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Review Article

A Review of the Studies on the Effect of Different Additives on the Fatigue Behavior of Asphalt Mixtures

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The fatigue phenomenon significantly weakens road pavement due to repeated reloading. To enhance fatigue resistance, numerous studies have explored various additives in asphalt mixtures. This review focuses on key variables influencing the effectiveness of additives, including fibers, polymers, nanomaterials, waste materials, and biomaterials, in improving the fatigue performance of asphalt mixtures. The study initially identifies different additives and fatigue testing methods used for asphalt mixtures. It evaluates the impact of factors such as modifier content and size, base asphalt binder type, mixing processes, dispersion behavior, and testing conditions on the fatigue behavior of modified asphalt mixtures. The cost-effectiveness and environmental impact of additive application have also been assessed. Additionally, research gaps and future prospects for modified asphalt mixes are outlined. Existing studies demonstrate the benefits of additives like basalt fiber, polyester fiber, styrene–butadiene–styrene (SBS), nanosilica, crumb rubber, and biooils in enhancing the fatigue life of pavement constructions. However, challenges exist in the application of modifiers due to limited practical implications and insufficient knowledge. Further research is needed on factors such as additives' dispersity, compatibility, aging resistance, economic viability, and modifying mechanisms in morphological and micromechanical aspects to enhance the fatigue performance of the modified asphalt mixture.

1. Introduction

Due to the rising cost of road pavement rehabilitation, various studies have been conducted to enhance asphalt pavement performance and service life [1]. Asphalt binder is the main and weakest component of the asphalt mixture and has a crucial effect on the performance of asphalt pavements [2]. Therefore, enhancing the asphalt binder characteristics resulted in improved resistance against pavement deteriorations, such as fatigue cracking and rutting [3]. The modification of asphalt binder is the most common method used to improve its rheological properties, hence, making asphalt mixtures with proper performances [4].

Fatigue cracking is one of the major distresses in asphalt pavements, which occurs as a result of repeated loading of vehicles and gradually generates due to the accumulation of micro and macrocracks. This mainly appears due to two key reasons, namely cohesive fracture in the asphalt binder or mastic phase, and adhesive failure at the interface of asphalt and aggregate [5, 6]. There is a large consensus that pavement performance is affected by the fatigue resistance of asphalt mixtures [7, 8]. The incorporation of modifiers to improve fatigue parameters in asphalt mixtures has been considered by researchers over recent years [9]. In this study, the influence of different modifiers on the fatigue behavior of asphalt mixtures is investigated.

There have been a variety of tests used to appraise the properties of asphalt mixtures. These tests provide various properties that can be used as inclusion parameters in the performance model of asphalt. Fatigue cracking, elastic stiffness, and properties related to permanent distortions can be described by employing these tests.

2. Methodology

In this study, a comprehensive review was conducted to assess the effect of various additives on asphalt mixture fatigue behavior. Relevant studies were identified through systematic searches in established databases based on predefined keywords, inclusion criteria, and exclusion criteria. Data extraction included the type of additive, dosage, test method, fatigue parameters, and key findings. Qualitative and quantitative synthesis, considering potential moderators, was employed to analyze the extracted data. Findings were organized by additive type, summarizing their impact on fatigue life, stiffness reduction, and crack growth. Mechanisms contributing to fatigue improvement were discussed, highlighting identified inconsistencies and limitations. Furthermore, the environmental impact and cost-effectiveness aspects of applying additives were reviewed. Knowledge gaps and future research directions were emphasized, concluding with the potential benefits of utilizing additives to enhance fatigue resistance in asphalt mixtures.

The various criteria that were utilized for the selection of relevant documents are as follows:

(1) Archive.
   (i) Google Scholar, Web of Science, and Scopus.
(2) Document types.
   (i) Journal article, conference proceeding, technical report, and dissertation.
(3) Selection criteria.
   (i) Relevant documents: documents focusing on the effect of additives on the fatigue behavior of asphalt mixtures.
   (ii) Period: The publication year was limited to January 2019–February 2024 to ensure the selection of recent documents. However, articles relevant to the scope of this article were considered from January 1986 to February 2024.
   (iii) Language: English.

