Jurnal Kejuruteraan 37(7) 2025: 3505-3518
https://doi.org/10.17576/jkukm-2025-37(7)-29

Asphalt for Road Infrastructure: A Review of Composition, Modification, and Sustainability

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Received 7 February 2025, Received in revised form 24 July 2025
Accepted 24 August 2025, Available online 30 October 2025

ABSTRACT

A key component of asphalt road pavement is well known for its strength and adaptability. The basic ingredients of asphalt, such as aggregates and binder, are examined in this overview along with how they interact to greatly affect pavement performance. A systematic literature review was undertaken using peer-reviewed journals, technical reports, and industry publications, focusing on advancements in asphalt materials and sustainable pavement technologies from the past two decades. The study investigates asphalt classifications according to aggregate structure, manufacturing temperature, and the use of additives or modifications to enhance performance under various traffic and environmental conditions. Advanced modifications, such as the incorporation of polymers, crumb rubber, and recycled asphalt pavement, are explored for their ability to enhance rheological properties while addressing sustainability concerns. The review also highlights innovative production techniques, which reduce energy consumption and emissions, making it a more sustainable alternative to conventional methods. Furthermore, factors influencing asphalt selection, such as climate adaptability, load-bearing capacity, fatigue resistance, and maintenance requirements, are analyzed to provide a comprehensive understanding of material behavior in real-world applications. The importance of proper mix design, compaction techniques, and quality control measures is emphasized to ensure optimal pavement longevity and performance. By integrating advanced material science and engineering practices, modern asphalt technologies aim to enhance road durability, reduce lifecycle costs, and minimize environmental footprint. This review underscores the critical role of material composition, innovative additives, and sustainable production techniques in optimizing asphalt performance for future road infrastructure developments.

Keywords: Asphalt performance; mix design; sustainability; modifiers and additives; road pavement

INTRODUCTION

Asphalt serves as the backbone of contemporary road infrastructure, offering both flexibility and resilience. Performance, cost, and environmental effect are all impacted by the enormous variations in its composition and qualities. The many kinds of asphalt materials, their properties, and their uses are examined in the previous research (Saboo & Das 2022; Kazim et al. 2024, Muftia et al. 2024). Bitumen, another name for asphalt, is an essential component used in the building and upkeep of roads. For engineers and researchers looking to increase its lifetime and performance, it is crucial to comprehend its fundamental parts and characteristics. This overview of the literature explores the basic elements of asphalt and how each element contributes to the overall functionality of asphalt pavements.

Despite extensive research into the development and modification of asphalt materials, notable gaps remain in the literature. One key gap lies in the long-term performance evaluation of modified asphalt mixtures under real-world conditions. While numerous studies have examined short-term properties such as initial stiffness, rutting resistance, and moisture susceptibility, there is a scarcity of longitudinal research that monitors ageing behavior, fatigue resistance, and degradation mechanisms over extended periods of service life (Zhao et al. 2017). This limits the predictive capacity of performance models and complicates maintenance planning. Another critical shortfall in existing research is the limited focus on sustainability and life-cycle analysis of asphalt materials. As environmental concerns rise, the industry increasingly turns to innovations such as warm mix asphalt (WMA), recycled asphalt pavement (RAP), and bio-based or polymer additives. However, many of these innovations lack comprehensive assessments regarding long-term durability, recyclability, energy savings, and carbon footprint over their full life cycle (Zaumanis et al. 2015). As a result, decision-makers often lack the data needed to compare conventional and advanced materials in terms of environmental and economic efficiency.

This review addresses these gaps by not only exploring the fundamental properties of asphalt and its constituents but also critically examining the state of research related to long-term performance and sustainable practices. By integrating recent advancements in material science with practical engineering perspectives, this paper aims to support the development of more durable, cost-effective, and environmentally responsible road infrastructure.

BASIC COMPONENTS OF ASPHALT

Aggregate, bitumen, mineral filler, and air spaces make up asphalt mixes (Wang et al. 2020; Tao et al. 2019; Chang et al. 2020; Pouranian & Haddock, 2019). The aggregate and binder are the two primary ingredients of asphalt. The longevity, performance, tensile strength, and stiffness of asphalt pavements are all greatly impacted by the strength and shape of the aggregates (Arasan et al. 2010; Al-Rousan, 2007). Because it directly affects how well asphalt pavements function, the aggregate needs to have the right size and shape for high-performance pavements (Gao et al. 2022). Asphalt mixes consist of approximately 95% aggregates and 5% bitumen. Aggregates are essential to the pavement's structural soundness. Aggregate strength and shape have an impact on interfacial shear strength (Pouranian & Haddock 2019; Gao et al. 2016). Accordingly, angular and rough aggregate particles are preferable than round and smooth aggregates (Arasan et al. 2011). According to Dong et al. (2023), the aggregates fall into the following categories:

1. Coarse Aggregates: These are typically stones and gravel that provide strength and load-bearing capacity to the asphalt mixture.
2. Fine Aggregates: Sand and smaller particles that fill voids between coarse aggregates, providing a dense structure and helping in the binding process.
3. Mineral Filler: These fine materials fill the microscopic voids within the asphalt mix, contributing to the overall density and stability of the mixture.

