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Review

Rutting and Aging Properties of Recycled Polymer Modified Pavement Materials

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Abstract: Recycled polymer-modified binders have emerged as a sustainable solution for improving the performance and durability of pavement materials. This review examines the rutting and aging properties of pavements modified with recycled polymers, highlighting their potential for sustainable infrastructure development. The incorporation of recycled polymers into bitumen enhances resistance to rutting and aging by improving the binder's mechanical stability and oxidative durability. Key laboratory techniques, including the Rolling Thin Film Oven Test (RTFOT) and Pressure Aging Vessel (PAV), are evaluated for their effectiveness in assessing the thermal and oxidative aging behavior of modified binders. The review demonstrates that recycled polymers improve binder elasticity, delay oxidative degradation, and mitigate deformation under repeated loading, thus extending pavement lifespan and reducing maintenance costs. However, challenges such as optimizing polymer dosage, ensuring homogeneity, and predicting long-term performance require further investigation. This paper underscores the environmental and economic benefits of utilizing recycled polymers in pavement construction and advocates for improved testing protocols and advanced characterization techniques to enhance the reliability and sustainability of polymer-modified pavements.

Keywords: recycled polymers; bitumen modification; rutting resistance; aging resistance; sustainable pavements; CRMB; SBS; PP; PET; LDPE; HDPE; PS

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1. Introduction

1.1. Chemical Composition of Bitumen

Bitumen binders are among the most common materials used in construction and infrastructure. As versatile materials, they find application in an extensive range of projects, including road construction, waterproofing, adhesives, and roofing. According to the research published by Holy and Remisova (2019), the chemical compound of bitumen binders consists of essential components like asphaltenes, resins, aromatics, and saturates. Asphaltenes are the most complex and high molecular-weight hydrocarbons that improve bitumen's viscosity and adhesive properties. Resins are sticky solids maltenes that play a vital role in binding aggregates in asphalt concrete mixtures and have a strong attraction to other substances. Aromatics act as the oily medium, and saturated is the law molecular weight and least complex of these four fractions in bitumen. They coat aggregates and compact bitumen used in road construction. The most important fraction of bitumen is assessing its ease of mixing and use at specific temperatures.

In addition to hydrocarbons, small amounts of sulphur, nitrogen, and oxygen compounds are inherent components of bitumen, the properties of which may vary by the nature of influence. Previous analysis of shows that most bitumen contains 82-88% of carbon, 8-11%of hydrogen, 0-6% of sulphur, and 0-1.5% of nitrogen. Sulphur compounds contribute to the adhesion and elasticity of the hot mix, while the nitrogen and oxygen ones influence the oxidative stability of the bitumen and the level of its ecological trace. It is important to note that bitumen mixtures contain different types of

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formulations with specific additives that provide certain unique properties, such as elasticity or stiffness and resistance to other physical characteristics, including aging (Holy & Remisova, 2019).

1.2. Physical Properties of Bitumen Binders

Bitumen's rheological behavior is controlled by elasticity, stiffness, flow characteristics, and strength, also identified as its main physical properties (Holy & Remisova, 2019). Bituminous binders must possess specific properties necessary for optimal performance in construction materials. One of these properties is hardness, which is measured by penetration test. Another vital property is viscosity, which affects the bitumen’s flow and coating during mixing and compacting during road construction. Different types of viscosity tests do the measuring of the viscosity; bitumen with low viscosity is suitable for hot weather, and bitumen with high viscosity is suited for cold weather conditions as the hardening occurs slowly. Secondly, the property fulfilled by the bitumen is the adhesion, which assumes the cementing of the binder to the other substrates, such as aggregates and the pavement surface, defending the tensile strength of the asphalt pavement material against complex loading and environmental conditions. The temperature at which bitumen becomes liquid is identified as the softening point, and for hot weather conditions, it is crucial to use bitumen with a high softening point (Zahedi, 2024).

1.3. Regulatory Standards and Specifications

Bitumen binders are employed fundamentally in all construction works, with regulated standards and specifications such as quality, safety, and sustainability guidelines. Australian Standards are maintained and developed by the Australian Asphalt Pavement Association, which originated in Australia, to give guidance/specifications for asphalt materials and their constructions in the nation. For example, the organization published the “Guide to Pavement Technology” series, which contains several details of the specifications of bitumen binders, including type, viscosity grade, performance requirements, and testing (De Carteret et al., 2009)

Correspondingly, the Australian Standards and State Road Authorities compel all stakeholders to follow the internationally accepted standards, which require strict compliance with qualitative testing and other quality assurance test methods. The AC use also highlights the application of environmentally friendly and recycled materials in manufacturing bitumen binders. As a result, the stakeholders guarantee that the QMS and the linked specifications maintain comprehensive adherence to enhance high-level safety, quality, and sustainability in construction in Australia.

1.4. Challenges and Innovations

The most critical challenges observed include aging, rutting, temperature sensitivity, and environmental risk that have adverse impact on the performance and sustainability of construction materials. The most critical challenge in aging are the mechanistic properties of bitumen binders that are affected because the binders age due to oxidation and thermal degradation and UV radiation reducing their viscosity and stiffness and increasing their risk of cracking (Polo-Mendoza et al., 2022). Bitumen binders as a material are now subject to environmental issues such as their energy consumption, emissions and sustainability and their environmental impact is an important issue in the construction sector. Carbon emissions and other environmental degradation come with bitumen extraction and refining too. So, there is a need for greener, more sustainable alternatives.

1.5. Bitumen Aging

The gradual breakdown of the materials of the pavement with time is known as pavement aging, and there are a broad range of aging mechanisms. The three main sources of damage are oxidative aging, moisture damage, and thermal fatigue. Asphalt properties, including stiffness, cohesion and fatigue resistance, are altered through these processes and have an effect upon pavement performance and life.

