Characterization of Epoxy Modified Asphalt

A Dissertation Submitted in Partial Fulfilment of the Requirement for the Award of the Degree of

MASTER OF ENGINEERING

in

INFRASTRUCTURE ENGINEERING

Submitted by

Pranav Karn

802123012

Under the supervision of

Dr. Abhinay Kumar	Dr. Tanuj Chopra
Assistant Professor	Assistant Professor
Department of Civil Engineering	Department of Civil Engineering

THAPAR INSTITUTE OF ENGINEERING & TECHNOLOGY (Deemed to be University)

DEPARTMENT OF CIVIL ENGINEERING

THAPAR INSTITUTE OF ENGINEERING AND TECHNOLOGY, PATIALA

PUNJAB-147004

JULY 2023

CANDIDATE DECLARATION

I hereby declare that the thesis titled "**Characterization of Epoxy Modified Asphalt**" is an authentic record of my work carried out as a requirement for the award of the degree of Master of Engineering in Infrastructure Engineering at Thapar Institute of Engineering and Technology (Deemed to be university), Patiala under the supervision of Dr. Abhinay Kumar, Assistant Professor, Civil Engineering Department, TIET, Patiala and Dr. Tanuj Chopra, Assistant Professor, Civil Engineering Department, TIET, Patiala. No part of the matter embodied in this report has been submitted to any other university or Institute for the award of any degree.

Date: 31-07-2023

Pranav Karn

802123012

This is to certify that the above declaration made by the student concerned is correct according to the best of my knowledge and belief.

Dr. Abhinay Kumar
Assistant Professor
CED, T.I.E.T, Patiala

Dr. Tanuj Chopra
Assistant Professor
CED, T.I.E.T, Patiala

ACKNOWLEDGEMENTS

When one holds profound affection for someone, simple gestures can suffice to demonstrate it. Recognizing that such work cannot be accomplished by a solitary individual, I seize this opportunity to express my gratitude and admiration for all those who supported me throughout the duration of this project. Completing my thesis would have been insurmountable without the invaluable assistance of numerous individuals, who provided direct or indirect aid through their constructive counsel. My duty is to extend my heartfelt appreciation to each person whose sincere contributions rendered this journey enlightening, informative, enjoyable, and unforgettable.

First of all, I want to thank my supervisor and mentor, Dr. Abhinay Kumar, Assistant Professor, Department of Civil Engineering, Thapar Institute of Engineering and Technology, Patiala, for his kind efforts and keen pursuits, which have helped me finish my work well. I want to thank my co-supervisor, Dr. Tanuj Chopra, Assistant Professor, Department of Civil Engineering, Thapar Institute of Engineering and Technology, Patiala, for all of the help, support, and technical advice he gave me while he was in charge of this research.

I would like to thank Mr. Jaspreet Singh, Lab Technician, for always helping me and providing me slots for experiments in the lab to finish my work.

I would also like to thank my parents and my friends for always supporting me and working with me. God is the last person I want to thank.

Pranav Karn

ABSTRACT

Asphalt pavements serve as the foundation of our transportation system, and their durability and effectiveness heavily rely on the properties of bitumen, which acts as the adhesive agent binding the aggregate materials together. Modified asphalt binders offer improved performance by enhancing the mechanical characteristics and resistance to rutting and fatigue of asphalt pavements.

Epoxy resin is a type of synthetic thermosetting polymer that is widely used in various industries and applications. It is created through a chemical reaction between epoxide monomers and a curing agent, typically a hardener. The resulting material is a highly durable and versatile substance with a wide range of properties.

This study aims to investigate the impact of epoxy modification on asphalt binder & mixtures properties. The base bitumen (VG 30) was modified by incorporating epoxy (combination of epoxy resin and hardener) at different contents of 1%, 2%, 3%, and 4% by weight of heat binder. The rheological properties of the binders were evaluated through tests such as high-performance grade (PG), MSCR (multiple stress creep and recovery), frequency sweeps, temperature sweeps, amplitude sweeps, SFP (Superpave fatigue parameter), LAS (linear amplitude sweep), and BBR (bending beam rheometer) tests. The mixture properties were tested through Marshall stability, ITS (indirect tensile strength), and TSR (tensile strength ratio) tests.

Through comprehensive analysis, the optimal dosage of the additive was determined to be 2-3% by weight, resulting in the most favourable modified asphalt binder and mixture properties. Pavement structural analysis showed that the selected pavement composition had the ability to resist higher traffic based on rutting and fatigue criteria as per IRC: 37-2018 when epoxy-modified bituminous concrete (BC) mixtures were used in the wearing course, than the mixture with unmodified VG 30 binder.

Keywords: modifier asphalt; epoxy; rutting; fatigue; rheology; asphalt mixture.

Table of Contents

List of Figures

List of Tables

1 INTRODUCTION

1.1 Introduction

Asphalt pavements are the lifeline of our transportation system. They are secure and dependable spaces for vehicles to travel. The durability and efficiency of asphalt pavements rely significantly on the characteristics of the bitumen, which acts as the adhesive binder to the aggregate materials. Researchers and experts have been exploring novel methods to enhance the attributes of bitumen, enabling it to perform more effectively under intense traffic conditions, adverse weather, and the challenges associated with aging.

Modifying bitumen using epoxy resins is one such strategy that has recently attracted much attention. The advantages of bitumen and epoxy are combined in epoxy modified asphalt (EMA), which has the potential to considerably increase the durability and efficiency of asphalt pavements. Epoxy resin is a type of synthetic thermosetting polymer that is widely used in various industries and applications. It is created through a chemical reaction between epoxide monomers and a curing agent, typically a hardener. The resulting material is a highly durable and versatile substance with a wide range of properties.

Understanding the behaviour of epoxy modified asphalt and determining whether it is appropriate for use in practical applications depend heavily on how well it is characterized. This study aims to characterize the key traits and potential benefits of EMA over traditional bitumen and a commercial polymer-modified bitumen (PMB) by undertaking a number of laboratory experiments and analysis. This thesis aims to advance our understanding of epoxy modified asphalt and its potential as a viable replacement for traditional bitumen in asphalt pavements. The results of this study will advance our understanding of EMA performance and direct the development of more resilient, long-lasting, and sustainable asphalt pavements.

The overarching objective of this study is to open the door for the more widespread acceptance and use of epoxy modified bitumen, which will ultimately increase the durability and performance of asphalt pavements, lower maintenance costs, and enhance the nation's transportation system as a whole.

1.2 Indian Road Infrastructure

Transportation holds great significance in the development of every country. The most widely utilized mode of transportation is road transportation. In order to facilitate the transportation of necessary resources and manpower for development, the availability of efficient road networks is crucial. As a nation's economy grows, transportation systems must keep pace with the increasing traffic demands. India has the world's second-largest road network, spanning approximately 63.72 lakh km. This extensive network includes National Highways, Expressways, State Highways, Major District Roads, Other District Roads, and Village Roads (as per the Ministry of Road Transport and Highways annual report for 2021-2022). As of July 2023, total expressway length in the country stands at 4,115 km. Table 1 shows the classification of Indian highways (MORTH, 2022).

Table 1. Classification of Indian highways (MORTH, 2022)

Category	Length
National Highways	1,40,995 km
State Highways	1,71,039 km
Other Roads	60,59,813 km
Total	63,71,847 km

In recent years, the government has made many comprehensive policies to encourage the private sector to invest money in the growth and development of the national highway. Previously, every investment used to be done by the government. Figure.1 shows the length of roads constructed each year.

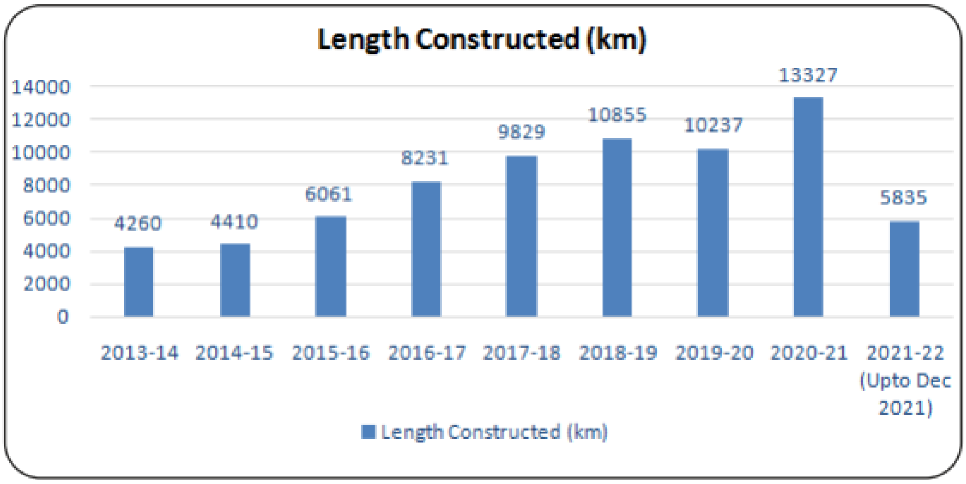


Figure 1. Construction of roads 2013-2022 (MORTH, 2022)

The development programs for the road infrastructure are as follows:

- Bharatmala Project
- National Highways Development Project (NHDP)
- India's Gati Shakti program

A pavement is an engineered structure consisting of several layers so that the overall structure is durable and serviceable for the traffic it is designed for. Pavement also allows adequate longitudinal and lateral friction for the vehicles to move and transfers the load from the vehicle tire to the earth bed.

In a flexible pavement, the stresses due to wheel loads are transferred to the underlying layers/courses by grain-to-grain contact. Figure 2 shows a cross-section of a typical flexible pavement consisting of subgrade, subbase, base, binder, and surface courses.

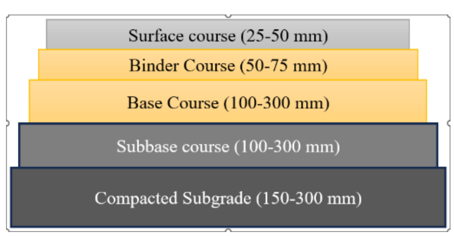


Figure 2. Flexible pavement cross-section

The surface course in a flexible pavement refers to the top layer of the pavement structure that directly interacts with the traffic load and provides a smooth and durable riding surface. It is the layer that is exposed to the environment and bears the brunt of the traffic loads and weather conditions. The primary purpose of the surface course is to distribute the traffic loads and protect the underlying layers of the pavement.

Typically, the surface course in a flexible pavement consists of one or more layers of asphalt concrete (also known as bituminous concrete or hot mix asphalt). Asphalt concrete is a composite material consisting of aggregates (such as crushed stone, gravel, or sand) bound together by asphalt binder. The aggregates provide strength and stability to the mixture, while the asphalt cement acts as a binder to hold the aggregates together.

1.3 Need for Modified Bitumen

Modified bitumen is bitumen or asphalt that has been enhanced with suitable additives to improve its performance characteristics. The need for modified bitumen arises from the limitations of conventional bitumen in meeting the increasingly demanding requirements of modern infrastructure in terms of increasing axle loads, tyre pressures, temperature and climate variations.

Modified bitumen is expected to surpass conventional bitumen in terms of durability, elasticity, fatigue resistance, and deformation resistance. Through the addition of polymers or additives, the properties of the binder are enhanced, enabling it to withstand heavier traffic loads, resist cracking, and maintain its integrity over a longer lifespan.

Conventional bitumen is susceptible to temperature-induced rutting and cracking, especially in regions with extreme climate conditions. Modified bitumen can be tailored to specific climate requirements by adjusting the type and quantity of polymers used. This allows for improved performance in both high-temperature and low-temperature environments, making it suitable for a wide range of geographical locations.

Bitumen naturally undergoes aging and oxidation, resulting in reduced flexibility and increased vulnerability to cracking. By incorporating polymers or antioxidants into the bitumen, modified bitumen can better resist the aging process and retain its properties for an extended period. The resistance to aging also ensures that the pavement remains intact and functional, thereby reducing maintenance and repair costs.

Modified bitumen exhibits superior adhesion to aggregates, enhancing the bond strength between the binder and aggregates. This leads to improved resistance against aggregate loss, stripping, and moisture damage. Modified bitumen is especially effective in waterproofing applications, such as roofing, as it forms an impermeable barrier against water penetration. Moreover, the incorporation of recycled materials and polymers derived from renewable sources further enhances the sustainability of modified bitumen.

Modified bitumen can be customized to meet specific project requirements, allowing for versatility in its application. It can be used in various types of pavements, including highways, airports, parking lots, and residential roads. Additionally, modified bitumen finds application in waterproofing systems for roofing and below-grade structures.

The need for modified bitumen arises from the limitations of conventional bitumen in meeting the performance demands of modern infrastructure. Through the addition of polymers or additives, modified bitumen offers improved performance, climate adaptability, aging resistance, adhesion, and waterproofing capabilities. Its use contributes to sustainable pavement solutions and provides versatility in various infrastructure projects.

In addition to polymers, there are various other materials/additives that are being investigated by researchers for the preparation of modified asphalt binders. Given the fact that addition of polymers typically increases the cost of the modified asphalt, there has been continued research to identify other potential materials for modification of the asphalt binders.

1.4 Epoxy modified asphalt binder

Epoxy modified asphalt binder refers to a type of modified asphalt where epoxy resin is added to the asphalt binder. Epoxy modified asphalt binder consists of three main components: epoxy resin, hardener for the resin, and asphalt binder. The epoxy resins used are typically bisphenol A (BPA) or bisphenol F (BPF), which are known for their high strength, chemical resistance, and adhesion properties. These resins are blended with the asphalt binder, which is a sticky, black, and highly viscous petroleum-based material. Figure 3 illustrates the chemical structure and attributes of epoxy resin. Its reactivity arises from the hydroxyl groups present at the main chain centre, as well as the epoxy groups at either end. The flexibility and chemical resistance stem from the incorporation of bonds within the main chain. Moreover, the resistance to heat and durability are due to the presence of benzene rings. The adhesion capabilities of epoxy resin can be attributed largely to the prevalence of secondary hydroxyl groups positioned on the main chain.

Epoxy modified asphalt binder is largely used for bridge decks where epoxy resin is used 40 to 60% by weight. Hot-mix epoxy asphalt concrete finds extensive application on steel bridges subjected to elevated temperatures and heavy axle loads. Its remarkable high-temperature stability, resistance to low-temperature cracking, and capacity to accommodate the deflections in steel components contribute to its popularity in such scenarios (Lou et al., 2021).

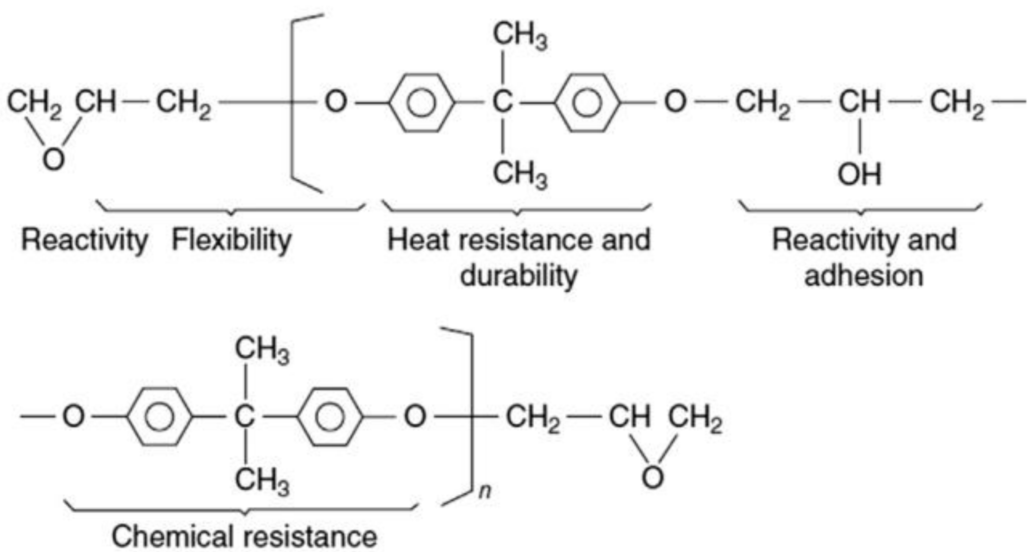


Figure 3. Structure and properties of epoxy resin (Xiang & Xiao, 2020)

1.5 Problem Statement

Literature review conducted on epoxy-modified asphalt (discussed in detail in Chapter 2) showed that the use of EMA has been majorly in bridge decks. Bridge decks typically employ a high percentage of epoxy resin, ranging from 40% to 60% by weight (Lou et al., 2021; Yin et al., 2015; Zhang et al., 2020; Cong et al., 2016). Consequently, the majority of research conducted thus far has focused on binder formulations with such high epoxy resin content.

However, for the applications in typical hot mix asphalt (HMA) used for highway pavements, such high dosages would lead to too high viscosity of the modified composite and pose workability issues. It may also change the viscoelastic nature of asphalt. It may also require much higher mixing and compaction temperatures, thus raising the energy requirements at the HMA production plants.

Given the widespread use of EMA (fabricated at much higher epoxy contents) in bridge decks, there arises a need to evaluate its performance properties when used for highway pavements. Thus, there is a need to evaluate the usefulness of EMA prepared at lower epoxy contents (say 1-5%) in terms of its physical and rheological performance a high (for rutting characterization), intermediate (for fatigue characterization), and low (for thermal cracking characterization) pavement temperatures.

1.6 Objectives

The research aims to achieve the following objectives:

- To determine the physical properties of epoxy modified asphalt prepared at various epoxy dosages, and compare the properties with unmodified bitumen and a commercial polymer modified bitumen.
- To determine the high, intermediate, and low pavement temperature rheological properties of epoxy modified asphalt prepared at various epoxy dosages, and compare the properties with unmodified bitumen and a commercial polymer modified bitumen (PMB).

- To prepare bituminous concrete (BC) mixtures with unmodified, epoxy modified, and PMB, and evaluate the Marshall properties of the different mixtures.
- Evaluate moisture damage of bituminous mix.
- To perform pavement structural analysis with epoxy modified asphalt mixtures used as wearing course mixtures in a selected flexible pavement composition using IITPAVE and IRC: 37-2018.
- To determine the optimal dosage of epoxy in bitumen that exhibits superior performance in comparison to other dosage levels.

2 LITERATURE REVIEW

2.1 Introduction

Epoxy asphalt combines the excellent properties of epoxy resins and asphalt binders. It has gained significant attention in recent years due to its exceptional durability, improved mechanical properties, and resistance to various forms of distress. This literature review aims to provide an overview of the research conducted on epoxy asphalt, highlighting its composition, properties, applications, and performance.

2.2 Review of research articles on epoxy modified asphalt

2.2.1 Cubuk *et al*. (2009)

The research team conducted a series of experiments involving the introduction of varying amounts of epoxy resin into bitumen with a 50/70 penetration grade. In all experiments, they consistently employed BPA type epoxy resin as the modifying agent. Epoxy resin was introduced into the heated bitumen at concentrations ranging from 1% to 6% by weight. The study aimed to investigate alterations in viscosity concerning both temperature and the concentration of the epoxy additive. To comprehensively assess the influence of epoxy, the authors employed a diverse range of asphalt binder testing methods, including rheological evaluation through dynamic shear rheometer and bending beam rheometer; thermal evaluation by differential scanning calorimetry; and aging characterization by rolling thin film oven and pressure aging vessel.

As depicted in Figure 4, it is observed that at temperatures below 110°C, the viscosity experiences exponential growth with increasing epoxy concentration, reaching its zenith at 2% (w/w). This behavior can be attributed to the heightened cohesion of bitumen at lower epoxy concentrations. However, at higher epoxy concentrations, a noticeable reduction in viscosity is evident, likely due to the dominance of epoxy-related effects. Conversely, at temperatures above 110°C, the impact of the epoxy additive on bitumen viscosity diminishes as the temperature increases.

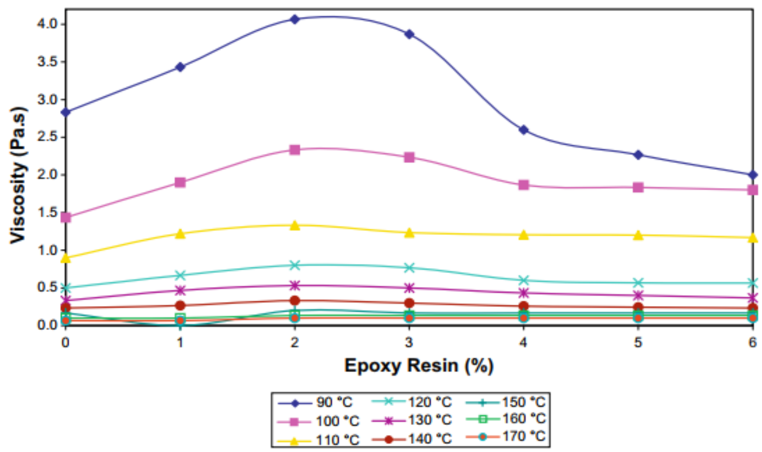


Figure 4. Function of epoxy concentration which indicates variation of bitumen viscosity (Cubuk et al., 2009)

One crucial aspect highlighted by the study is the determination of the optimum dosage of epoxy resin that yields the best rheological and performance properties. The authors found that an additive concentration of 2% (w/w) achieved the most favorable results, indicating that an appropriate level of epoxy content is crucial to achieve desired performance improvements.