The way that various-sized particles are distributed throughout the aggregate mix affects the asphalt's void content and compactness. In contrast to rounded and smooth pebbles, angular and rough-textured aggregates offer superior interlocking and stability. Binder, typically a bitumen, provides cohesion and flexibility by acting as the glue that binds the aggregates together. It is a complex combination of hydrocarbons that forms a sticky, black material that holds particles together. Bitumen is often separated into four main components based on its physical and solubility characteristics: saturates (S), aromatics (A), resins (R), and asphaltenes (A), which affect how well the material performs in road applications. To enable a more differentiated investigation of the material, bitumen was separated into its four main components using a slightly modified version of ASTM Standard 4124 (Figure 1) (ASTM 2001).

The elasticity and adhesive properties of bitumen are preserved by resins, which are polar, intermediate-weight molecules with functional groups like oxygen and sulfur that improve adhesion and cohesion. They stabilize asphaltenes by keeping them from precipitating (Prosperi & Bocci 2021; Ghasemirad et al. 2020). The heaviest, most polar molecules with a high molecular weight are asphaltenes, which provide structures rigidity and strength. However, too much of these might make a material more brittle, which could cause a fracture at low temperatures. Aromatics, which include unsaturated cyclic hydrocarbons, help bitumen stay uniform and flexible at different temperatures by dissolving asphaltenes and resins and promoting viscosity and flexibility. Last but not least, bitumen gains fluidity and temperature sensitivity from saturates (also known as oils), a low-weight, non-polar component that can volatilize over time and has little adhesive strength. The performance of bitumen is determined by the interactions of these elements, particularly its durability and resistance to deformation under various stress and climates (Prosperi & Bocci 2021; Ghasemirad et al. 2020). Depending on the crude and the use of the bituminous products, bitumen is made from the leftover crude oil after atmospheric distillation and through a variety of process and basic product combinations. The bitumen will exhibit varying rheological behaviors depending on temperature due to the displacement of its colloidal equilibrium, which is influenced by the chemical composition and concentrations of its constituents (ASTM 2001). Bitumen selection is therefore a crucial stage in the mix design process.

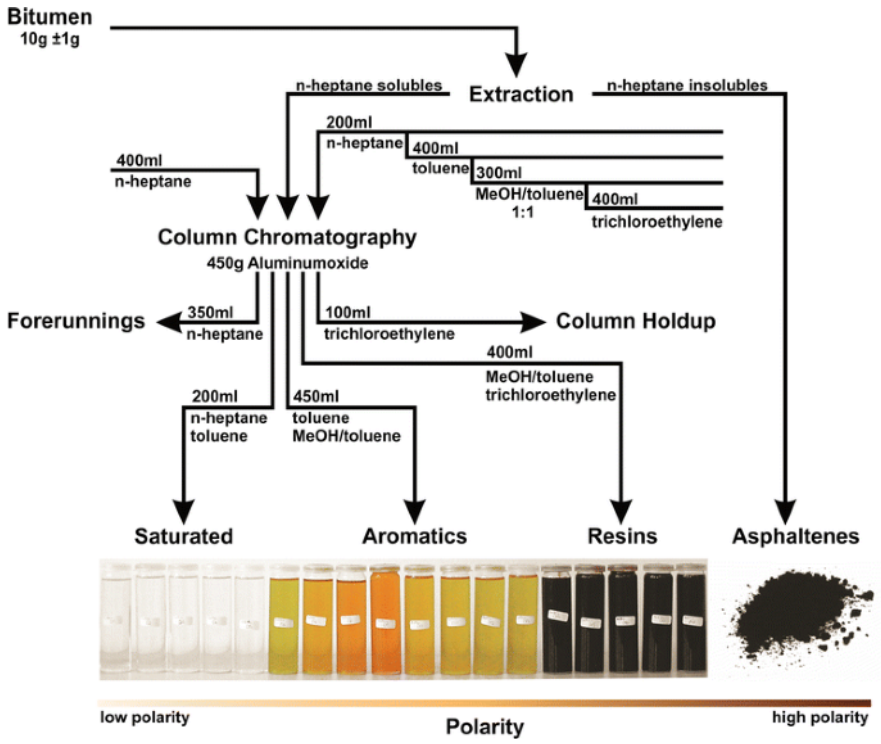

FIGURE 1. Bitumen separation (ASTM, 2001)

Li & Greenfield (2014) have suggested a 12-component bitumen molecular model to reflect the Strategic Highway Research Program (SHRP) core bitumen AAA-1, which has a penetration of 150/200. The molecular structures of the twelve elements in this model are seen in Figure 2. Asphaltene-phenol, asphaltene-pyrrole, and asphaltene-thiophene are all present in asphaltenes (A). The resins (R) are represented by five distinct types of molecules: quinolinohopane, thioisorenieratane, benzobisbenzothiophene, pyridinohopane, and trimethylbenzeneoxane. Perhydrophenanthrene-naphthalene (PHPN) and dioctylcyclohexane-naphthalene (DOCHN) make up the aromatics (A). The saturates (S) are squalene and hopane. The bitumen molecular model's chemical makeup is displayed in Table 1 (Gao et al. 2022).