3. Fatigue Tests

The most common experiments used to measure the fatigue resistance of modified asphalt mixtures include the indirect tensile fatigue test (ITFT), bending beam fatigue test (BFT), and direct tension cyclic fatigue test (DTCFT) [10–12], which are the focus of this paper. The information regarding each test is summarized in Table 1.

3.1. Indirect Tensile Fatigue Test (ITFT). The ITFT simulates the repeated traffic loading experienced by asphalt pavements by applying cyclic diametric compressive stresses to a cylindrical sample. During the test, the sample is subjected to either controlled stress or strain loading conditions. Under controlled stress, the tensile strain within the sample increases with each loading cycle, while under controlled strain, the tensile stress gradually decreases [13]. The test continues until a critical crack propagates through the center of the sample, typically along the horizontal axis due to the induced tensile stresses. The primary outcome of the ITFT is the fatigue life (Nf), which represents the number of loading cycles endured by the sample before failure under a specific stress or strain level [14].

3.2. Bending Beam Fatigue Test (BFT). The bending BFT is another established method for assessing the fatigue resistance of asphalt mixtures, complementing the widely used ITFT. It simulates the repeated bending stresses experienced by asphalt pavements under traffic loading, particularly at locations like joints and edges. During the BFT, a prismatic asphalt beam sample is subjected to cyclic loading at three points, typically configured as two supports and a central loading point. This induces tensile stresses on the bottom surface of the beam and compressive stresses on the top, mimicking the flexural stresses occurring in real pavements. The test can be conducted under controlled stress or fixed controlled stress, similar to the ITFT [15].

3.3. Direct Tension Cyclic Fatigue Test (DTCFT). During the DTCFT, a cylindrical asphalt sample undergoes cyclically applied axial tensile loading, inducing uniform tensile stresses throughout its cross-section. This loading mode directly replicates the tensile stresses experienced by asphalt pavement under traffic load, unlike the indirect approach of the ITFT. The test outputs the Nf, reflecting the number of loading cycles endured before failure, typically characterized by a vertical crack propagating through the sample center [16].

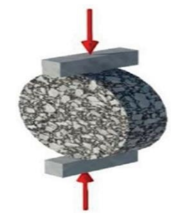
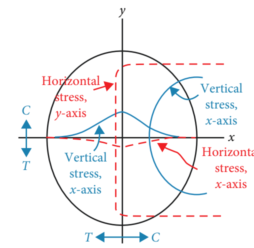
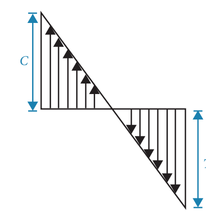
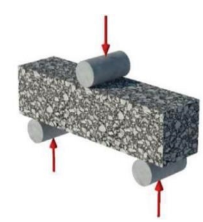
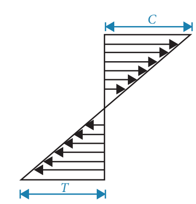
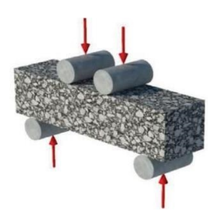
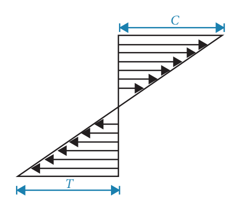
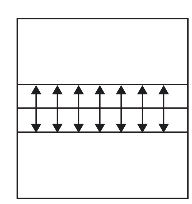
4. Asphalt Additives

Additives, the materials which at the time of making asphalt, are added to the asphalt binder or mixture in order to obtain certain changes leading to modifications in the technical properties of the asphalt mixture [17]. Additives in asphalt are not a novel issue; however, over the recent decade, it has been studied extensively. A myriad of researchers have always been seeking reasons to justify using additives to modify the properties of asphalt binder or aggregates. Lewandowski [18] expressed that the main reasons for modifying the asphalt binder by employing various additives can be summarized as follows:

(i) Obtaining softer mixtures at lower service temperatures and decrease in the cracking.
(ii) Obtaining stiffer mixtures at higher temperatures and decrease in the rutting.
(iii) Increasing the strength and resistance of mixtures.
(iv) Enhancing the fatigue resistance of mixtures.
(v) Decreasing the structural thickness of pavements.

