PERFORMANCE CHARACTERISTICS OF WARM MIX ASPHALT

A THESIS

Submitted in partial fulfilment of the requirements for the award of the degree of

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this thesis entitled **"PERFORMANCE CHARACTERISTICS OF WARM MIX ASPHALT"**, in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of **Chemical Engineering** of the Indian Institute of Technology Roorkee is an authentic record of my own work carried out during a period from **January, 2011** to**, December 2015** under the supervision of **Dr. V.K Agarwal**, Professor, Department of Chemical Engineering, Indian Institute of Technology Roorkee, Roorkee, **Dr. Satish Chandra**, Director, CSIR-Central Road Research Institute (formerly Professor, Department of Civil Engineering, IIT Roorkee) and Dr. S. Gangopadhyay, Director (Retired), CSIR-Central Road Research Institute, New Delhi. The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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ABSTRACT

India is a vast country, having widely varying climate and traffic in terms of both load and volume.. In general, roads in India are mainly bitumen-based roads. During construction of the bituminous pavement, the temperature of the bituminous mix must be high enough to ensure the workability of the mix. To counteract reduced workability of bituminous mix, generally the temperature is increased to reduce the viscosity of the bitumen binder and hence to improve the workability and flow of the bituminous mix. This increase in the temperature of the mix often results in increased plant emissions and fumes at the construction site. With the increasing prices of crude oil and depleting reserves of natural non-renewable resources over time, the need for adopting sustainable approaches in various construction activities is strongly required.

The hot mix asphalt industry in India is constantly exploring technological improvements that will enhance the materials performance, increase construction efficiency, conserve resources, and advance environmental stewardship. These goals can be achieved by involving methods to reduce production and compaction temperatures of Hot Mix Asphalt (HMA). With the reduced production temperature of the bituminous mix the additional benefit of decreased emissions from burning fuels, fumes, and odour generated at the plant and the paving site as well as comparatively lower quantities of fuel consumption can be achieved.

Warm Mix Asphalt (WMA) is a technology that allows significant lowering of the production and paving temperature of Hot Mix Asphalt (HMA). By reducing the viscosity of bitumen and/or increasing the workability of mixture, some WMA technologies can reduce the mixing temperature to 100ºC and even lower without compromising the performance of asphalt. When asphalt mixture is produced at lower temperatures, there are many potential benefits achieved such as reduced energy consumption (fuel) in the plant and reduced greenhouse gas emissions, improved working conditions, better workability and compaction. The mechanism of WMA is to use some additives or technologies to modify the rheological behaviour of asphalt binders, and thus improve the workability of the mixture at lower temperature. Several technologies and additives are available in the country today to produce WMA.

The present study investigates the effects of three different types of warm mix asphalt additives on the properties of asphalt binders and mixtures. Two types of binders are considered in this research viscosity grade bitumen VG-30 and polymer modified bitumen PMB40, and three types of warm

mix additives Sasobit®, Evotherm™ and Rediset® are used. The study is carried out in two parts; Part 1 is the Characterization of Warm Asphalt Binders, and part 2 is the Characterization of Warm Asphalt Mixes. Warm asphalt binders were prepared using two virgin binders (VG 30 and PMB 40) and three warm mix additives at three different doses, so as to create a total of 18 warm asphalt binders. The rheological tests were performed to evaluate the response of warm asphalt binders at different temperatures and different loading frequencies.

It was reported by many researchers that the SHRP rutting parameter G*/sinδ is not very effective in predicting the rutting performance of binders, especially in case of modified binders as its value is highly sensitive to shear rate. To explain how the asphalt binder contributes to the rutting behaviour of the pavement, zero shear viscosity (ZSV) seems to be adequate. Moreover bituminous binder in an asphalt mixture is mixed with mineral fillers not as bitumen alone but, forming bitumen-filler mastic. The ZSVs of bitumen-filler mastics, as opposed to those of plain bitumen, may be more appropriate in establishing a correlation with the permanent deformation properties of asphalt mixtures. Therefore in this study bitumen-filler-mastics were prepared by adding four different concentrations of limestone filler to warm mix binders. Filler was added to get the filler-bitumen ratio of 0.5, 1.0, 1.3 and 1.5 by weight of the binder. Thus a total of 72 formulations of bitumen-filler mastic were prepared. Frequency sweep tests were conducted to determine Zero Shear Viscosity of warm mix binder and bitumen-filler-mastic. Conventional rutting parameter G*/sinδ is also determined over a temperature range to evaluate Failure temperature of warm mix binder and bitumen filler mastic. Various other properties like temperature susceptibility, aging index, short term and long term aging, creep stiffness and m-value of warm asphalt binders were also evaluated. Fourier Transform Infrared Spectroscopy was performed to find the aging characteristics of warm mix asphalt binders.

Performance properties of Warm Asphalt Mixes were evaluated and compared with Hot Asphalt Mixes. Indirect tensile strengths (ITS), tensile strength ratio (TSR),moisture induced sensitivity test, resilient modulus, dynamic creep, fatigue strength, and rutting depths of WMA mixtures were found and compared with that of HMA mixtures. The effects of aging of warm asphalt mixes were evaluated by artificially aging the mixture samples in the oven at 85ºC for 120 hours. The aged samples were then tested for all the performance properties.

The Viscosity-temperature susceptibility test results showed that the addition of warm mix additives make VG30 and PMB40 binder more temperature susceptible in the temperature range of 60°C to 135°C, which shows that addition of these additives can reduce the mixing and compaction temperatures. Rutting factor G*/sinδ of control binders improves with the addition of Sasobit® at higher dosage, whereas it reduced with the addition of Evotherm™ and Rediset®. Temperature sweep test results showed that failure temperature of VG-30 improved with the addition of Sasobit®, while it showed very marginal change with Rediset® and Evotherm™. In the case of bitumen – filler mastic, addition of warm mix additives improved the failure temperature values of VG 30 based mastics.

Zero shear viscosity values indicated that Sasobit® is effective in enhancing the rut resistance of bitumen-filler mastic at its all doses with VG30, but it showed improvement at the dose of 3 percent and above for mastic prepared from PMB40 binder. Bitumen-filler mastics prepared from Rediset® and Evotherm™ modified binders showed improved ZSV only at higher filler-binder ratio of 1.3% and 1.5% which indicates improved resistance to rutting**.** The results showed that the Evotherm™ and Rediset® do not alter any property of bitumen, but are effective only when mixed with bitumen in presence of aggregate/filler part.

It was observed that reduced mixing temperatures significantly reduced the aging index of the binder containing warm mix additives. Long term aged warm mix binders with Evotherm™ and Rediset® additive showed better fatigue cracking resistance, whereas Sasobit® modified warm mix binders showed low fatigue cracking resistance as compared to control binders. Fourier Transform Infrared Spectroscopy (FTIR) for asphalt binders is used as an indicator of oxidation (aging). FTIR analysis confirmed that binders containing warm mix additives age less as compared to the control binders.

The long term conditioning of the mixtures was done by aging them in an oven for 5 days (120 hours) at 85ºC. The effect of aging on moisture resistance and permanent deformation of warm mix asphalt was compared with that of hot mix asphalt. It was observed that the warm asphalt mixes have better TSR values than the control hot mix asphalt. However after the MIST conditioning of the samples, warm mix samples containing Sasobit® additive were found to be more susceptible to moisture induced damage in comparison to control VG 30 hot mix asphalt samples. Evotherm™ and Rediset® based warm mix samples showed improved resistance to moisture induced damage in comparison to control hot mix asphalt.

Warm asphalt mixes showed better resilient modulus values than the control hot mix asphalt. Un-aged control HMA mixes showed more permanent accumulated strains than WMA mixes. The results showed that un-aged warm asphalt mixes will have more resistance to permanent deformation than the hot asphalt mixes. Whereas in the case of aged samples, the WMA mixes showed almost similar extent of permanent accumulated strain as in the control HMA mixes except the Evotherm™ modified mixes. Wheel rutting test results indicated that the warm asphalt mixes had significantly lower rutting depths than the control hot asphalt mixes. The results of four point bending beam test at different strain levels showed that the addition of warm mix additives improved the fatigue life of warm asphalt mixes.

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CHAPTER 1

INTRODUCTION

1.0 General

India is a huge country and has extensively varying climate and traffic in terms of axle load and volume. India has a road network of approximately 4,689,842 km in 2013, the second largest road network in the world (Indian road network-www.nhai.org.in). The quantitative density of India's road network is similar to that of the United States and much higher than that of China. However, qualitatively India's roads are a mix of modern national highways, rural roads and narrow, unpaved roads. In general, roads in India are mainly bitumen-based roads and hot bituminous mix is used as the main paving material for these roads.

Hot Mix Asphalt (HMA) is a combination of approximately 95% of stone aggregate and 5% of bitumen, a product of crude oil distillation. Bitumen is heated up to a temperature of 160ºC, and is combined and mixed with the aggregate at a hot mix plant. Temperature monitoring is very critical to aggregate coating, stability of the mixture during production and compaction of the bituminous mix, and eventually the performance of the bituminous pavement. During the construction of the bituminous pavement, the temperature of the bituminous mix should be sufficiently high to make sure that the mix will remain workable. To counteract reduced workability of bituminous mix, generally the temperature of the mix is increased so that the viscosity of the bitumen binder decreases and hence improves the workability of the bituminous mix. Density of the mix is frequently used to estimate the quality of the pavement especially for dense graded and gap-graded asphalt mixes. Higher values of density are related to lower permeability of the mix to air and water, which enhances the performance of the asphalt mix. If the asphalt mix is difficult to compact and target densities are not achieved due to reduced workability of the mix, the usual response is to increase the temperature of the mixture so as to improve the workability of the mix and hence achieve the desired compaction during the construction of the pavement. Raising the production temperature of the mix to address these issues is expedient but not very effectual. Raising the temperature of the mix to achieve slight improvement in the workability of the mix leads to the increased greenhouse gas (GHG) emissions and fumes at the construction site, and it also results to the excessive ageing of the binder.

The Environmental Protection Agency of US has reported that, one hot mix asphalt plant produces approximately 200,000 tons of hot mix asphalt per year and that releases about 13 tons of CO (carbon monoxide), 2.9 tons of NO (nitrogen oxides), 5 tons of VOCs (volatile organic compounds), 0.4 tons of SO (sulphur oxides), and 0.65 tons of hazardous air pollutants (US EPA 2000). The asphalt industry is constantly exploring methods and technologies to produce and compact the asphalt mixes at lower temperatures, so that the emissions from these hot mix plants can be reduced, without hampering the performance characteristics of the asphalt mixes. Current regulations in India, concerning GHG emissions and pollution control are making it essential to work on reducing the HMA production temperature to a great extent. In last few years stack emissions have reduced significantly owing to improved pollution control features, but still further reductions in greenhouse gasses emission are required for a clean and better environment.

The current environment policies and regulations in India are such that in some ozone non-attainment areas, the hot-mix plants are many times required to restrict their operations in daytime during some times of the year when ozone formation is difficult. In India, the Supreme Court has banned the use of Hot Mix Plants (HMP) in metropolitan cities like Delhi to reduce CO_2 emission (Venkat, 2011). With environmental emissions laws forever being tightened, it is the right time for India to shift its way towards environment friendly pavement construction technologies.

These goals can be achieved by involving methods to reduce production and compaction temperatures of Hot Mix Asphalt. With the reduced production temperature of the bituminous mix, the additional benefits of decreased emissions from burning fuels, fumes, and odour generated at the plant and the paving site as well as comparatively lower quantities of fuel consumption can be achieved. Bituminous pavement industry has been since long experimenting with various alternatives of hot mix asphalt like cold mix asphalt and foamed bitumen to achieve environmental benefits and to save non-renewable sources of energy. But the cold mix asphalt technology has been proved inferior to hot mix asphalt technology (AAPA advisory note, 2007). Cold mix asphalt needs longer curing times. Cold mix asphalt usually leads to higher percentage of air voids so it is mainly used for open and coarse graded mixtures. Foamed bitumen does not require longer curing times but it has a constraint that the foamed bitumen can coat only fine aggregates well and hence is more suitable for recycling applications. Cold mixes are unable to achieve the same performance characteristics as hot mixes. The Warm Mix Asphalt (WMA) technology was introduced in the last few years to address these issues. Warm mix asphalt is produced at a temperature of 30^0C to 60^0C lower than that of conventional Hot Mix Asphalt (HMA).

1.1 Warm Mix Asphalt Technology

In recent times the highway engineers have shifted their focus towards sustainability and environmentally friendly practices in pavement construction. In the field of asphalt production and placement, new technologies have emerged that may reduce fuel consumption and lower emissions as well as provide other benefits to contractors and transportation agencies. Generally the hot mix asphalt is produced at temperatures between 140 °C – 180 °C and compacted at temperatures between 120 °C – 150 °C. These high temperatures make sure that aggregate is dry; the bitumen binder has very low viscosity so that it coats the aggregate well and hence HMA is workable. Bituminous mixes containing polymer modified binders require even higher temperatures to have improved workability.

At very low temperatures, the bituminous binder becomes thicker which makes coating of the aggregates and compaction of the mix very difficult. Sometime the binder becomes so hard, that the desired compaction is impossible to achieve. Production of asphalt mixtures using warm mix asphalt additives is one such method which can reduce the pollution levels and also allows using other lower temperature asphalt mix benefits. Asphalt mixtures on the basis of their mixing temperature and energy consumed for the heating process of materials are divided into 4 categories:

a) Cold mix asphalt (CMA) – the asphalt mixture is produced at an ambient temperature using bitumen emulsion or foam.
b) Half warm mix asphalt (HWMA) – the asphalt mixture is produced at a temperature below water vaporization.
c) Warm mix asphalt (WMA) – the asphalt mixture is produced in a temperature range of 110 °C to 140 °C.
d) Hot mix asphalt (HMA) – the asphalt mixture is produced in a temperature range of 150 °C to 180 °C.

WMA is a modification to hot mix asphalt mixture that is produced, placed and compacted at a temperature 10 °C – 50 °C lower than the temperatures of conventional hot mix asphalt mixture.

When asphalt mixes are produced at reduced temperatures, many other potential benefits are achieved such as reduced energy (fuel) consumption which implies significant reduction in the green house gas emission values. Typical expected reductions are 30 to 40 percent for CO_2 and sulphur dioxide (SO_2), 50 percent for volatile organic compounds (VOC), 10 to 30 percent for carbon monoxide (CO), 60 to 70 percent for nitrous oxides (NOx) and 20 to 25 percent for dust

(Silva et al. (2009), Mallick & Bergendahl (2009)). Fundamentally, WMA is not different than HMA – it is produced by the use of same aggregates and bituminous binder that are heated to obtain proper mixing and workability – the only difference lies specifically in the temperature used to obtain desired mixing and workability.

There are many different processes, and commercially available products, that can be used to achieve this reduction in temperature, but generally WMA technologies can be separated into four categories:-

i. **Water based processes**

   It is a non-additive process and is based on foaming. Bitumen foam is generated by spraying water into the heated bitumen (175 °C – 180 °C) or by adding moist sand (fine mineral particles) into asphalt mixture. Foam ensures sufficient coating of the aggregates that makes asphalt mix workable at lower temperatures. Some examples are:- WAM-Foam, Terex WMA System, Double Barrel Green; Low Energy Asphalt (LEA), Ultrafoam GX e.t.c.

ii. **Water bearing additives**

   They are natural and synthetic zeolites and these are also based on foaming. Natural or synthetic zeolites are added into the asphalt mixture at the prescribed dosage, during asphalt mix production and foam is caused. These zeolites are basically synthetic aluminium silicates having entrapped water inside. When zeolite is added to the mix at the same time as the binder, the chemically bound water is released from the additive during the mixing process. The released water creates a foaming effect of the asphalt binder and, thereby, temporarily increases workability and enhances aggregate coating at lower temperatures. AsphaMin (synthetic zeolite), Advera WMA Zeolite (synthetic zeolite) and natural zeolite are some of the products available in this category.

iii. **Organic additives**

   These are the wax additives such as Fischer Tropsch, Montan waxes, fatty acid amides. These organic waxes have longer chemical chain lengths having their melting point above 100°C. These waxes when added to the bitumen, reduces the viscosity of the bitumen binder at asphalt production and compaction temperatures. The use of organic additives enables asphalt mix production and laying temperatures to be reduced by 20 °C – 30 °C. Sasobit®, Ashphaltan B, Licomont BS 100 are some of the organic additives available commercially.

iv. **Chemical additives**

Some of these additives change asphalt binder structure and reduce viscosity that allows reduction in asphalt mix producing and laying temperatures about 40 °C, whereas some of them work on the principle of surface chemistry. When these surfactant based additives are introduced in to the bitumen-aggregate mix, a significant portion of the heat energy is replaced by chemical energy, thereby allowing the bitumen to coat the aggregate at a lower temperature. Iterlow T, Cecabase, Rediset® , Evotherm™, Rediset LQ, Zycotherm are some of the exmaples.

1.2 Advantages of WMA

As mentioned earlier also that warm mix asphalt is not very different from conventional hot mix asphalt; the difference lies in the way it is produced. To produce hot mix asphalt extremely high temperatures are required to fluid the bitumen and to mix the bitumen completely with the aggregate. High temperatures will lead to more manageable asphalt with great workability while placing, and compacting the mix. Warm mix asphalt is produced when water, chemicals or other additives are used to produce asphalt at lower temperatures. Emissions of greenhouse gases during warm mix asphalt production are significantly lower than during hot mix asphalt production. With a reduction of about 40°C in asphalt mix production temperature, about one third of the CO emissions produced can be reduced. Reduction in energy/fuel consumption is also a benefit of WMA. For WMA production the energy consumption is about 60 % – 80 % of that for HMA production, depending on the extent of production temperature being reduced.

Apart from these obvious advantages, warm mix asphalt offers many other benefits such as, reduction in paving cost. Use of warm mix additives/process will make the asphalt mix workable at lower temperatures and for a longer time, which will extend paving window i.e., the warm mix can be hauled over longer distances and will also allow the construction of roads in winter season (i.e. it will extend the paving season). The lower production temperatures will result in less oxidation of binder during production and lay down of asphalt mix, which may lead to greater fatigue resistance. The viscosity of warm mix asphalt is lower than that of hot mix, making it easier to compact and also the asphalt aggregates could be coated at lower temperatures. The improved workability of the asphalt mix will also allow more Reclaimed Asphalt Pavement (RAP) to be incorporated in the mixes. Use of warm mix asphalt technology will also help in reducing the construction time because the traffic can be allowed on the pavement earlier than on the conventional hot mix asphalt pavement.

1.3 Disadvantages of Warm Mix Asphalt

Potential drawbacks of the WMA technology include an increased susceptibility to moisture damage. In case of warm mix asphalt technology the bituminous mix is produced at lower temperatures which may lead to incomplete drying of the aggregates since the aggregates are not exposed to high temperatures and the resulting trapped water in the aggregates may cause moisture damage. Another concern of WMA technology is increased potential for rutting, which might be due to less aging (stiffening) of the binder, and compaction issues at the lower placement temperatures. It is also not known as how these various warm mix additives will affect the short term and long term aging of the binders and how these wma additives will affect the characteristics of the mixtures and hence the pavement performance. These potential distresses are important and need to be carefully evaluated to ensure the viability and long term performance of WMA. Characteristics of Warm Asphalt Mix vary considerably depending on the additive/process used.

1.4 Objectives of Research

Warm mix asphalt is comparatively a new technology in India that still needs to be studied and developed according to Indian climatic and traffic conditions. It is only about 5 years since the earliest WMA field tests were started in India and therefore the long-term performance of warm mix asphalt technology is still not proved. In developing countries like India, due to lack of research on this technology and due to short usage of time the disadvantages of warm mix asphalt technology are obvious to occur.

The present research study is aimed at investigating the effects of the three different types of warm mix asphalt additives on the properties of asphalt binders and mixtures. The specific objectives of the research include the following:

- To conduct a thorough review of literature on warm mix asphalt technology, the various types of additives available, and the performance properties of these wma mixes.

- To investigate the effects of warm mix additives on the properties of binders like penetration, softening point, viscosity, penetration index (PI), viscosity-temperature susceptibility (VTS) and penetration viscosity number (PVN).
- To determine the optimum dosage of additives for VG-30 and PMB 40 binders on the basis of Marshall stability values, retained strength values and air voids.
- To study the performance properties of warm asphalt mixes in comparison to that of hot mix asphalt in terms of indirect tensile strength, tensile strength ratio, moisture induced sensitivity test (MIST), rutting performance, dynamic creep, resilient modulus and beam fatigue test.
- To investigate the rheological properties of various warm mix binders at high temperatures using dynamic shear rheometer (DSR) and at low temperatures using bending beam rheometer (BBR).
- To determine the aging indices of warm mix binders with respect to control binders.
- To investigate the effects of short term and long term aging on the properties of warm mix binders and WMA mixtures.

1.5 Scope of Research

Two types of binders are considered in this research viscosity grade bitumen VG-30 and polymer modified bitumen PMB40. Three types of warm mix additives Sasobit®, Evotherm™ and Rediset® are used. Aggregates are taken from a single source. The objectives stated in section 1.4 are achieved through the following studies.

- Comparing the indirect tensile strengths (ITS), tensile strength ratio (TSR), resilient modulus, dynamic creep, fatigue strength, and rut depths of warm asphalt mixtures with conventional HMA mixtures. A total of 300 Marshall samples were prepared at different mixing temperatures (135ºC, 125ºC, 115ºC, 100ºC) with varying dosages of warm mix additives and these samples were then tested for Marshall stability and retained strength. On the basis of air voids, Marshall strength and retained strength at optimum doses and temperatures. A total of 240 Marshall samples were then prepared and tested for ITS, TSR, resilient modulus, static and dynamic creep. A total of 24 beams were prepared and tested for beam fatigue strength and 24 rutting slabs were prepared and tested for rutting strength of warm mix and hot mix asphalt.

- The aging characteristics of warm asphalt mixes were evaluated by artificially aging the asphalt mixture samples in the oven at 85ºC for 120 hours. The oven aged samples were then tested for moisture susceptibility test and permanent deformation test like dynamic creep test, resilient modulus and moisture induced stripping test. Binders were also extracted from the aged mixture samples and these recovered binders were then tested to compare the aging index with the binders aged in the rolling thin film oven and the pressure aging vessel.
- Comparing the rheological properties of warm mix binders with the control binders. Frequency sweep and temperature sweep tests were conducted to study the effects of the warm mix additives on the complex modulus (G*), phase angle (δ), complex viscosity (η*) and G*/sinδ. Bitumen-Filler mastics were prepared by adding calculated mass of limestone filler to virgin and warm mix binders. Frequency sweep tests were done on these bitumen-filler mastics to investigate the ZSV (zero shear viscosity) of the binders. A total of 100 formulations were prepared and tested using dynamic shear rheometer (DSR).
- Viscosity of the VG 30 and PMB 40 binders containing warm asphalt additives was studied by measuring the viscosity of the binders with varying dosages of warm mix asphalt additives in a Brookfield viscometer at different temperatures.
- Short term aging of warm mix binders and control binders was done in a rolling thin film oven (RTFO) at two different temperatures to study the effects of short term aging on properties of the warm mix and control binders. The RTFO residues were further aged in the pressure aging vessel (PAV) to simulate long term aging. Aged binders were then tested to determine the viscosities, G* and δ values, binder stiffness and m-values. A total of 14 rolling thin film oven and 14 pressure aging vessel test procedures were carried out. To quantify and validate the extent of aging in binders, Fourier Transform Infrared Spectroscopy (FTIR) was carried out on warm mix binders and control binders.

1.6 Outline of Report

The thesis is organized in the following chapters:

Chapter 1: This chapter gives a general introduction of the warm mix asphalt technology, its advantages and drawbacks. It further presents the objectives and scope of the research.

Chapter 2: This chapter presents a comprehensive review of literature on warm mix asphalt products, various processes, and earlier research work done in India and abroad on warm asphalt binders and mixtures.

Chapter 3: This chapter gives the details of the materials used and experimental work carried out in the present research work.

Chapter 4: This chapter presents the results obtained from the binder characterization tests on various binders with and without warm mix asphalt additives.

Chapter 5: This chapter presents the results obtained from the mixture characterization tests to evaluate the performance of warm asphalt mixes in comparison to hot mix asphalt.

Chapter 6: The major conclusions drawn from the study are given in this chapter.

CHAPTER 2

REVIEW OF LITERATURE

2.0 General

The bituminous mixes in India are produced by employing traditional Hot Mix Asphalt (HMA) technology. Aggregates and bitumen are often mixed at temperatures of 150ºC to 175ºC. During construction, the temperature of the mix should be high enough to achieve the workability of the mix however the temperature should not be too high at which excessive binder hardening occurs. Modern pavement performance requirements often state the use of polymer-modified binders (PMB). With the Superpave Performance Grade (PG) system, polymer modification is frequently used as a measure to increase the resistance of the asphalt mix towards permanent deformation at high temperatures on high-volume roads. Mixes made with polymer-modified binders are believed to be more difficult to work than mixes made with unmodified binders. To improve the workability of PMB mixes generally the production, placement and compaction temperatures are raised. For some improvement in the workability, increasing the mix temperature often results in increased GHG emissions and fumes at the paving site.

All around the world the efforts are being put forward to protect the environment. Currently the emphasis of every industry is on reducing the carbon emissions in view of reducing greenhouse effect. One of the newest technologies of the asphalt industry is warm mix asphalt (WMA), which can lower the plant and field operation temperatures by as much as 40-50°C by using diverse techniques such as organic/chemical additives, emulsions, material/plant foaming, and synthetic binders. Warm-mix asphalt (WMA) has been gaining popularity in the asphalt industry primarily because of its ability to lower the energy required to blend asphalt mixes, which in turn results in less fuel consumption, slower aging of the asphalt binder and reduced emission of greenhouse gases. With the increasing popularity of WMA technology, the need arises to perform detailed research to determine the performance characteristics of warm asphalt mixes and to evaluate the effect of warm mix additives on the properties of the control binders.

The warm mix asphalt technology was first developed in Europe in 90'ies and then United States from the year 2002 started conducting a lot of laboratory testing and field trials of WMA. The European countries and the U.S are already using the warm mix technology to produce asphalt mixes at lower temperatures. The Warm mix technology in India is quite new with very few laboratory evaluation and field evaluation studies carried out since 2009. While the energy savings and the reduction in carbon emissions by using WMA are quite appealing, the performance of these mixes in India is not well known. The asphalt mix designs, type and quality of bituminous binders, equipment, climate conditions, highway engineering practices in India are very different from those in the western countries and thus warm mix asphalt technology needs investigations and extensive research before being completely adopted in India.

Many researchers have evaluated the effect of warm mix additives on the performance characteristics of asphalt mixes and on the binder properties. The main focus is to reduce mixing and compacting temperature while achieving similar performance properties as that of hot mix asphalt. Major studies carried out by researchers are discussed below.

2.1 Literature on Warm Mix Binder Properties

Study of **Biro et al. (2009)** indicated that bituminous binders modified with inorganic additive (Asphamin®) do not show significant changes in binder properties when compared with the virgin binders. During the preparation of asphalt mixture, foaming materials like Asphamin® and water generally evaporate. So their effect on binder's rheological properties is negligible. Further they reported that when the organic wax based additive like Sasobit® is used with PG 64-22 the effect on flow, stiffness, and creep response is significant. However, these wax based additives affect the properties of asphalt mixture and asphalt binder when mixed with binder to reduce its viscosity.

Phillips and Robertus (1996) postulated that rutting in an asphalt pavement is dependent on the zero-shear-viscosity of the binder. They evaluated the data from rutting and dynamic-creep tests. A good correlation of rutting rate of the mix and zero shear viscosity of the binder is found for all the binders tested which included unmodified and polymer-modified bitumen at various polymer concentrations and degrees of bitumen/polymer compatibility. The effect of binder elasticity was also examined. Their results indicated that zero shear viscosity is the key parameter determining the binder contribution to permanent deformation in pavement rutting.

Hossian et al. (2012) reported a reduction in the viscosity of the base binder and thus reduction in mixing temperature with increase in the dosage (1 to 3%) of Sasobit®. Reduction in mixing temperature of 11°C with 3% Sasobit® was found to be at desired viscosity of 170 mPas. On the other hand, no positive effect was observed for any dose of Aspha-Min. Addition of Sasobit® up to 3% increased the aliphatic content indicating an increased complex component (G*) which increases the elastic modules of the binder while there was no notable change in the aliphatic content of the binder due to increase in content of Aspha-Min. Such results are in agreement with the DSR test data where the G* value increases with the increase of Sasobit® content in the binder.

Xiao et al. (2012) studied the rheological properties of short term aged warm mix binders. They used Cecabase, Sasobit®, Evotherm™, and Rediset® as non-foaming warm mix additives in their study and found reduction in high temperature viscosity with these additives. These additives lower the mixing and compaction temperatures of the mixture. Additionally, WMA additives especially Sasobit® and Evotherm™ with base binder increases the failure temperature of both un-aged and short term aged binders. However, slight decreases in failure temperatures of binders were observed with addition of Cecabase. Therefore, these WMA additives are expected to improve the rutting resistance of the mixtures. The binders containing Sasobit® exhibited the lowest phase angle and greatest complex modulus at various shear strain levels regardless of aged states. In addition to this, the oscillation tests indicated that the short term aged and un-aged binders with warm mix additives generally have comparable visco-elastic properties. The binders modified with Sasobit® exhibited slightly higher complex modulus and a slightly lower phase angle corresponding to all the frequencies and hence results in a higher rutting resistance.

Xin et al. (2012) studied high and low temperature behaviour, temperature sensitivity, and fatigue resistance properties of Crumb Rubber Modified Asphalt (CRMA) with different doses of two warm mix additives; Sasobit® and Evotherm™. The CRMA with Sasobit® showed better high temperature behaviour. $G^*/\sin\delta$ values and failure temperature increase with increasing content of both additives. Addition of 3% Sasobit® improved high temperature performance significantly. Further ZSV values of CRMA increased significantly with increases in the Sasobit® whereas, ZSV increased marginally with Evotherm™. Intermediate temperature behaviour of binder with Evotherm™ was better than that with Sasobit®.

Biro et al. (2009) studied the zero shear viscosity (ZSV) of five different grades of asphalt binders modified with two warm asphalt additives, Asphamin® and Sasobit®. Different rheological models and test methods were used to calculate ZSV's. Their results indicated that the ZSV of all the binders was increased after the addition of the warm asphalt additives as shown in figure 2.1. It was also observed that ZSV determined by using different test methods results in different ZSV values. They also stated that the selection of the test methods and the testing parameters are very crucial in determining the ZSV values of bituminous binders.

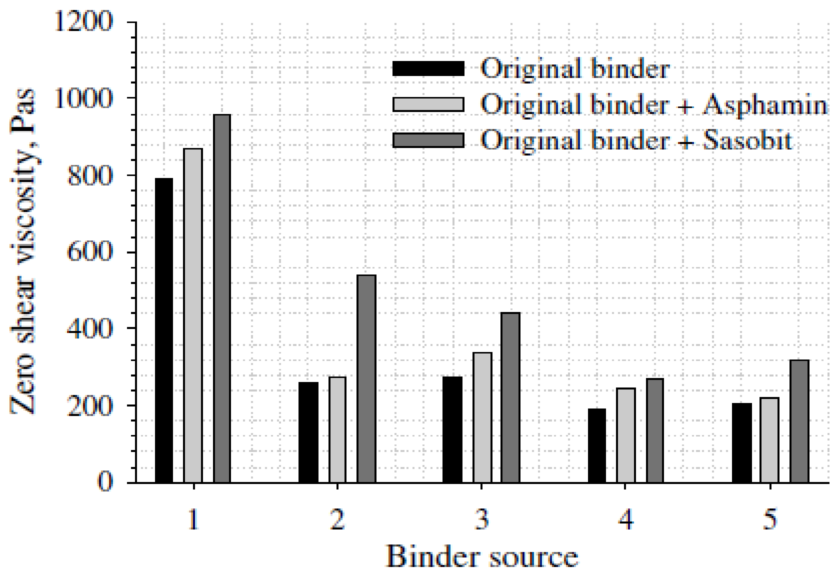


Figure 2.1: ZSV values for the five binders with and without warm asphalt additives calculated by Burger's model

Zhifei et al. (2010) studied the effect of wax based wma additive, Sasobit® on the temperature susceptibility of asphalt binders. Penetration test and viscosity test were performed at different temperatures and Penetration index (PI), viscosity-temperature susceptibility (VTS) values and penetration-viscosity numbers (PVN) were calculated to estimate the temperature susceptibility of Sasobit® modified and control binders. The results showed that with the increasing dose of Sasobit® the PI and PVN of asphalt binders increased. This indicates that the temperature susceptibility of the control binders improved in the range of 15°C to 60°C after the addition of Sasobit® additive. However with regard to VTS values, it was observed that the addition of Sasobit® can make the asphalt binder more temperature susceptible in the range of 60°C to 135°C, especially at high content of Sasobit®.

Liao and Chen (2011) opined that current rutting parameter G*/sinδ is not reflected in rutting performance of asphalt pavement in some cases as it does not consider the recovery phase during oscillatory testing. ZSV of bituminous binders is an alternate performance indicator of rutting resistance. They studied rutting behaviour of binder and it's mastic in term of zero shear viscosities for three different concentrations of limestone filler. ZSV was determined by two types of measurement techniques, through oscillatory and viscometry testing and it was found that Cox-Merz rule was obeyed by the bitumen-filler mastics at low concentrations (15% and 35%) of limestone filler. At high filler concentration (65%) two different values of complex viscosity were obtained by two techniques for a given oscillation frequency and therefore Cox-Merz rule was not found suitable. They attributed this behaviour of mastic at high limestone concentration to filler particle-particle interaction in mastic suspension.

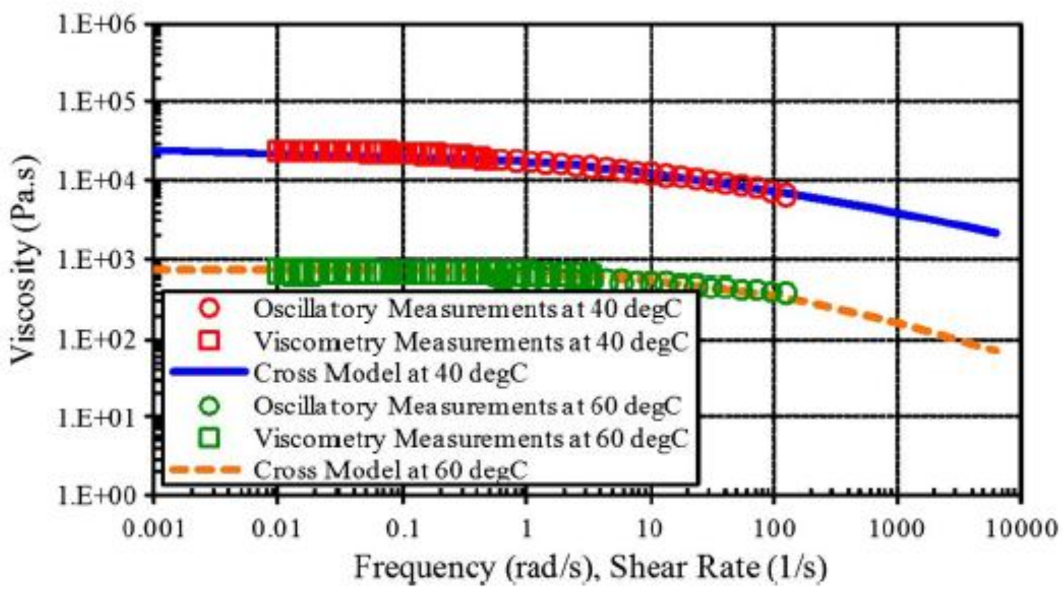


Figure 2.2: Actual Viscosity measurements and predicted viscosity values using Cross model for 40/60 pen grade bitumen

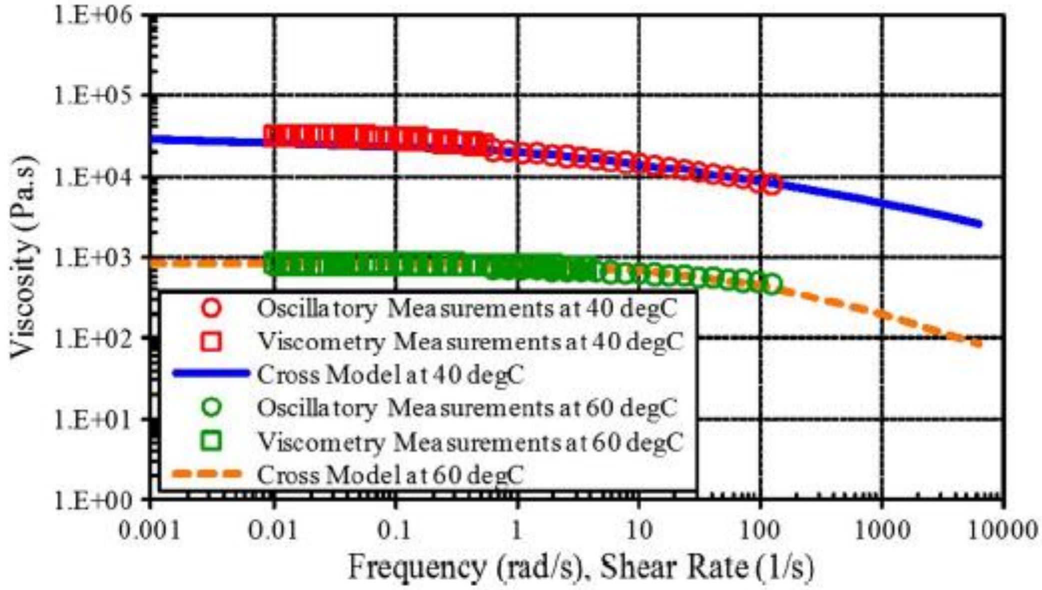


Figure 2.3: Actual Viscosity measurements and predicted viscosity values using Cross model for 15% limestone bitumen-filler mastic

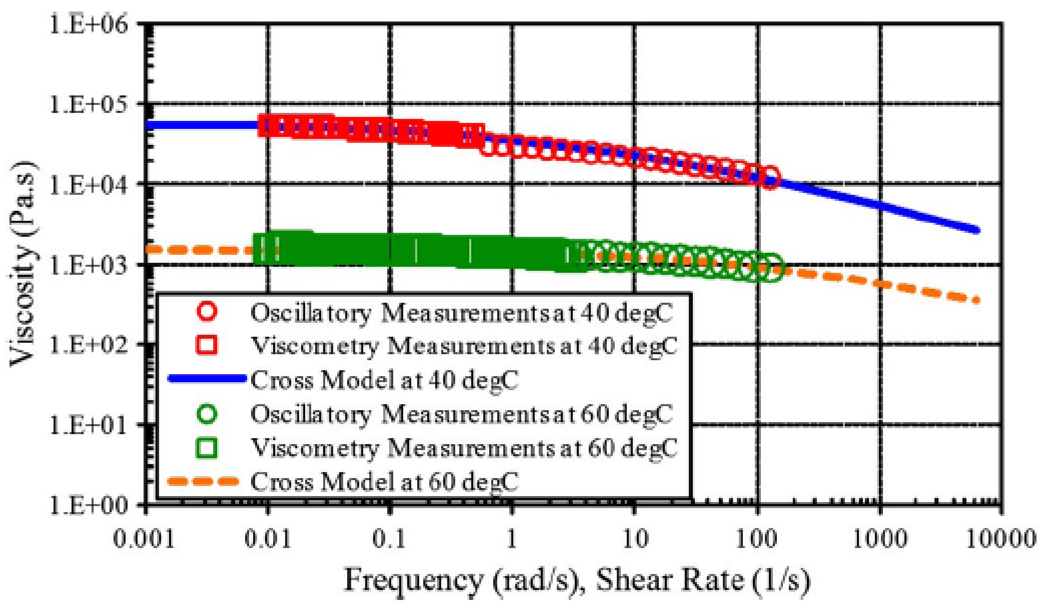


Figure 2.4: Actual Viscosity measurements and predicted viscosity values using Cross model for 35% limestone bitumen-filler mastic

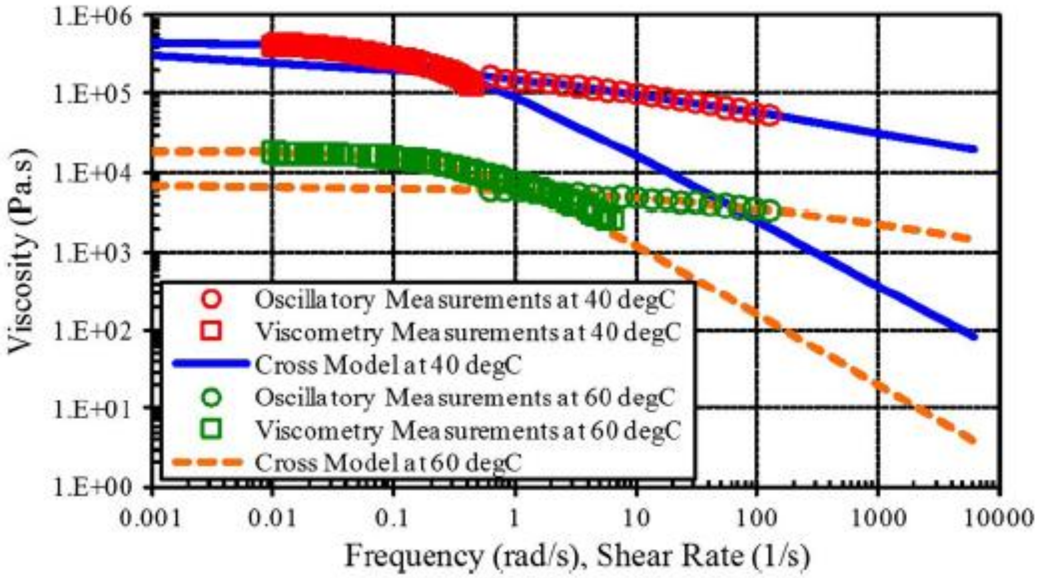


Figure 2.5: Actual Viscosity measurements and predicted viscosity values using Cross model for 65% limestone bitumen-filler mastic

Liao et al. (2012) performed DSR oscillatory and wheel tracking tests to determine the fatigue properties of a range of bitumen-filler mastics and asphalt mixtures at a temperature of 20°C. Filler particle-particle interaction and filler-bitumen interaction were quantitatively estimated according to the increased rate of stiffening ratio. Two regions of dilute and concentrated suspension (35% and 65% filler by mass of bitumen) were used to interpret the effect of filler on mastic stiffness. It was found that the filler content had a significant influence on stiffness of bitumen-filler mastic; the high filler content (filler concentrated suspension) shows a rapid increase in the stiffening ratio. Significant improvement on the fatigue life of mastic was observed after the addition of the mineral filler to bitumen, owing to the stiffening effect and interruption of filler particles to the crack growth in the mastic.

Silva et al. (2010) optimized warm asphalt mixes using different blends of binders and synthetic paraffin wax based wma additives. They stated that synthetic paraffin wax additives produced energy efficient asphalt mixtures at reduced production and construction temperatures. However, the sustainability of these mixes during the life cycle of the pavement can only be estimated by optimizing the performance of the mixtures. Therefore they aimed to assess the properties of different blends of control binders from softer to harder ones containing a range of synthetic wax contents, as well as the performance of the corresponding warm mix asphalts, that could ultimately lead to more sustainable mixtures. It was concluded that different blends should be selected to maximize the temperature reduction, and to improve the fatigue or the rut resistance, without hampering the other properties of the mixture.

Anderson and Goetz (1973) found that placement workability and mechanical performance of asphalt mixture are influenced by the combination of asphalt binder and filler and quality of mastics. The effect of the filler in mastic was found to be dependent on volumetric filling effect or an interaction between the filler and the bitumen due to the surface characteristics and fineness of the filler. The latter effect is related to physicochemical aspects that explain the specific interfacial interaction of bitumen–filler systems.

Gandhi and Amirkhanian (2008) studied the aging properties of warm mix binders, by simulating the aging of warm mix asphalt in the laboratory. They prepared asphalt mixtures by using two different binder sources and two different warm asphalt additives (Asphamin® and Sasobit®). The asphalt mixtures were aged in the oven, and the binders were extracted for testing. The binders extracted from un-aged mixture samples were considered as short term aged binders and the binders extracted from oven aged mixtures were considered as long term aged binders. They carried out various tests like viscosity, high and low temperature properties and Gel Permeation Chromatography on aged and un-aged binders. It was observed from the results that the binders extracted from the WMA experienced less aging as compared to the binders extracted from control HMA. They also found that warm mix additives did not affect the fatigue cracking parameter ($G^*.\sin\delta$) of the binders significantly. However, the binders containing Asphamin® wma additive exhibited significantly increased m-values.

Crews et al. (2012) in their research predicted the stiffness ($G^*/\sin\delta$) of binder treated with a surfactant-based warm-mix additive as a function of mix production temperature, mix storage and haul time, and warm-mix additive dosage. Asphalt binders were treated in the laboratory with 0.0%, 0.5%, and 1.0% of surfactant-based warm-mix additive and these treated binders were then exposed to short term aging in a rolling thin-film oven at 130°C, 145°C, and 163°C for 0, 25, 55, 85, and 115 min. Regression analyses of their laboratory data yielded equations that correlated binder stiffness with the formulation (dosage) and process variables (aging temperature and time). The predictive value of these laboratory-developed equations was found to be good when the measured stiffness of binder extracted from field mix obtained from the paver site was compared with binder stiffness calculated with the laboratory-developed equations.

Banerjee et al. (2012) studied the aging properties of various warm mix additives namely Sasobit®, Rediset®, Cecabase® and Evotherm™. These additives were added to a PG 64-22 grade binder at different dosages to produce warm mix binders. They studied the rheological properties of these warm mix binders by performing frequency sweep test over a range of different loading frequencies and at three different temperatures with varying degrees of exposure to oxidative aging. The Rediset® WMA binder showed the lowest shear modulus, followed by the Evotherm™. Sasobit® modified binder showed the highest shear modulus. It was concluded in their study that the Sasobit® WMA binder will have a significantly lower modulus over time as compared to the control PG 64-22 binder and the Rediset® WMA binder will have the lowest modulus in the short-term aged as well as long term aged binders.

Anderson et al. (2002) also studied the zero shear viscosity of asphalt binders. They used various methods for finding the ZSV of binders from both creep and dynamic data. A series of creep and dynamic experiments were performed on ten unmodified and modified binders. The data obtained from these tests was evaluated to determine ZSV values. The authors concluded that the obtained ZSV values from these two different methods provided very similar results when applied over a wide range of test temperature. The binders ranked relatively different when ranked according to their Superpave grading temperature or their ZSV.

Dongre and D'Angelo (2002) stated in their research paper that various parameters have been reported in literature to refine the current Superpave high temperature binder specification. One parameter relates the phase angle directly to accumulated strain obtained from the creep recovery test. They also stated a method to predict the accumulated strain using the current Super pave parameters G^* and $\sin(\delta)$. They also proposed Zero-shear viscosity as a high temperature specification parameter. They evaluated various criteria proposed for high temperature specification by examining the correlation of each criterion to performance properties of the pavement. Results show that out of all the methods the zero-shear viscosity correlates quite well with performance and is the best parameter among all evaluated.

Farshidi et al. (2013) hypothesized that reduction in temperature while mixing and compaction will impact the oxidative aging behavior of the asphalt mixes. They made an attempt to quantify these impacts through characterization of field-aged unmodified and rubber-modified binders extracted and recovered from cores taken from 13 test sections representing seven different WMA technologies and associated hot-mix controls. Dynamic shear rheometer (DSR) was used to evaluate the binder rheological properties at high temperatures with respect to expected rutting performance. The bending beam rheometer (BBR) was used to characterize low-temperature properties. The organic wax based additive showed better resistance to rutting failure in all the tests, and this was credited to the crystallized wax structure which the wax based additive forms in the binder. They observed that all the test results are influenced by the production and placement temperatures, which indicate that some mixes produced at very low temperatures, might experience early rutting failure on the pavements that are exposed to high ambient temperatures and heavy traffic loading. With regards to the results of accelerated load testing, they concluded that zero shear viscosity (ZSV) is a better indicator of the rheological behavior of asphalt binders. ZSV was indicated to be a more suitable parameter for predicting the rutting performance of rubberized binders than the current Superpave criterion $G^*/\sin\delta$.

2.2 Literature on Performance Properties of Warm Mix Asphalt

Hurley and Prowell (2005, 2006) have indicated that when the asphalt mix production temperatures are decreased, the mixes exhibit increased tendency towards moisture damage and permanent deformation. It happens because the aggregates are not heated at high temperatures and hence they do not dry completely, thus the asphalt mix producers should be careful while lowering down the mixing temperatures and also sufficient amount of anti-stripping agents should be used.

Olof (2006) studied potential benefit of WMA in cold weather conditions of Iceland and found them suitable for cold weather paving. However, to decrease moisture susceptibility and rutting, anti-stripping agents may be needed. Indeed, it is beneficial for cold weather paving when warm mix asphalt is produced at hot mix asphalt temperatures and extended paving season is achieved. He conducted survey towards interest of professionals of the paving industry in Iceland and reported that they are positive towards using WMA and in investigating it further for Icelandic weather conditions.

Prowell (2007) studied the WMA technology as a means to reduce the bituminous mix production and compaction temperatures. He reported that WMA is a technology which allows the mixing and compaction of asphalt mixes at a lower temperature than conventional HMA mixes. Mixing temperature of asphalt about 100°C to 140°C is possible in WMA in place of 150°C to 180°C mixing temperature of HMA.

Hill, B., et al. (2012) evaluated the low-temperature fracture properties of WMA mixtures. They used disk-shaped compact tension, indirect tension, and acoustic emission tests to characterize the low-temperature properties of the mixture. The average crack mouth opening displacement (CMOD) fracture energies at a rate of 1.0 mm/min for the HMA and WMA mixtures were measured by the Disk-Shaped Compact Tension (DC (T)) test at -12°C and are shown in Figure 2.6. The results showed that the chemical additives improved fracture energy in comparison with HMA and that the organic and foaming additives reduced fracture energy.

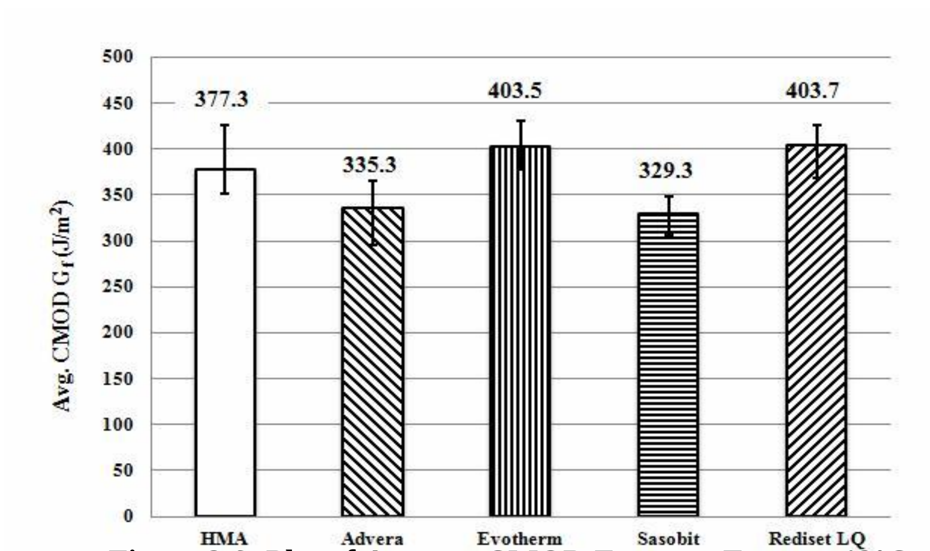


Figure 2.6: Plot of Average CMOD Fracture Energy -12°C

They observed similar results for indirect tension creep compliance test, in which the two chemical additive-modified WMA systems increased mixture creep compliance, while the other two systems did not significantly alter creep compliance as compared with the control HMA mixture.

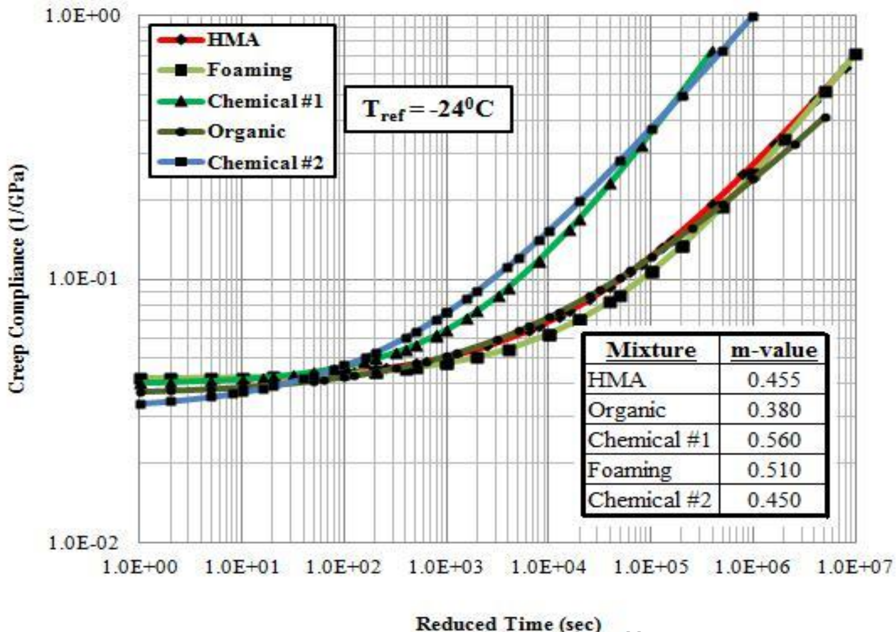


Figure 2.7: Fitted Creep Compliance of Different WMA Mixtures

Tao and Mallick (2009) described two technologies which are used for WMA production. In the first technology proprietary mineral or additive like Rediset WMX, Sasobit®, Cecabase, and Evotherm™ is blended with asphalt binder to lower the viscosity value of the binder. This process is known as non-foaming WMA technology. In the second technology foaming material like Asphamin is added to the mixture with the binder and a very fine water spray is created. Due to this the volume of binder expands which increases the compatibility and workability of mixture at lower temperature also. Crystalline water is released in the form of vapour during laying and compaction. This physical production process is called the foaming technology.

Kandhal (2010) classified different WMA technologies in to 3 groups as given below.

I. Foaming technology in which water is used to causes the hot asphalt binder to foam (examples: WAM Foam, zeolite, Double Barrel Green and Low Energy Asphalt).

II. Wax or organic additive (example: Sasobit®).

III. Surfactants or chemical additives (examples: Rediset WMX, Evotherm™ and REVIX).

He described the advantages of WMA technology such as, energy savings in producing asphalt mix, decreased emissions from asphalt plants, potential of decreased asphalt binder aging during production, extended paving season especially in colder winter months and/or in places located on high altitudes, and compaction aid for stiffer mixes.