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1.5.1. Mechanisms of Aging

Different mechanisms deteriorate the asphalt materials. X. Wang et al. (2019) examined the aging of bitumen from pieces from bridge decks, traffic lanes, and ramps. The samples were tested using four experiments: Fourier transform infrared spectroscopy, dynamic shear rheometer, gel permeation chromatography, and fluorescence microscope. As a result, the age of the top of the pavement is much more important than the other two layers. The study identified the primary processes of bitumen aging as oxygen absorption, change in viscoelastic properties and molecular weight alteration. The asphalt starts to age when oxygen and UV rays get to it. The resultant chemical oxidation of the asphalt binder in such a process forms stiffening compounds, e.g., carbonyl groups or cross-linked structures. The moisture damage factor involves water penetrating and travelling through the design system such that the asphalt binders are stripped, and the aggregate is displaced; the asphalt bolts and loses adhesion between each confined layer. Pavement materials expand and contract with temperature change, which causes pullout tension and leads to thermal fatigue cracking and surface distress. All aging mechanisms are correlated and promote each other, accelerating pavement destruction, and they cannot resist loading and other environmental distress any longer.

1.5.2. Factors Influencing Aging

Considering the prominent influence of bitumen aging, several papers were performed to reveal the influence of the aging phenomenon factor. Tauste et al. (2018) mainly focused on a review of the factors that influence bitumen aging and pavement aging, which are affected by oxidation, UV radiation, binder composition, additives, and testing methods. Also, temperature and humidity are environmental conditions that impact pavement aging, traffic loading, material properties, construction practices, and maintenance activities. Mechanical stresses arising from the factors above lead to material degradation and traffic loading strain between the applied loads and the Pavement. Composition, aging sensitivity, and asphalt binder rheology influence pavement aging. The performance and durability of pavements result from pavement construction with asphalt mixture production and placement methodologies. Maintenance practices that slow material aging include seal coating, crack sealing, and surface renewal, that is, chip sealing. To optimise effective aging mitigation strategies and to design durable pavement systems, the stakeholders in the construction and maintenance of pavements need to understand these factors.

1.5.3. Laboratory Aging

The bitumen aging identification in the field is difficult and expensive as it involves precipitation, temperature, and sunlight (any other), which depends on the specific field condition (Yahaya et al., 2019). The aging process can be divided into two processes: long-term aging and short-term aging. Several failing pavement tests are used to characterise pavement aging and quantify its effect and extent on pavement performance and sustained service. There are many established laboratory test methods for short- and long-term aging. For the majority of the time, the thin film oven test (TFO) and the rolling thin film oven test (RTFOT) currently simulate short-term aging, whereas Pressure Acing vessel (PAV0 simulates long term aging. are used to identify pavement aging and measure its impact and extent on pavement performance and longevity. Many established laboratory test methods for short and long-term aging exist, and most of the time, the thin-film oven test (TFO) and the rolling thin-film oven test (RTFOT) currently simulate short-term aging and Pressure aging vessel (PAV0 conducted to simulate the long term aging. Rheological tests, e.g., dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests, are used to study the performance of asphalt binders subjected to dynamic loading and temperature variations, and the test set-up is designed to enable the understanding of the modification of rheological properties brought about by the aging. (Jiang et al., 2021).

The properties of same grade bitumen derived from different crude sources were studied by Hofko et al. (2017) with regard to the effect of aging. Long- and short-term laboratory experiments were conducted using RTFOT, PAV and RTFOT+PAV methods. Standard tests were performed on the properties, and the rheological data was determined using a dynamic shear rheometer (DSR) test. This resulted in more severe aging of the bitumen with PAV aging, but how it aged the bitumen after short-term aging had less effect on the properties of the bitumen.

In a study conducted by Jian et al., (2021), they studied the effects of various ageing methods on both the performance of bitumen and the composition of molecular components. The study was conducted on two virgin bitumen types, and experiments were conducted using three aging methods: RTFOT, PAV, and RTFOT+PAV. It is found that the combined test RTFOT+PAV aging had the most impact on the properties of the bitumen, with RTFOT having a more substantial effect than PAV. When long-term aging facilities are lacking, the study recommends using RTFOT rather than PAV.

Lu et al. (2008) conducted a study aiming to simulate the aging of bitumen in laboratory conditions using various methods At various temperatures and various durations: PAV, RTFOT and RCAT (Rotating Cylinder Aging Test). The binders tested were A120, B85 and PMB20 unmodified and polymerised (SBS). Additionally, they compare laboratory results for the samples of roads of different ages to field conditions and ascertain the extent to which we can predict actual field conditions. They found that the road sample did not age nearly as much as the laboratory-predicted values. The researchers assumed the low air space in the roads combined with the protective screens to account for the results. The long-time aging tests RCAT and RTFOT, however, showed some discrepancies. However, finally, the short-term aging test RCAT and RTFOT gave similar results, thus indicating that short-term simulation, rather than the long time test, is preferred.

The effects of laboratory short-term aging on bitumen properties were studied by Yahaya et al. (2019). The same grade of bitumen (80/100 pen grade) was procured from two different sources; 60/70 pen bitumen (A80, B80 and B60) was used by the researchers. To determine the aged and unaged bitumen properties, they carried out the standard RTFO test and common standard tests, including dynamic shear rheometer (DSR), viscometer, and Fourier transform infrared spectroscopy. The finding was that aging duration and temperature increased the viscosity linearly at a faster rate with higher temperatures. In addition, the aging indices G* were found to increase with increased age and temperature. The research also demonstrated that the severity of the aging would increase the carbonyl and the sulfoxide indices.

In a further article, Hofer et al. (2023) compared chemical and mechanical analyses of field and laboratory-aged bitumen by RTFOT, PAV or Viennese Binder Aging (VBA) using an unmodified 70/100 penetration graded bitumen and actual field sample of the same base binder. Data analysis consisted of dynamic shear rheometer (DSR) and Fourier transform infrared (FTIR). This has confirmed that we simply could not achieve the field aging level in either of the experiments. Nevertheless, these VBA samples show more similarities to field samples than the other laboratory aging methods.

1.6. Rutting

1.6.1. Mechanisms of Rutting and Factors Influencing

The mechanisms of rutting are associated with permanent deformation under repeated loading. Traffic loading factors and their concentration, including traffic volume and composition, channelisation and lateral wander, climate conditions, pavement structure, material quality, and construction techniques, control frictional forces and pressure on the layers shearing and compacting. This dynamic method results in the material's viscous and plastic deformation throughout the compaction process. This phenomenon led to the breakdown of the internal structure of the asphalt mixture and permanently deformed the pavement's surface. Excessive moisture and temperature fluctuation facilitate these processes as they make the asphalt binder more susceptible to softening and cohesion and decrease resistance to deformation. Rutting is identified as the key mechanism of plastic deformation that ultimately leads to an inferior quality of the payment and comes at a high

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cost for maintenance and repair. Thus, understanding these mechanisms is essential for the development of effective rutting control strategies and the design of durable pavement system (P Pavement systems (Pan et al., 2023 and Sinanmis & Woods, 2022).

