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Behavior analysis of polymer modified bitumen in wet process: A literature review

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ABSTRACT

Huge polymer waste is currently the largest threat to the world. Extensive research is needed to develop various techniques for utilizing large amounts of polymer waste in beneficial ways. The road industry serves as an optimal sector for incorporating various waste polymers in the construction of flexible pavement. A variety of polymers have been proven as a potential modifier to improve the strength, stability, and durability of asphalt due to better resistance of bitumen to various distresses, such as rutting, fatigue, and thermal cracking. This study explores technical aspects and highlights the effects of several types of polymer addition in bitumen and its effects on both bitumen and asphalt. Additionally, the review discusses the compatibility, challenges, and prospects of polymer-modified bitumen. This study examines the impact of plastomeric polymer additives on the physical, rheological, and thermal properties of bitumen, providing a detailed comparison of their influence on the performance characteristics of asphalt mixtures. Studies show that adding 2–8% polymer by bitumen weight enhances asphalt stiffness, but mixing and storage methods greatly affect binder stability. The paper provides useful insights and recommendations for the design, construction, and maintenance of flexible pavements using polymer waste as a modifier in bitumen.

Keywords: flexible pavement, polymer modified bitumen, asphalt, plastic waste management.

INTRODUCTION

Plastic is a manmade material, created for convenience, and over time, its versatile uses have made it nearly impossible to replace. However, its non-biodegradable nature and poor disposal practices have turned it into a serious environmental challenge. The United Nations Environment Program (UNEP) claimed that every year, around 300 million tons of plastic waste are created worldwide [1] of which only 9% are recycled, 12% are incinerated, and 79% are accumulated in landfills in the natural environment [2]. Therefore, finding effective ways to reduce, reuse, and recycle plastic waste is a global challenge [3] and a priority for sustainable development. India is considered one of the fastest-growing plastic markets, with production rising at a rapid pace, around 16% annually. In comparison, China's growth stands at nearly 10% per year, as highlighted in several studies [4, 5]. Rapid population growth, urbanization, changes in lifestyle, and development activities are some of the factors contributing to the rise in plastic waste [6]. Plastic's affordability, durability, and versatility made it a popular material for a variety of applications, which led to a sharp increase in plastic production over the last seven decades [7]. One of the severe problems of landfill plastic waste management is that pollutants from plastic waste infiltrate into groundwater with rainfall [8], which is then consumed by humans daily [9]. Figure 1 presents the percentage-wise distribution of different polymer waste types in India. According to [10] 75.8% of the plastic garbage produced ended up in landfills and the environment, with only 8.4% recycled.

A promising way to utilize plastic waste is in the construction of flexible pavements, which are widely used for road construction [11, 12]. The

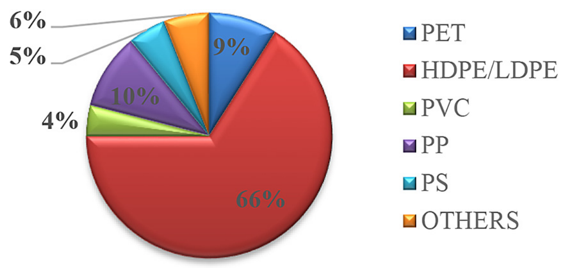

Figure 1. Percentage of polymer waste in India [14]

wearing course of flexible pavement is usually made of bituminous mixtures [13].