Xiao et al. (2010) researched rutting performance of different WMA technologies. They observed that the best rutting resistance is exhibited by the mixture with Sasobit® additive while Aphamin and Evotherm™ do not show any significant improvement rutting performance.

Punith and Xiao (2011) reported that WMA mixture does not show significant difference in dry ITS values. Except mixtures with Evotherm™ and 10% crumb rubber (CR), all after mixtures containing moist aggregates and Warm Mix Additives gave the minimum wet ITS requirement. Improved TSR value was obtained for mixture with Sasobit® indicating improvement in resistance to moisture susceptibility. Remarkably less susceptibility to warm water bath treatment was shown by mixture containing Sasobit®, thus improving the moisture resistance of mixtures resistance to moisture susceptibility was almost similar for virgin mix and mixtures with Evotherm™ and Asphamin. **Kakade et al (2011)** also reported greater resistance to moisture induced damage for Sasobit® based WMA as compared to conventional HMA.

Colbert et al. (2011) studied the low-temperature performance of WMA paving materials. Sasobit® (0.5, 1.0, 1.5 and 3.0% by weight of binder) was used to improve low-temperature field performances. They found that the low viscosity condition was induced by Sasobit® resulting in low strain levels. As compared to unmodified binder the creep stiffness of the 3.0% Sasobit®-modified binder was higher. Cracking temperature of the mixture with Sasobit® up to 1.5% was found to have reduced by 3.2 % while it reduced by 5.6% when Sasobit® content was 3%. They also reported that asphalt mix will be more susceptible to cracking at lower temperatures if there is more Sasobit® content in the asphalt binder. Although Sasobit® create lower viscosity conditions in asphalt, higher concentration of Sasobit® could create reductions in low-temperature cracking resistance performance.

Liu et al. (2011) also evaluated experimentally the engineering properties of Sasobit®-modified WMA binders and mixes. They reported that the addition of Sasobit® significantly reduces both mixing and compaction temperatures of mixes and also impacts the performance grade of binders. They observed that when the Sasobit® dosage is raised from 0% to 3%, the high temperature asphalt grade increased from 58°C to 76°C, and the low temperature grade increased from 28°C to 16°C. The rutting factor (**G^*/ sin δ)** value was also found to be increased with an increase in

Sasobit® dosage. This effect of Sasobit® addition on **G^*/ sin δ** was more evident at higher temperatures, indicating improved rutting resistance of the binders. The creep stiffness increased, and m-value decreased with increasing dosage of Sasobit® which indicates that the addition of Sasobit® additive increases the chances of low temperature cracking. They also reported that with increasing temperatures the dynamic modulus $|E^*|$ decreases for all mixes and at all loading frequencies. At constant temperature, the $|E^*|$ increased with the increase of loading frequency for all mixes.

Zhao et al. (2012) studied effects of various warm additives on the rutting performance of asphalt concrete with different binders and mixing temperature applications. The authors adopted three levels of mixing and compaction temperatures as shown in Table 2.1

Table 2.1 Mixing and Compacting Temperatures

Treatment levels	Mixing temperatures, ºC	Compacting temperatures, ºC
High level	150	135
Medium level	135	120
Low level	120	105

They observed that there is a number of factors affecting rutting performance such as; type of binder source, mixing and compacting temperature, total void in mix and additives. At low mixing temperature age-hardening of the binder will be low and hence making it less stiff. Therefore at low mixing temperature rutting susceptibility of asphalt will increase as compared to HMA. They developed a rutting model as given in Equation (2.1) for four independent variables such as temperature (T), additives dose, voids in total mix (VTM) and $G^*/\sin\delta$.

$$\textbf{Rut depth} = 16.4 + 0.627\,VTM - 0.00226\,G^*/\sin\delta - 2.25\,Additive - 0.0630\,T \quad \text{---- (2.1)}$$

From Figure 2.8 it was observed by the authors that the mean rut depths of chemical warm additives are at the same level as the control binder (no additive). The addition of chemical additives did not soften the binder and their rutting behaviours are statistically the same as the virgin binder. Wax additives increased the binder stiffness, and improved the rutting susceptibility due to a lower production temperature. However, the stiffening effect of wax additives may have negative influence on mixture’s resistance to cracking.

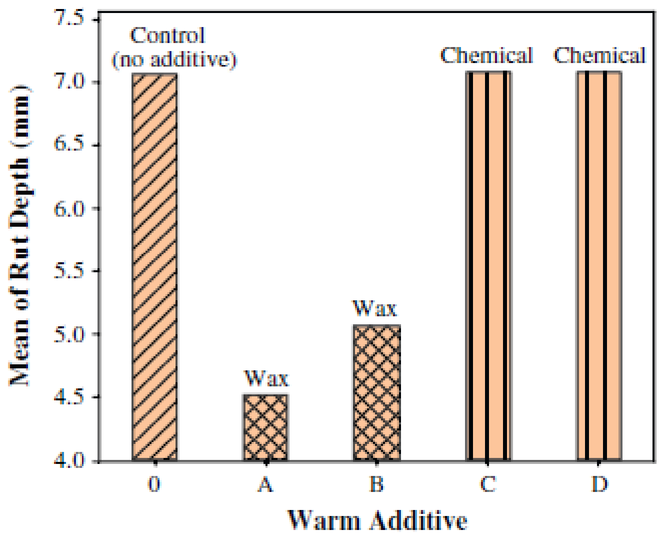


Figure 2.8: Warm additive effect on Rutting Depth

A similar type of research was conducted by **Liu et al (2011)** also and they have also reported several benefits of Sasobit® modified binders and mixes over conventional hot mix asphalt.

Kim et al. (2012) carried out laboratory and field studies on two widely used warm mix asphalt (WMA) approaches – foaming and emulsion technology. Trial pavement sections of the WMA mixtures and their counterpart hot-mix asphalt (HMA) mixtures were implemented in Antelope County, Nebraska a more realistic evaluation of the WMA approaches. Various experimental evaluations of the individual mixtures were conducted on field-mixed loose mixture that was collected while the laying of the field stretch. Various laboratory tests were conducted determine the moisture damage potential of the mixture. The test results showed that warm mixes have greater susceptibility to moisture conditioning in comparison to the control hot mixes. Data collected while field performance evaluation for three years after placement showed satisfactory rutting and cracking performance of both the WMA and HMA sections, which was in agreement with laboratory evaluations. The authors stated that even if the field performance data indicated similar performance of WMA and HMA sections, a cautious inspection of field sections over a long period of time was necessary because moisture damage can occur at a later stage of pavement distress. **Jamshidi et al (2012)** also did not find much difference between performance related properties of HMA and Sasobit® based WMA, but authors were of the opinion that aspects related to environment and energy must be incorporated in superpave mix design methods.

Caro et al. (2012) determined the resistance of warm mix asphalt to moisture damage by conducting dynamic mechanical analyzer (DMA) testing and a fracture mechanics model. In their study they evaluated the moisture susceptibility of three different warm mixtures. The analysis is based on a viscoelastic-fracture model, in which the input parameters are the results from the relaxation modulus and Dynamic Mechanical Analyzer (DMA) test conducted on various specimens representing the fine matrix portion of the actual mixtures, and from surface free energy tests. The results suggest that moisture caused more damage in two out of the three evaluated WMA fine mixtures in comparison to the damage observed in the control-HMA specimens.

Arshad et al. (2012) found that the volumetric properties of conventional HMA are similar to that of the Sasobit® based WMA produced at lower temperatures. They proposed a dosage of 1.5% of Sasobit® to achieve the similar design parameters as specified in the Malaysian specification of road works.

Khan and Chandra (2012) used Brookfield Viscometer to determine the viscosity of bituminous binders with different combinations of additives at different temperatures ranging from 90ºC to 160ºC. Two binders VG 30 and CRMB 55 and two additives Sasobit® and Evotherm™ were used. The results showed that the viscosity of the bituminous binders varies exponentially with the temperature and linearly to the dose of Warm Mix additives and the mixing temperature can be reduced by 20ºC to 25ºC while laying and compaction temperature can be reduced by 10ºC to 15ºC by using these additives.

Kavussi et al. (2014) studied the moisture susceptibility of warm mix asphalt with respect to aggregate gradation, hydrated lime and Sasobit®. Indirect Tensile Testing was performed on dry and saturated samples and response Surface Methodology was applied to analyze the data. The results indicated that the Indirect Tensile Strength at saturation condition (ITSsat) for the first and second order terms of the aggregate grading, hydrated lime and Sasobit® contents, were statistically significant at 90% confidence level. Whereas at dry condition (ITSdry) parameters the Tensile Strength Ratio (TSR) and Indirect Tensile Strength, the interactions between grading and Sasobit® contents were rather poor.

Behl et al. (2011) made first trial of warm mix in India over a 500 m section of road at Bawana Industrial area in Delhi. The section was placed using a surfactant based warm mix additive with CRMB. Based on laboratory evaluation and field evaluation, it was concluded that the addition of warm mix additive of 0.5% by weight of bitumen helps in substantially lowering down the mixing and compaction temperature. WMA can be successfully laid at lower temperature as low as 100ºC as compared to conventional hot mix (155ºC). Warm mixes indicated improved resistance to permanent deformation as obtained from the wheel tracking tests. There was no significant difference in compacting hot bituminous mix at 140-130ºC and the warm mix at 90-80ºC.

Wenyi et al. (2012) used fracture energy parameters to determine the influence of incomplete drying of mixes on their mechanical properties. Fracture energy-based parameters [energy ratio (ER); ratio of energy ratio (RER)] were determined from the mixture tests (resilient modulus, creep compliance, and indirect tensile strength (ITS) at 5ºC). Testing of mixes was done with fully and partially dried aggregates and some of the aggregates were subjected to moisture conditioning. The results indicated that (a) resilient modulus, creep compliance, and ITS were all affected by the presence of moisture in mixes; (b) the trend and the degree of influence of moisture for different mechanical parameters were different; (c) the moisture conditioning process caused larger decrease in modulus and ITS values than did incomplete drying of aggregates and (d) fracture energy-based parameters (ER and RER) appeared to be more-distinctive moisture effect and damage indicators than the other parameters.

Kuang (2012) found that the mixtures prepared and compacted at 145°C/130°C have better shear capability than the mixtures prepared at the combination of 130°C /115°C yet performed almost same as the HMA temperature combination of 160°C /145°C. He studied the performance characteristics of warm asphalt mixes at different doses of warm mix additive and 0.5% content of Evotherm™ as the optimum content for the asphalt mixtures. Hamburg WTD testing indicated no moisture damage in for all the prepared samples. He concluded that warm mix additive can statistically reduce the rut depth. The mix types with Evotherm™ additive present better rutting resistance with a reduced creep slope as compared to the HMA samples.

Rashwan (2012) studied three warm mix additives i.e. Advera, Sasobit® and Evotherm™ with two types of aggregates; he prepared the mixes at 120ºC and 110ºC and studied the performance properties of WMA in different applications. He conducted dynamic modulus test and flow tests to characterize the stress-strain relationship and permanent deformation properties of WMA in comparison to control HMA. He found that WMA mixtures had lower dynamic modulus |E*| values compared to control HMA mixes. It is due to the lower aging of WMA mixtures as they were exposed to lower production and compaction temperatures compared to the HMA control mixtures. The rutting resistance of WMA mixtures was found to be significantly lower than that of HMA mixtures based on flow number test results.

Arega et al. (2011) investigated the influence of natural wax in asphalt binders, warm-mix asphalt (WMA) additives, and reduced short-term aging on viscosity, stiffness, susceptibility to permanent deformation, fracture resistance, and thermal cracking resistance of asphalt binders. Short-term aged binders with high natural wax content demonstrated strong interactions with some of the WMA additives and increased susceptibility to permanent deformation. The PAV residues of binders with WMA additives had similar or lower fracture resistance compared with PAV residues of binders that were subjected to conventional short-term aging. Results from this study suggest that strategies such as the use of recycled asphalt to compensate for the initially reduced stiffness of binders in WMA mixtures must be carefully selected for each asphalt binder WMA additive pair to avoid an adverse impact on the fatigue cracking performance of the mix.

Silva et al. (2010) assessed the properties of various blends of base bitumen (softer to harder ones) containing a range of synthetic wax contents. The performance properties of warm mix asphalts were evaluated in order to get more sustainable mixtures. The different blends of various grades of bituminous binder and varying additive contents were prepared and characterized by conducting tests like penetration, softening point, viscosity and rheology. The performance characteristics of WMA and HMA were studied in terms of moisture sensitivity, mixture stiffness, resistance to fatigue failure and permanent deformation. The results indicated that the workability and compaction properties of the WMAs is similar to that of the corresponding HMA mixtures and the addition of synthetic waxes does not significantly change the moisture sensitivity of the WMA mixtures. The addition of wax additive increases the stiffness modulus and the rut resistance of the WMA mixtures but the fatigue resistance of the mix can only be enhanced by using softer grade of binders, due to the brittle behavior of the additive.

Diefenderfer and Hearon (2008) studied Sasobit® warm-mix materials. The authors compared laboratory test results with trial sections implemented in Virginia. They concluded that the HMA and WMA sites evaluated in their study performed similar for the first two years of service. The performance of the WMA and HMA sections was similar with respect to moisture susceptibility, rutting potential, and fatigue resistance.

Leng et al. (2014) characterized the mechanical properties of warm-mix asphalt prepared with two additives: Evotherm™ and Rediset®. The performance properties of the control SMA (stone matrix asphalt), Evotherm™ SMA, and Rediset® SMA were evaluated and compared through various tests like Complex modulus test, loading wheel track, indirect tension, and semi-circular beam at various curing time periods after compaction. They concluded that both warm SMA mixtures provided lower tensile strengths and complex modulus than the control SMA. The rutting and fracture resistance potentials of the two warm SMA mixtures were found similar to that of the control SMA. It was observed that curing time effect on the performance of the two warm SMA mixtures varied depending on the material property measured as well as the additive type as shown in the Figures 2.9 -2.11.

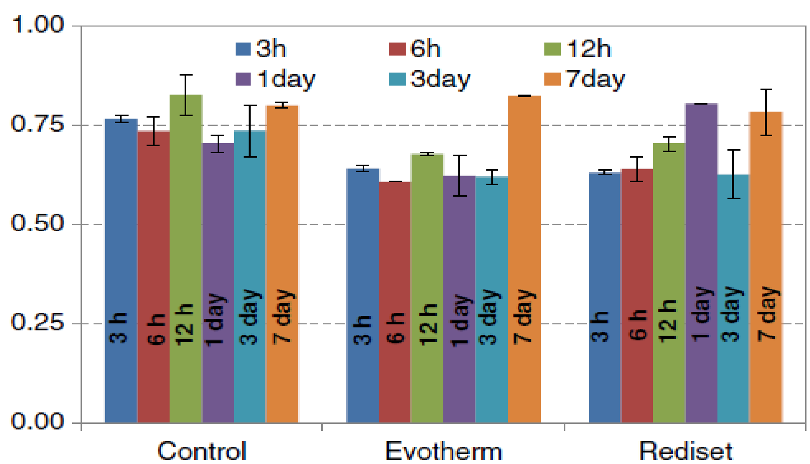


Figure 2.9: Indirect Tensile Strength (MPa)

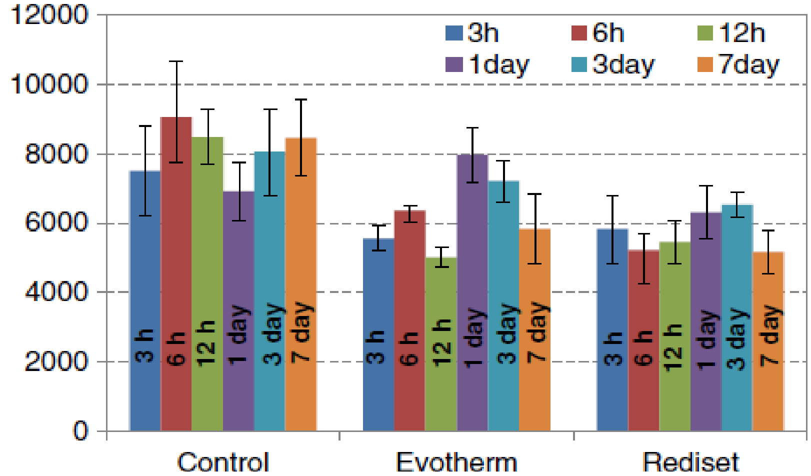


Figure 2.10: Complex modulus (MPa) at 10Hz

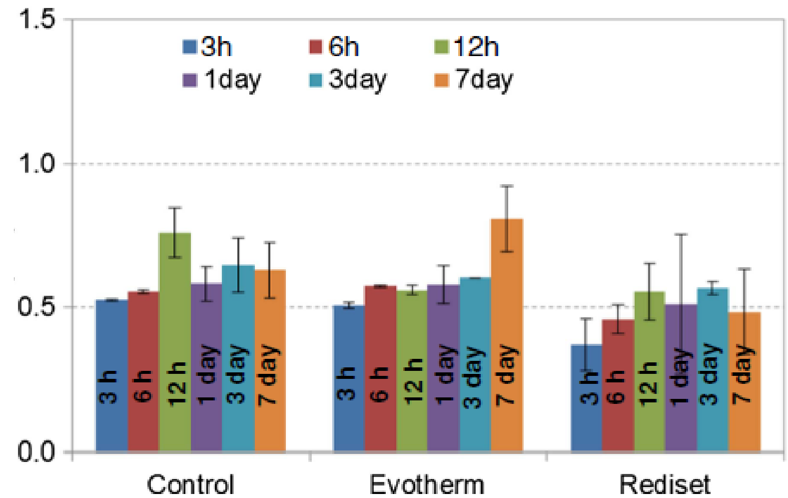


Figure 2.11: Rut Depth (mm) under dry condition at 20000 cycles

The results were compared statistically it was observed that the control SMA provided higher modulus and tensile strength in comparison to the Evotherm™ SMA and Rediset® SMA. The rut resistance and fracture resistance potentials of the three mixtures were statistically similar.

2.3 Literature on Energy Savings & Emission Reduction

One of the major advantages of warm mix asphalt is the reduction in the mixing and compaction temperatures. Decrease in the production and compaction temperatures of hot mix asphalt will directly lower the fuel usage and decrease the emissions connected to fuel use. The reduction in energy consumption due to lower mixing and compaction temperatures of WMA is the most obvious benefit of WMA and is the most discussed in literature. Studies have shown that energy consumption reductions of about 30% can be achieved by lowering the production temperatures at the asphalt plant. The reduction in energy consumption reduces the cost of the asphalt production The National Institute for Occupational Safety and Health (NIOSH), USA evaluated the potential health effects of occupational exposure to asphalt **(Olof, 2006)**. The principle adverse health effects are irritation of membranes of the conjunctivae and the respiratory tract. Based on studies conducted on animals, it is reported that asphalt left on the skin for long periods of time could result in local carcinomas. Therefore to keep the application temperature of heated asphalt as low as possible.

Mallick and Bergendahl (2009) found that addition of 1.5% of Sasobit® will generally lead to about 10–30ºC of reduction in mixing and paving temperatures as compared to HMA. They calculated that with these levels of Sasobit®, CO2 emission reductions around 32% from direct reductions and another 8% reduction from energy savings is possible. Hence an estimated joint reduction of about 40% can be achieved with the use of warm mix asphalt technology.

Larsen et al. (2004) found that energy or fuel can be saved approximately 30% and an equivalent emission reduction of CO_2 by opting WAM foam production temperatures between 100 and 120°C. For base course and wearing course mixtures WAM Foam process is suitable in Europe. In addition, they and Soto and Blanco (2004), indicated that on the road, in terms of longitudinal smoothness, (average) rut depth, and surface texture the behaviour of hot mixture sections and the corresponding the WAM foam sections is similar.

Middleton and Forfylow (2009) found that fuel consumption and emissions directly connected to fuel use reduced due to lowered temperature in production of WMA. This would lower the emissions of gaseous pollutants like NOx, CO, SO_2 and greenhouse gases (CO_2). In general, there would be reduction in emissions of hazardous air pollutants with decrease in the temperature of the asphalt production. Thus, even in area of strict air pollution regulations the asphalt plant can be operated. The decreased rate of cooling will allow more time for laying and compaction of asphalt and longer haul distances, which would facilitate paving season to be extended even during extreme weather conditions.

Lower fuel usage should lower the emissions of greenhouse gases (CO_2) and gaseous pollutants (CO, NO_x, SO_2). **Keches and LeBlanc (2007)** stated that Sasobit® in asphalt mixes allows reduction of carbon dioxide (CO_2) emissions since the temperature needed to mix is approximately 20ºC lower, 130ºC instead of 150ºC, than the conventional HMA temperature. They calculated the amount of emissions saved per year on the basis of reduction in energy required for producing asphalt mix at lower temperature the carbon dioxide emissions saved by producing asphalt mix materials at low temperatures were also calculated. Their results given in Table 2.2 & 2.3 indicate a significant reduction in carbon dioxide emissions achieved by using WMA in place of HMA.

Table 2.2: Yearly saving of Carbon Dioxide (CO2) emissions based on Energy Needed for Asphalt Industry

Q (per year for 500 million tonnes)	5.75E+16 J
U.S. Carbon Dioxide Emissions	1.67E+09 tonnes 1.67E+12 kg
U.S. Total Energy Use	3.27E+16 BTU 3.45E+19 J
CO2 Emissions Per Year (asphalt industry)	2.78E+09 kg 2.78E+06 tonnes
CO2 Emission Prevented Per Year (16%)	4.44E+05 tonnes

Q is the Heat energy required to raise the temperature of asphalt mix to a given temperature.

Table 2.3: Carbon Dioxide (CO2) Emissions Savings per Year Based on Measured Emissions from Asphalt Mix Materials

Mass of CO2 emitted (based on 60g HMA)	8.33E+02 mg 8.33E-04 kg
CO2 Emissions Released Per Year	6.94E+06 tonnes
CO2 Emissions Prevented Per Year	3.33E+06 tonnes

Romier et al. (2006) used the LEA (low energy asphalt) process in their research and stated that energy consumption and greenhouse gas emissions can be reduced significantly by adopting LEA process. This process involves the manufacture and application of asphalt mixes at a temperature lower than 100°C. They indicated that LEA mixes offer a performance equivalent to that of HMA. In this method they combined the action of the mixing energy, temperature, and water on the components of the mix, its bitumen, and aggregate skeleton. To prepare the LEA mix they heated only the coarse aggregates and the rest of the aggregate skeleton is used cold and wet. The results indicated that significant savings in mixing energy can be achieved and gas emissions are reduced to a great extent.

There are not much extensive studies or reports available in literature on the quantification of the reduction in fuel consumption at hot mix plants due to reduction in the mixing and compaction temperatures. **Kristjansdottir (2006)** estimated during some field trials of WMA that 10-30% of reduction in fuel consumption can be achieved depending on how much the production temperature is reduced.

2.4 Summary

The different warm mix additives affect the binder properties differently and also these warm mix additives affect the moisture susceptibility, rutting potential and resilient modulus of asphalt mixes differently. It is observed that not all the warm mix additives reduce the binder viscosity; hence the viscosity-temperature plots cannot be used to find out optimum mixing and compaction temperatures for warm mix asphalt. Therefore a methodology needs to be formulated to find the optimum mixing and compaction temperatures for warm mix asphalt.

Most of the studies available in literature are on conventional binders whereas modern performance requirements often dictate the use of polymer modified asphalt binders. Polymer binders are required to be heated to high temperature to make the mix workable. Effect of warm mix additives on performance of PMB is still not investigated much in literature. The durability of asphalt pavements constructed with WMA needs to be investigated in terms of binder effects (because the binder is either foamed or chemically modified) and increased potential for moisture damage. Conflicting results are sometimes reported in literature on effect of Warm mix additives on rutting resistance of a mix. This aspect needs to be investigated in detail to arrive at definite conclusions on their performance.

WMA technology is in very primitive stage in India and no thorough research has been conducted to investigate many aspects of warm mix asphalt. Therefore, a thorough understanding of the warm mix binder properties and performance of warm asphalt mixes is necessary in order to be able to implement WMA in India.

CHAPTER 3

EXPERIMENTAL PROGRAMME

This chapter provides a description of the materials used in this study, the research plan to complete the proposed study and the experimental procedures followed to accomplish the objectives of the research.

3.1 Materials Used

Bituminous binders, warm mix additives and stone aggregates are used in this study as described below.

3.1.1 Binders

Two different binders namely viscosity grading bitumen (VG-30) and polymer modified bitumen (PMB-40) were selected for this study, as they are the most widely used binders for road construction in India. The binders were procured from OOMS Polymer Modified Bitumen Pvt. Ltd in 10kg sealed containers to prevent oxidation and premature aging. Different physical and consistency properties of selected binders were determined as per relevant Bureau of Indian Standards (BIS) and results are shown in Table 3.1 and 3.2 for VG30 and PMB 40 respectively.

Table 3.1: Physical Properties of VG-30 (BIS: 73, 2006)

Parameter	**Reference Test Method (BIS)**	**VG-30**	
		Result	**Specified limits**
Absolute Viscosity at 60°C, P	1206 (Part 2) (1978)	2528	Min 2400
Kinematic Viscosity at 135°C, cSt	1206 (Part 3) (1978)	567	Min 350
Penetration at 25C, 100g, 5s, 0.1mm	1203 (1978)	62	50-70
Softening Point °C	1205 (1978)	52	Min 47
Test on Residue from RTFO test			
Viscosity Ratio at 60°C, P	1206 (Part 2) (1978)	1.9	Max 4

Table 3.2: Physical Properties of PMB-40 (BIS: 15462, 2006)

Parameter	Reference Test Method (BIS)	PMB-40	
		Result	Specified limits
Penetration at 25C, 100g, 5s, 0.1mm	1203 (1978)	47	30-50
Softening Point °C	1205 (1978)	60	Min 60
Flash Point, °C	1209 (1978)	278	Min 220
Elastic recovery of half thread in ductilometer	15462, (2004)	70	Min 70
Separation, difference in softening point	15462, (2004)	2	Max 3
Viscosity at 150°C,P	1206 (Part I) (1978)	3.52	3-9
Test on Residue from RTFO test			
Increases in softening point, °C, max	1205 (1978)	3	Max 5
Reduction in penetration of residue, at 25°C, %	1203 (Part 2) (1978)	11	Max 35

3.1.2 Aggregates

The quartzite aggregates used in the study were collected from a local stone crusher. They were tested for their physical properties and found suitable as per MoRTH-2001 Specifications for bituminous concrete. The physical properties of aggregates were studied as per BIS codes [IS: 2386-1963 (Part 1-6)] and the results are shown in Table 3.3.

Table 3.3: Physical properties of the aggregates

S.No	Test		Results	Recommended Value as per MoRTH section 500 clause 509
1	Specific gravity	Coarse aggregate	2.67	-
		Fine aggregate	2.56	
		Filler	2.36	
2	Water absorption		0.45%	2% maximum
3	Flakiness and Elongation Indices		21%	30% maximum
4	Aggregate Impact value		21%	24% maximum
5	Stripping of Bitumen aggregate		98%	95% minimum
6	Soundness with Sodium Sulphate, %		10%	12% maximum

3.1.3 Warm Mix additives

Three different warm mix additives were used in this study. Warm mix additives are generally categorized in to 4 different categories; organic wax based additives, chemical additives, synthetic zeolites and surfactant based additives. In this research study, a wax based additive (Sasobit®), a chemical based additive (Rediset®), and a surfactant based additive (Evotherm™) were selected. These are briefly described below and shown in Figure 3.1.

Sasobit®

Sasobit®is a Fischer – Tropsch (FT) wax and it is available in India in the form of white coloured granules. It is a long - chain aliphatic hydrocarbon wax with a melting point between 85°C and 115°C, high viscosity at lower temperature and low viscosity at higher temperature. It is obtained from coal gasification using the Fischer-Tropsch process.

Evotherm™

Evotherm™ is a liquid based warm mix additive. It was developed by MeadWestvaco Corporation with no water that would reduce an internal friction between binder and aggregate and between coated aggregate particles during mixing and compaction. According to the manufacturers, an emulsion is created when Evotherm™ is mixed with the asphalt. When this emulsion is used for mixing the aggregates, it creates better workability, aggregate coating, adhesion, and increased compaction.

Rediset®

Rediset® more commonly known as Rediset® is a combination of organic additives and surfactants that is developed to enhance the adhesion between asphalt and aggregates. The manufacturer of Rediset®, Azko Nobel claims that the surfactants improve the wetting ability of the asphalt binder for better coating with the aggregates, and the organic additives provide a reduction of the viscosity of the binder and a lubricating effect for easier coating and compaction. It is supplied in pellet form that can be added at a dosage rate of 1.5% to 2.5% by weight of binder either to the asphalt or the mixture. Rediset® is said to improve the cohesive strength of the asphalt and reduces the rutting and moisture sensitivity of the final pavement.

(a) (b) (c)

Figure 3.1: Additives used (a) Evotherm™ (b) Rediset® (c) Sasobit®

3.2 Experimental Plan

The proposed research is carried out in two parts addressing the specific objectives of the research. Part 1 is the Characterization of Warm Asphalt Binders, and part 2 is the Characterization of Warm Asphalt Mixes, both the parts were carried out simultaneously. The details of the experimental plan are outlined in the following sections.

3.2.1 Characterization of Warm Asphalt Binders

Part 1 of the study was conducted to study the rheological properties of the VG30 and PMB40 binders modified with different types of warm mix additives. Sasobit®, Evotherm™ and Rediset® were used to modify neat VG30 and PMB40 binders. The rheological tests were performed to evaluate the effects of warm mix additives on the viscosity of the binders and to study the effect of these warm mix additives on the properties of mastics prepared by using limestone dust filler material at different filler/binder (F/B) ratios. The tests were also done to evaluate the response of warm asphalt binders at different temperatures and different loading frequencies. Zero shear viscosities of warm asphalt binders and mastics were also studied to estimate the rutting potential of these binders. Various other properties like temperature susceptibility, aging index, short term and long term aging, creep stiffness and m-value of warm asphalt binders were also evaluated. Fourier Transform Infrared Spectroscopy was performed to find the aging characteristics of warm mix asphalt binders. Figure 3.2 and 3.3 show the testing plan followed to study the rheological and ageing properties of the warm asphalt binders.

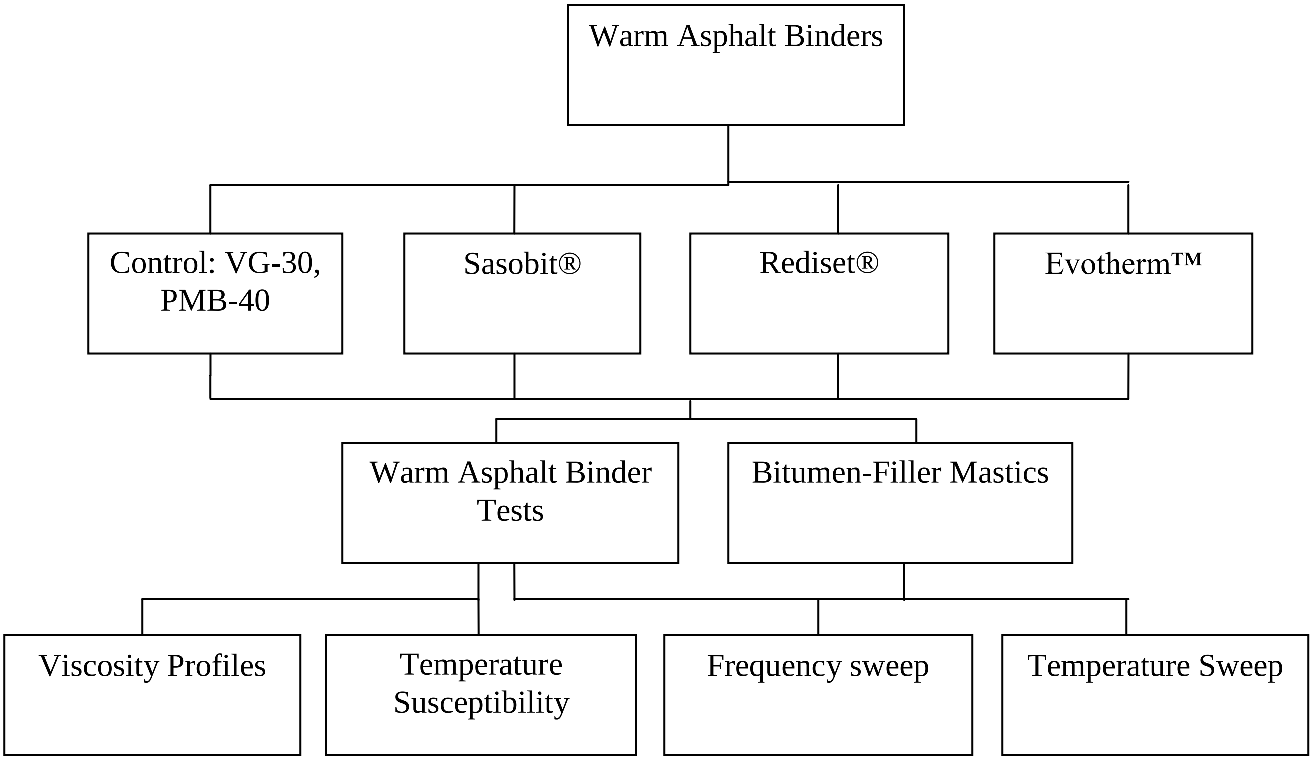


Figure 3.2: Experimental plan for rheological tests on warm asphalt binder

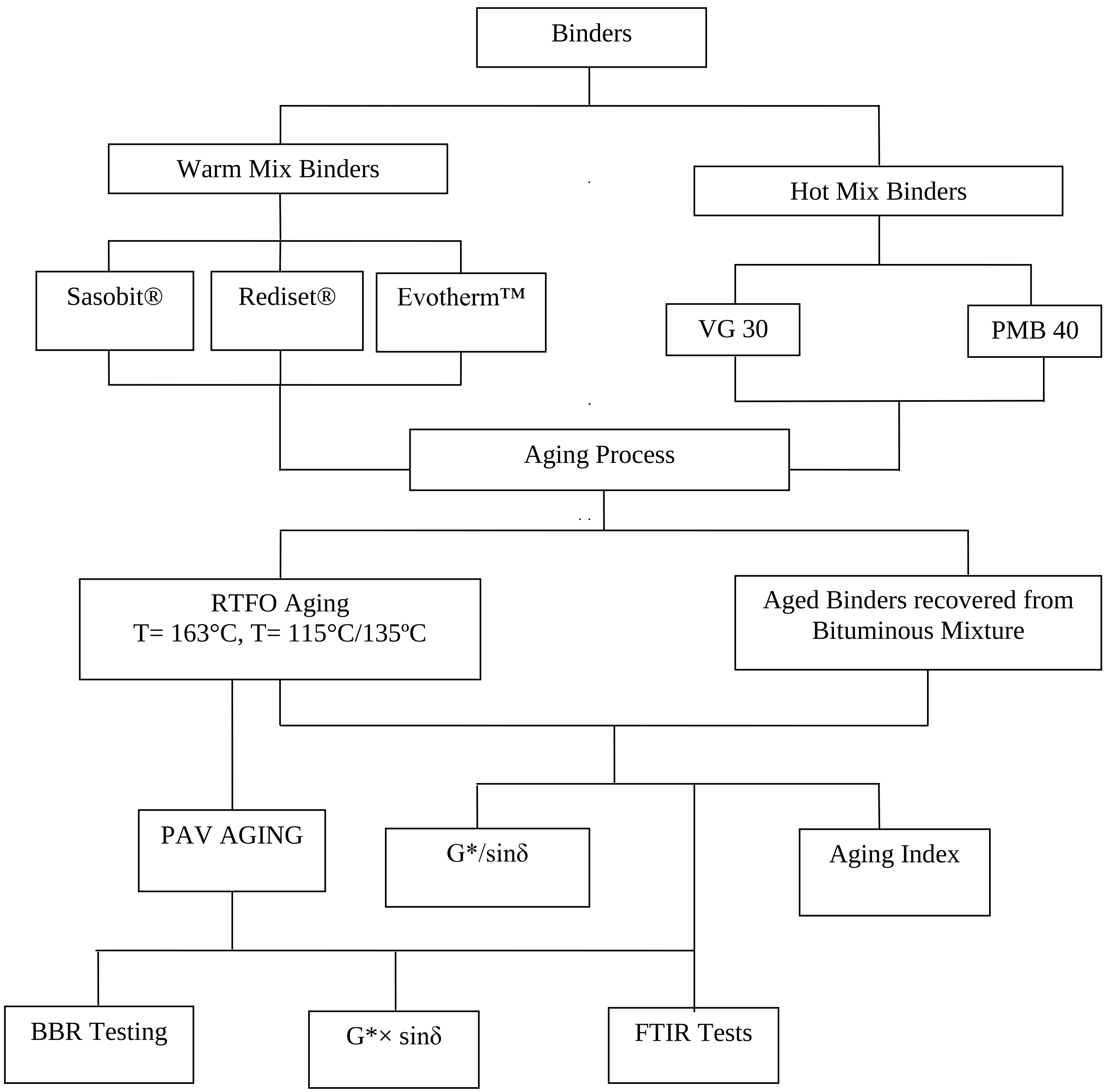


Figure 3.3: Experimental plan for Ageing of Warm mix binders

3.2.2 Characterization of Warm Asphalt Mixes

Part 2 of the study was conducted to find the optimum doses of the warm mix additives and to find the optimum mixing temperature for the production of bituminous mixture using the warm mix additives. The performance properties of the bituminous mixtures produced with VG30 and PMB40 binders modified with different warm mix additives are also studied in this part. The main objective of the task 2 was to study the performance of warm mix asphalt (WMA) with respect to hot mix asphalt (HMA). This task was carried out as per the experimental plan shown in Figure 3.4.

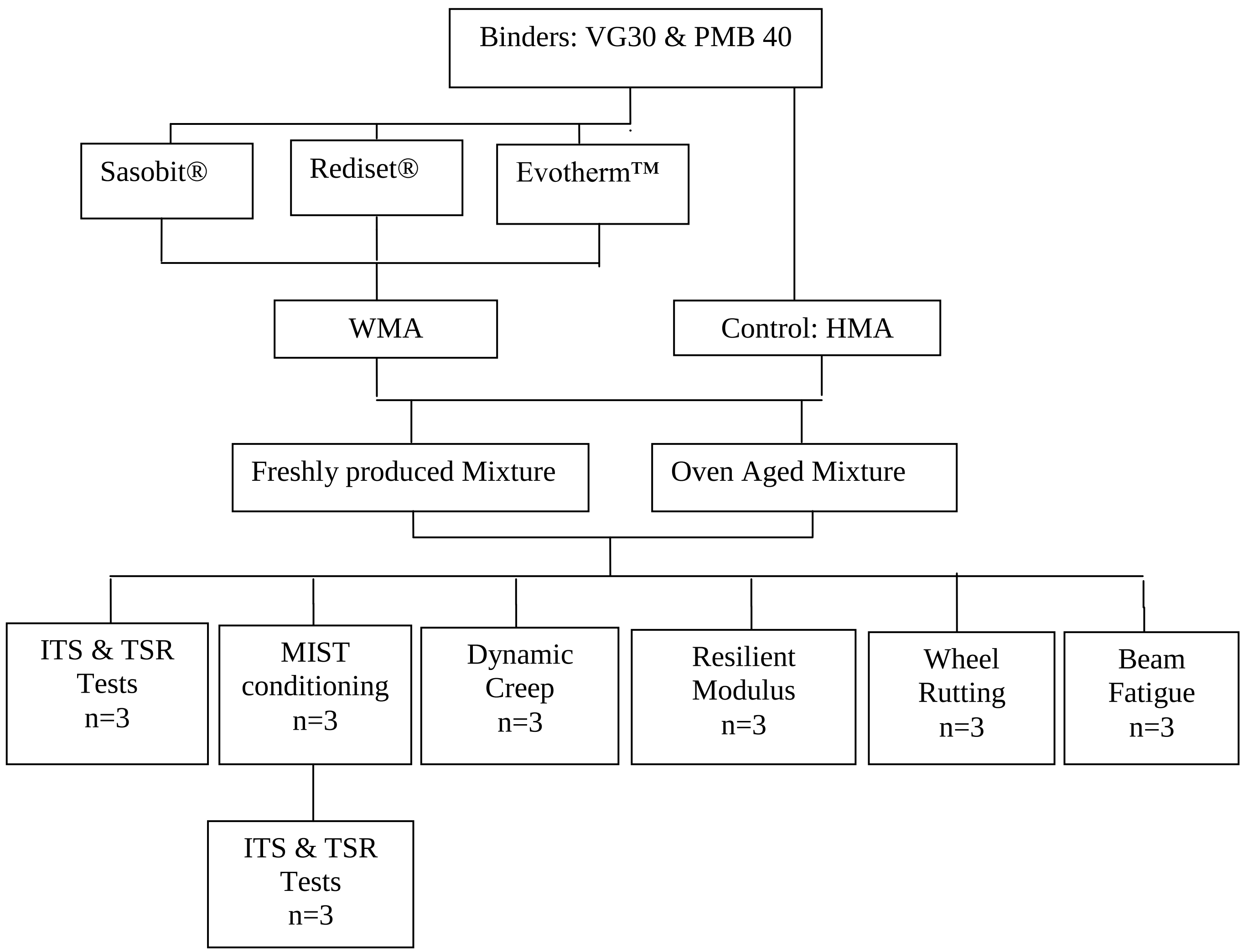


Figure 3.4: Experimental plan for investigating performance of warm mix asphalt

3.3 Experimental Procedures

3.3.1 Warm Asphalt Binder and Mixture Preparation

Warm asphalt binder was prepared using two different binders and three warm mix additives at three different doses, so as to create a total of 18 warm asphalt binders. Sasobit® was added at 2%, 3% and 4% by weight of the bitumen, Rediset® was added at 1%, 2%, 3% by weight of the bitumen and Evotherm™ was added at 0.5%, 1%, and 1.5% by weight of the bitumen. The process of making warm mix binders involved the addition of the warm mix additive at the desired concentration to the control binders (VG-30 and PMB-40), followed by mixing in an electric high shear mixer for 15-20 minutes at a temperature of 150ºC for VG-30 based binders and 170ºC for PMB-40 based binders.

The Marshall method of mix design for the 40mm BC grading with 13.2mm nominal aggregate size was followed in this study. The aggregate gradation was selected as recommended by MoRTH-2001 Specifications for bituminous concrete, and was obtained by adopting mid-point grading as shown in Table 3.4.

Table 3.4: Aggregate Gradation for Bituminous Concrete

Grading	**2**	**Grading Adopted**
Nominal aggregate size	**13.2 mm**	
IS Sieve Size (mm)	**Cumulative % by weight of total aggregate passing Recommended Range (MoRTH-2001)**	
19	100	100
13.2	79-100	90
9.5	70-88	79
4.75	53-71	62
2.36	42-58	50
1.18	34-48	41
0.600	26-38	32
0.300	18-28	23
0.150	12-20	16
0.075	4-10	7

Three Marshall Specimens each were prepared at four different (4.5%, 5%, 5.5%, 6%) percentage of bitumen content by weight of the total mix, by applying 75 blows on each face of the sample. Optimum binder content was calculated as per Asphalt Institute Manual MS-2 by taking the bitumen content corresponding to 4.0% air voids and checking other parameters of Marshal stability, voids in mineral aggregates (VMA), voids filled with bitumen (VFB), bulk density and flow value as per MORTH specification-2001 for bituminous concrete. Table 3.5 shows the values of optimum binder content (OBC) obtained for VG-30 and PMB-40 binder

Table 3.5: Optimum binder content values

Type of the binder	Optimum binder content obtained Percent by weight of the total mix
VG-30	5.1%
PMB-40	5.2%

The mix design results of control HMA were adopted for WMA also. The obtained mix design and OBC were used to make warm asphalt mixes with various warm binders. A total of 18 warm asphalt mixes and two control hot asphalt mixes were prepared. Warm asphalt mixes were prepared at four different temperatures i.e. at 135ºC, 125ºC, 115ºC, 105ºC for VG-30 based warm asphalt mixes and at 145ºC, 135ºC, 135ºC and 115ºC for PMB-40 based warm asphalt mixes. Marshall stability, retained stability, bulk density and air voids were calculated for all the mixes and the optimum dosage of the warm mix additive and the optimum mixing temperature was obtained by comparing the results of WMA and HMA. Further performance characterization of warm asphalt mixes was carried out at these fixed dosages of additives and at optimum mixing temperatures.

3.3.2 Binder Characterization

A Brookfield viscometer (Figure 3.5a) was used to find the viscosity of the binders with and without warm asphalt additives. The viscosities of the binders were measured at various temperatures ranging from 100ºC to 150ºC as per AASHTO T316 (AASHTO standards 2004). Penetration tests were conducted at three different temperatures 15ºC, 25ºC, 30ºC using a standard penetrometer (Figure 3.5b) as per IS-1203. The viscosity values and penetration values were used to calculate Penetration Index (PI), Viscosity Temperature Susceptibility (VTS) and Penetration Viscosity Number (PVN), which were further used to determine the temperature susceptibility of warm mix binders in comparison to control binders. All the viscosity and penetration measurements were repeated on three samples.

(a) **(b)**

Figure 3.5: (a) Brookfield Viscometer, (b) Penetration Test Apparatus

Anton Paar dynamic shear rheometer (DSR) (Figure 3.6) was used to study the rheological properties of the warm mix binders. Failure temperature was evaluated by performing temperature sweep test on DSR over a temperature ranging from 43^0C to 85^0C on warm mix binder and bitumen-filler mastic samples. 25 mm diameter plate is used at 12% controlled linear strain and 10 red/sec angular frequency with 1mm gap between parallel plate. Complex modulus (G*), phase angle (δ), complex viscosity (η*), and G*/sinδ values were measured. The dynamic oscillatory testing was performed on the base bitumen and bitumen-filler mastics under small strain-controlled loading conditions by applying a sinusoidal angular displacement of constant amplitude within the linear viscoelastic domain. Frequency sweeps were performed over a range from 0.1 to 20 Hz (0.625 to 125 rad/s) at 40^0C and 60°C to measure the complex dynamic viscosity (η*), complex modulus (G*), and phase angle (δ). Test geometries with gaps at test temperatures were 25-mm-diameter parallel plates with a 1-mm gap at 60°C and 8-mm-diameter parallel plates with a 2-mm gap at 40°C.

To study the effect of warm mix additives on the rheological properties of bitumen-filler mastics, limestone mineral filler was used for preparing the mastic. The filler-to-bitumen ratio was taken as

0.5, 1.0, 1.3, and 1.5 to prepare the bitumen-filler mastics from virgin as well as warm mix binders. Frequency sweep and temperature sweep tests were performed on these mastics. Bitumen-filler mastics were studied with an understanding that in an asphalt mixture, bituminous binder occurs not as bitumen alone but is mixed with mineral fillers. Therefore the zero shear viscosities of bitumen-filler mastic as opposed to those of plain bitumen may be more appropriate in establishing a correlation with the permanent deformation properties of asphalt mixtures.

Figure 3.6: Dynamic Shear Rheometer

The warm mix binders and control binders were aged in a rolling thin film oven (RTFO) (Figure 3.7) to simulate the process of short term aging. The aging of binders was done as per AASHTO T240. Since the warm mix asphalt is mixed at a lower temperature than hot mix asphalt, the RTFO aging of warm mix binders was conducted at a lower temperature also to simulate the aging process of these binders in a better way. The lower temperature for RTFO aging of warm mix binders was selected corresponding to the optimum mixing temperatures of warm mix asphalt. Warm mix binders were aged at lower temperatures as well as at 163ºC also to have better comparison with the aging of control binders (VG-30 & PMB-40). The RTFO residues were tested for $G^*/\sin\delta$, viscosity and aging indices were calculated for all the binders.

The RTFO aged binder residues were further aged in the pressure aging vessel (PAV) (Figure 3.8) to simulate long term aging of the binders. The PAV aging of all the binders were carried out as per AASHTO R28. The temperature for aging of warm mix binders and as well as the control binders was kept similar, as the warm mix asphalt and hot mix asphalt are subjected to similar field condition once they are placed on the pavement. The PAV residues were tested for stiffness, m-value, G*× sin δ, and FTIR spectrometry. The bending beam rheometer (BBR) (Figure 3.9) was used to measure the stiffness and the rate of change of stiffness i.e. m-value of the binders with and without the warm asphalt additives. The BBR test was carried out as per AASHTO T313.

Figure 3.7: Rolling Thin Film Oven

Figure 3.8: Pressure Aging Vessel

Figure 3.9: Bending Beam Rheometer

The binders from warm asphalt mixes and hot asphalt mixes were extracted using a rotovapor as per ASTM D2172 and ASTM D5404 and were then recovered using abson recovery method. Fourier transform infrared spectrometry (FTIR) was used as a tool to quantify the amount of aging occurred in the binders with and without warm mix additives. The test was carried out on the RTFO residues, PAV residues and the recovered binders. FTIR tests were performed on these extracted binders in order to see the effect of low mixing and compaction temperatures on the aging of warm asphalt mixes. The FTIR peaks of these recovered binders were compared with those of RTFO aged binders.

FTIR measurements were taken on a Shimadzu IR Prestige 21 instrument (Figure 3.10) equipped with a Deuterated Triglycine Sulfate (DTGS) detector. IR spectrometer parameters are set to scanning range 4000-400cm^{-1}, resolution 4cm^{-1} and number of scans 200. The instrument was flushed with nitrogen, and 50 background spectra were collected. Sample in free flow condition was placed on KBr plate and formed as thin film. Recorded spectra were processed using IR Solution software Version 1.50 for baseline correction, smooth and peak identification.

Figure 3.10: FTIR Instrument

3.3.3 Mixture Characterization

The optimum binder content, optimum dosage of the additives and optimum mixing temperatures were obtained by conducting tests on Marshall Specimens. Further performance tests on mixtures were conducted at OBC and optimum dose of the additives. The air voids in the mix were maintained at 7$\pm$ 0.5% for the tests like Indirect tensile strength (ITS), Tensile strength ratio (TSR) and Moisture induced sensitivity test (MIST) and at 5% for other performance related tests like resilient modulus, dynamic creep tests, beam fatigue and wheel rutting tests. A total of 240 Marshall Specimens were prepared to perform all these tests. 120 of these Marshall specimens were artificially aged in the oven as per AASHTO R30 at 85ºC for 120 hours. A total of 24 slabs of 300x300x50mm dimensions were made for wheel rutting tests and 24 beams of dimensions 380x63x50mm were made for fatigue tests at air voids of 5%.

Figure 3.11: Marshall Setup for ITS Test

The moisture susceptibility of warm and hot mixes was evaluated through the tests like ITS (indirect tensile strength), TSR (tensile strength ratio) and MIST (moisture induced sensitivity test) on un-aged as well as oven aged samples. ITS test was carried out as per ASTM: D6931-12. The splitting tensile strength of a cylindrical bituminous mix (Figure 3.11) specimen placed with its axis horizontal between the plates of a compressive testing machine was measured. TSR test was done as per AASHTO T283. It is the ratio of wet ITS to the dry ITS of Marshall specimens. For wet ITS the Marshall specimens were immersed in water at 60ºC for 24 hours and then kept in water bath at 25ºC for 2 hours. The Marshall specimens for dry ITS were conditioned in an air chamber at 25ºC for 4 hours before testing.

In most of the studies available in literature, the researchers have added 2%-3% of water in addition to the absorption value of aggregates, in to the mix before it was heated. This was done to simulate the condition that if the moisture contained in the aggregate does not completely evaporate during mixing due to the low mix temperatures, water may be left in close contact with the aggregate surface, which could lead to increased susceptibility to moisture damage. Whereas in the present study no additional moisture was added in to the mix. The aggregates were obtained from local source and were used to prepare asphalt mixes as per the bituminous mix design adopted in the study.

The MIST test was carried out as per ASTM: D 7870-13. The accelerated moisture conditioning was provided to the Marshall specimens under cyclic loading by simulating the action of traffic on wet pavement. When a tire rolls over a wet pavement, the water caught between the tire and the pavement is subjected to high pressure, which forces the water into the accessible pores. Once the tire rolls away from that region, the pressure is reduced and water drains. This condition was replicated in the laboratory using the Instro Tek MIST machine (Figure 3.12-3.15) as per ASTM: D 7870-13 by cyclically applying and removing high pressure from unsaturated compacted samples. To further accelerate the potential damage to the core, the test is performed at elevated temperature of 60° C. The Marshall specimens were conditioned at 60ºC and 40 psi for 3500 cycles before testing. After the completion of 3500 cycles, the MIST conditioned samples were then conditioned in water bath at 25ºC for 2 hours. The conditioned specimens were then tested for ITS.

Figure 3.12: Front view of Instro Tek MIST

Figure 3.13: Side view of Instro Tek MIST

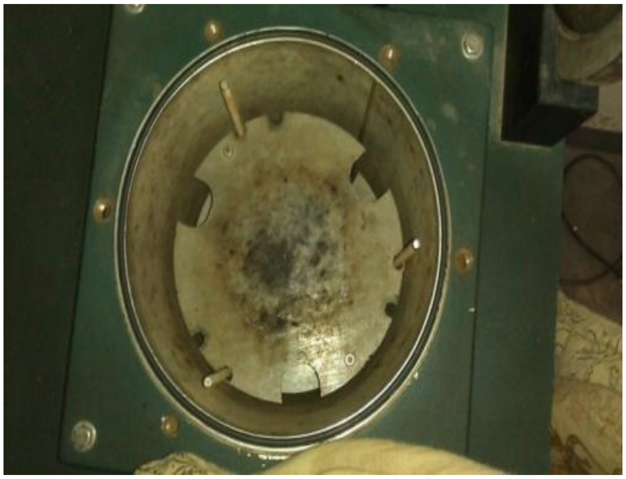


Figure 3.14: Specimen chamber of MIST

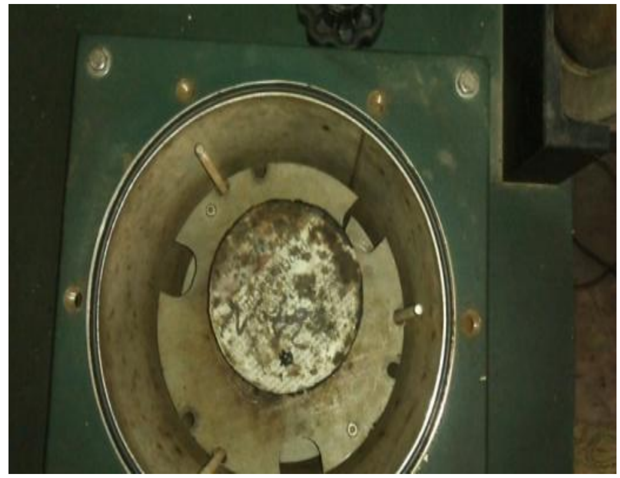


Figure 3.15: Specimen Chamber containing sample

Resilient Modulus is an important parameter to determine the performance of the pavement, to analyze the pavement response to traffic loading. The resilient modulus test of bituminous mixtures is conducted through repetitive applications of compressive loads in a haversine waveform using Universal Testing Machine (UTM) (Figure 3.16-3.17). The compressive load is applied along a vertical diametric plane of a cylindrical specimen of asphalt concrete. The resulting horizontal and vertical deformations of the specimen are measured. Poisson's ratio values are calculated using recoverable vertical and horizontal deformations. Using the calculated Poisson's ratio, the resilient modulus values are subsequently calculated. In this study Resilient Modulus test was carried out as per ASTM: D7369-11 at 25ºC and at 45ºC. Specimens were conditioned at the selected test temperatures for 6 hours prior to testing. The test was conducted by applying a compressive load in the form of Haversine wave with a load time of 0.1 second and a rest period of 0.9 seconds. This test was done on both un-aged as well as aged samples.