Several factors contribute to the rutting in pavements, including internal, external, and human-related factors. Internal factors, such as properties of the material used in the asphalt mixture (internal friction and cohesion properties, balance of the amount of binder, aggregate gradation and angularity, and surface layer thickness), are related to the internal factors. The external factors could be termed as the external load, including traffic, axle load and environmental factors, such as temperature and moisture. The rutting resistance decreases with an increase in temperature as the binder melts. Constructing quality is based on the degree of compaction, temperature, and degree of segregation suffered as a result of human-related factors. (Pan et al., 2023).

1.6.2. Measurement and Evaluation of Rutting

Methods and techniques for measuring and evaluating rut depths in pavement are numerous. These include field surveys, pavement distress indices, and laboratory testing including Oscillation Test (Dynamic Shear Rheometer - DSR), Creep and Recovery Test (MSCR), Viscous Component of Creep Stiffness (Gv), Zero Shear Viscosity (ZSV) and Low Shear Viscosity (LSV), Shenoy's Rutting Parameter and, in recent years, numerical modelling of the rutting behavior of pavement materials. Radhakrishnan et al. (2018) studied evaluating rutting parameters using nine different types of bitumen, including unmodified as well as polymer and crumb rubber-modified bitumen binders subjected to various parameters, including temperature, loading time, stresses, strains, etc. The $G^*/\sin\delta$, Shenoy's parameters, viscosity, oscillation, creep and recovery modes, wheel tracking rut depth, and other parameters were studied to evaluate the rutting resistance.

1.7. Bitumen Modification

Due to the challenges mentioned above and the need to optimise and minimise production costs, research and innovations of advanced bitumen formulations and technologies have been actively discussed. Celoglu et al. (2018) explore the impact of Styrene–butadiene–styrene (SBS), Trinidad Lake Asphalt (TLA), Iranian Gilsonite (IG), and American Gilsonite (AG) as bitumen modifiers, Olabemiwo et al. (2017) focused on enhancing the thermal aging resistance of ANB through polymer modification, Gokalp and Uz (2021) conducted a study into enhancing aging resistance using waste engine oil (WEOIL), Nordiana et al. (2019) used waste cooking oil (WCO) as the modifier for bitumen in order to assess the rutting resistance, Ansar et al. (2022) conducted a study utilising polycarbonate (PC) and polytetrafluoroethylene (PTFE) as bitumen modifiers at varying percentages and Lin et al. (2022) investigate the aging properties of the bitumen using bio-oil derived from bamboo charcoal. Another successful technology actively discussed is the various research on enhancing the bitumen properties by incorporating crumb rubber modifier(CRM). Further, Nanotechnologies, such as nano clays and nano-silica, are being developed to improve bitumen binders' properties, reduce aging, and make the binder eco-friendly by reducing moisture and rallying activities. These advancements aim to reduce the environmental impact of construction materials.

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2. Discussion

2.1. Crumb Rubber Modified Bitumen

2.1.1. Introduction

Crumb Rubber Modified Bitumen is an innovation in road building. It is a product made by combining bitumen and finely ground rubber extracted from used crushed tires. The procedure begins with the extraction of trashed tires that are suitable for this process and further extraction of finely ground rubber. Afterwards, the rubber is received by processing the rubber through cryogenic grinding or ambient grinding to ensure the necessary particle size distribution. Later, the rubber is combined with bitumen in predetermined proportions in a specialised blending unit or a modified asphalt plant, resulting in many CRMB (N.S. Mashaan, 2012).

One of CRMB's main advantages is that it performs functionally better than bitumen. The rubber added fundamentally changes the properties of the binder, thereby giving it more excellent elasticity, physical durability, and resistance to aging and cracking. Thus, the asphalt pavement produced is more resilient to deformation and fatigue experienced under heavy traffic loads. For this reason, CRMB is particularly suitable for application in high-stress areas such as highways, bridges, and intersections (Crumb Rubber Modified Bitumen (CRMB), n.d.).

As well as a few environmental benefits, CRMB also provides waste rubber from discarded tyres for recycling, keeping the volume of waste tyres in landfills or incinerators to a minimum. Korycki (2024) suggests that using crumb rubber in ELT could reduce more than 450,000 tons of tire waste annually in Australia, reducing the tire waste that goes into landfills or incinerators. According to Korycki (2024), using crumb rubber in ELT can reduce more than 450,000 tons of waste tyres annually in Australia. Retaining virgin bitumen helps reduce the disposal of environmental nuisance toilets involved with tire disposal, conserves resources, and cuts energy costs.

In addition to the environmental benefits achieved with high-performance pavements, CRMB also offers large economic 'bottom line' savings, typically saving in excess of 50 % over the pavement's life cycle. CRMB eliminates the need for frequent maintenance and has a longer service life, consequently lowering the pavement's overall lifecycle costs in comparison to conventional hot mix asphalt.

2.1.2. Properties of CRMB

All other parameters, indeed, could not be same, but the unique properties of the CRMB, Crumb Rubber Modified Bitumen, distinguish it from the conventional bitumen and make it more useful in road construction. Also, the most important characteristic feature of CRMB is the excessively increased elasticity on a fine ground, which does not deform or crack because of thermal cycles, which saves elongation and contraction. Compared to Anusha and Jagadeesh (2021), crumb rubber corresponds to an increase in the elastic recovery of the binders and pavements made with them and reduces the critical rutting parameter value in the former and extends the benefit of lifespan.

CRMB also offers the benefit of higher resistance to rutting and cracking, which are common distresses associated with heavily trafficked roads or environmental conditions. The crumb rubber increases the binder's thermal properties. It also increases the time for resistance to permanent deformation that develops over more wheeled loads. Consequently, it also makes the binder more resistant to fatigue cracking. This results from the binder's elasticity and the rubber's damping. According to their findings, CRMB reduces pavement fatigue, thus reducing cracking and enriching sustainability benefits (Anusha & Jagadeesh, 2021).