Bitumen is a viscous and sticky material by-product of crude oil that acts as a binder for the aggregates in asphalt mix [15]. However, bitumen has some limitations, such as high temperature susceptibility leads to cracking and rutting of pavement [16]. These limitations affect the performance and durability of the pavement and increase the maintenance cost and frequency. In the last few decades, various studies and research have been carried out regarding the use of polymer in road construction [17]. The plastic man of India, R Vasudevan, has developed a novel method for constructing asphalt pavement using leftover plastic garbage [18]. This process facilitates the eco-friendly disposal of waste. Additionally, this method has encouraged the waste plastic to be valued further. Polymers are utilized in road construction through two primary methods [19]. The first is the dry process, where plastic waste is coated onto aggregates before being incorporated into the asphalt mix, forming Plastic-Coated Aggregates, also known as dry process [20]. The second method is the wet process, in which polymers are directly blended into bitumen to enhance its properties before application [21]. A major limitation of the dry process is the release of hazardous gases, such as dioxins, when plastic-coated aggregates come into contact with hot bitumen during the preparation of the bituminous mixture [22]. These toxic emissions pose severe health risks to humans and other living organisms. Research indicates that dioxins can persist in the human bloodstream for several years and have been linked to an increased risk of blood cancer [23]. The use of polymers in bitumen through the wet process for road construction is comparatively safer than the dry process [24–26].

Table 1. Classification of rubber and polymer-based bitumen modifiers

Polymer based modifier	Examples
PMB(P)-Plastomeric	PE, EVA, EBA, EMA etc.
PMB(E)-Elastomenc	SIS, SBS, block copolymer, and ETP, etc.
Synthetic Rubber	SBR latex
NRMB	Latex or Rubber Powder
CRMB	Crumb Rubber

Note: EMA – ethylene methyl acrylate, EBA – ethylene butyl acrylate, SIS – styrene-isoprene-styrene, EVA – ethylene vinyl acetate, PMB – polymer modified bitumen.

The Indian Standard code (IS 15462:2004) categorizes polymer and rubber-modified bitumen into four distinct types: PMB(P), which is based on plastomeric thermoplastics; PMB(E), derived from elastomeric thermoplastics; NRMB, utilizing natural rubber; and CRMB, which incorporates crumb rubber as the modifier (Table 1).

Among the various available modifiers, polymer is selected for this study due to its well-established ability to significantly improve the mechanical and rheological behavior of bitumen [27, 28]. This review paper primarily discusses the wet process of polymer utilization in asphalt, commonly known as PMB (Polymer Modified Bitumen), with a specific focus on plastomeric-based polymer modification [PMB(P)]. In the wet process, different types of modifiers are blended with bitumen in suitable proportions, and the resulting modified bitumen is then used in the construction of flexible pavements [29, 30]. This modification aims to address the shortcomings of virgin bitumen temperature susceptibility and improve bituminous road performance [31]. The primary objective of this modification is to enhance the durability of flexible pavements, which may be affected by temperature and wheel load [32–34]. Asphalt exhibits significant temperature sensitivity, becoming brittle in cold conditions and softening into a liquid at high temperatures. This characteristic contributes to cracking failures in winter and rutting distress in summer, affecting pavement durability. For effective road construction, the ideal bitumen binder should exhibit specific characteristics at both high and low service temperatures. It needs to maintain its integrity and avoid breaking or deforming under the constant heat cycling it experiences during its design service life [35–37]. These issues reduce road durability, making modifications like polymer additives essential for improved performance [38]. Additionally, high temperatures can cause bitumen to rise to the surface, leading to bleeding and reduced skid resistance [39]. The lack of elastic recovery further contributes to fatigue and thermal cracking [40]. These limitations can be mitigated by modifications in virgin bitumen for flexible pavement construction. Polymers play a crucial role in modifying bitumen to enhance its temperature susceptibility [41]. Elastomeric polymers like SBS improve elasticity, reducing rutting at high temperatures and preventing cracking in low-temperature conditions [42, 43]. Plastomeric polymers, including LDPE and EVA, increase stiffness and rutting resistance but may reduce flexibility in colder climates [44]. CRMB enhances thermal stability, elasticity, and aging resistance, improving pavement durability under varying temperatures [45]. Each polymer alters the rheological behavior of bitumen differently, and the selection of polymer depends on climatic conditions, traffic load, and performance requirements [46]. Determining the appropriate polymer dosage is critical for achieving adequate stiffness, balanced ductility. Studies have been conducted – and are still ongoing – on the modification of bitumen using polymers. However, most of these focus on a specific type of polymer or a particular performance characteristic. In this review paper, various categories of polymers—including plastomeric, elastomeric, natural, and crumb rubber – have been briefly discussed with a special emphasis on the wet process of modification. The review not only considers the optimum polymer content but also correlates the findings with advanced characterization techniques such as DSR (dynamic shear rheometer), DSC (differential scanning calorimetry), TGA, XRD (x-ray diffraction), and others. This review aims to bridge the existing research gaps by providing a comprehensive and systematic analysis of the performance and structural characterization of polymer modified bitumen.