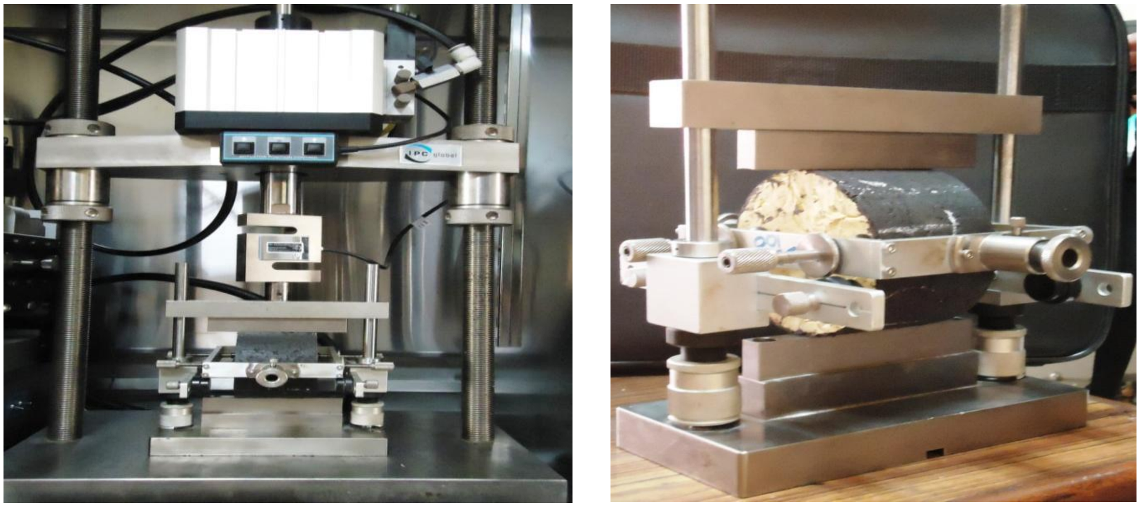


Figure 3.16: UTM for Resilient Modulus Test and Setup

Figure 3.17: Samples in environment chamber UTM

The dynamic creep test is effective in identifying the sensitivity of asphalt concrete mixtures to permanent deformation or rutting. The test was conducted as per NCHRP 9-19 (unconfined) at a test temperature of 40ºC. Marshall specimens were placed in the temperature control cabinet for 2 hours to bring the core temperature of the specimens to the test temperature before testing. Seating stress of 11 kPa was applied on the specimen to ensure a positive contact between the loading plate and the specimen. A cyclic stress of 69 kPa having a haversine waveform with loading period of 0.1 seconds followed by a rest period of 0.9 seconds was applied for 3600 cycles, and total accumulated strain (%) was recorded (Figure 3.18). This test was conducted on un-aged as well as aged specimens for both WMA and HMA.

Figure 3.18: Dynamic creep test in progress

Fatigue life of compacted HMA and WMA was determined as per AASHTO: T 321-07 under repeated traffic loading. Three replicate beams were prepared for each test using automatic roller slab compactor (Figure. 3.19). Specimen beams were conditioned in an environment chamber at 25ºC for two hours prior to testing. The beams were subjected to repeated sinusoidal loading at a frequency of 10 Hz subjecting the beams to four-point bending (Figure. 3.20) with free rotation and horizontal translation at 200, 300 and 400 micro strain levels and the deflection of the beams were measured using the CDAS (control and data acquisition system).

Figure 3.19: Beams prepared using automatic slab roller compactor

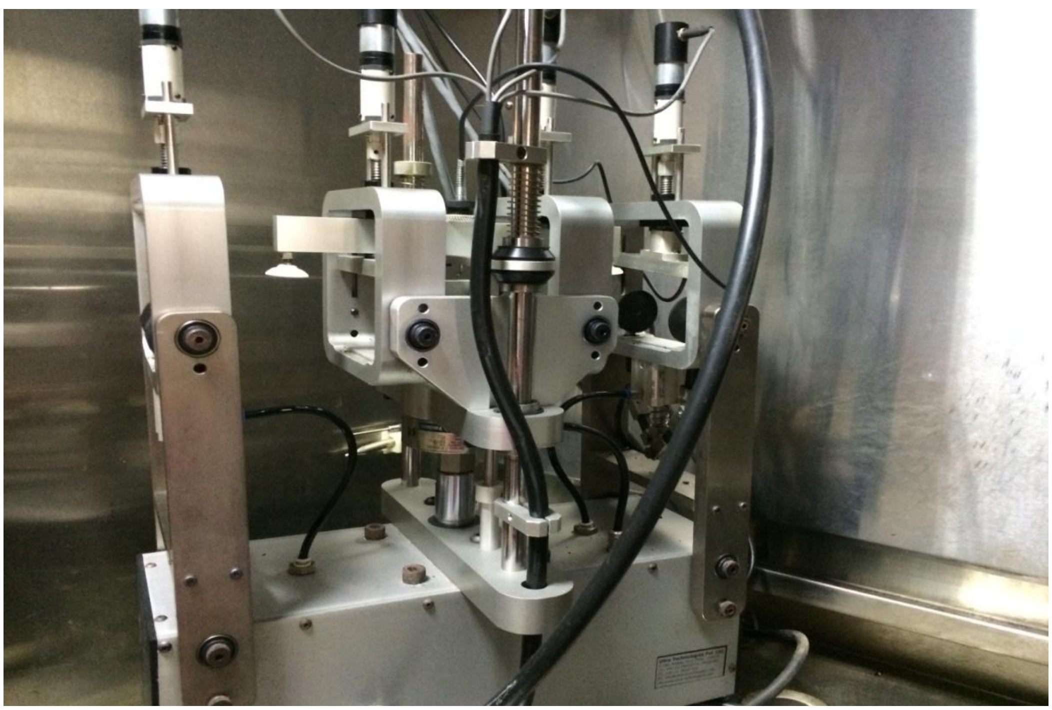


Figure 3.20: Four point Bending Beam Apparatus inside UTM

Wheel tracker device (WTD) was used to assess the resistance to rutting of warm and hot asphaltic materials under conditions which simulate the effect of traffic. Here, a loaded wheel tracks a sample under specified conditions of load, speed and temperature while the development of the rut is monitored continuously during the test. 24 slab specimens were prepared in laboratory by using warm mix binders as well as control binders. The slabs were conditioned at 60ºC for 2-3 hours prior to testing. Repetitive loading is considered essential to properly measure, the influence of mixture composition on resistance to permanent deformations. The rate of permanent deformation accumulation increases rapidly at higher temperatures; thus the laboratory testing was conducted at a higher temperature of 60°C. The test method covers the determination of rut depth of rectangular specimen (slab) of bituminous mixes (Figure 3.21). Rutting in the specimen occurs due to repetitive action of wheel subjected to standard axle load. The slab specimens were subjected to reciprocate load repetitions for 10,000 passes or till a rut depth of 10mm. The wheel tracking apparatus (Figure 3.22) consists of loaded wheel which bears on a sample held on a moving Table and the moving Table reciprocates with simple harmonic motion with a frequency of 42 passes per minute. The wheel is fitted with solid rubber tire and the mixes were evaluated under a loaded wheel (520 ± 5 N) (European Standard- PrEN 13108/12697-22, 2002)

Figure 3.21: Wheel Rutting Test Samples

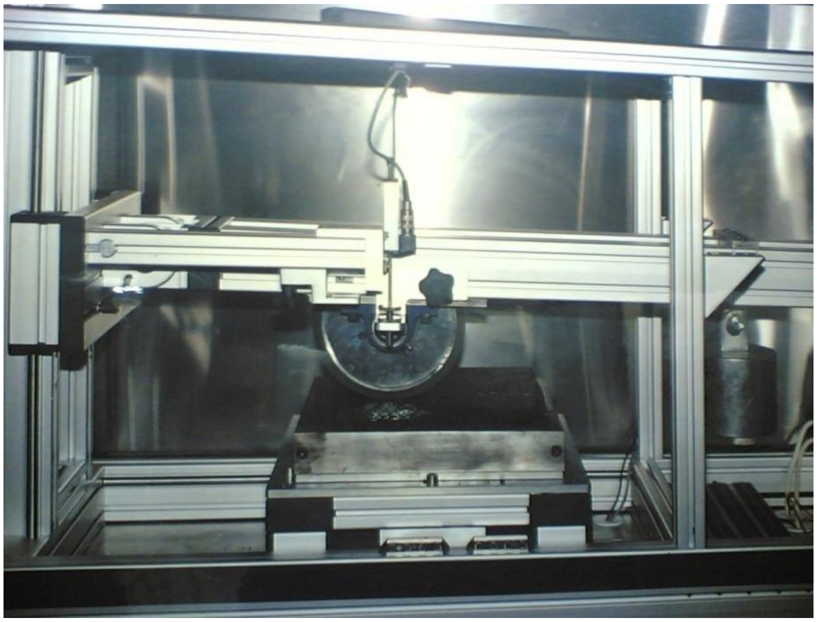


Figure 3.22: Wheel Rutting Machine

3.4 Summary

This chapter describes the testing protocol on binders and mixes followed in this research. Various tests for characterization of binders and bitumen-filler mastics are explored in detail. These include viscosity profiles, temperature susceptibility, frequency sweep, temperature sweep tests, short term and long term ageing of binders, ageing indices, stiffness and m-value and FTIR spectroscopy.

Similarly, tests conducted on bituminous mixtures for comparing the strength and performance characteristics of warm mix asphalt with hot mix asphalt are included in this chapter. Test results on binders are presented in chapter 4 while those on mixtures are discussed in chapter 5.

CHAPTER 4

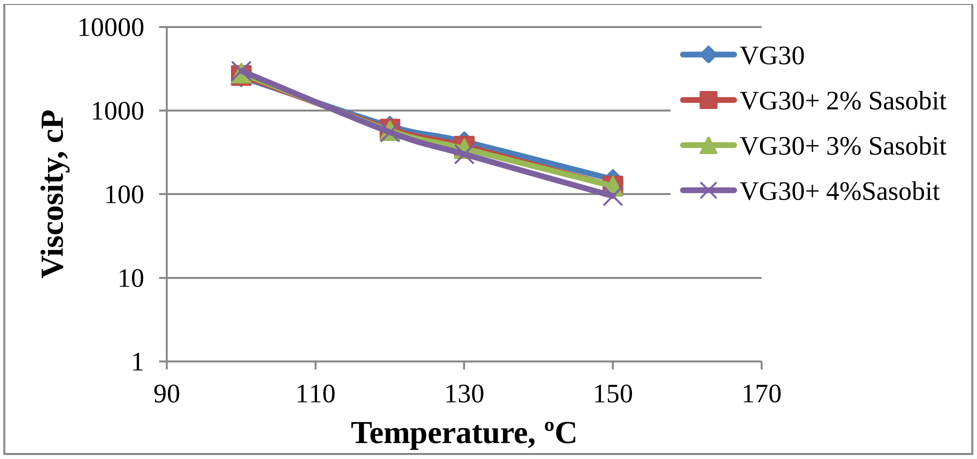
CHARACTERIZATION OF WARM ASPHALT BINDERS

VG-30 and PMB-40 binders were modified with Sasobit®, Evotherm™ and Rediset® at three different dosages and 18 formulations of warm mix binders were prepared. To observe the effect of warm mix additive on rheological properties of binder in the presence of aggregates, binder-filler mastic was prepared using lime stone filler. Four doses of filler were taken to produce 72 formulations of mastics. These warm mix binders and bitumen-filler mastics were characterized by the different tests and results are reported in this chapter.

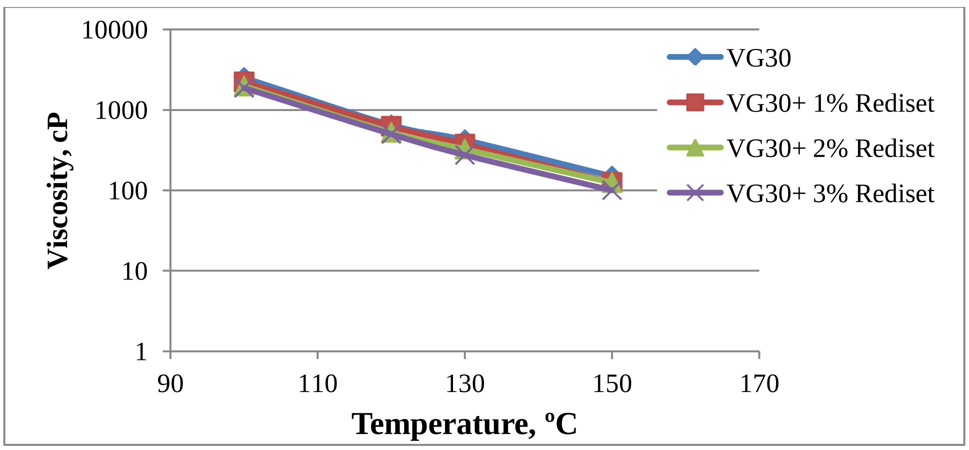
4.1 Effect of temperature on Viscosity of Binders

Figure 4.1 and 4.2 show the viscosity vs. temperature plots of VG 30 and PMB 40 binders with and without warm asphalt additives. It is observed that the addition of warm mix additives at different dosages did not alter the viscosity of the virgin binders substantially. Figure 4.1 (a) indicates that addition of Sasobit® slightly increased the viscosity of the VG 30 at temperature below 100ºC. Beyond 100ºC the viscosity reduces with increase in the concentration of Sasobit®. The viscosity decreases more noticeably at higher concentration of Sasobit® at 150ºC which is the potential ability of Warm Mix Asphalt additive to reduce the mixing temperature. Higher viscosity is observed at temperature below 100ºC because the melting point of Sasobit® is about 95ºC-100ºC. The manufacturer also claims that Sasobit® melts at temperatures 95ºC to 115ºC, and Sasobit® is completely soluble in the binder at temperatures above 115ºC and forms a homogeneous solution with the binder, resulting in a significant reduction in the viscosity of the binder. At temperature below 110ºC -115ºC, the Sasobit® additive remains present in the binder as a wax due to which it shows increase in the viscosity of the virgin binder. Similar trend was seen when PMB 40 was modified with Sasobit®. Figure 4.2 (a) shows that addition of Sasobit® increased the viscosity of PMB 40 at lower temperature and starts showing reduction in the viscosity at temperatures above 115ºC with a significant viscosity reduction in the temperature range of 130ºC-170ºC.

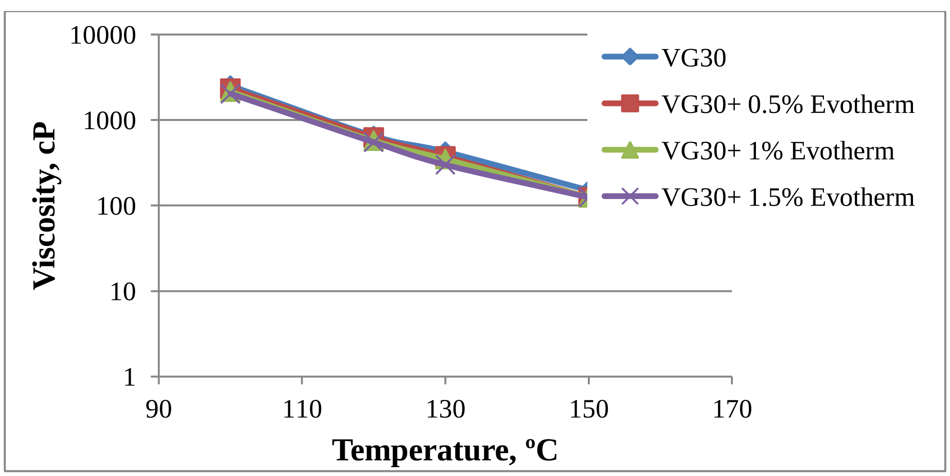
Rediset® is a chemical based additive; it shows some reduction in the viscosity of the virgin binder. Figure 4.1 (b) and 4.2 (b) show that addition of Rediset® decreased the viscosity of the virgin binders. Reduction in viscosity was more in the case of PMB40 than that in VG30. The melting point of Rediset® is around 110ºC, which explains that why Rediset® showed the reduction in viscosity of the virgin binders at temperatures above 110ºC. Evotherm™ had no significant effect on viscosity of two binders. VG 30 showed no reduction in viscosity after adding Evotherm™ additive, whereas PMB40 showed slight reduction. This shows that this additive does not interfere much in the viscosity reduction of the virgin binder. This goes with the claim of the manufacturer that Evotherm™ additive does not change the viscosity of the asphalt binder. It only works in the mix by reducing the internal friction between the aggregate and the binder resulting in low mixing and compaction temperature of the mix. Evotherm™ is a surfactant based additive which promotes interfacial adhesion between the binder and the aggregate. When added to the bitumen-aggregate mix, a portion of the Evotherm™ molecules migrate to the bitumen-aggregate interface and the polar heads are attracted to non polar properties of the aggregate, and hence increasing the workability of the mix at lower temperatures which also explains as to how Evotherm™ helps in achieving asphalt mix workability at lower temperatures. This aspect is further studied in section 4.3.



(a) Sasobit®

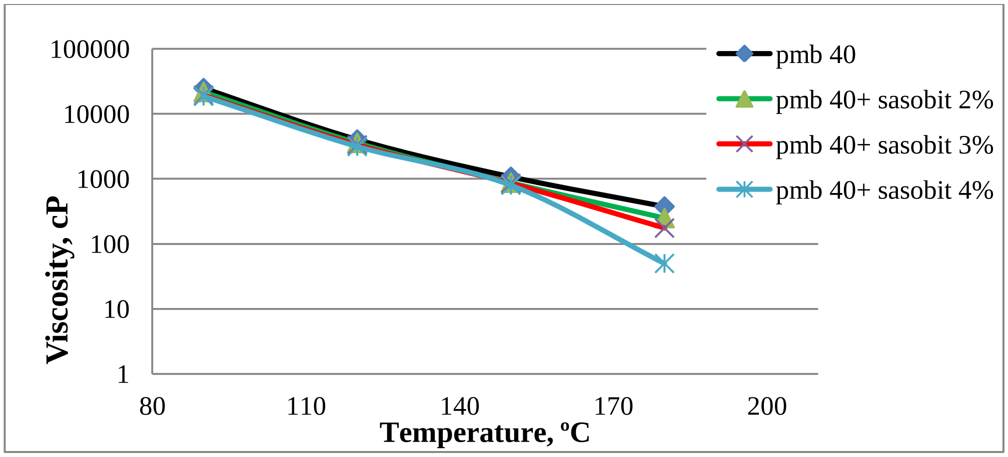


(b) Rediset®

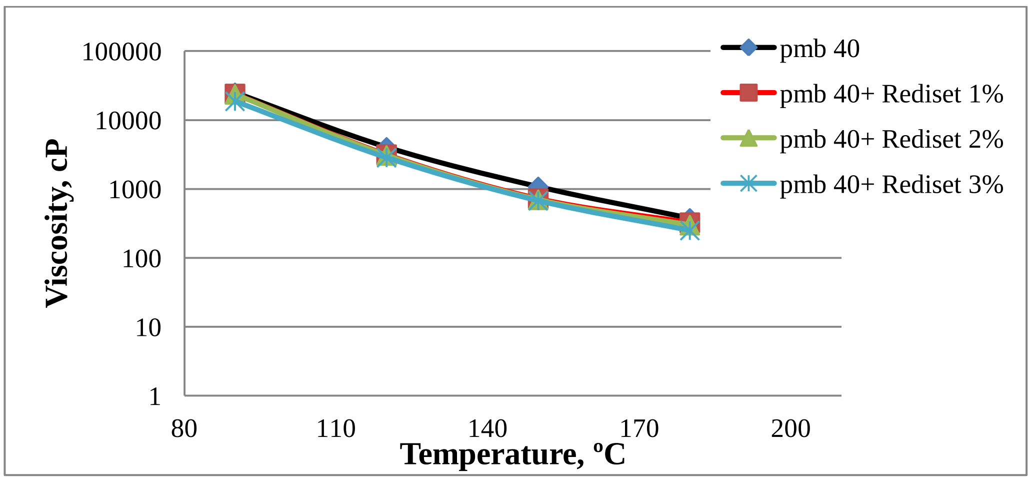


(c) Evotherm™

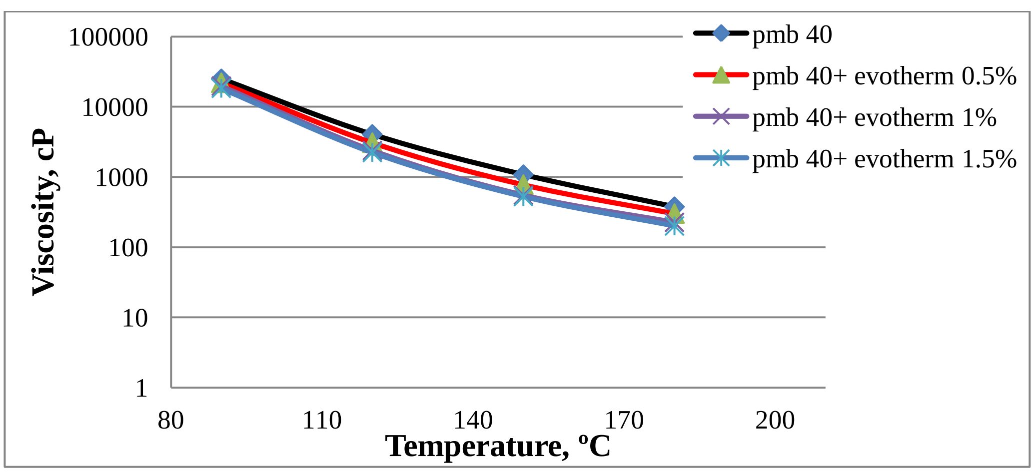
Figure 4.1: Viscosity of VG30 binder modified with additives



(a) Sasobit®



(b) Rediset®



(c) Evotherm™

Figure 4.2: Viscosity of PMB 40 binder modified with additives

4.2 Temperature Susceptibility of Warm Asphalt Binders

The test results of penetration and calculated PI (penetration index) for VG-30 based warm mix asphalt binders are given in Table 4.1. As may be seen, PI of Evotherm™ modified VG30 binder increases marginally with the increase in the concentration of Evotherm™. At low concentration of Evotherm™ (up to 1%) the PI is similar to that of neat VG30 binder. The addition of Sasobit® and Rediset® additives on the other hand show significant improvement in the penetration index (PI) of the binder. The increase in PI value of WMA binders indicates a significant reduction in temperature susceptibility of the binders.

The test results of penetration and calculated PI for PMB-40 based warm mix asphalt binders are given in Table 4.2. Significant improvement in the PI value of warm mix binders was observed with the addition of various warm mix additives. Evotherm™ showed increase in PI value at the dosage of 0.5% but at higher dosages of Evotherm™ the PI value decreased whereas Sasobit® and Rediset® WMX showed significant increase in the PI value of virgin PMB40 binder. This shows that the temperature sensitivity of PMB40 binder decreased after the addition of warm mix additives in the temperature range of 15°C to 30°C.

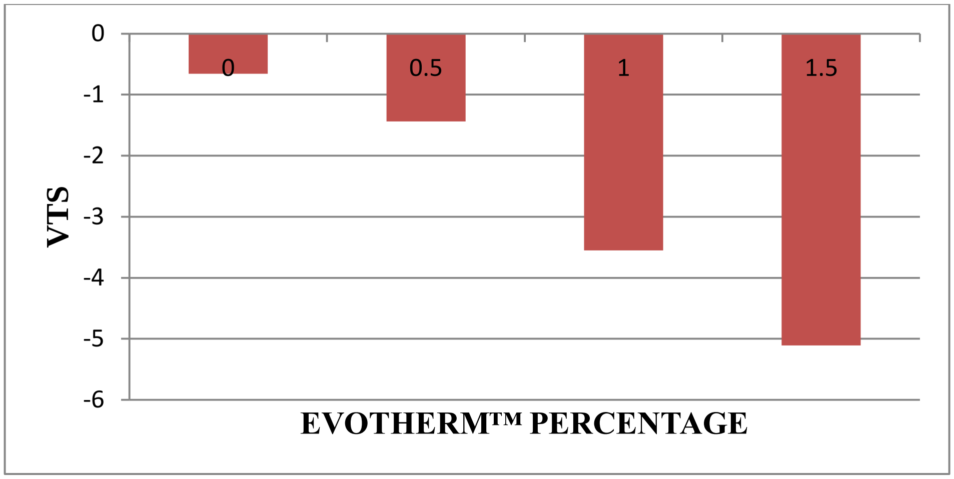
The increase in the penetration index of binders with the addition of additives shows that these additives reduce the temperature sensitivity of VG30 and PMB40 in the temperature range of 15°C to 30°C. Therefore warm mix binders are expected to be less temperature susceptible.

Table 4.1: Penetration Index of VG30 binders

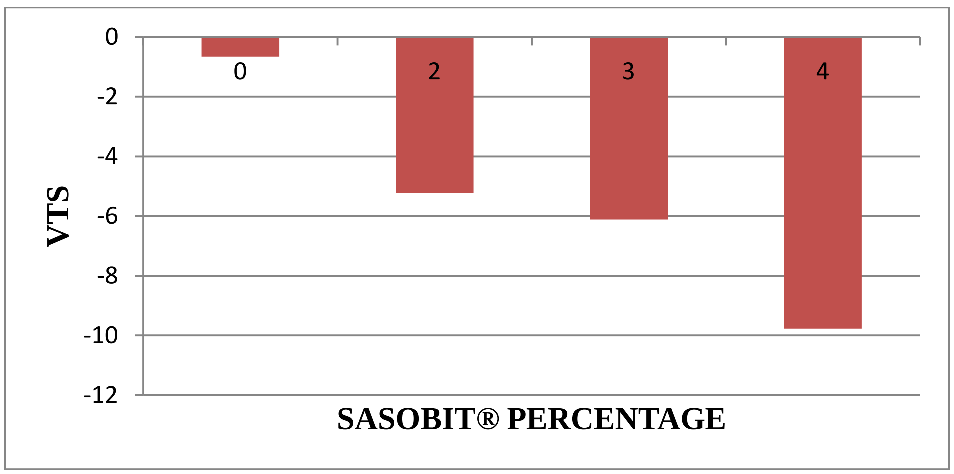
Additive Dose, %	Penetration at 15^0C	Penetration at 25^0C	Penetration at 30^0C	Penetration Index
VG-30 binder				
0	23.0	49.3	82.5	-0.625
Evotherm™				
0.5	18.0	46.3	77.0	-0.625
1.0	17.3	44.3	72.6	-0.44
1.5	11.0	38.6	64.6	0.714
Sasobit®				
2	23.3	32.0	54.0	-0.76
3	14.3	25.3	40.0	0.10
4	11.4	21.6	34.3	2.76
Rediset®				
1	10.3	58.1	72.7	5.22
2	4.6	45.4	69.1	0.623
3	1.5	41.9	66.3	0.050

Table 4.2: Penetration Index of PMB40 binders

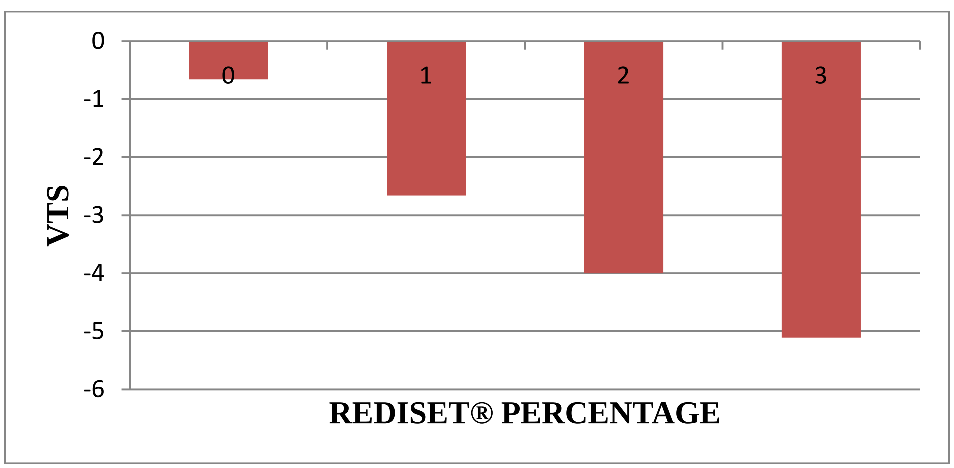
Additive Dose, %	Penetration at 15^0C	Penetration at 25^0C	Penetration at 30^0C	Penetration Index
PMB 40 binder				
0	25.0	34.0	47.5	2.23
Evotherm™				
0.5	28.6	52.6	65.6	5.32
1.0	26.0	41.0	61.0	1.03
1.5	24.0	36.0	60.6	-0.625
Sasobit®				
2	13.0	25.0	29.0	8.26
3	12.0	23.0	28.6	6.12
4	11.0	21.0	26.0	5.81
Rediset®				
1	27.0	37.0	44.5	6.75
2	26.0	35.0	43.6	5.52
3	25.0	34.0	41.3	6.39



(a)

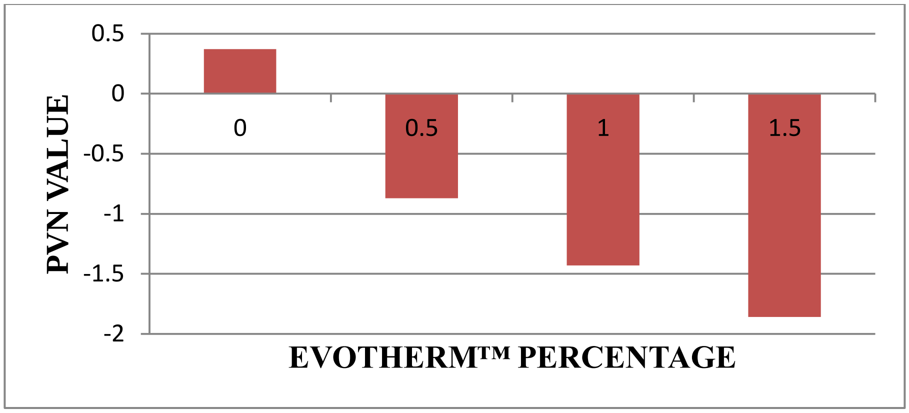


(b)

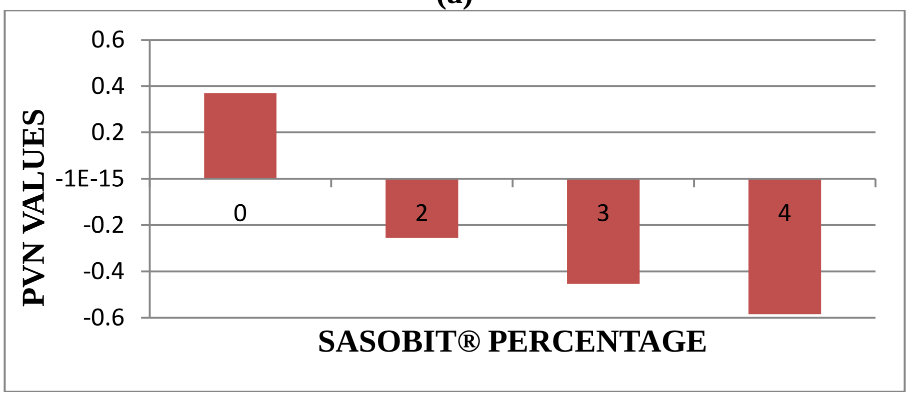


(c)

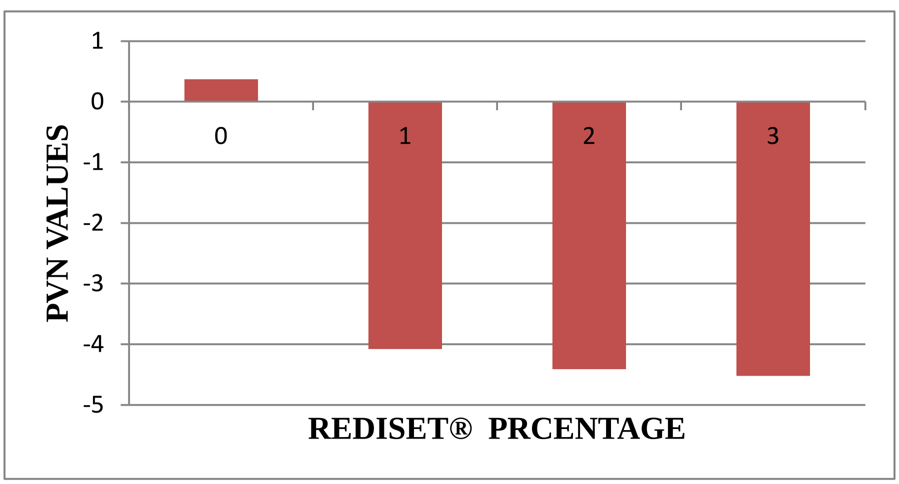
Figure 4.3: Effect of (a) Evotherm™ (b) Sasobit®(c) Rediset® concentration on VTS of VG-30 bitumen



(a)



(b)



(c)

Figure 4.4: Effect of (a) Evotherm™ (b) Sasobit®(c) Rediset® concentration on PVN of VG-30 bitumen

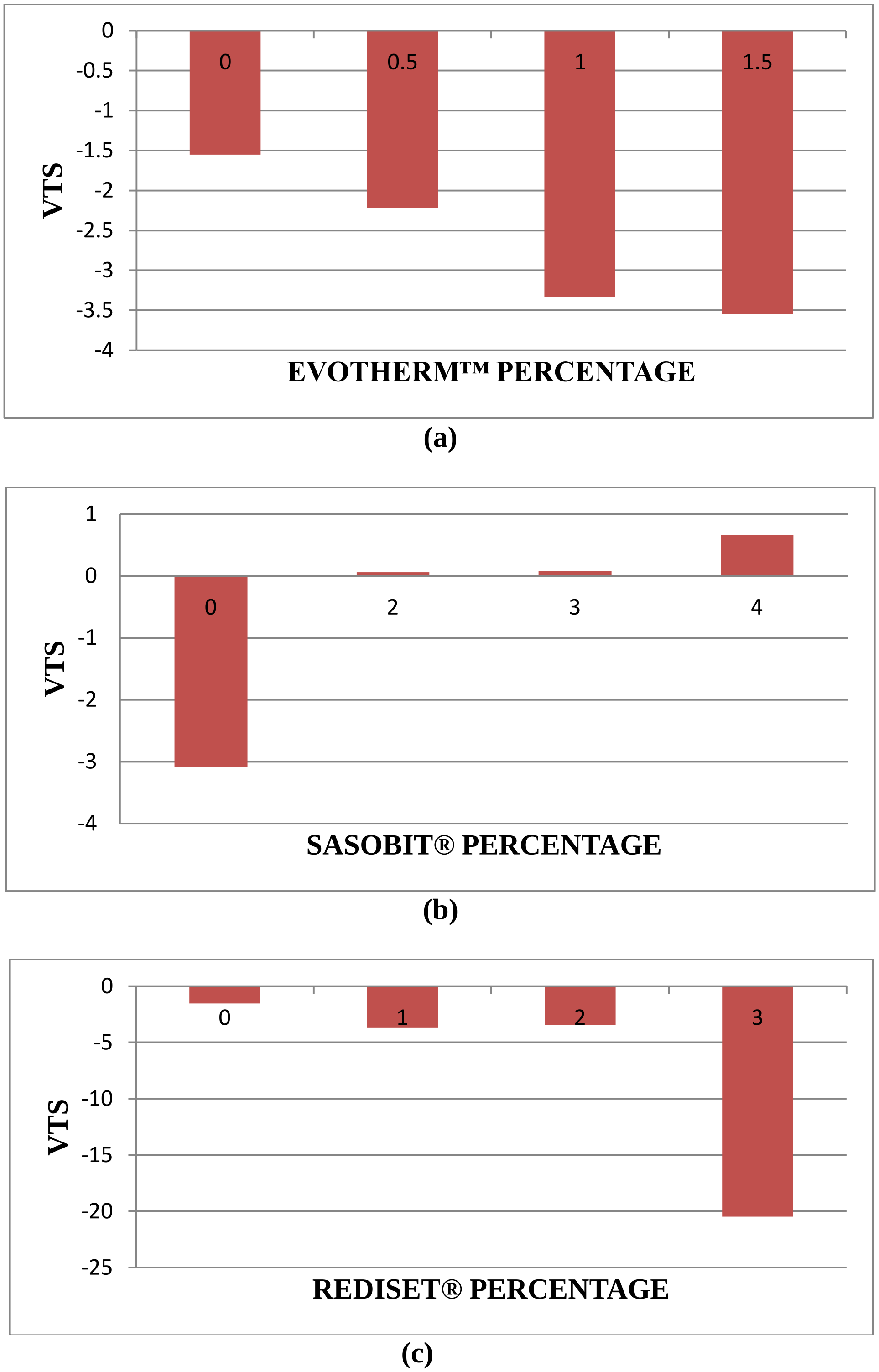
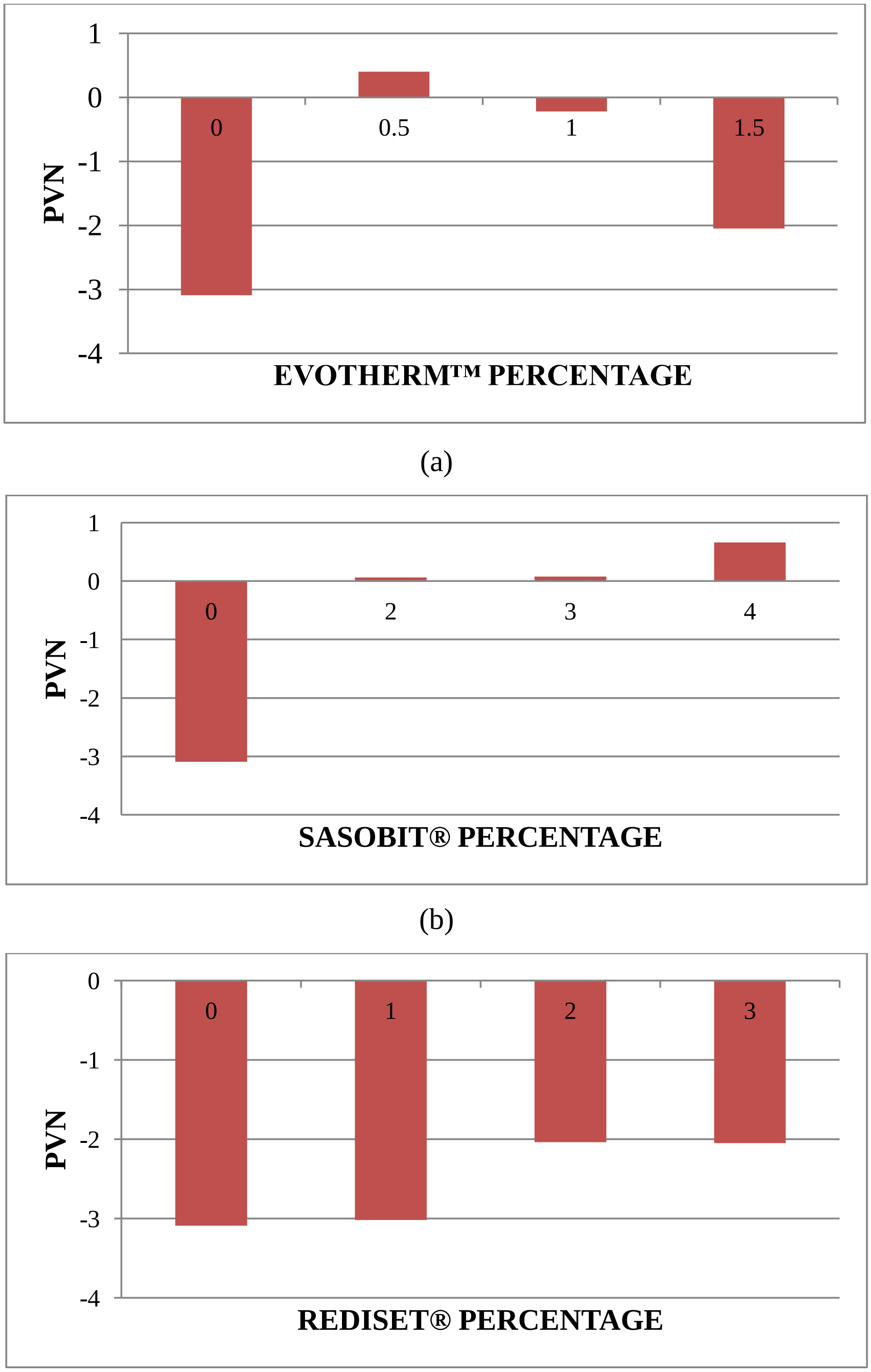


Figure 4.5: Effect of (a) Evotherm™ (b) Sasobit®(c) Rediset® concentration on VTS of PMB-40 binder



(a) (b) (c)

Figure 4.6: Effect of (a) Evotherm™ (b) Sasobit®(c) Rediset® concentration on PVN of PMB-40 bitumen

Figures 4.3 and 4.4 show the VTS (viscosity temperature susceptibility) and PVN (penetration viscosity number) plots with respect to the concentration of warm mix additives in VG-30 binder. It is seen that VTS of VG30 decreases with an increasing dose of Evotherm™ in the binder. It reflects that the addition of Evotherm™ can make the bitumen more temperature susceptible in the temperature range of 60°C to 135°C, which means the Evotherm™ modified binder will be more workable in this temperature range and hence would result in the reduction in the mixing and compaction temperatures. Similar trend is observed for Sasobit® and Rediset® modified VG30 binder.

The PVN is based on penetration at 25°C and the viscosity at 60°C. It was observed that the addition of warm mix additives to VG30 binder decreases the PVN value. With the increasing concentration of warm mix additives the PVN values show a decreasing trend. This indicates that the addition of these additives makes the VG30 bitumen more temperature susceptible in the temperature range of 25 -60°C, binders will experience more rutting damage at in-service pavement temperature. However, it will be too early to draw any conclusion at this stage because much variation in the viscosity of VG 30 was not observed when Evothern™ and Rediset® additives were added.

It is observed that Evotherm™ and Rediset® follow the similar trend for PMB40 as they did for VG30 binder. With increasing dosages of these additives the VTS of PMB40 decreases, making PMB40 more temperature susceptible in the temperature range 60C-135C. Whereas with the increasing dose of Sasobit® the VTS of PMB40 increases. This shows that the addition of Sasobit® improves the temperature susceptibility of PMB40 binder, which means that Sasobit® modified binder, will be less affected by temperature change in comparison to other additives and hence leads to the less reduction in the mixing and compaction temperature of asphalt in comparison to other additives.

The addition of Evotherm™ did not show a definite trend on the PVN value of PMB40 binder. But other two additives show increase in PVN with increase in the dose of additive. The addition of Sasobit® greatly improves the temperature susceptibility of PMB40 bitumen which can lead to better rutting resistance at in-service pavement temperature.

4.3 Effect of additives on rheological properties of binders and mastics

4.3.1 Temperature sweep tests

Temperature sweep tests were conducted to evaluate the effect of warm mix additives and limestone filler on high temperature performance of base binders VG-30 and PMB-40. According to SHRP specification, G*/sinδ at angular frequency of 10 rad/sec and strain value of 12%, defined as rutting factor, can be used to evaluate the resisting contribution of binder against permanent deformation at high temperature. Therefore G*/sinδ value at 10 rad/sec, is measured over wide range of temperatures with each formulation of warm mix binder and its mastic and test results are presented in Figures 4.7 to Figure 4.30. G*/sinδ value at 60°C, 10 rad/sec and 12% strain value was also measured by DSR and results are presented in Table 4.3. The G*/sinδ reduces with increase in test temperature because asphalt binder starts exhibiting fluid nature at high temperature. Test results of VG-30 and PMB40 with Sasobit®, Evotherm™ and Rediset® are presented in Figure 4.7 through Figure 4.12. Results indicate that rutting factor G*/sinδ for VG-30 with Sasobit® is greater than that for VG-30 without Sasobit® and increases with addition of Sasobit® dose at low temperature. VG-30 with Sasobit® content more than 2% exhibits higher values of rutting factor when compared with virgin binder even on higher temperature. These results suggest that Sasobit® dosage of more than 2% is suitable for VG 30 based warm mixes. However Evotherm™ with VG-30 shows a slight reduction in rutting performance as compared with virgin binder. Figure 4.9 indicates that Rediset® at the dosage of 1% with VG 30 shows reduction in the values of rutting factor at low temperatures, whereas considerable increase is observed in the rutting factor at temperatures higher than 58ºC. Improvement was observed at higher dosages of Rediset®. However, similar results are obtained at 2% and 3% of Rediset® indicating that 2% dose of Rediset® is the optimum dose for VG-30. Figures 4.10 - 4.12 indicate that warm mix additives do not improve the rutting factor G*/sinδ with PMB-40. Smaller dose of Sasobit® (up to 3%) with PMB-40 shows reduction in G*/sinδ. Evotherm™ with PMB-40 gives lower values of G*/sinδ as compared with virgin binder, and this reduction increases with increases in Evotherm™ content. Rediset® also gives lower values of G*/sinδ as compared to PMB 40.

According to SHRP specifications limiting value of G*/sinδ for un-aged binder is 1 kPa and corresponding temperature is regarded as failure temperature or maximum service temperature. Limiting value of G*/sinδ is indicated in plots and corresponding failure temperature is listed in Table 4.4 (second column with no filler). Addition of Sasobit® dose in VG-30 binder improves failure temperature remarkably. As illustrated in Table 4.4 the failure temperature of virgin VG-30 is 76°C while it is 83°C with 3% of Sasobit® and 84°C with 4% of Sasobit®. Failure temperature is also used to determine the performance grade of the binder. Sasobit® dose of 3% increases failure temperature considerably. So a Sosobit® dose of 3% may be regarded as optimum for VG-30. However Sasobit® with PMB-40 did not improve failure temperature significantly. Evotherm™ with VG-30 has no effect on failure temperature while it reduces the failure temperature of PMB-40. These results suggest that Evotherm™ is not suitable for high service temperature with both binders. Addition of Rediset® also did not show any effect on failure temperature at the dosage of 1% and 2% but showed slight improvement PMB40+Rediset showed no improvement in the failure temperature.

High temperature rutting performance of bitumen-filler mastic is shown in Figures 4.13 to 4.30 which indicate that for each formulation of warm mix binder rutting factor G*/sinδ increases with increases in concentration of limestone filler and in most of the cases this trend continues as the temperature increases. It means that the rate of increase of rutting factor with filler concentration is higher at higher temperature. Asphalt binder produces stiff mix with filler when compared with base binder due to its filling effect. Limestone filler makes the mix hard and improves the stability. Therefore results appear to be reasonable. Table 4.3 shows G*/sinδ values at 60°C which also indicates increase in rutting factor with filler concentration. Mastic of VG30 showed improvement in rutting factor with all the three additives whereas the mastic of PMB40 showed improvement in the rutting factor only at higher doses of Sasobit®. Mastic of PMB-40 with 0.5% of Evotherm™ with 1.5 F/B ratio gave G*/sinδ value of 60.88 kPa while it was 32.17 kPa without filler. Similar results are shown by other formulations also. Even the warm mix binders having poor rutting performance as compared to virgin binder showed great improvement by adding filler and gave better rutting resistance as compared to virgin binder. Further, failure temperatures of mastics are listed in Table 4.4 which indicates increase in failure temperature with increase in filler concentration. Similar to rutting factor, warm mix binder with filler shows greatly improved failure temperature unlike their performance with neat binder. High temperature rutting behaviour of base binder was improved considerably with limestone filler. Further from Table 4.4 it is observed that failure temperature of most of warm mix binder with F/B ratio 1.3 and 1.5 are almost equal. It is also observed from plots of G*/sinδ Vs temperature that curves corresponding to F/B ratio 1.3 and 1.5 nearly overlap in most of the cases. This is because at high filler concentration interaction between filler particle starts dominating and filler starts gathering into groups which deteriorates the cohesion of the binder. These results indicate that F/B ratio of 1.3 is optimum for high temperature rutting behaviour of warm mix asphalt.