Durability is another crucial issue; the payment surface should consist of improved resistance to ravelling and, therefore, should be better able to resist aging and other forms of substantial deterioration. Crumb rubber acts as a barrier, preventing the binder from oxidising and degrading under UV and other factors; treating the binder with crumb rubber improves road surface properties and causes the structure to become more durable and low maintenance. Many researched the

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relationship between CRMB and rheological characteristics, demonstrating how proper mix designs strengthen the durability of the road structure.

2.1.3. Factors Affecting CRMB Performance

Several previous studies have observed that the blending conditions crucially affect the performance of the crumb rubber-modified bitumen. Jamal and Giustozzi (2020) researched the importance of using low-content CRMB on Australian roads, and the study was conducted using two shear mixing rates (700 rpm and 3500 rpm) and with three different mixing times(30min,60min, and 90 min). After conducting several tests, including the master curve, black diagram, and multiple stress creep recovery research, they concluded that the applied mixing rate had a higher impact on bitumen properties than the mixing time. Also, according to the MSCR test, it was observed that within a small amount of CR additive, the rutting resistance can improve significantly.

In M. R. Ibrahim et al. (2013), rheology investigations are conducted on the crumb rubber-modified bitumen under different conditions. External factors like mixing temperature, duration, type of mixing and rate play a major role in determining the CRMB performance shown by the study. The resulting performance of the mixer, also depends on the internal factors of addition percentage, crumb rubber size, and microstructure. In addition, the findings of N. S. Mashaan and Karim (2012) revealed the effect of the bitumen content and blending time on its rheological behaviour. Erasure, duration, type of mixing, and rate, which can be described as external factors. Internal factors like percentage of addition, crumb rubber size, and microstructure also affect the resulting performance of the mixer. Further, the research carried out by N. S. Mashaan and Karim (2012) showed that the content of the crumb rubber and the blending time significantly influence the rheological behavior of the bitumen.

2.1.4. Aging Resistance

It was proven that the aging mechanism in Crumb rubber-modified bitumen is much more complex and leads to improved performance of resistance to aging. A study was conducted by Ali et al. (2013) to investigate the properties of aged rubberised bitumen using 80/100 penetration grade bitumen by adding 8% and 16% CRM by binder weight. The samples were aged using RTFOT to simulate short-term aging, and a pressure aging vessel (PAV) was done to simulate long-term aging. The aged and unaged properties of the composites were determined by using standard tests such as penetration test, softening point test, Brookfield viscosity test and DSR analysis. To assess the aging effect on the bitumen binder, it is possible to use the ratio of bitumen properties before and after aging — the aging index. Consequently, it is able to calculate the viscosity aging index (VAI), penetration aging ratio (PAR) and aging index for the rutting factor. Comparison of the modified and unmodified bitumen was able to yield large findings by demonstrating that the CRM-modified bitumen displayed lower indexes of viscosity and rheological properties, as well as a reduced softening point increment and penetration aging ratio and that the crumb rubber-modified bitumen has the high aging resistance. CRMB shows aging resistance that increases when the crumb rubber content increases.

2.1.5. Rutting Resistance

The elasticity, viscosity, and softening points of rubberised bitumen binders are higher than those of conventional binders, providing improved resistance to rutting. The CRMB is always watching increased elasticity and viscosity, but it is also important to cut rutting as it can withstand deformation and recover deformation shape due to the vehicle loadings. High softening points will allow the pavement to withstand an increasing temperature, and binders will be able to hold a mix together and restore the total structure. In Gohar et al. (2022), they studied the rutting resistance of crumb rubber-modified bitumen. Wet process rubber modification was carried out through this, and the crumb rubber modification was made with 9.5% and 15% by weight of the bitumen. Further, the

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study demonstrated that improved properties such as viscosity, hardness, and deformation resistance improve the rutting resistance of bitumen.

2.1.6. Fatigue Resistance

Fatigue resistance can be identified as the material's ability to withstand frequent stresses and temperature changes while operating continuously. Variations in temperature place a tremendous strain on the material. They typically decrease the durability of the payment, forming cracks or deformations that could make it unsafe for road users and increase the maintenance cost. Wang et al. (2020) carried out research to investigate the fatigue resistance of crumb rubber-modified bitumen using four different crumb rubber content, which are 5%,10%,15% and 22%, with conducting fatigue performance tests named frequency sweep tests, TS and LAS test. The study concluded that the crumb rubber-modified bitumen exhibits high resistance to fatigue when compared with the virgin bitumen.

2.1.7. Environmental and Economic Benefits of Using CRMB

The most impressive thing about CRMB is that it also creates environmentally friendly products and excellent engineering materials. CRMB provides a way to address the issue of how to dispose of the millions of tires produced worldwide. When scrap tires are substituted for more expensive virgin polymers, more money, energy, and pollution savings are achieved. Studies show that although CRM pavement has a high initial cost and energy usage compared with regular asphalt paving, CRM has more than two to four years longer service life, which can reduce the maintenance cost due to the advanced performance (Riekstins et al., 2022).

2.1.8. Challenges Associated with the Implementation of CRMB

As a major disadvantage of crumb rubber-modified bitumen (CRMB), CRMB storage is unstable. That way, it cannot be used for additional purposes. Homogeneity, phase separation and temperature stability are influential on storage stability. Blending techniques that eliminate this should be used, and the mix should be consistent. The CRMB is also challenging to implement due to the worker's exposure to CRMB emissions. Selecting the health effects is much more important than identifying them, and the handling should be done under the above-mentioned general guidelines aiming to improve health and safety. However, although CRMB is seen as a sustainable technology, the high environmental toxicity, including emissions, air quality, and water quality, disadvantages the technology. Also, the supply chain challenges are other issues that must be systematically tackled (Denneman et al. 2015; Buchagul 2019).