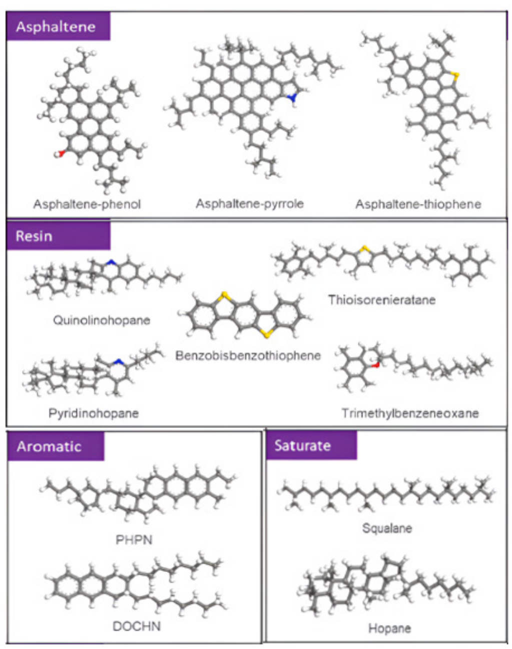

FIGURE 2. The molecular structures of bitumen (Li & Greenfield 2014)

TABLE 1. Chemical composition of bitumen molecular model used for Molecular Dynamic simulation (Gao et al. 2022)

Fractions	Molecules in Model	Molecular Formula	Number of Molecules
Saturate	Squalane	$C_{30}H_{62}$	4
	Hopane	$C_{35}H_{62}$	4
Aromatic (Naphthene aromatic)	PHPN	$C_{35}H_{44}$	11
	DOCHN	$C_{30}H_{46}$	13
Resin (Polar aromatic)	Quinolinohopane	$C_{40}H_{59}N$	4
	Thioisorenieratane	$C_{40}H_{60}S$	4
	Benzobisbenzothiophene	$C_{18}H_{10}S_2$	15
	Pyridinohopane	$C_{36}H_{57}N$	4
	Trimethybenzeneoxane	$C_{29}H_{50}O$	5
Asphaltene	Asphaltene-phenol	$C_{42}H_{50}O$	3
	Asphaltene-pyrrole	$C_{66}H_{81}N$	2
	Asphaltene-thiophene	$C_{51}H_{62}S$	3

INTERACTIONS BETWEEN COMPONENTS

The interactions between aggregates and binder have a significant impact on asphalt performance. Aggregates and binders interact through a combination of mechanical interlock, chemical bonding, and physical adhesion, all of which critically influence the long-term performance of construction materials like concrete and asphalt. Aggregates provide the structural skeleton and affect workability, strength, and durability, while the bitumen holds the system together. The surface texture, shape, and mineralogy of aggregates determine how well they bond with the binder; rough, angular aggregates promote better mechanical interlock, while chemical interactions, such as those between hydration products in cement and silica in aggregates, can strengthen or degrade the bond depending on reactivity. In asphalt, bitumen-aggregate adhesion depends on polarity and surface energy compatibility, often improved with anti-stripping agents. Long-term performance is shaped by the durability of this interface, as environmental and mechanical stresses (e.g., moisture, thermal cycling, loading, chemical attack) can lead to stripping, cracking, or deterioration. The final characteristics of the asphalt pavement are greatly influenced by variables including mixing temperature, binder quantity, and aggregate gradation. To get the desired qualities, it is crucial to choose the right amounts of aggregates and binder throughout the mix design process. The Marshall Mix Design and Superpave Mix Design are two popular mix design techniques. A long-lasting and sturdy pavement is the result of proper compaction during laying, which guarantees the elimination of air spaces and sufficient aggregate interlocking. Water can cause stripping and a loss of structural integrity by weakening the link between the aggregates and binder. To lessen this problem, anti-stripping products and appropriate drainage system are essential.

TYPES OF ASPHALT MATERIALS

ASPHALT MATERIAL- BASED ON PRODUCTION TEMPERATURE

The asphalt used in road building is classified as either Hot Mix Asphalt (HMA), Warm Mix Asphalt (WMA), or Cold Mix Asphalt (CMA) based in large part on the manufacturing temperatures. These asphalt types vary in terms of qualities including longevity, environmental effect, and adaptability to various climates and traffic conditions. HMA is renowned for its strength and capacity to tolerate deformation under strong loads, making it ideal for roads with high traffic and stress. It is typically made at temperatures between 150°C and 170°C (Jabatan Kerja Raya, 2017). The optimal bonding of the bitumen with aggregates, which is made possible by this high manufacturing temperature, enhances pavement performance. However, the significant greenhouse gas emissions brought on by the energy-intensive HMA production process are causing increasing concern, particularly in metropolitan regions (Milad et al. 2022).