4.1. Types of Asphalt Additives. Bahia et al. [19] categorized asphalt additives according to their components. Asphalt additives are divided into different groups, such as polymers (elastomeric and plastomeric), fillers, fibers, hydrocarbons, and crumb rubber (CR) [19]. In recent years, the variety of used additives in asphalt pavements has increased. It is mainly because of the increase in traffic loads and maintenance costs. In addition, virgin asphalt binder cannot satisfy the required engineering characteristics for all weather conditions and increased loads. The most common types of asphalt mixture additives are shown in Table 2. In this study,

Table 1: Summarized information for fatigue tests.

Test type	Loading waveform	Loading mode	Loading configuration	Stress distribution
Indirect tension test	Haversine, sinusoidal, and triangular	Stress/strain controlled		
Two-point beam bending test	Haversine, sinusoidal, and triangular	Stress/strain controlled		
Three-point beam bending test	Haversine, sinusoidal, and triangular	Stress/strain controlled		
Four-point beam bending test	Haversine, sinusoidal, triangular, and trapezoidal	Stress/strain controlled		
Direct tension cyclic fatigue test	Haversine, sinusoidal, and triangular	Stress/strain controlled		

the most frequently used additives for enhancing the fatigue performance of asphalt mixtures are highlighted.

5. Effect of Different Modifiers on the Fatigue Behavior of Asphalt

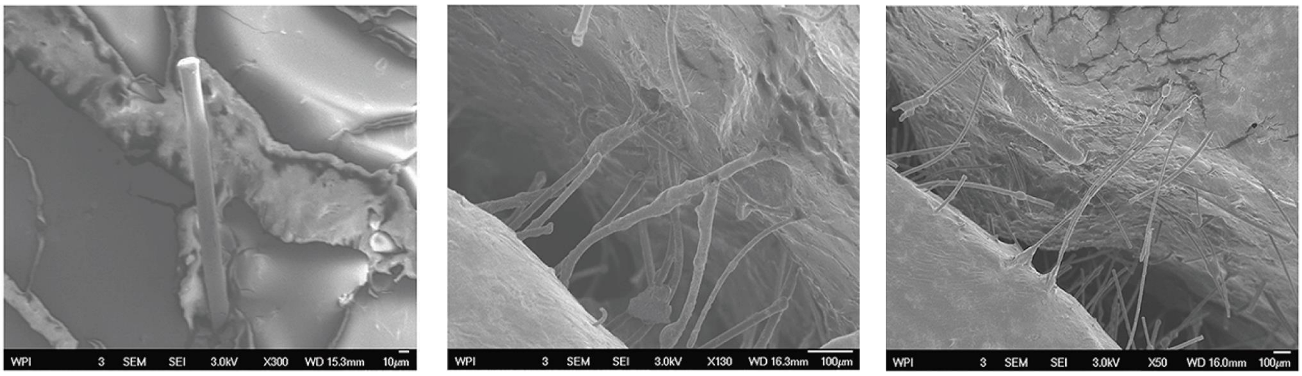
5.1. Fibers. Among asphalt modifiers, fibers have been increasingly used for their significant impact on enhancing the performance of asphalt mixtures, particularly fatigue behavior [20–22]. Moreover, fibers make a considerable contribution toward infrastructure and structural construction as well [23]. Many studies have evaluated the influence of fiber on the asphalt mixture and have demonstrated that fiber incorporation can absorb a portion of the shear force and make a connection with the aggregates. Therefore, fiber addition augments the tensile strength and ductility of the asphalt mixture and hinders the propagation of microcracks [24]. The usage of different synthetic fibers in the asphalt mixture (such as,

Table 2: Types of asphalt mixture additives.