Objective

The main aim of this paper is to review the related studies about the behavior analysis of bitumen and asphalt with different kinds of polymer modifiers, their effects, and the optimum percentage for modification, especially using the wet mixing process.

Incorporation of polymer in bitumen

Considerable effort remains in progress to improve mechanical properties, evaluate environmental impact, ensure long-term performance, and ensure compatibility with other additives [47]. Research indicates that modifying bitumen with polymers leads to improved pavement performance [48]. However, several technical challenges remain, such as determining the exact optimum dosage required to achieve desirable results, identifying the most effective mixing process, understanding the impact of storage conditions, and evaluating the extent of physical blending between the modifier and virgin bitumen [49–52]. Assessing the compatibility of a modifier with bitumen is crucial to ensure its suitability for use [53]. This evaluation involves several key parameters, including the modifier's melting temperature, its physical form, and its effects on bitumen's molecular structure, enthalpy, adhesion, and ductility [54]. To evaluate the compatibility and effectiveness of a modifier in bitumen, several advanced tests such as DSR, DSC, RTFOT (rolling thin film oven test), PAV (pressure aging vessel), FTIR (fourier transform infrared spectroscopy), XRD, SEM (scanning electron microscopy), and TGA are commonly conducted apart from conventional tests. Table 2 presents a summarized overview of the effects of plastomeric and elastomeric polymer modifiers commonly incorporated into bitumen. It outlines the key performance enhancements achieved through polymer modification, including improvements in rheological behavior, thermal stability, aging resistance, and mechanical properties. These modifications contribute significantly to the durability and functional efficiency of bituminous materials, making them more suitable for diverse environmental conditions and traffic loads.

METHODS AND DISCUSSION

This review paper briefly summarizes selected studies in a way that provides a concise and effective crux of multiple research works, especially by including a wide range of plastomeric-type modifiers used in polymer-modified bitumen. Additionally, for a deeper understanding of PMB behavior, related studies involving advanced characterization techniques such as XRD, SEM, TGA, DSC, DSR, RTFOT, PAV, BBR (Bending