2.2.2 Yu *et al*. (2009)

Epoxy asphalt blends were created by amalgamating styrene–butadiene–styrene (SBS) modified binder with epoxy resin. The research involved an examination of the curing process and the morphology of epoxy asphalt using infrared spectroscopy and a fluorescent microscope, respectively. Several variables, including the epoxy resin content, the ratio of curing agent to epoxy resin, and the curing temperature, were meticulously investigated to gain insights into their influence on the properties of epoxy asphalt. For the curing process, Methyl tetrahydro phthalic anhydride (MTHPA) was utilized as the curing agent. Epoxy asphalt samples were prepared with epoxy resin contents ranging from 10% to 50% by weight, which also included the curing agent.

According to Figure 5, the initial viscosity of all epoxy asphalts was around 600–800 mPa s, and after 50 minutes of curing at 120°C, the viscosity dropped to less than 2 Pa s. For the SBS modified asphalt mixture, an ideal asphalt viscosity of 600–800 mPa s is needed during the blending process, while a suitable viscosity of about 2 Pa s is required for compacting the mixture.

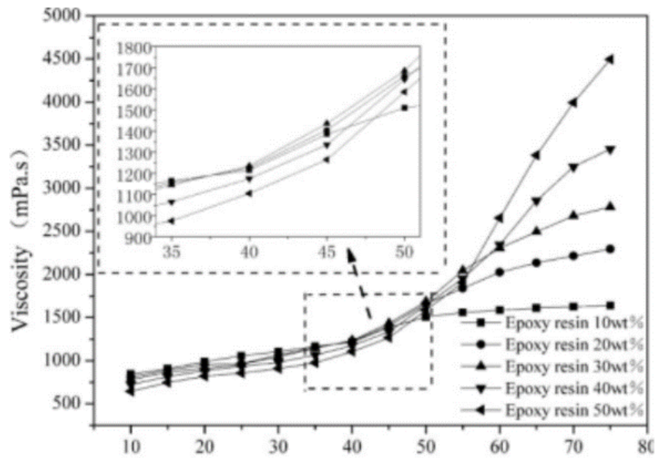


Figure 5. Effect of curing time on viscosity of epoxy asphalts. (Yu et al., 2009)

The mechanical properties exhibited a significant increase in tensile strength when the epoxy resin content surpassed 30% by weight. This enhancement is due to the formation of a continuous network within the epoxy modified asphalt. In contrast, the elongation at the breaking point of the epoxy modified asphalt reduced as the epoxy content increased.

2.2.3 Peiliang *et al*. (2010)

This research study delves into the application of epoxy-asphalt and its blend in long-span orthotropic steel deck bridges, capitalizing on its exceptional properties, including heat resistance, absence of bleeding, resistance to low-temperature cracking, and resistance to aggregate scattering. The primary objective of the study is to investigate how varying proportions of epoxy resin influence the rheological characteristics of epoxy-asphalt binders using a dynamic shear rheometer. The epoxy resin utilized in this research is diglycidyl ether of bisphenol A, with an epoxy value of 0.52 mol/100 g. Epoxy-asphalt compositions were prepared with epoxy resin contents of 10%, 20%, 30%, 40%, and 50% by weight, inclusive of the curing agent.

The experimental results demonstrate that the addition of epoxy enhances the viscoelastic performance of the asphalt binder at high pavement temperatures. This enhancement is characterized by increased elasticity, as evidenced by higher G* values and lower δ values for epoxy-asphalt compositions with higher epoxy resin concentrations. Furthermore, the introduction of epoxy resin improves the viscous behavior of the asphalt.

The results from creep tests indicate that the epoxy-asphalt binder not only exhibits resistance to deformation at elevated temperatures but also showcases satisfactory strain recovery capabilities.

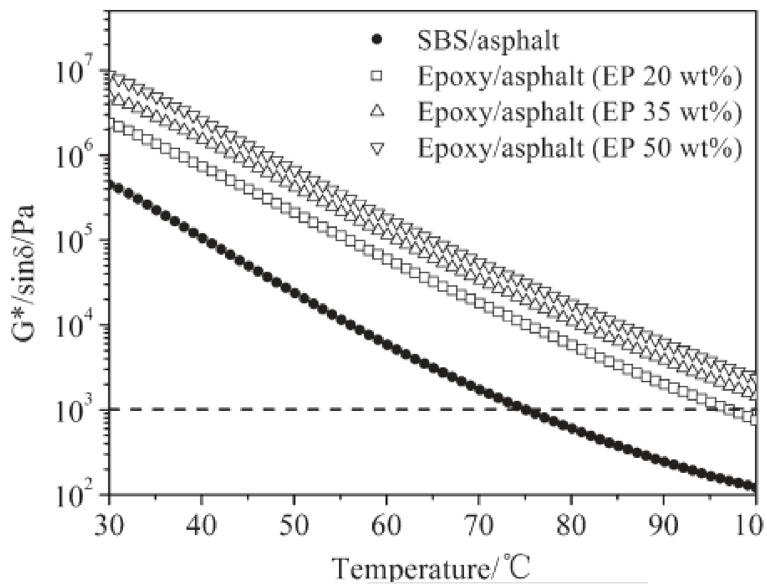


Figure 6. Variation of G*/sinδ. At with temperature (Peiliang *et al*., 2010)

The findings presented in Figure 6 demonstrate a noticeable improvement in the maximum rutting temperature when epoxy resin is employed as a modifier. In the case of the unmodified original asphalt binder, the maximum rutting temperature is recorded at 75°C. However, when 20 wt% of epoxy resins are incorporated into the asphalt binder, the maximum rutting temperature increases significantly to 96°C. This observation suggests that the performance of epoxy-asphalt binders surpasses that of the unmodified original asphalt binder. It is worth noting that higher values of $G^*/\sin\delta$ correspond to increased resistance against rutting.

The conclusion drawn from the study is that asphalt, being a thermoplastic material, has limitations in applications where excessive heat is involved. However, by blending epoxy resin with asphalt, a new material is obtained, offering enhanced heat resistance and higher strength. The dynamic shear rheometer testing shows that epoxy-asphalt with 20 wt % epoxy resin has a significantly higher complex modulus compared to the original asphalt binder. Moreover, the presence of epoxy resin significantly affects the phase angle, with a higher epoxy resin content leading to more pronounced effects. In addition to increased resistance to permanent deformation at high temperatures, epoxy resin also improves strain recovery and reduces the temperature sensitivity of asphalt.

2.2.4 Cong *et al*. (2011)

Compared to conventional pavement, steel bridge deck pavement experiences substantially greater deformation and higher temperatures. The epoxy resin employed in this study was diglycidyl ether of bisphenol A, with an epoxy value of 0.52 mol/100g. Epoxy-asphalt blends with epoxy resin contents of 0%, 20%, 35%, and 50% by weight, which also included the curing agent, were prepared, respectively. To tackle the challenges posed by these conditions, modified asphalt concrete utilizing epoxy asphalts was implemented for paving the steel bridge deck. The primary objective of this research was to investigate the influence of varying epoxy resin contents on the fatigue life and creep properties of the epoxy asphalt mixture.

The study involved subjecting the epoxy asphalt mixtures to an indirect tension fatigue test under different stress levels to evaluate their fatigue characteristics. Additionally, a static creep test, comprising loading and recovery periods, was conducted to assess the behavior of the asphalt mixture. The results indicated that the inclusion of epoxy resins in the asphalt substantially improved the fatigue life and recovery elasticity, thereby enhancing the overall fatigue properties.

Figure 7 shows findings from the indirect tensile fatigue test conducted on asphalt mixtures with varying epoxy resin contents, analyzed at different stress levels corresponding to their fatigue life. In comparison to the control mixture (containing 0 wt % epoxy resin), the epoxy asphalt mixtures exhibit a substantial increase in the number of repetitions to failure (Nf). For instance, at a stress level of 0.369 MPa, the Nf values for three epoxy asphalt mixtures are significantly higher—18 times higher for a 20 wt % epoxy resin content, 54 times higher for a 35 wt % epoxy resin content, and 74 times higher for a 50 wt % epoxy resin content—compared to the Nf value of the control mixture. These results clearly demonstrate that epoxy resin can greatly enhance the fatigue properties of asphalt mixtures.

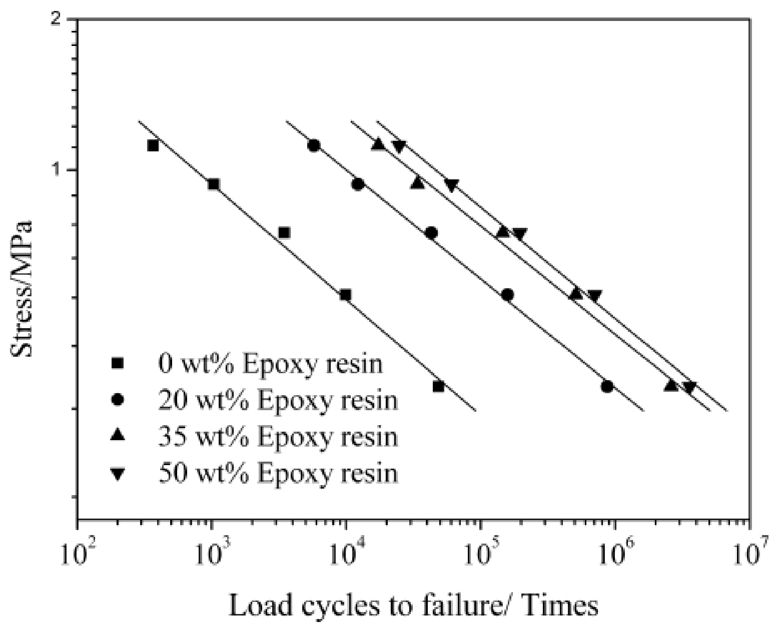


Figure 7. Fatigue life of epoxy asphalt mixtures (Cong et al., 2011).

One possible explanation is that epoxy resin can effectively absorb and distribute the concentrated stress generated during fatigue loading, thus delaying the development of micro-cracks and consequently postponing damage to the asphalt mixtures. Furthermore, at lower stress levels, elastic strain plays a dominant role in the fatigue process, and this elastic strain recovers after unloading. As stress levels increase, plastic deformation becomes the dominant factor. Epoxy resin can enhance the elasticity of asphalt, leading to a significant improvement in the fatigue properties of the asphalt mixture, especially at lower stress levels.

In comparison to the control asphalt mixture, where the epoxy resin content is 0 wt %, the inclusion of epoxy resin significantly enhances the loading repetitions to failure (Nf) in epoxy asphalt mixtures. Furthermore, an increase in epoxy content corresponds to an extension in fatigue life, particularly when the epoxy resin content is below 50 wt %.

2.2.5 Kang *et al*. (2015)

The paper explores epoxy asphalt binder, a paving material distinguished by its unique thermosetting characteristics in contrast to conventional modified asphalt binders. In evaluating its properties, the researchers adopted a standard test method commonly used to assess the tensile properties of plastics. However, the relationships between these tensile properties and crucial road-paving attributes, such as temperature stability and durability, remain uncertain.

To investigate the characteristics of epoxy asphalt binder, the researchers conducted dynamic shear rheometer (DSR) tests, enabling a comparison of its rheological performance with that of the base asphalt binder and Styrene-Butadiene-Styrene (SBS) modified asphalt binder. Furthermore, they utilized fluorescence microscopy to track the microscopic structural changes in epoxy asphalt and employed Scanning Electron Microscope (SEM) to examine the fracture profile of epoxy asphalt at a temperature of -40 °C.

Figure 8 illustrates the strains exhibited by the three binders over the first and last five cycles, presented in logarithmic coordinates, under the conditions of 60 °C and 300 Pa. The strains of the base asphalt, depicted by the black lines, displayed rapid and substantial increases, ranging from circle 0.6 to approximately 70. This suggests that the base asphalt is highly susceptible to quick and pronounced deformation under these conditions, which could potentially lead to pavement deterioration. In contrast, the strains of SBS modified asphalt, indicated by the blue lines, were significantly smaller, approximately one order of magnitude lower, with values ranging from 0.5 to nearly 4.

Additionally, the elasticity recovery of SBS modified asphalt at the beginning of the test reached an impressive 96%, surpassing that of the base asphalt. This indicates that SBS modified asphalt exhibits superior resistance to rutting compared to the base asphalt. On the other hand, the strains of epoxy asphalt, represented by the red lines, remained nearly unchanged from their initial state throughout the test, in contrast to the other two binders. The absolute strains observed in epoxy asphalt remained below 0.01, representing only 0.1% of the strains observed in SBS modified asphalt. Consequently, it can be inferred that epoxy asphalt behaves in a completely elastic manner under these conditions and demonstrates superior resistance to rutting in comparison to the other two binders.

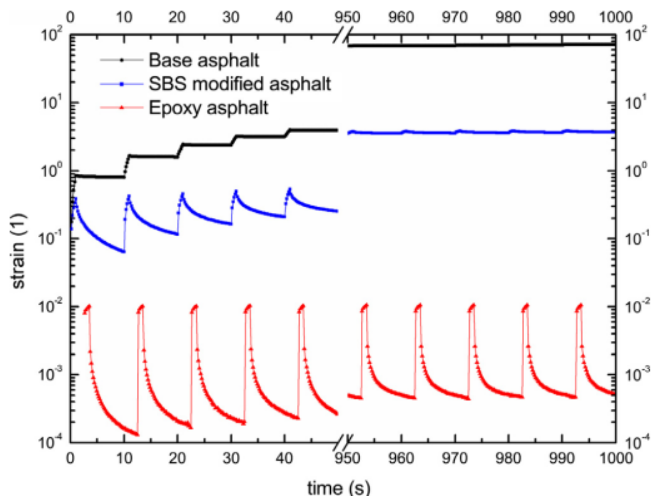


Figure 8. Creep and recovery curves of the three binders (60°C, 300 Pa) (Kang et al., 2015).

DSR tests were conducted to evaluate the rheological performance of epoxy asphalt binder with that of the base asphalt binder and SBS modified asphalt binder. The results reveal that the creep strains exhibited by epoxy asphalt are significantly lower, ranging from 10^{-7} to 10^{-2} times those of the base asphalt and 10^{-6} to 10^{-2} times those of SBS modified asphalt. In both creep and recovery experiments, epoxy asphalt consistently displays complete elasticity even after 100 loading-unloading cycles, underscoring its outstanding resistance to rutting. In contrast, the base asphalt binder and SBS modified asphalt binder behave like Newtonian liquids under the same conditions.

A DSR temperature sweep demonstrates that epoxy asphalt exhibits remarkable thermal stability over a wide temperature range, from -30°C to 120°C. These experiments establish the exceptional rheological properties of epoxy asphalt, as acknowledged by pavement design and construction experts, making it a highly promising material for various applications. To understand the underlying reasons for epoxy asphalt's remarkable properties, a comprehensive investigation was conducted using DMTA, SEM, and fluorescence microscopy. This analysis revealed the presence of two transition peaks at -22°C and 28°C, imparting toughness at low temperatures and elasticity at high temperatures to the material. The excellent rheological properties of epoxy asphalt are attributed to the formation of unique "bimodal networks," as confirmed through microscopy and viscosity/modulus analysis during the curing reaction. Consistency among all the test results, including DSR temperature sweep, DMTA temperature sweep, creep, and creep and recovery, suggests a promising and efficient alternative method for characterizing temperature sensitivity in base asphalt binders or modified asphalt binders through a wide-range temperature sweep using DSR.

In conclusion, epoxy asphalt exhibits superior rheological properties compared to other binders known to the authors. However, its widespread application is hindered by complex construction technology, prompting ongoing efforts to simplify the construction process.

2.2.6 Cong *et al*. (2015)

This study delves into the rheological and fatigue properties of epoxy asphalt binder, a thermosetting polymer-modified substance employed in asphalt concrete due to its ability to maintain stability at high temperatures and resist cracking and water damage. The performance of the binder is assessed using the dynamic shear rheometer (DSR) test with column specimens. To evaluate the binder's characteristics, the time-temperature superposition principle (TTS) is implemented, enabling the calculation of rheological properties at different temperatures and frequencies. Furthermore, mathematical models are utilized to elucidate the material's behavior.

In the dynamic experiment, a graphical representation called a black diagram is generated. This diagram illustrates the magnitude (or norm) of the complex shear modulus (|G*|) against the phase angle (δ). It is worth noting that the plot does not include frequency or temperature, thus encompassing all dynamic data within a single graph. This eliminates the necessity for manipulating raw data through time-temperature superposition (TTS). A seamless and uninterrupted curve within the black diagram signifies a dependable time-temperature equivalence, indicating consistent behavior across varying conditions. Conversely, a disjointed curve in the black diagram suggests a breakdown of TTS. This could arise due to factors such as a high wax content in bitumen, a bitumen with a high asphaltene structure, or a bitumen with substantial polymer modification. For the specific case of epoxy asphalt binder, Figure 7 illustrates a continuous curve, affirming the reliable application of the time-temperature equivalence principle in this typical scenario.

The study finds that epoxy asphalt binder demonstrates superior elastic/viscous capabilities compared to other binders. The fatigue properties are examined through stress-controlled tests, revealing the effect of temperature and stress level on fatigue life. Predictive fatigue models are proposed to estimate the binder's fatigue performance. The results contribute valuable insights into the properties of epoxy asphalt binder and offer potential applications in pavement engineering.

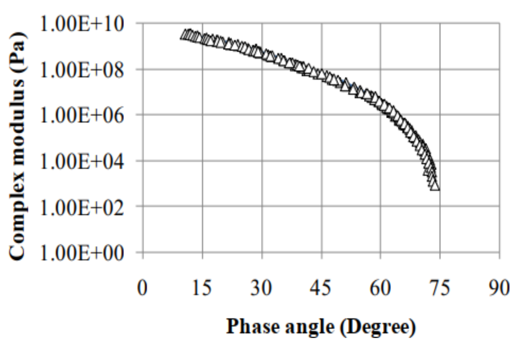


Figure 9. Black Diagram for the Epoxy Asphalt Binder (Cong et al., 2015).

2.2.7 Xue & Qian. (2016)

In order to elevate the performance of epoxy asphalt concrete (EAC), we formulated a variant known as fiber-modified epoxy asphalt concrete (FEAC), which integrates mineral fibers. A comprehensive examination of FEAC properties was undertaken, encompassing a range of fiber contents and lengths, employing both viscosity and direct tensile tests. Furthermore, we scrutinized the performance of FEAC across varying fiber contents through an array of laboratory experiments.

Upon observing Figure 10, it becomes evident that the viscosity of FEAC amplifies progressively over time, with a notable acceleration occurring once the viscosity surpasses approximately 1000 mPa s. Notably, the inclusion of mineral fibers serves to heighten the viscosity of FEAC, with the augmentation becoming more pronounced as the fiber content increases. Additionally, it's important to note that FEAC manifests as a thermoset material; once it achieves complete curing, the resulting hardness renders it unsuitable for paving and compacting. The velocity at which FEAC cures is intimately tied to the rate of viscosity growth. As such, the rate of viscosity increase assumes a position of paramount importance for FEAC.

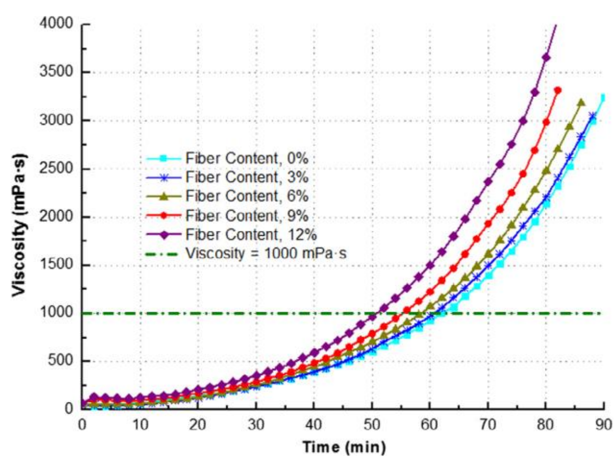


Figure 10. Viscosity of FEA at different fiber contents (fiber length = 2 mm) (Xue & Qian., 2016).

Mineral fiber enhances the viscosity of FEA and reduces the permissible construction time of FEAC, posing higher demands and more challenges to the construction process.

However, when using a fiber length of 8 mm, the allowable construction time of FEAC is less than 50 minutes, failing to meet the performance requirement of FEA. Through direct tensile testing, we observed substantial improvements in the tensile strength and fracture elongation of FEA by incorporating mineral fiber with the appropriate length and content.