2.1.9. Life Cycle Assessment of CRMB

In all industries, life cycle assessment (LCA) is an important tool for gaining a holistic picture of a product or process's environmental impact to make sustainable decisions. Pavement performance and environmental benefits from crumb rubber-modified bitumen are investigated using LCA. Focusing on energy usage, climate change, global warming potential, economy, etc., can be done with life cycle assessments. Piao et al. (2021) have conducted a life cycle assessment on the impacts of climate change and cumulative energy demand. Three different kinds of asphalt mixes were included in the study, and the data are compared in terms of different mechanical tests, such as water sensitivity tests, and wheel tracking tests. Overall, the study finds that the CUR for CR-modified pavement is small enough for the cumulative energy demand of CR-modified pavement to be comparable to polymer-modified pavement. Farina et al. (2014) compared the production of crumb rubber bitumen mixture via wet and dry processes. Gross energy requirement and global warming potential were recognised as the main energy and environmental indicators. Service life and maintenance frequency was assumed in the life cycle assessment. On the other hand, key findings of the research indicate that the wet process has significant power and environmental triumph over

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the dry process. Riekstins et al. (2022) conducted a necessary study for the economic and environmental analysis of CRM asphalt by wet process. The main areas considered were annual energy use, global warming potential and economy. The findings are significant, which show that the asphalt with crumb rubber modifications has a long pavement life with less energy use and less cost than conventional pavement. As an environmentally friendly technology, the CRMB can also be considered as a technology that has demonstrated a clear trend in saving energy and lowering greenhouse gas emissions.

2.2. Styrene-Butadiene-Styrene (SBS)

Styrene-butadiene-styrene (SBS) is one of the most commonly used thermoplastic elastomer modifiers of polymer-modified asphalt (PMA) to improve pavement flexibility and durability under changing environmental stresses (Zhu et al. 2014). Hassanpour-Kasanagh et al. (2020) note that elastic recovery, stiffness and resilience of SBS-modified binders are improved compared to that of normal binders, which are essential for long-term pavement performance. It provides better elasticity and better temperature resistance than ordinary asphalt, says SBS research, and could protect pavements against stresses like rutting when hot and cracking when cold. Despite these setbacks, SBS can become relatively expensive and prone to UV radiation and aging and oxidation; thus, studies of recycled SBS-modified materials are warranted (Yang et al., 2024).

2.2.1. Aging Resistance

SBS polymers enhance the aging resistance of asphalt binders by providing an elastic network in the bitumen matrix. Hassanpour-Kasanagh et al. (2020) indicate that the viscoelastic properties of SBS-modified binders are better retained over time than those of unmodified or recycled modified binders. SBS can better resist aging under oxidative and thermal stress, as evidenced by multiple Stress Creep Recovery (MSCR) and Linear Amplitude Sweep (LAS) tests. It was statistically found that the aging resistance index increased up to 25% when the binder was substituted from 5% SBS, meaning the redounding is so substantial for conventional binders. In addition (Hassanpour-Kasanagh et al., 2020). resistance of asphalt binders by forming an elastic network within the bitumen matrix improves durability. According to Hassanpour-Kasanagh et al. (2020), SBS-modified binders retain their viscoelastic properties better over time compared to unmodified or even some recycled-modified binders. According to Hassanpour-Kasanagh et al., (2020), multiple Stress Creep Recovery (MSCR) and Linear Amplitude Sweep (LAS) tests demonstrate that SBS can maintain higher resistance to aging, particularly under oxidative and thermal stresses. Statistically, 5% SBS increased the aging resistance index by approximately 25%, indicating substantial enhancement compared to conventional binders(Hassanpour-Kasanagh et al., 2020).

SBS, however, is not an aging-resistant material. According to Yang et al. (2024) studies, unsaturated bonds in SBS permit the crushing to take place gradually under UV irradiation, and the binder resilience also decreases with time. Alternative measures have been used earlier to increase SBS's durability under aging conditions, such as the addition of antioxidants or sulphur vulcanization (Yang et al., 2024).

2.2.2. Rutting Resistance

Strengthening of rutting resistance is the principal benefit of SBS in pavement materials. The effect of SBS-modified binders on the elastic properties, which decrease the probability of permanent deformation at high temperatures, is a common problem in the surfaces of load-bearing roads used in areas of high traffic volume. According to tests performed by Zhu et al. (2014), SBS-modified binders increase the rutting resistance roughly 40% more than non-modified binders. This improvement is attributed to the polymer's ability to maintain elasticity and stiffness under load (Zhu et al., 2014) (Hassanpour-Kasanagh et al., 2020), thereby reducing the permanent deformation seen in hot conditions (Zhu et al., 2014).

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SBS also develops a rutting resistance superior to some recycled modifiers, particularly at higher dosages. For example, binders modified with 3–7% SBS showed better resistance than binders modified with 100% recycled high-density polyethylene (HDPE) due to the problems with phase separation in the HDPE binder. Further, composite modifiers that incorporated recycled SBS were developed to trade off cost and performance but are not always as effective at resisting rutting as pure SBS-modified binders (Hassanpour-Kasanagh et al., 2020).

2.2.3. Environmental and Economic Befits and Challenges

Using SBS in pavement applications also has the twofold environmental impact we describe. SBS gives the pavement higher longevity without requiring frequent repair (Hassanpour-Kasanagh et al., 2020). (Besides the high production cost, SBS is nonrenewable, and the nature of the environment). These problems are overcome through research into using recycled SBS and hybrid modifiers with ground tire rubber (GTR) and HDPE. Using recycled composite the performance of these recycled composites is similar to that of SBS regarding rutting resistance, but they may offer cost and environmental savings (Yang et al., 2020).

Although SBS-modified pavements have environmental values, they also entail economic and technical limitations. However, SBS is costly and, according to Yang et al. (2024), has a narrow-spread adoption, particularly in areas with limited resources for infrastructure. However, SBS is not directed towards the same bitumen types, which can impact its ability to maintain storage stability, resulting in additional maintenance costs should the storage degrade. This emphasises the necessity of moving away from the recycled modifiers and hybrid solutions and mitigating some of such economic and environmental burdens with low or no compromise on both the parametric (Yang et al., 2024).

2.3. Recycled Polypropylene (PP)

The application of Polypropylene (PP), which is recyclable, stiff, and has good temperature resistance, as a material for pavement modification is gaining attention because it is economical and sustainable. Recycled polymers, particularly PP, are pushed to replace the traditional bitumen modification to obviate associated environmental issues and improve pavements' performance and duration (Nizamuddin et al., 2021). The PP is shown to be thermodynamically stable and resistant to degradation and is highly beneficial as a modifier in asphalt pavements in high-stress situations. The role of recycled PP in enhancing pavement durability in terms of its aging and rutting resistance and economic and environmental implications are reviewed in this review (Salehi et al., 2021).