Types of additives	Purpose	Example
Filler	(i) To fill the holes (ii) To increase durability and aggregate-asphalt binder adhesion	Lime Portland cement Fly ash
Elastomers	To increase: (i) Stiffness at higher temperatures (ii) Elasticity at temperatures within the average range in order to resist cracking To decrease: (i) Stiffness at a lower temperature in order to resist thermal cracking	Natural rubber Styrene butadiene Styrene (SBS) Tire rubber (TR) Styrene butadiene rubber (SBR)
Fibers	To improve: (i) Tensile resistance (ii) Cohesion	Natural fibers Asbestos Polyester Fiberglass
Plastomers (thermoplastic)	To increase: (i) Performance at a higher temperature (ii) Structural strength (iii) Resistance against rutting	Polyvinyl chloride (PVC) Ethylene vinyl acetate (EVA) Ethylene polypropylene (EPDM)
Waste materials	Substitution of asphalt mixture component with cheaper materials	Recycled rubber Waste plastics Waste polymers Waste engine oil Waste cooking oil
Warm mix asphalt	(i) To reduce the production temperatures (ii) Improve the workability	Evotherm Sasobit Rediset Iterlow T
Nanomaterials and nanocomposites	To improve mechanical performance and aging characteristics	Nanoclay Nanosilica Nanotubes
Adhesion improvers	To enhance the bonding strength between asphalt and aggregate	Organic amines Amides ZycoTherm
Antioxidants	To minimize the aging effect on asphalt mixture	Organic phenylamines Zinc dithiocarbonates Lignin
Natural asphalt	(i) To construct sustainable pavements (ii) To reduce the cost of asphalt pavement (iii) To increase resistance against rutting	Rock asphalt Gilsonite

polyamide, polyacrylonitrile, polyester, and glass fibers) has constructive influences on the fatigue life of the mixture [25, 26]. It is shown that significant enhancements in the impact resistance, strain capacity, and crack control of the fiber composites could be envisaged even with low-modulus synthetic fibers [27]. Different types of modifier fibers, such as cellulose, polyester, carbon, glass, basalt, and natural fibers, have been extensively examined in various studies [28–30].

Natural fibers are a cost-effective alternative to synthetic fibers. Various natural fibers, such as cellulose, sisal, jute, bamboo, kenaf, coconut, banana, date palm, and hemp, have been investigated in different asphalt mixture types. Some research highlights the noticeable improvements achieved in asphalt mixture performance, including enhanced control of drain down [31–33], increased durability, and improved tensile strength [34]. The findings underscored the potential of utilizing natural fibers in asphalt mixtures as a sustainable and effective solution, offering benefits in terms of performance and cost compared to synthetic counterparts. In a study conducted by Oda et al. [35], the effect of natural fibers on the mechanical performance of stone mastic asphalt (SMA) mixture was evaluated. Results revealed that the fatigue performance of the SMA mixtures with cellulose fibers, sisal, and coconut shells was not significantly different [35]. Ferreira da Costa et al. [36] explored the impact of varying banana fiber lengths (5, 10, 15, and 20 mm) on performance of mixtures, maintaining a constant dosage of 0.3% by weight. The study concentrated on indirect tensile strength, resilient modulus, dynamic modulus, and fatigue life. Their results indicate that longer fibers exhibit greater effectiveness in retarding crack propagation and improving fatigue life under high stresses, in comparison to shorter fibers.



(a) (b) (c)

Figure 1: SEM images of (a) fiber pull-out behavior and (b, c) bridging behavior between two fracture surfaces [38].

Polypropylene, cellulose, and polyester fibers (PFs) are the mostly used fibers in asphalt mixtures. Among these fibers, polypropylene is preferred over others due to its cost-effectiveness and strong bonding with asphalt binder, resulting in reduced cracking and enhanced fatigue life [27, 37]. In a study conducted by Wang et al. [38], the fatigue cracking resistance of asphalt mastic reinforced by polypropylene fiber was evaluated. Two key variables of fiber content and length used in the asphalt mastic were considered, and the fracture behaviors of the samples were assessed using the single edge notch three-point bending (SENB) test. It was concluded that both fiber length and content substantially enhanced the fracture characteristics of asphalt mastics. Longer fibers and a higher content resulted in higher strength; however, the increases were not consistent across the various fiber contents, which is probably because of variations in mixing uniformity. Longer fibers increase pull-out length, which assists the system in delaying the appearance and propagation of cracks. Similar to this, additional fibers lead to a denser fiber distribution, which leads to a greater amount of fiber in the bridging mechanism and improves the resistance to cracking. As evidenced by scanning electron microscope (SEM) images (Figure 1), it also represented that crack bridging and fiber pull-out were the two prominent toughening mechanisms in fiber-reinforced asphalt mastics [38].