Table 2. Summary of polymer additives used as modifiers in bitumen

S.No	Bitumen grade	Modifier	Suitable addition	Method/Test	Outcome	Refere-nces
1.	60/70 Penetration	EVA	5%	Fluorescent microscopy, DSC, DSR	The modification increases the binder stiffness (complex modulus), binder elasticity (storage modulus), and elastic behavior (phase angle) with an increase in polymeric dominant PMB	[78]
2.	B 40/50 penetration	Nitrile Rubber	5%	DSR, DSC, TGA, FTIR	Used (NBR) from the shoe sole and rheological characteristics were measured with DSR. 5% resulted in the highest values of moduli, both at high temperature and at low frequency	[79]
3.	B 100/130	PET	1–3%	SEM	An increase in added PET polymer waste raises the softening temperature, indicating greater material hardness.	[80]
4.	B 60–70 penetration	Nano-Clay	4%	Dynamic creep test	Almost 80% enhancement in the rutting performance of control mixes	[81]
5.	VG 40	Bakelite	1–5%	Marshal Stability Test, Softening Point Test, Penetration Test	The penetration value is lowest at 1.75%, indicating greater enhancement in shear resistance at high temperatures. The softening point value, which is highest at 1.75% of Bakelite, indicates a better improvement in resistance to deformation.	[82]
6.	B 50–70	Phenol-Formaldehyde	1–4%	Viscosity, DSR	viscosity, softening point, glass transition temperature, and stability, increase, and heat sensitivity, surface energy, penetration, and stripping decrease when bitumen is modified with the addition of 2% by weight phenol formaldehyde	[83]
7.	B 200	Cellulose Fibre	0.2–0.4%	Penetration Test, Softening Point Test, Viscosity	Experimental results indicate that the viscosity of the fiber-reinforced asphalt binders is increased by the addition of fibers, especially when the fiber concentration is medium and coarse	[84]
8.	B160/220 & B70/100	Recycled LDPE	2–5%	DSC, Softening Point, controlled stress rheometer	Bitumen modification by 4 or 5% LDPER led to a relevant increase in binder viscosity, whereas the viscosity curves show an abrupt decrease in binder viscosity between 100–120 °C, above the polymer melting point.	[85]
9.	VG 30	GMA-g-LDPE	3–6%	Softening Point, Ductility, Penetration, Storage Stability, DSR Test	The increasing extent of the softening point of GMA-g-LDPE modified bitumen is greater than that of the LDPE modified bitumen. The compatibility between GMA-g-LDPE and bitumen is reinforced which increases the ductility at low temperatures.	[86]
10.	Bitumen C320	R-LLDPE		RV, Softening Point, FTIR, TGA, MDSC	The melting enthalpy, degree of crystallinity, and thermal stability were improved. Modified blends have more ability of resistance against permanent deformation at high temperatures as compared to base bitumen.	[87]
11.	Bitumen Type C	Waste EMR Plastic	7.5%	RTFOT, RLITT	The density of the mix increased with an increase in the binder content	(Jafar, 2016)
12.	VG-30	Sulphur	2–3%	Viscosity Test, RTFOT, Storage Stability Test	Sulphur modified bitumen binder does not exhibit phase separation under elevated temperature. SMB binder shows good storage stability.	[88]
13.	VG 30	Crumb Rubber	18%	SEM, Indirect Tensile Strength Test	Specimens subjected to dynamic load aging have a shinier surface compared to those aged without loading. No Specific change was observed in the IDT value	[89]

14.	B35/50	SBS	2-4% SBS + 3% PP, LDPE & PS	Softening Point. Penetration & Elastic Recovery	The use of SBS in reduced considerably the penetrability of SBS/RPMB, an increase of more than 30% in softening point & increased the elastomeric characteristics of the mixture to more than 70%	[90]
15.	VG 10	EVA	5%	Fluorescence Microscopy, Storage Stability Test	The shear rate increases as the % modifier increases. With inc. in temp. decrease in G* for PMB is less than that of base bitumen	[91]
16.	VG 10 and VG 30	SMA	6%	Indirect Tensile Strength, Moisture Susceptibility Test. Four-Point Beam Bending Test.	SMA gave the best performance in fatigue (five times higher than other mixes)	[92]
17.	B50/70	SBS	5%	Dynamic bitumen tests, direct tensile test, Fluorescence Microscopy, Qwin Plus image analysis. Penetration, Softening Point Tests	Increases the softening point and reduces penetration. This indicates increased stiffness (hardness) of the PMBs. Less sensitive to permanent deformation.	[93]
18.	PMB45/80-55	SMA	(> 7%)	Dynamic bitumen tests, direct tensile test	Higher air void content, complex viscosity, and complex modulus, low susceptibility to loading time, drop in stiffness modulus	[94]
19.	VG 30	PET bottles	2%	FTIR spectroscopy, DSR, Frequency sweep test, Bending beam rheometer, Hot water stripping test, RTFOT	Better rutting resistance and elastic responses than the base bitumen binder and shows lower stiffness.	[95]
20.	B70/100	EVA	7%	DSR, Fluorescence Microscopy, RTFOT	After aging, the penetration values of PMBs are decreased, while the softening point is increased.	[96]
21.	60/70	APP	2–2.5%	Thin Film Oven Test, Marshall stability test	Enhanced resistance towards moisture susceptibility, improves stability and durability	[97]
22.	PG70	SBR	2–8%	RV and DSR test, RTFOT, PAV, SEM	Improvement in temperature resistance, better anti-aging performance	[98]
23.	60/70, 85/100	Chloroprene Rubber	3–7%	RV, DSR, MSCR, and LAS tests	Increases softening point and viscosity of the asphalt binder	[99]
24.	PG70	PAN	8.5–10%	DSR, The frequency sweep test, penetration test, softening point test	Provide more improvements in stability, mechanical, rheological, and thermal properties	[100]
25.	60/70	SIS	5–10%	RV, DSR, and the bending beam rheometer	Increased the viscosity and had a positive effect on the rutting resistance of the binder, better the cracking resistance, improved the stiffness	[101]
26.	PG50/60	PP	5%	Marshall Test, Indirect Tensile Strength Test, Drain Down, Penetration Test	Improvement in resistance to deformation, reduced bleeding phenomenon, improved tensile strength ratios, decreased surface deflection	[102]
27.	VG30	EPDM	6–8%	Penetration, softening, and frequency sweeps test, binder yield energy tests, Hamburg wheel tracking, stiffness modulus,	Enhanced the rutting resistance, fatigue performance, stiffness, and tensile strength	[103]