2.3.1. Aging Resistance

Here, a critical problem with recycled PP is aged resistance, an issue with many pavement materials. Traditional asphalt can degrade under thermal and UV stresses, causing cracking and brittleness on the surface. Thermal aging tests show that recycled PP significantly enhances the aging resistance of the binder, as asphalt modified by PP retained approximately 20% more viscoelastic properties than unmodified asphalt (Nizamuddin et al., 2021). Meant to interpret in vivo structural properties, PP’s structural stability proves most resistant to long-term residence in high temperatures. It was also shown that recycled PP-modified asphalt had lower oxidative degradation rates in comparison to virgin asphalt because the polymer has a stable molecular composition. Nizamuddin et al. (2021) reported that recycled PP-modified asphalt has good flexibility and adhesion properties that prevent common problems in aged pavements, such as cracking and brittleness (Nizamuddin et al., 2021).

2.3.2. Rutting Resistance

Another significant benefit to our rutting resistance is using reclaimed PP in the pavement materials. The rigidity and higher melting point of PP make it appropriate for applications requiring high resistance to deformation at loads. However, a series of recent evaluations of PP-modified

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asphalt has shown that the PP reduced the damage due to the formation of ruts compared to conventional bitumen by 35%. Salehi et al. (2021) have shown that recycled PP can improve pavements at bearing traffic stresses (Marshall Stability tests). This lessening of rutting susceptibility is particularly beneficial because severe rutting can lead to major maintenance problems on high-traffic roads. Salehi et al. (2021) support the work further as the reduction in rut depth under sustained loads is also found (Salehi et al., 2021).

2.3.3. Environmental and Economic Befits and Challenges

It has a significant environmental footprint because it does not use virgin polymers, which leads to less plastic waste in the environmental system. Polypropylene is one of the most commonly used plastics in the world and is being used in its recycling through the use of roads. The results of life cycle assessment (LCA) studies on recycled PP-modified asphalt reduce CO_2 emissions by up to 15 % and reduce the environmental footprint of road construction (Nizamuddin et al., 2021). Recycled PP happens to be economically more accessible than virgin polymer, so it provides a cheaper alternative for infrastructure project implementations largely backed by a lack of resources.

However, compatibility and stability are weak points. In certain cases, recycled PP can be incompatible with bitumen and may phase separate during mixing because of its nonpolar nature. To solve these compatibility problems, techniques such as adding compatibilizers and reactive modifiers have been addressed (Nizamuddin et al., 2021). Recycled PP may have lower production costs compared with virgin PP, but it needs process and quality control investment that may jeopardize its wide outreach.

2.4. Recycled Polyethylene Terephthalate (PET)

PET, a recycled polyethylene terephthalate, has recently received more use in pavement materials due to its beneficial durability and sustainability properties. There are several plastics on the planet, but two of them have become particularly burdened: plastic PET is used everywhere as a plastic bottle, for example. Using recycled PET to make pavement materials results in a better environment and less environmental impact. PET's high temperature and wear properties make it an excellent additive to asphalt to improve stability and durability. Based on pet-modified asphalt studies, these mechanical properties show improvement in moisture resistance and rutting performance, similar to the application in heavy-duty pavements (Usman & Kunlin, 2024) (Mushtaq et al., 2022).

2.4.1. Aging Resistance

As PET is thermally stable, it has good potential for aging resistance improvement of asphalt pavements. When combined with PET, asphalt can be slowed down by PET in terms of its aging, and that can take out the oxidative degradation enabled for asphalt when it combines with air, and those oxidative peaks decrease with that. Maharaj et al., (2019) demonstrated that PET modified asphalt performed better in accelerated weathering tests than conventional asphalt with better structural integrity. However, adding PET increases the resistance to environmental factors, such as UV, without suppressing brittleness and cracking with time (Maharaj et al., 2018). Also, PET's chemical structure, characterised by its high crystallinity, leads to strong PET and asphalt bonding and PET, resisting the fast breaking down of asphalt under radically different climatic conditions. However, these characteristics of PET-modified asphalt are more durable to thermal and UV-induced aging (Usman & Kunlin, 2024).

2.4.2. Rutting Resistance

Among the most essential advantages of using PET in asphalt is its improved rutting resistance. The high melting point and rigidity of PET contribute to asphalt's resistance to deformation, and this is very important in areas of high traffic. Marshall Stability and creep tests confirmed that PET-

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modified asphalt had approximately 20 per cent better rutting resistance (Usman et al., 2024). The increase in stiffness and viscosity from including PET limited the depth of rut formed from the repeated traffic loads (Usman & Kunlin, 2024). Maharaj et al. (2019) also reported that asphalt mixtures containing 5% PET had Marshall stability values up to 50% higher than unmodified mixtures. These results demonstrate PET's ability to reduce pavement deformations as well as minimise structural damage to the pavement under sustained stress (Maharaj et al., 2018).

2.4.3. Environmental and Economic Befits and Challenges

Because recycled PET reduces plastic waste in landfills and oceans and lowers the need for virgin materials, the environmental advantages of using recycled PET in pavement materials are considerable. Recycling PET as an asphalt additive streamlines both stops to help move towards sustainable development goals, reduce waste, and use more eco-friendly construction methods. Mushtaq et al. (2022) described how not only can PET be used for pavement construction, but it also means longer-lived roads with fewer costly repairs (Mushtaq et al., 2022).

Nonetheless, the widespread adoption of PET-modified asphalt introduces some challenges. The high energy cost of processing PET for asphalt applications is one problem. PET also has challenges with the compatibility of PET with bitumen, as non-polar PET may separate phases if not properly mixed. These methods aim to improve compatibility at the cost of increased overall production costs (Maharaj et al., 2018). PET further offers performance benefits, but more research is needed to achieve a balance between performance and cost-effectiveness on asphalt with respect to PET content, especially in climates with severe temperature ranges.

2.5. Recycled Low-Density Polyethylene (LDPE)

Recycled low-density polyethylene (LDPE), a major contributor to municipal plastic waste, is an eco-friendly and cost-effective alternative to changing pavement. Since the global environmental crisis, incorporating LDPE into asphalt reduces plastic waste and improves the mechanical properties of asphalt pavements (Singh & Gupta, 2024) (Li et al., 2024). Polyethylene LDPE is one of the most common and easiest-to-modify types of polyethylene that can be used in packaging applications. Results from the studies indicate that LDPE-modified asphalt has improved stiffness and high durability under different temperature environments, making it an ideal material for road construction, more predominantly in extreme temperature regions (Ullah et al., 2024).