Foaming methods or additives are used to reduce the viscosity of the binder, enabling effective coating at lower temperatures. (Caputo et al. 2020; Kheradmand et al. 2014). Consequently, WMA reduces energy consumption and fume emissions, improving working conditions and air quality. In countries like Malaysia, where sustainable construction practices are valued highly, these benefits are particularly advantageous. WMA can perform similarly to HMA in some situations, making it a promising alternative for meeting infrastructure project needs while reducing environmental effect (Piccone et al. 2020; Yang et al. 2022; Ma et al. 2019).

Because CMA is made at room temperature and employs emulsified or cutback asphalt instead of heat, it is an energy-efficient choice, especially for low-traffic and rural applications. A weaker binder-aggregate bond limits CMA's strength under high traffic, despite the fact that it is affordable and suitable for short-term or low-traffic solutions. Studies conducted in Malaysia and other nations have shown that CMA performs better in low-stress environments than high-load ones (Shaffie et al. 2021; Chatterjee et al. 2024; Rohaizat & Mohamad Taher, 2024). The need to balance cost-effectiveness, environmental sustainability, and long-term durability is reflected in the choice to utilize HMA, WMA, or CMA asphalt. Because

WMA offers a sustainable solution without compromising the lifetime needed for infrastructure projects, Malaysia and other countries have embraced it more (Al-Hashimi et al. 2023; SIRIM, 2023). Because of its strength, HMA continues to be the preferred material for heavy-duty and high-traffic applications despite its detrimental environmental consequences. However, WMA provides a more ecologically friendly choice that may be utilized for a range of applications, whereas CMA offers a low-cost, low-energy solution for low traffic and temporary purposes. These differences enable tailored solutions to meet the diverse needs of infrastructure development worldwide, including Malaysia's focus on sustainable. Table 2 summarised the comparison between HMA, WMA, and CMA in term of production temperature, durability, strength, environmental impact and applications.

ASPHALT MATERIAL - BASED ON AGGREGATE STRUCTURE

The performance of asphalt mixtures is significantly influenced by the properties of the aggregates used in the mix. There are two primary types of aggregates used in asphalt mixtures: coarse aggregates and fine aggregates. The asphalt mix's skeleton is usually made up of coarse particles, with fine aggregates filling in the spaces between the larger aggregates. Gravel and crushed stone are examples of natural aggregates whose angularity and roughness improve their capacity to interlock and connect with asphalt, improving stability and deformation resistance (Kandhal & Parker, 1998). Because of environmental concerns, recycled asphalt pavement, or RAP, has become more popular. According to Valdés et al. (2011), the quality and structure of the recycled aggregates can have an impact on how well asphalt mixes perform overall when RAP is included. By concentrating on aggregate structure, Pouranian (2019) presents a sophisticated method for comprehending and creating asphalt mixes. To specify the aggregate structure of asphalt mixes containing a blend of fine and coarse aggregate stocks, a framework was created. The new framework aims to offer a more precise way to forecast pavement performance by highlighting the significance of particle shape, size, and arrangement.

The distribution of particle sizes within the aggregate mix is represented by the aggregate gradation. Dense packing from well-graded aggregates can improve asphalt mixes' mechanical qualities. Since aggregate structure is the primary load-bearing element of mixes, aggregate gradation plays a crucial role in rutting resistance. While appropriate interlock between fine crushed aggregate increases rut resistance, segregation within the coarse mixed specimen displayed the greatest amount of deformation (Golalipour et al. 2012). The significance of aggregate gradation in asphalt mixture design is emphasized by the Superpave (Superior Performing Asphalt Pavements) system. Appropriate gradation may greatly enhance asphalt pavement performance under a range of loading scenarios (Zeiada et al. 2022).

The strength, durability, and performance of asphalt mixes under traffic loads are all greatly impacted by the shape and texture of the aggregates. Specifications for aggregate and asphalt mixes should carefully take into account the aggregate surface roughness, which is strongly connected to the mixtures' performance. By choosing aggregates with advantageous morphological properties, bituminous pavement mixes can operate at their best. It is advised to use aggregates with rough textures and angular forms to enhance the mixture's mechanical qualities and resistance to deformation brought on by traffic. When compared to rounder stones, angular aggregates offer superior interlock and stability. According to Miller et al. (2011), aggregates with a rough texture increase the bitumen's adherence.