28.	VG10	PVC	1–1.5%	Softening point test, penetration test, BBR, DSR test, Hot water stripping test	Improved the fatigue characteristics, improved performance and stability	[104]
29.	VG30	ABS	4%	Penetration, softening point, viscosity test and DSR, Marshall stability test	improvement in high-temperature performance, softening point, and increased rutting resistance	[105]
30.	PG80-100	PANI (Polyaniline)	1%	Penetration test, softening point test, ductility and viscosity test, Spectral, thermal, and SEM	Improved physical, thermal, and anti-stripping properties, extended the life of Pavement Surfacing and Performance	[106]
31.	PG 60/70	PU	0.5–1.5%	foaming tests, Temperature sweep tests, Penetration test, softening point, viscosity test	Improved storage stability, viscosity, enhanced performance, elastic behavior, and lower temperature susceptibility	[107]
32.	PG 80/100	HDPE	5%	Penetration test, Ductility test, Flexural test, Marshall test, Softening point test	Softening point was raised by 69%, more resistant to deformation, Marshall Quotient increased by 55%, improving the resistance to moisture susceptibility	[108]
33.	PG60/70	Natural Rubber	7%	Rotational viscosity test, DSR test, Multiple stress creep recovery test	Improves binder's resistance to rutting, thermal cracking, and fatigue, resulting in an improvement of the PG grade, reduces temperature sensitivity	[109]
34.	PG150/200 by Repsol YPF	Recycled Polyethylene	< 5%	Steady flow tests, Modulated differential scanning calorimetry, tensile tests	Increase in the values of the storage and loss moduli, and viscosity, as well as an apparent decrease in thermal susceptibility, higher resistance to permanent deformation or rutting	[110]
35.	B 160–220	Crumb Rubber	8%	Rotational Viscometer, DSR, Penetration test, Softening test	Reduced temperature susceptibility and superior performance properties were observed	[111]
36.	PG60/70	PMMA	7%	Resilient modulus test, Hot storage stability test, Marshall stability test, RTFOT	Aging properties improve, reduce temperature susceptibility, enhance rutting resistance, tensile strength increase	[112]
37.	PG 85-100	PBR	1–1.5%	XRD, FTIR, BBR, DSR	Increases resistance to fatigue, low-temperature cracking, and durability	[113]
38.	AC-10	PAM	7.5%	Rutting test, Anti-cracking test, Marshall immersion test, Thermal conductivity test	Improve the moisture resistance, enhance crack resistance, and improve thermal insulation properties, temperature stability performance	[114]
39.	PG 64-22	PEG	5–10%	Indoor irradiation test, Shear strength test, DSR	Increased resistance to deformation, improved low-temperature behavior, improved the elastic property	[115]
40.	PG-70	PTFE	5%	SEM, FTIR, XRD, RTFOT, PAV , DSR, RV test	Increased viscosity, increased rigidity, improved stiffness, and other mechanical properties	[116]