2.5.1. Aging Resistance

Resistance to aging is one of the most critical challenges of pavement life. Improvement of the aging resilience of asphalt with LDPE modification has been achieved with increased stiffness and elasticity of the asphalt binder, causing greater durability and resistance to cracking with time. Ullah et al. (2024) suggest that adding LDPE in the appropriate proportions (3–7%) can greatly diminish degradation created by environmental facets, for example, UV openness and oxygen, which are standard in conventional asphalt emulsions. The higher viscosity and more elevated softening point that drive the delayed aging process and increase the life of pavements (Singh & Gupta, 2024) (Ullah et al., 2024) lead to this performance improvement in LDPE-modified binders.

Moreover, Hui Li et al. (2024) also find that LDPE's polymer structure accounts for its aging resistance. At 2–5% concentrations, LDPE substantially improves durability and deformation resistance, particularly in warmer climates where aging typically accelerates. Excessive LDPE concentrations (>6%), however, may negatively influence the ductility and flexibility of the binder, resulting in brittleness at lower temperatures (Li et al., 2024).

2.5.2. Rutting Resistance

A key issue addressed by LDPE modification is rutting, a common form of deformation in flexible pavements in high-traffic and high-temperature conditions. According to studies, the LDPE

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modification contributes significantly to improving the rutting resistance of asphalt by increasing the stiffness and reducing the penetration of asphalt binder. Results from studies by Ullah et al. (2024) show that the rutted depth of 3% to 7% of LDPE asphalt mixtures decreased by up to 33% compared to conventional binders. Additionally, at 5% LDPE, rutting depth was reduced by 24%, indicating that polymer stabilising asphalt under repeated loading and high temperatures is quite effective (Ullah et al., 2024).

Furthermore, Singh and Gupta (2024) found that traditional mixtures gained a 42.3% improvement in rutting life, peaking at 42.3%, when applied with LDPE-modified asphalts. Results from the 3D-Move pavement analysis showed that LDPE reduces interlayer deflections, decreasing the pavement's sensitivity to routing under prolonged traffic loads. The above resistance is accentuated by using LDPE in conjunction with high-viscosity binders, distributing stress over the pavement layers and alleviating surface deformation (Singh & Gupta, 2024).

2.5.3. Environmental and Economic Befits and Challenges

There are substantial environmental benefits from using LDPE in asphalt. This approach also reduces landfill waste by using recycled plastics and removing the greenhouse gas emissions from the disposal of traditional plastic through incineration. According to research, Using LDPE in asphalt reduces plastic waste by up to 750 kg per kilometer of single-lane pavement (Singh & Gupta, 2024)—effective solution for pavement modification. Given the global environmental crisis, incorporating LDPE into asphalt not only reduces plastic waste but also enhances the mechanical properties of asphalt pavements (Singh & Gupta, 2024) (Li et al., 2024). As one of the most common types of polyethylene used in packaging, LDPE is widely available and adaptable to modification processes for pavement applications. Studies show that LDPE-modified asphalt exhibits enhanced stiffness and increased durability under various temperature conditions, making it highly suitable for road construction, particularly in regions experiencing extreme temperatures (Ullah et al., 2024).

2.6. Recycled High-Density Polyethylene (HDPE)

Asphalt pavement is increasingly recognised as a valuable additive that incorporates recycled high-density polyethylene (HDPE). Paved with HDPE has unique advantages for performance, such as increased durability and resistance to deformation (Alghrafy et al., 2021). Integrating HDPE into asphalt addresses engineering and environmental challenges with the rapid increase in plastic production and waste. HDPE addresses this fundamental roadblock due to studies showing it can modify the bitumen, improving mechanical properties and thermal stability, which makes it a potential replacement for more traditional polymers in asphalt modification (Nizamuddin et al., 2020) (Jessica et al., 2023).

2.6.1. Aging Resistance

However, HDPE in asphalt pavements notably increases aging resistance through oxidation-reduction and preservation of mechanical strength. As shown in Alghrafy et al. 's (2021) study, HDPE-modified asphalt had lower oxidation rates during short-term aging, as measured by the Aging Index (AI), than virgin asphalt. For example, the AI values decreased by an average of 25%, showing a huge delay in the aging process (Alghrafy et al., 2021), with HDPE contents 2–6 wt. %. This also helps make the HDPE in the asphalt more resistant to temperature variations, something essential to aging. Secondly, HDPE increases the softening point of asphalt from 44.1 °C to 83.7 °C when HDPE content reaches 6%, which leads to the binder's resilience against thermal degradation (Nizamuddin et al., 2020).

2.6.2. Rutting Resistance

HDPE modification also reduces rutting, which is the permanent deformation caused by excessive traffic loads and high temperatures. HDPE strengthens the asphalt binder by stiffening it and reducing its susceptibility to deformation. According to Jessica et al. (2024), adding 2 % HDPE improved asphalt's response to stress under high temperatures with reduced rutting depth of about 20 % in high-temperature regions. Moreover, the Multiple Stress Creep Recovery (MSCR) test results showed that all HDPE-modified binders are more resistant to high-temperature creep (the primary agent of rutting). Hardened cold creep (HDPE) is modified to raise the softening point modestly, which raises the resistance threshold and produces longer-lasting pavements in climates that experience higher temperatures (Nizamuddin et al., 2020).

2.6.3. Environmental and Economic Befits and Challenges

Secondly, asphalt integration with HDPE avoids landfill volumes by stopping plastic waste from being sent to landfills. Plastic HDPE waste streams, where they become predominant, are very sustainable as the opportunities for repurposing them can be used within the pavements employing HDPE grease recycling. Studies estimate that each kilometre of HDPE-modified pavement can end up being made up of up to 500 kilos of recycled plastic and reduces carbon emissions by one-third of what conventional asphalt production amounts to (Nizamuddin et al., 2020) (Jessica et al., 2023).

HDPE-modified asphalt economically reduces costs in locations where HDPE waste is plentiful , and disposal costs are high. However, some problems still exist: for instance, the consistency of recycled HDPE properties depends on the source of the material. The mechanical performance of HDPE-modified binders can be affected by melting temperature, density, and contamination level variability. However, standardisation in recycling processes and quality control in HDPE recycling material are necessary for reliable use in asphalt pavements (Alghrafy et al., 2021).