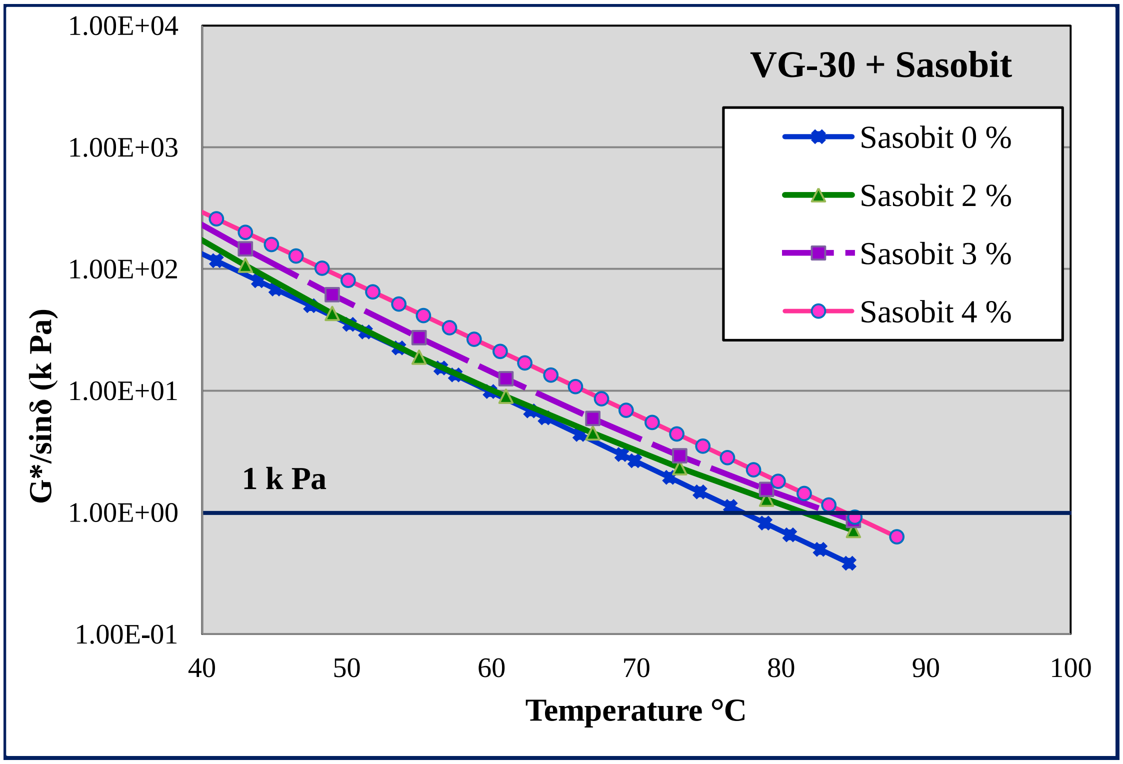


Figure 4.7: G*/sinδ Vs Temperature for VG-30 with Sasobit®

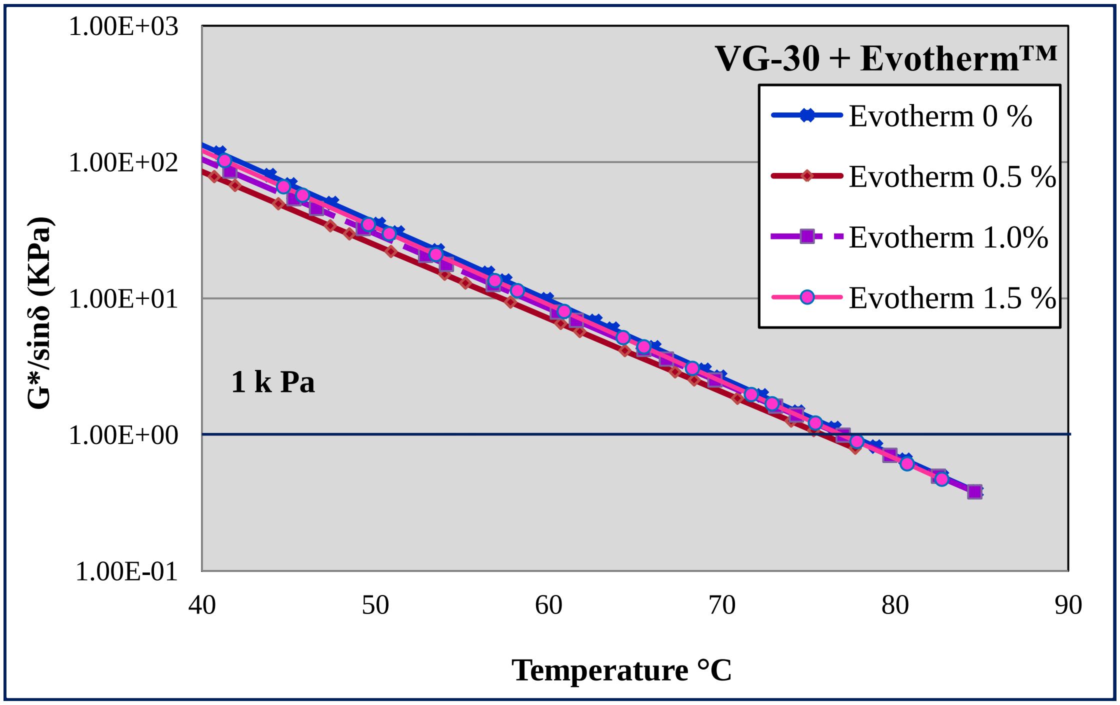


Figure 4.8: G*/sinδ Vs Temperature for VG-30 with Evotherm™

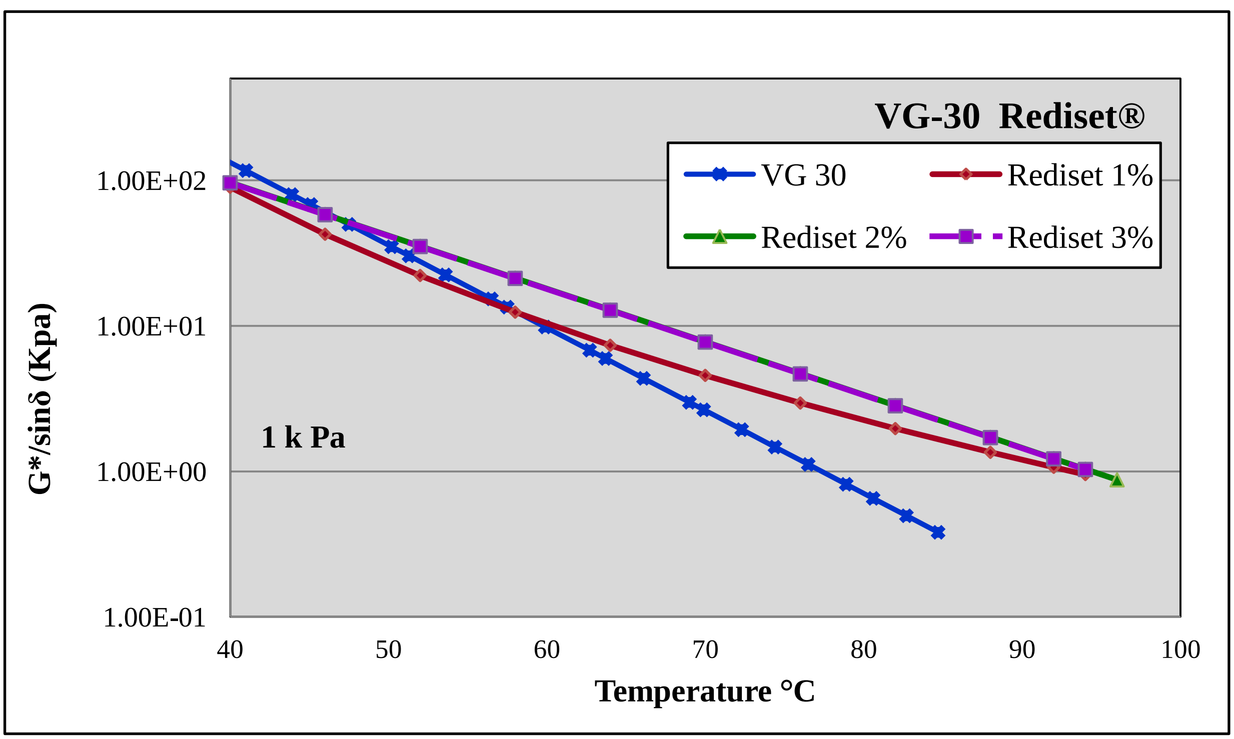


Figure 4.9: G*/sinδ Vs Temperature for VG-30 with Rediset

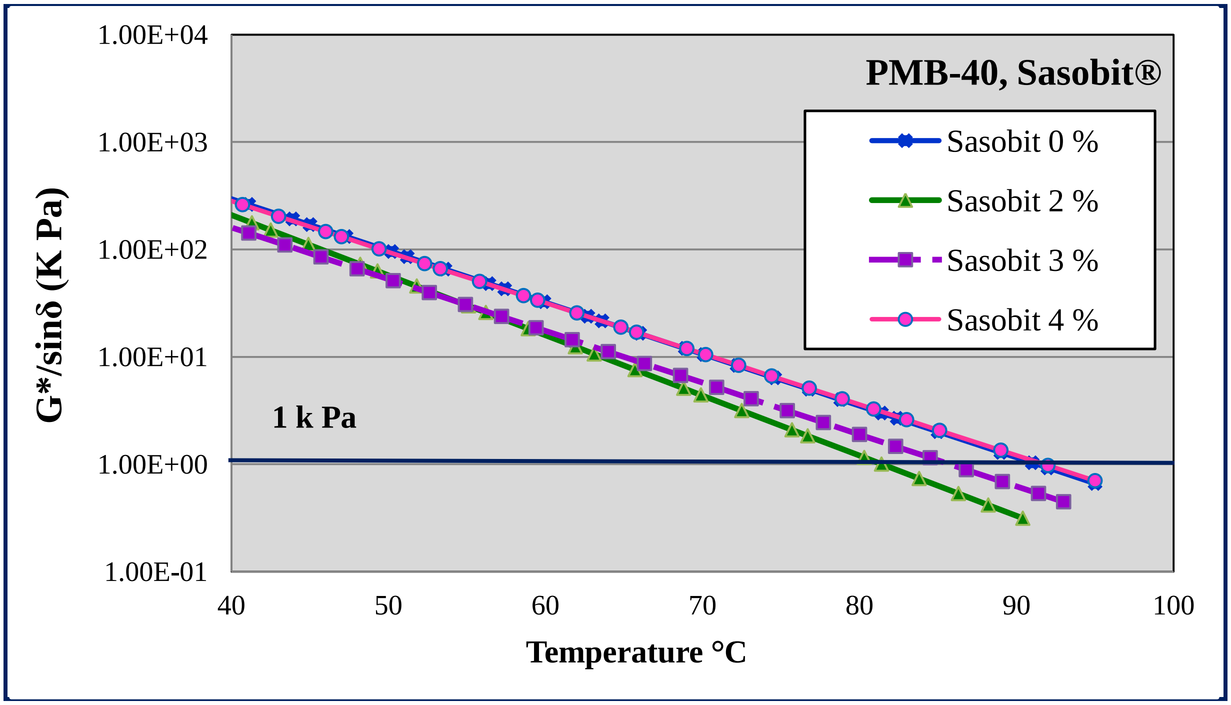


Figure 4.10: G*/sinδ Vs Temperature for PMB-40 with Different doses of Sasobit®

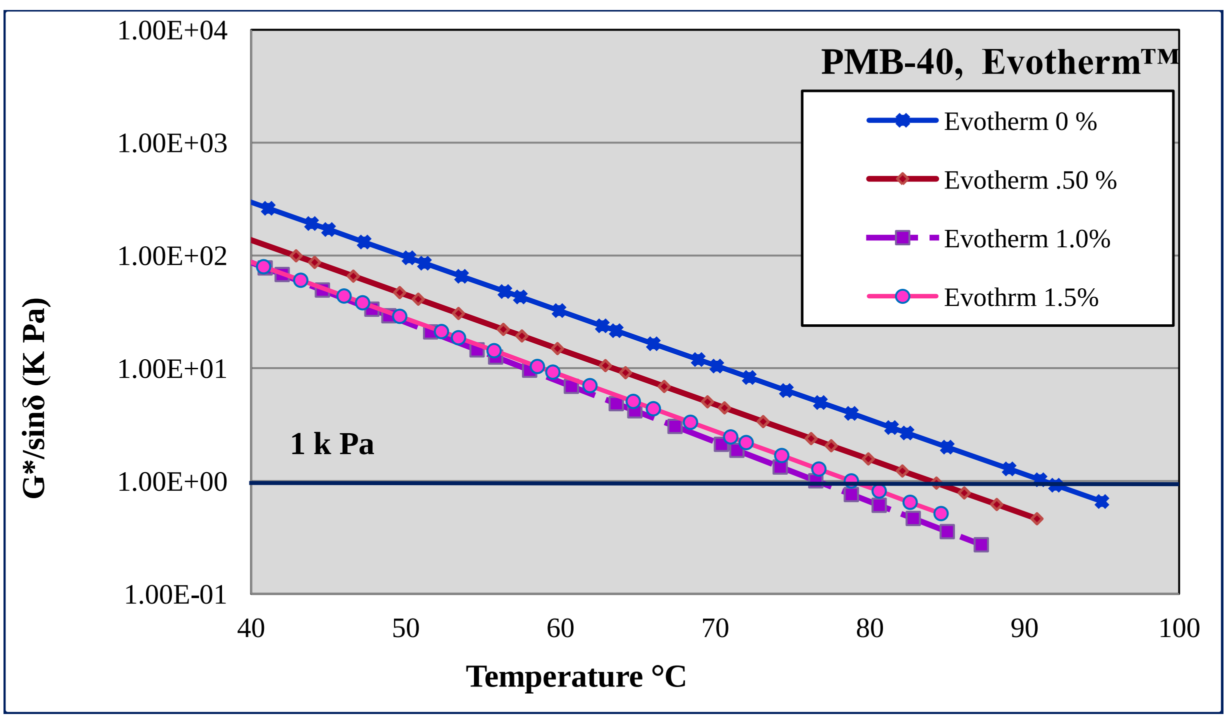


Figure 4.11: G*/sinδ Vs Temperature for PMB-40 with Different doses of Evotherm™

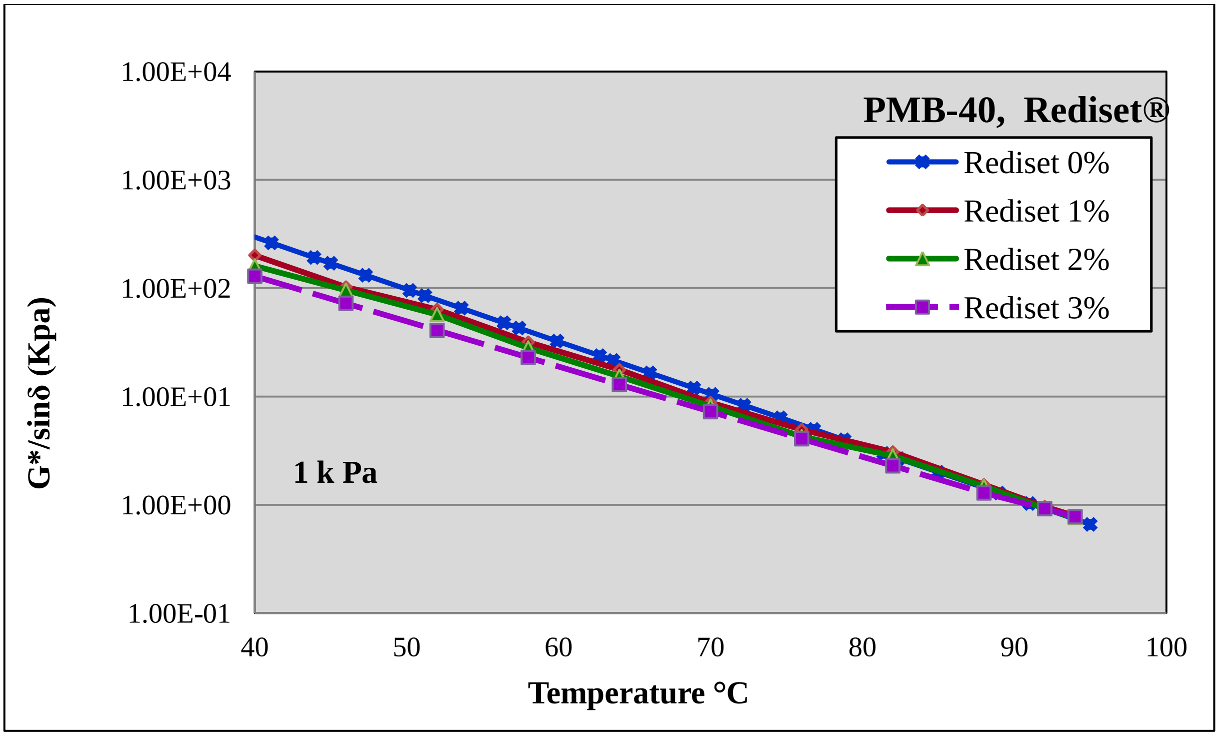


Figure 4.12: G*/sinδ Vs Temperature for PMB-40 with Different doses of Rediset®

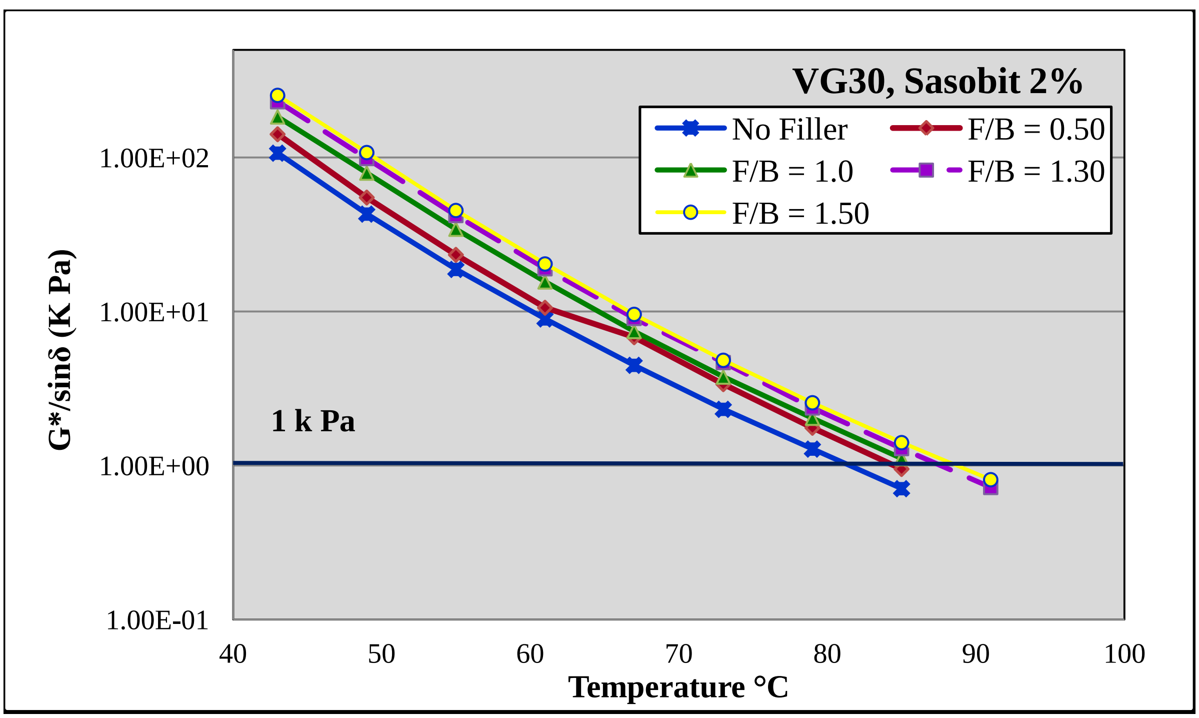


Figure. 4.13: G*/sinδ Vs Temperature for bitumen filler mastic with VG-30 and Sasobit® 2%

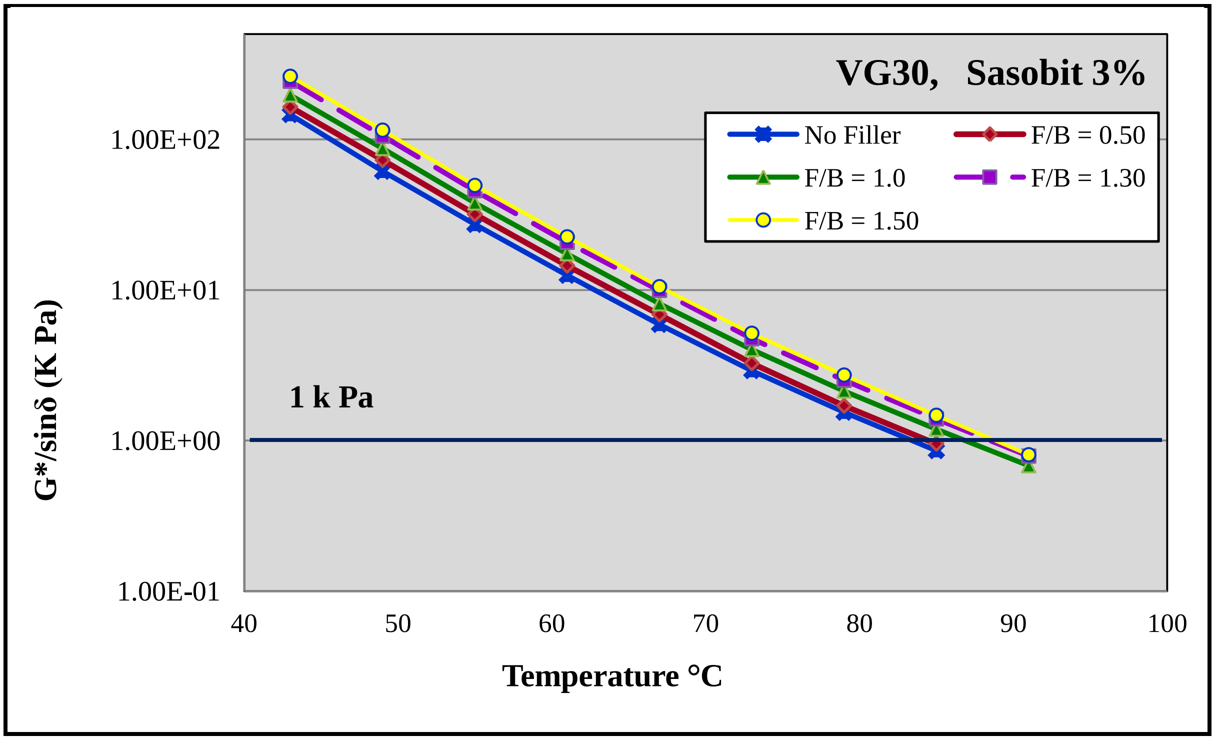


Figure. 4.14: G*/sinδ Vs Temperature for bitumen filler mastic with VG-30 and Sasobit® 3%

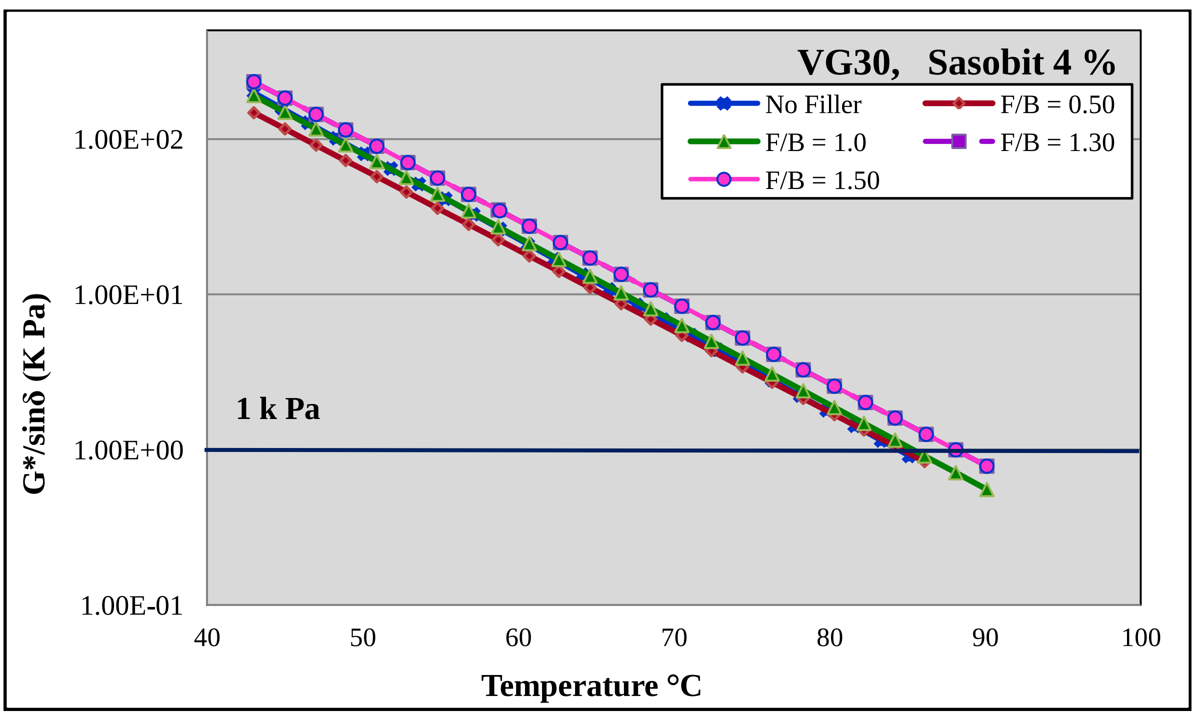


Figure. 4.15: G*/sinδ Vs Temperature for bitumen filler mastic with VG-30 and Sasobit® 4%

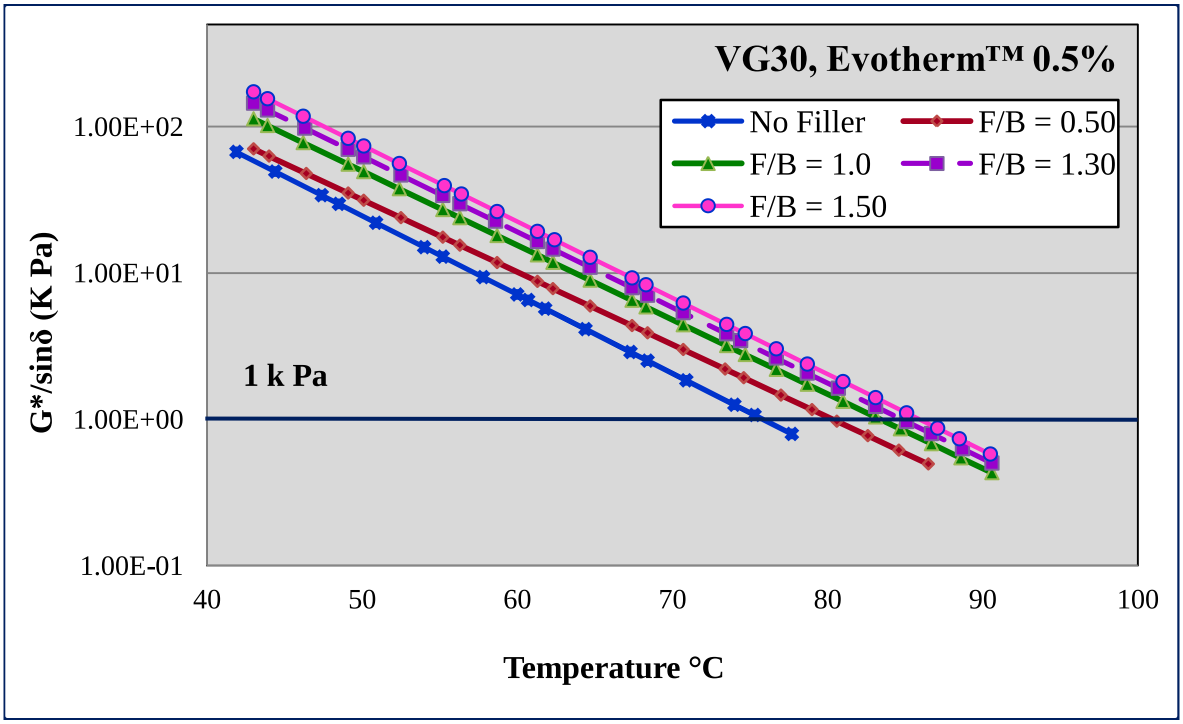


Figure. 4.16: G*/sinδ Vs Temperature for bitumen filler mastic with VG-30 and Evotherm™ 0.5%

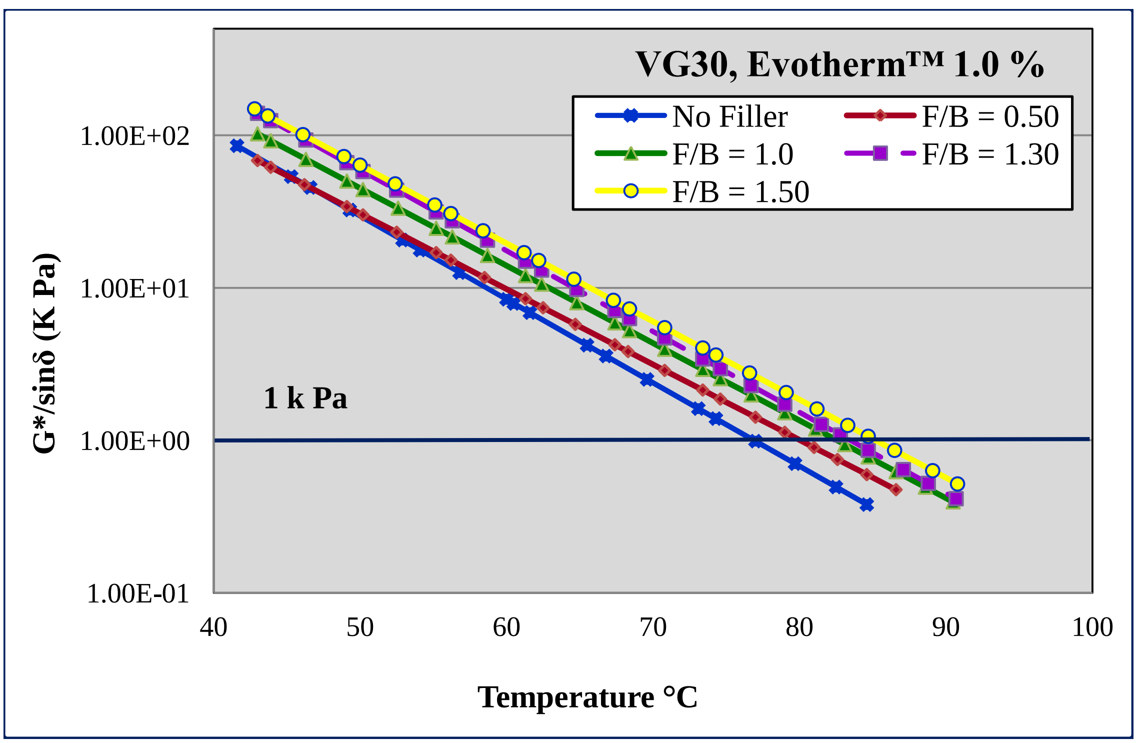


Figure. 4.17: G*/sinδ Vs Temperature for bitumen filler mastic with VG-30 and Evotherm™ 1.0%

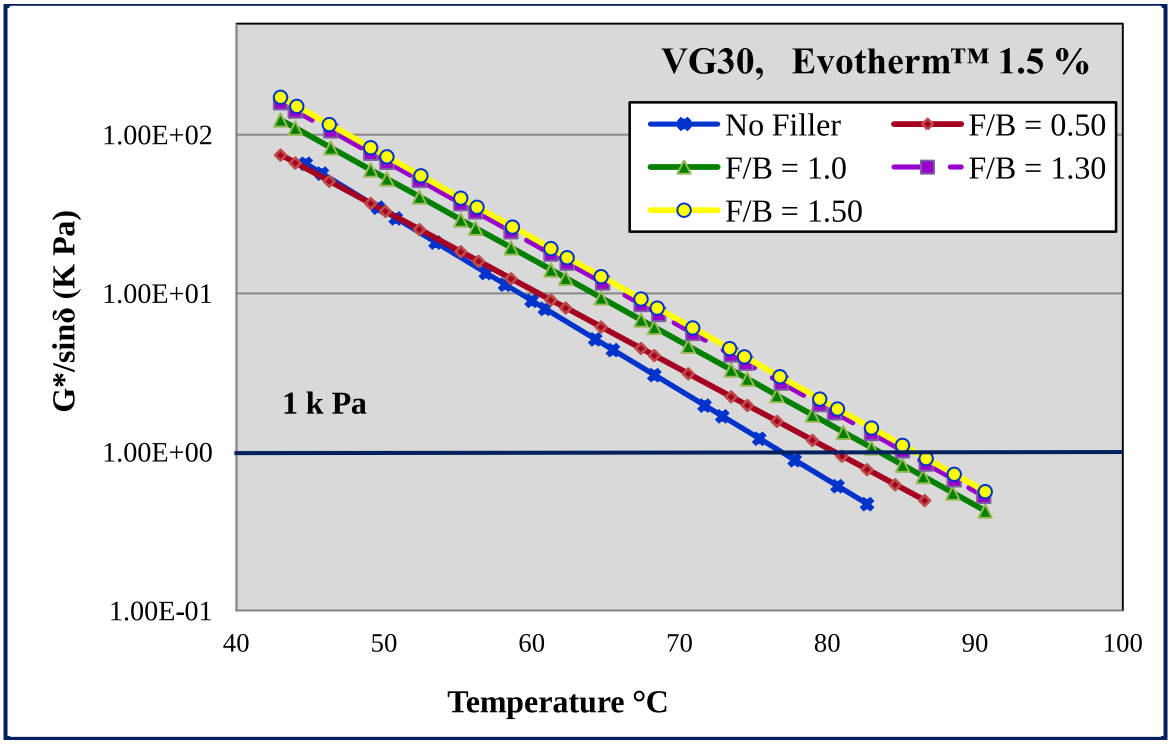


Figure. 4.18: G*/sinδ Vs Temperature for bitumen filler mastic with VG-30 and Evotherm™ 1.5%

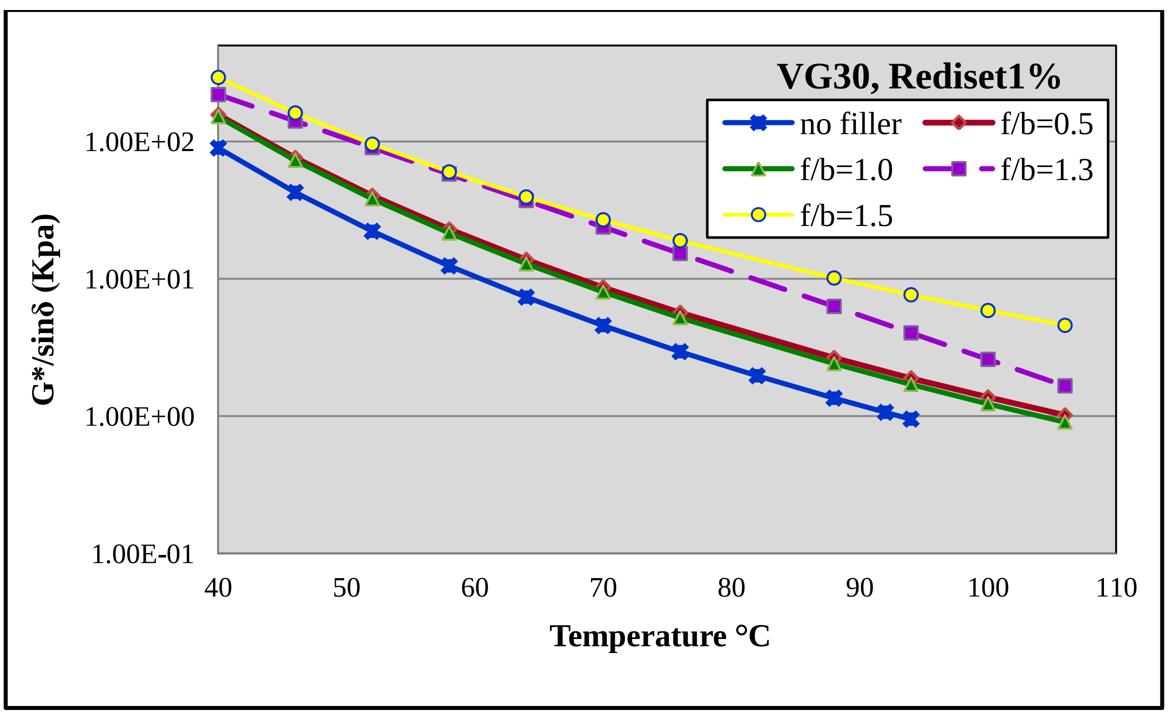


Figure. 4.19: G*/sinδ Vs Temperature for bitumen filler mastic with VG-30 and Rediset® 1.0%

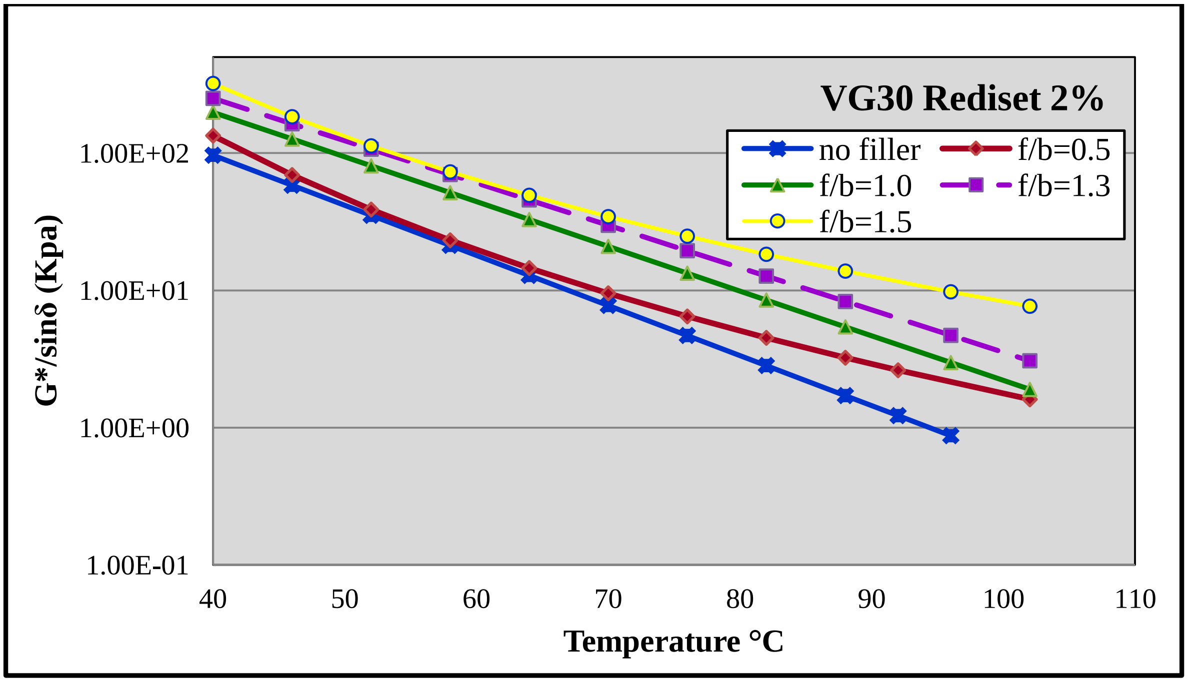


Figure. 4.20: G*/sinδ Vs Temperature for bitumen filler mastic with VG-30 and Rediset® 2.0%

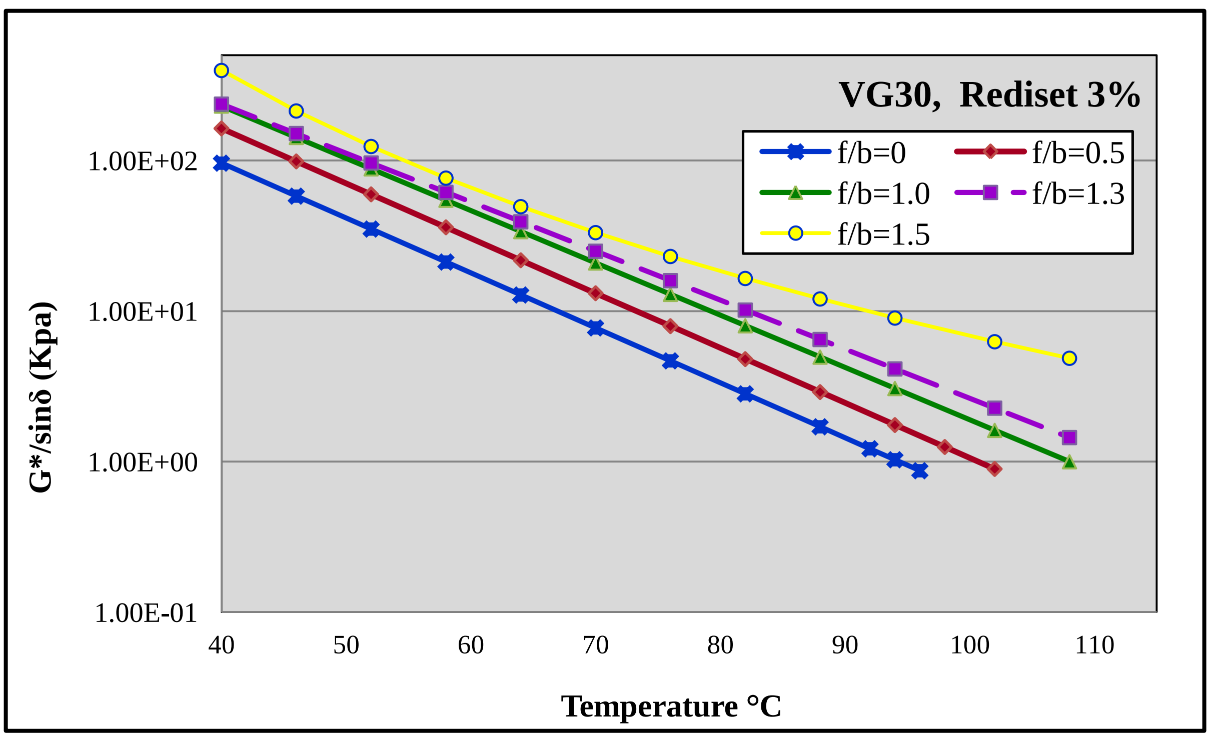


Figure. 4.21: G*/sinδ Vs Temperature for bitumen filler mastic with VG-30 and Rediset® 3.0%

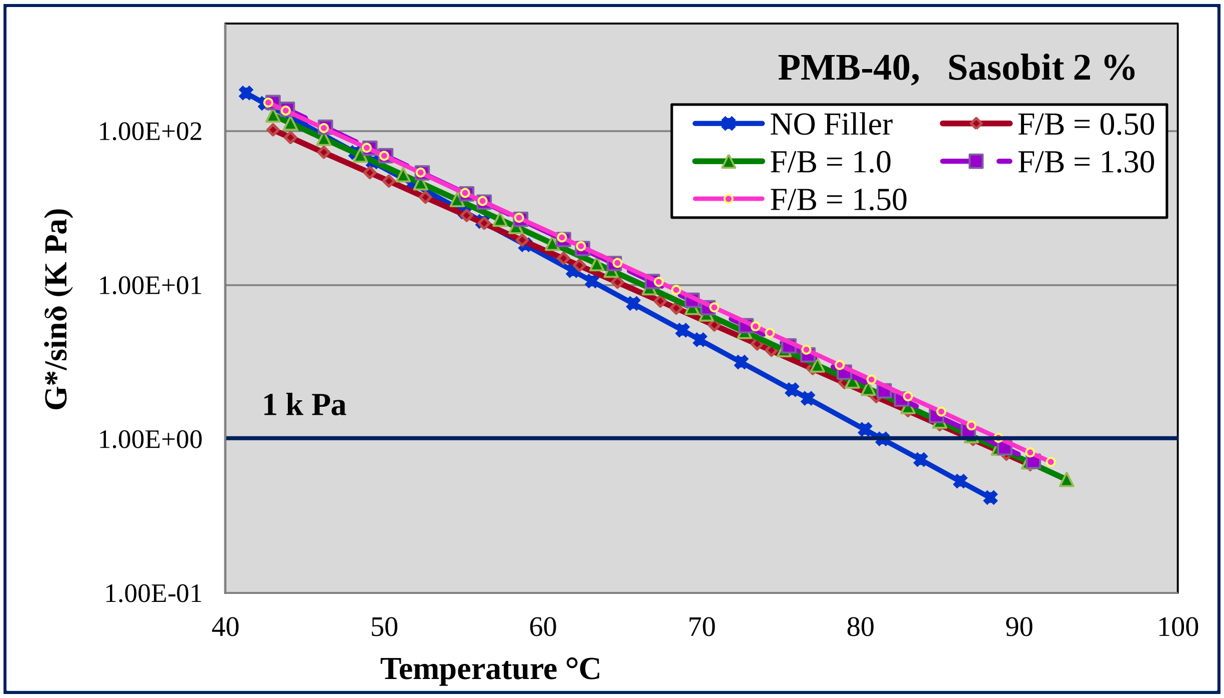


Figure. 4.22: G*/sinδ Vs Temperature for bitumen filler mastic with PMB-40 and Sasobit® 2%

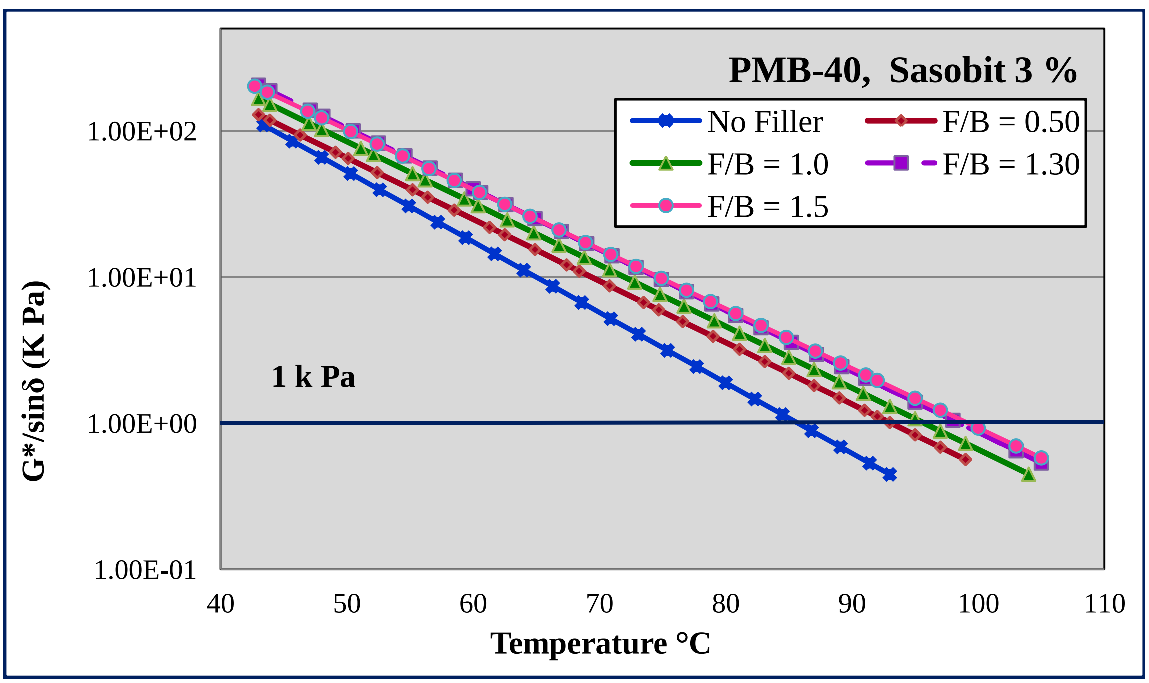


Figure. 4.23: G*/sinδ Vs Temperature for bitumen filler mastic with PMB-40 and Sasobit® 3%

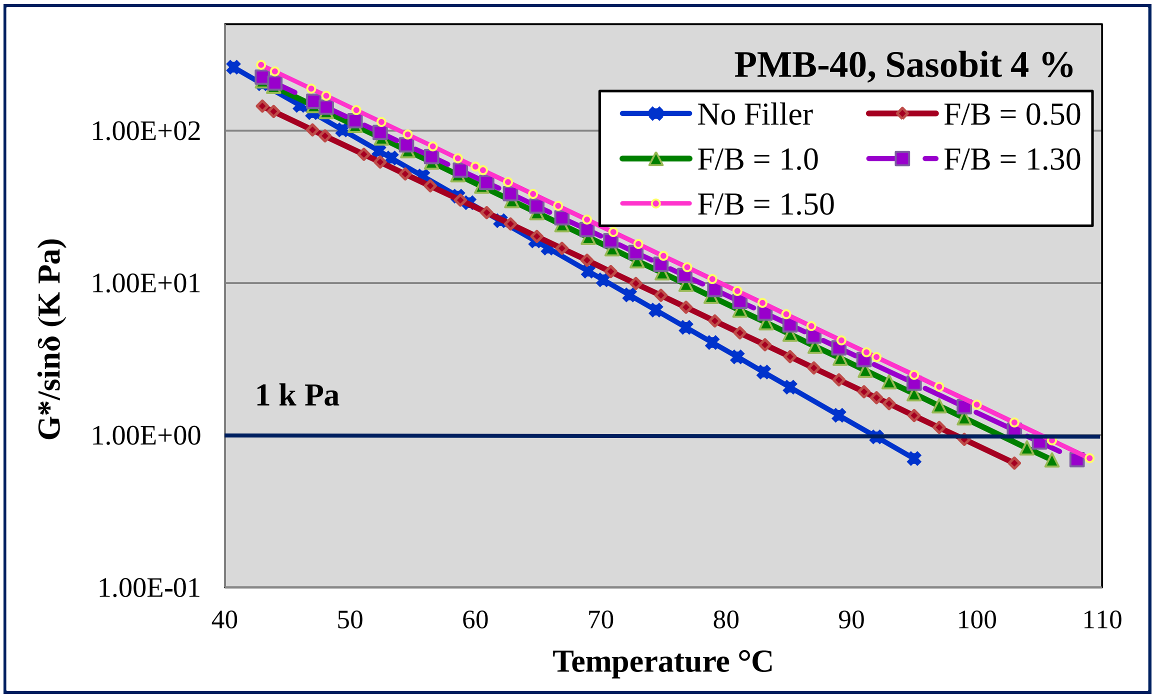


Figure. 4.24: G*/sinδ Vs Temperature for bitumen filler mastic with PMB-40 and Sasobit® 4%

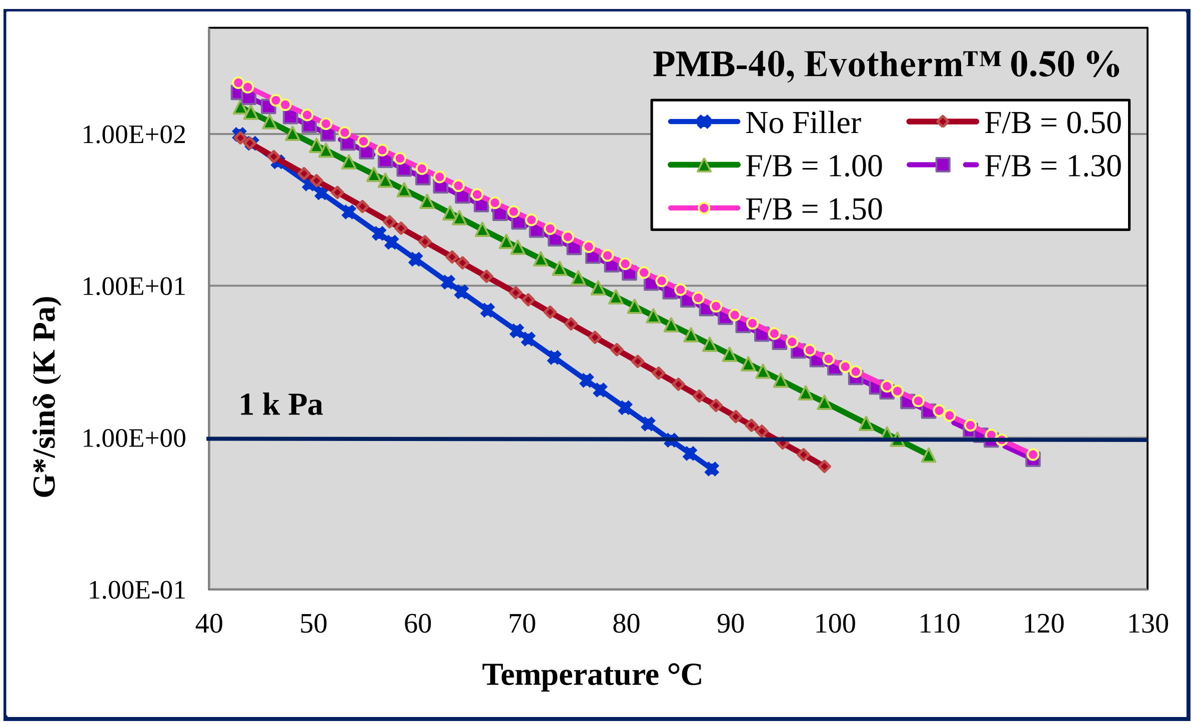


Figure. 4.25: G*/sinδ Vs Temperature for bitumen filler mastic with PMB-40 and Evotherm™ 0.50%

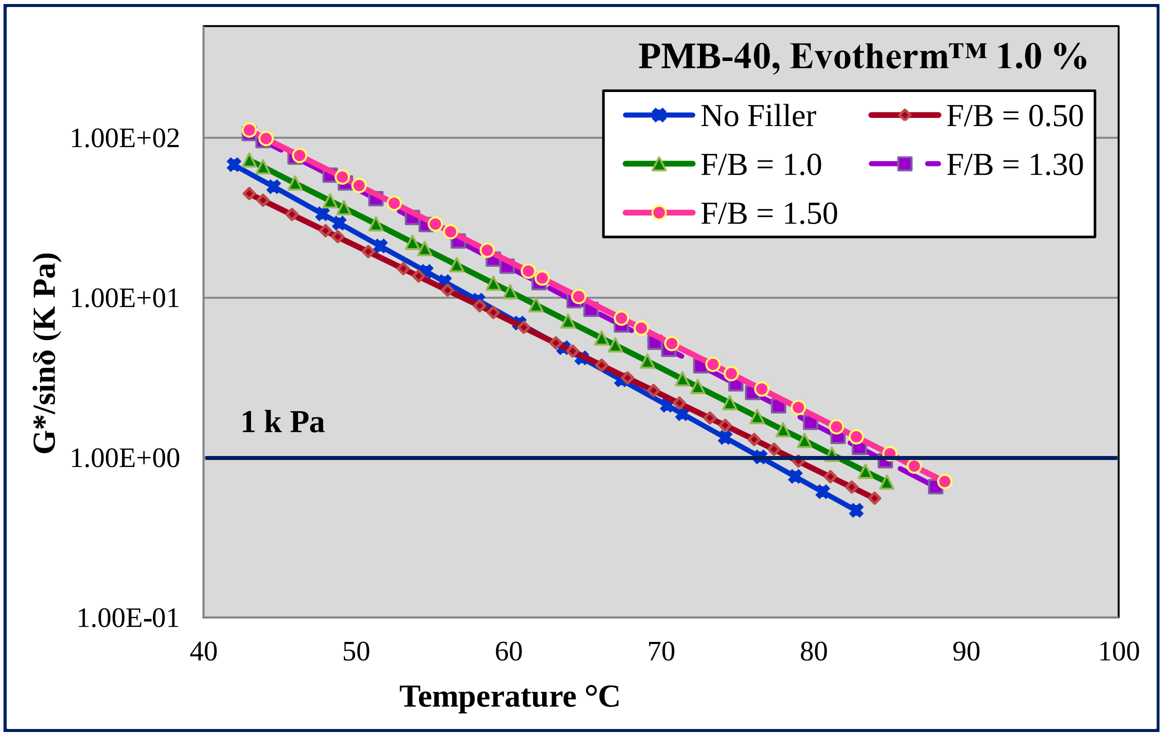


Figure. 4.26: G*/sinδ Vs Temperature for bitumen filler mastic with PMB-40 and Evotherm™ 1.0%

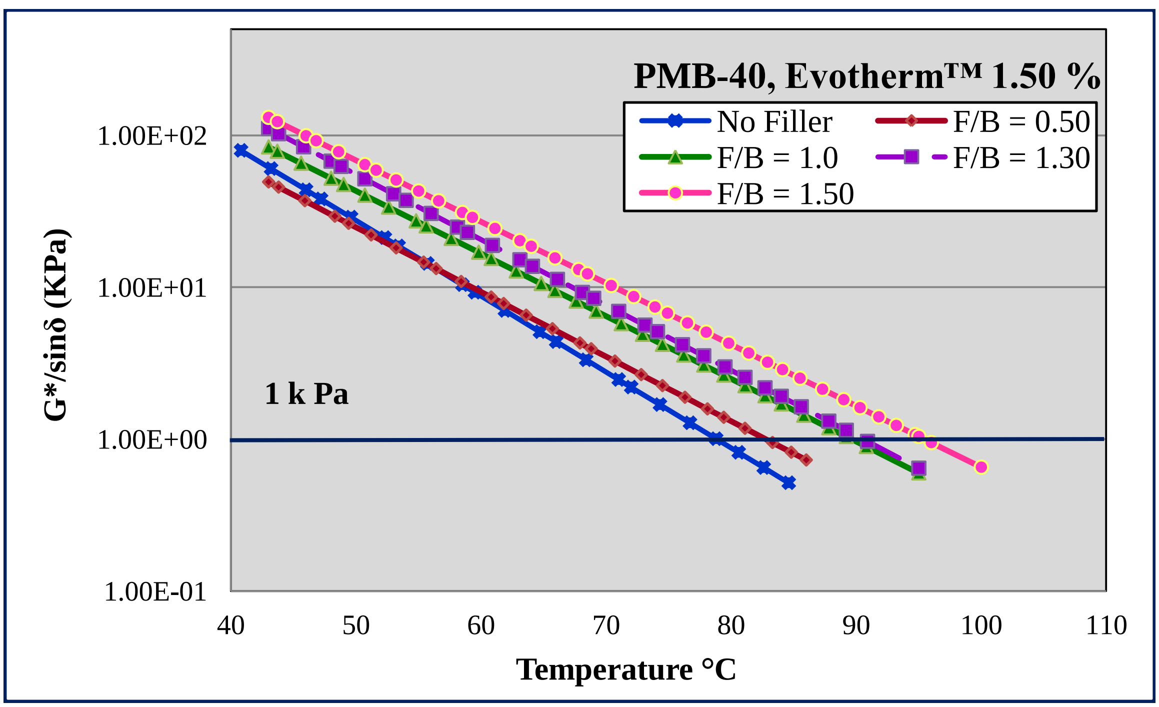


Figure. 4.27: G*/sinδ Vs Temperature for bitumen filler mastic with PMB-40 and Evotherm™ 1.5%

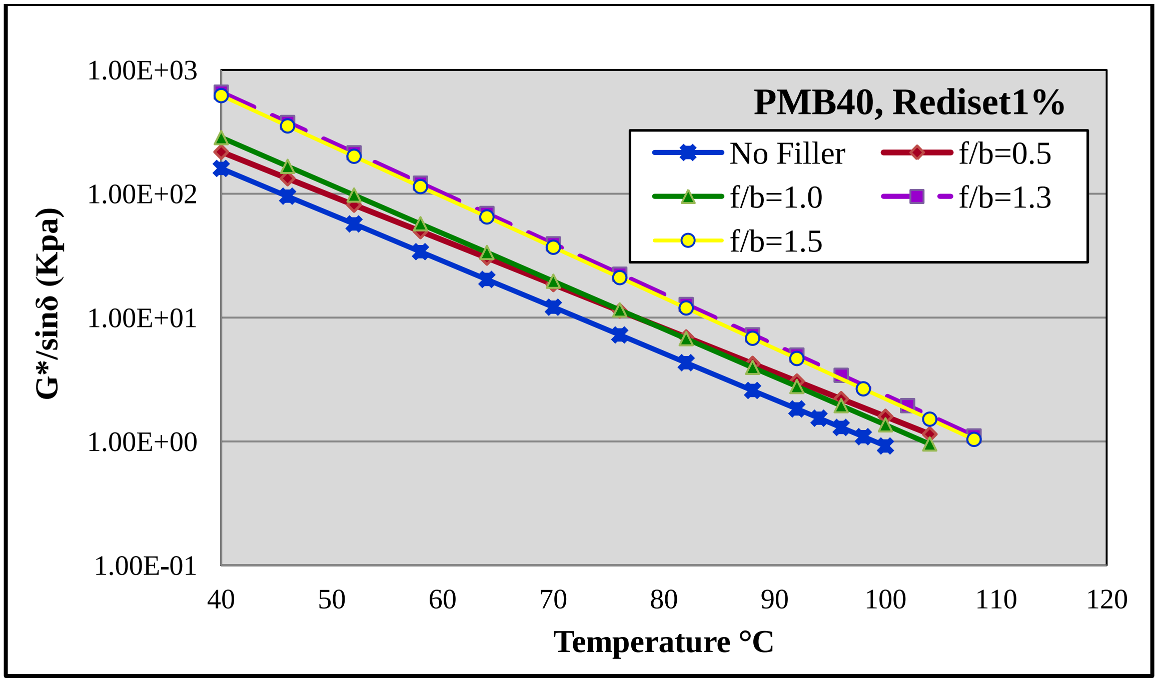


Figure. 4.28: G*/sinδ Vs Temperature for bitumen filler mastic with PMB-40 and Rediset® 1%