Two common methods are used to construct fiber-reinforced asphalt mixtures. The first method is the wet procedure, in which the fibers are mixed with the asphalt binder prior to the incorporation of aggregates. In this method, fibers should be dispersed well in the asphalt matrix to prevent cluster formation [39]. The second method is the dry procedure, which is the most common technique. In the dry method, the fibers and aggregates are mixed prior to the addition of the asphalt binder. Good dispersion and diminished variability in experimental results have been reported when the dry method is employed [40, 41].

The high lipophilicity and strong coating ability of basalt fibers (BFs) lead to delayed fatigue crack propagation and remedied internal defects in the asphalt mixture due to the crossing of fibers through the micropores [42]. Wang et al. [43] concluded that the BF incorporated between fillers releases the stress concentration in the critical area and reduces the fatigue failure made by cyclic loading. Qin et al. [44] used different lengths (6 , 9, and 15 mm) and contents (3%–10%) of BF in asphalt mastics. They revealed that the crack resistance of asphalt mastics was affected by the adsorption and content of fibers. In another study, Lou et al. [45] investigated on BF-reinforced hot mix asphalt (HMA) with different fiber lengths of 3, 6, 9, 12, and 15 mm 19.0, and 26.5 mm nominal maximum aggregate size. It was concluded that fiber length has a considerable influence on the fatigue behavior and crack resistance of HMA mixture. Besides, the optimum fiber length obtained from fatigue and cracking test results was highly attributed to the nominal maximum aggregate size [45]. In the research carried out by Cheng et al. [46], the fatigue performance of asphalt mixtures containing diatomite, BF, and compounds of diatomite and BF was evaluated using a four-point bending fatigue test adopting strain control loading mode. The change of stiffness modulus based on loading cycles is shown in Figure 2, which can be seen that the fatigue process comprises two main stages. The first stage

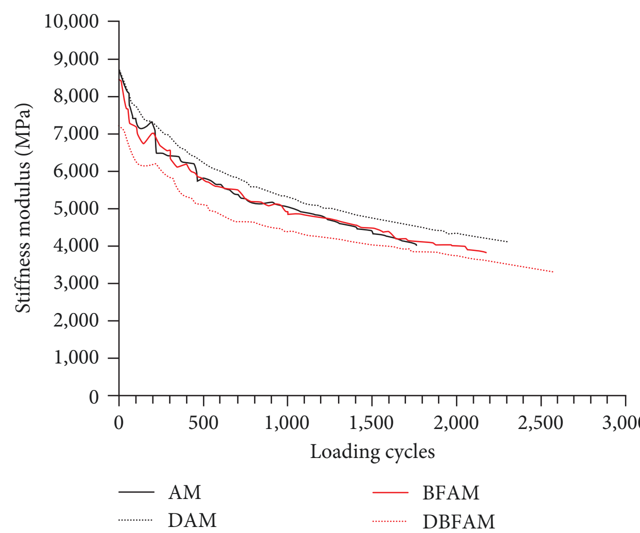


Figure 2: Stiffness modulus of different mixtures subjected to fatigue test [46].