2.2.8 Yu *et al*. (2016)

Epoxy asphalt has found widespread application in bridge deck pavement. However, its construction process poses several challenges, such as high construction temperature, handling high viscosity, and limited construction time, all of which ultimately affect the pavement's performance. To address these issues, this study proposes the use of foamed epoxy asphalt. The epoxy resins provided was E-51.

The foamed epoxy asphalt samples were prepared in the laboratory using a foaming machine with varying foaming water content. Subsequently, a comprehensive evaluation was conducted, including viscosity-temperature performance, failure temperature, ZSV at 60℃, temperature sensitivity, and storage stability, assessed through rotational viscometer, temperature sweep, frequency sweep, and storage tests. Additionally, the morphological and chemical changes of non-foamed and foamed epoxy asphalt with different foaming water content were characterized using fluorescence microscopy and infrared spectroscopy.

The temperature at which failure occurs, corresponding to a $G^*/\sin\delta$ value of 1.0 kPa, can be derived from the outcomes depicted in Figure 11. Clearly, it is evident that the failure temperatures for foamed epoxy asphalt are comparably lower when contrasted with those of epoxy asphalt without foaming.

Furthermore, with an increase in the amount of water used for foaming, the failure temperature of foamed epoxy asphalt experiences a gradual decline. This behavior is greatly influenced by the foaming mechanism. A higher expansion ratio leads to a deceleration in the chemical interaction between epoxy resins and curing agents, resulting in reduced resistance to rutting in foamed epoxy asphalt compared to its non-foamed counterpart. However, this effect also induces a decrease in the system's viscosity, thereby moderating the pace of the chemical reaction. This lowered viscosity brings benefits by facilitating the creation of a cross-linked network, extending the permissible construction window, and overall enhancing the performance of epoxy asphalt.

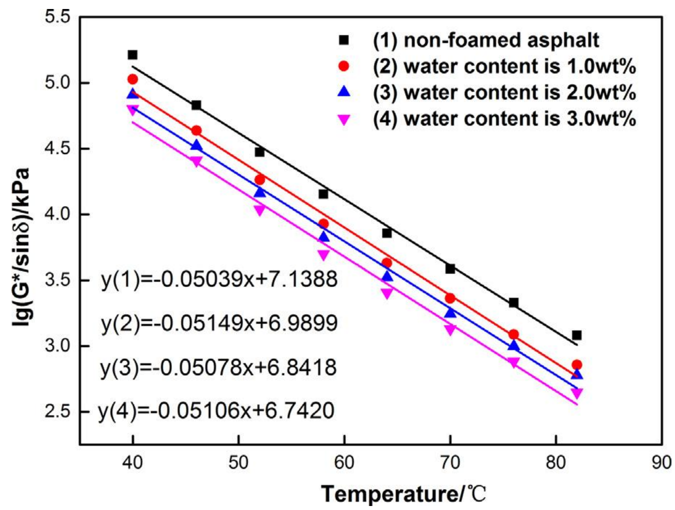


Figure 11. G*/sinδ results of foamed epoxy asphalt (Yu et al., 2016).

The research findings demonstrate that the incorporation of foaming water heightens the workability of mixtures involving foamed epoxy asphalt binder, and it prolongs the permissible timeframe for construction activities. In comparison to non-foamed epoxy asphalt, foamed epoxy asphalt strikes a balance between failure temperature and viscosity at 60℃, while simultaneously enhancing its responsiveness to temperature changes and its storage stability. Notably, the quantity of foaming water exerts a noticeable influence: its increase correlates with a reduction in failure temperature, viscosity at 60℃, and storage stability to a certain extent, while also augmenting temperature susceptibility.

2.2.9 He *et al*. (2021)

Polyurethane/epoxy resin modified asphalt (PEA) holds significant promise as an ideal adhesive intermediary for steel-ultra high-performance concrete (UHPC) composite bridge deck pavements. This investigation is centred on a thorough examination of the curing mechanism of PEA, a process analyzed through FTIR and fluorescence microscopy (FM) evaluations. Additionally, a comprehensive assessment of the mechanical and engineering properties of PEA is carried out, with comparisons drawn against those of styrene-butadiene-styrene (SBS) modified asphalt. This comprehensive analysis encompasses a range of evaluations, including viscosity measurements, tensile strength tests, pull-out resistance assessments, and dynamic shear rheometer (DSR) tests.

The G* of all five materials demonstrates an upward trend with increasing frequency. This phenomenon occurs because at higher frequencies, the loading time for a single cycle becomes shorter, leading to reduced shear deformation within the binders. Consequently, the complex modulus registers an increase. Among the tested frequencies, the complex modulus of PEAs stands out as higher and exhibits a slower rate of increase compared to SBA and BA. This observation indicates that the incorporation of polyurethane/epoxy resin into the asphalt significantly enhances its resistance to deformation and reduces its susceptibility to changes in loading frequency.

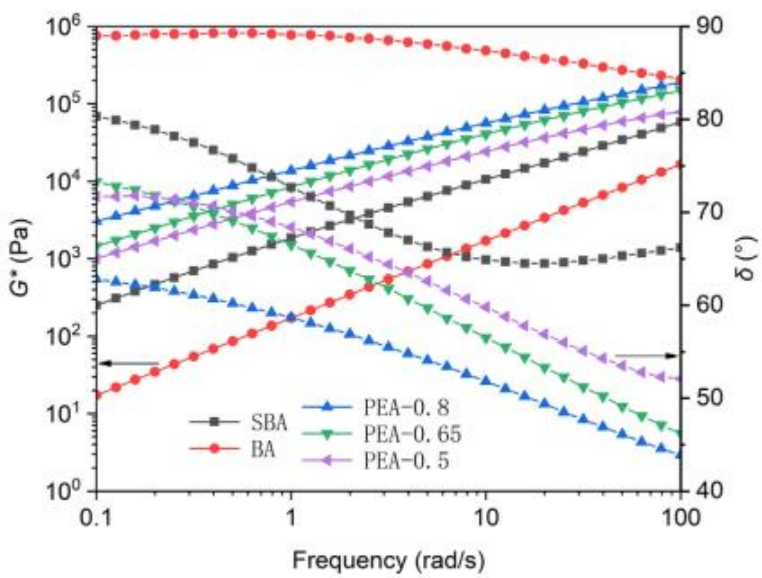


Figure 12. Complex modulus and phase angle with frequency curves of SBA, BA, and PEAs (He et al., 2021).

At a frequency of 0.1 rad/s, the phase angle of SBA measures 80.3°, while the phase angle of BA is nearly 89°, signifying a more viscous state. Conversely, the phase angles of PEA-0.5, PEA-0.65, and PEA-0.8 are recorded at 71.7°, 73.3°, and 62.8°, respectively, which are considerably lower than that of BA. Furthermore, the phase angle of PEAs exhibits a more rapid decrease with increasing frequency when compared to BA. These findings suggest that the inclusion of polyurethane/epoxy resin significantly increases the proportion of elastic components within the asphalt, thereby enhancing its ability to withstand permanent deformation.

To evaluate the high-temperature stability of PEA, a series of tests including temperature sweeping, frequency sweeping, and Multiple Stress Creep and Recovery (MSCR) tests were conducted. The results of these assessments unequivocally demonstrate that the addition of polyurethane/epoxy resin substantially augments the presence of elastic components in PEA, resulting in improved resistance to deformation at elevated temperatures.

2.2.10 Bahmani *et al*. (2022)

The utilization of adjusted bitumen has proven to be a reliable strategy for reinforcing asphalt's resilience against moisture-related issues. In this investigation, a combination of mechanical methodologies and micro-mechanism analyses is employed to delve into the impact of epoxy resin-modified bitumen on the susceptibility of asphalt mixtures to moisture. The specific epoxy resin employed in this study belongs to the category of Bisphenol-A Diglycidyl Ether, commercially identified as YD128. The hardener selected for this experimentation is Cyloalphatic Amine, known in the commercial sphere as KH-816. The study encompasses the examination of six variations of bitumen samples, ranging from the foundational bitumen to modifications involving 1% to 5% epoxy resin content.

In Figure 13, the impact of epoxy resin-modified bitumen on the Indirect Tensile Strength (ITS) values of asphalt mixtures is illustrated. The asphalt mixtures were prepared using varying percentages of epoxy resin (ranging from 0% to 5%) mixed with either limestone or siliceous aggregates, under both wet and dry conditions.

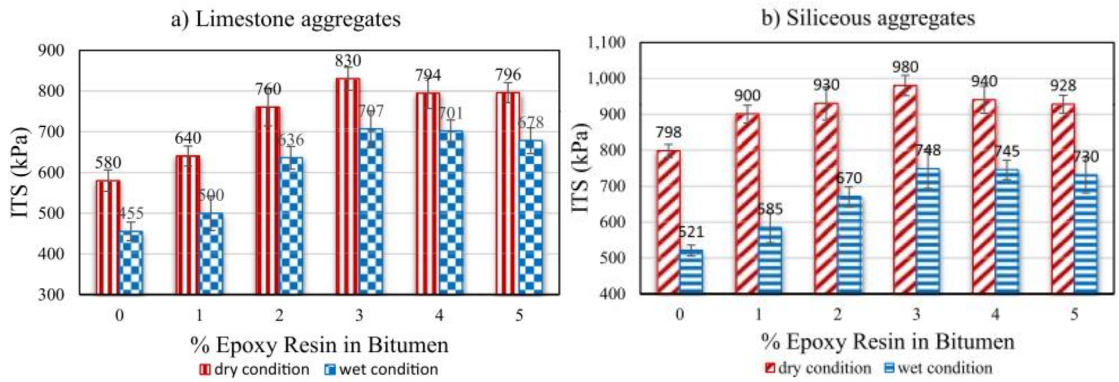


Figure 13. ITS values for asphalt mixture sample containing modified asphalt with epoxy resin with (a) Limestone or (b) Siliceous aggregates (Bahmani et al., 2022).

The findings illustrate an enhancement in the ITS values of both dry and wet asphalt samples due to the inclusion of epoxy resin. Specifically, every asphalt mix containing epoxy resin demonstrates markedly higher ITS values when compared to the mixture with the standard bitumen. Within the combinations examined, asphalt mixtures containing 3% epoxy resin displayed the highest ITS values for both limestone and siliceous aggregates, irrespective of the testing conditions being wet or dry.

2.3 Summary and Findings of Literature Review

Researchers have evaluated the performance of epoxy modified asphalt. Performance indicators such as rutting resistance, fatigue life, moisture susceptibility, and adhesion strength have been assessed to understand the behavior of epoxy asphalt under different loading and environmental conditions. Overall, studies have reported favorable results, indicating that epoxy asphalt can significantly improve the performance of asphalt pavements and extend their service life.

Epoxy asphalt, as a polymer-modified asphalt, offers numerous advantages over conventional binders, including improved mechanical properties, durability, and adhesion. It has demonstrated promising performance in various applications, such as bridge decks, airports, and high-traffic pavements. Literature review shows that the epoxy dosages used are typically quite high (20 to 60% by weight of binder). Highway pavement may require a much less dosages of practical applications & cost-effectiveness. Further research is needed to understand the properties of EMA binder at high, intermediate, and low temperatures.

3 MATERIALS AND METHODOLOGY

3.1 Aggregates

In the field of building and construction, aggregate materials play a crucial role in various applications. These materials are combined with substances like cement, bitumen, lime, gypsum, or other adhesives to create concrete or mortar. Aggregates contribute essential attributes to the final product, including volume, stability, resistance to wear or erosion, and other desired physical properties. Commonly utilized aggregates encompass a range of materials such as sand, crushed or broken stone, gravel (pebbles), crushed blast-furnace slag, boiler ashes (clinkers), burned shale, and burned clay. Fine aggregate typically includes components like sand, crushed stone, or crushed slag screenings, while coarse aggregate comprises materials such as gravel (pebbles), fragments of broken stone, slag, and other coarser substances. These aggregates are fundamental building blocks in construction, contributing to the structural integrity and durability of various construction materials and structures. In this study, the aggregates used were graded as per the requirements of Bituminous Concrete-2(BC-2 of 13.2 mm nominal maximum aggregate size). BC-2 is commonly used as the top wearing course on flexible pavements in India.

3.1.1 Grain size analysis of BC-2

Sieves of different sizes as per IRC 111-2009 were used: 19mm, 13.2 mm, 9.5mm, 4.75mm, 2.36mm, 1.18mm, 600μm, 300μm, 150μm, and 75μm. Then the aggregates were washed and dried. Then they were placed. Corresponding to the BC-2 gradation, the aggregates were sieved and fractionated into various size fractions as shown in Table 2. The gradation used is shown in figure 14. For one Marshall sample of standard dimensions (100mm diameter & about 63.5mm height), aggregates were sieved for a batch size of 1150g.

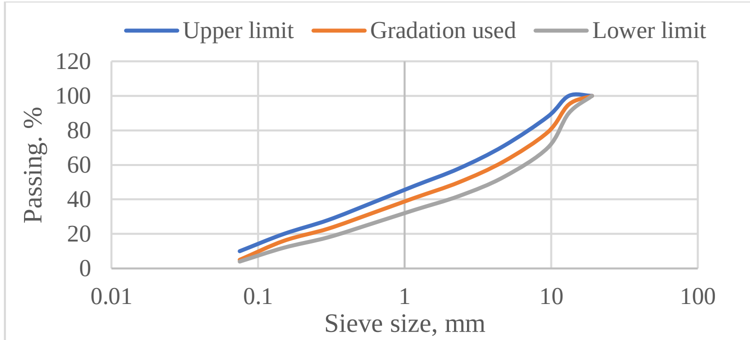


Figure 14. Graphical representation of grain sieve analysis of BC-2

Table 2. Calculation of aggregates for one 1150 g batch of BC-2

Sieve size, mm	% Passing	% Retained	Aggregate quantity(g)
19	100	0	0
13.2	95	5	57.5
9.5	79	16	184.5
4.75	62	17	195.5
2.36	50	12	138
1.18	41	9	103.5
0.6	32	9	103.5
0.3	23	9	103.5
0.15	16	7	80.0
0.075	5	11	126.5
Pan			57.5

3.2 Basic tests on aggregates:

3.2.1 Los Angeles Abrasion Test (IS: 2386-Pt 4)

Figure 15. Los Angeles Abrasion Test

Procedure:

- The test sample comprises cleaned aggregates that have been thoroughly dried in an oven operating within a temperature range of 105℃ to 110℃. For this investigation, Grade C aggregates were selected, involving the use of 2.5 kg of aggregates ranging in size from 10 to 6.3 mm, and an additional 2.5 kg of aggregates sized between 6.3 to 4.75 mm.
- A representative 5 kg sample of Grade C aggregates is necessary for the testing procedure.
- Choose the abrasive charge (i.e., 8 steel balls).
- Open the protective cover of the testing apparatus.
- Place the aggregates and the designated steel balls into the cylinder.
- Ensure a tight seal by firmly closing the protective cover.
- Initiate the rotation of the machine at a consistent speed, maintaining a steady range of 30 to 33 revolutions per minute (rpm).
- Allow the testing apparatus to complete 500 revolutions when dealing with Grade C aggregates.
- Once the specified number of revolutions is reached, cease the operation of the machine.
- Gently remove the dust cover that encases the cylinder.
- Extract the aggregate materials from the cylinder.
- Separate and isolate the steel balls from the extracted aggregates.
- Sieve the aggregate material using a 1.70 mm IS sieve.
- Thoroughly clean the material that surpasses the 1.70 mm size threshold.
- Thoroughly dry the washed aggregates in the oven until a consistent weight is achieved.
- Precisely weigh the dried aggregates using a scale capable of measuring to the nearest gram.

- Determine the percentage of material loss by comparing the initial weight of the sample to its final weight following the abrasion test.

Table 3. Observation table of Los Angeles Abrasion Test

Weight of the specimen taken, W_1 (g)	5000
Weight of aggregates passing on 1.70 mm IS sieve, W_2 (g)	1060
Abrasion value :(W_2/W_1) *100	21.2%

3.2.2 Impact Test (IS: 2386-Pt 4)

Figure 16. Impact Test

Procedure:

- The test specimen comprises aggregates ranging from 10 mm to 12.5 mm in size. These aggregates are subjected to drying by heating at temperatures of 100°C to 110°C for a duration of 4 hours, followed by cooling.
- Material sieved using 12.5 mm and 10 mm mesh sieves, designated for analysis per Indian Standards (IS).

- Carefully pour the aggregates into the measuring cylinder until it's approximately one-third full.
- Delicately consolidate the material by applying precisely 25 controlled taps using the rounded tip of the tamping rod.
- Repeat the process by adding two more layers in a similar manner until the cylinder is completely filled.
- Level off any excess aggregates protruding from the top of the cylinder.
- Find the precise weight of the aggregates, recorded to the nearest gram (W_1).
- Place the impact apparatus on a solid, level surface, ensuring that it is steady and that the hammer guide columns are perfectly vertical.
- Securely attach the cup at the base of the apparatus. Place the entire test sample within the cup and compact it by gently tapping the material with the tamping rod 25 times.
- Lift the impact hammer until its lower surface is positioned 380 mm above the aggregate sample's surface in the cup. Allow the hammer to fall under gravity on the aggregates. Repeat this action 15 times, with each fall spaced at a minimum interval of one second.
- Remove the crushed aggregates from the sieve them using a 2.36 mm IS sieve. Weigh the portion that remains on the sieve.
- Record the observations in the provided table and use the data to calculate the aggregate impact value.

Table 4. Observations table of Impact Test

Total Initial Sample Weight (W_1), (g)	344
Weight of Portion Passing 2.36 mm Sieve (W_2),(g)	60
Aggregate Impact Value, calculated as (W_2/W_1)*100	17.44%

3.2.3 Shape Test (IS: 2386-Pt 1)

Figure 17. Thickness and length gauge

Procedure:

- The sample is passed through IS sieves of sizes 20, 16, 12.5, 10, and 6.3 mm.
- A minimum of 200 pieces from each fraction being tested are collected and their weight is measured (W_1 gm).
- Employ the standard thickness gauge to isolate the flaky components.
- Weigh the flaky material that passes through the designated gauge with precision, ensuring an accuracy of at least 0.1 percent of the total test sample.
- Utilize the standard-length gauge to separate the elongated components.
- Weigh the elongated material that remains on the designated gauge with meticulous accuracy, maintaining at least 0.1 percent precision of the entire test sample.

Table 5. Observation table of Shape test

Sieve size, mm	Pieces	Total weight, W_1 (g)	Weight of flaky aggregate, W_2 (g)	Weight of non-flaky aggregate, W_3 (g)	Weight of elongated aggregate, W_4 (g)
20-16	200	1154	232	922	90
16-12.5	200	700	82	618	166
12.5-10	200	360	76	284	42
10-6.3	200	230	18	212	46

Calculation:

Combined Index of 20-16 mm =$((W_2/W_1) + (W_4/W_3)) * 100$ = 10.26%

Combined Index of 16-12.5 mm =$((W_2/W_1) + (W_4/W_3)) * 100$ = 38.57%

Combined Index of 12.5-10 mm =$((W_2/W_1) + (W_4/W_3)) * 100$ = 35.98%

Combined Index of 10-6.3 mm =$((W_2/W_1) + (W_4/W_3)) * 100$ = 29.52%

Average = 28.58% < 35% ok

3.2.4 Specific Gravity of Aggregate

Specific gravity is determined by calculating the ratio between the weight of a specific volume of a material and the weight of the same volume of water. In accordance with IS-2386(3) standards, various materials including coarse aggregate, fine aggregate, stone dust, cement, and asphalt are subjected to specific gravity tests to evaluate their specific gravity values. These tests provide essential information about the density and composition of these materials, aiding in their characterization and assessment for various construction and engineering purposes.

a. Specific Gravity of Coarse Aggregate

The specific gravity of an aggregate is regarded as an indicator of the material's strength or quality. Generally, aggregates with a lower specific gravity tend to be weaker compared to those with a higher specific gravity. This characteristic is valuable for the overall identification and assessment of aggregates, assisting in understanding their inherent strength and quality.

Procedure

- Take a sample of about 2 kg of aggregate. Do not use aggregate that has been heated in a lab.
- The clusters are washed well to get rid of the smaller dust particles on their surface.