TABLE 2. Comparison between HMA, WMA and CMA

Property	Hot Mix Asphalt (HMA)	Warm Mix Asphalt (WMA)	Cold Mix Asphalt (CMA)
Production Temperature	150–170°C (JKR 2017)	100–140°C (JKR 2017)	0–30°C Ambient temperature (no heating) (JKR 2017)
Durability	Highly durable, ideal for high-traffic areas and heavy loads. Excellent binder-aggregate bonding for heavy-duty applications like highways. (Gaudenzi et al. 2021; Alsarayreh et al. 2024)	Similar to HMA, though slightly less resistant to deformation under intense traffic loads. Additives or foaming techniques can improve durability. (Alsarayreh et al. 2024; Milad et al (2022)	Lower durability; best suited for low-traffic, temporary applications, or rural roads. (Alsarayreh et al. 2024; Boateng et al. 2021)

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Property	Hot Mix Asphalt (HMA)	Warm Mix Asphalt (WMA)	Cold Mix Asphalt (CMA)
Strength	Excellent compaction, strong bonding between binder and aggregates, ideal for highways, airports, and other heavy-duty infrastructure (Kamarudin et al. 2017)	Strength comparable to HMA when additives or foaming techniques are used, but less effective for extreme loads (Milad et al (2022)	Lower strength, not suitable for heavy-duty infrastructure; optimal for low-stress environments. (Boateng et al. 2021; Al-Busaltan et al. 2012; Daneshvar et al. 2022)
Environmental Impact	High energy consumption and greenhouse gas emissions due to high production temperatures. Offset by long service life and reduced maintenance. (Milad et al. 2022; Chaves-Pabón et al. 2024)	Lower fuel consumption and emissions, more environmentally friendly than HMA due to reduced production temperature (Belc et al.2021; Milad et al. 2022)	Least environmental impact during production, as it requires no heating. However, lower durability may lead to more frequent repairs. (Dash et al. 2022; Shanbara et al. 2021)
Applications	Best for high-traffic, heavy-duty infrastructure like highways, airports, and urban streets. (Chaves-Pabón., et al. 2024)	Versatile for high- and moderate-traffic roads, including urban, rural, and colder climates. Faster construction and reduced fume emission (Milad et al. 2022)	Suitable for low-traffic areas, temporary road repairs, and rural infrastructure. Low-cost option (Dash et al. 2022)

The function of aggregate structure in asphalt pavements has been examined by Shashidhar et al. (2000) and Hafiz et al. (2021). This study probably investigates how aggregates' structural characteristics such as their angularity, size distribution, and shape, affect asphalt pavement performance. They proposed that aggregates' shape and interlocking qualities can greatly improve asphalt pavements' longevity and performance. Granite and limestone are examples of angular aggregates that improve interlocking and stability, which results in higher mechanical performance. For load transmission and deformation resistance, the internal skeleton structure which is defined by contact sites, contact line length, and contact orientation is essential. Granite had greater connection and more contact points, which increased its flexural stiffness and dynamic stability. Granite earned the greatest grey relational grade, according to grey relational analysis, which demonstrated its better mechanical performance based on strength and shape criteria. According to Dong et al. (2023), the surface morphology of aggregate particles has a major influence on how well they adhere to asphalt, offering insights on how to improve the performance of asphalt pavement. Following abrasion, the textural complexity of granite and limestone surfaces both diminish, with limestone exhibiting more notable alterations. While granite simply creates surface adhesion without an underlying structure, asphalt may penetrate the surface of limestone to create an embedded structure that improves adhesion. Aggregates' angularity coefficient varies with abrasion, which impacts how well they adhere to asphalt. According to scanning electron microscopy (SEM) study, limestone adheres to asphalt better than granite because of its more complex surface structure.The performance of asphalt mixes is also influenced by the aggregates' mineral makeup. The characteristics of various minerals can influence how the asphalt behaves overall. Compared to calcareous stones, silica-rich silica aggregates typically offer greater strength and wear resistance. According to a report by Wang et al. (2020), siliceous aggregates can increase asphalt mixes' fatigue resistance, making them more appropriate for high-traffic regions. The durability of asphalt mixes can also be impacted by the chemical makeup of the particles. By examining the development of asphalt pavement materials and structures from the first roadways to the present, Liu et al. (2020) emphasize improvements in mix design, materials, and performance assessment. It was suggested to use a novel approach to group asphalt pavement materials into three major groups, which may then be further separated based on their mechanical characteristics. It was suggested to use a universal asphalt pavement classification (UAPC) technique, which allowed asphalt pavements all over the globe to be categorized into six varieties. This study discovered that asphalt pavement materials and structures have been getting stronger over the last century.

ASPHALT MATERIAL - BASED ON ADDITIVES AND MODIFICATIONS

Modified asphalt is a better bitumen made by adding inorganic or organic materials or by gently oxidizing asphalt. The road performs better in both hot and cold weather when the modifier is uniformly mixed into the asphalt, forming a network structure (Liu and Wei, 2021). The performance of flexible pavements may be greatly enhanced by altering the bitumen, which enables them to endure hard conditions and high traffic volumes with little environmental impact and at a reasonable cost. To improve the rheological characteristics of bitumen, several materials were employed, including waste plastic, polymers, geopolymers, nanotechnology, and crumb rubber (CB).