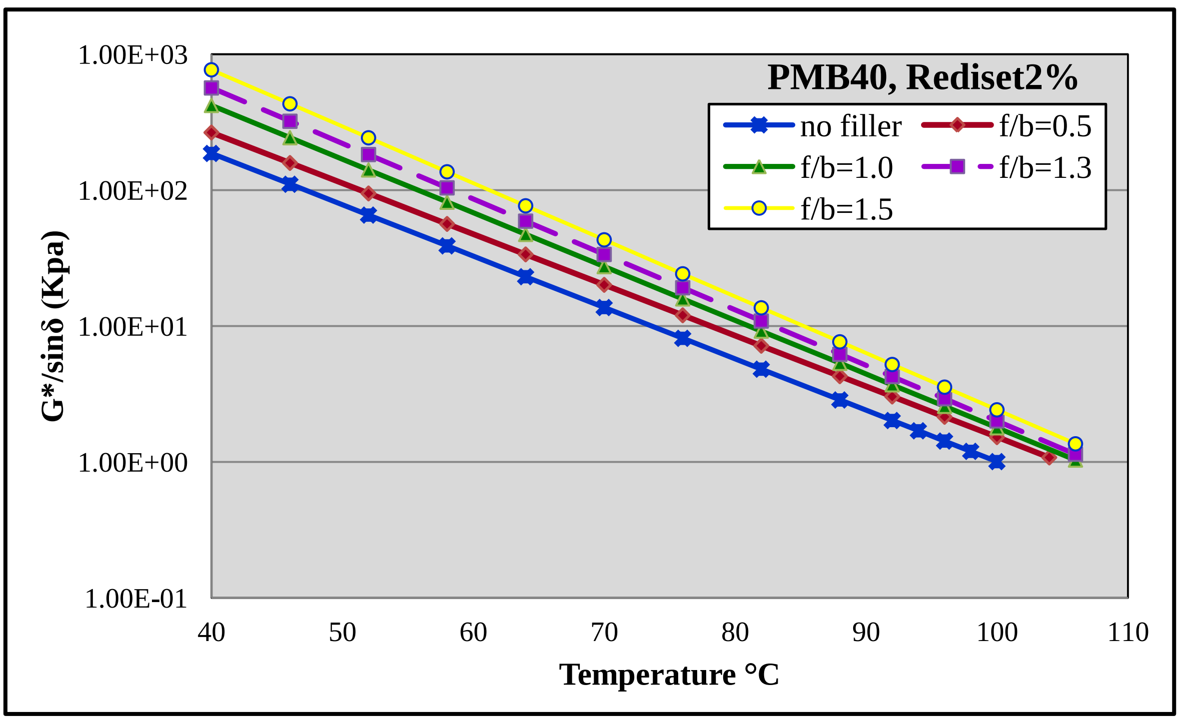


Figure. 4.29: G*/sinδ Vs Temperature for bitumen filler mastic with PMB-40 and Rediset® 2%

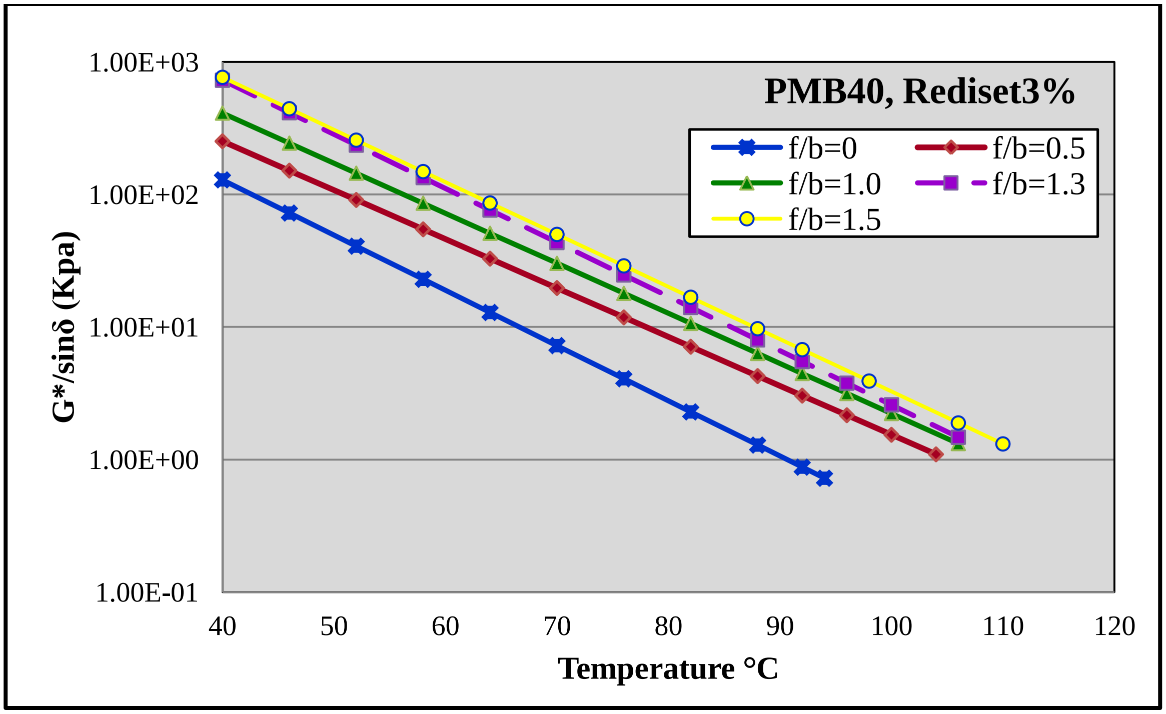


Figure. 4.30: G*/sinδ Vs Temperature for bitumen filler mastic with PMB-40 and Rediset® 3%

Table 4.3: Rutting Factor G*/sinδ (k Pa) at 60°C 10 rad/sec and 12% Strain Value

Type of Binder	No Filler	F/B= 0.50	F/B = 1.0	F/B = 1.3	F/B = 1.5
VG-30	9.68	10.06	14.03	15.38	18.32
VG-30 + Sasobit® 2%	10.60	12.70	18.72	22.85	24.56
VG-30 + Sasobit® 3%	14.95	17.38	20.8	24.85	26.98
VG-30 + Sasobit® 4%	19.22	22.63	23.18	29.91	29.91
VG-30 + Evotherm™ 0.5%	7.11	10.14	15.45	19.11	22.45
VG-30 + Evotherm™ 1.0%	8.41	9.84	14.12	17.53	19.6
VG-30 + Evotherm™ 1.5%	8.98	10.53	16.39	20.67	21.85
VG-30 + Rediset® 1%	10.30	15.20	17.00	21.10	23.00
VG-30 + Rediset® 2%	15.00	17.70	19.00	24.00	26.00
VG-30 + Rediset® 3%	18.00	21.30	23.00	26.20	28.00
PMB-40	32.17	11.87	17.53	18.63	22.38
PMB-40 + Sasobit® 2%	15.80	17.07	19.91	22.8	22.68
PMB-40 + Sasobit® 3%	17.38	24.80	31.97	40.16	39.75
PMB-40 + Sasobit® 4%	31.78	31.31	45.12	49.36	57.93
PMB-40 + Evotherm™ 0.5%	14.62	20.76	38.68	53.41	60.88
PMB-40 + Evotherm™ 1.0%	7.45	7.25	11.09	15.54	16.91
PMB-40 + Evotherm™ 1.5%	8.74	9.16	16.18	20.02	25.68
PMB 40 + Rediset® 1%	16.00	19.30	23.50	28.15	30.00
PMB 40 + Rediset® 2%	19.00	24.80	35.00	39.70	41.00
PMB 40 + Rediset® 3%	21.20	32.70	41.00	47.30	51.20

Table 4.4: Failure Temperature (°C) from Rutting Consideration (G*/sinδ = 1 kPa)

Type of Binder	No Filler	F/B= 0.50	F/B = 1.0	F/B = 1.3	F/B = 1.5
VG-30	76	80	83	83	85
VG-30 + Sasobit® 2%	81	84	86	88	88
VG-30 + Sasobit® 3%	83	84	87	88	89
VG-30 + Sasobit® 4%	84	85	86	88	88
VG-30 + Evotherm™ 0.5%	76	80	83	85	86
VG-30 + Evotherm™ 1.0%	77	80	83	83	85
VG-30 + Evotherm™ 1.5%	77	81	84	85	86
VG-30 + Rediset® 1%	76	80	83	84	86
VG-30 + Rediset® 2%	76	82	84	88	89
VG-30 + Rediset® 3%	78	83	86	88	89
PMB-40	91	82	86	87	89
PMB-40 + Sasobit® 2%	81	87	88	88	89
PMB-40 + Sasobit® 3%	86	93	96	99	100
PMB-40 + Sasobit® 4%	92	99	102	104	106
PMB-40 + Evotherm™ 0.5%	84	95	105	115	115
PMB-40 + Evotherm™ 1.0%	76	79	82	84	85
PMB-40 + Evotherm™ 1.5%	78	83	89	90	95
PMB 40 + Rediset® 1%	82	86	89	90	92
PMB 40 + Rediset® 2%	86	88	94	99	102
PMB 40 + Rediset® 3%	89	90	95	103	110

4.3.2. Frequency Sweep tests

ZSV is an alternate performance indicator of rutting resistance of a bituminous binder. It is the complex viscosity of the binder at zero oscillation or zero shear condition or when shear rate approaches to zero. In this study ZSV is determined by oscillatory measurement technique by employing Dynamic Shear Rheometer. As it is not possible to conduct oscillatory test at zero frequency, it is conducted at most possible low frequency and ZSV is estimated by using a mathematical model which relates complex viscosity of the binder with frequency. In this study complex viscosity is measured over a frequency range of 25 to 0.1 Hz (157 rad/sec to 0.625 rad/sec) at two test temperatures 60°C and 40°C and viscosity at low oscillation condition ranging from 0.01 to 0.001 rad/sec was determined by using Cross model.

The Cross model describes a flow curve of asphalt binder. The equation of flow curve contains four parameters as follows:

$$\boldsymbol{\eta = \eta_\infty + (\eta_0 - \eta_\infty)/(1 + k\omega^m)} \qquad \textbf{.... 4.1}$$

Where η= apperent viscosity (Pa-s), η_0= ZSV (Pa-s), η_∞ = viscosity at infinite shear rate (Pa-s), ω=Angular Frequency (rad/sec); and k and m are material constants (Cross, 1965).

Non linear regression analysis was performed to estimate four parameter $\eta_\infty, \eta_{0,}$ k and m by using measured data of DSR. In all case η_∞ was close to zero. The complex viscosity of warm mix binder and its mastic was calculated over angular frequency ranging from 0.001 rad/sec to 10000 rad/sec by using cross model at two test temperatures. Frequency sweep tests were conducted at 60ºC and 40ºC. Bituminous binder in an asphalt mixture occurs not as bitumen alone but is mixed with mineral fillers, forming bitumen-filler-mastic. The ZSV of bitumen filler mastic, as opposed to those of plain bitumen, may be more appropriate in establishing a correlation with the permanent deformation properties of asphalt mixtures. Also, many of the warm mix additives like Evotherm™ and Rediset® do not alter the viscosities of bitumen as they only become effective when mixed with bitumen in presence of aggregates. Therefore, it will be appropriate to study the effect of addition of warm mix additive on the ZSV of both bitumen and bitumen-filler-mastic.

Complex viscosity values at 60°C for different warm mix binders and mastics are presented in Figure 4.31 to Figure 4.54. Similar plots were made for all binders and mastics at 40ºC also. The data from these frequency sweep plots were used to calculate ZSV by using Cross model. ZSV values of warm mix binders at 60°C and 40°C are listed in Table 4.9 and Table 4.10 respectively. As may be observed, complex viscosity at 40°C is quite larger than that at 60°C. It is because asphalt binder behaves like more viscous material at lower temperature. It is also observed that complex viscosity increases with decrease in oscillation and decreases at higher oscillation.

Figure 4.31 indicates that ZSV at 60°C of binder VG-30 with Sasobit® is remarkably higher than Virgin binder and it increases with addition of Sasobit® dose. The similar pattern is observed at 40°C also. Since ZSV is an indicator of rutting resistance of a binder, VG30 with 4% Sasobit® will have better resistance to rutting. However Rediset® and Evotherm™ with VG-30 shows slight reduction in ZSV. Figure 4.32 and Figure 4.33 show that both Rediset® and Evotherm™ when added to VG 30 binder reduces the ZSV of the binders at 60ºC and similar trends are observed when these binders were tested at 40ºC. This indicates that Rediset® and Evotherm™ are not effective in improving the rutting resistance. The smaller dose of Sasobit® decreases the ZSV of PMB-40 at both temperatures. While higher doses of Sasobit® with PMB-40 improve ZSV values at the two temperatures. Thus Sasobit® will be effective with PMB-40 only if 3% or more Sasobit® is used. Further Rediset® and Evotherm™ with PMB-40 decreased the ZSV at both the temperature which confirm that Rediset® and Evotherm™ will not be suitable for rutting with PMB-40 as well.

Complex viscosity of mastics presented in Figures 4.37 to 4.54 and ZSV listed in Table 4.9 and 4.10 indicate that complex viscosity of mastics is greater than that of warm mix binder. This is because the addition of filler in the binder produces a stiff mix with greater viscosity and at same time filler improves stability of the binder due to its filling effect. It is observed that increase in concentration of lime stone dust filler in mastic increases the ZSV. The bitumen filler mastic up to a limited concentration of filler will show remarkable improvement in rutting resistance. Further Tables 4.9 and 4.10 indicate that at both test temperatures, ZSV of mastic prepared with VG-30 increases with Sasobit® dose at all filler concentrations. It is indicating that Sasobit® improves the rutting performance of mastic also. Rutting performance of mastic of PMB-40 with higher dose (3% and 4%) of Sasobit® is quite good as compared with neat PMB-40. The ZSV value of mastics with F/B ratios of 1.3 and 1.5 are almost same for most of the warm mix additives. Plot of complex viscosity for 1.5 F/B ratio is sometime overlapping with that for 1.3 F/B ratio or lowers also in some cases. This is because of dominating effect of filler to filler interaction in mastic at high concentration of limestone filler as stated earlier. Therefore Filler-bitumen ratio of 1.3 is taken optimum for the purpose of improving performance of the mix against permanent deformation.

Addition of Rediset® to VG 30 and PMB 40 reduces their ZSV at both the test temperatures i.e. 60ºC and 40ºC, but an improvement in the ZSV was observed in the case of binder filler mastic. The improvement goes on increasing with the increasing dose of Rediset® additive and also with the increasing filler content. At higher filler-binder ratios of 1.3 and 1.5, the Rediset® modified binders showed improved ZSV which indicates improved resistance to rutting. This behaviour of the additive indicates that Rediset® does not alter the properties of the binder but shows the improvement in the properties when filler is added to the binder.

Addition of Evotherm™ to VG30 binder makes slight change in the ZSV with respect to that of neat binder, and at low temperature, it reduces to a level below the ZSV of the neat binder when Evotherm™ dose is higher. In the case of PMB, the ZSV reduces considerably when Evotherm™ is added to the neat binder. These results suggest that the Evotherm™ is not very effective when added to the neat binder. However, the ZSV of binder-filler mastic show improvement in the case of both binders and the maximum ZSV is obtained at filler-binder (F/B) ratio of 1.5 and Evotherm™ dose of 0.5 percent. At higher doses of Evotherm™, the ZSV reduces for VG30 as well as for PMB 40 binder – filler mastics. Whereas it is not the case with the Sasobit® where ZSV of the mastic increased with increasing dose of the additive.

The melting point of Sasobit® is between 90-100°C and hence it is hypothesized that when Sasobit® is added to the binders and tested at 60°C and 40°C, the paraffin wax is in the crystalline state, thereby increasing the stiffness of the binders, which results in increase in the ZSV of the binders and mastics. Evotherm™, on the other hand, is a surfactant, and when added to the bitumen-filler mastic, a portion of the Evotherm™ molecules migrate to the bitumen- filler interface and the polar heads are attracted to the polar properties of the limestone filler. It reduces the viscosity of the bitumen-filler mastic, which also explains as to how Evotherm™ helps in achieving asphalt mix workability at lower temperatures. As the F/B ratio is increased to 1.5%, Evotherm™ shows significant improvement in ZSV values of PMB-40 as well as VG-30. Rediset® is a chemical based additive which has its melting point between 80-95C and it slightly reduces the viscosity of the binder but improves the surface tension between the binder and the aggregate and hence allows the production and compaction of mixes at lower temperatures.

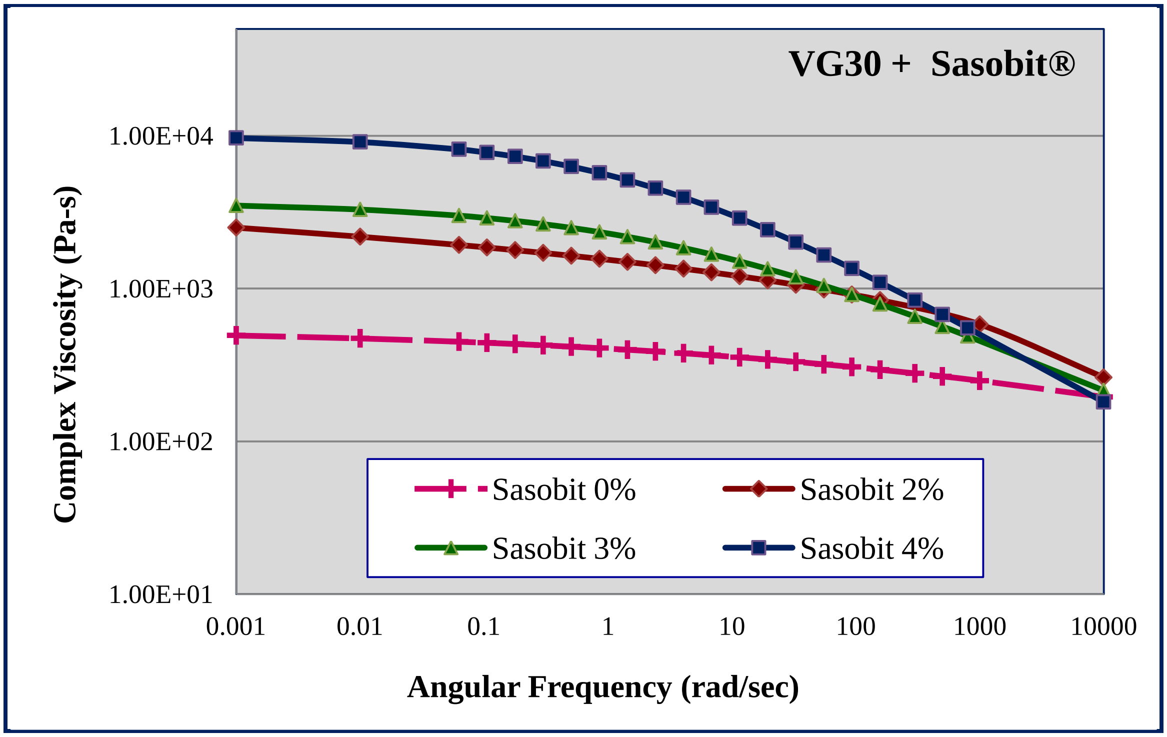


Figure. 4.31: Complex Viscosity (η*) at 60°C for Sasobit® modified VG 30

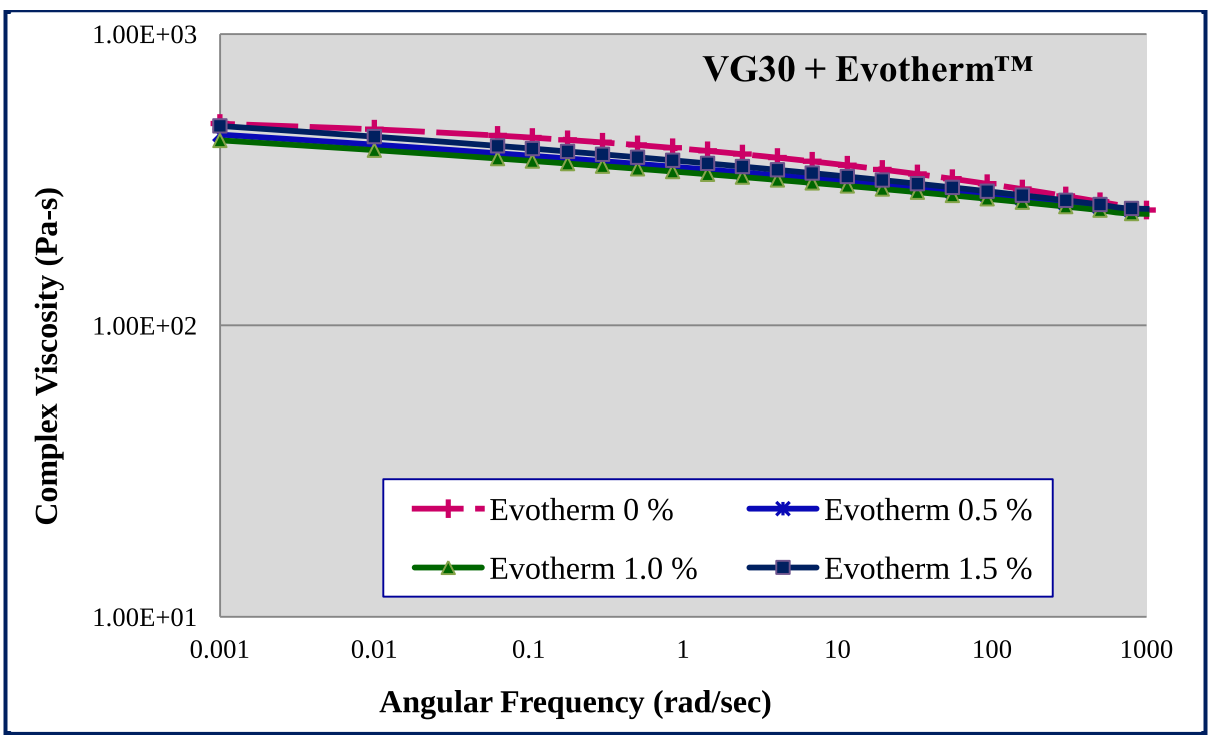


Figure. 4.32: Complex Viscosity (η*) at 60°C for Evotherm™ modified VG 30

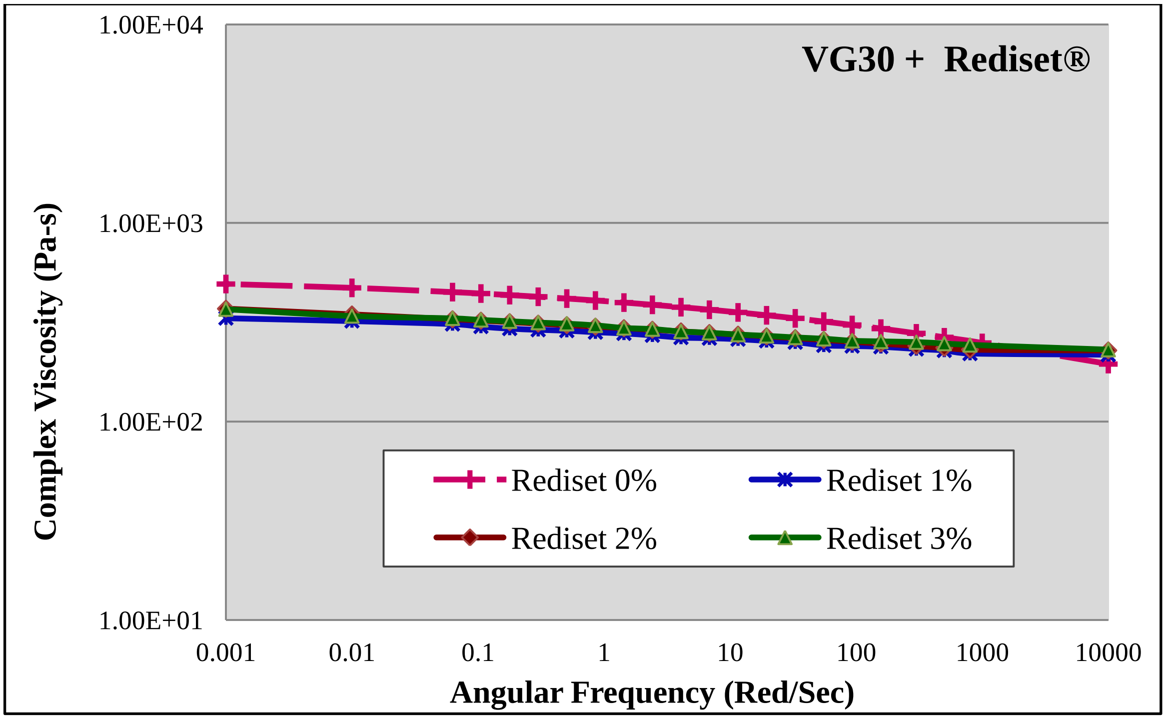


Figure. 4.33: Complex Viscosity (η*) at 60°C for Rediset® modified VG 30

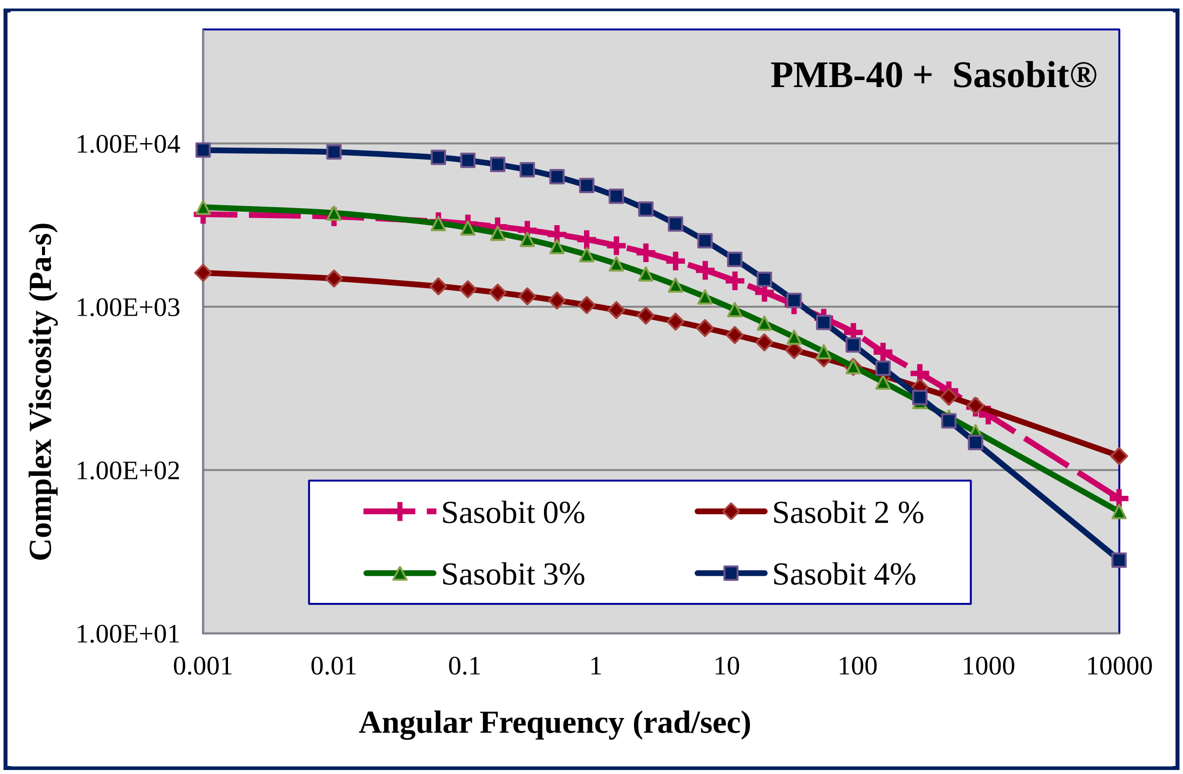


Figure. 4.34: Complex Viscosity (η*) at 60°C for Sasobit® modified PMB 40

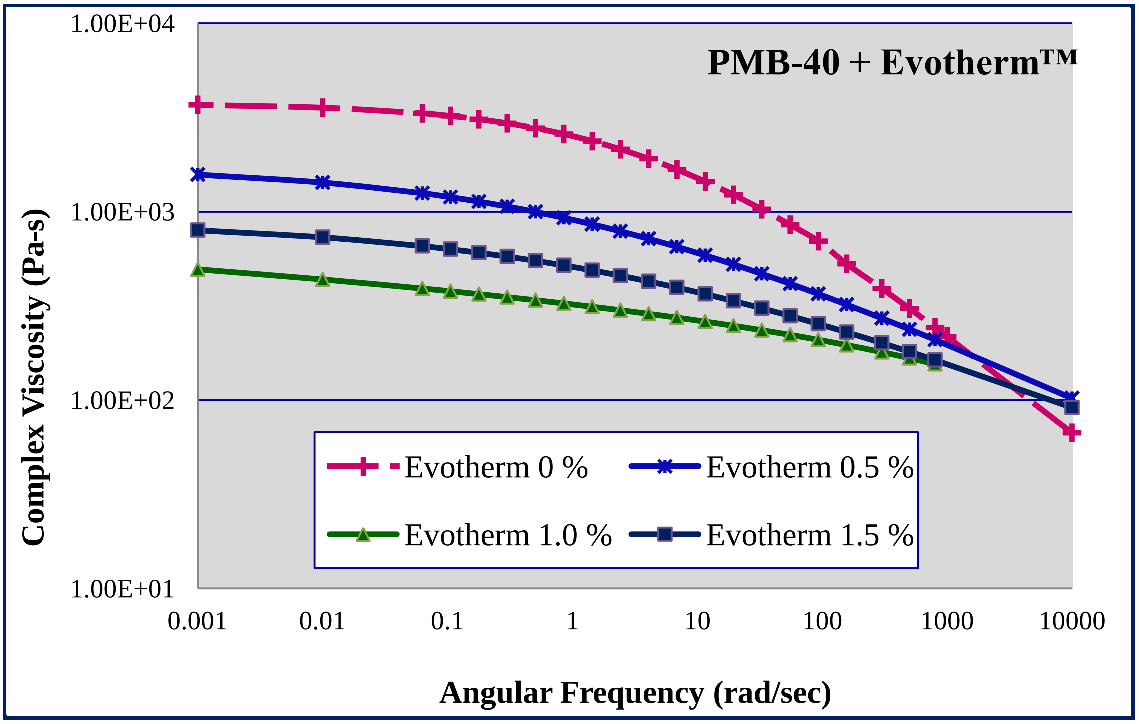


Figure. 4.35: Complex Viscosity (η*) at 60°C for Evotherm™ modified PMB 40

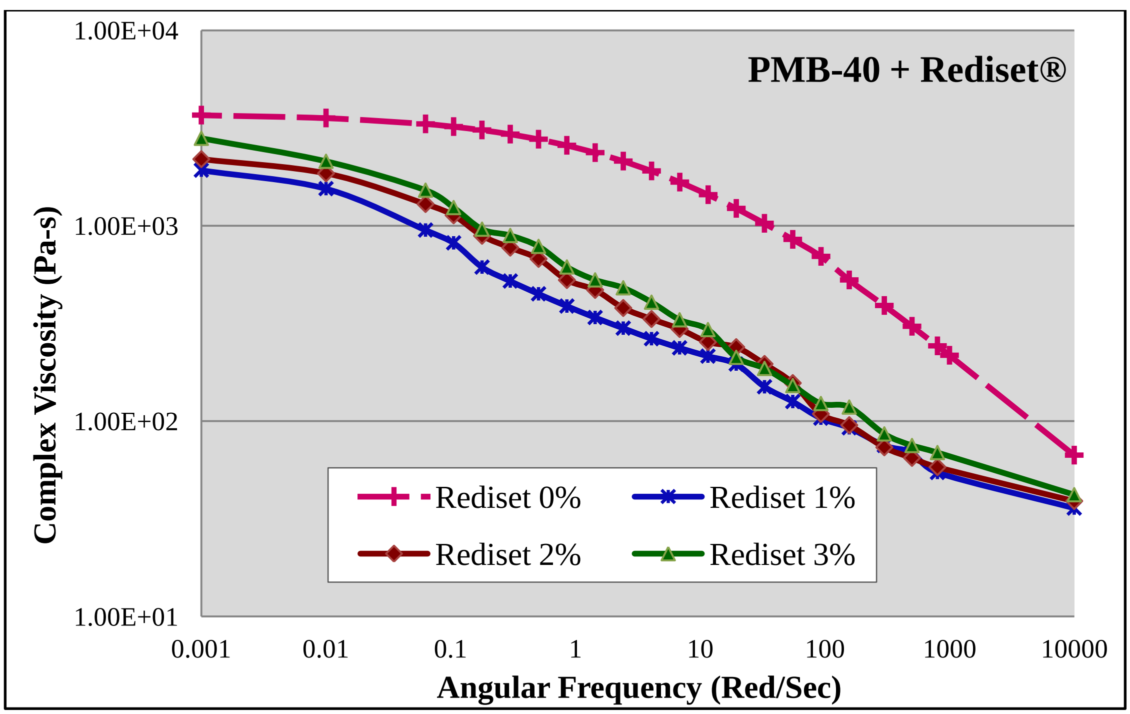


Figure. 4.36 Complex Viscosity (η*) at 60°C for Rediset® modified PMB 40

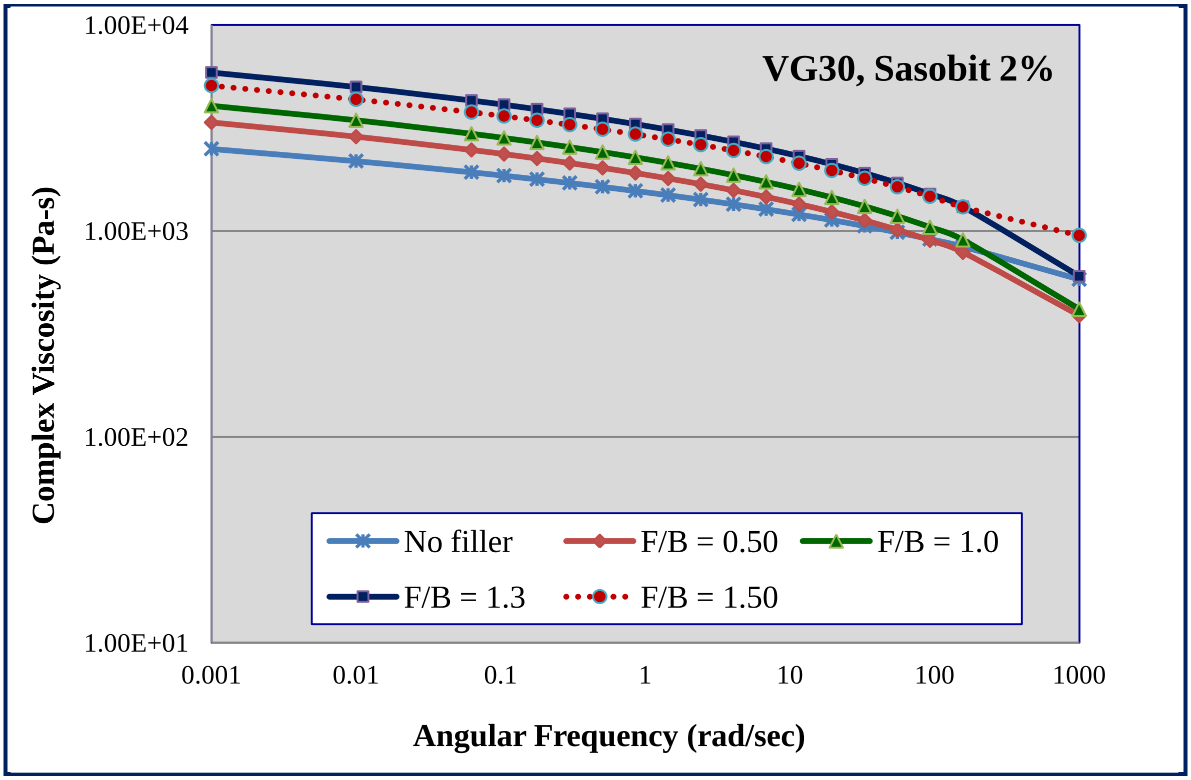


Figure. 4.37: Complex Viscosity (η*) at 60°C for Mastic with VG-30 and 2% Sasobit®

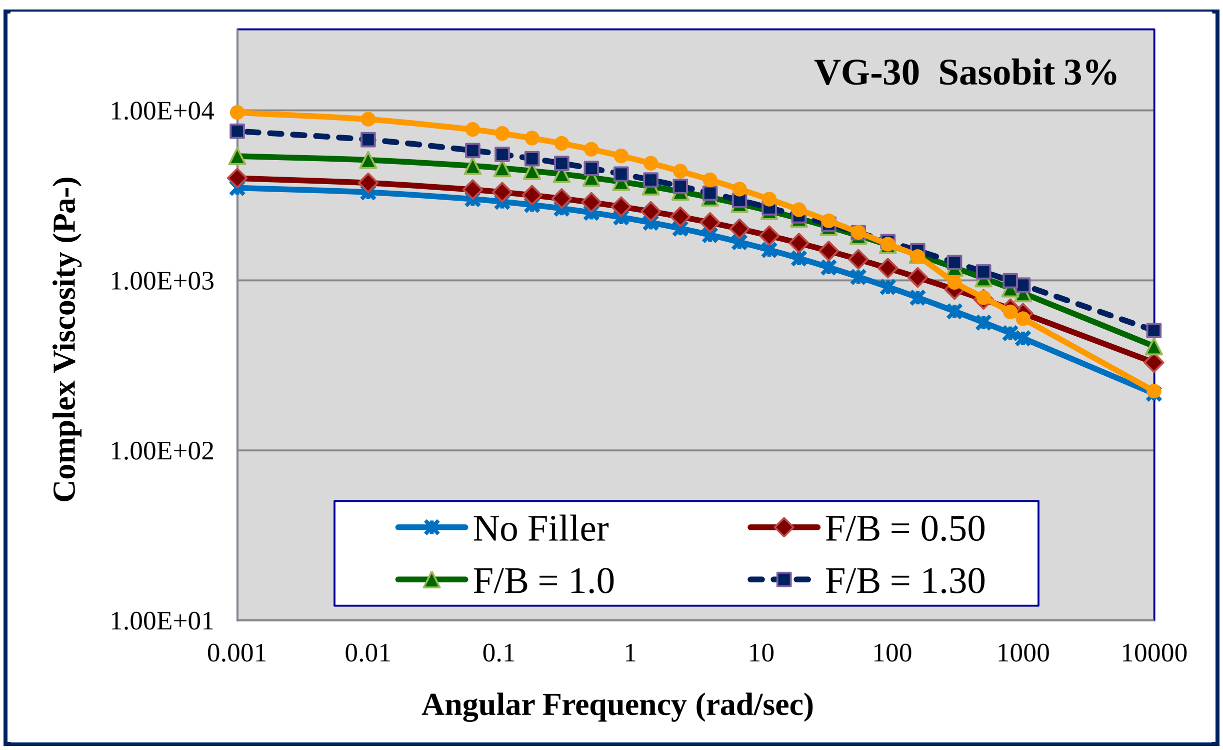


Figure. 4.38: Complex Viscosity (η*) at 60°C for Mastic with VG-30 and 3% Sasobit®

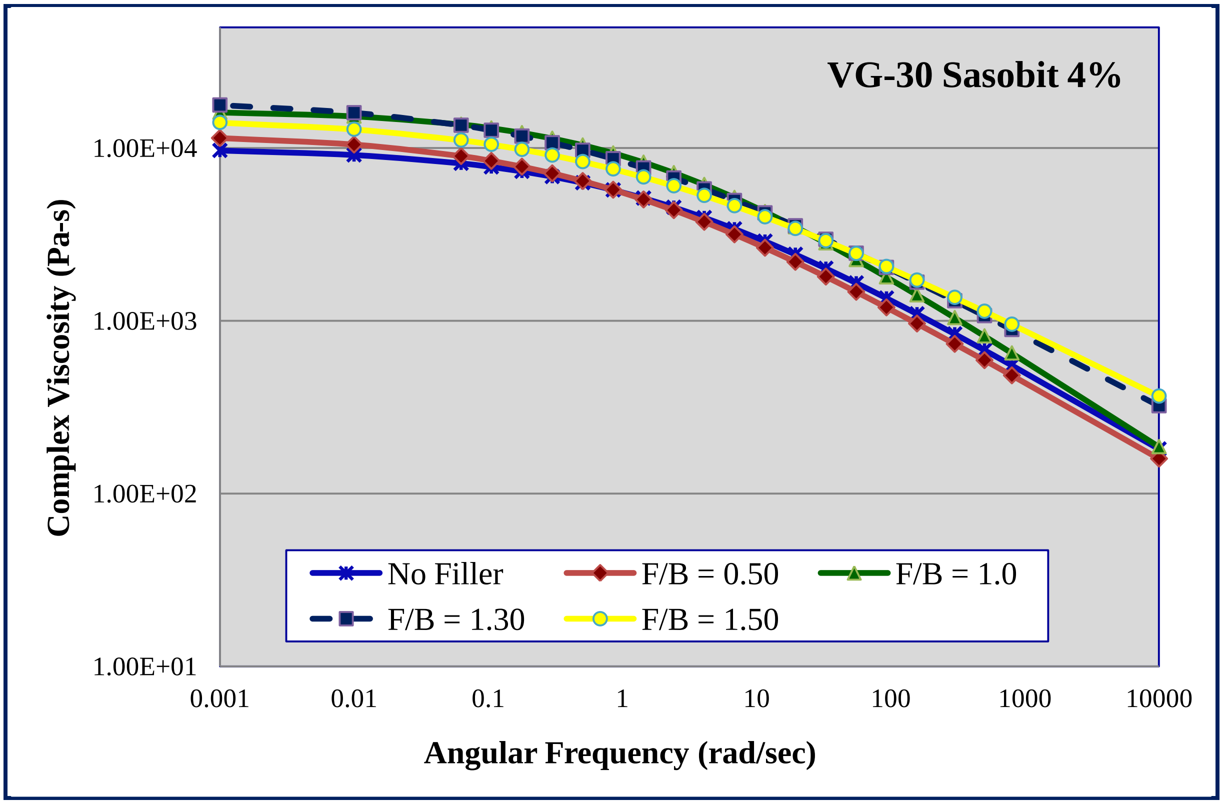


Figure. 4.39: Complex Viscosity (η*) at 60°C for Mastic with VG-30 and 4% Sasobit®

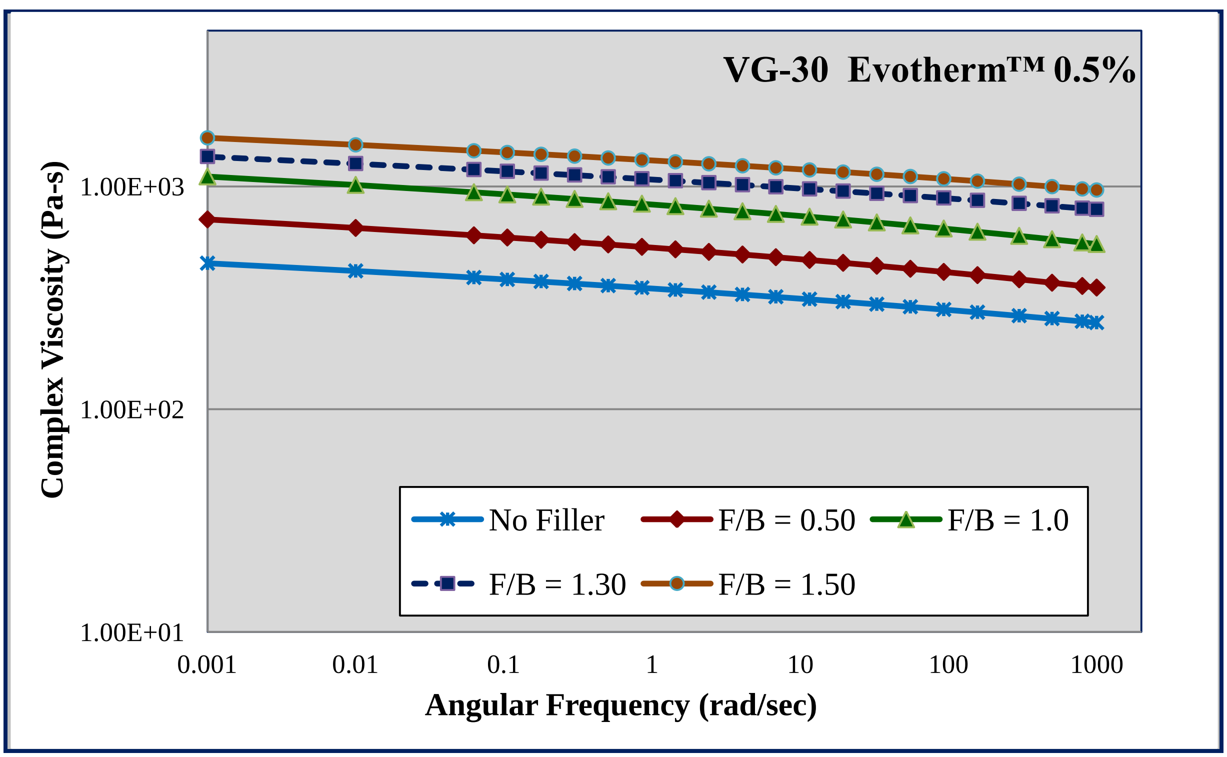


Figure. 4.40: Complex Viscosity (η*) at 60°C for Mastic with VG-30 and 0.5% Evotherm™

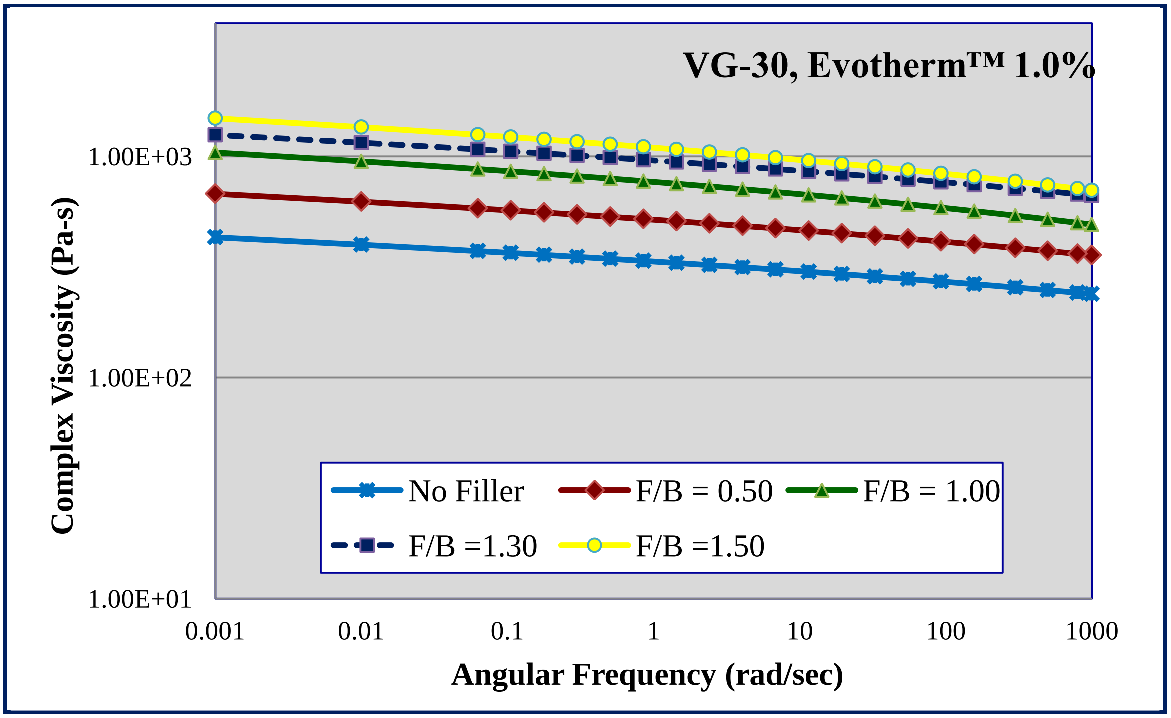


Figure. 4.41: Complex Viscosity (η*) at 60°C for Mastic with VG-30 and 1.0% Evotherm™

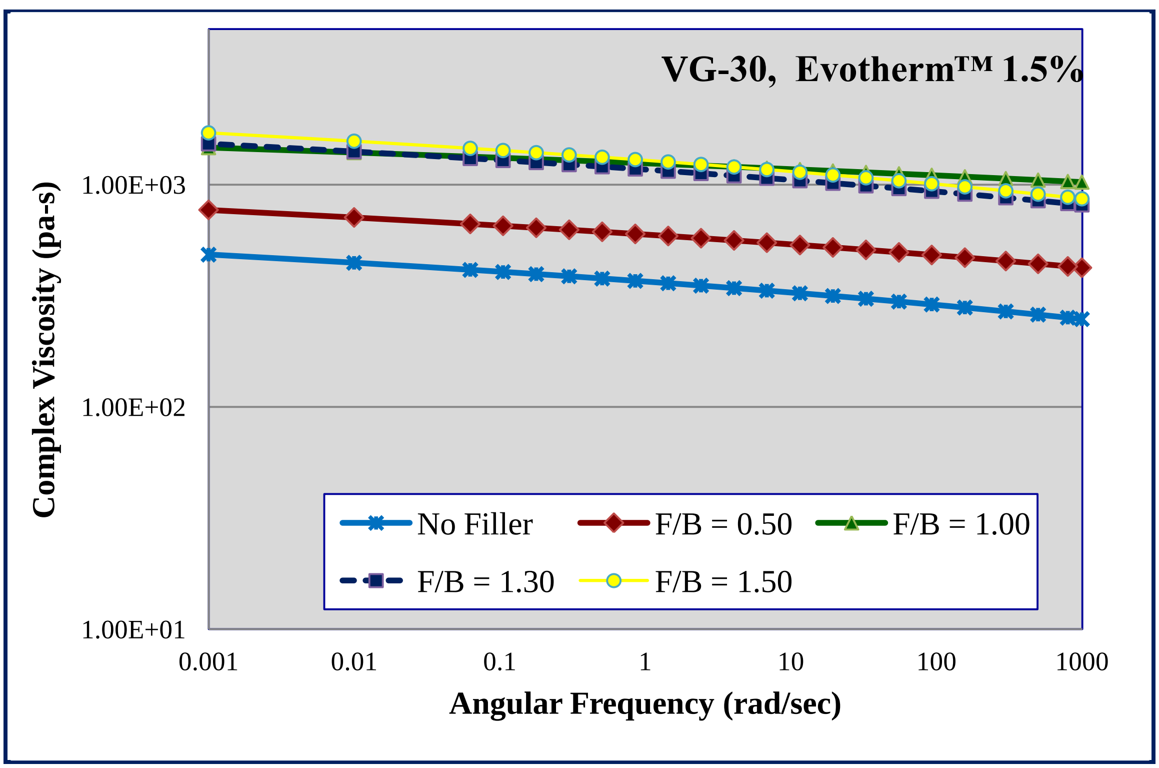


Figure. 4.42: Complex Viscosity (η*) at 60°C for Mastic with VG-30 and 1.5% Evotherm™

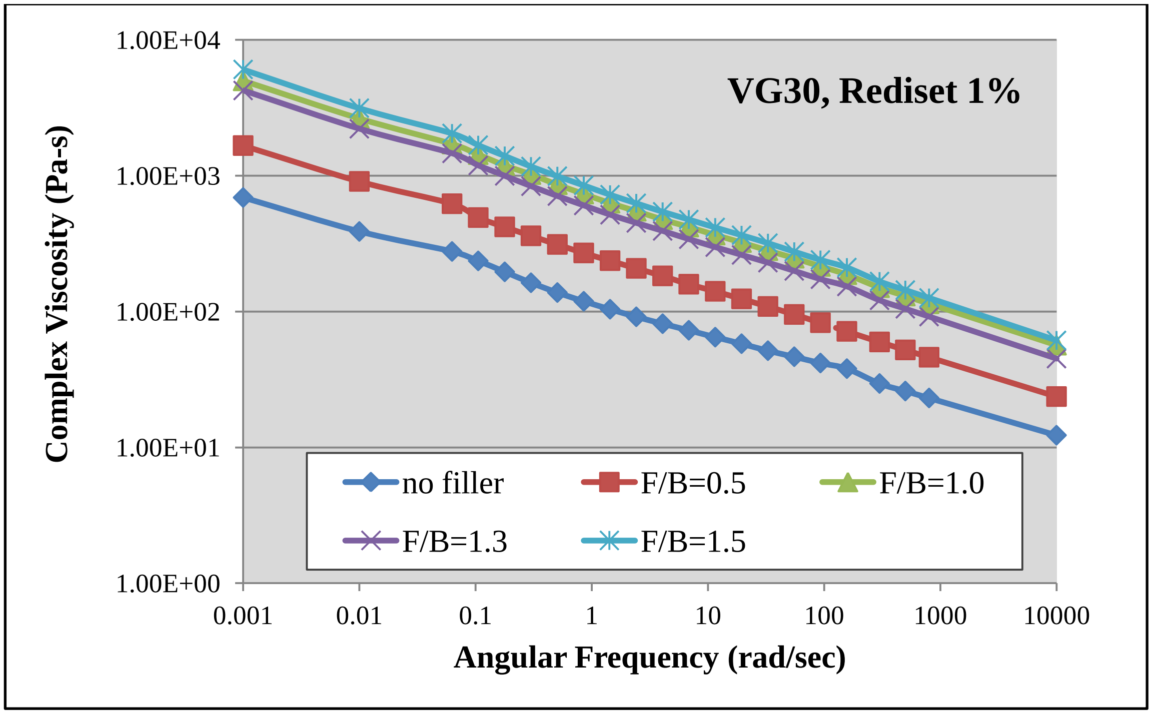


Figure. 4.43: Complex Viscosity (η*) at 60°C for Mastic with VG-30 and 1% Rediset®