- Washed aggregates in basket submerged in 22°C-32°C purified water, 5 cm above basket top, as shown in Figure 18.
- Release trapped air by raising basket 25 mm above water, allowing 25 drops to fall (1 drop/second). Submerge gravel-filled basket for 24 hours.
- 24 hours later, weigh in 22°C to 32°C water (W_1), drain, and transfer aggregates to dry cloth.
- Then, the empty basket is put back into the water, 25 drops are added, and the basket is weighed in water. (W_2)
- Aggregates dried on cloth, shifting if needed, away from sunlight and heat until fully dry.
- After the first 10 minutes, you can use unheated air to speed up the process for rocks that are hard to dry and weigh. (W_3)
- The aggregates are then put in the small tray and baked in an oven at 100° C to 110° C for 24 hours.
- After 24 hours, the pieces are taken out of the oven, put in an airtight container to cool, and then measured. (W_4)

Figure 18. Buoyancy balance

The specific gravity of coarse aggregate	$\frac{(w_2 - w_1)}{(w_2 - w_1) - (w_3 - w_4)}$	2.66

b. Specific Gravity of Fine Aggregate:

The Specific Gravity of fine aggregate is a metric defined as the ratio of the Weight of the Fine Aggregate to the Weight of an equal volume of water. This measure provides valuable insights into the strength and quality of the material. Figure 19 provides a visual representation of a Pycnometer, which is an instrument commonly used to determine the specific gravity of materials like fine aggregate.

Figure 19. Pycnometer

Procedure:

- Get a clean and dry pycnometer and determine its empty weight (W_1 g).
- Weigh approximately 1 kg of clean fine aggregate (finer than 6.3mm) in pycnometer (W_2 g) for specific gravity calculation.
- Add distilled water to the pycnometer containing the aggregate sample, maintaining a temperature of 27°C, so that the sample is just submerged.
- Immediately after submersion, eliminate any trapped air from the sample by shaking or rotating the pycnometer. Cover the hole at the top of the sealed pycnometer with a finger.
- Clean the exterior of the pycnometer. Now, fill the pycnometer with water until it reaches the hole at the top. After confirming that no trapped air remains, weigh it (W_3 g).
- Transfer the aggregate out of the pycnometer, ensuring complete transfer. Clean the pycnometer thoroughly.

- Fill pycnometer with distilled water, remove air, weigh (W4 g).
- For mineral filler, use specific gravity bottle, fill one-third, follow similar procedure for specific gravity determination.

The specific gravity of filler	$\frac{(w_2 - w_1)}{(w_2 - w_1) - (w_3 - w_4)}$	2.6
The specific gravity of fine aggregate	$\frac{(w_2 - w_1)}{(w_2 - w_1) - (w_3 - w_4)}$	2.88

3.3 Bitumen

3.3.1 Introduction

Bitumen is a highly viscous, black or dark-coloured semi-solid material that is commonly known as asphalt or asphalt binder. It is a vital component used in various construction and infrastructure projects around the world. Bitumen is primarily derived from crude oil through a process called fractional distillation.

One of the key reasons for the importance of bitumen is its use in road construction. It is the main binding agent in asphalt concrete, commonly used for surfacing roads, highways, and airport runways. Bitumen's sticky nature allows it to hold together aggregates like gravel, sand, and crushed stone, forming a durable and flexible pavement surface. It provides excellent resistance to heavy traffic loads, weathering, and wear and tear.

Another significant application of bitumen is in the roofing industry. It serves as a waterproofing agent in the production of roofing materials such as shingles, sheets, and membranes. Bitumen's water-resistant properties make it ideal for protecting buildings and structures from water damage.

Furthermore, bitumen finds use in the construction of waterproofing systems for tunnels, bridges, dams, and reservoirs. Its ability to create a tight seal helps prevent the ingress of water, protecting the structural integrity of these infrastructures.

Additionally, bitumen is employed in the manufacturing of various industrial products. It serves as a raw material for producing adhesives, sealants, corrosion-resistant coatings, electrical insulation materials, and soundproofing products.

From an environmental standpoint, bitumen also plays a role in sustainable construction practices. It can be recycled and reused, reducing the demand for new bitumen and minimizing waste.

For my research program, VG 30 Bitumen is been used.

3.3.2 Preparation of epoxy modified asphalt (EMA)

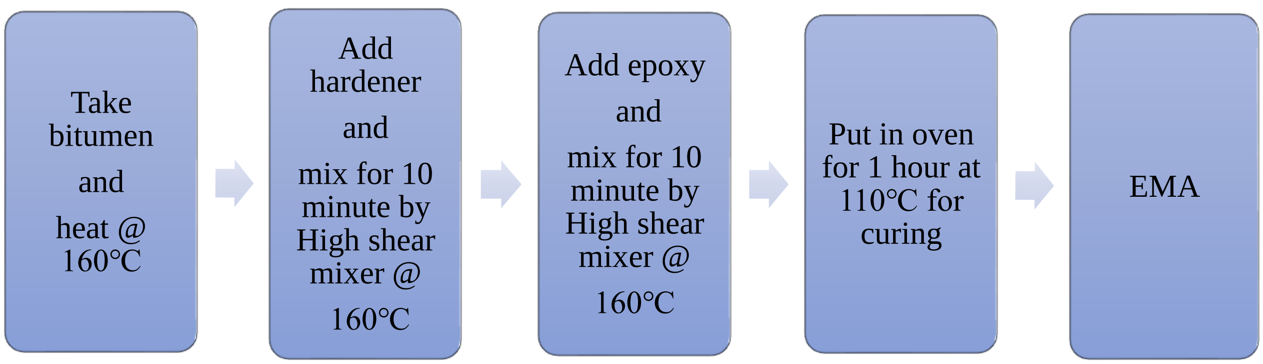


Figure 20. Flowchart for EMA preparation.

Procedure to prepare epoxy-modified asphalt (with VG 30 bitumen):

- The modifier is prepared with two components: (1) epoxy and (2) hardener (curing agent). The epoxy and hardener have to be combined in a ratio 5:3(Bahmani et al. (2022)).
- The base (unmodified) bitumen (VG 30) is conditioned in the oven at 160 °C.
- The table below shows the quantities of epoxy and hardener corresponding to the selected dosages of the modifier (1%, 2%, 3%, and 4%).

Table 6. Quantities of epoxy and hardener corresponding to the selected dosages of the modifier (1%, 2%, 3%, and 4%).

Sn No.	Base bitumen (g)	Modifier dosage, %	Epoxy (g)	Hardener (g)	Total (epoxy + hardener)
1	300	1	1.9	1.1	3
2	300	2	3.8	2.3	6
3	300	3	5.6	3.4	9
4	300	4	7.5	4.5	12

The procedure to prepare modified asphalt with 300 g base bitumen is as follows:

- Weigh 300 g base bitumen in a 500 ml container and place it in an oven maintained at 160 °C.
- Add the required quantity of hardener to the base bitumen and use the high shear mixer to blend the hardener with the base bitumen for 10 minutes. Gradually, increase the rpm of the high shear mixer to 8000 rpm.
- Figure 21 shows the high shear mixer (Make:1 KA T18).

Figure 21. High shear mixer

- Now, add the required quantity of epoxy to the mixture prepared above, and continue blending in the same way as above for 10 minutes.

- At all times, the bitumen container must be placed on a hot plate with frequent checks of the temperature to ensure that the blending takes place at 160 ± 5 °C.
- Maintain an oven at 110 °C. As soon as the blending is completed, place the modified bitumen in the oven at 110 °C for 1 hour for curing of the epoxy.
- Take out the cured and blended bitumen from the oven and keep it at room temperature (approx. 25 °C) for 24 hours.
- Now, the bitumen EMA can be used for further testing and evaluation.

3.4 Basic Tests on Bitumen

3.4.1 Penetration test (IS: 1203-1978)

The measurement assesses the bitumen's degree of hardness or softness, gauging the vertical depth, in tenths of a millimetre, to which a standardized loaded needle can penetrate within a span of 5 seconds. The Bureau of Indian Standards (BIS) has established uniformity in equipment and testing protocols through IS: 1203 (1978). This involves a penetrometer comprising a needle assembly with a total mass of 100 g, along with a mechanism for controlled release and locking at any position.

For the test, the bitumen was rendered pourable and meticulously stirred until homogeneous. It is then poured into containers, ensuring a depth of at least 15 mm over the projected penetration distance. Conducted at a specific temperature of 25 °C, it's crucial to recognize that the penetration value is substantially influenced by factors like pouring temperature precision, needle size, applied needle load, and test temperature.

In classification, a bitumen grade denoted as 40/50 signifies that the penetration value ranges from 40 to 50 tenths of a millimetre under standard test conditions. In regions with elevated temperatures, a preference exists for lower penetration grades. Refer to Figure 22 for an illustrative depiction of the penetration test setup.

Figure 22. Penetration test equipment

3.4.2 Softening Point (IS 1205-1978)

The softening point to the temperature at which bitumen achieves a specific level of softening as per the test's criteria. This examination is carried out using the Ring and Ball apparatus. An arrangement involves suspending a brass ring containing a bitumen test specimen within a liquid medium such as water or glycerine, which is maintained at a designated temperature. Atop the bitumen sample, a steel ball is positioned, and the liquid medium is then gradually heated at a rate of 5 °C per minute. The temperature is recorded when the softened bitumen makes contact with a metal plate placed at a predetermined distance below.

Typically, a higher softening point signifies reduced susceptibility to temperature variations and is favored in regions with elevated temperatures. Refer to Figure 23 for an illustration of the equipment used to determine the softening point.

Figure 23. Softening Point test equipment

3.4.3 Ductility Test (IS:1208-1978)

Ductility is a distinctive quality of bitumen that grants it the ability to undergo substantial deformation or elongation. This property is quantified as the distance in centimeters to which a standard specimen can be stretched without fracturing, forming a resulting briquette with precisely 1 square centimetre dimensions. The procedure involves several steps: the bitumen sample is heated, poured into a mold assembly, and positioned onto a plate. Following cooling in ambient air and subsequently in a water bath at a temperature of 27°C, excess bitumen is meticulously removed, and the surface is smoothed using a heated knife.

The assembled mold containing the sample is then left within the water bath of the ductility machine for approximately 90 minutes. Afterward, the mold's sides are carefully detached, securing clips to the machine, which is then set into motion. The distance achieved before the sample thread ruptures is recorded as the ductility value in centimetres. This value can be influenced by variables such as pouring temperature, testing temperature, and the rate of elongation.

The Bureau of Indian Standards (BIS) stipulates a minimum ductility requirement of 73 cm. Figure 24 provides an illustration of the apparatus employed in the ductility test. Table 7 shows results of basic test of bitumen conduct in lab.

Figure 24. Ductility test equipment

Table 7. Result of Softening Point, Penetration and Ductility tests

	VG 30	E1	E2	E3	E4	PMB
Softening Point (°C)	52	48.5	48	47.25	44.25	68
Penetration (mm)	23	31	42.5	41	33	25
Ductility (cm)	61	100 Full scale	77	76	75.5	73

3.5 DSR (dynamic shear rheometer)

The Dynamic Shear Rheometer (DSR) is a crucial tool used for the analysis of the viscous and elastic properties of asphalt binders, especially at medium to high temperatures. This analysis holds significant importance in the context of the Superpave PG asphalt binder specification. Much like other testing procedures for Superpave binders, the selection of test temperatures is tailored to match the actual temperatures expected in the specific region where the asphalt binder is intended for use.

The Dynamic Shear Rheometer (DSR) is employed to assess the viscous and elastic characteristics of asphalt binders, particularly at elevated temperatures. This assessment plays a pivotal role within the framework of the Superpave PG asphalt binder specification. Similar to other tests conducted for Superpave binders, the choice of test temperatures is determined by the real-world temperature conditions anticipated in the region where the asphalt binder will be deployed. Figure 25 provides an illustration of the DSR assembly.

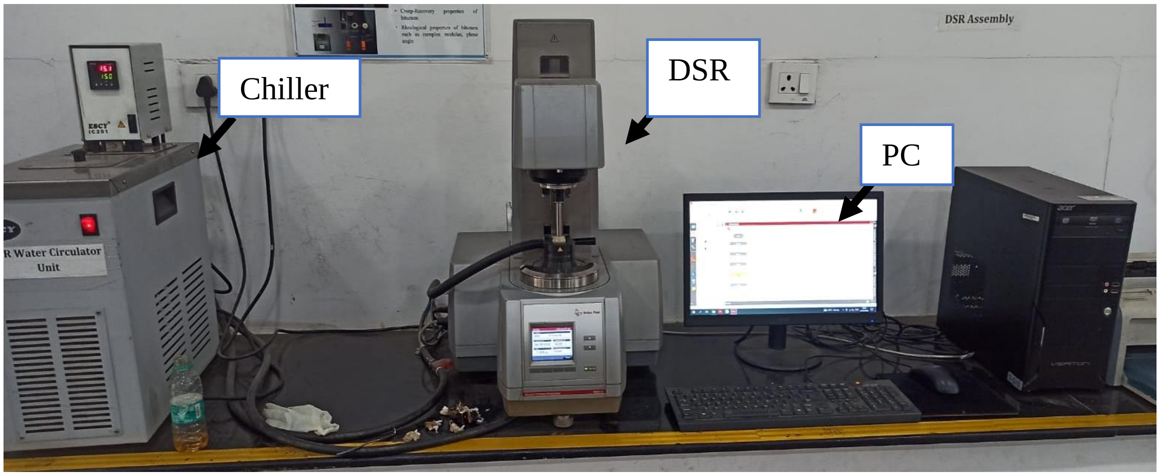


Figure 25. DSR Assembly

3.5.1 Binder grading (Rutting factor): (IS: 15462-2019)

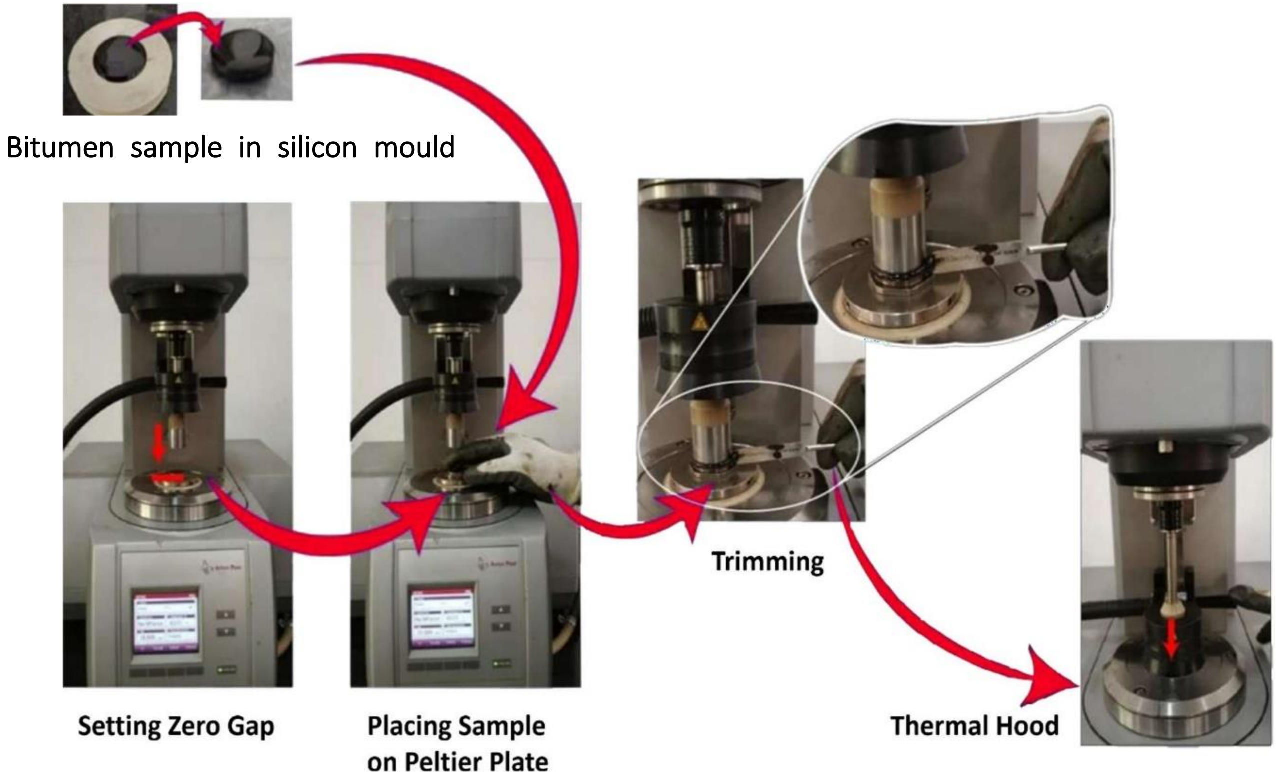


Figure 26. Sample Preparation for DSR (Mahajan, 2022)

Procedure:

- Condition the asphalt binder in an oven until it reaches a suitable fluid state for pouring the test specimens.
- Preheat the Dynamic Shear Rheometer (DSR) to the selected testing temperature. This preheating procedure ensures that both the upper and lower plates are adequately heated, facilitating the adhesion of the asphalt binder specimen to these plates.
- Position the asphalt binder sample between the testing plates.
- Carefully bring the testing plates together until the space between them matches the specified test gap, increased by 0.05 mm.
- Use a heated trimming tool to shape the specimen to fit the edges of the testing plates.

- For a more precise calculation of complex modulus, trim the remaining sample around it.
- Gradually move the testing plates together to reach the desired testing gap, which leads to a slight bulge in the perimeter of the asphalt binder specimen.
- Ensure that the specimen is at the selected testing temperature for at least 10 minutes before commencing the test.
- The DSR software determines an appropriate torque level for rotating the upper plate, considering the material under test. This torque ensures that measurements fall within the specimen's linear behavior range.
- The specimen undergoes a conditioning phase in the DSR for 10 cycles at a frequency of 10 rad/sec (1.59 Hz).
- Following the conditioning phase, the DSR proceeds to record test measurements during the subsequent 10 cycles. The collected data is then processed by the software to yield values for complex modulus (G*) and phase angle (δ). A schematic diagram of the Dynamic Shear Rheometer is illustrated in Figure 26.

Calculation:

The calculations are based on the following equations, as utilized by the DSR software:

$$\tau_{max} = \frac{2T}{\pi r^3} \tag{3.1}$$

$$\gamma_{max} = \frac{\theta \cdot r}{h} \tag{3.2}$$

Where:

τ_{max} = maximum applied stress

γ_{max} = maximum resultant strain

T = maximum applied torque

r = specimen radius

θ = deflection angle (in radians)

h = specimen height

Then, the complex modulus (G*) and phase angle (δ) is determined by:

$$G^* = \frac{\tau}{\gamma} \tag{3.3}$$

δ = phase angle calculated from the time lag between the occurrence of τ_{max} and γ_{max}

It's important to note that the phase angle is bound within a range of 0° to 90°. To quantify the time delay, it can initially be expressed in seconds and then converted into an angular measurement by dividing it by the frequency of oscillation and subsequently multiplying by 360°.

3.5.2 MSCR test: (IS: 15462-2019)

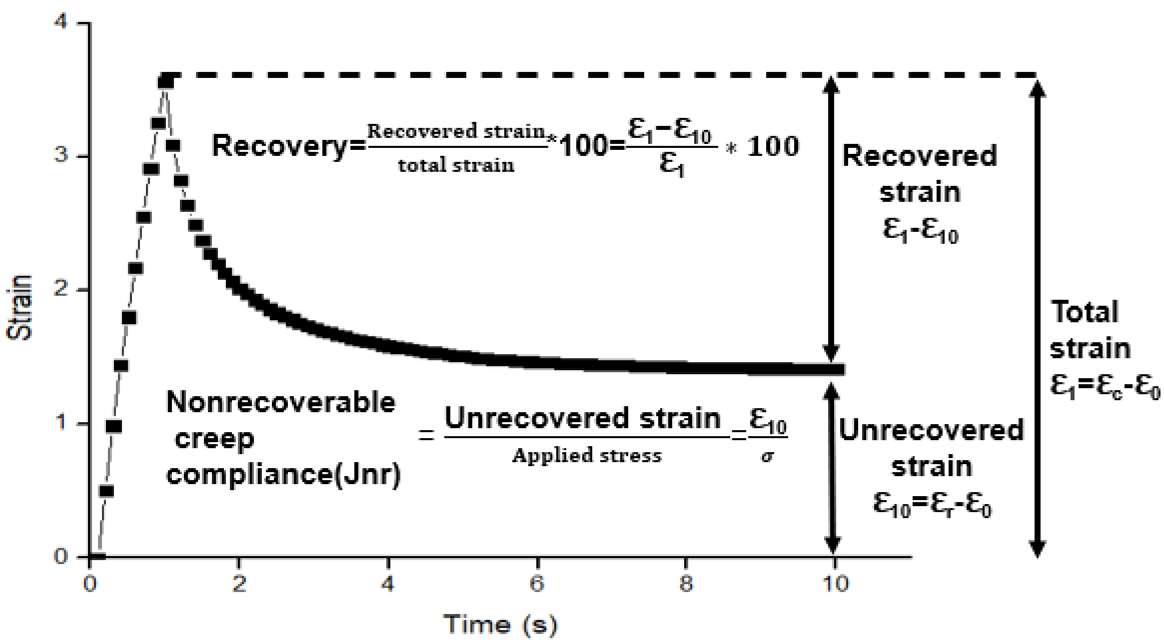


Figure 27. MSCR Principle and Equations

- Let specimen temperature come to thermal equilibrium to the desired temperature(i.e.,64°C) for the experiment. If it’s there, then use the same specimen for the MSCR test but allow it to remain unloaded for at least 1 minute.