Polymers are frequently utilized to improve and alter bitumens' rheological characteristics. Numerous studies have documented the performance of polymer-modified asphalt in a variety of settings, demonstrating its value as a pavement material during the past 50 years (Motamedi et al. 2021; Porto et al. 2019; Lat et al. 2019; Yildirim, 2007). The longevity of roadway pavement may be considerably increased by modification employing polymer bitumen (Padhan et al. 2015). Polymers are added to bitumen to increase its stiffness, cohesiveness, and elasticity. Bitumens that have undergone polymer modification are more resistant to thermal cracking at low temperatures and permanent deformation at high temperatures (Alsolieman et al. 2021). The two main types of polymers are plastomers and elastomers. Elastomers are often utilized to increase the binder's low and high operating range, whilst plastomers are helpful additions that enhance the binder's high working temperature (Ameri et al. 2013; Kok et al. 2011). Material attributes including polymer type, content, binder grade, and supply, as well as the asphalt-modifier mixing procedure, affect the properties of polymer-modified asphalt. Polymer modification has several benefits, including improved binder qualities through increased viscosity and softening point, decreased penetration, and improved performance quality (Mansourian et al. 2019; Alsolieman et al. 2021; Yan et al. 2019). Additionally, the polymer-modified asphalt can also improve the mechanical properties of the mixture in terms of stiffness, strength and resistance to deformation.

Fibers' strong reinforcing qualities and ability to enhance their contact with soil particles make them a popular addition to asphalt in construction. There is a significant financial benefit to using fibers in asphalt mixes as they enhance the performance of asphalt pavements and extend their service life (Wu et al. 2007). The benefits of fibers in asphalt have been demonstrated in a number of studies, including improved resilience to fatigue, low temperatures, rutting, and moisture (Peltonen et al. 1991; McDaniel et al. 2003). The notion of incorporating fibers into asphalt mixes to improve their qualities is continuously supported by recent research. Natural, inorganic, and polymer fibers are the three primary forms of fibers, each with special characteristics. Since the 1960s, fibers have been used in pavements because studies have shown that they significantly increase performance at high temperatures and strengthen resistance to fractures at low temperatures. Additionally, fibers are a crucial component for improving concrete performance throughout that time because they stop reflection fractures from forming and spreading in pavements (Li et al. 2023).

An increasingly popular option for improving asphalt performance is rubber-modified asphalt (RA) due to its superior flexibility and adhesion at low temperatures (Yan et al. 2022). The wet and dry processes are the two main ways that crumb rubber (CR) is added to asphalt. In the wet process, CR is mixed with the bitumen at temperatures ranging from 160°C to 200°C while adhering to predetermined shear rates and times. The bitumen's qualities are much enhanced by this procedure (Bilema et al. 2023). On the other hand, the dry technique eliminates the requirement for pre-treatment by introducing CR directly into the asphalt mixture before compaction. Additionally, rubber modification has a number of important benefits, such as increased durability, rut resistance, and environmental advantages. Rubber particles are added to asphalt to improve its resistance against aging and cracking. Rubber-modified asphalt is especially well-suited for areas with harsh weather and high highway traffic loads since it also increases fatigue resistance and lowers the chance of thermal cracking (Khiong et al. 2021).

Due to the financial and environmental advantages, waste materials are increasingly being included in bitumens and mixes (Xu et al. 2022; Mokhtar et al. 2023). In particular, there is increasing interest in adding recovered plastic trash to asphalt. Recycling plastic waste as a modifier in the production of asphalt can result in comparable performance to virgin polymers, while also drastically lowering construction costs and assisting in the reduction of environmental contamination (Mashaan et al. 2021). It is advantageous for the ecology and the economy to reuse waste plastic in buildings. Carbon emissions and landfill trash may both be decreased by using recycled plastic in asphalt when creating roads. By strengthening it, this procedure increases the asphalt's resistance to heat, moisture, and other harm (Li et al. 2022).

Because they assist in raising the asphalt's viscosity and improve its resilience to rutting at high temperatures and cracking at low temperatures, nanoparticles are increasingly being used as modifiers in asphalt. Because of their special physical and chemical characteristics, nanoparticles have been utilized more and more recently to alter polymer-based asphalt. To improve asphalt, materials such as carbon nanotubes, nano-clay, and nano-MMT are frequently used in asphalt (Li et al. 2021; Mehmet et al. 2017). According to research, adding nanoparticles to asphalt causes them to spread uniformly, enhancing characteristics including resistance to cracking at low temperatures, fatigue, anti-skid performance, aging resistance, durability, water stability, and ease of construction. Strong connections between nano-CaCO3 particles and other molecules improve high-temperature performance and aging resistance. Asphalt's aging resistance and chemical durability are enhanced by nano-ZnO, which excels in optical, electrical, and magnetic qualities. Nano-ZnO disperses uniformly throughout the asphalt, creating a network structure that, as its concentration rises, greatly improves high-temperature stability and viscosity (Zhai et al. 2020; Zhao et al. 2017). Significant strength can be provided by a Stone Matrix Asphalt (SMA) mix with a greater bitumen concentration. According to Song et al. (2018), SMA is a hot bituminous mixture that has been treated with polymers and contains a significant amount of coarse aggregate and rich bitumen-filler mastic.

