and 123°C compared well with control binders aged at the standard temperature (163°C).
- For asphalt mixtures, volumetric and Marshall parameters improved with increase in WMA additive dosage, indicating improved compactability and workability of warm mixes at lower production temperatures. Bulk density of warm mixes was comparable to the control mixes after reduction in production temperatures in the range of 20–30°C. Even upto 40°C reduction in production temperatures, warm mixes with 0.6% Evotherm, 2% and 3% Sasobit met all specifications related to volumetrics and Marshall parameters.

- Mix performance results showed that the addition of WMA additive (either Sasobit or Evotherm) improved moisture damage resistance, resilient modulus, rutting resistance, and fatigue resistance compared to control HMA mixes upto 20°C reductions in production temperatures. Decrease in production temperatures led to decrease in the properties of bituminous concrete mixes. Warm mixes with PMB and CRMB binders showed similar moisture susceptibility performance compared to control mixes at reductions of mixing and compaction temperatures in the range of 20–30°C. The performance of warm mixes (at 30°C reduction in production temperature) in terms of resilient modulus, rutting resistance and fracture life were comparable to control mixes produced at standard production temperatures (*i.e.* 0°C reduction).
- The increase in additive content (either Evotherm or Sasobit) improved the mix properties at different production temperatures, except the fatigue resistance for warm mixes with Sasobit. The increase in Sasobit dosage from 1% to 2% increased the fatigue resistance, whereas the increase from 2% to 3% decreased the fatigue resistance.
- Warm mixes prepared at different contents of Evotherm and Sasobit with PMB binder showed higher resistance against permanent deformation, fatigue, and moisture-induced damage in comparison to those with CRMB binder as observed from dynamic creep, indirect tensile fatigue, and moisture susceptibility tests.
- The statistical analysis using ANOVA indicated that main effects of all factors (binder type, additive content, and reduction in production temperature) had significant effect on all the evaluated mix properties.

Overall, the basic premise of this research study was that the use of WMA additives with modified asphalt binders can be a favourable combination to bring down the mixing and compaction temperatures associated with these binders without compromising the performance of the mixes. The findings of this study indicate that it is possible to achieve a reduction of 30°C in the production temperatures with both modified binders (PMB and CRMB) with the selected WMA additives (Evotherm and Sasobit). It must, however, be pointed out that dosage of WMA additive significantly influences the achievable reductions in production temperatures. From overall considerations of asphalt binder rheology and bituminous concrete mix characteristics, it is recommended to use a dosage of 0.6% for Evotherm and 2% for Sasobit with both PMB and CRMB binders.

### **8.3 Recommendations for Future Research**

This thesis presented the rheological evaluation of two types of modified binders with two WMA additives and their dosage rates, and evaluation of modified bituminous mix properties as function of modified binder type, WMA additive type, WMA additive content, and reduction in production temperatures. Based on the present research, the following recommendations are made for future work:

1. Evaluation of the performance of warm mixes with different aggregate sources and gradations.
2. The present research is limited to laboratory investigations. Field sections must be laid to estimate benefits of WMA technologies in terms of reductions in fuel/energy consumption, emissions, and long-term

pavement performance to inculcate further confidence on the technologies among highway practitioners in India.



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## Publications from the Present Research

### International/National Journals

1. **Julaganti, A.**, Choudhary, R., and Kumar, A. “Effect of Lowering in Production Temperatures on Aging Characteristics of Warm Asphalt Binders”. *Journal of Cleaner Production*, Elsevier. [Under Review]
2. **Julaganti, A.**, Choudhary, R., Kumar, B., and Kumar, A. “Prediction of Fatigue Life of Warm Asphalt Mixes using Symbolic Regression Approach”. *Journal of Transportation Engineering, Part B: Pavements*, ASCE. [Under Review]
3. **Julaganti, A.**, Choudhary, R., and Kumar, A. “Rheology of Modified Binders under Varying Doses of WMA Additive–Sasobit”. *Petroleum Science and Technology*, 35(10), 975–982. DOI:10.1080/10916466.2017.1297827.
4. **Julaganti, A.**, Choudhary, R., and Kumar, A. “Moisture Susceptibility of WMA Mixes with Modified Bituminous Binders”. *Petroleum Science and Technology*, 35(10), 1014–1021. DOI:10.1080/10916466.2017.1303721.
5. **Julaganti, A.**, Choudhary, R., Porwal, S. S., and Kumar, A. (2017). “Effect of Reduction in Production Temperatures on Properties of BC Mixes with an Organic WMA Additive”. *International Journal of Engineering Sciences and Research Technology*, 6(2), 433–442. DOI: 10.5281/zenodo.291866.

6. Kumar, A., **Julaganti, A.**, Choudhary, R., and Porwal, S. S. (2016). “Evaluation of State-of-Art (SOA) Warm Mix Asphalt with Modified Binders”. *Journal of Indian Highways*, Indian Roads Congress, 44(12), 23–31.
7. Choudhary, R. and **Julaganti, A.** (2014). “Warm Mix Asphalt: Paves Way for Energy Saving”. *International Journal -Recent Research in Science and Technology*, 6(1), 227–230.

## International/National Conferences

1. **Julaganti, A.**, Choudhary, R., and Pattanaik, M. L. (2015). “Moisture Susceptibility of Modified Binder Mixes with Evotherm”. 3<sup>rd</sup> Conference of Transportation Research Group of India (CTRG–2015), December 17–20, Kolkata, India.
2. Kumar, A., Choudhary, R., and **Julaganti, A.** (2015). “Field performance of Warm Mix Asphalt Containing Evotherm: A Review”. Two-day National seminar cum Workshop on Advances in Civil and Infrastructure Engineering (AICE-2015), Tezpur University, May 8–9, Tezpur, India.
3. Choudhary, R., **Julaganti, A.**, and Banerji, A. K. (2015). “Effect of Compaction Temperature on Mechanical Properties of Modified Binder Mixes”, 14<sup>th</sup> Annual International Conference on Asphalt Pavement Engineering and Infrastructure, Liverpool John Moores University, February 11–12, Liverpool, UK.
4. **Julaganti, A.** and Choudhary, R. (2014). “Evaluation of Volumetric Properties of Bituminous Mixes with Evotherm”. International Conference on Sustainable Civil Infrastructure, October 17–18, Hyderabad, India.

5. Choudhary, R. and **Julaganti, A.** (2014). “Warm Mix Asphalt: Paves Way for Energy Saving”. International Conference on Emerging Challenges and Issues in Environmental Protection, Raipur Institute of Technology, January 23–24, Raipur, India.
6. Choudhary, R. and **Julaganti, A.** (2013). “Effect of Sasobit® on Mix Design Parameters”. 12<sup>th</sup> Annual International Conference on Pavement Engineering and Infrastructure, Liverpool John Moores University, February 27–28, Liverpool, UK.
7. Choudhary, R. and **Julaganti, A.** (2012). “Effect of Mixing and Compaction Temperatures on HMA with WMA Additives”. 11<sup>th</sup> Annual International Conference on Pavement Engineering and Infrastructure, Liverpool John Moores University, February 15–16, Liverpool, UK.
8. Choudhary, R., Gao, E., and **Julaganti, A.** (2011). “Performance History of Warm Mix Asphalt”. National Conference on Recent Advances in Civil Engineering, Institute of Technology, Banaras Hindu University, October 14-16, Varanasi, India.