Note: ABS – acrylonitrile butadiene styrene, AC – asphalt cement, APP – atactic polypropylene, BBR – bending beam rheometer, DSC – differential scanning calorimetry, DSR – dynamic shear rheometer, EPDM – ethylene propylene diene monomer, EVA – ethylene vinyl acetate, FTIR – fourier transform infrared spectroscopy, HDPE – high-density polyethylene, IDT – indirect tensile test, LAS – linear amplitude sweep, LDPE – low-density polyethylene, MDSC – modulated differential scanning calorimetry, MSCR – multiple stress creep recovery, PAM – polyacrylamide, PAN – polyacrylonitrile, PAV – pressure aging vessel, PBR – polybutadiene rubber, PET – polyethylene terephthalate, PG – performance grade, PMB – polymer modified bitumen, PMMA – polymethyl methacrylate, PP – polypropylene, PTFE – polytetrafluoroethylene, PU – polyurethane, PVC – polyvinyl chloride, R-LDPE – recycled low-density polyethylene, RLITT – repeated load indirect tensile test, RTFOT – rolling thin film oven test, RV – rotational viscosity, SBS – styrene-butadiene-styrene, SEM – scanning electron microscopy, SIS – styrene-isoprene-styrene, SMA – stone mastic asphalt, VG – viscosity grade, XRD – x-ray diffraction.

Beam Rheometer), Marshall, and many more tests have been reviewed. The aim is to highlight, in a single view, the optimum polymer content and corresponding performance outcomes. The major insights drawn from previous studies are summarized as follows.

Thermal stability

PMB shows better thermal stability than virgin bitumen, as evident from DSC and TGA tests. DSC results indicate a higher glass transition temperature (T_g) in PMB, reflecting improved heat resistance [55–59]. TGA analysis also shows delayed degradation in PMB, starting around 370–400 °C, while virgin bitumen begins degrading near 300–320 °C. This confirms that polymer additives enhance the thermal durability of the binder under high-temperature conditions [60–62].

Viscoelastic behavior

From the DSR tests analysis, it's clear that PMB shows higher stiffness and better elasticity compared to virgin bitumen, thanks to its increased complex shear modulus (G*) and lower phase angle (δ) [63–66]. This means PMB handles deformation and rutting in flexible pavement much better at high temperatures. The Marshall test studies show that PMB mixes have higher stability and less flow, proving that these carry heavier loads and last longer [67, 68]. Overall, these results make it obvious that adding polymers boosts the viscoelastic behavior of bitumen.

Phase structure

XRD and SEM together give a clearer picture of how polymers affect bitumen at the micro and structural levels. XRD helps identify changes in the crystalline or amorphous nature of the blend, especially when polymers like LDPE or PET are added [69]. A shift in peak intensity or the appearance of new peaks shows improved blending or molecular rearrangement. SEM reveals how evenly the polymer spreads – smoother, more uniform surfaces mean better interaction [70]. Overall confirms that polymer modification improves the internal structure of bitumen.

Storage stability

Storage stability of PMB ensures the polymer remains well blended during high-temperature storage [71–74]. The cylinder tube test measures softening point or penetration differences between top and bottom samples. Viscosity tests and microscopic methods like FTIR and DSC further assess phase separation and chemical changes. The storage stability of PMB still has significant research potential to improve understanding of long-term polymer–bitumen interactions.