- When a creep load of 0.1kPa is applied for 1s, it follows with zero creep recovery for another 0.9s, and then combines it becomes 1 complete cycle. Record stress and stain for every 1s creep cycle and 0.45s for zero creep recovery cycle, including every 1s and 10s.
- Allow no rest repeated the same test for another 9 cycles having stress and stain for 1s and 10s.
- Repeated the same test for 3.2kPa for further 10 cycles as the above two steps.
- For every twenty creeps and recovery, stains should calculate the following:
- The initial creep stain value of every cycle is denoted by $\varepsilon_{0.}$
- The stain value after the creep cycle (i.e., after 1s) is denoted by εc.
- To adjust the stain value of the creep cycle (i.e., after 1s):

$$\varepsilon_1=\varepsilon_0+\varepsilon c$$

- The stain value after the recovery cycle (i.e., after 10s) is denoted by εr.
- To adjust the stain value of the recovery cycle (i.e., after 10s):

$$\varepsilon_{10}=\varepsilon_0+\varepsilon r$$

3.5.3 Frequency sweep

In Dynamic Shear rheometer (DSR), a frequency sweep refers to a test procedure where the frequency of the applied oscillatory shear strain or stress is varied over a specific range while measuring the corresponding rheological response of a material.

We have performed this test from frequency 0.1 rad/s to 100 rad/s at different temperatures of 20 to 70 ℃.

The purpose of the frequency sweep test is to investigate the viscoelastic behavior and response of the material under different rates of deformation. By varying the frequency, the DSR can explore the material's response to different deformation speeds, capturing the dynamic rheological properties over a range of frequencies.

We have performed this test from frequency 0.1 rad/s to 100 rad/s at different temperatures of 20 to 70 ℃.

3.5.4 Temperature sweep

In Dynamic Shear rheometer (DSR), a temperature sweep refers to a test procedure where the temperature of the sample material is varied over a specific range while measuring its rheological response.

In this experiment, the temperature sweep ranges from 25℃ to 80℃ at a constant shear strain of 0.1% and frequency of 1.59Hz.

The purpose of a temperature sweep test is to investigate the effect of temperature on the material's rheological behavior. By varying the temperature, the DSR can examine how the material's viscoelastic properties change as a function of temperature.

3.5.5 Amplitude sweep

In Dynamic Shear rheometer (DSR), an amplitude sweep, also known as strain or stress sweep, refers to a test procedure where the amplitude of the applied oscillatory shear strain or stress is varied over a specific range while measuring the resulting rheological response of a material.

In this experiment, shear strain varies from 0.1% to 100% at a constant temperature of 60℃.

The purpose of the amplitude sweep test is to investigate the linear viscoelastic region (LVR) of the material, which refers to the range of deformation where the material's response is directly proportional to the applied strain or stress. By varying the amplitude, the DSR can explore the material's behavior across different levels of deformation.

3.6 Bending Beam Rheometer (BBR): (ASTM D6648)

The BBR test serves as a valuable tool for evaluating the stiffness and flexibility of asphalt binders, particularly at low temperatures. This assessment provides insights into the asphalt binder's ability to resist cracking under such conditions. When combined with the DSR test, the BBR test contributes to determining the low-temperature Performance Grade (PG) of an asphalt binder. As with other Superpave binder tests, the selection of test temperatures is tailored to correspond with the expected temperature conditions in the specific region where the asphalt binder will be utilized. A visual representation of the BBR is presented in Figure 28.

Figure 28. Bending Beam Rheometer (Source: Pavement Interactive).

3.6.1 Sample Preparation

- Heated asphalt is poured into a rectangular mold to form the asphalt beam. The aluminium mold pieces are greased with oil jelly, and plastic bits are stuck on the dirty faces. The end pieces are treated with a release agent made of glycerine and talc, forming a paste-like substance.
- After cooling for approximately 45 to 60 minutes, excess asphalt from the top surface is cut away using a hot tool. The test specimens are kept in their molds at room temperature before testing, ensuring the tests are conducted within 4 hours of placing the samples.
- To remove the sample from the mold, the entire assembly is placed in a freezer or ice bath at -5°C for 5-10 minutes. Avoid using the rheometer testing bath to prevent drastic temperature changes in the bath.
- Once the aluminium and plastic strips are removed, the asphalt beams are heated and strengthened in the test bath for one and a half hours. Afterward, the beams are checked, and the operator must plan the equipment and sample preparation carefully due to the test method's small margin of error.

Procedure

- Set the BBR fluid bath to the desired test temperature using clear fluids like ethanol, methanol, or glycol-methanol mixtures with a specific gravity less than 1.05.

- Heat the PAV-aged binder until it becomes fluid to pour. Stir occasionally during heating to ensure homogeneity while keeping the sample covered.
- Stir the sample to eliminate air bubbles and pour it into two aluminium BBR molds, ensuring there's excess sample along the top.
- Allow the molds to cool at room temperature for 45 to 60 min, then trim the top of the sample flush with the mold.
- To demold the samples, cool the mold in an ice bath or freezer at -5°C for 5 to 10 minutes, ensuring that you remove the beam without causing any damage.
- Place the beams in the BBR bath at the test temperature for 60 minutes to condition them.
- Position the test beam on the test supports and manually apply a 35 mN contact load for no more than 10 seconds to ensure continuous contact between the loading head and the beam during the test.
- Activate the automatic testing system, which applies a 0.22 lb (980 mN) seating load for 1.0 second, reduces it to 35 mN for 20 seconds to allow the beam to recover, and then applies 980 mN test load for 240 seconds while recording deflection readings over time.
- Remove the test load and end the test.
- Repeat steps 4 to 6 for the second beam.

3.7 Pressure Aging Vessel (PAV): (ASTM D6521)

The standard PAV procedure involves taking RTFO aged asphalt binder samples, transferring them to stainless steel pans, and aging them for 20 hours inside a heated vessel pressurized at 2.1 MPa. Subsequently, the samples are stored and used for conducting physical property tests. Figure 29 shows pressure aging vessel.

Figure 29. Pressure Aging Vessel (Source: Pavement Interactive).

Procedure:

- Heat the asphalt binder aged using Rolling Thin Film Oven (RTFO) until it reaches a fluid consistency for pouring.
- Stir the sample and pour 50 g of it into a thin film oven pan that has already been pre-cooked. Prepare as many pans as needed for testing at moderate and cold temperatures (typically one to three pans are sufficient).
- Place the pans in a pan stand and then into a Pressure Aging Vessel (PAV) that has been preheated.
- Seal the PAV and allow it to return to the temperature at which the aging process was initiated.
- The aging temperature depends on the intended usage conditions. For conditions requiring a Performance Grade (PG) of 52 or lower, the PAV is set at 90°C. For PG 58 or higher, the PAV temperature is set at 100°C. In desert climates, it is recommended to perform the PAV at 110°C.
- Once the PAV reaches the desired temperature, increase the pressure to 300 psi (2.07 MPa) and maintain it for 20 hours.
- After the aging time is completed, slowly release the air pressure and remove the pans from the PAV.
- Transfer the contents of the pans into a single container with a depth between 14 and 40 mm and place it in 163°C oven for 15 minutes.

- Next, place the container in a vacuum oven at 170°C for 30 minutes to eliminate any trapped air. Trapped air bubbles could cause premature failure in the Dynamic Shear Rheometer (DTT) test if not properly removed.

3.8 BC mix design (IRC 111, 2009)

According to IRC 111-2009, it's essential for bituminous concrete mixes to be designed meticulously, meeting specific criteria to ensure satisfactory stability and durability. The mixture, both in its design and application, must meet the criteria outlined in the provided Table 8. These criteria are determined through the Marshall method of design, which is currently recommended due to its simplicity and consistency.

Table 8. Requirements of mixes

Marshall flow, (mm)	2-4
% air voids in mix	3-5
% voids filled with bitumen	65-75
% voids in mineral aggregate (VMA)	14 min

Procedure:

a) Different batches of bituminous concrete-2 had been prepared according to grain sieve analysis which is 1150±5 g in weight. Then placed these prepared batches in an oven at 180±5°C for 4hr.

b) Heated batch of BC-2 is poured into a mixing container and mixed aggregate thoroughly.

c) Put bitumen in an oven at 160±5°C and pour it into a mixing container.

d) Mix bitumen and aggregate thoroughly at a mixing temperature of 160±5°C.

e) Placed prepared asphalt mix in an oven at 160±5°C for 2hr.

f) Again, placed it in mould and compacted it with compacter by applying 75 blows.

g) The formed specimen is placed at room temperature i.e., 25°C for one day before extraction. Figure 30 shows procedure for sample preparation for mix design

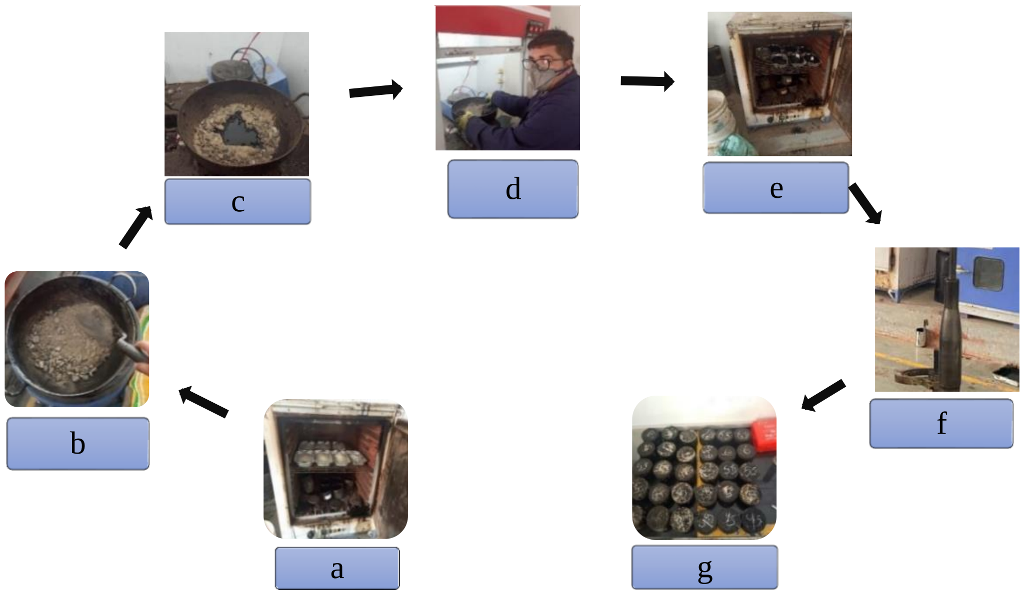


Figure 30. Procedure for sample preparetion for mix design.

3.8.1 Stability test

Stability is peak load resisted by the specimen when tested at 60 °C and a displacement rate of 50 mm/min. The Marshall stability test assembly is shown in Fig. 31.

Figure 31. Marshall setup for stability and flow

3.8.2 ITS test

The Indian Road Congress (IRC) 111 code establishes the concept of Indirect Tensile Strength, a pivotal mechanical characteristic of construction materials, especially those applied in road and pavement engineering. This property significantly contributes to the assessment of how well these materials endure and maintain performance across diverse loading and environmental scenarios. Figure 32 shows ITS test setup.

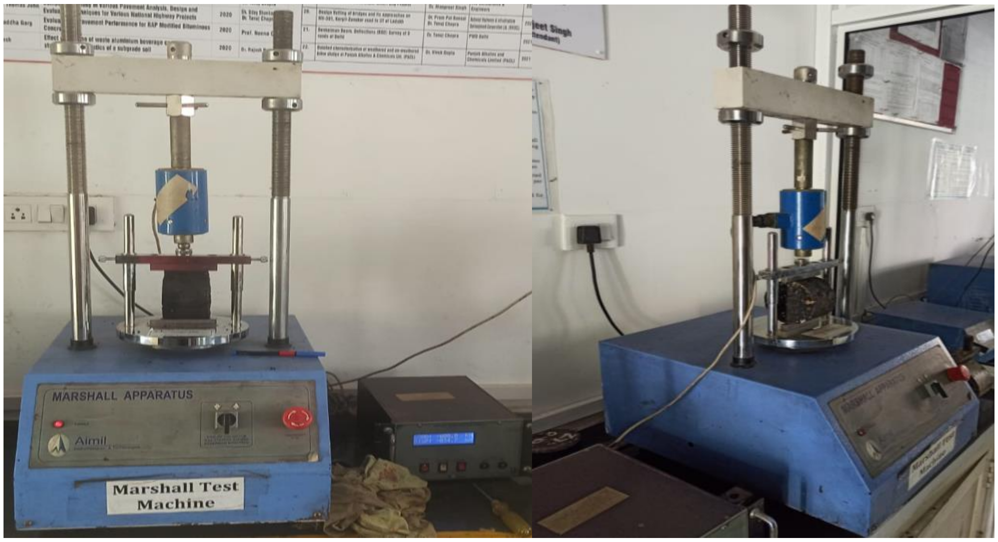


Figure 32. ITS test setup

Procedure:

- Prepare 12 distinct Marshall mix specimens with varying dosages in pair whereas only 20 blows are given in both sides.

Wet Specimen Preparation:

- Select six Marshall mix specimens with different dosages and immerse them in water.
- Wrap saturated specimens in plastic film, seal in a plastic bag with 10ml water, freeze at -18°C for at least 16 hours.
- After freezing, transfer the specimens to a water bath set at 60°C for a duration of 24 hours. Remove the plastic film and bag once the specimens are in the water bath.
- Following the 24-hour period, transfer the samples to water at room temperature for an additional 2 hours.

Both Dry and Wet samples:

- Lastly, conduct Indirect Tensile Strength (ITS) tests on all 12 samples after measuring the diameter and height of each specimen.
- Calculate the maximum tensile stress at the point of fracture using the formula: Indirect Tensile Strength (ITS) = 20000 * Maximum Load (N) / (π * Diameter (mm) * Height (mm)).

Figure 33. Samples for wet ITS test.

3.8.3 Pavement Structure Analysis

For design of pavement structure Resilient modulus is required which is obtained by help of ITS value. Resilient Modulus of 102 mm diameter specimens with polymer modified binder mixes at 35°C.

$$Mr = 1.1991 \times ITS + 1170 \quad (3.4)$$

Where,

ITS = Indirect tensile strength in kPa,

Mr = Resilient modulus in MPa

By using Equation 3.4, we can calculate resilient modulus of wearing course of pavement structure. Flexible pavement composition considered for 30 msa traffic level.

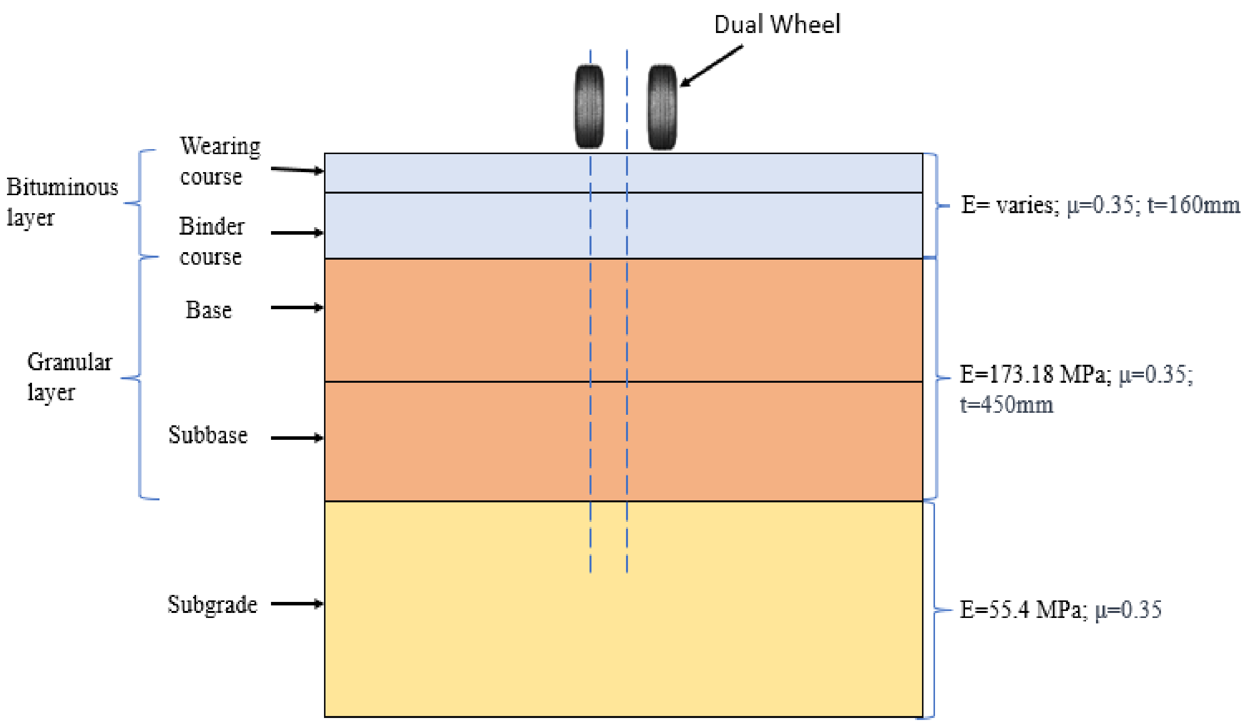


Figure 34.Flexible pavement composition considered for 30 msa traffic level.

Procedure:

- For design of pavement 30 msa of design traffic and 6% of effective CBR of subgrade is taken in consider.

- Effective resilient modulus of Subgrade = $17.6(6.0)^{0.64}$ = 55.4 MPa (less than 100 MPa, the upper limit).
- The pavement structure is pre-determined to check reliability of modified asphalt as shown in figure 34 only resilient modulus of wearing course resilient modulus varies.
- Resilient modulus of the granular layer = $0.2 \times (450)^{0.45} \times 55.4$ =173.18 MPa
- The allowable compressive strain (ε_c) was obtained from rutting equation (Equation 8.4) as 416 µs.

$$T_R = 1.41*10^{-8}*(\varepsilon_c)^{-4.5337} \quad (3.5)$$

$$T_F = 0.5161*10^{-4}*C*(\varepsilon_t)^{-3.89}*(M_R)^{-0.854} \quad (3.6)$$

Where,

T_R = Subgrade rutting life (msa)

ε_c = Vertical compressive strain at the top of the subgrade.

T_F = Fatigue life of bituminous layer (msa)

ε_t = Horizontal tensile strain at bottom of bituminous layer.

- The allowable horizontal tensile strain (ε_t) was obtained from fatigue equation (Equation 8.5) as 213 µs for sample VG 30 likewise calculated for each dosage of EMA.
- Using iitpave software computed each horizontal tensile strain and Vertical compressive strain and compared them.

4 RESULTS AND DISCUSSION

4.1 DSR Result

4.1.1 PG Grade

The primary objective of utilizing higher temperature grades for base bitumen binders blended with epoxy resin is to bolster their resistance to rutting, which can be caused by heavy traffic or elevated climatic temperatures. Figure 35 illustrates the results of the failure temperature for both control and epoxy-modified binders in both unaged and short-term aged states. Failure temperature is defined as the temperature at which G*/sin δ = 1.0 kPa (for unaged binders) and G*/sin δ = 2.2 kPa (for short-term aged binders). The introduction of epoxy into the binders results in an increase in the G*/sin δ parameter, thereby enhancing their properties at high temperatures. This enhancement signifies improved resistance to rutting, which is a critical aspect of asphalt binder performance.

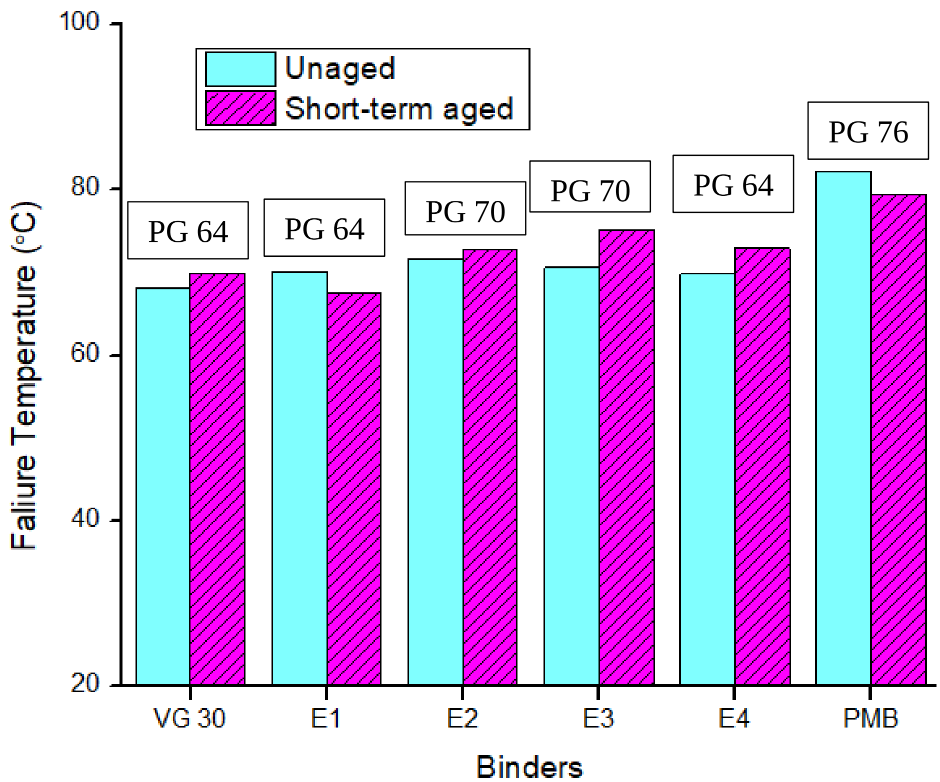


Figure 35. High PG Grade of different bitumen samples.