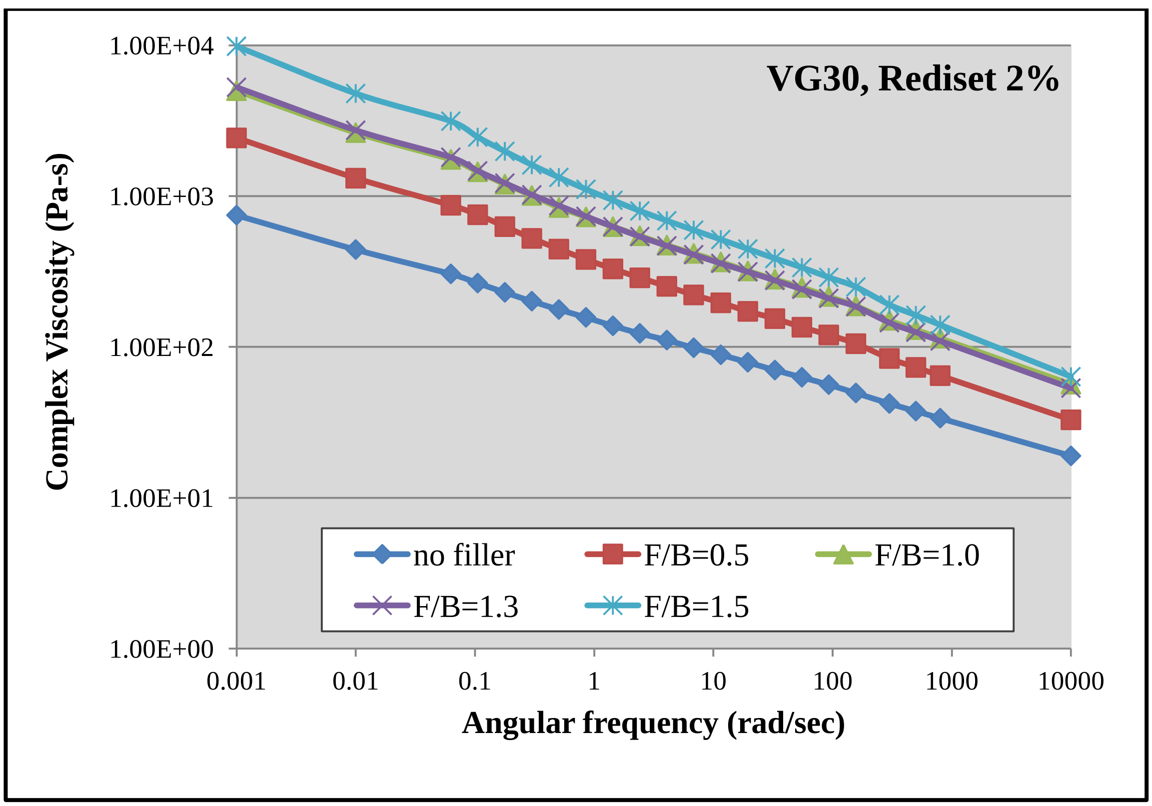


Figure. 4.44: Complex Viscosity (η*) at 60°C for Mastic with VG-30 and 2% Rediset®

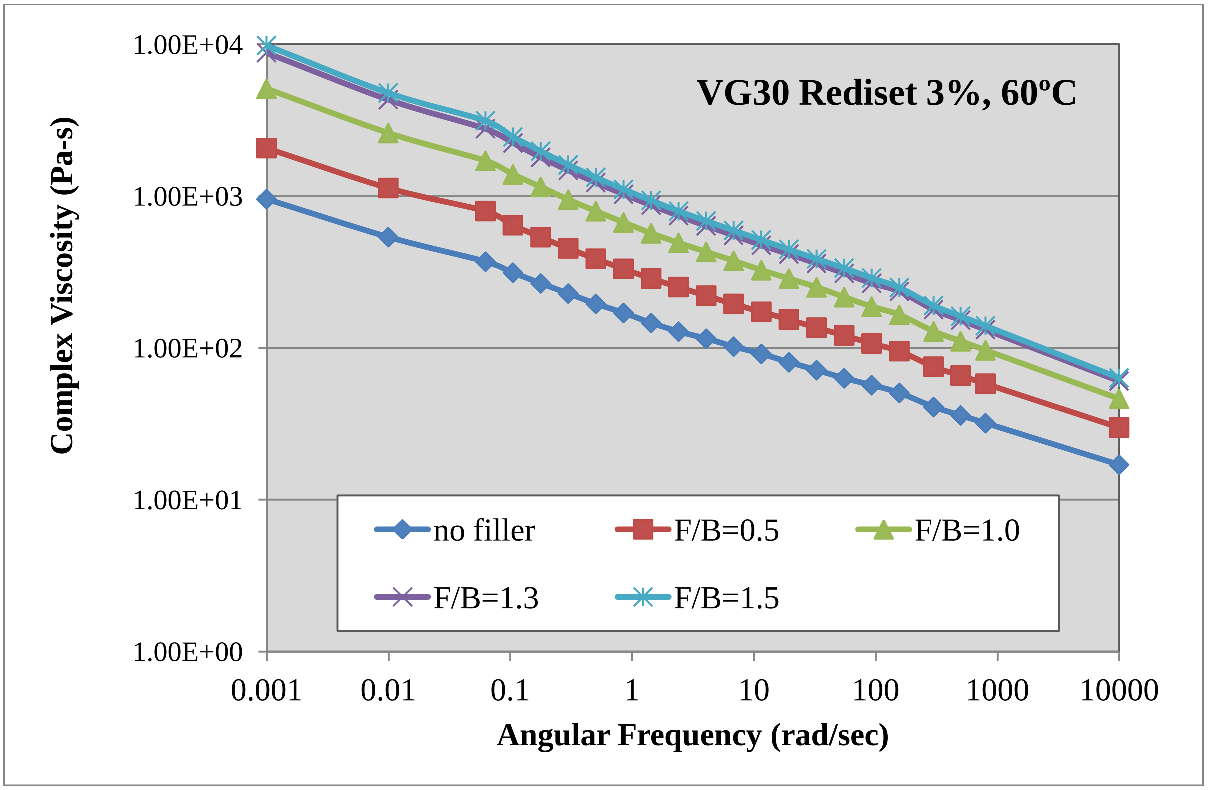


Figure. 4.45: Complex Viscosity (η*) at 60°C for Mastic with VG-30 and 3% Rediset®

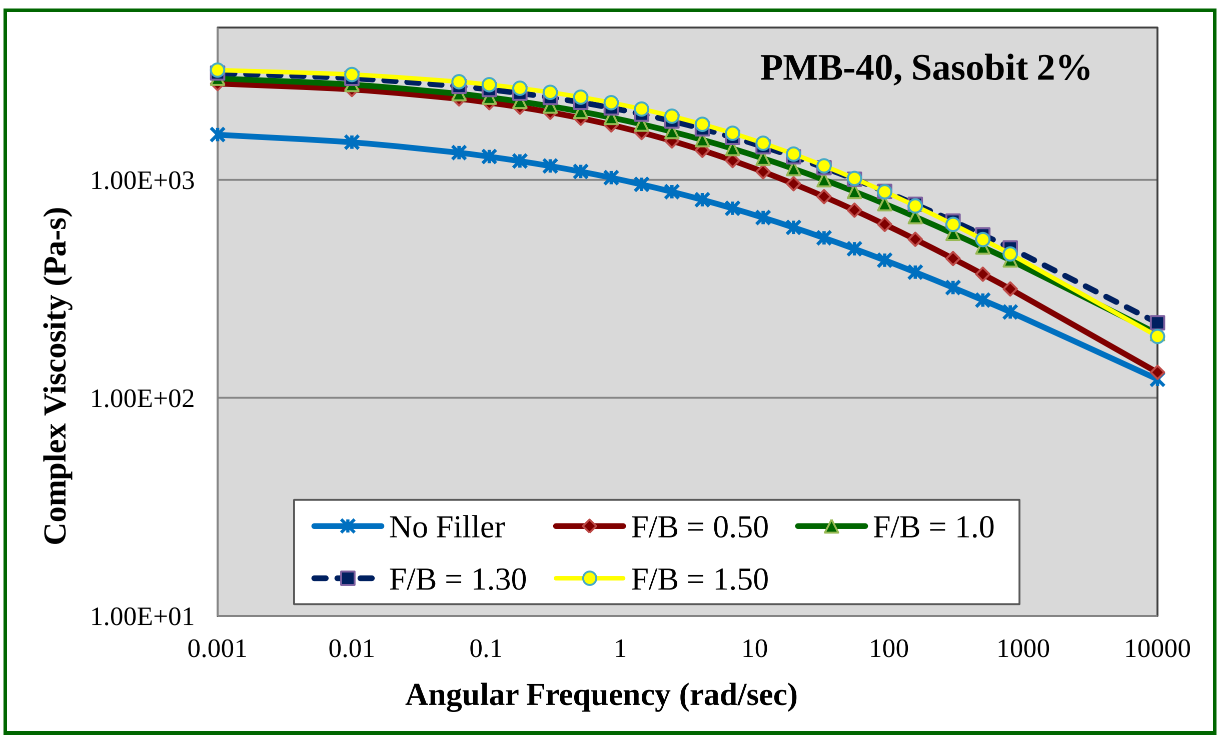


Figure. 4.46: Complex Viscosity (η*) at 60°C for Mastic with PMB 40 and 2% Sasobit®

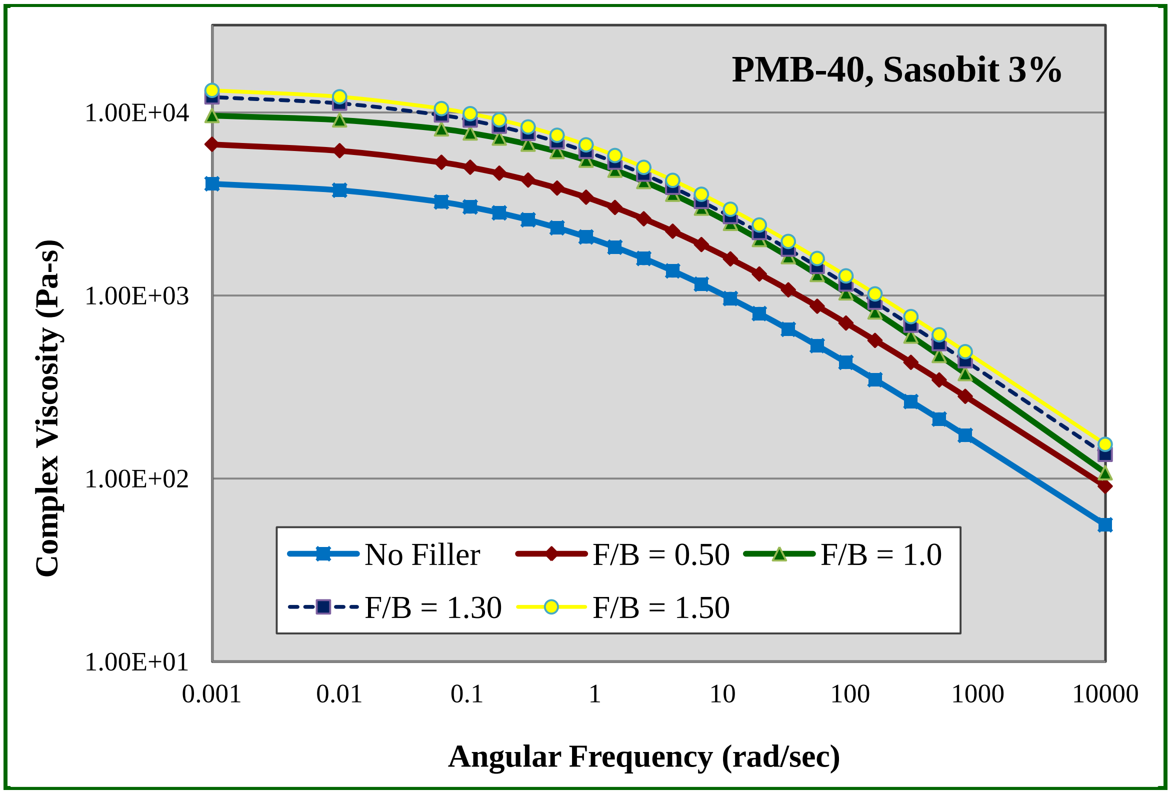


Figure. 4.47: Complex Viscosity (η*) at 60°C for Mastic with PMB 40 and 3% Sasobit®

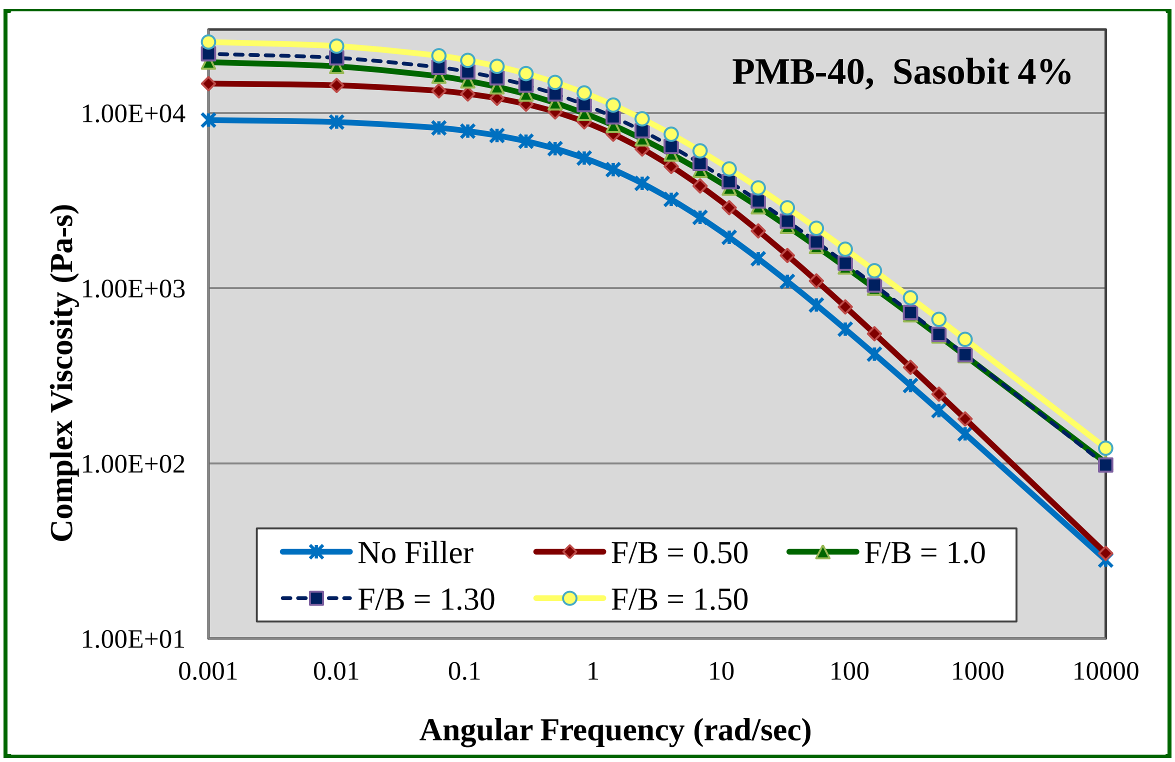


Figure. 4.48: Complex Viscosity (η*) at 60°C for Mastic with PMB 40 and 4% Sasobit®

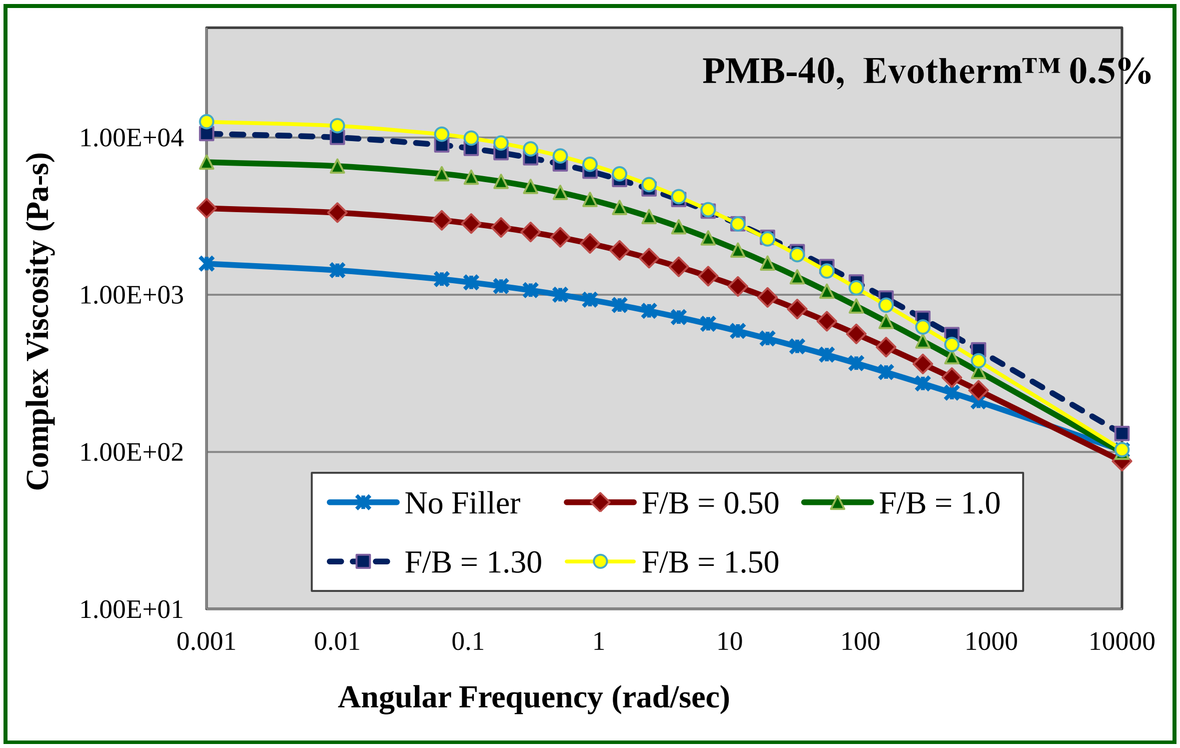


Figure. 4.49: Complex Viscosity (η*) at 60°C for Mastic with PMB 40 and 0.5% Evotherm™

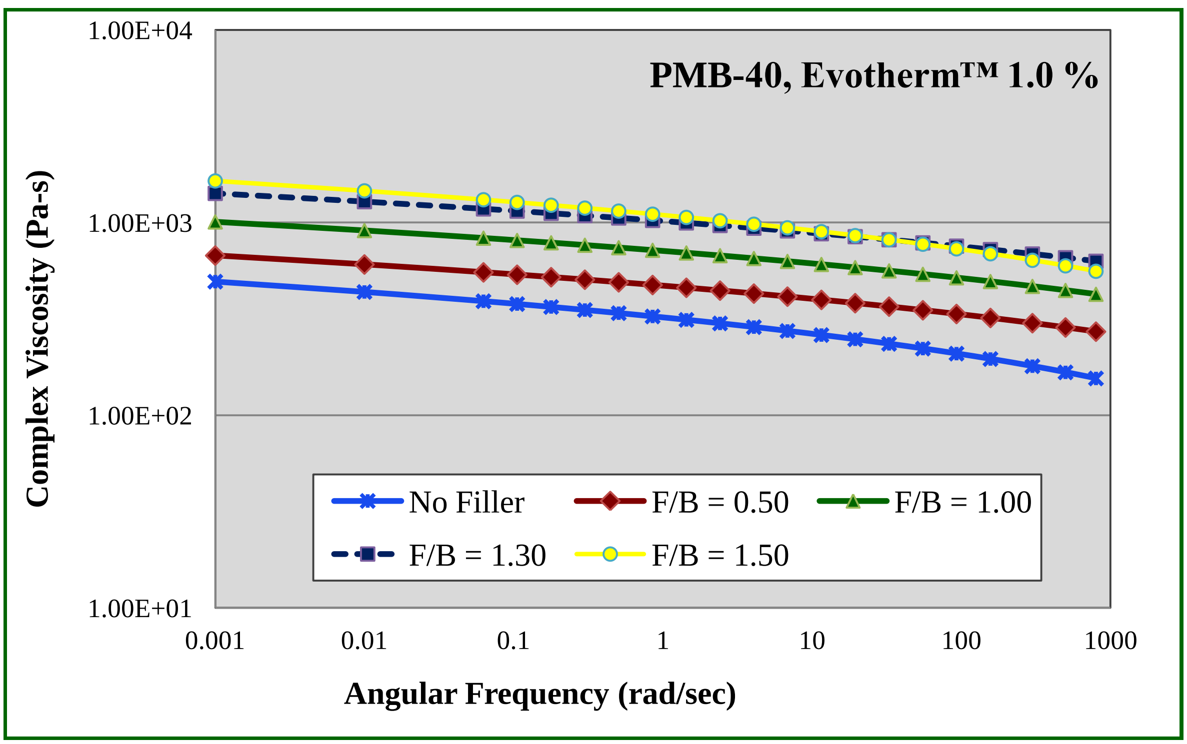


Figure. 4.50: Complex Viscosity (η*) at 60°C for Mastic with PMB 40 and 1.0% Evotherm™

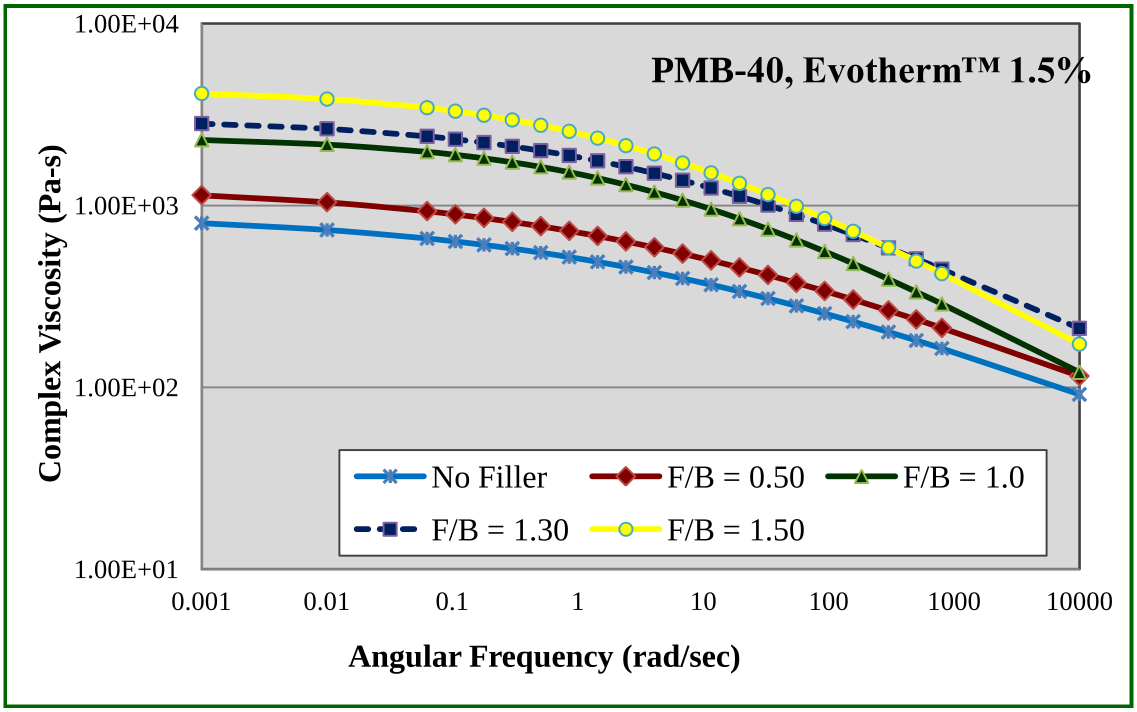


Figure. 4.51: Complex Viscosity (η*) at 60°C for Mastic with PMB 40 and 1.5% Evotherm™

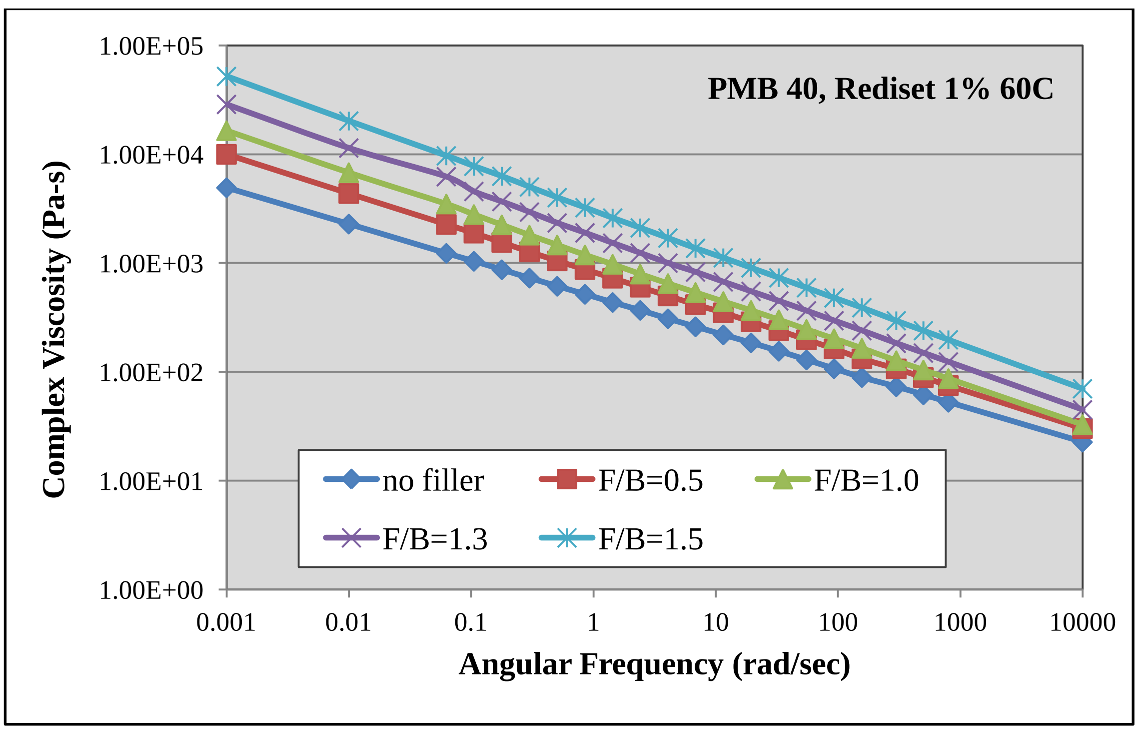


Figure. 4.52: Complex Viscosity (η*) at 60°C for Mastic with PMB 40 and 1% Rediset®

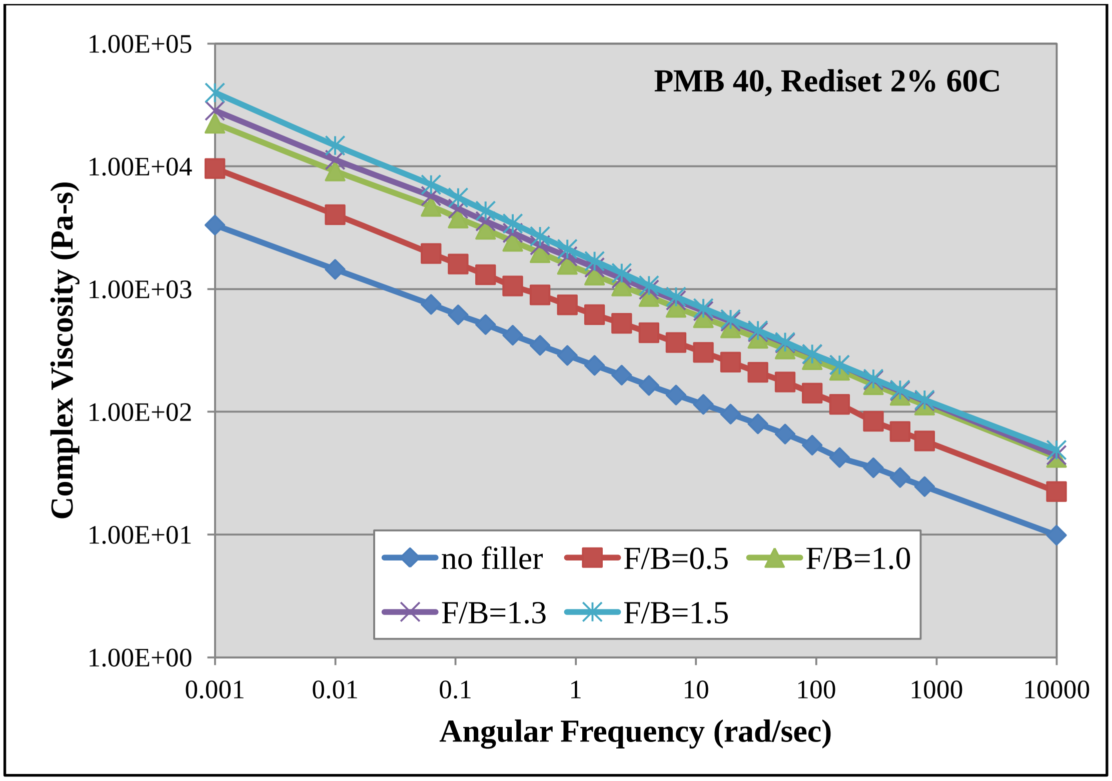


Figure. 4.53: Complex Viscosity (η*) at 60°C for Mastic with PMB 40 and 2% Rediset®

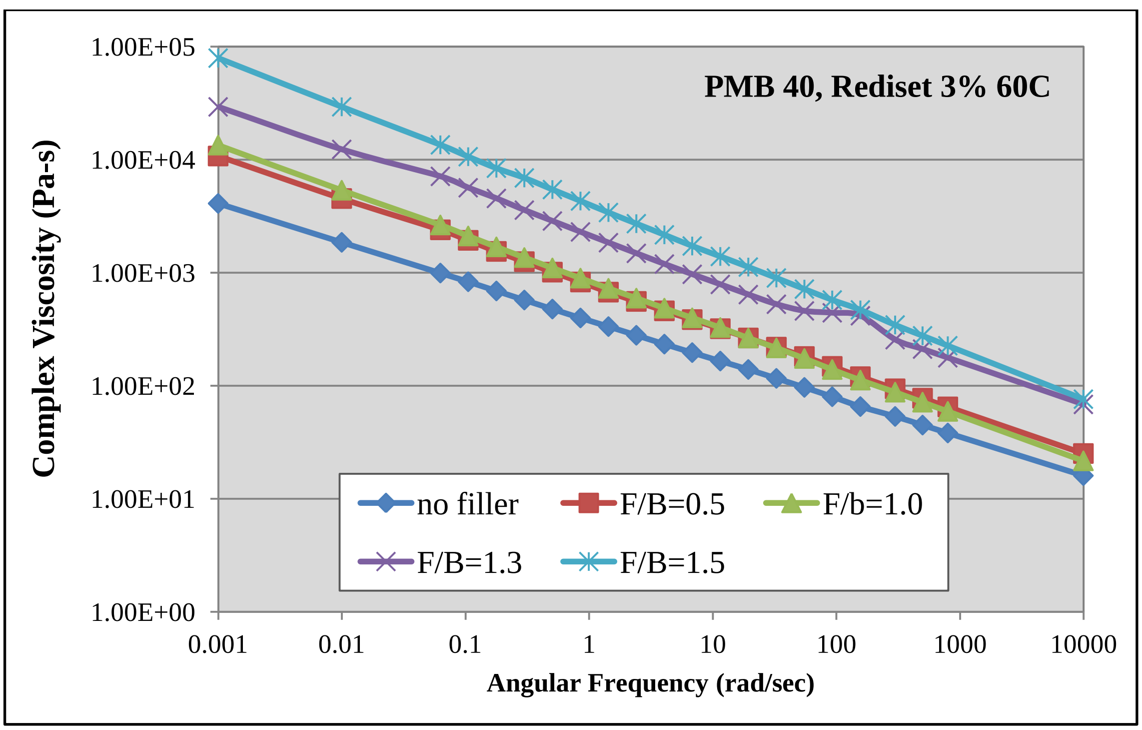


Figure. 4.54: Complex Viscosity (η*) at 60°C for Mastic with PMB 40 and 3% Rediset®

Table 4.5: Zero Shear Viscosity (Pa-s) at 60°C by Cross Model

Type of Binder	No Filler	Filler-Binder (F/B) ratio			
		0.50	**1.0**	**1.3**	**1.5**
VG-30	542	937	1123	1236	1674
VG-30 + Sasobit® 2%	2181	2864	3443	4995	4349
VG-30 + Sasobit® 3%	3495	3990	5374	7531	9715
VG-30 + Sasobit® 4%	9669	11402	16095	17712	14811
VG-30 + Evotherm™ 0.5%	452	710	1108	1361	1650
VG-30 + Evotherm™ 1.0%	431	678	1041	1251	1488
VG-30 + Evotherm™ 1.5%	483	769	1467	1525	1708
VG-30 + Rediset® 1%	461	668	994	1240	1696
VG-30 + Rediset® 2%	497	729`	1104	1329	1721
VG-30 + Rediset® 3%	555	907	1543	1504	1951
PMB-40	3728	4170	4595	4827	4946
PMB-40 + Sasobit® 2%	1614	2764	2923	3090	3187
PMB-40 + Sasobit® 3%	4067	6686	9595	12129	16814
PMB-40 + Sasobit® 4%	9119	14706	19539	21786	25440
PMB-40 + Evotherm™ 0.5%	1573	3541	6960	10567	12575
PMB-40 + Evotherm™ 1.0%	437	607	910	1285	1462
PMB-40 + Evotherm™ 1.5%	789	1138	2294	2816	4119
PMB-40 + Rediset® 1%	1433	2308	3216	4287	5210
PMB-40 + Rediset® 2%	1334	3601	4456	5241	6975
PMB-40 + Rediset® 3%	1409	3751	4453	5924	7897

Table 4.6: Zero Shear Viscosity (Pa-s) at 40°C by Cross Model

Type of Binder	No Filler	Filler-Binder (F/B) Ratio			
		0.50	1.0	1.3	1.5
VG-30	31868	41997	62142	63204	90321
VG-30 + Sasobit® 2%	57148	81907	117327	128716	150237
VG-30 + Sasobit® 3%	72478	92193	134086	180559	195889
VG-30 + Sasobit® 4%	138241	142604	189278	230761	158523
VG-30 + Evotherm™ 0.5%	35644	59236	76487	100303	114535
VG-30 + Evotherm™ 1.0%	21983	36359	61479	75111	96551
VG-30 + Evotherm™ 1.5%	23550	37430	62655	72695	95715
VG-30 + Rediset® 1%	10725	34382	187536	189842	232818
VG-30 + Rediset® 2%	11235	55284	110392	424419	697619
VG-30 + Rediset® 3%	14698	44902	157182	449007	800254
PMB-40	67736	81446	104932	186432	214582
PMB-40 + Sasobit® 2%	37707	66173	78394	93292	123014
PMB-40 + Sasobit® 3%	76049	108986	163157	193179	213774
PMB-40 + Sasobit® 4%	112707	164036	218238	169732	291544
PMB-40 + Evotherm™ 0.5%	49420	70496	130271	158037	193919
PMB-40 + Evotherm™ 1.0%	20785	27954	43153	67536	72544
PMB-40 + Evotherm™ 1.5%	22981	30840	61873	86175	95518
PMB-40 + Rediset® 1%	22624	35331	110001	188720	185894
PMB-40 + Rediset® 2%	24935	41270	124530	174804	235042
PMB-40 + Rediset® 3%	20603	38827	134369	228721	296167

4.4 Effect of warm asphalt additives on aging characteristics

Bitumen ageing occurs during the mixing and construction process as well as during long term service in the road. Several methods have been proposed to replicate the effect of ageing and, therefore, to foresee bitumen behaviour during application and service life. To simulate the age hardening occurring during plant mixing and lay down the most utilized test is Rolling Thin Film Oven Test (RTFOT, ASTM D-2872). To simulate long-term ageing during service life of the pavement the Pressure Ageing vessel Test (PAV, AASHTO PP1) was adopted in SHRP binder specifications.

The binders used in this study were also aged in the RTFO and PAV. Control binders i.e. VG-30 and PMB-40 were aged in RTFO at 163ºC whereas the VG based warm binders were aged at two different temperatures, 163ºC and a lower temperature of 115ºC. Similarly PMB-40 based warm binders were aged in RTFO at 163ºC and at 135ºC. The lower temperatures for RTFO were selected on the basis of the temperatures at which the warm mixes were prepared. As it will be reported in the next chapter, VG 30 based warm mixes were prepared at 115ºC and PMB 40 based warm mixes were prepared at 135ºC. RTFO aging is done to simulate the short term aging of binders, which occurs due to the exposure of binders to high temperatures during bituminous mix production. Since the warm mixes were prepared at lower temperatures, the RTFO test was done at lower temperatures as well as at 163ºC to check the aging in warm mix binders.

After the binders were aged in RTFO, the PAV aging was carried out for all the binders at 100ºC. Since WMA and HMA are exposed to similar conditions in the field after being placed, the PAV aging temperatures were kept same for both WMA and HMA. After the binders were aged in RTFO and PAV, $G^*/\sin\delta$, viscosity, aging index, $G^*.\sin\delta$, stiffness and m-values of the binders with and without warm asphalt additives were found and compared to determine the effects of the warm asphalt additives on these properties.

The aging properties of warm mix binders were studied at the optimum dosages of additives. The optimum dosages were found on the basis of ZSV and rutting parameter values and also on the basis of values of mix design parameters i.e. Marshall stability, retained stability, air voids. The dosage at which the modified binder gave similar values of these parameters as to that of HMA, were selected as optimum dosage of the additive. The detailed discussion on this subject has been given in Chapter 5. The optimum dose for Sasobit®, Evotherm™ and Rediset® is 3%, 0.5% and 3% respectively for VG 30 by weight of the bitumen. For PMB 40 the optimum dose for Sasobit®, Evotherm™ and Rediset® is 3%, 1% and 3% respectively by weight of the bitumen.

4.4.1 Aging Index

These RTFO residues were tested for their viscosity in Brookfield viscometer at 135ºC at 20 rpm with spindle number 27. Un-aged binders were also tested for their viscosity under same conditions. When the asphalt mixes are prepared, a binder is exposed to heat and due to this exposure to high temperatures the binder undergoes maximum hardening. As a result of this hardening, there is a significant increase in the viscosity of the binder and the extent of the hardening can be quantified in terms of viscosity as per equation 4.2 (Roberts, et al., 1996)

$$Aging\ Index = \frac{Viscosity\ of\ Aged\ Binder}{Viscosity\ of\ Un{-}aged\ Binder} \qquad 4.2$$

Tables 4.11 and 4.12 show the viscosity of the un-aged binders and the binders aged at 163ºC and at lower temperatures. Since warm asphalt is mixed at lower temperature than normal hot mix asphalt, it was decided to measure the aging index of the binders when aged in RTFO at a lower temperature as well as at 163ºC. The aging indices were calculated as per equation 4.2 and these are also given in Tables 4.12 & 4.12

Table 4.7: Viscosity of Aged and Un-aged VG-30 based warm mix binders

Binder	Viscosity (Pa-s) of			Aging Index at	
	Un-aged binder	Aged at 163ºC	Aged at 115ºC	163 ºC	115 ºC
VG 30	620	1050	--	1.69	--
VG 30 + 3% Sasobit®	500	750	600	1.50	1.20
VG 30 + 0.5% Evotherm™	675	980	875	1.45	1.30
VG 30 + 3% Rediset®	515	800	650	1.55	1.26

Table 4.8: Viscosity of Aged and Un-aged PMB-40 based warm mix binders

Binder	Viscosity (Pa-s) of			Aging Index at	
	Un-aged binder	Aged at 163ºC	Aged at 135ºC	163 ºC	135 ºC
PMB 40	1402	2250	--	1.60	--
PMB 40+ 3% Sasobit®	1050	1550	1350	1.48	1.29
PMB 40+ 1% Evotherm™	1075	1450	1225	1.35	1.14
PMB 40 + 3% Rediset®	1150	1725	1400	1.50	1.24

It is observed that the aging indices of the binders aged in RTFO at lower temperatures are significantly lower than the control binders aged at 163ºC. It can also be seen that the warm binders aged at 163ºC also gave lower aging indices in comparison to control binders aged at 163ºC. This concludes that the addition of warm mix additive to bituminous binder makes the binder resistant to aging and when the mixes are prepared at lower temperatures. The binders will have much lower aging than the conventional hot mix binders. To substantiate this further, the warm mixes were prepared in the laboratory along with the hot mixes. The VG 30 hot mixtures were prepared at 150ºC and VG30 based warm mixtures were prepared at 115ºC, whereas PMB 40 hot mixtures were prepared at 165ºC and PMB 40 based warm mixtures were prepared at 135ºC. These mixes were then compacted to Marshall specimens. The binders were recovered from these mixes and recovered binders were tested for their aging indices. Figure 4.55 shows the aging indices of the recovered binders. It is observed that aging indices for the binders recovered from warm mixes are significantly lower than those of the binders recovered from conventional hot mixes. It suggests that warm mix asphalt prepared at lower temperature will undergo lesser hardening as compared to hot mix asphalt.

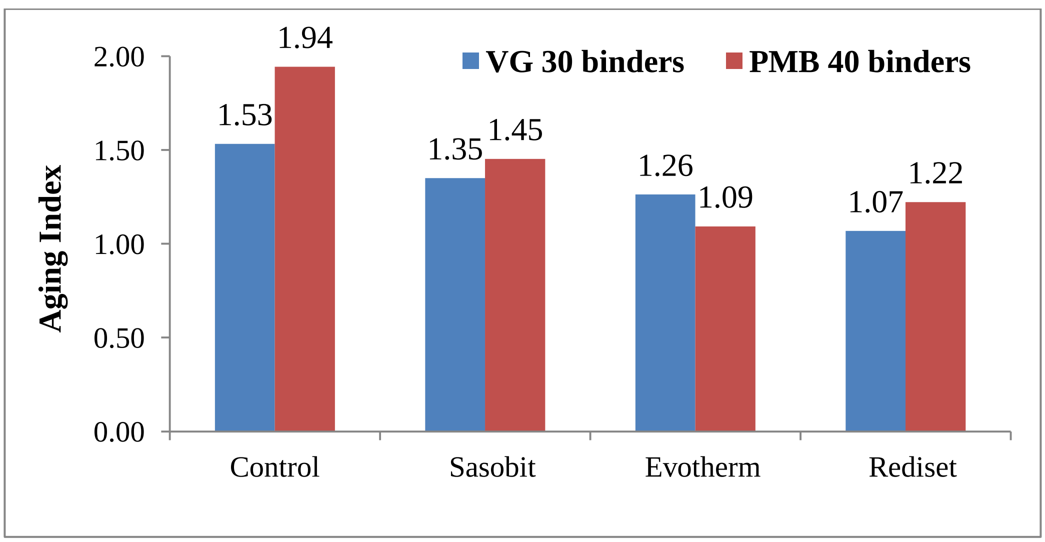


Figure 4.55: Aging indices of binders recovered from mixes

4.4.2 Effect of aging on rutting parameter

Traffic load repetitions cause cumulative permanent deformations in the pavement mixtures, especially during hot weathers. This type of deterioration is called as rutting. Rutting behaviour of a pavement is related to both binder properties and aggregate properties. G*/sinδ value is considered as a numerical indicator of rutting resistance (Anderson and Kennedy, 1993; Airey, 2004), Higher G*/sinδ values are favourable for permanent deformation resistance. Rutting parameters at 60 °C for all RTFO aged binders were calculated and are presented in Figure 4.56 and 4.57. Figure 4.56 shows the rutting parameter value of VG 30 based warm mix binders aged at 163ºC and at 115ºC, while Figure 4.57 shows these values for PMB 40 based warm mix binders aged at 163ºC and 135ºC.

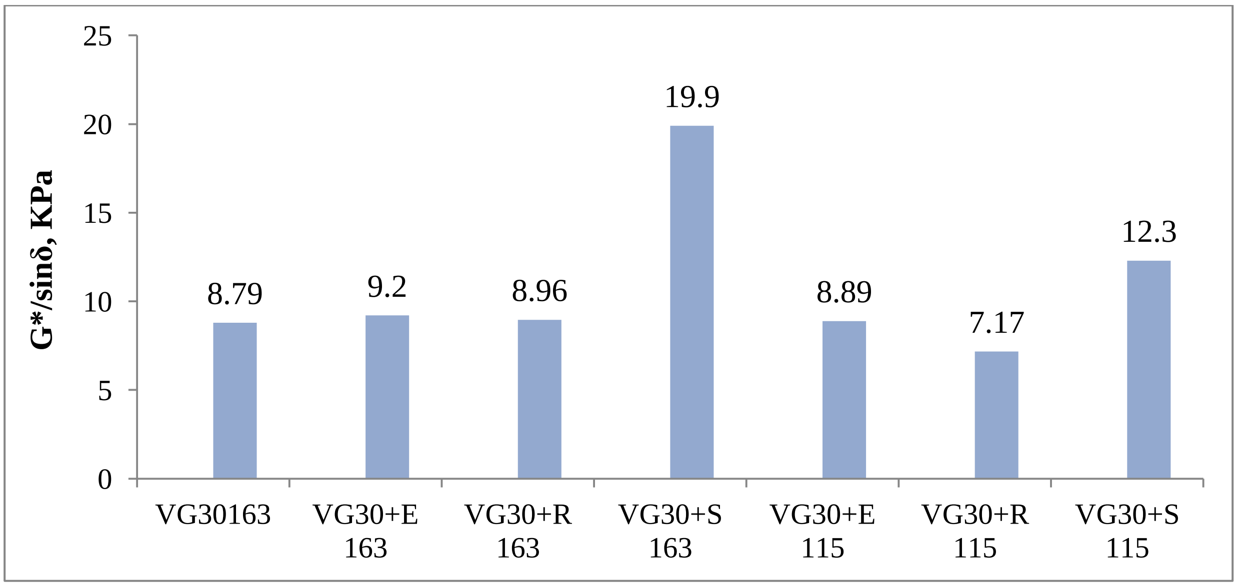


Figure 4.56: Effect of additives on rutting parameter of VG 30 binder

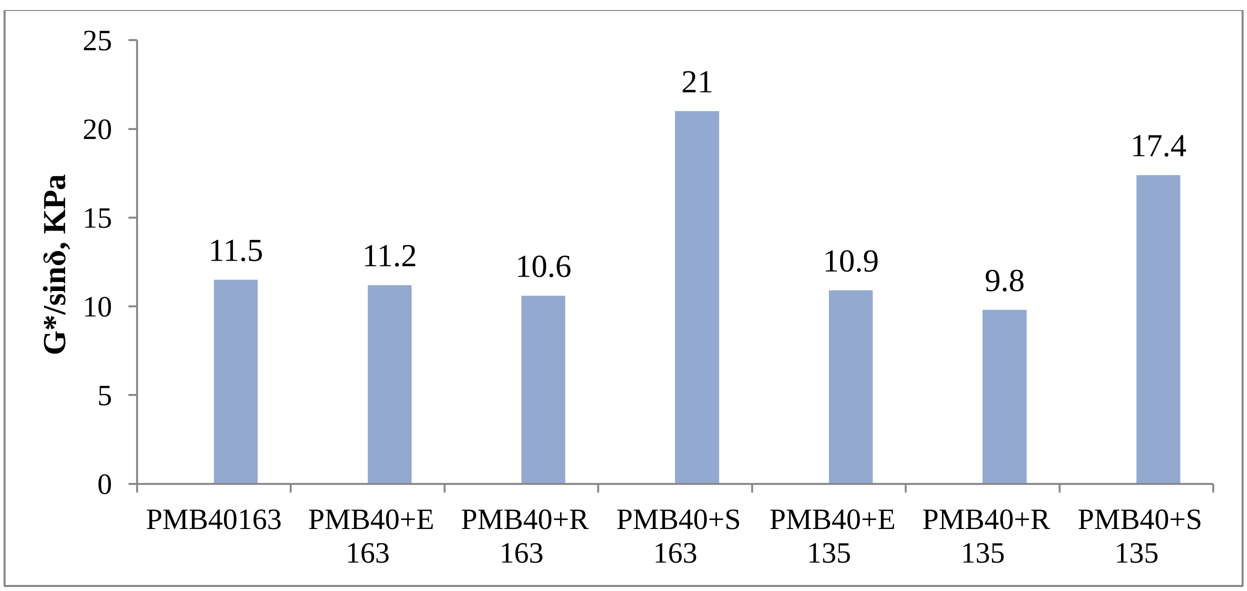


Figure 4.57: Effect of additives on rutting parameter of PMB 40 binder

It can be observed that binders containing Sasobit® had the highest G*/sinδ value. The binders which were aged in RTFO at lower temperatures showed lower values of G*/sinδ, in comparison to those aged at 163ºC. Rediset® modified binders showed slight reduction in the G*/sinδ values which indicates that addition of Rediset® makes the binder susceptible to rutting. Evotherm™ based warm binders aged at 163ºC and at lower temperature showed comparable values of G*/sinδ to that of control binder aged at 163ºC. This shows that Evotherm™ warm mixes prepared and compacted at lower temperatures will have comparable resistance to rutting to that of control hot mixes. Sasobit® modified binders showed significantly higher values of G*/sinδ at both the aging temperatures in comparison to control binders. This increase in the rutting resistance of the binders containing Sasobit® is attributed to of the presence of wax crystals in the binders, which cause an increase in the complex modulus of the binders and not due to the increased aging of the binders.

4.4.3 Effect of aging on fatigue parameters

In the situation of lack of flexibility, repeated traffic loads cause fatigue (alligator) cracking which is counted as an important deterioration mode for HMA pavements (Abo-Qudais and Shatnawi, 2007). G*.sinδ value of long term aged binder is considered as a numerical indicator of fatigue resistance (Anderson and Kennedy, 1993: Airey, 2004, Al-Khateeb et al., 2009). Lower G*.sinδ values are favourable for better fatigue performance.

The effect of the warm asphalt additives were studied on the fatigue parameter (G*.sinδ) of the binders with and without the additives. The RTFO residues were further aged in PAV at 100ºC to simulate long term aging. The PAV residues were then tested to determine the G*.sinδ values. Fatigue parameters at 25 °C for all binders were calculated and are presented in Figure 4.58 and 4.59.

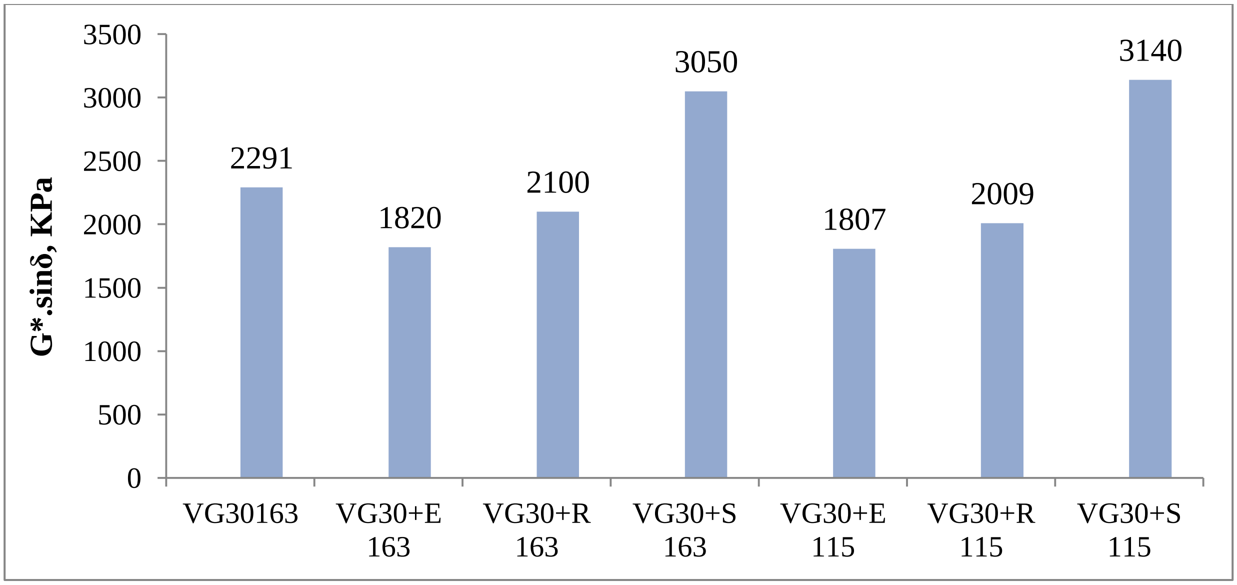


Figure 4.58: Effect of the additives on fatigue parameter of VG 30 binder

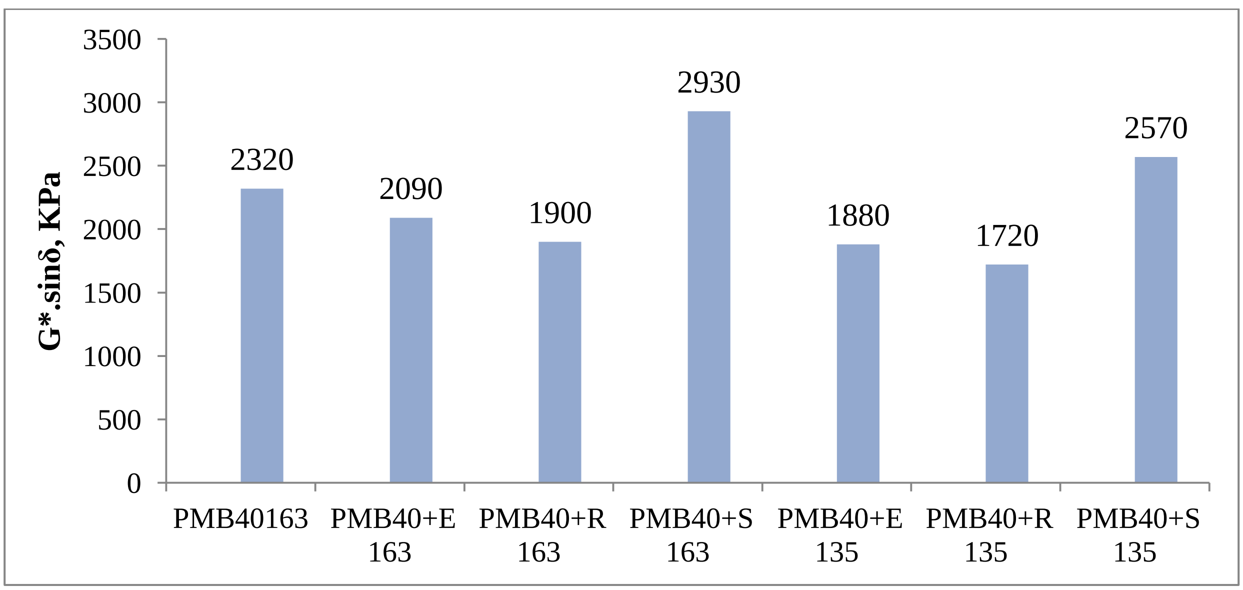


Figure 4.59: Effect of the additives on fatigue parameter of PMB 40 binder

These Figures show that neat VG 30 and PMB 40 binders have higher G*.sinδ than the Evotherm™ and Rediset® warm mix binders. Evotherm™ and Rediset® warm mix binders RTFO aged at 163ºC as well as at lower temperatures showed lower value for fatigue parameter, which indicates that these warm mix binders will have better fatigue cracking resistance. Whereas Sasobit® modified binders showed significantly higher values of G*.sinδ as compared to control binders. This increase in G*.sinδ may not be due to increased aging because the Sasobit® modified binders had lower aging indices. Therefore this increase in G*.sinδ values may be due to the reason that at low temperature Sasobit® is present in binder in the form of solid wax and forms wax crystal within the binder and hence the binder containing Sasobit® becomes stiffer which leads to higher values of G*.sinδ. However, it should be considered that aged asphalts are more brittle and susceptible to the fatigue cracking in cold weathers. This is expected and in harmony with literature as stated by Gandhi (2008) that some binders which were produced at lower mixing and compaction temperatures than usual show better fatigue cracking performance. Superpave mix design has a specification requirement for G*sinδ which indicates that this value must be less than 5,000 KPa, all the warm mix binders aged at 163ºC as well as at lower temperatures satisfy this criterion.