FACTORS AFFECTING ASPHALT SELECTION

The primary factors in asphalt choosing are durability, duration, and performance; it's not only about putting black material on a road (Lin et al. 2023; Li et al. 2024). The incorrect mixture may cause potholes, early road deterioration, and other structural problems that may require expensive repairs later on (Shahid et al. 2019; Jones, 2023). The optimal asphalt mix is chosen based on more than just surface characteristics. A number of variables, such as traffic volume and load, climate, environmental issues, cost, and construction time, will determine which asphalt mix performs best over time. The number of cars that use a certain road segment over a predetermined amount of time is referred to as the traffic volume. Usually, it is expressed as vehicles per hour (vph) or vehicles per day (vpd) for a specific period of time. Engineers utilize these factors, together with traffic volume, to decide which asphalt mix is best for a particular road. When choosing pavement thickness and maintenance requirements, traffic volume is a major factor. According to the number of vehicles per day, Table 3 displays the traffic volume categories (Jabatan Kerja Raya Malaysia, 2017; Asphalt Pavement Alliance, n.d.); Asphalt Pavement Association of Indiana, n.d.).

TABLE 3. Traffic Volume Categories (Jabatan Kerja Raya Malaysia (2017)

Low Traffic Volume	Roads with less than 1,000 vehicles per day.
Moderate Traffic Volume	Roads with 1,000 to 10,000 vehicles per day.
High Traffic Volume:	Roads with 10,000 to 30,000 vehicles per day.
Very High Traffic Volume	Roads with over 30,000 vehicles per day.

The weight and distribution of vehicles on the road, including axle load, load repetitions, and vehicle kinds, are referred to as traffic loads. Asphalt needs to be able to sustain enormous loads and continuous traffic in order to be long-lasting and durable (Jia et al. 2015). Depending on traffic speed, an asphalt pavement mix with a good load rate guarantees a long-lasting paved surface that doesn't deteriorate significantly over time. A sturdy asphalt mix is required in high-traffic areas, truck lanes, and crossroads where significant loads are present. High rut resistance, good stability from the aggregate skeleton, improved skid resistance, increased durability, improved aging properties from the thicker bitumen coating, less water spray, improved visibility, and less noise from traffic are some of the benefits of stone mastic asphalt (Maharaj et al 2021). Meanwhile, because it lowers friction and improves driving pleasure, a fine-graded asphalt mix could be important for high-speed roads. Rust-resistant mixtures are required in high-traffic regions to provide a smooth driving surface and prolong pavement life. The impact of pavement erosion and deterioration over time is greatly influenced by traffic volume and vehicle loads. As vehicle loads and traffic volume rise, pavement longevity decreases. The primary reason for bad road conditions brought on by large vehicle loads, such as trucks or buses, is pavements' lack of structural capability (Luskin & Walton 2002).

When selecting an asphalt mix, the local environment plays a crucial role in determining how resilient it is to extreme heat, heavy precipitation, and weather patterns. Temperature variations, precipitation, and exposure to harsh weather all have a significant impact on the asphalt's performance. In areas with wide temperature variations, thermal cracking is frequent (Gong et al. 2022; Superior Aggregates, n.d.). The ideal timing to install asphalt depends on a number of variables, such as the ground's moisture level and temperature. While cold weather may prevent the asphalt from setting correctly, hot weather might cause the asphalt to cool too rapidly, resulting in cracking and other issues (Monraz Company, n.d.). Additionally, since wet asphalt can move and skid, resulting in damaged and uneven surfaces, it is imperative that asphalt be laid on dry ground. In certain situations, flexible asphalt mixtures with anti-cracking additives could be required. While a drainage-friendly asphalt mix is required in wetter regions, hot mix asphalt is frequently used in colder locations because of its resistance to low temperatures (Taherkhani et al. 2021).

Selecting the appropriate asphalt material involves balancing immediate cost considerations with long-term environmental and economic impacts. Lifecycle cost analysis and sustainability assessments should be integrated into the decision-making process to ensure optimal material performance, reduced environmental harm, and overall cost efficiency throughout the pavement's life. Adding recycled components to asphalt mixes has been standard practice since the late 1970s. The majority of asphalt pavement building techniques utilized in the past several decades are acknowledged as sustainable due to time-improving techniques and the use of recycled raw materials. Asphalt mixes can benefit from the use of a variety of waste materials from various sectors, such as tire rubber, iron slag, foundry sand, and shingles (Vasudevan et al. 2024). Recycling has an impact on the amount of raw materials used and the processing that goes into incorporating them into pavement. For instance, oil may be saved by reusing the bitumen in recovered asphalt pavement (Taha 1999). Additionally, reusing aggregate saves the environment and permits fewer mining operations.