Figure 35, also shows that the bitumen sample E3, which has a Performance Grade of PG 70, performs better compared to other epoxy dosages and the control VG 30 base bitumen binder. However, the PMB binder showed the highest failure temperature.

4.1.2 MSCR

Figure 36 presents the non-recoverable creep compliance (Jnr) values for asphalt binders under two stress levels: 0.1 and 3.2 kPa tested at 64°C. Jnr parameter indicates the ability of the asphalt binder to resist permanent deformations. A lower Jnr value signifies better performance of the asphalt binder sample in terms of resistance against permanent deformation. The results demonstrate that the addition of epoxy resin significantly reduces the Jnr value compared to the base asphalt binder. Among the epoxy modified binders, E2 and E3 exhibit superior performance compared to E1 and E4. From IS:15462-2019, different traffic levels are provided to different Jnr values.

Table 9.Traffic levels according to Jnr results

Jnr	Traffic Levels	samples
≤ 0.5	E	PMB
0.5 - 1	V	E3, E2, E1
1 - 2	H	E4
2 - 4.5	S	VG 30

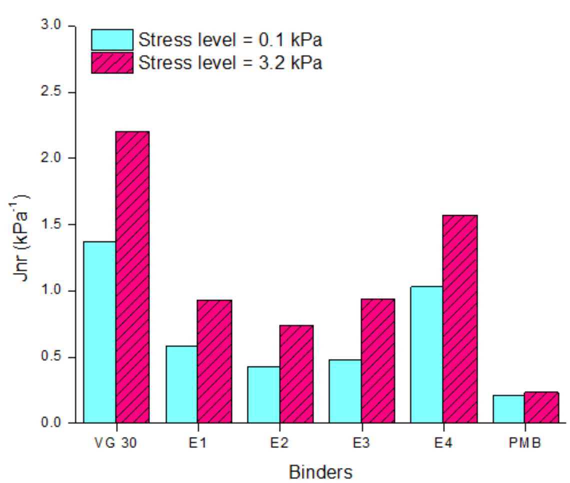


Figure 36. Non-recoverable creep compliance of results.

Figure 37 shows the results of elastic recovery at 0.1 and 3.2 kPa stress levels, respectively. In Figure 37, a higher R value indicates that the asphalt binder is more capable of recovering the applied strains after being subjected to loading. This signifies a larger proportion of elastic strains and a reduced amount of plastic deformation following the loading. Figure 37 illustrates that all epoxy contents enhance the R value and consequently improve the flexibility of the modified asphalt binder compared to the base binder. However, the highest recovery is observed for PMB. Notably, among the epoxy modified binders, E3 displays the most favorable results in terms of improved recovery.

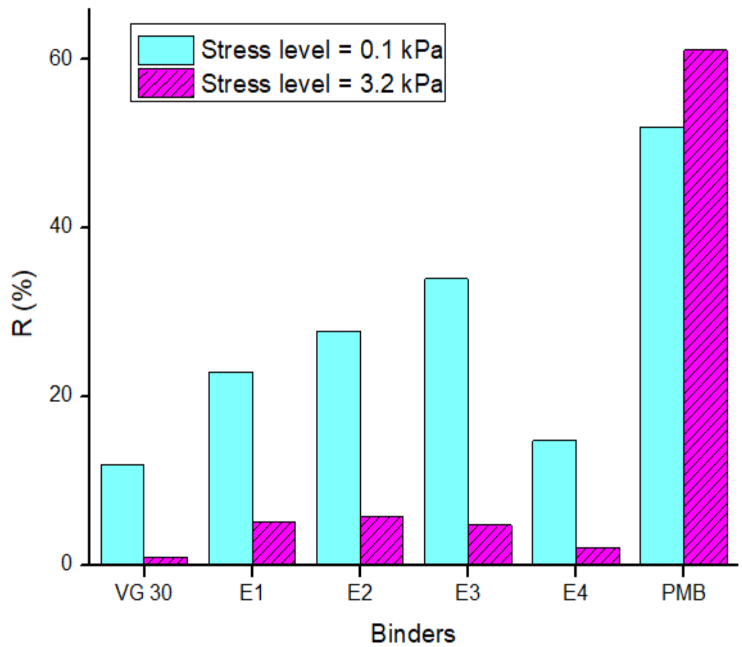


Figure 37. Elastic recovery results.

4.1.3 G* Master Curve

G* master curves were generated based on frequency sweeps conducted at temperatures of 20, 30, 40, 50, 60, and 70°C using short-term aged binder samples. The reference temperature employed for these sweeps was 30°C, while the frequency range varied from 0.1 to 100 rad/s (equivalent to 0.015 Hz to 15.91 Hz) at each temperature. The construction of the G* master curve allowed for the observation of the binder's rheological response across a broader frequency domain. In this context, the behavior of the asphalt binder in the lower frequency region of the master curve corresponds to the high-temperature regime, while the higher frequency region corresponds to the lower-temperature regime (Tarar et al., 2021). The smooth and coherent G* master curves illustrate the effective application of the time-temperature superposition principle to epoxy-modified asphalt binders.

Figure 38 illustrates that higher E3 (a parameter) results in higher G* values at lower frequencies, indicating improved resistance to deformation at higher service temperatures. Conversely, at higher frequencies associated with lower temperatures, an increase in G* is also observed, suggesting enhanced performance in lower-temperature conditions. This data underscores the positive impact of epoxy modification on the binder's rheological properties across a wide temperature and frequency spectrum.

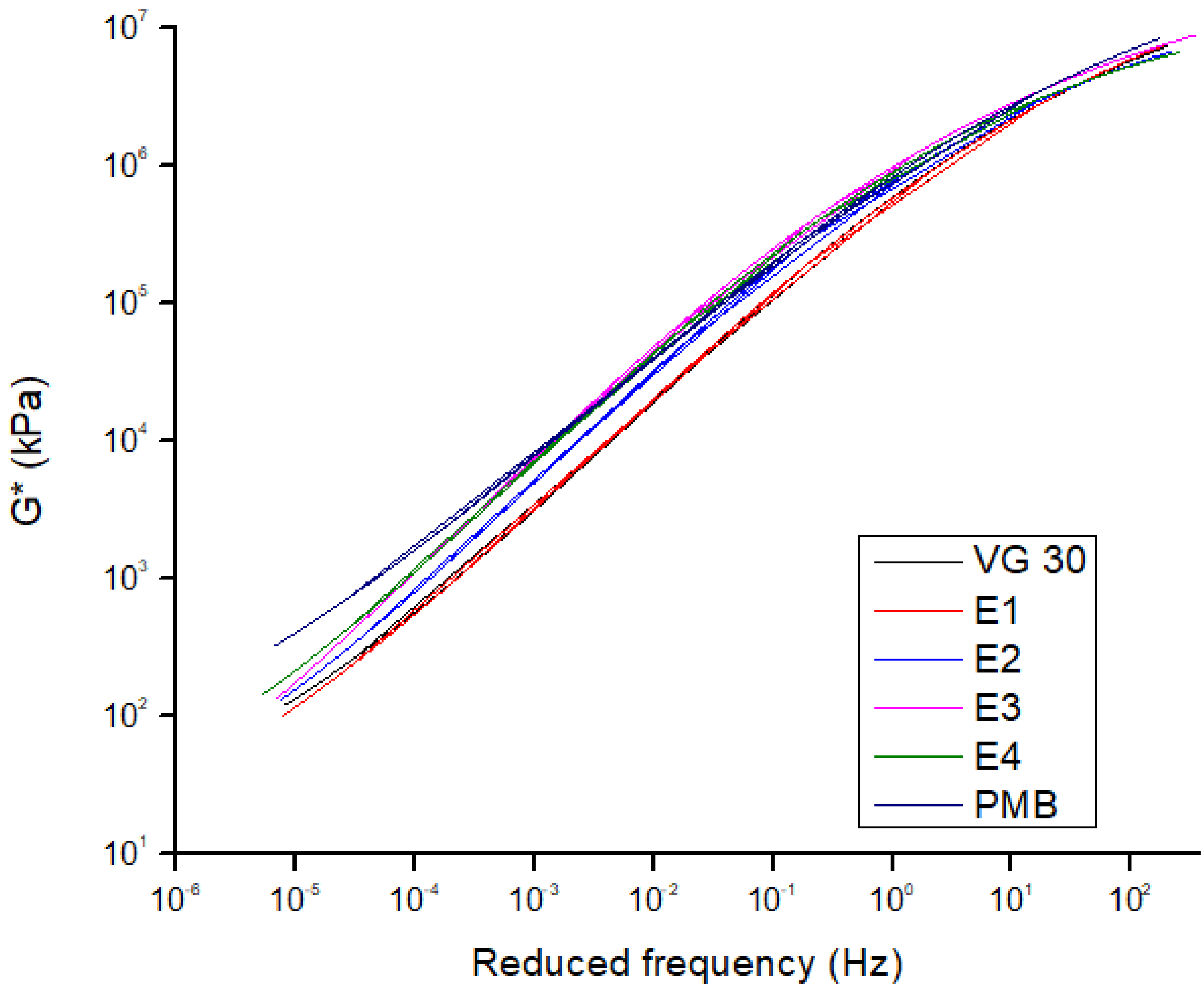
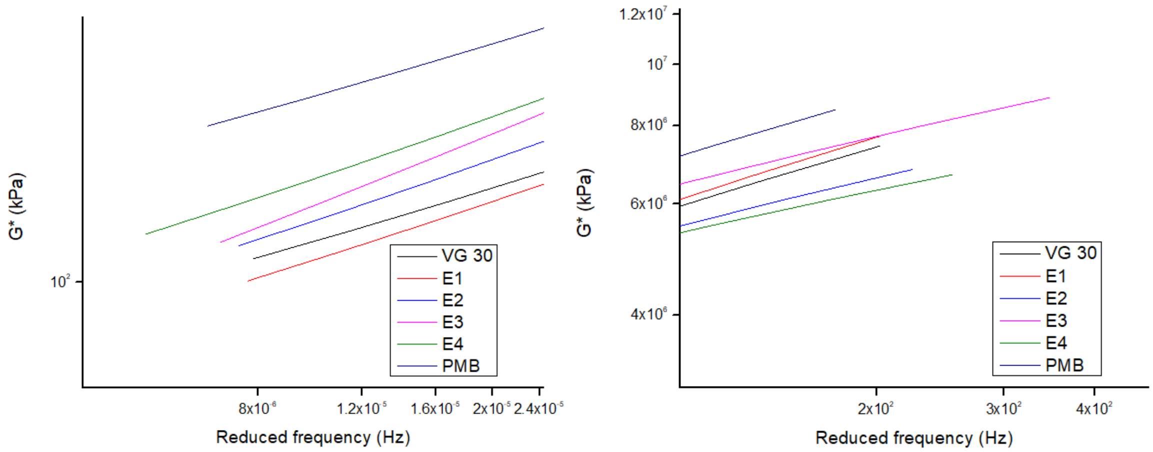


Figure 38. G* Master curve.



Upper region **Lower region**

Figure 39. Result showns of G* curve at upper and lower region.

4.1.4 Temperature Sweeps

Figure 40 depicts the temperature variation of G* (complex shear modulus) and δ (phase angle) of the bitumen samples. As anticipated, the G* values exhibit a decreasing trend with rising temperature, while the δ values show an increasing trend. This behavior is observed consistently across all the bitumen samples.

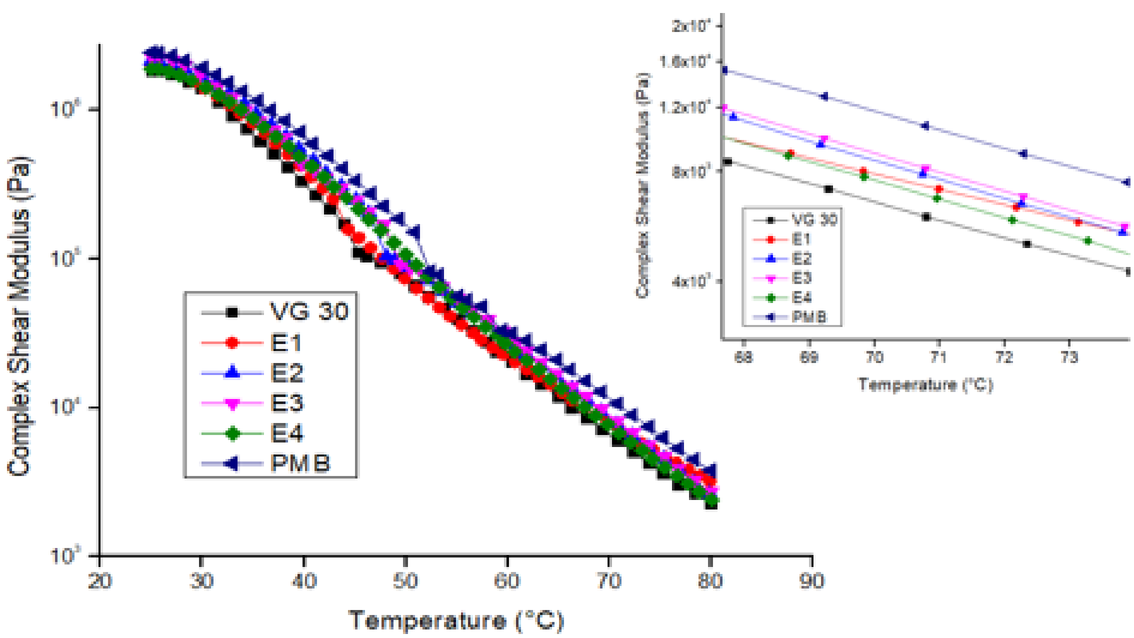


Figure 40. Temperature sweep results for G*.

A clear observation from the figure is that the E3 sample stands out with its high G* values compared to the other samples. This shows that the E3 sample demonstrates superior characteristics in terms of stiffness (higher G*) when compared to the other samples. Highest G* values were observed for PMB.

4.1.5 Frequency Sweeps

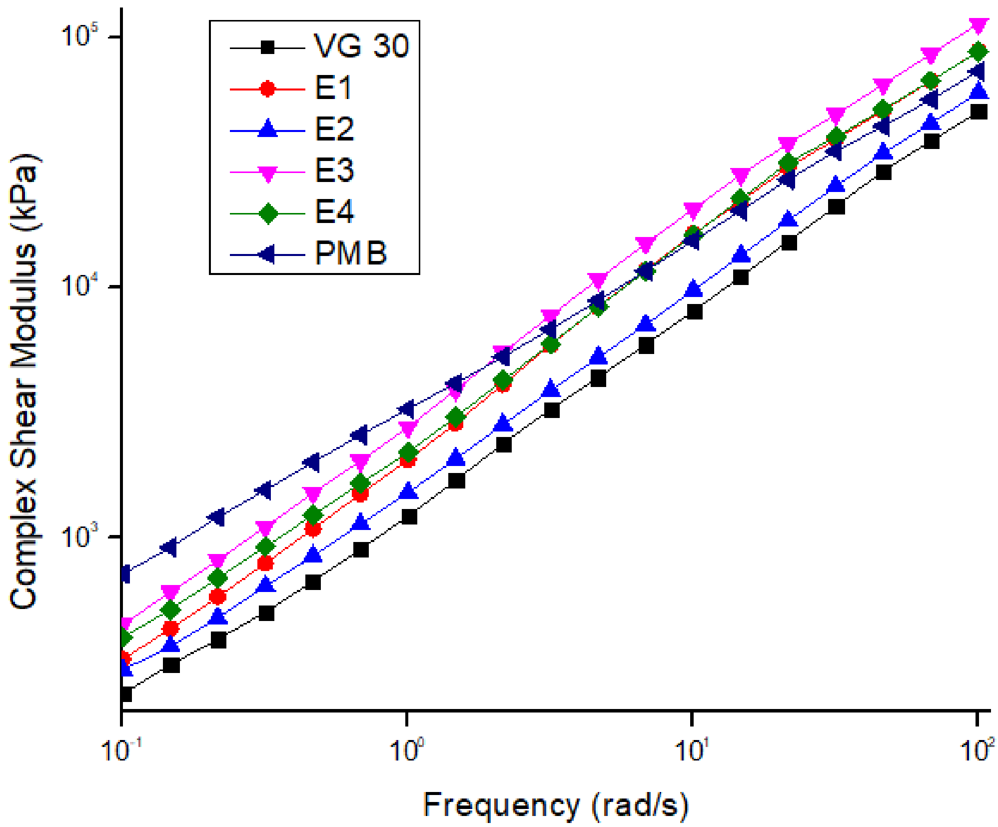


Figure 41. Frequency sweep results at 60°C.

Figure 41 depicts the outcomes of a frequency sweep for various binders at 60°C. Here, "frequency" can also be equated with the speed of vehicles on the road. Upon careful examination of the graph, it becomes evident that the PMB binder performs admirably in comparison to the others at lower frequencies. However, when it comes to higher frequencies or speeds, the E3 sample is excellent.

4.1.6 Zero Shear Viscosity

The introduction of the Superpave rutting parameter was a response to the limitations encountered when evaluating the performance of modified asphalt binders. In order to address these limitations, the ZSV (Zero Shear Viscosity) parameter was proposed, specifically designed to assess the binder's ability to withstand long-term deformation under sustained loads.

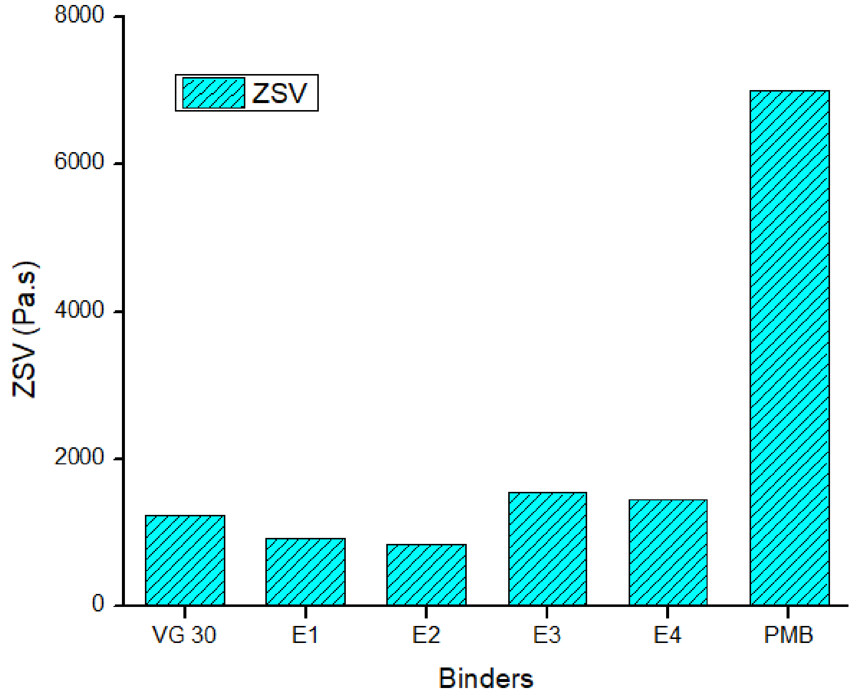


Figure 42. Results of Zero Shear Viscosity.

Figure 42 clearly illustrates that the ZSV of the E3 binder exhibits favourable performance when compared to VG 30. However, it is worth noting that the commercial modified binder showcases the highest performance among all the binders that were tested. This indicates that the commercial modified binder demonstrates superior resistance to long-term deformation, as evaluated by the ZSV parameter, compared to both the E3 binder and the VG 30 binder.

4.1.7 Amplitude sweeps

In this experiment, shear strain varies from 0.1% to 100% at a constant temperature of 60℃. The purpose of the amplitude sweep test is to investigate the linear viscoelastic region (LVR) of the material, which refers to the range of deformation where the material's response is directly proportional to the applied strain or stress. The linear limit is calculated on basic of condition that the strain at which the complex value reduces to 95% of its original value.