4.4.4 Effect on stiffness and m-value

The bending beam rheometer (BBR) test was conducted on the PAV aged samples to evaluate the stiffness and the m-value of the control and modified binders. The BBR test was conducted at -20ºC. Figures 4.64 and 4.65 show the stiffness values for VG 30 and PMB 40 control and wma binders respectively. Figure 4.66 and 4.67 show the m-value for VG 30 and PMB 40 binders respectively.

In the case of VG 30 binder, Evotherm™ warm mix binder showed the lowest stiffness values for the samples aged at 163ºC as or at 115ºC, whereas Sasobit® and Rediset® warm mix binders showed higher stiffness values in comparison to the control VG 30 binder. Also Sasobit® and Rediset® modified VG 30 binders had lower m-values for the samples aged in RTFO at 163ºC as well as at lower temperature in comparison to control VG 30 binder (Figure 4.62). For PMB 40 binders; Sasobit® modified binders showed higher stiffness values and lower m-values in comparison to control PMB 40 binder. A lower m-value indicates lesser ability to relax stresses. This shows that Sasobit® and Rediset® wma binders will have increased tendency towards cracking at low temperatures. However the reason for the increase in the stiffness of the binders containing Sasobit® and the reduction in the m-values is again due to wax crystallization, which caused an increase in the resistance to plastic deformation in the binder (Edwards, **et** al., 2006). Whereas for PMB 40 binders, the Rediset® modified wma binders showed comparable stiffness values to control binders when short term ageing was done at 163ºC, but showed reduced stiffness and higher m-value when ageing was done at 115ºC. This shows that when warm mixes were prepared using PMB 40 binders at lower temperatures, they will have improved resistance towards low temperature cracking.

Figures 4.60 – 4.63 shows that Evotherm™ modified warm mix binders have significantly lower stiffness value than the control VG 30 binders and they have significantly higher m-values when aged at 163ºC as well as at lower temperatures than the control binder. This means Evotherm™ warm mix binders will have improved resistance for low temperature cracking.

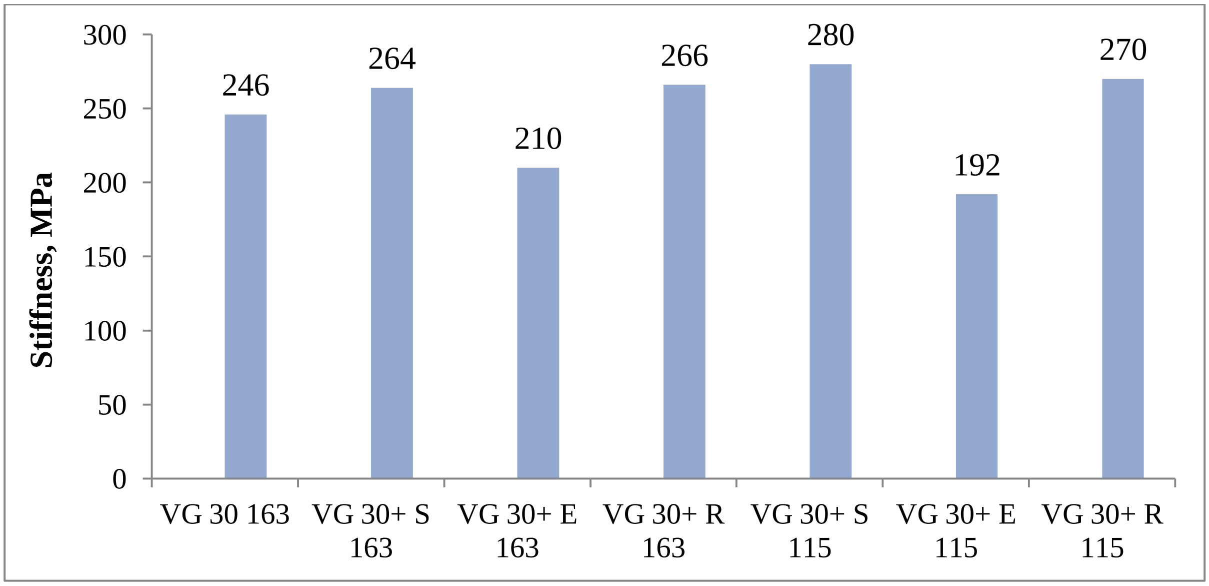


Figure 4.60: Stiffness of VG 30 warm mix binders

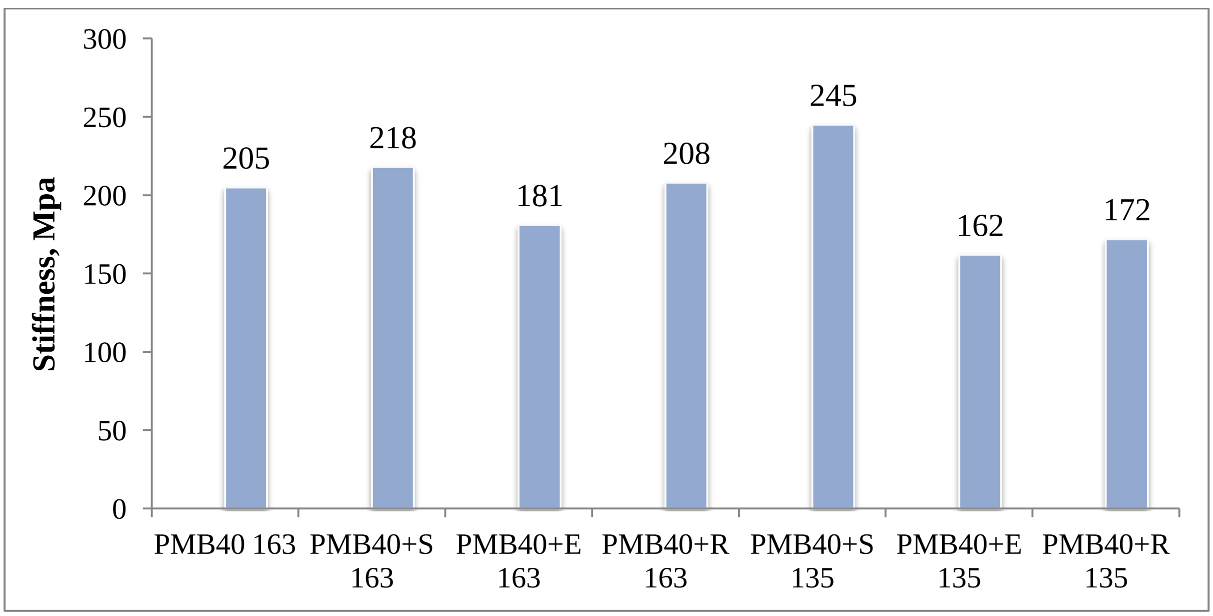


Figure 4.61: Stiffness of PMB 40 warm mix binders

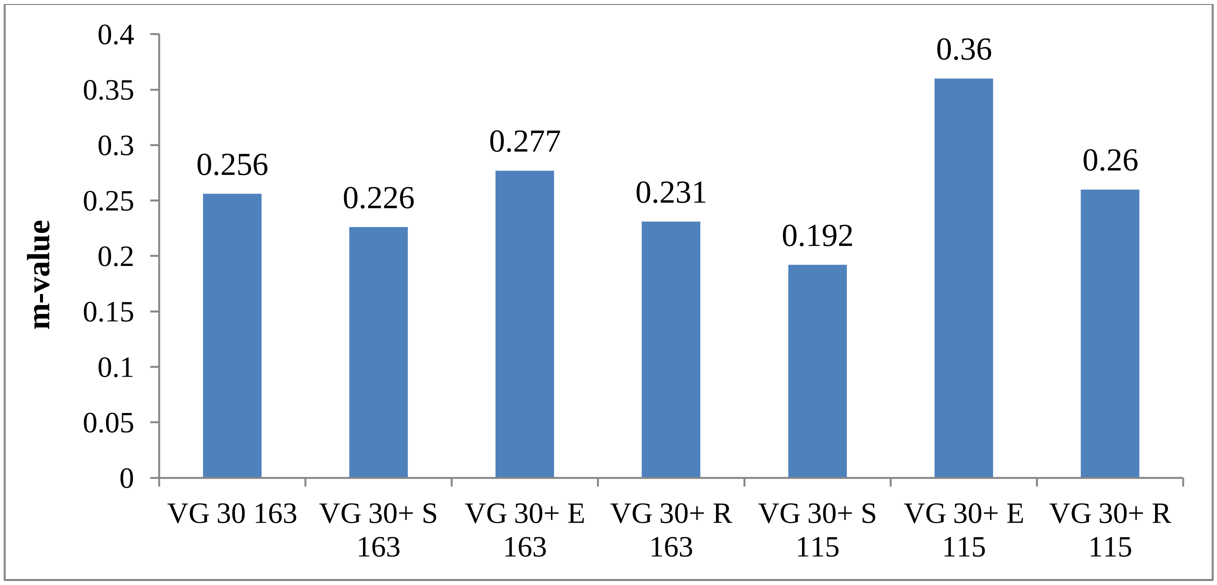


Figure 4.62: m-values for VG 30 warm mix binders

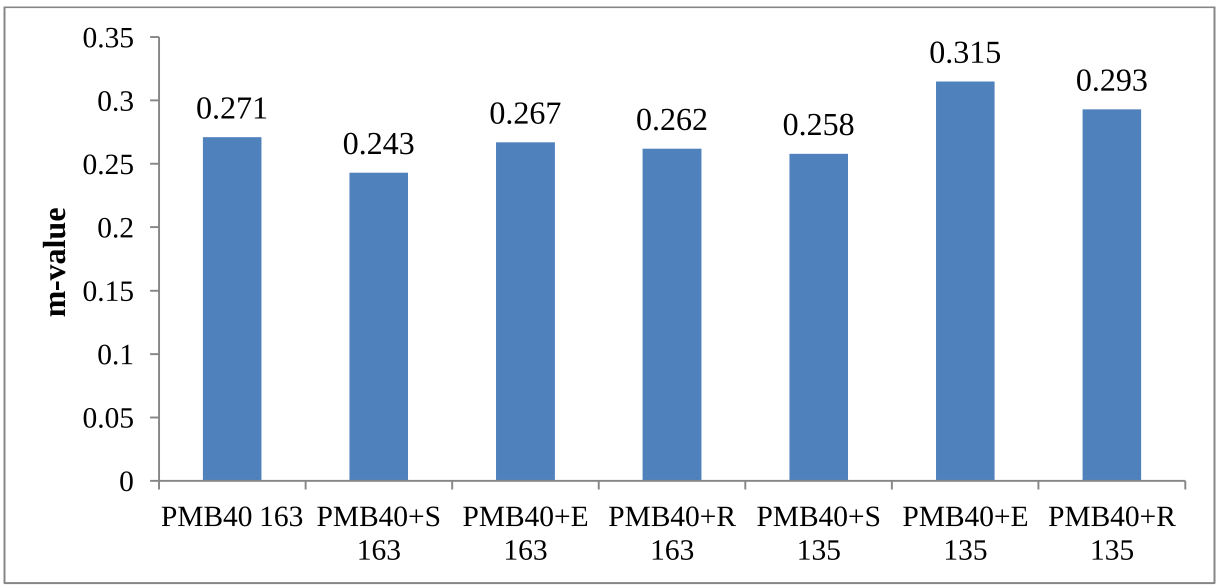


Figure 4.63: m-values for PMB 40 warm mix binders

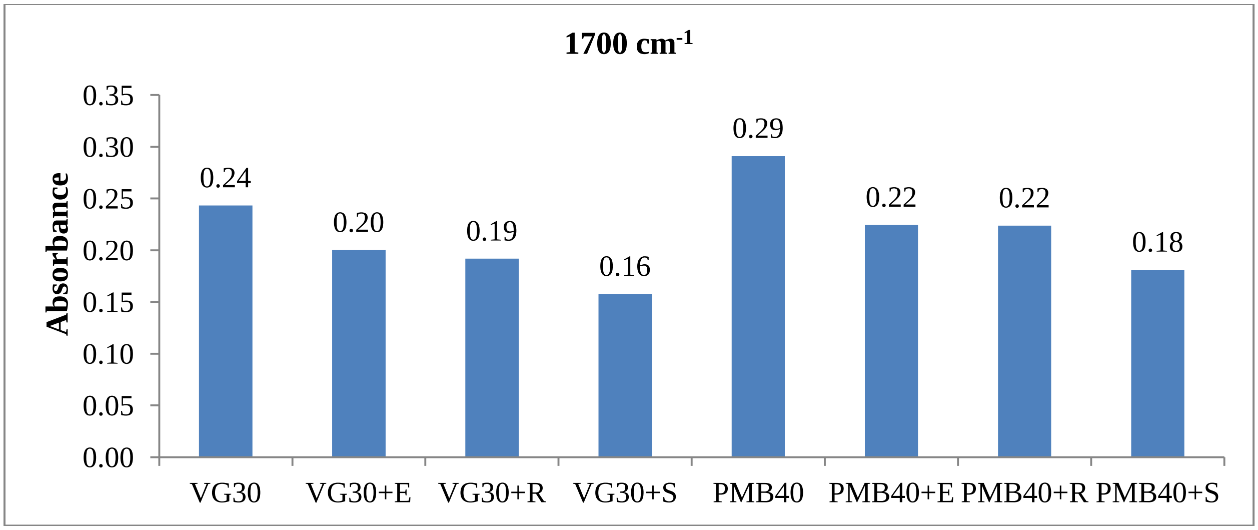
4.5 Fourier Transform Infrared Spectroscopy (FTIR)

The aging indices of various warm mix and control binders reported in Section 4.4.1 indicate that warm mix asphalt experiences less aging due to exposure to lower temperatures in comparison to hot mix asphalt. Therefore it was decided to use FTIR spectroscopy to quantify the aging in the binders with and without warm mix additives.

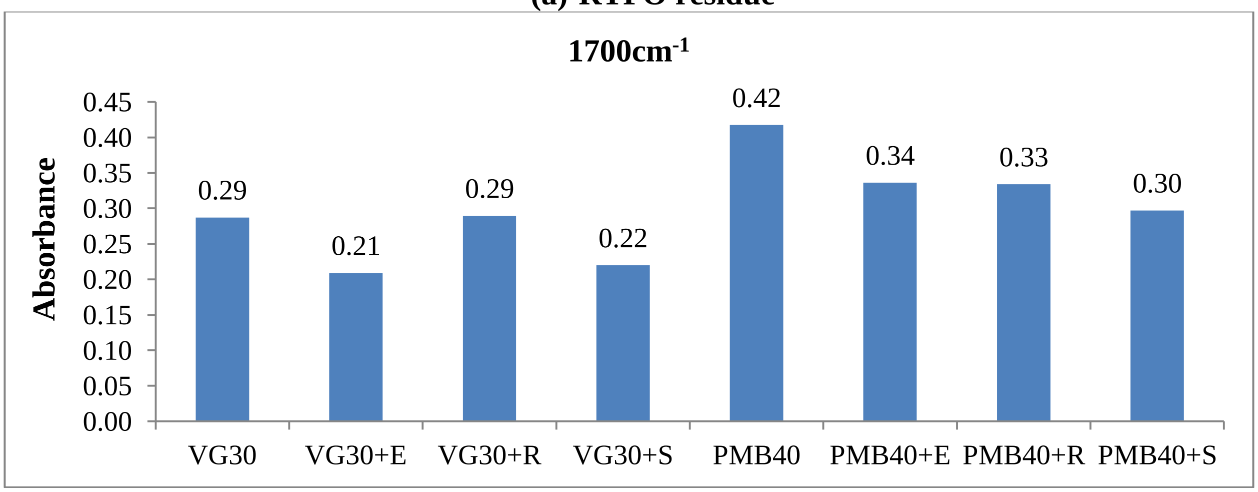
Fourier Transform Infrared Spectroscopy (FTIR) for asphalt binders is used as an indicator of oxidation (i.e. aging), as it allows the identification of the formation of two chemical entities resulting from oxidation: the Carbonyl (C=O) and Sulfoxide (S=O) groups. In order to eliminate the influence of sample preparation (thickness of the binder film), results are given relative to the reference band. The relative increase of C=O and S=O functional groups reflects asphalt aging. In this study samples were prepared by laying the binders as a thin film on KBr plates as shown in Figure 4.64. The functional characteristics are determined by measurement of the infrared absorption bands corresponding to CO and SO functions. They are represented respectively by absorption bands around wave numbers 1700 cm^{-1} and 1030 cm^{-1}. The IR absorbance peaks at these wave numbers represent the amount of carbonyl and sulfoxide bonds in the binders respectively, which are the indication of aging in the binder. FTIR spectra of different binders are given in Appendix 1.

Binders aged in RTFO and PAV and recovered binders from the mixes are tested for absorbance peaks. The absorbance of the binders at 1700 cm^{-1} and 1030 cm^{-1} are shown in Figures 4.65 and Figure 4.66 respectively.

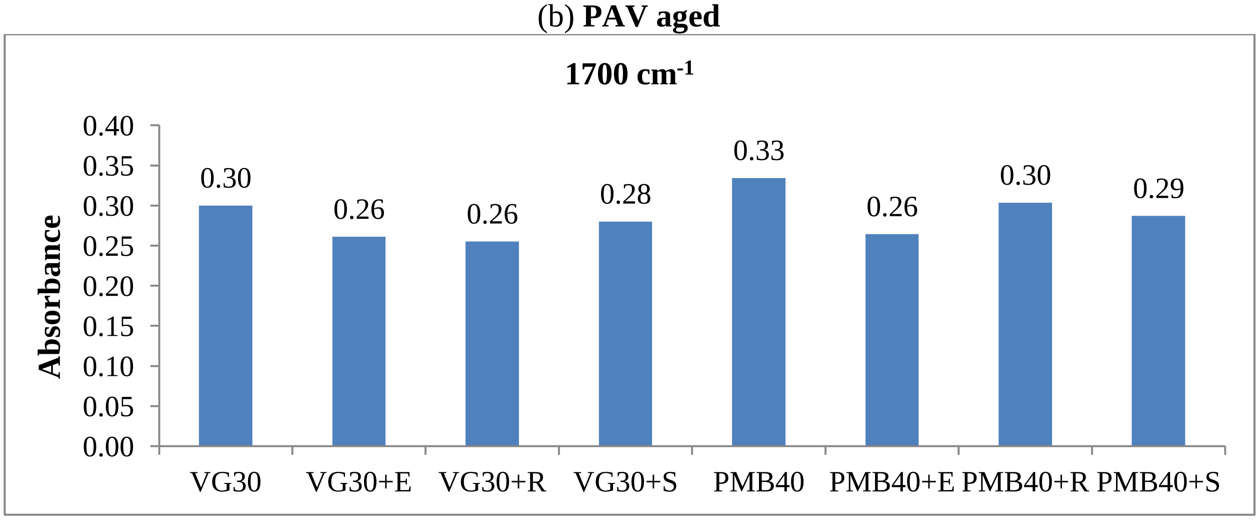
Figure 4.64: Bitumen binder film on Kbr plate



(a) RTFO residue

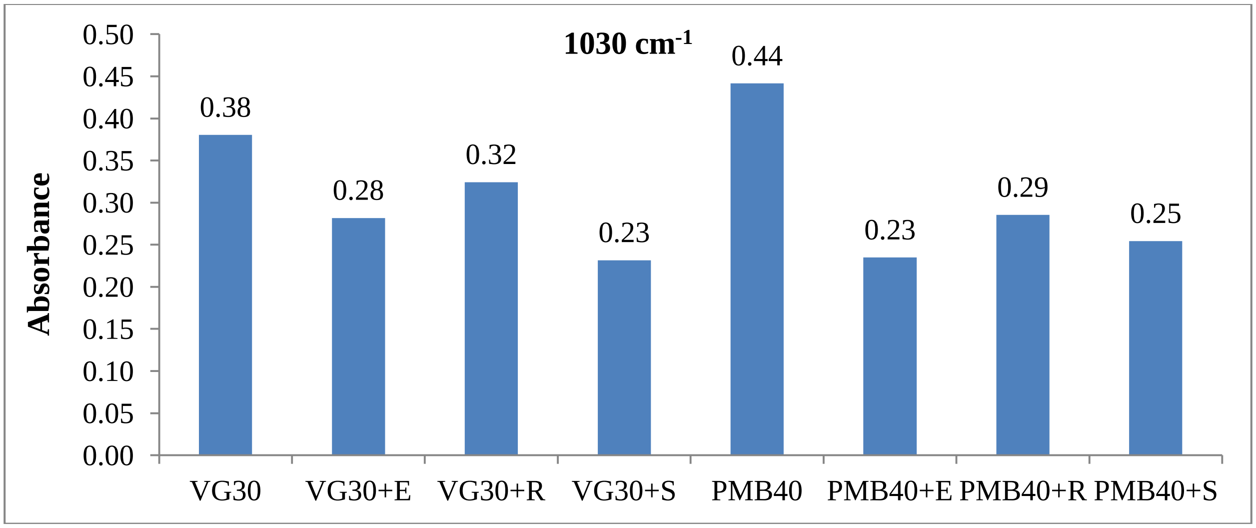


(b) **PAV aged**

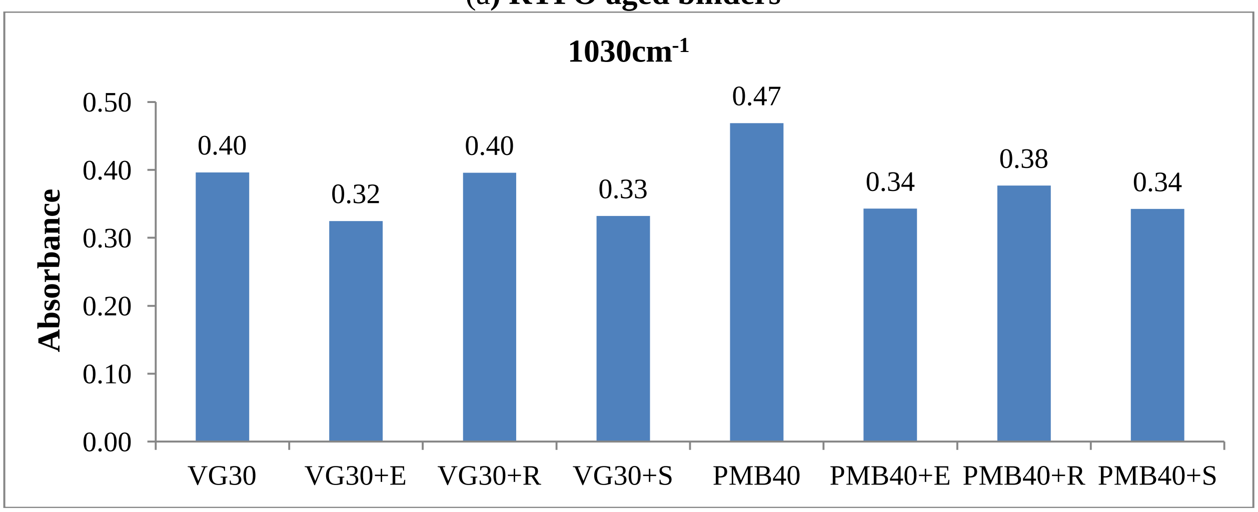


(c) **Recovered Binders**

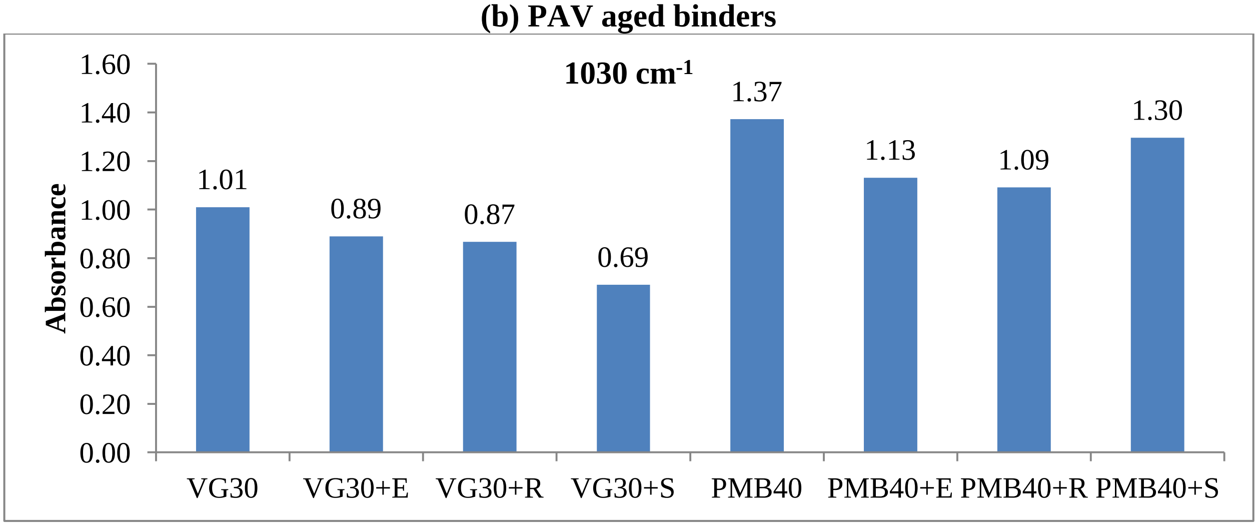
Figure 4.65: FTIR absorbance of the binders at 1700cm^{-1}



(a) **RTFO aged binders**



(b) PAV aged binders



(c) Recovered binders

Figure 4.66: FTIR absorbance of the binders at 1030cm^{-1}

Figure 4.65 shows a decrease in the absorbance of warm mix binders at 1700cm^{-1} in all the three cases, i.e. for RTFO aged, PAV aged and recovered binders. This indicates a reduction in the amount of carbonyl bonds present in the warm mix binders. Similarly, Figure 4.66 also shows a reduction in the absorbance of warm mix binders at 1030cm^{-1} in all the three cases, i.e. for RTFO aged, PAV aged and recovered binders, which indicates that warm mix binders have lower amount of sulfoxide bonds present in comparison to control VG 30 and PMB 40 binders.

Above results indicate that warm mix binders have oxidized/aged lesser than the control VG 30 and PMB 40 binders, which is in accordance with the results obtained for aging indices. This also confirms that the higher values of $G^*/\sin\delta$ and $G^*.\sin\delta$ obtained for Sasobit® modified binders was not due to increased aging but due to the wax crystallization.

4.6 Summary

This chapter describes various tests conducted to characterize warm mix binders. Frequency sweep and temperature sweep tests were carried out on 18 binders and 72 bitumen-filler mastics. Zero shear viscosities of warm asphalt binders and mastics were calculated to estimate the rutting potential of these binders. Tests were conducted to find the Penetration Index, Viscosity Temperature Susceptibility and Penetration Viscosity Number which were used to determine the temperature susceptibility of warm mix binders. Short term and long term aged binders were tested to find the aging characteristics of warm mix binders in comparison to control binders. Fourier Transform Infrared Spectroscopy was performed to quantify the effect of warm mix additives on the aging of binders.

CHAPTER 5

CHARACTERIZATION OF WARM ASPHALT MIXES

Sasobit®, Evotherm™ and Rediset® are used in this research to modify VG-30 and PMB-40 binders. Each warm mix additive was added at three different dosages to the binders. Marshall method of mix design was adopted to find the optimum binder content (OBC) for both the binders i.e. VG 30 and PMB 40.These warm mix binders were then used to prepare Marshall specimens and optimum dosages of the additives were found. Optimum mixing temperatures were also found. The performance tests were then carried out at the optimum dosage of the additive and optimum mixing temperatures. The results are reported in this chapter. The results reported are the average of three samples unless specified otherwise.

5.1 Optimum dose of additives and optimum mixing temperature

As reported in Chapter 4, the addition of Evotherm™ and Rediset® to the binder does not change the viscosity of the binder. The Sasobit® being a wax based additive, showed changes in the viscosities of the neat binders at a temperature more than 105ºC, which is higher than the melting point of Sasobit®. As a result, the viscosity-temperature plots could not be used to find the optimum mixing temperatures for warm mix asphalt. Therefore a different methodology was adopted to determine the optimum mixing temperatures and optimum doses of the warm mix additives.

The Marshall specimens were prepared at various dosages of warm mix additive and at different mixing temperatures ranging from 100ºC to 150ºC. These specimens were then tested for stability, retained stability and air voids. The optimum dose and mixing temperature were selected where these properties (Marshall stability, retained stability and air voids) of warm mix specimens were same as those for hot mix specimens.

Table 5.1 shows the dosages of warm mix additives used by weight of the bitumen. The warm asphalt mixtures were prepared with at 135ºC, 125ºC, 115ºC and 105ºC with VG 30 and at 145ºC, 135ºC, 125ºC and 115ºC with PMB 40.

Table 5.1: Dosages used for various warm mix additives

Sasobit®	Evotherm™	Rediset®
2%	0.5%	1%
3%	1.0%	2%
4%	1.5%	3%

Table 5.2 shows the values of Marshal stability, retained stability and air void content obtained for control hot mix asphalt at 150ºC for VG 30 binder and at 165ºC for PMB 40 binder.

Table 5.2: Parameters for Hot mix asphalt

Binder	Marshall Stability, KN	Retained Stability, %	Air Voids, %
VG 30	14.04	59.05%	4.04
PMB 40	22.80	76.83%	4.64

Tables 5.3 - 5.5 shows the values of these parameters obtained for VG30-Sasobit®mix, VG30-Evotherm™mix and VG-30 Rediset® mix respectively**.**

Table 5.3: Parameters for VG30-Sasobit®asphalt mix

Sasobit®Dose	Mix Preparation Temperature			
	135ºC	125ºC	115ºC	105ºC
Marshall Stability, KN				
2%	18.62	17.10	14.31	10.82
3%	19.43	17.25	**15.6**	11.17
4%	19.81	18.51	15.11	11.80
Retained Stability, %				
2%	62.97	62.73	63.58	56.55
3%	76.70	73.38	**73.26**	69.38
4%	52.42	52.77	58.09	59.02
Air Voids, %				
2%	2.08	2.56	2.64	3.34
3%	2.48	2.90	**3.92**	4.39
4%	2.50	2.07	3.20	3.96

Table 5.4: Parameters for VG30-Evotherm™asphalt mix

Evotherm™Dose	Mix Preparation Temperature			
	135ºC	125ºC	115ºC	105ºC
Marshall Stability, KN				
0.5%	19.16	18.55	**18.01**	17.67
1.0%	20.10	18.8	17.9	17.23
1.5%	19.83	18.10	17.62	16.09
Retained Stability, %				
0.5%	73.43	73.56	**71.81**	69.17
1.0%	72.4	70.26	69.41	70.11
1.5%	70.89	66.1	61.6	57.8
Air Voids, %				
0.5%	3.19	3.87	**4.01**	4.99
1.0%	3.57	3.99	4.19	5.07
1.5%	3.49	3.97	4.32	5.40

Table 5.5: Parameters for VG30-Rediset® asphalt mix

Rediset® Dose	Mix Preparation Temperature			
	135ºC	125ºC	115ºC	105ºC
Marshall Stability, KN				
1%	19.12	17.30	16.68	10.11
2%	21.39	17.63	17.05	10.21
3%	21.80	18.44	**17.35**	11.01
Retained Stability, %				
1%	64.05	63.60	53.3	50.04
2%	70.12	69.41	65.63	63.26
3%	77.26	75.37	**72.50**	68.9
Air Voids, %				
1%	2.5	3.75	3.75	4.18
2%	2.17	2.58	3.67	3.86
3%	2.98	3.17	**4.17**	5.42

Similar results for PMB 40 are given in Tables 5.6 – 5.8

Table 5.6: Parameters for PMB 40-Sasobit®asphalt mix

Sasobit®Dose	**Mix Preparation Temperature**			
	145ºC	135ºC	125ºC	115ºC
Marshall Stability, KN				
2%	26.34	24.9	17.43	10.8
3%	28.35	**25.27**	19.16	14.43
4%	29.01	26.15	20.41	13.14
Retained Stability, %				
2%	78.15	77.5	75.31	70.72
3%	80.6	**79.33**	78.12	75.36
4%	77.62	75.8	73.62	71.80
Air Voids, %				
2%	2.9	3.31	4.50	5.9
3%	3.8	**4.31**	5.19	6.67
4%	3.55	4.84	5.46	6.81

Table 5.7: Parameters for PMB 40-Evotherm™asphalt mix

Evotherm™Dose	**Mix Preparation Temperature**			
	145ºC	135ºC	125ºC	115ºC
Marshall Stability, KN				
0.5%	25.63	24.32	22.8	19.68
1.0%	26	**24.82**	22.04	19.9
1.5%	25.43	23.21	21.47	18.83
Retained Stability, %				
0.5%	81.9	79.51	76.33	71.4
1.0%	82.63	**81.11**	79	76.85
1.5%	80.42	79.89	76.3	73.89
Air Voids, %				
0.5%	3.20	3.87	4.91	6.02
1.0%	3.69	**4.48**	5.38	6.2
1.5%	3.88	5.05	5.67	6.19

Table 5.8: Parameters for PMB 40-Rediset® asphalt mix

Rediset® Dose	Mix Preparation Temperature			
	145ºC	135ºC	125ºC	115ºC
Marshall Stability, KN				
1%	24.6	19.3	17.98	13.45
2%	24.8	20.51	18.92	15.6
3%	25	**22.36**	18.68	16.31
Retained Stability, %				
1%	77	75	72	69
2%	77	74.2	71.84	69.74
3%	79	**76.13**	71.88	68.09
Air Voids, %				
1%	2.68	3.55	3.97	4.21
2%	3.20	3.77	4.29	4.86
3%	3.51	**4.44**	5.18	6.16

The air voids in asphalt mixtures is an important control parameter for the quality of asphalt being laid and compacted. For good performance, it is essential that the amount of air voids be controlled during the mix design process and during production. Hence air voids was the critical parameter in deciding the optimum additive dosage and optimum mixing temperature. In addition to the air voids, a dose and a mixing temperature which provided better or comparable values of other two parameters (Marshall stability and retained stability) were selected as optimum. Table 5.9 shows the optimum dosages and optimum mixing temperatures selected for three additives.

Table 5.9: Optimum dose and mixing temperature for additives

Warm mix Additive	VG-30		PMB-40	
	Optimum dose, %	Optimum mixing temperatures, ºC	Optimum dose, %	Optimum mixing temperatures, ºC
Sasobit®	3.0	115	3.0	135
Evotherm™	0.5	115	1.0	135
Rediset®	3.0	115	3.0	135

5.1.1 Marshall blows for 5% Air Voids (AV)

The optimum mixing temperature for VG 30 based warm mixes is obtained as 115ºC whereas it is 135ºC for PMB 40 based warm mixes. These lower mixing temperatures are expected to vary the compaction effort required to achieve the design air voids of 5%. To demonstrate the variation in the compaction effort required for warm mixes, the Marshall samples were prepared with varying number of blows and the air voids were calculated in each sample. Table 5.10 and Table 5.11 show the different number of blows used for both VG 30 and PMB 40 warm mixes and corresponding air voids as obtained for different asphalt mixes.

Table 5.10: Variation in air voids with blows for VG30 based mixes

Number of blows	Air voids (%) in the mix with			
	VG 30	VG 30 + Sasobit®	VG 30 + Rediset®	VG 30 + Evotherm™
20	8.21	7.78	8.73	9.23
30	-	7.32	-	-
35	7.46	-	-	-
40	6.91	5.65	7.10	7.11
60	6.24	5.01	4.95	6.11
70	5.41	4.22	3.65	5.02
75	4.99	-	-	-

Table 5.11: Variation in air voids with blows for PMB 40 based mixes

Number of blows	Air voids (%) in the mix with			
	PMB 40	PMB 40 + Sasobit®	PMB 40 + Rediset®	PMB 40 + Evotherm™
30	-	7.10	7.03	8.64
35	-	6.71	-	-
40	7.78	-	6.47	7.04
45	7.02	6.21	-	-
55	6.33	5.87	5.64	-
60	-	-	5.01	5.88
65	-	5.09	-	5.01
75	5.05	-	-	-

Figure 5.1 and 5.2 show the graphical representation of air voids with number of blows. The number of blows required for achieving 5% and 7% air voids for various asphalt mixes were obtained from these figures.

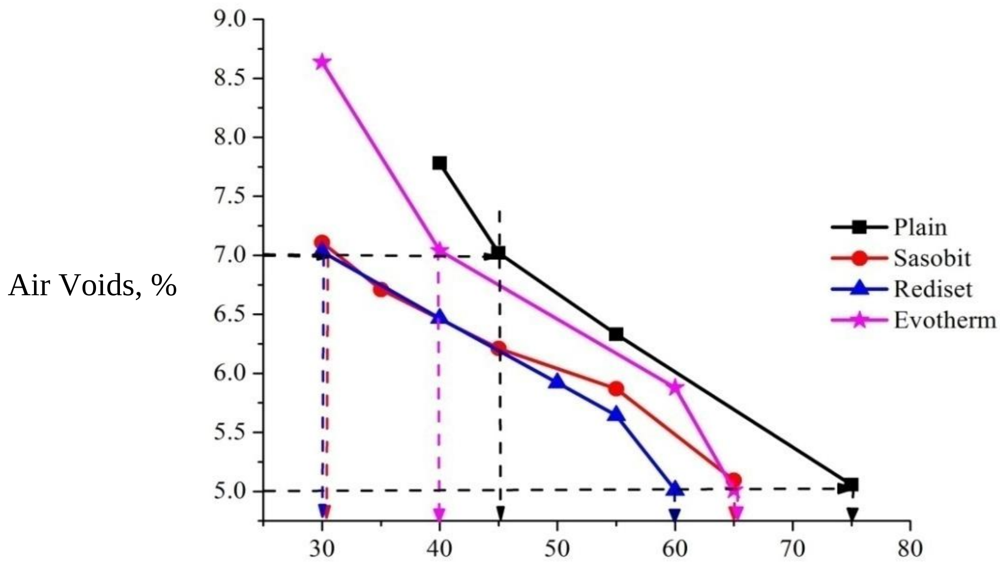


Figure 5.1: Air Voids v n PMB 40 based mixes

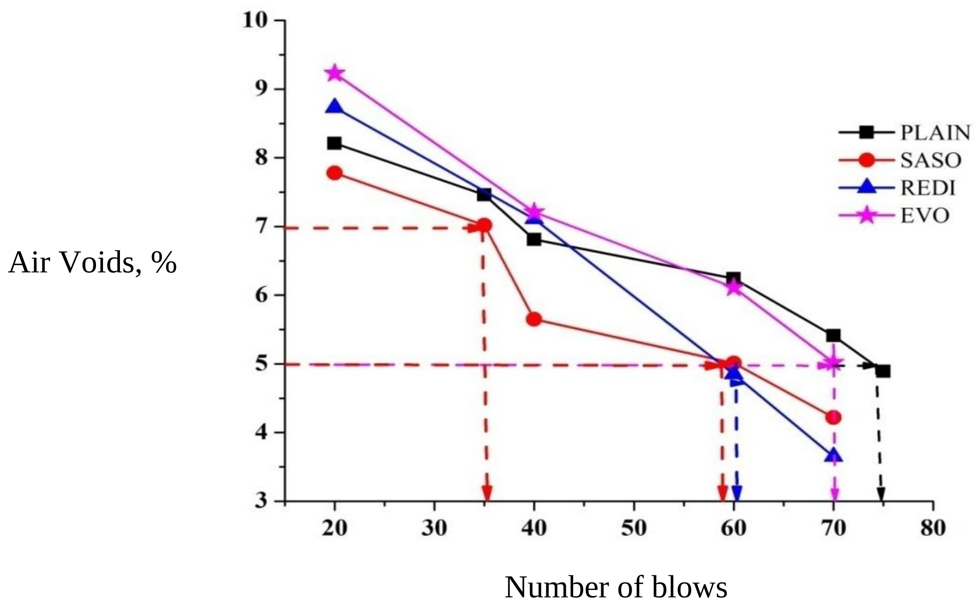


Figure 5.2: Air Voids with number of blows in VG 30 based mixes

Table 5.12 shows the number of blows required for compacting the warm mixes and hot mixes to achieve 5% air voids and 7% air voids. Marshall samples were prepared with 7% air voids for TSR test whereas 5% air voids were maintained for all other performance tests. It was observed that warm asphalt mixes required lesser number of blows to achieve the air voids similar to those in asphalt mixes, which shows that warm asphalt mixes will need less compaction effort in comparison to hot asphalt mixes to achieve similar densities.

Table 5.12: Number of blows for 5% and 7% air voids

Mix Type	Number of blows for	
	5 % air voids	7 % air voids
Plain PMB40	75	45
PMB + Sasobit®	65	30
PMB + Rediset®	60	30
PMB + Evotherm™	65	40
Plain VG30	75	40
VG + Sasobit®	60	35
VG + Rediset®	60	40
VG + Evotherm™	70	40

5.2 Performance Properties of the Mixes

The performance properties of the mixtures containing warm asphalt additives were evaluated and compared with those of the conventional HMA. Tensile Strength Ratio (TSR), Moisture Induced Sensitivity Test (MIST), resilient modulus and dynamic creep, rutting and fatigue characteristics of warm mix asphalt were studied. The effects of aging on the properties of WMA are also evaluated.

For the ease of reporting the results, the nomenclature as given in Table 5.13 is used for mix identification.

Table 5.13: Identification of Different Mixes

Type of binder	Type of additive	Mix Identification (ID)
PMB 40	No additive (Plain)	PP
PMB 40	Evotherm™	PE
PMB 40	Rediset®	PR
PMB 40	Sasobit®	PS
VG 30	No additive (Plain)	VP
VG 30	Evotherm™	VE
VG 30	Rediset®	VR
VG 30	Sasobit®	VS

Effect of aging on the properties of warm mix binders is presented and discussed in Chapter 4. Various properties of warm mix binders were studied to evaluate how the warm mix additives will affect the performance of the warm mix asphalt. To corroborate those results, prepared specimens were aged in an oven as per AASHTO: R 30-2. For long term mixture conditioning, the compacted mixture specimens of warm mix asphalt as well as hot mix asphalt were conditioned in an oven for 5 days (120 hours) at 85ºC. The effect of aging on moisture resistance and permanent deformation of warm mix asphalt was compared with that of hot mix asphalt.

During the production of WMA, aggregates and bitumen are not heated to as high a temperature as it is used for HMA. Under these circumstances some residual moisture would probably remain trapped inside the mix and this can cause the loss of adhesion between the asphalt binder and the aggregate. Therefore, moisture susceptibility has been a primary concern for some WMA approaches, whereas in this study, the aggregates were dry and there was no residual moisture hence the loss of adhesion due to moisture is not a concern here.

The wet and dry indirect tensile strengths (ITS) are used to calculate the tensile strength ratio (TSR) which was is a measure of moisture susceptibility of the mix. Moisture-induced damage is one the major causes of deterioration of asphalt pavements. Moisture-induced damages are caused mainly by the generation of pore water pressure in asphalt mixtures when traffic passes over a pavement. The Moisture Induced Sensitivity Tester (MIST) was used to simulate the phenomenon of repeated pore pressure generation and deterioration in the laboratory. The MIST was used to condition Hot Mix Asphalt (HMA) and warm mix asphalt (WMA) samples. The conditioned samples were then tested for wet ITS and TSR to find the moisture induced damage in WMA in comparison to HMA.

5.2.1 Tensile Strength Ratio (TSR)

Figures 5.3 – 5.6 show the TSR values for the un-aged and aged samples with and without MIST conditioning. The values reported are average of three values, coefficient of variation was found to be in the range of 0.03-0.20. In the case of un-aged PMB – 40 mixes, Evotherm™ shows TSR value of 86% which is higher than that of the control mix. The Sasobit® showed lesser TSR value than the control PMB 40 mix. When the MIST conditioned samples were tested for TSR values, it was observed that the warm asphalt mixes have better TSR than the control PMB 40 hot mix samples. In the case of aged PMB 40 based mixes, Evotherm™ blend showed a greater TSR than the control mixes, whereas Sasobit® and Rediset® warm mixes showed TSR comparable to that of control mixes. Warm mixes showed better resistance to moisture induced damage than control hot mix asphalt.

Figure 5.4 shows that the un-aged VG 30 mixes containing the warm asphalt additives had significantly higher TSR values than control mixes. It suggests that the addition of the warm asphalt additives improves the moisture susceptibility of the un-aged mixes. However the MIST conditioned warm mix samples showed improved TSR except in the case of Sasobit®. This shows that warm mix samples containing Sasobit® additive will be more susceptible to moisture induced damage than control VG 30 hot mix asphalt samples. Evotherm™ and Rediset® based samples showed improved resistance to moisture induced damage in comparison to control hot mix asphalt. Figure 5.6 shows similar behaviour for aged VG 30 control and warm mix asphalt samples. Evotherm™ and Rediset® warm mix samples after aging also showed better resistance to moisture damage in comparison to aged control VG 30 mixes, whereas aged Sasobit® warm mix samples showed reduced resistance to moisture damage.

The above results indicate that the Evotherm™ warm mix additive is more resistant to moisture susceptibility during un-aged period and also after the aged period. The Sasobit® and Rediset® show TSR comparable to that of control HMA mix. However, the TSR of mix type VS after MIST was extremely low indicating higher susceptibility of Sasobit® modified VG 30 to moisture damage during service life of the pavement.

The above observations reveal that among the different mixes prepared using different binders and warm mix additives; Evotherm™ shows highest resistance to moisture damage just after the pavement has been laid and also during its service life. It means the Evotherm™ imparts anti-stripping properties to the mix, and this property of the additive is reported by other researcher also (Yu, 2012). Evotherm™ is a surfactant based additive. In the mixing drum, a portion of the Evotherm™ molecules migrate to the asphalt-aggregate interface and the polar heads are attracted to the polar properties of the aggregate and the non-polar tails are dissolved in the asphalt. Evotherm™ molecules form micelles in the bitumen. If there is any residual moisture present on the aggregate surface or pores (due to the lower mixing temperatures), it will be captured by the Evotherm™ molecule micelles. Since Evotherm™ heads are attracted to polar material, they "pickup" the residual moisture and capture them within the micelles forming stable micro-dispersions of water droplets within the bitumen (like a water-in-oil emulsion) and provides anti-stripping properties to the asphalt mix.

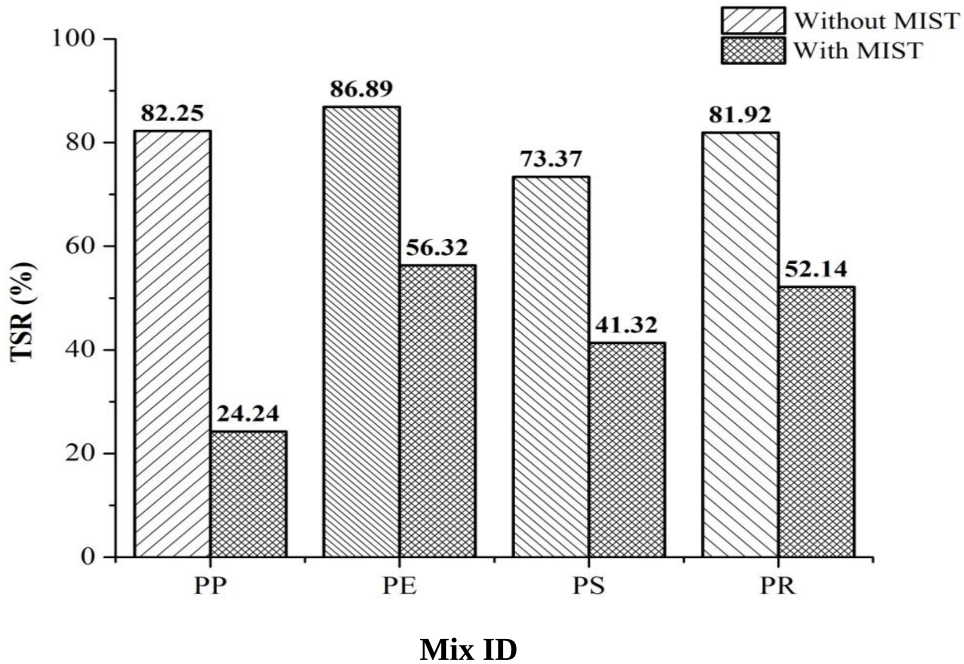


Figure 5.3 TSR of Un-aged Mixes with PMB – 40 binder

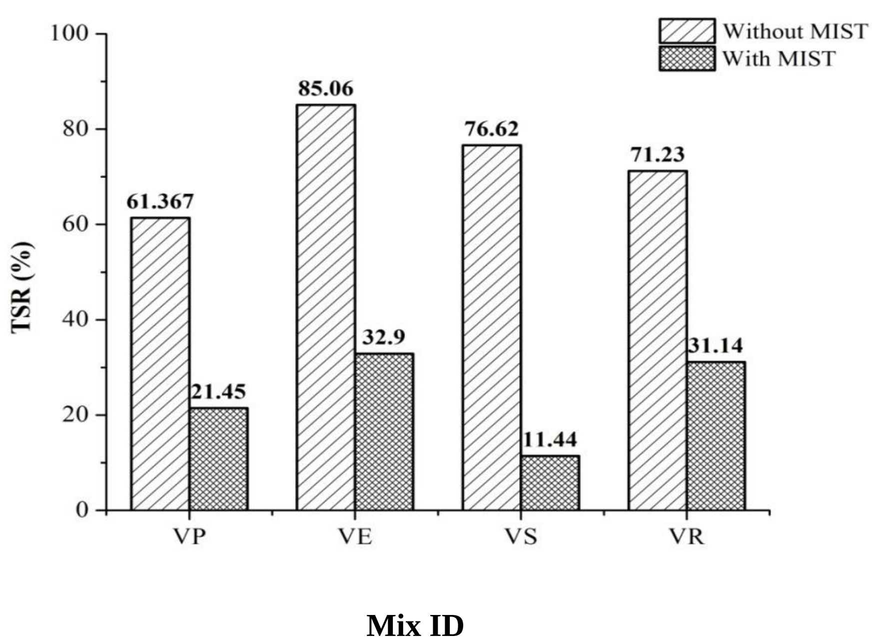
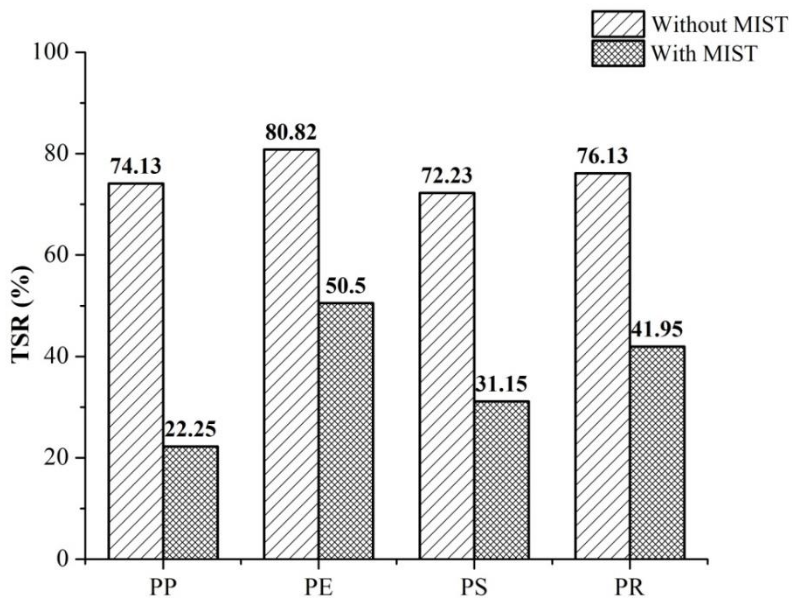
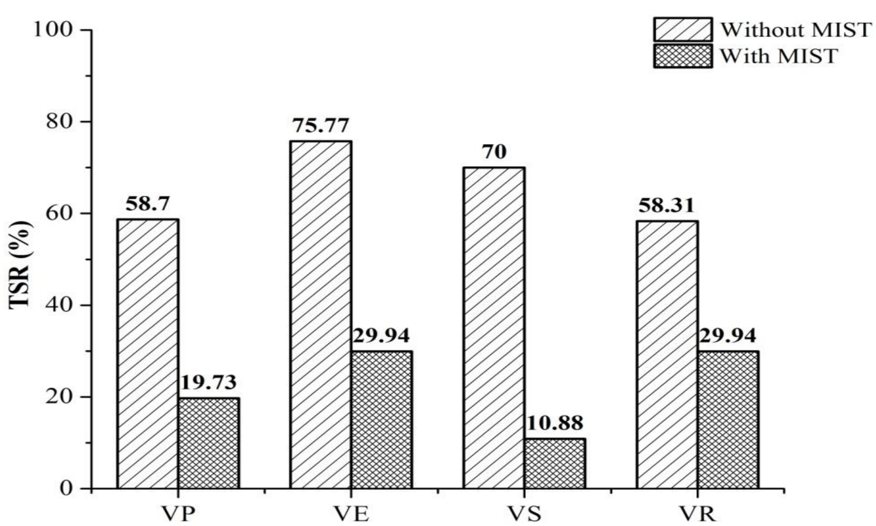


Figure 5.4 TSR of Un-aged Mixes with VG30 binder



Mix ID

Figure 5.5: TSR of Aged Mixes with PMB – 40 binder



Mix ID

Figure 5.6: TSR of Aged Mixes with VG 30 binder

5.2.2 Resilient Modulus of Warm Mixes

Resilient modulus is an important property for design and mechanistic analysis of pavement response under traffic loading. The resilient modulus of asphalt mixes at low temperatures is somewhat related to cracking also. Researchers have shown that the stiffer asphalt mixes at lower temperatures are more prone to cracking (Roberts, et al., 1996). Figures 5.7 to 5.10 show the comparison of resilient modulus of un-aged and aged mixes at 25°C and 45°C. The values reported are average of three values and coefficient of variation was found to be in the range of 0.02-0.07. It is found that addition of warm mix additives improves the stiffness modulus of a mix substantially when compared with control HMA mix. The WMA mixes are produced at much lower temperature and hence the aggregate and bitumen are exposed to lower temperature which leads to less aging of the warm mixes. At both the test temperatures the warm mixes containing Sasobit® showed higher resilient modulus values in comparison to other mixes, both in un-aged and aged condition. Evotherm™ and Rediset® based warm mixes also showed higher resilient modulus than the control hot mix asphalt. Thus it could be inferred that the addition of warm asphalt additives makes the mixtures stiffer and which are expected to be less prone to cracking as compared to the control mixes.