Although there has been a significant increase in the utilization of recycled raw materials, asphalt batch plants continue to generate 97% more CO2 than they did in 1970 (Taha 1999). But since 1970, the number of mixes developed has grown by 250 percent. The Environmental Protection Agency has taken these sources off its list of significant sources of air pollution due to the decreases in emissions. Recent advancements in warm-mix asphalt technology have the potential to lower pollutants, fuel consumption, and the temperatures needed to create and install the material.

When it comes to cost efficiency, an asphalt mix needs to be carefully assessed to make sure it satisfies project requirements without incurring needless costs. Installation, maintenance, repairs, and recycling at the end of their useful lifetimes are all included in the life-cycle cost analysis, which is necessary to comprehend the long-term financial effects of various asphalt mixtures. The secret to achieving long-term performance at the lowest cost is a well-planned asphalt mix. Long-term maintenance and repair needs will be decreased by investing a little more up front in a higher-quality mix (Xiao et al. 2019).

Lifecycle cost analysis (LCCA) provides a comprehensive framework for evaluating the economic performance of asphalt materials throughout their functional lifespan, incorporating initial construction costs, maintenance and rehabilitation expenses, user delay costs, and end-of-life recycling or disposal values (Federal Highway Administration (FHWA), 1998). Although certain asphalt types such as polymer-modified asphalt or stone matrix asphalt (SMA) may have higher initial costs, their improved durability and extended service life can result in significant long-term cost savings by reducing maintenance frequency and prolonging pavement life (Huang, 2004). Using durable materials also helps minimize agency expenditures and user-related delays. For instance, incorporating reclaimed asphalt pavement (RAP) may slightly reduce initial stiffness, but optimized mix designs can maintain performance standards while lowering material and production costs. Asphalt is one of the most recycled construction materials, and the use of RAP significantly reduces lifecycle costs while promoting circular economy practices by conserving raw materials and reducing landfill waste (Asphalt Pavement Alliance, 2024). Moreover, selecting asphalt types that are resilient to climate-related stresses—such as temperature fluctuations and increased precipitation—further enhances economic value by lowering climate-induced repair needs over time.

It is feasible to drastically reduce traffic and the associated car emissions since asphalt paving road construction is usually completed during off-peak hours. Although asphalt may be made traffic-ready somewhat rapidly, curing time needs to be carefully considered, particularly in high-traffic locations. In reality, a little job for a small parking lot or residential street will often take a few days to a week. (Lin et al. 2020), However, depending on the length and complexity, medium to large projects usually take one to three weeks.

Considering these elements, it's critical to select a pavement type that strikes a balance between upfront expenses, long-term durability, and maintenance needs (Liang et al. 2024). More robust and long-lasting asphalt materials are required to handle higher traffic volumes, particularly those involving large trucks. Furthermore, roads with significant traffic, particularly those with large trucks and buses, require asphalt mixtures with higher durability.

CONCLUSION

The following conclusions are drawn from this review:

1. Components and Interactions: Aggregates and binder are the primary components of asphalt, and their interactions significantly impact durability, strength, and stability. Proper mix design, including aggregate gradation and binder content, is critical for achieving desired performance.
2. Types of Asphalt: Hot Mix Asphalt (HMA) provides superior strength but has high greenhouse gas emissions. Warm Mix Asphalt (WMA) and Cold Mix Asphalt (CMA) offer more environmentally friendly alternatives with varied applications.

3. Modified Asphalt: Modifications, including polymers, crumb rubber, and recycled materials, improve rheological properties and pavement performance. Sustainable practices, such as incorporating recycled asphalt pavement, reduce environmental impact without compromising quality.
4. Factors in Selection: Durability, performance under load, cost and environmental considerations are key factors in asphalt selection. Advanced technologies and sustainable materials are essential for reducing environmental impact while maintaining performance in road construction.

This review emphasizes the need for continual innovation and research in asphalt materials to meet evolving infrastructure demands and environmental challenges. While sustainable asphalt materials show significant promise in reducing environmental impact and improving pavement efficiency, their long-term performance remains insufficiently understood. Current research often emphasizes short-term laboratory results, which may not fully capture how these materials behave over extended periods in real-world conditions. Therefore, future studies should concentrate on reviewing and assessing the long-term performance of sustainable asphalt materials, including their durability, aging behavior, structural integrity, and maintenance needs under various climatic and traffic conditions.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support from the Ministry of Higher Education, Malaysia (MOHE) under the Fundamental Research Grant Scheme (FRGS) (FRGS/1/2024/TK01/UITM/02/10) managed by Universiti Teknologi MARA.

DECLARATION OF COMPETING INTEREST

None.

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