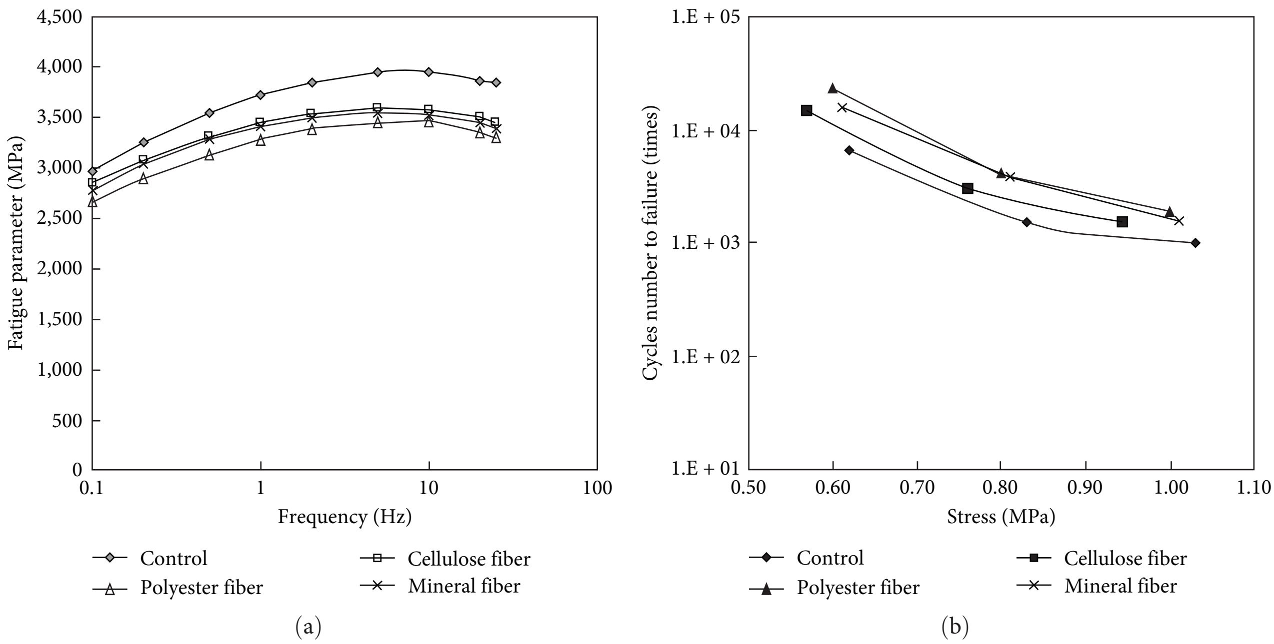


Figure 3: (a) Fatigue parameters of asphalt mixtures at 15°C, and (b) Nf versus stress levels for different asphalt mixtures [47].

is the sharp reduction of stiffness modulus caused by material deterioration. In the second stage, fatigue damage occurs under alternating loads within the initiation and propagation of microcracks. It can be found that diatomite–basalt fiber-modified asphalt mixture (DBFAM) has the highest fatigue life, followed by diatomite-modified asphalt mixture (DAM), basalt fiber-modified asphalt mixture (BFAM), and control asphalt mixture (CAM).

Ye et al. [47] evaluated the fatigue response of asphalt mixtures made by different types of fibers, including PFs, cellulose fibers, and mineral fibers with different quantities. As depicted in Figure 3(a), the fatigue parameters (E^* sin delta) of fiber-modified asphalt mixtures obtained from dynamic response measurements were decreased, implying an improvement in fatigue properties. Moreover, ITFT test results at different stress ratios (Figure 3(b)) revealed that PFs had the best effect on the fatigue performance of the mixture among the modifiers.

In the study conducted by Shen et al. [48], the effect of three types of fibers, namely BF, PF, and lignin fiber (LF), on the fatigue resistance of steel slag asphalt mixtures was investigated. The three-point bending (3PB) test was performed at 15°C at a loading frequency of 10 Hz considering three different stress ratios of 0.3, 0.4, and 0.5. The results of this research showed that fibers can increase the fatigue life of steel slag asphalt mixtures by enhancing fracture energy. Moreover, BF had the greatest effect on the enhancement of the fatigue properties of asphalt mixtures. Table 3 presents a summary of findings obtained from other previous studies on the effect of fibers on the fatigue performance of asphalt mixtures.

5.2. Nanomaterials. Nanotechnology, emerging over recent centuries, has captured the attention of scientists and is an extension of scientific domains addressing particles smaller than 100 nm. The physics and chemistry of nanosized particles exhibit distinctions from conventional materials, mostly due to the heightened surface area-to-volume ratio of nanometer-sized grains, cylinders, and plates, as well as quantum effects resulting from spatial confinement [64–67]. In addition, the high surface area-to-volume ratio provides tremendous potential for chemical reactivity [67].