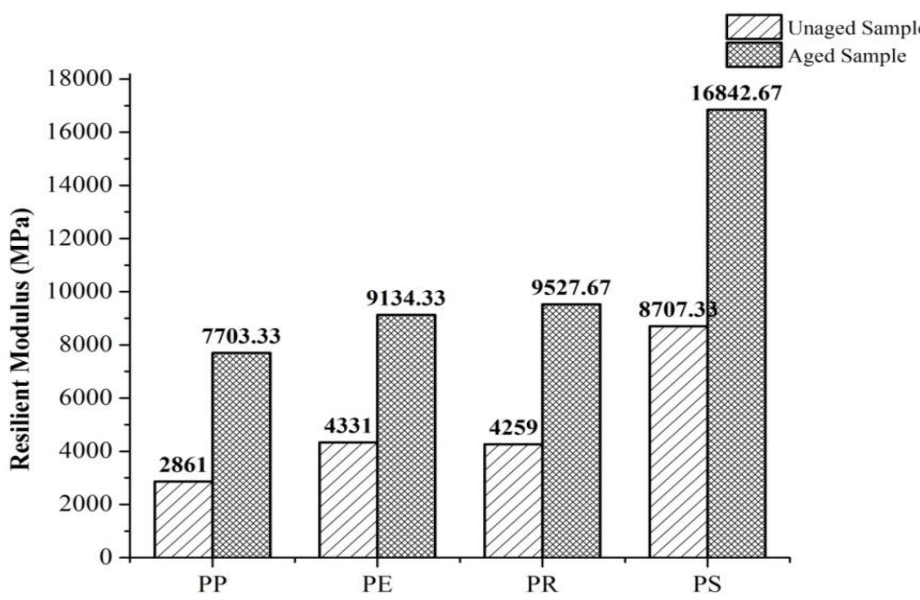


Figure 5.7 Resilient Modulus of Un-aged and Aged Mixes with PMB 40 at 25°C

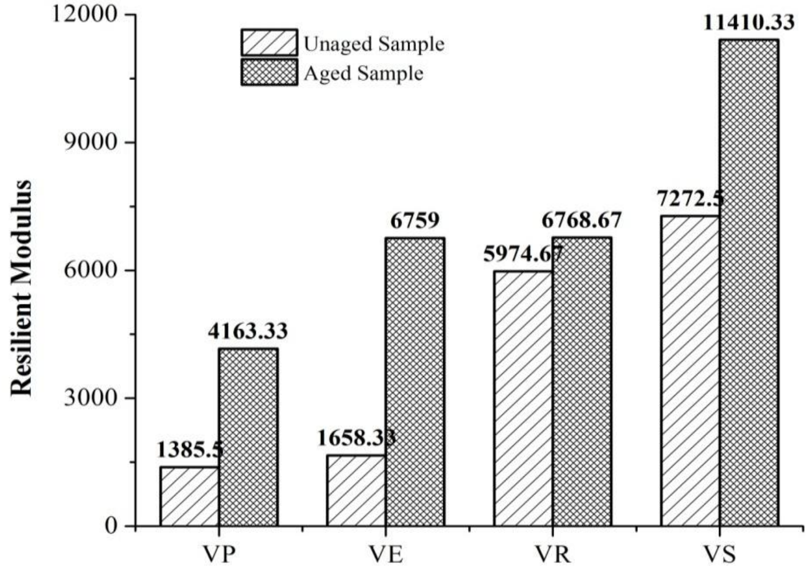


Figure 5.8 Resilient Modulus of Un-aged and Aged Mixes with VG 30 at 25°C

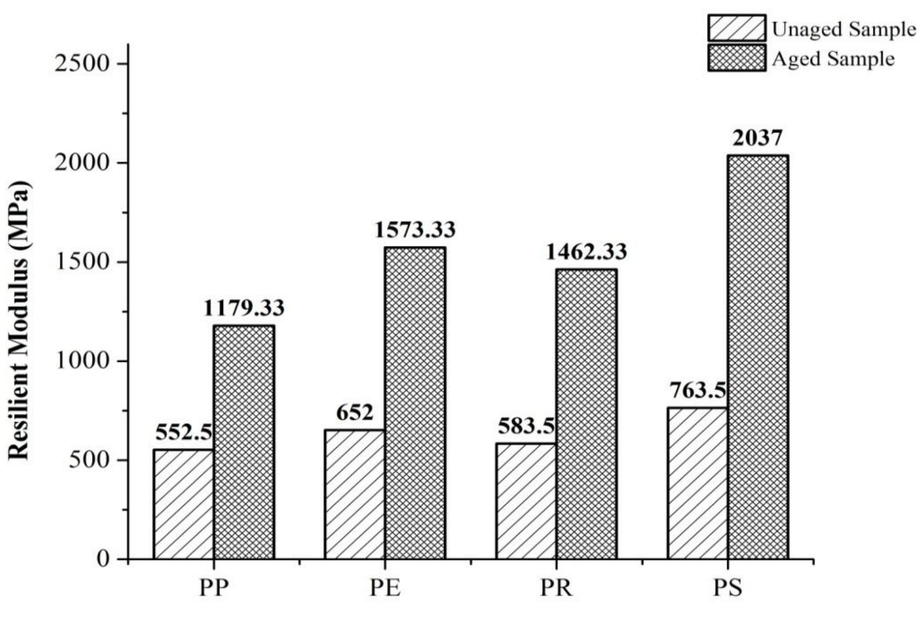


Figure 5.9 Resilient Modulus of Un-aged and Aged PMB 40 Mixes at 45°C

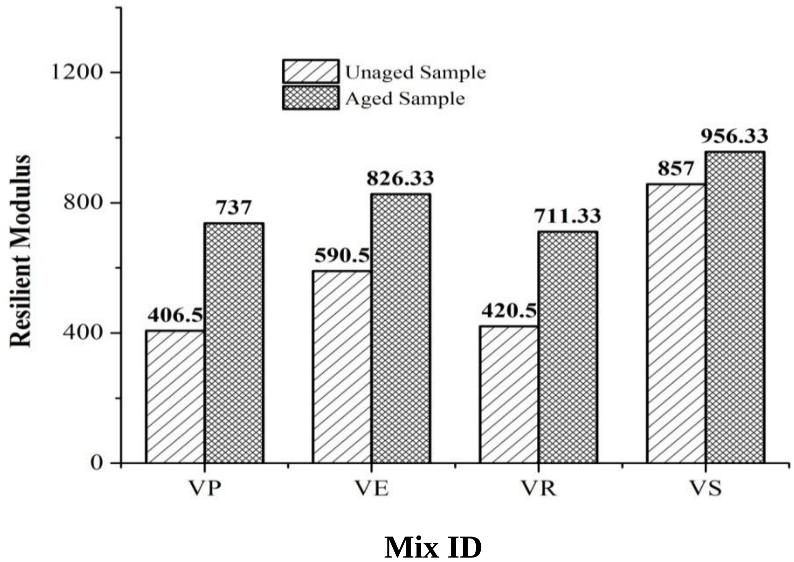


Figure 5.10 Resilient Modulus of Un-aged and aged VG 30 mixes at 45°C

5.2.3 Dynamic Creep Test of Warm Mixes

Mechanical behaviour of asphalt is dependent on ambient temperature due to its viscoelastic properties. Asphalt becomes softer and less viscous at high temperatures. Due to this, the asphalt binder becomes more susceptible to experience permanent deformation and thus accelerates rutting in wheel tracks. Moreover, stress induced by loading is another main parameter that leads to permanent deformation in asphalt pavement.

The deformation resistance characteristics of bituminous mixtures were evaluated through a dynamic creep test at 40ºC. The total permanent strains in the different mixes at 40°C are given in Table 5.14. The values reported are average of three values, standard deviation **(σ)** was calculated and is mentioned in Table 5.14. Figures 5.11 and 5.12 show the total accumulated strain in aged and un-aged mixes with PMB 40 and VG 30 binders respectively. The total permanent strain in a mix is an indicator of rutting and the results plotted in these Figures show low permanent deformation in mixes with warm mix additives when compared with control mixes. The permanent strains in warm mix with PMB are consistently lower than those in the mixes with VG 30. It is attributed to the higher viscosity of PMB 40 as increased resistance to rutting is offered by stiffer binders (Roberts et al. 1996)). Further, in the case of un-aged samples, the control HMA mixes showed more permanent strains than WMA mixes. The freshly prepared warm mixes with both binders showed less permanent strain in comparison to control HMA mix. In the case of aged samples, the WMA mixes showed almost similar extent of permanent strain as in the control mixes except in the Evotherm™ modified mixes. Evotherm™ modified warm mixes showed higher permanent deformation after aging. Better stiffness and resistance to permanent deformation was observed in the aged and un-aged mixes prepared with Sasobit®.

Table 5.14: Dynamic Creep Test results at 40°C

Mix ID	**Total permanent strain, %**			
	Un-aged mix		**Aged mix**	
	Average value	Standard deviation	Average value	Standard deviation
PP	0.648	0.058	0.150	0.015
PE	0.392	0.010	0.316	0.007
PS	0.346	0.026	0.152	0.005
PR	0.442	0.054	0.225	0.006
VP	0.672	0.020	0.221	0.017
VE	0.456	0.091	0.384	0.042
VR	0.479	0.019	0.267	0.027
VS	0.367	0.054	0.234	0.018

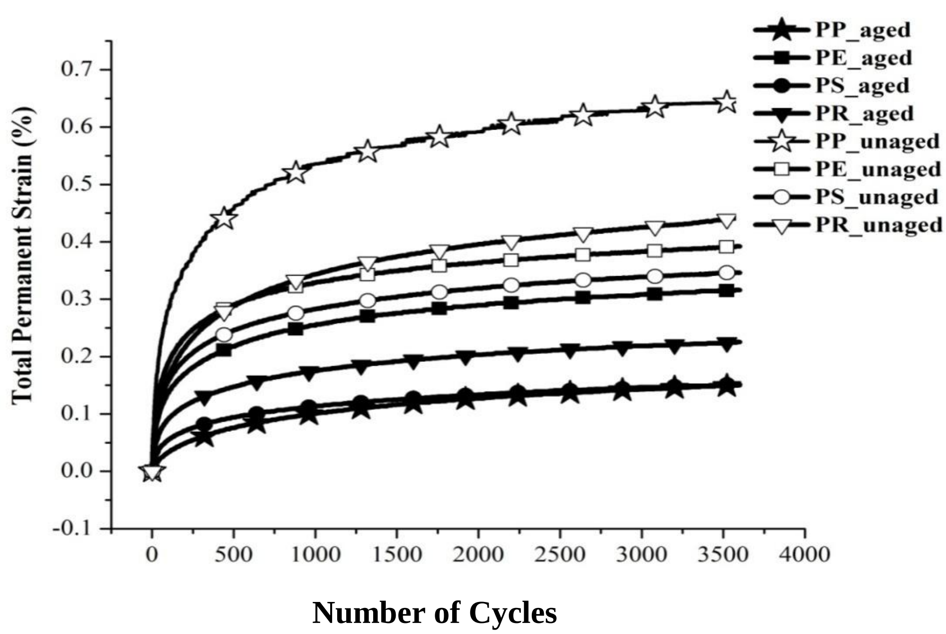


Figure 5.11 Total permanent Strain for aged and un-aged mixes at 40°C with PMB 40

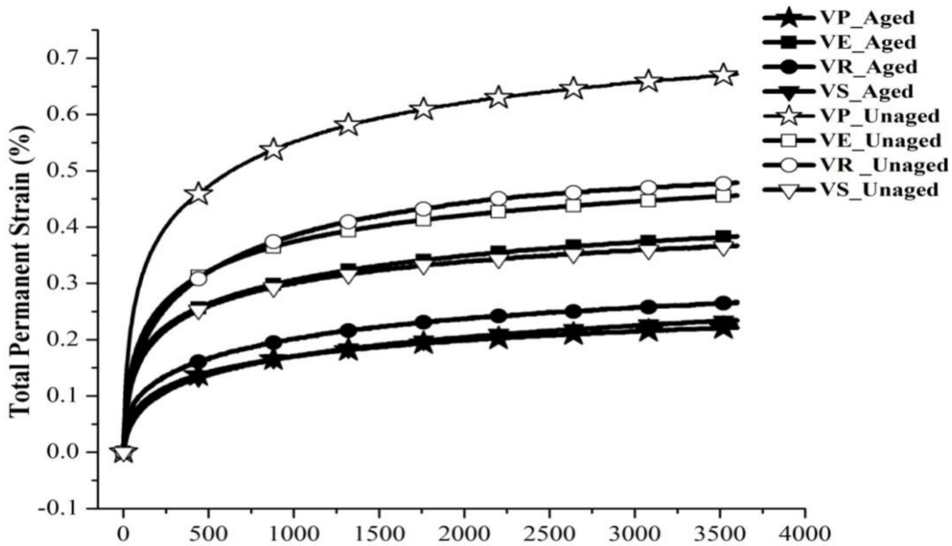


Figure 5.12 Total permanent Strain for aged and un-aged mixes at 40°C VG 30

5.2.4 Rutting Characteristics of Warm Mixes

Rutting is observed as the main distress mechanism typically occurring in countries with high pavement in-service temperature like India. Figure 5.13 shows the rut depths in asphalt mixes with and without warm mix additives. As may be seen, the warm asphalt mixes had significantly lower rutting depths than the control hot asphalt mixes. This observation is same for both VG 30 and PMB 40 based mixes. Asphalt mixes containing Sasobit® showed the lowest rut depth values than the other mixes. This observation is consistent with the results reported in Chapter 4 on the binder properties, where the addition of 2% Sasobit® significantly increased the binder complex modulus and the resistance to permanent deformation. Hence it can be concluded that the addition of Sasobit® warm mix additive improves the rutting resistance of the asphalt mixtures. Evotherm™ and Rediset® modified warm mix asphalt also showed lesser rut depths than the control hot mix asphalt. Other researchers, who have studied the effect of Evotherm™ and Rediset® additive on the rutting and fatigue characteristics of asphalt mixes, have also reported similar observations (Zhen Leng et, al.2014).

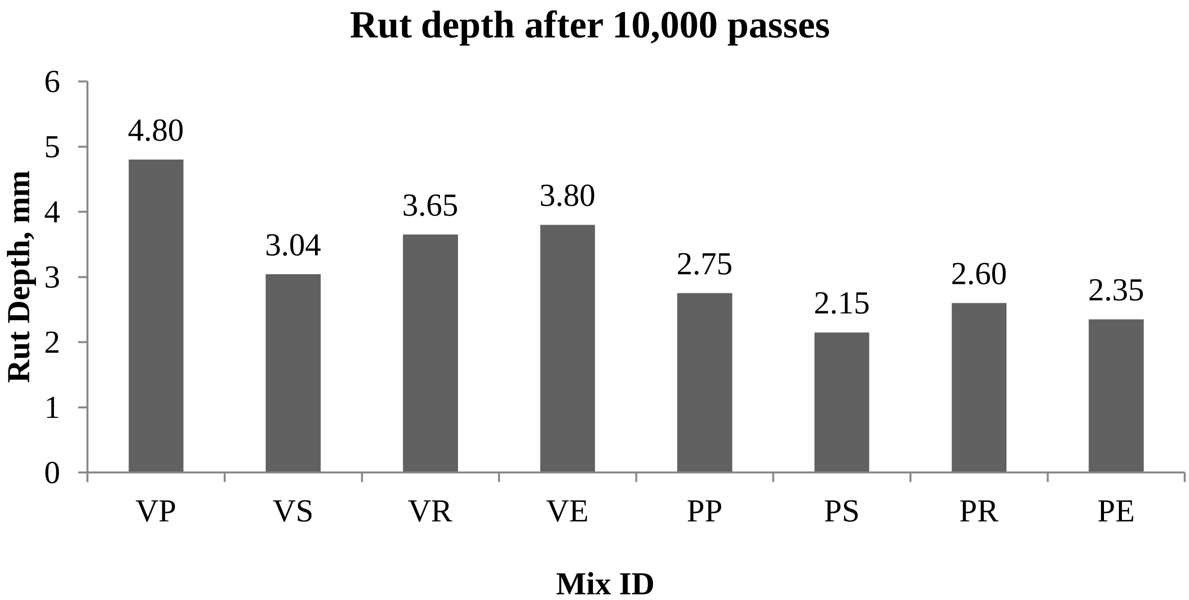


Figure 5.13: Rut depths of Asphalt mixes with and without warm mix additives.

5.2.5 Fatigue Characteristics of Warm Mixes

Fatigue cracking is the accumulation of damage under repeated load applications in an asphalt pavement. Fatigue life of a pavement is commonly defined as the number of load cycles to fail the asphalt concrete at strain (or stress) occurring at the bottom of the asphalt layer. To understand the ability of an asphalt pavement laid and compacted at lower temperatures to resist fractures from repeated loading condition, it is essential to study the fatigue characteristics of asphalt mixes prepared at lower temperatures. The failure criteria used to interpret fatigue test results is a very important factor in establishing the fatigue life. In a controlled stress test condition, failure is generally defined as the breaking of the sample. On the other hand, in controlled strain test condition, failure is defined at a specific percentage of reduction in modulus; a 50% reduction is typically used. In this study controlled strain test was used and the failure criteria selected was defined as the loading cycle when stiffness modulus of the beam reduces to 50 percent of its initial value.

Table 5.15 and 5.16 show the results of four point bending beam test on VG 30 and PMB 40 based warm and hot asphalt mix sample beams at three different strain levels. Results reported in Table 5.15 indicate that the addition of warm mix additives improved the fatigue life of VG 30 asphalt mix. The sample beams prepared with warm mix binder failed at higher number of cycles in comparison to control hot mix asphalt beams. The mixes containing Evotherm™ significantly improved the fatigue life of the mix at all strain levels, whereas the mixes containing Sasobit® showed the minimum improvement in fatigue life of the mix in comparison to control hot mix, at lower strain levels of 200 and 300 micron. At higher strain level of 400 micron however all the three warm mix additives showed similar results.

Table 5.15: Fatigue life of VG30 based asphalt mixes

Mix ID	Number of cycles to failure at a strain level of					
	200 μ		300 μ		400 μ	
	Average value	Standard deviation	Average value	Standard deviation	Average value	Standard deviation
VP	104262	3725.7	21450	2518.7	1355	202.9
VE	333430	3803.5	47835	3302.1	3655	262.3
VS	155711	2906.2	24643	2175.0	3447	331.6
VR	267335	5435.5	28283	2578.8	3591	73.5

Table 5.16: Fatigue life of PMB 40 based asphalt mixes

Mix ID	Number of cycles to failure at a strain level of				
	200 μ	300 μ		400 μ	
		Average value	Standard deviation	Average value	Standard deviation
PP	>400000	26203	1330.7	2039	156.9
PE	>400000	92500	2460.7	29647	3506.5
PS	>400000	63530	2579.5	22802	2707.5
PR	>400000	41311	1023.2	14062	941.86

In the case of PMB 40 based hot and warm mixes, the beams could not break even at 4, 00,000 load cycles at the lower strain of 200 micron. Therefore performance of these mixes cannot be compared at this strain level. At higher strains, mixes containing Evotherm™ and Sasobit® additives showed significant improvement in the fatigue lives of asphalt mixes.

5.3 Summary

This chapter describes the method adopted for finding optimum additive dosage and mixing temperature. Performance properties of warm mixes have been evaluated and discussed in comparison to hot mixes. Moisture resistance of warm and hot mixes was evaluated by conducting tests like indirect tensile strength (ITS), tensile strength ratio (TSR) and moisture induced sensitivity test (MIST). Other performance related tests like resilient modulus, dynamic creep, beam fatigue and wheel rutting were also conducted. Effect of aging on the moisture resistance and permanent deformation of warm mixes was evaluated and compared with that of hot mixes.

CHAPTER 6

CONCLUSIONS

6.1 Introduction

The present research study is conducted to evaluate the influence of warm mix additives on performance of bituminous binders and mixes. Two types of binders; VG-30 and polymer modified bitumen PMB40, and three types of warm mix additives; Sasobit®, Evotherm™ and Rediset® are considered. Effect of temperature on the viscosity of the binders containing warm asphalt additives were studied by measuring the viscosity of the binders with varying dosages of these additives. Frequency sweep and temperature sweep tests were conducted to study the effects of the warm mix additives on the complex modulus (G*), phase angle (δ), complex viscosity (η*) and G*/sinδ of binders. Bitumen-Filler mastics were prepared by adding calculated mass of limestone filler to virgin and warm mix binders and the ZSV of these binders were evaluated. The effects of short term and long term aging of binders with warm mix on viscosity, G* and δ values, binder stiffness and m-values are also evaluated. The binders recovered from asphalt mixtures were tested for the aging index. To quantify and validate the extent of aging in binders, Fourier Transform Infrared Spectroscopy (FTIR) was carried out on binders with and without warm asphalt additives.
Marshall method of mix design was followed to design the bituminous mixes. Performance properties of Warm Asphalt Mixes were evaluated and compared with Hot Asphalt Mixes. Indirect tensile strengths (ITS), tensile strength ratio (TSR), moisture induced sensitivity test (MIST), resilient modulus, dynamic creep, fatigue strength, and rutting depths of WMA mixtures were evaluated and compared with that of HMA mixtures. The effects of aging of warm asphalt mixes were evaluated by artificially aging the mixture samples in the oven at 85ºC for 120 hours. The aged samples were then tested for all the performance properties.

Based on the results reported in the preceding chapters, the major conclusions of this research are given below.

6.2 Conclusions based on binder characterization

(i) Evotherm™ and Rediset® do not significantly affect the viscosity of the binders, whereas the addition of Sasobit® decreases the viscosity of the binders. Reduction in viscosity is more evident at higher concentration of Sasobit®. The decrease in the viscosity of the binders is due to the dissolution of the wax in the binder. At temperatures below 105ºC, the binders containing Sasobit® had increased the viscosity of the binders because the melting point of Sasobit® granules is 95ºC to 105ºC and below 105ºC the Sasobit® additive remains in the binder as a wax due to which it shows increase in the viscosity of virgin binder.

(ii) Addition of warm mix additives to VG30 and PMB40 binder increases the penetration index of the binder, which indicates that these additives reduce the temperature sensitivity of two binders in the temperature range of 15°C to 30°C. The Viscosity-temperature relations show that the addition of warm mix additives make VG30 and PMB40 binders more temperature susceptible in the temperature range of 60°C to 135°C, which shows that addition of these additives can reduce the mixing and compaction temperatures. Further, addition of warm mix additives to VG30 binder reduces the PVN value of the binder; indicating that these additives make the bitumen more temperature susceptible in the temperature range of 25°C to 60°C. This implies that these wma binders can experience more rutting damage at in-service pavement temperature.

(iii) Rutting factor $G^*/\sin\delta$ of control binders improves with the addition of Sasobit® at higher dosage, whereas it reduced with the addition of Evotherm™. Addition of Rediset® improved the rutting factor values of VG 30 binder but reduced for PMB 40. The Failure temperature of VG-30 improved with the addition of Sasobit®, while it showed very marginal change with Rediset® and Evotherm™. For PMB 40 binder, all the three warm mix additives did not show much improvement in the failure temperature values.

(iv) In the case of bitumen – filler mastic, addition of warm mix additives improved the failure temperature values of VG 30 based mastics. For PMB-40 binder mastic, 0.5 percent Evotherm™ showed the highest value of failure temperature at F/B ratio of 1.3% and 1.5%. Similarly, 3% Rediset® showed significant improvement in failure temperature at F/B ratio of 1.3% and 1.5%. These results show that the Evotherm™ and Rediset® do not alter any property of bitumen, but are effective only when mixed with bitumen in presence of aggregate/filler part.

(v) ZSV of both binders i.e. VG 30 and PMB 40 increased with increase in Sasobit® dose while it did not show any improvement with Evotherm™ and Rediset® for both test temperatures of 60°C and 40°C.

(vi) Sasobit® is found effective in enhancing the rut resistance of bitumen-filler mastic at its all doses with VG30, but it showed improvement at the dose of 3 percent and above for mastic prepared from PMB40 binder. Bitumen-filler mastics prepared from Rediset® and Evotherm™ modified binders showed improved ZSV only at higher filler-binder ratio of 1.3% and 1.5% which indicates improved resistance to rutting.

(vii) No definite trend is observed for ZSV of polymer modified binder with warm mix additive. It might be due to the reason that the temperature of 60°C is too low to test modified binders, as they are still in the range of viscoelastic behaviour even at low frequencies, which makes it difficult to measure the ZSV. This is in consistent with an earlier study done by Biro Szabolcs et al. (2008), where it was observed that Cross model cannot be adapted well to polymer modified binders to find ZSV since their curves do not reach a plateau at low frequency.

(viii) Warm mix binders were short term aged in the RTFO at different temperatures and it was observed that reduced mixing temperatures significantly reduced the aging index of the binder containing warm mix additives. The recovered binders from the warm asphalt mixtures and hot asphalt mixtures also showed similar results. Recovered binders with warm mix additives have lower aging indices than the binders recovered from hot mix asphalt.

(ix) RTFO aged Rediset® modified binders showed slight reduction in the $G^*/\sin\delta$ values in comparison to aged control binders which indicates that addition of Rediset® additive to binder makes it susceptible to rutting. Evotherm™ based wma binders aged at 163ºC as well as at lower temperatures showed comparable values of $G^*/\sin\delta$ to that of control binders aged at 163ºC. Sasobit® modified binders showed significantly higher values of $G^*/\sin\delta$.

(x) After long term aging the warm mix binders with Evotherm™ and Rediset® additive showed better fatigue cracking resistance, whereas Sasobit® modified warm mix binders showed significantly higher values of G*.sinδ as compared to control binders.

(xi) Evotherm™ warm mix binders are expected to have improved resistance to low temperature cracking as these binders showed the lowest creep stiffness values for the samples aged at 163ºC as well as at lower temperatures. These binders also had significantly higher m-values, indicating their better ability to relax stresses than other warm mix binders as well as control binders.

(xii) Sasobit® and Rediset® warm mix binders showed higher creep stiffness values and lower m-values in comparison to the control VG 30 binder. However for PMB 40 based binders Rediset® warm mix binder showed reduced stiffness values and also improved m-values when aged at lower mixing temperature, which indicates their improved resistance to low temperature cracking. Sasobit® modified PMB-40 binders showed higher stiffness values and lower m-values in comparison to control PMB 40 binder.

(xiii) Fourier Transform Infrared Spectroscopy (FTIR) for asphalt binders is used as an indicator of oxidation (aging), as it allows the identification of the formation of two chemical entities resulting from oxidation: the Carbonyl (C=O) and Sulfoxide (S=O) groups. Binders aged in RTFO and PAV and recovered binders from mixes are tested for absorbance peaks. The FTIR analysis confirmed that the absorbance of warm mix binders was less as compared to controlled binders in all the three cases. It confirmed that binders containing warm mix additives age less as compared to the control binders.

6.3 Conclusions Based on Mix Characterization

(xiv) The compacted mixture specimens of warm mix asphalt as well as hot mix asphalt were conditioned in an oven for 5 days (120 hours) at 85ºC. The effect of aging on moisture resistance and permanent deformation of warm mix asphalt was compared with that of hot mix asphalt In the case of un-aged mixes, the warm asphalt mixes had better TSR values than the control PMB 40 hot mix asphalt. However, in the case of aged PMB 40 based mixes, Evotherm™ warm mix asphalt showed a greater TSR value than the control mixes, whereas Sasobit® and Rediset® warm mixes showed almost comparable TSR values to those of control mixes.

(xv) Un-aged VG 30 mixes containing the warm asphalt additives had significantly higher TSR values than control mixes. However after the MIST conditioning of the samples. The warm mix samples containing Sasobit® were found to be more susceptible to moisture induced damage in comparison to control VG 30 hot mix asphalt samples. Evotherm™ and Rediset® based warm mix samples showed improved resistance to moisture induced damage in comparison to control hot mix asphalt. Aged VG-30 mixes also showed similar behaviour.

(xvi) Warm asphalt mixes showed better resilient modulus values than the control hot mix asphalt at both test temperatures of 25ºC and 45ºC.

(xvii) Un-aged control HMA mixes showed more permanent accumulated strains in dynamic creep tests than WMA mixes. This shows that warm asphalt mixes will have more resistance to permanent deformation than the hot asphalt mixes. Whereas in the case of aged samples, the WMA mixes showed almost similar extent of permanent accumulated strain as in the control HMA mixes except the Evotherm™ modified mixes. Evotherm™ modified warm mixes showed higher permanent deformation after aging.

(xviii) Wheel rutting tests on control and warm asphalt mixes indicated significant improvement in the rutting resistance of warm mix asphalt specimens as shown in Table 6.1.

Table 6.1 Rut depth in different mixes

Type of Mix	**Rut depth, mm**	**Ratio with respect to control mix**
VG 30 (control)	4.80	--
VG30 + Sasobit®	3.04	0.633
VG30 + Rediset®	3.65	0.760
VG30 + Evotherm™	3.80	0.792
PMB 40 (control)	2.75	--
PMB 40 + Sasobit®	2.15	0.782
PMB 40 + Rediset®	2.60	0.945
PMB 40 + Evotherm™	2.35	0.855

(xix) Addition of warm mix additives improved the fatigue life of asphalt mixes. Mixes containing Evotherm™ additive showed highest fatigue life in comparison to other warm mix additives as shown in Table 6.2.

Table 6.2 Fatigue lives of different mixes at strain level of 300 microns

Type of Mix	Number of cycles to failure	Ratio with respect to control mix
VG 30 (control)	21450	--
VG30 + Sasobit®	24643	1.15
VG30 + Rediset®	28283	1.31
VG30 + Evotherm™	47835	2.23
PMB 40 (control)	26203	--
PMB 40 + Sasobit®	63530	2.42
PMB 40 + Rediset®	41311	1.57
PMB 40 + Evotherm™	92500	3.53

6.4 Contribution of the Research

The concept of warm mix asphalt is new in India and due to limited research on WMA mixes; the technology is not yet accepted. The low mixing and compaction temperatures offer many advantages like energy savings, the reduction in carbon emissions and improved workability of bituminous mixes but the performance of these mixes in India is not well known. In this research detailed performance properties of various warm asphalt mixes and binders have been studied. The outcome of this research has contributed to the formation of Indian Roads Congress (IRC) guidelines for the use of warm mix asphalt in India (IRC SP101: 2014). The results of this research will pave the way for the wide acceptance of warm mix asphalt technology in India. This research has also dealt with some contradictions which were found in literature worldwide, that warm asphalt mixes will have inferior moisture and rutting resistance than hot mix asphalt.

Very few researchers have studied the short term and long term aging of warm mix binders in comparison to control binders' worldwide. Aging Indices of various warm binders and control binders were studied in detail and it was confirmed by conducting FTIR analysis that warm mix binders age less in comparison to control hot mix binders. It has also been presented in this research that rheological studies on bitumen-filler mastics of warm mix binders is a better way to characterize these binders, since the warm mix additives do not always change the viscosity parameters of the bituminous binders significantly.

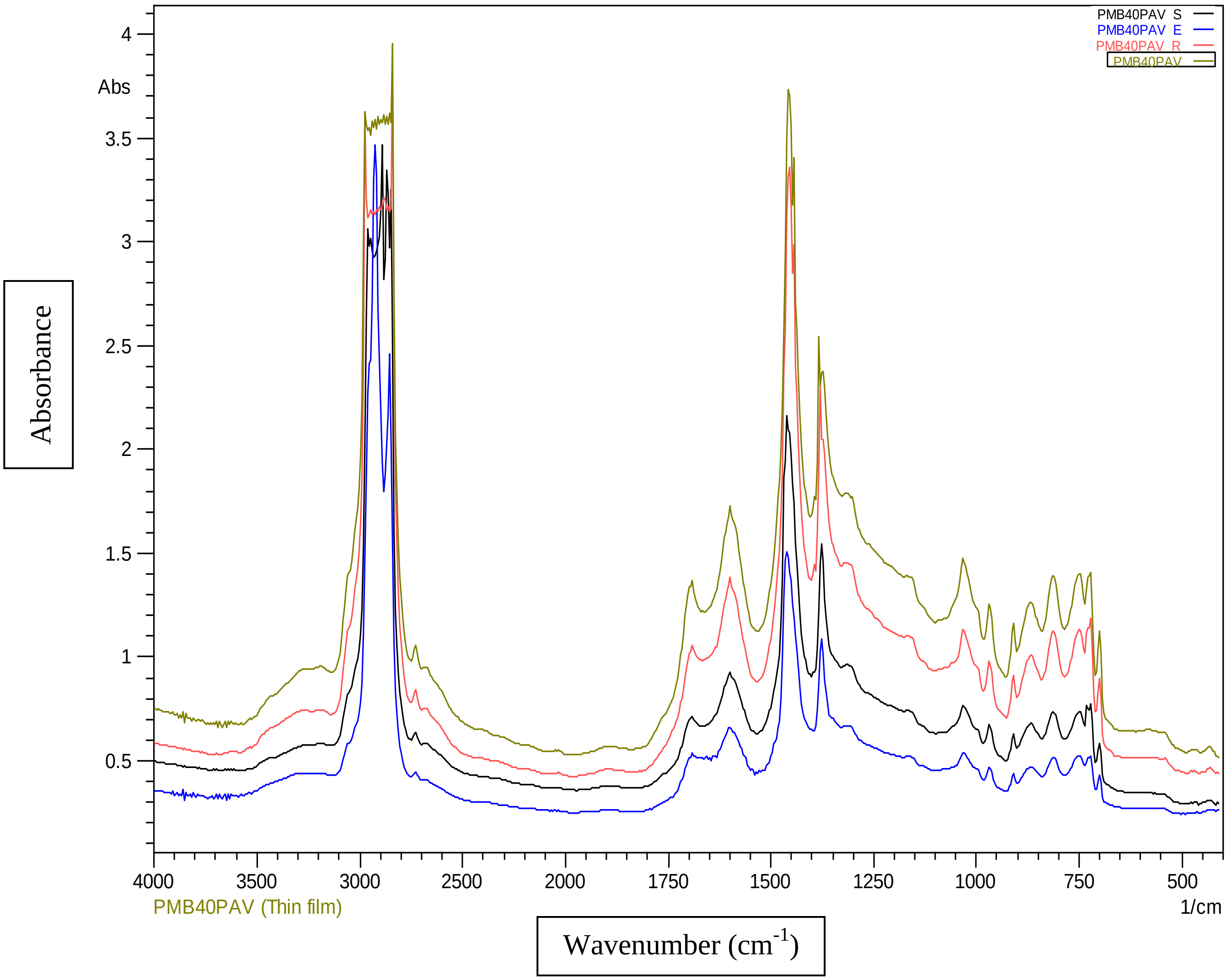
6.5 Recommendation for Future Research

There has been very little research on warm mix asphalt in India. While several aspects of warm mix asphalt have been addressed in this study, there are still some concerns and unknown parameters which need to be studied. It is recommended that the following topics should be investigated in detail to compliment the findings of this study.

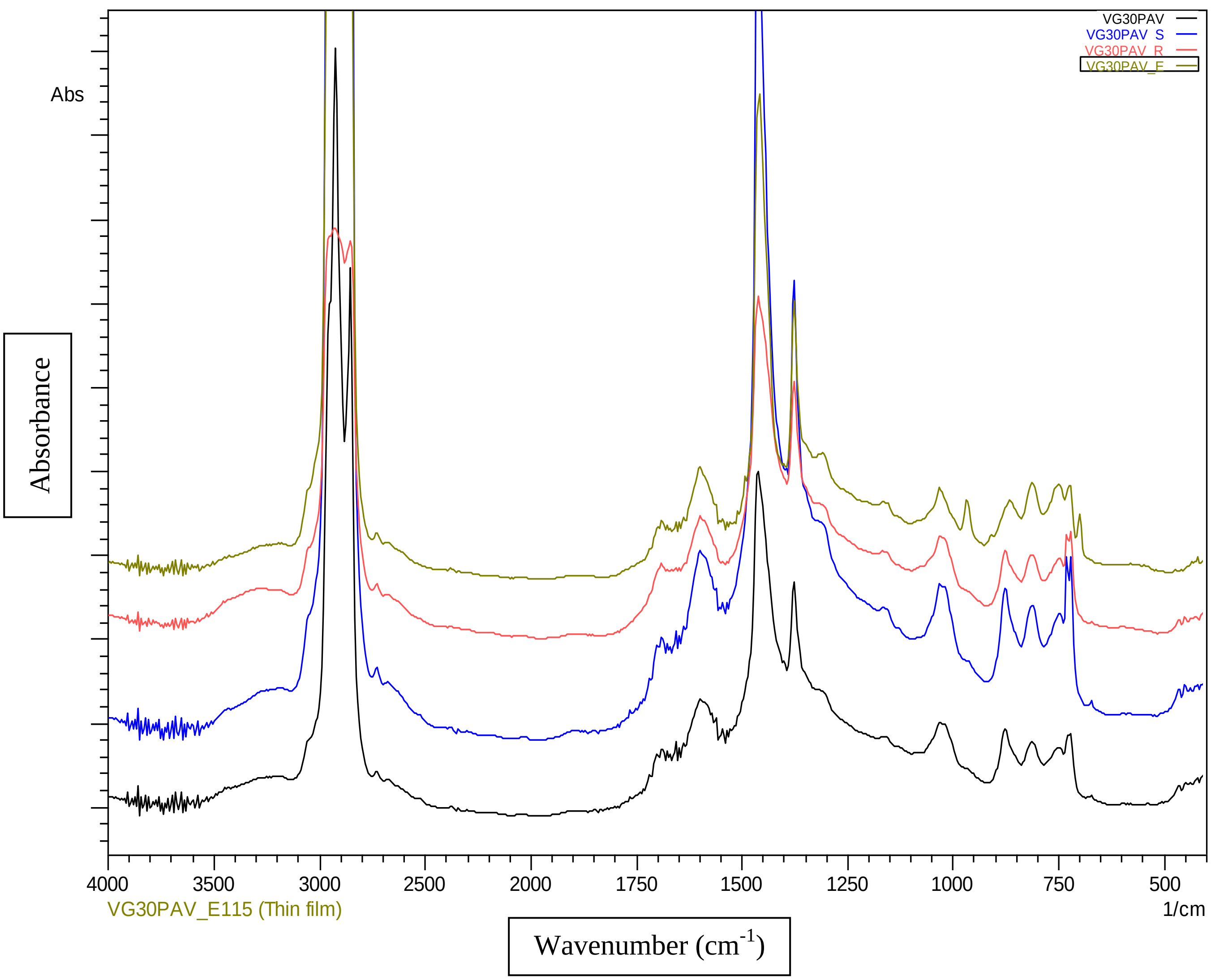
- Evaluating the performance of warm mix asphalt containing recycled asphalt pavement material and rejuvenating agents.
- Life cycle cost analysis of WMA pavements versus HMA pavements.
- The present study has focused on bituminous concrete mixes. The performance of other mixes like dense bituminous macadam (DBM), stone matrix asphalt (SMA) and open graded friction course (OGFC) containing warm mix additives may be studied.
- It is understood that due to lower mixing and compaction temperatures there will be lot of energy savings and carbon emission reduction, but no quantification of this is available in literature. This can certainly be good research topic for further work.
- Changes in asphalt mix design procedure due to the use of warm mix asphalt additives should also be studied in future research.
- It has been reported in literature that moisture susceptibility can be a concern in usage of WMA technology if the aggregates contain bound moisture. While preparing warm asphalt mixes the working temperatures are very low in comparison to HMA, due to which the bound moisture may not completely evaporate which will lead to poor moisture resistance of the asphalt mixes. This aspect should be studied in detail in future by using aggregates with varying moisture content.

APPENDIX 1: FTIR Spectra

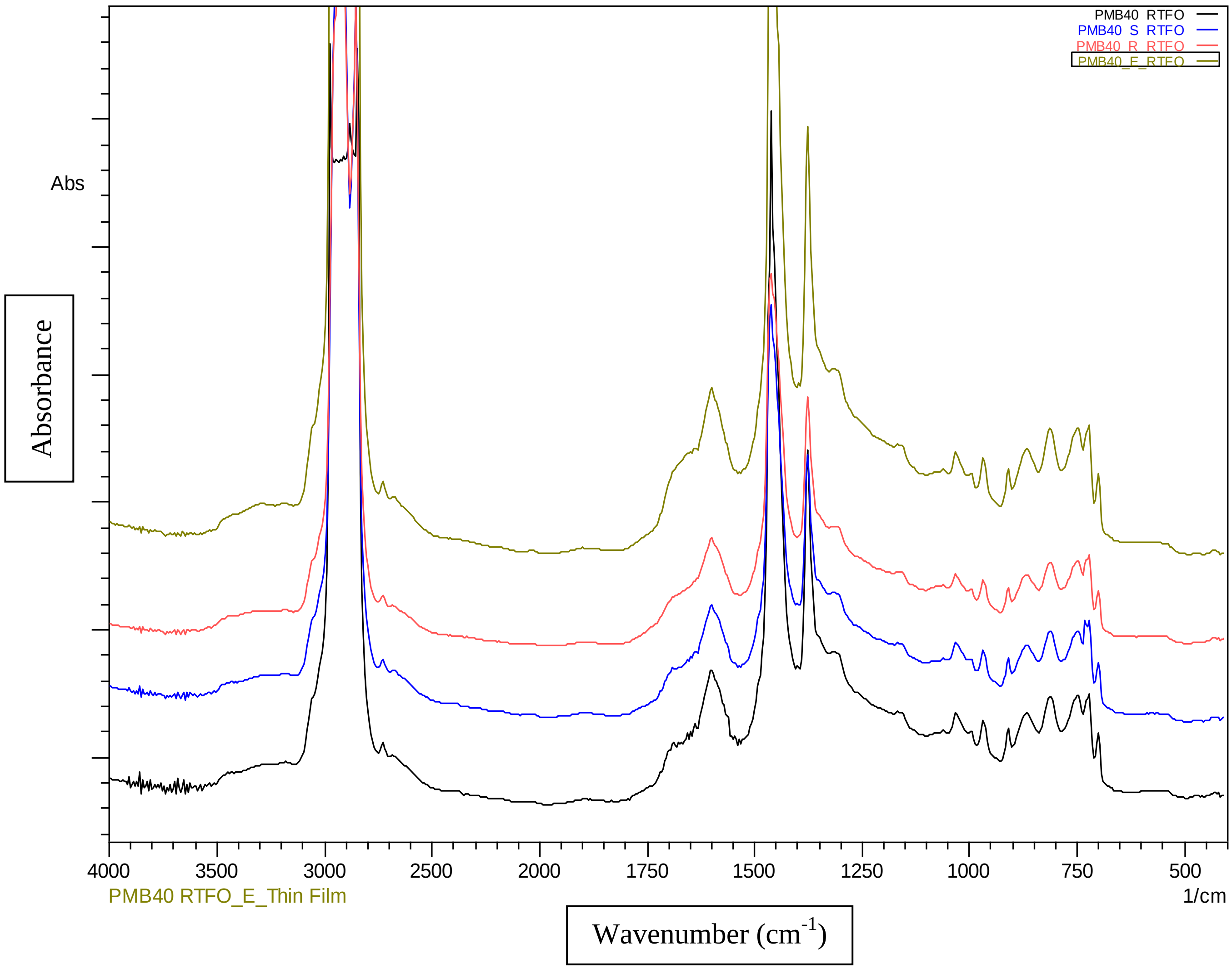
A1: FTIR Spectra of PAV aged PMB 40 binders



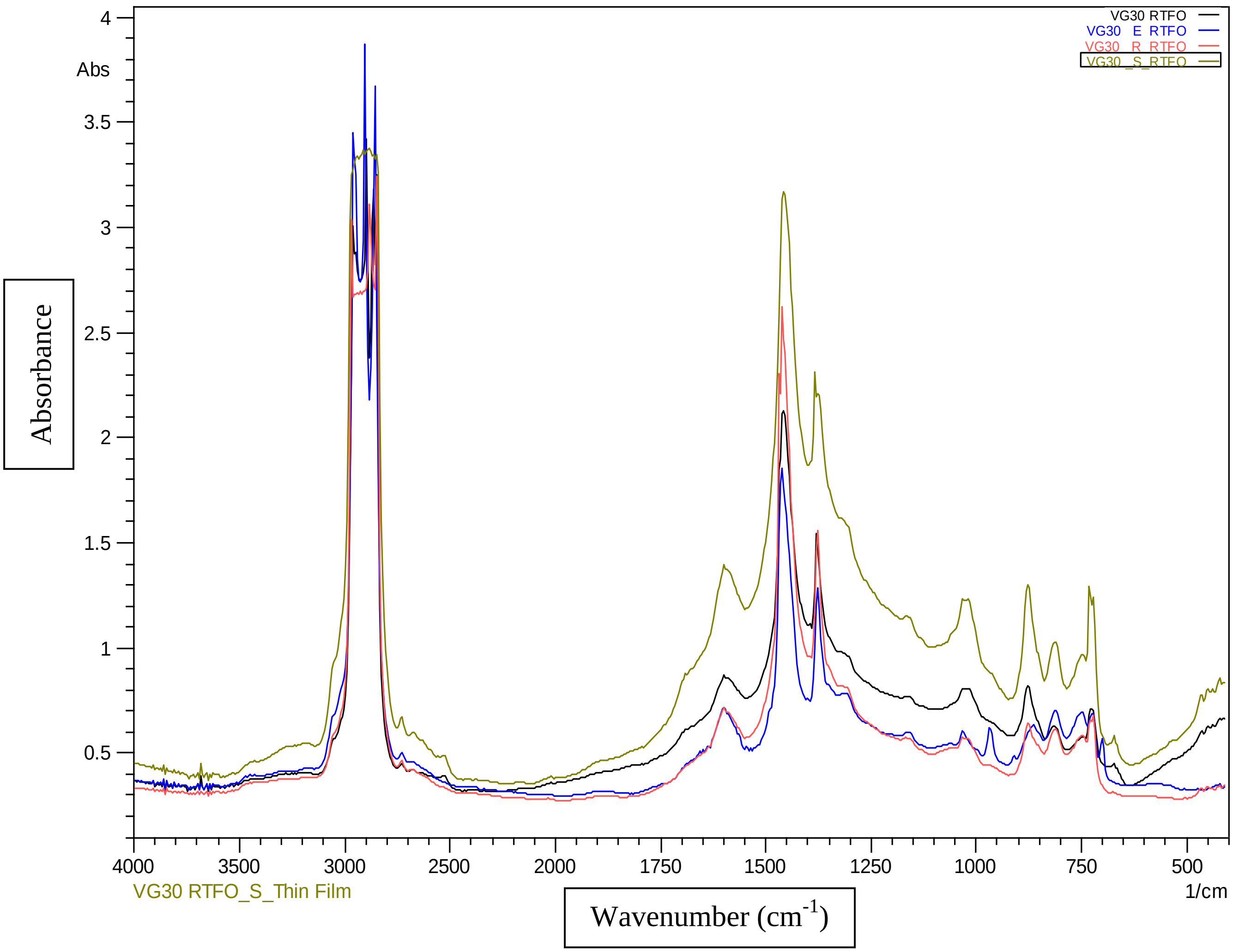
A2: FTIR Spectra of PAV aged VG 30 binders



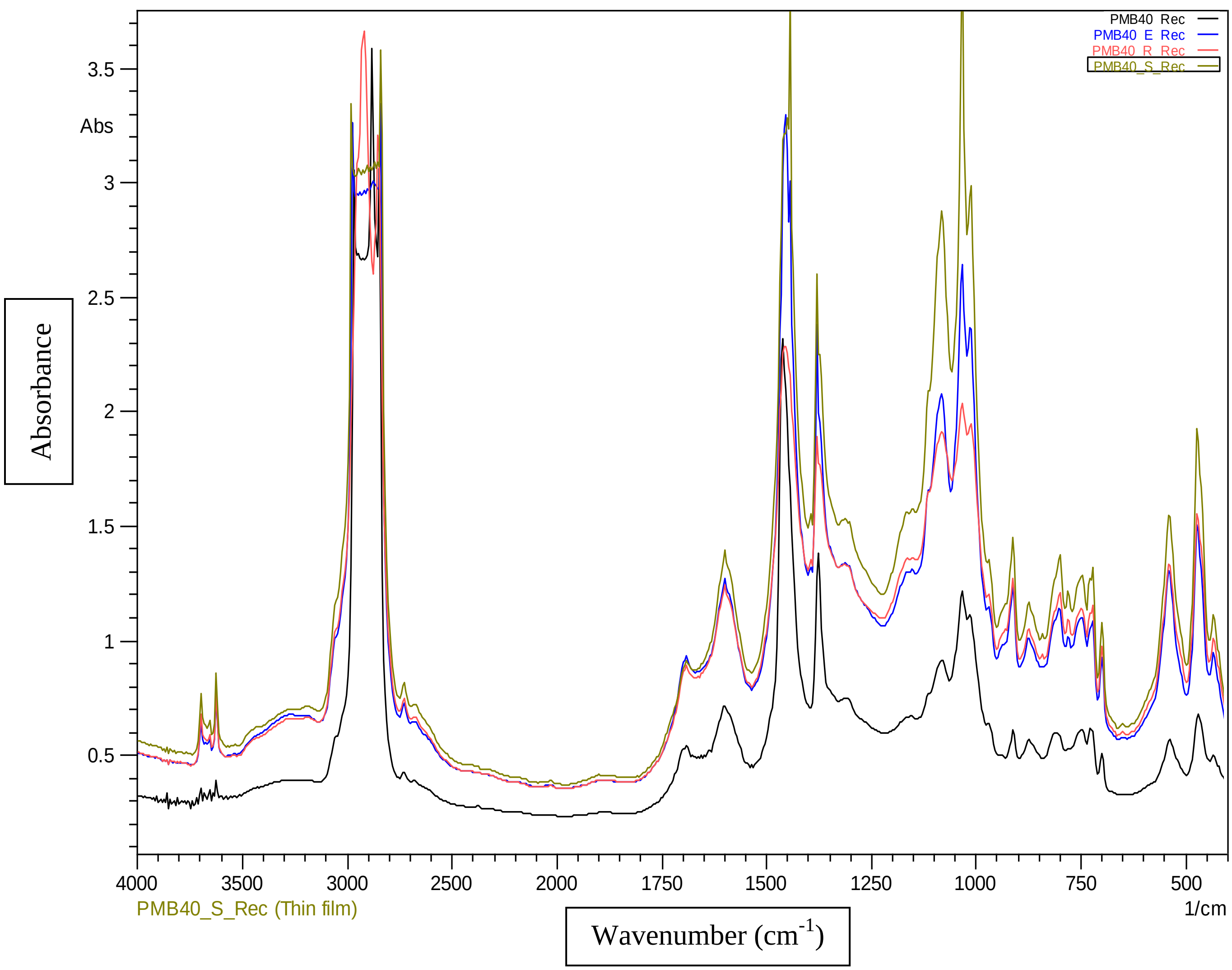
A3: FTIR Spectra of RTFO aged PMB 40 binders



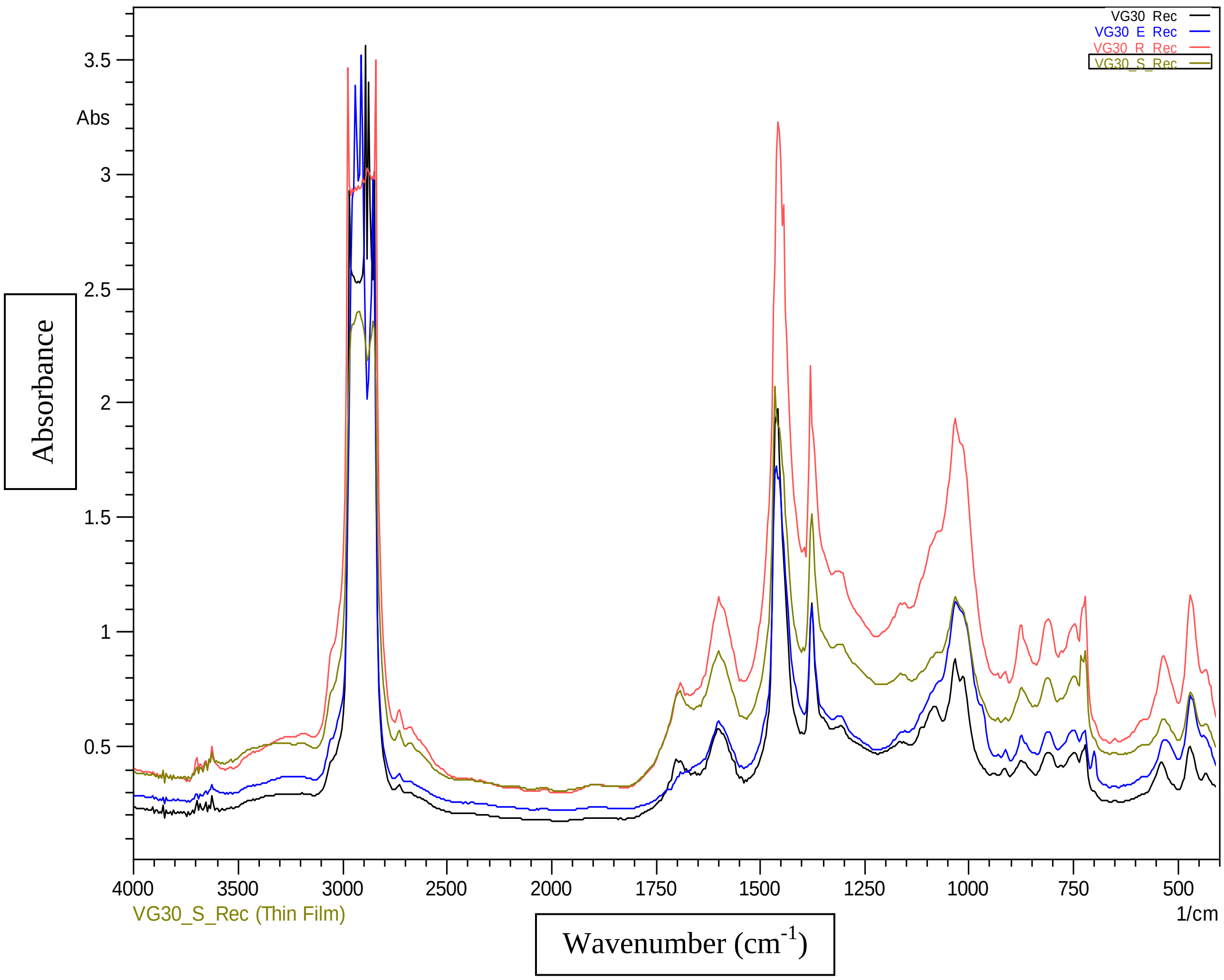
A4: FTIR Spectra of RTFO aged VG 30 binders



A5: FTIR Spectra of Recovered PMB 40 binders



A6: FTIR Spectra of Recovered VG 30 binders



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