According to Figure 43, it is evident that the linear limit of all binders exceeds 0.1%. This observation implies that for frequency sweeps and temperature sweeps tests, a strain value of 0.1% was chosen. As a result, it becomes apparent that all binders exhibit behavior within the limits of LVE (Linear Viscoelastic) behavior.

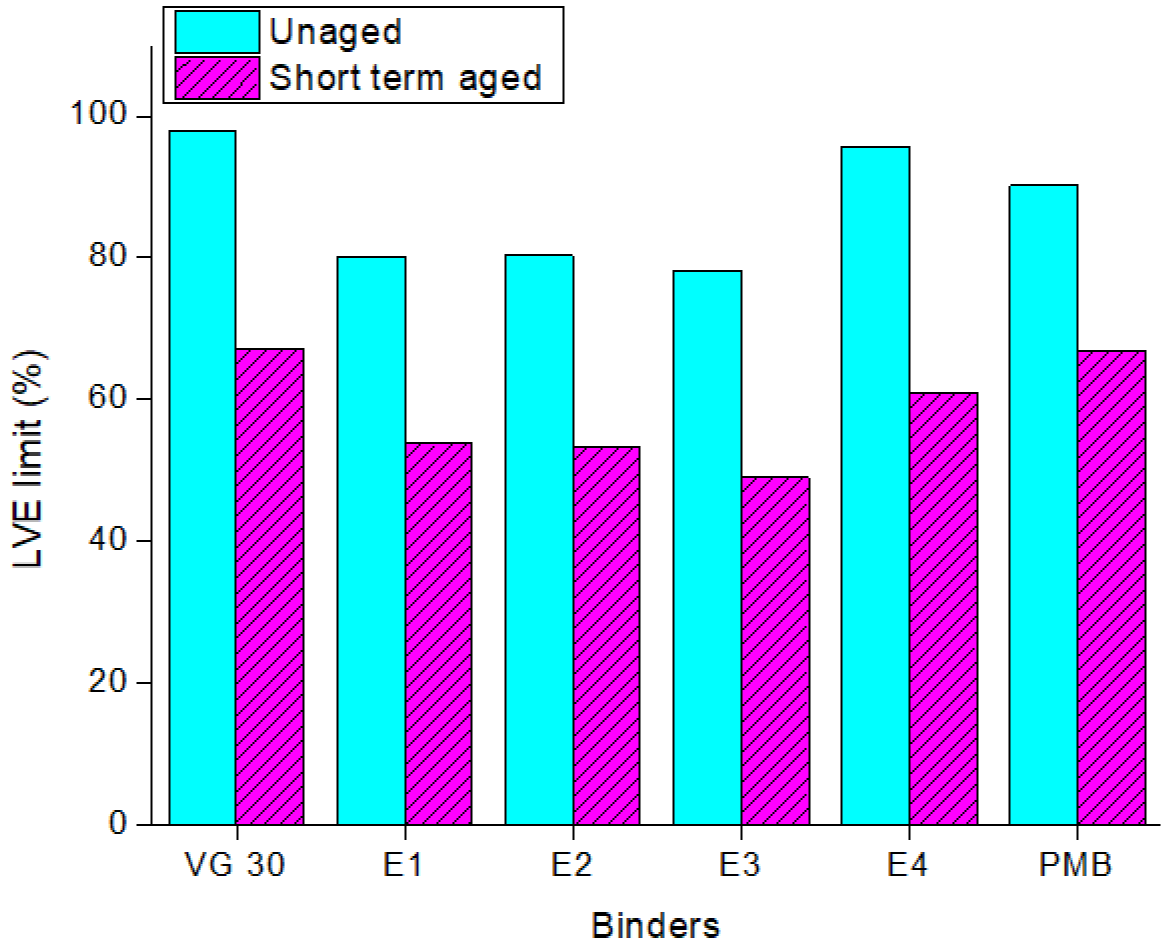


Figure 43. Amplitude sweep results.

4.1.8 Superpave fatigue parameter

In this study, various binder samples are examined using the Dynamic Shear Rheometer (DSR) to assess their fatigue characteristics represented by the parameter G*sin δ at a temperature of 25°C. Figure 44 illustrates the results, indicating that the fatigue parameters of the control sample range from 4000 kPa to 5000 kPa, while VG 30 and PMB samples are around 3000kPa. Therefore, it can be inferred that the control samples are better suited for use in lower temperature conditions.

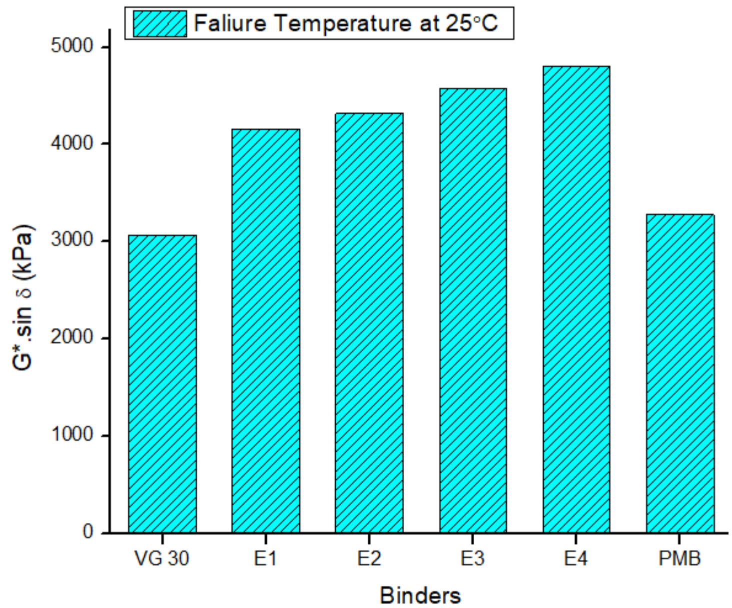


Figure 44. Results of fatigue parameter at 25℃.

4.1.9 Fatigue Performance through LAS Test

4.1.6.1 Strain Response Curve

This plot serves as a valuable tool for analyzing the strain dependency and damage inflicted on asphalt binder during shear loading. The widening of the peak on the graph indicates a decreased reliance on the applied strain in this particular shear loading scenario. A broader peak is indicative of a superior binder performance.

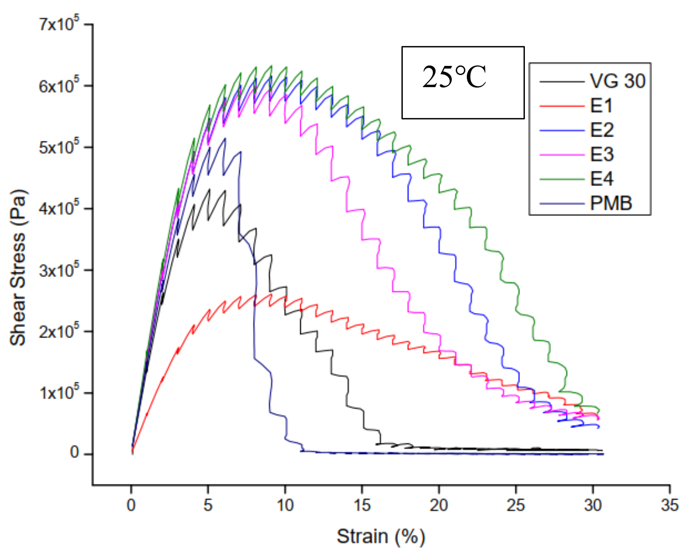


Figure 45. Effective shear stress versus shear strain for different bitumen samples.

Upon examination of the figure 45, it can be observed that every modified bitumen, except E1, demonstrates improved performance compared to the base binder. Further investigation reveals that E3, E2, and E4 exhibit high fatigue life, suggesting their enhanced durability and ability to withstand repeated loading cycles.

4.1.6.1 Number of Cycles to Fatigue Failure (N_f)

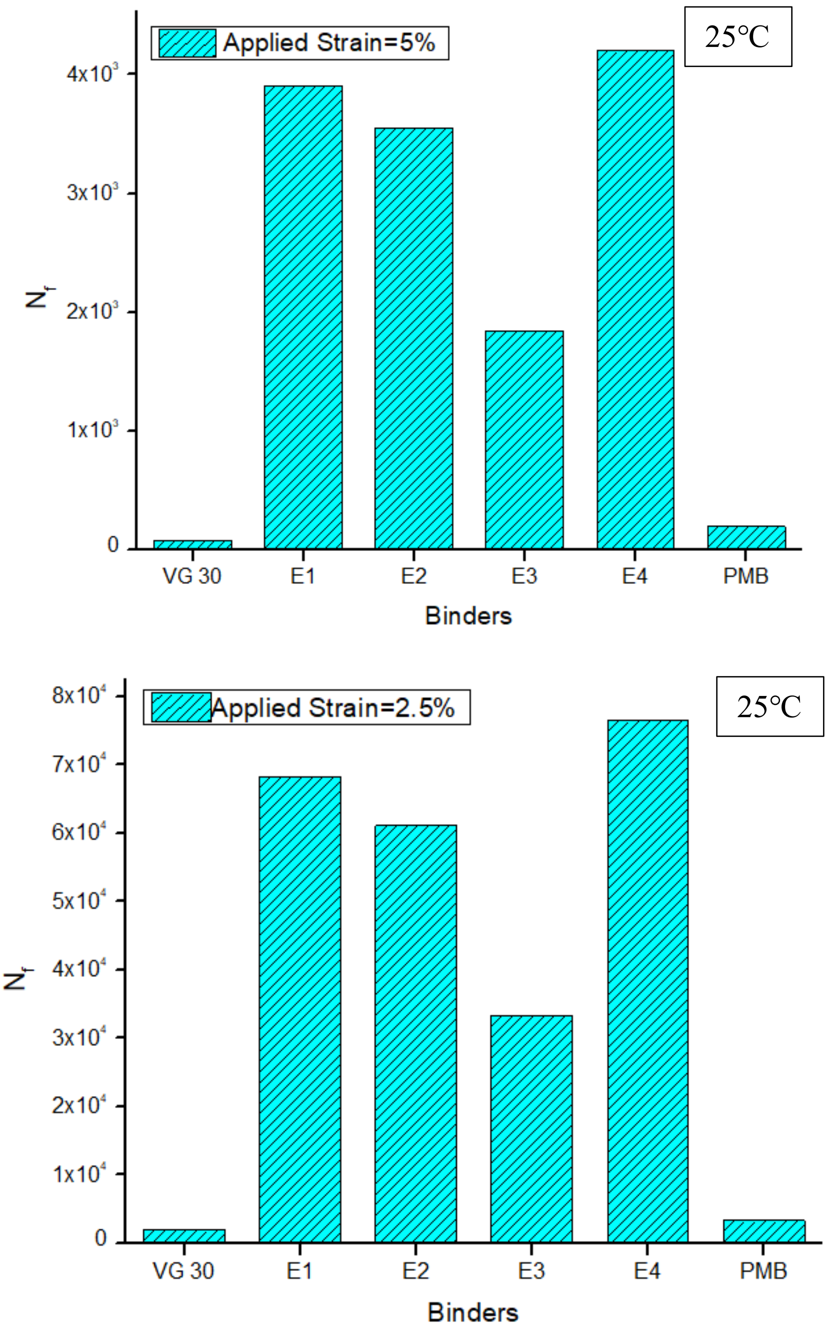


Figure 46. Linear amplitude sweeps test results.

The graph shows that the fatigue life of a given binder is longer when the Number of Cycles to Fatigue Failure (Nf) is higher. It is clear that epoxy-modified binder has a high Nf value compared to base binder and industrial binder at both 2.5% and 5% of applied strain. E1, E2, E3, and E4 have Nf values of 68,219, 61,066, 33,346 and 33,346 respectively, which are higher than VG 30 and PMB, which have Nf values of 1,902 and 3,279 in 2.5% of applied strain.

4.1.10 BBR Test

The material with low creep stiffness and high m-value is considered to have good cracking resistance at low temperatures. Figure 47 and 48 shows that E3 performed much better than the VG 30 binder and PMB so it can be concluded that our control modified binder is a success.

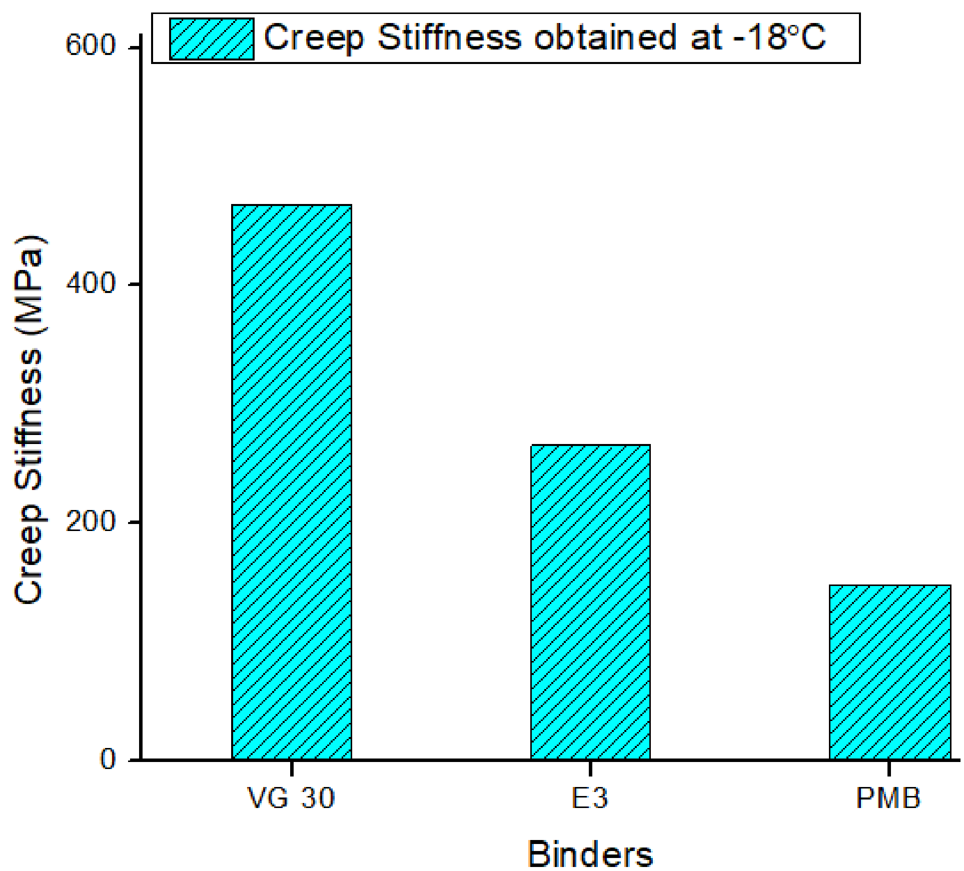


Figure 47. Creep Stiffness result of BBR.

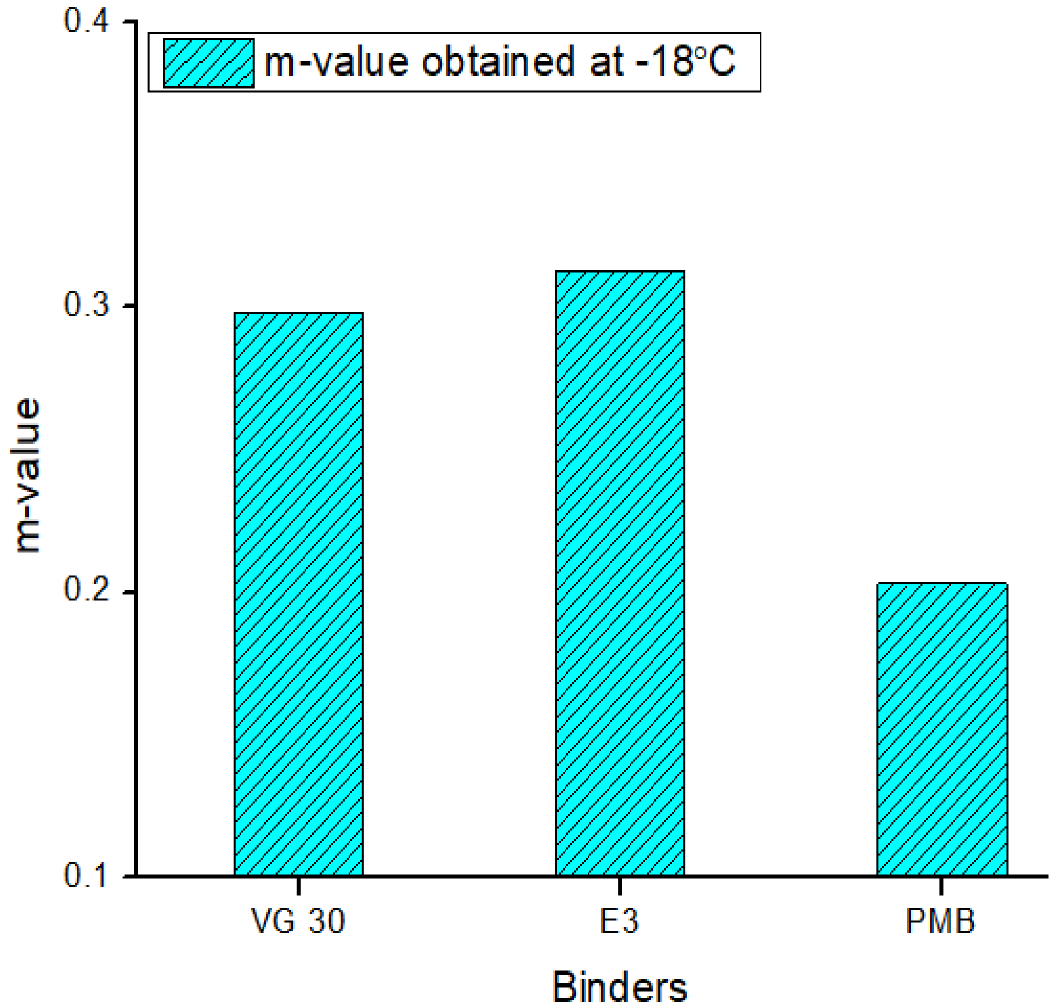


Figure 48. m-value results of BBR.

4.2 Marshall mix Result

4.2.1 Marshall stability results

Figure 49, it becomes evident that the E3 sample, encompassing a 3% epoxy modification within the asphalt mix, exhibits superior performance in comparison to the base binder. Yet, it falls short of attaining the level of performance showcased by the Industrial binder. Nonetheless, the epoxy-modified asphalt mixture with a 3% epoxy content remains a practical consideration, given its enhanced outcomes relative to the base binder

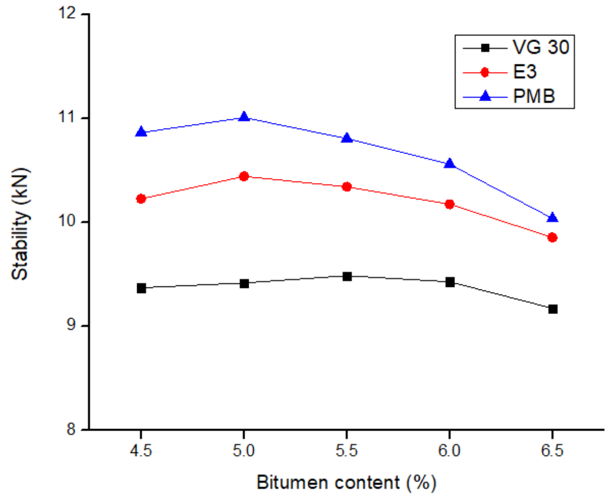


Figure 49. Marshall stability result.

4.2.2 ITS test

Figure 50 and 51 depicts the ITS and TSR results for BC mixtures incorporating modified bitumen with epoxy resin, ranging from 0% to 4%, as well as PMB, tested under both wet and dry conditions. The discernible trend is that the inclusion of epoxy resin to modify the bitumen has yielded an augmentation in the ITS values for both wet and dry asphalt specimens, alongside the TSR value. Consequently, the ITS parameter values across all samples containing varying proportions of epoxy resin surpass those of the base bitumen sample, although they remain below the values observed for the PMB sample.

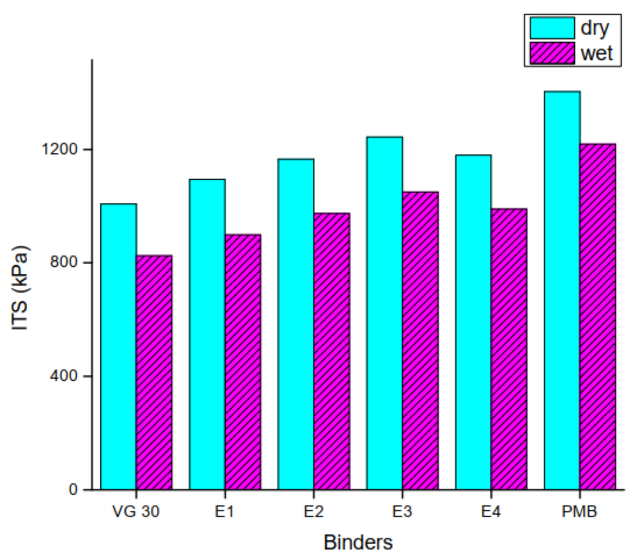


Figure 50. ITS result for asphalt mixtures.