2.7. Recycled Polystyrene (PS)

Asphalt pavements modified with recycled polystyrene (PS), sourced primarily from packaging and disposable products, exhibit promise of modifying asphalt due to its rigidity and comparatively high melting point. Secondly, the use of PS in asphalt leads to improvements in road durability and a reduction in maintenance costs; thus, ESL is an attractive solution for high-traffic roads. Zhu et al. (2014) studied the possible use of PS as a modifier that improves the bitumen matrix stability, thus improving the resistance of the pavement to thermal variations and deformation (Zhu et al. 2014).

2.7.1. Aging Resistance

PS is offered as one of the notable benefits of PS in asphalt modification because PS contributes to aging resistance. The improved oxidation resistance of PS-modified asphalt has been shown to help prevent early cracking and reduce pavement maintenance. One example, as seen by Zhu et al., is that PS increases the material's stiffness at high temperatures, reducing the effect of oxidative aging on the asphalt binder (Zhu et al., 2014). This stiffening effect is desirable in areas that get warmer because standard asphalt tends to age and soften faster. Although appropriate, over PS content could lower temperature flexibility significantly below room temperature, indicating that optimal PS content is needed to achieve balanced performance.

2.7.2. Rutting Resistance

It demonstrates that PS modification of asphalt greatly reduces the amount of rutting, a critical issue in asphalt pavements subjected to heavy traffic. PS raises the stiffness of the asphalt binder and causes permanent deformation under prolonged loading conditions. Zhu et al. suggested that the rutting resistance is improved by about 15% relative to unmodified asphalt when PS is incorporated at 3 to 5 % weight (Zhu et al., 2014). By modifying this, rutting is minimised, and PS-modified asphalt is suitable for highways undergoing heavy traffic and in extreme temperature regions. In addition, the rigidity of PS maintains the integrity of the pavement structure, helping to resist rutting.

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2.7.3. Environmental and Economic Befits and Challenges

Higher benefits, from an environmental and economic standpoint, are found in using recycled PS in pavement materials. The result is that this approach reduces plastic waste and diverts it from landfills, bringing environmental sustainability to this process. PS-modified asphalt has improved durability, prolonging the pavement life cycle and economically reducing road maintenance costs. Despite this, challenges exist, such as inconsistent quality of recycled PS, which can result in variations in pavement performance. PS is also non-biodegradable, so recycling the pavement as it approaches the end of its life cycle is a challenge. However, PS is an applicable asphalt modifier as long as quality control is exercised (Zhu et al., 2014).

2.8. Waste Cooking Oil (WCO)

As one of the byproducts of domestic and industrial food preparation, Waste Cooking Oil (WCO) shows potential as a recycled asphalt pavement additive. Like petroleum-based binders, WCO's organic composition allows it to act as a rejuvenator for reclaimed asphalt pavement (RAP) (Jain & Chandrappa, 2023). This role employs both environmental concerns related to the disposal of WCO and the demand for sustainable road material. The studies indicate that WCO can reduce binder viscosity and enable better blending with aged asphalt to provide better pavement flexibility and durability (Jain & Chandrappa, 2023),(Xu et al., 2023).

2.8.1. Aging Resistance

There is much-published data on WCO's effectiveness in improving the aging resistance of asphalt. It replaces lost essential oils that tend to oxidise and other environmental factors and reduces stiffness that happens in old binders. Adding 6% WCO to asphalt reduced the asphaltene to maltene ratio— an indicator of asphalt's aging—by more than 20% compared to untreated asphalt (Jain & Chandrappa, 2023). Furthermore, WCO-modified binders in mixtures with high RAP content generally showed reduced long-term stiffness and retained flexibility under various aging conditions, indicating increased service life. Maltenes present in WCO counteract aging effects in binders containing up to 7% WCO, as Jain and Chandrappa (2023) indicated.

2.8.2. Rutting Resistance

Despite this, WCO enhances aging resistance, while its effects on rutting are nontrivial. High WCO content may lower rutting resistance by softening the asphalt. Jain & Chandrappa (2023) studies have found that a WCO concentration is optimal at 3–5%, balancing flexibility and resistance while retaining rutting performance among conventionally tackified asphalt. However, WCO-modified asphalt may be prone to deformation under high loads and temperatures in areas where sunlight is very concentrated (Xu et al., 2023). Accordingly, a lower dosage, below 5%, is probably optimum to slow rut resistance without compromising flexibility.

2.8.3. Environmental and Economic Befits and Challenges

The benefits of the use of WCO in asphalt for the environment are substantial. By modifying the WCO, each kilometre of WCO-modified pavement would be able to repurpose hundreds of kilos of waste oil by mitigating its harmful environmental impact. On the economic side, the WCO system offers savings by reducing dependence on virgin petroleum-based binders because they are prepared from industrial waste products. However, issues such as variability in Pavement WCO quality can result in inconsistent pavement performance. Further, WCO is to be refined to reduce impurities in WCO, such as fatty acids and water, in order to continue the effectiveness of WCO as a rejuvenator (Xu et al., 2023) (Jain & Chandrappa, 2023).

3. Conclusion

The research paper on recycled polymer-modified pavement materials discusses the complexities of pavement performance and sustainability using different bitumen modifiers. This study systematically looked at bitumen's chemical and physical properties, environmental and regulatory challenges, and bitumen modifications to increase resistance to rutting and aging. The research focused on recycled materials, including crumb rubber, styrene-butadiene-styrene (SBS), polypropylene (PP), polyethylene terephthalate (PET) and waste cooking oil (WCO), highlighting the advantages and disadvantages associated with each material's use in pavement applications.

They find that crumb rubber and SBS modifiers can improve elasticity and recovery, reducing pavement deformation in heavy traffic and under adverse weather. Results from laboratory tests prove that the pavement undergoes longer-lasting rutting and fatigue resistance. The study also points out the environmental advantages of recycling polymers, as greenhouse gases are lowered, and landfill waste is reduced.

While these benefits may exist, challenges remain, such as material incompatibility, storage instability, and the economic feasibility of large-scale implementation. Overall, the review presents recommendations for continued innovation in bitumen modification and suggestions for optimizing recycled polymers in pavement materials to achieve durable, sustainable infrastructure.

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