Blending constraints

Based on several research findings, the mixing of polymers with bitumen faces key limitations (Figure 2). Most studies highlight that temperature control is critical – too low leads to poor blending, while too high causes polymer

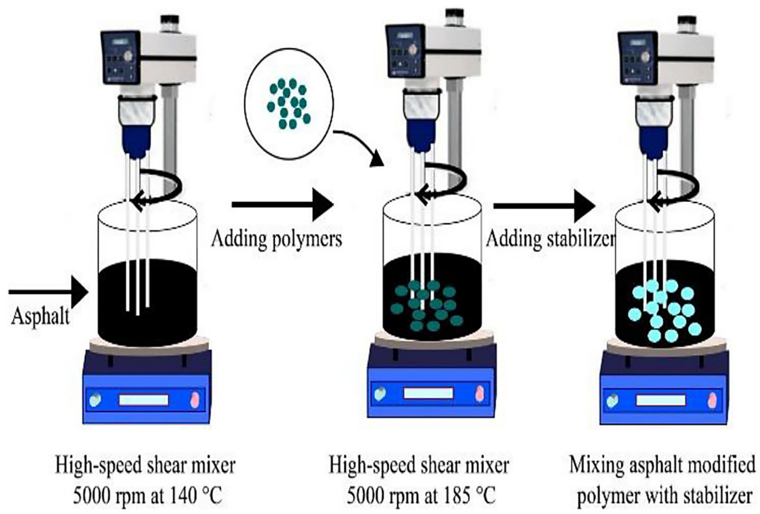

Figure 2. Blending of polymer in bitumen [75]

degradation [76, 77]. Compatibility is also a concern, as phase separation and the creaming effect are common with certain polymers. High shear mixing is often required, which isn't always accessible.Also, improper mixing time – whether too short or too long – can affect performance. Many papers also point out high energy costs and poor storage stability as recurring issues, along with safety risks due to fumes from some polymers during heating.

CONCLUSIONS

This comprehensive review has elucidated the intricate interplay between modifiers and the resulting alterations in bitumen properties. Through exhaustive examination of the literature, the profound influence of modifiers, mainly polymers, on bitumen's rheological, thermal, mechanical, stability, and aging characteristics is delineated. The penetration test reveals that PMB possesses lower penetration values compared to virgin bitumen, resulting in increased stiffness and improved resistance to rutting at elevated temperatures. Likewise, the softening point test indicates that PMB has a higher softening point, which helps minimize deformation and bleeding in hot weather. Regarding ductility, although virgin bitumen generally has higher values, PMB enhances elasticity and tensile strength, reducing the likelihood of cracking in cold climates and enhancing fatigue resistance. Additionally, the stripping value test shows that PMB has lower stripping values than virgin bitumen, signifying stronger adhesion to aggregates and superior resistance to moisture-related damage. XRD analysis of PMB shows improved crystalline structure and phase stability, enhancing mechanical strength and durability. SEM images reveal a more uniform, less porous morphology with better adhesion, reducing moisture susceptibility. These structural enhancements contribute to superior performance in flexible pavements compared to virgin bitumen. DSC and TGA confirm improved thermal stability and resistance in PMB. RTFOT indicates better aging durability, while FTIR shows reduced oxidation, enhancing chemical integrity. These factors make PMB superior to virgin bitumen for flexible pavements.

Our synthesis reveals that the incorporation of modifiers engenders substantial improvements in the rheological attributes of bitumen, manifesting in enhanced resistance to deformation and reduced susceptibility to temperature fluctuations. Furthermore, modifiers have been shown to augment the fatigue resistance and overall durability of bituminous mixes, thus prolonging pavement service life. Of particular significance is our detailed analysis of DSR test studies, which has yielded valuable insights into the modulation of bitumen viscoelastic properties by various modifiers. The accompanying table provides a succinct summary of pertinent findings, delineating the impact of modifiers on complex modulus, phase angle, and other key DSR parameters.

In essence, this paper underscores the pivotal role of modifiers in tailoring bitumen properties to meet stringent performance criteria in contemporary road infrastructure applications. By leveraging a nuanced understanding of modifier effects, researchers and practitioners can optimize bituminous formulations to achieve desired performance characteristics, thereby advancing the sustainability and resilience of transportation infrastructure.

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