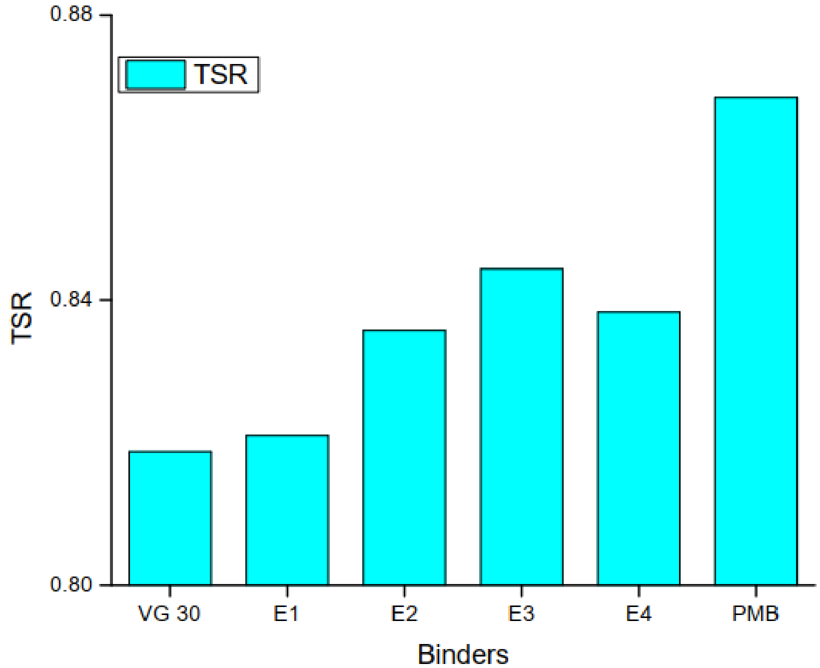


Figure 51. TSR results of asphalt mixtures.

Of particular significance, the asphalt mixtures containing 3% epoxy resin demonstrate the highest ITS and TSR values for both wet and dry conditions within the EMA samples, aligning with the findings of Bahmani et al. (2022). Conversely, the asphalt mixtures featuring the base bitumen display the lowest ITS values, while the industrially modified asphalt records the highest values.

4.2.3 Pavement Structure Analysis

The resilient modulus (M_R) of EMA BC mixtures were assessed at a temperature of 35℃, which aligns with the annual average pavement temperature recommended by IRC: 37 (2018). The determination of the resilient modulus (M_R) relied on an empirical formula that required the corresponding ITS value, as shown in equation 3.4.

Figure 52 illustrates that the M_R of EMA mixture samples outperform that of the base binder (VG 30). Highest, M_R is observed for PMB mixture. E3 mixture showed the highest MR among all epoxy mixtures. Upon analyzing the data, a substantial 10.6% increase in the Resilient Modulus (M_R) of the E3 sample becomes evident when compared to the base sample.

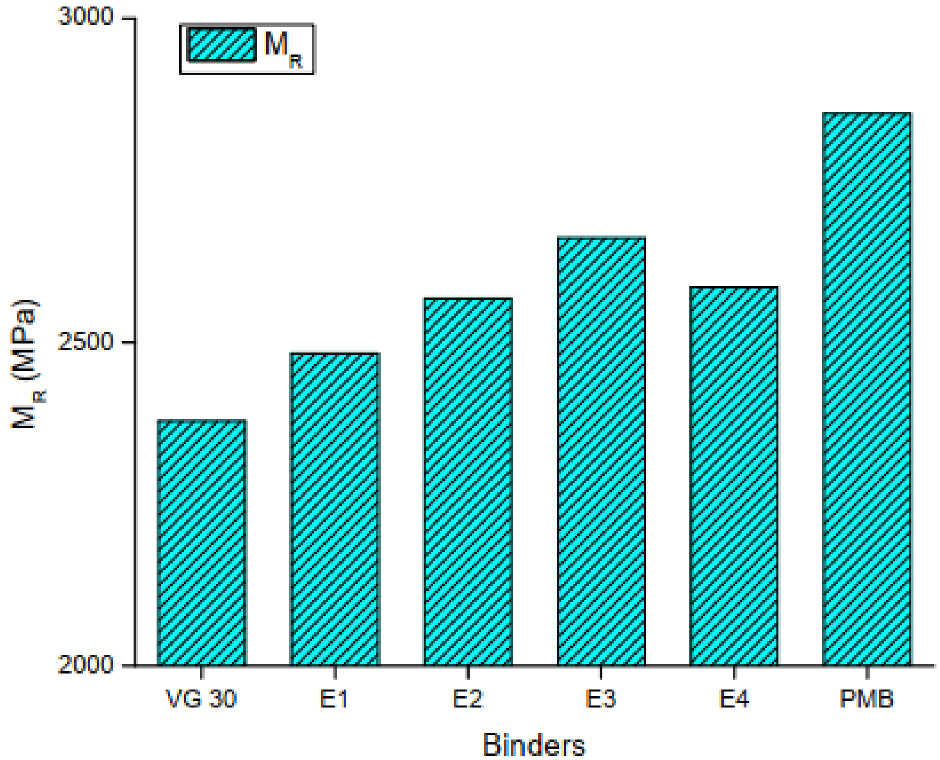


Figure 52. Resilient modulus (M_R) of EMA samples.

Figures 53 and 54 depict the pavement structure's rutting and fatigue life. It is evident from both figures that the E3 sample, among the base binder and EMA mixture, exhibited lower values of ε_t and ε_c (strain) and higher values of fatigue life (T_F) and rutting life (T_R). The PMB results demonstrated superior performance across all parameters.

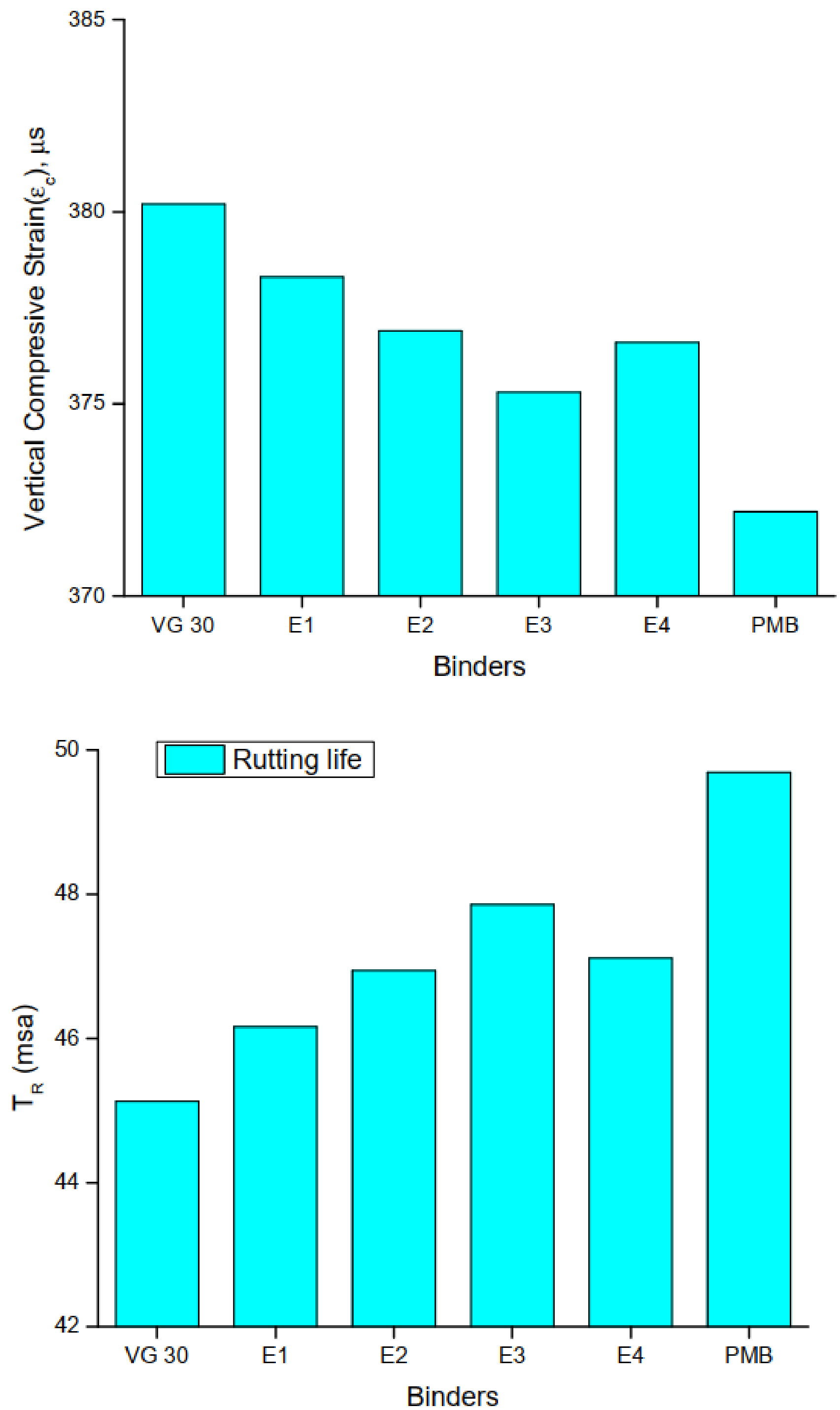


Figure 53. Result of pavement structure analysis T_R and ε_c.

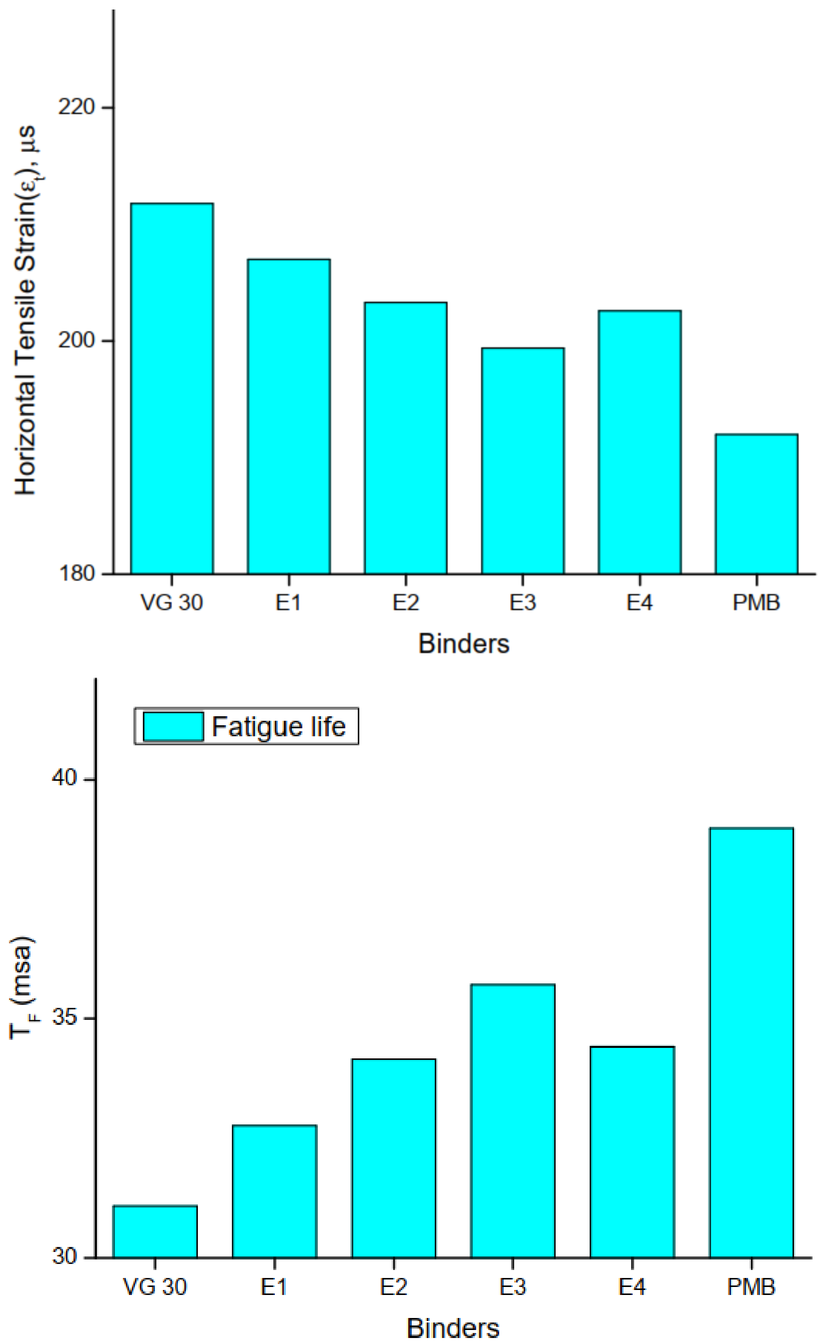


Figure 54. Result of pavement structure analysis T_F and ε_t.

5 SUMMARY & CONCLUSIONS

5.1 SUMMARY

Asphalt pavements serve as the backbone of our transportation system, providing secure and reliable spaces for vehicles to traverse. The durability and efficiency of these pavements heavily rely on the characteristics of the bitumen, which acts as the adhesive binder for the aggregate materials. To enhance the performance of bitumen under challenging conditions such as intense traffic, adverse weather, and aging, researchers and experts have been exploring innovative methods. One such approach involves incorporating epoxy resin, a synthetic thermosetting polymer widely used in various industries and applications. Epoxy resin is produced through a chemical reaction between epoxide monomers and a curing agent, typically a hardener, resulting in a highly durable and versatile material with a wide range of properties.

This study aimed to assess the impact of incorporating epoxy resin on asphalt binder characterization and mix design parameters. Specifically, it focused on evaluating the rheological properties of epoxy-modified asphalt binder and characterizing the mixture fabricated using this modified binder. Six samples were prepared for this study, including one commercial modified binder and five control binders, each with varying levels of epoxy resin modification (0%, 1%, 2%, 3%, and 4%).

The objectives of this study were divided into four tasks, each carried out independently to accomplish the goals of the research. **Task 1** focused on examining the rheological properties of epoxy-modified asphalt binder at high temperatures. Various tests were conducted, including PG grade, MSCR, frequency sweep, G* curve, temperature sweep, ZSV, and amplitude sweep. **Task 2** concentrated on studying the rheological properties of epoxy-modified asphalt binder at intermediate temperatures, employing tests such as SFP and LAS. **Task 3** aimed to investigate the rheological properties of epoxy-modified asphalt binder at low temperatures, with tests specifically designed for BBR analysis. **Task 4** focused on Marshall stability result of three different samples and also ITS and TSR test of all samples.

5.2 CONCLUSIONS

In this research, the focus was on studying the properties and performance of the mixture of Epoxy modified asphalt binder. Based on the test results and subsequent discussion, the following conclusions can be drawn:

- EMA binders with 2-3% content had better rutting resistance than control VG30 binder as observed from MSCR J_{nr}, MSCR recovery, temperature and frequency sweeps, and high PG grades. The optimum dosage was identified as 2-3% by weight of asphalt binder.
- LAS fatigue test showed that EMA binders had higher fatigue lives than control and commercial PMB binders.
- BBR low temperature tests showed better relaxing and lower stiffness of the E3 binder compared to control VG 30.
- EMA mixtures had higher Marshall stability, ITS, and TSR values signifying better stability and moisture damage resistance.
- Pavement structural analysis showed higher rutting and fatigue lives of a flexible pavement composition.

6 References

1. ASTM D6521. (2018). Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV). ASTM International, west Conshohocken, PA.

2. ASTM D6648. (2016). Standard Test Method for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR). ASTM International, west Conshohocken, PA.

3. Amirkhanian, S. (2020). Utilization of scrap plastics in asphalt binders. In Eco-efficient pavement construction materials (pp. 13-32). Woodhead Publishing.

4. Bahmani, H., Sanij, H. K., & Peiravian, F. (2022). Estimating moisture resistance of asphalt mixture containing epoxy resin using surface free energy method and modified Lottman test. International Journal of Pavement Engineering, 23(10), 3492-3504.

5. Bureau of Indian Road Congress, IRC 111, Specifications for Dense Graded Bituminous Mix, 2009.

6. Bureau of Indian Road Congress, IRC 37, Tentative Guidelines for the Design of Flexible Pavements, 2018.

7. Bureau of Indian Standards, IS 1203, Methods for testing tar and bituminous materials: determination of penetration, 1978.

8. Bureau of Indian Standards, IS 1205, Indian standard methods for testing tar and bituminous materials, 1978.

9. Bureau of Indian Standards, IS 1208, Methods for testing. tar and bituminous materials: determination of ductility, 1978.

10. Bureau of Indian Standards, IS 2386 (Part I) Method of test for aggregates for concrete (Part I) Particle size and shape, 1963.

11. Bureau of Indian Standards, IS 2386 (Part IV) Methods of test for aggregate for concrete Part IV Mechanical Properties, 1963.

12. Bureau of Indian Standards, IS 15462. Polymer Modified Bitumen - Speciation, 2019.

13. Cong, P., Chen, S., & Yu, J. (2011). Investigation of the properties of epoxy resin-modified asphalt mixtures for application to orthotropic bridge decks. Journal of Applied Polymer Science, 121(4), 2310-2316.

14. Cong, P., Liu, N., Shang, H., & Zhao, H. (2015). Rheological and fatigue properties of epoxy asphalt binder. International Journal of Pavement Research and Technology, 8(5), 370.

15. Cong, P., Tian, Y., Liu, N., & Xu, P. (2016). Investigation of epoxy-resin-modified asphalt binder. Journal of Applied Polymer Science, 133(21).

16. Cubuk, M., Gürü, M., & Çubuk, M. K. (2009). Improvement of bitumen performance with epoxy resin. Fuel, 88(7), 1324-1328.

17. He, Q., Zhang, H., Li, J., & Duan, H. (2021). Performance evaluation of polyurethane/epoxy resin modified asphalt as adhesive layer material for steel-UHPC composite bridge deck pavements. Construction and Building Materials, 291, 123364.

18. Kang, Y., Song, M., Pu, L., & Liu, T. (2015). Rheological behaviors of epoxy asphalt binder in comparison of base asphalt binder and SBS modified asphalt binder. Construction and Building Materials, 76, 343-350.

19. Luo, Z., Liu, T., Wu, Y., Yuan, H., Qian, G., Meng, X., & Cai, J. (2021). Study on Epoxy Resin-Modified Asphalt Binders with Improved Low-Temperature Performance. Advances in Civil Engineering, 2021, 1-15.

20. Mahajan, S. (2022). Rheological Characteristics of Chemically Treated Binders (Master's thesis).

21. Peiliang, C., Jianying, Y., & Shuanfa, C. (2010). Effects of epoxy resin contents on the rheological properties of epoxy-asphalt blends. Journal of applied polymer science, 118(6), 3678-3684.

22. Tarar, M. A., Khan, A. H., Rehman, Z. U., & Inam, A. (2021). Changes in the rheological characteristics of asphalt binders modified with soybean-derived materials. International Journal of Pavement Engineering, *22*(2), 233-248.

23. Wang, X., Ma, B., Chen, S., Wei, K., & Kang, X. (2021). Properties of epoxy-resin binders and feasibility of their application in pavement mixtures. Construction and Building Materials, 295, 123531.

24. Xiang, Q., & Xiao, F. (2020). Applications of epoxy materials in pavement engineering. Construction and Building Materials, 235, 117529.

25. Yin, H., Zhang, Y., Sun, Y., Xu, W., Yu, D., Xie, H., & Cheng, R. (2015). Performance of hot mix epoxy asphalt binder and its concrete. Materials and Structures, 48, 3825-3835.

26. Yu, Jianying, Peiliang Cong, & Shaopeng Wu. Laboratory investigation of the properties of asphalt modified with epoxy resin. Journal of Applied Polymer Science 113, no. 6 (2009): 3557-3563.

27. Yu, X., Dong, F., Ding, G., Liu, S., & Shen, S. (2016). Rheological and microstructural properties of foamed epoxy asphalt. Construction and Building Materials, 114, 215-222.

28. Zhang, Z., Sun, J., Jia, M., Qi, B., Zhang, H., Lv, W., ... & Liu, Y. (2020). Study on a thermosetting polyurethane modified asphalt suitable for bridge deck pavements: Formula and properties. Construction and Building Materials, 241, 118122.