However, while the macroscopic behavior of asphalt binder depends heavily on its micro- and nano-scale properties, the unique and superior properties of nanomaterials offer exciting possibilities for enhancing asphalt-pavement performance [65]. In the past few years, several studies have been conducted focusing on using nanomaterials to improve the service life of asphalt pavement against vehicles' dynamic loads through the application of nanomaterials. Many studies have demonstrated that the asphalt mixture reinforced by nanoparticles has better fatigue performance compared to that mixture with base asphalt binders [68–70]. Santagata et al. [71] investigated the effect of different nanoparticles, namely organophilic nanoclay and multiwall carbon nanotubes, on the fatigue behavior of dense graded asphalt mixtures through the DTCFT. The obtained results were interpreted using a simplified viscoelastic continuum damage (S-VECD) model. Damage characteristic curves (DCCs) showed that both nanomaterials enhanced the damage endurance capability of the asphalt mixture. Besides, whöler curves exhibited the better performance of the mixture including organophilic nanoclay, in which the barrier effects made by intercalated or exfoliated structures seemed to be more effective than those created by carbon nanotubes in combating crack initiation and retarding crack propagation [68].

Zangena [72] found that the use of aluminum oxide (Al_2O_3) and nanosilica improved the fatigue resistance of

Table 3: Impact of different fibers on the fatigue performance of asphalt mixture.

Materials	Dosages	Fiber cut length	Type of asphalt binder	Optimum content based on fatigue results	Fatigue test	Test temp	Mode of loading	References
CF	1%, 3%, and 5% by wt. of asphalt binder	20 mm	PG 64-16	3%	ITFT	5°, 25°C	Controlled stress	Arabani and Shabani [49]
	Using up to 3% of CF significantly improved the fatigue life of the asphalt mixture due to the augmentation of the binder-aggregate bonds							
GF	0.1%–0.5% by wt. of mix.	20 mm	80–100 pen grade	0.3%	ITFT	40°C	—	Abdelaziz et al. [50]
	Addition of 0.1%, 0.2%, and 0.3% GF increased the fatigue life of the asphalt mixture by about 28.2%, 37.2%, and 44.4%, respectively							
GF	0.15 by wt. of mix.	10 mm	PG 64-16	—	4BFT	25°C	Controlled strain	Shukla et al. [51]
	Using GF improved the fatigue life of the asphalt mixture by 29% and 28% at strain levels of 300 and 500 μ, respectively							
GF	0.3% and 0.6% by wt. of mix.	6 and 12 mm	60–70 pen grade	—	ITFT	25°C	Controlled stress	Enieb et al. [25]
	GF increased the fatigue resistance of the asphalt mixture by imparting desirable tensile strength to the mixture. Furthermore, the aged mixtures reinforced by GF had higher fatigue resistance. The GF length did not have a significant impact on fatigue performance Fiber length had no significant effect on the mechanical properties of asphalt mixtures							
Polyolefin-glass fiber	0.06%, 0.12%, and 0.18% by wt. of mix.	12 mm	PG 64-16	0.12%	ITFT	20°C	Controlled stress	Ziari and Moniri [52]
	Incorporation of 0.12% polyolefin-glass fiber in asphalt mixtures increased the fatigue life at both stress levels of 250 and 500 kPa by approximately 67% and 41%, respectively							
GF + diatomite	0.1%–0.3% by wt. of mix.	12 mm	AH-90	—	ITFT	16.5°C	—	Guo et al. [53]
	Diatomite and GF enhanced the fatigue behavior of the control asphalt mixture. GF solved the disadvantage of diatomite on low-temperature deformation property of asphalt mixture							
Steel fiber	2%–4% by wt. of asphalt binder	1, 3, 5, and 7 mm	80–100 pen grade	4%	4PBT	15°C	—	Liu et al. [54]
	5 mm length and 4% content of steel fiber showed the best healing performance and the fatigue life recovery rate reached 70.77%							
Steel fiber	1% by wt. of asphalt binder	25 mm	—	—	4PBT	25°C	—	Paluri et al. [55]
	(i) Using fibers contributed toward dissipating energy and helped to bridge the cracks distributed during fatigue loading (ii) The addition of steel fibers increased the calculated fatigue strength of the RAP-based concrete mixby 50%–65%							
Rock wool fiber	0.2, 0.4, 0.6, and 0.8% by wt. of mix.	—	60–70 pen grade	0.8%	ITFT	15°, 25°C	Controlled stress	Behbahani et al. [56]
	The fatigue life of modified mixtures with different amounts of rock wool from low to high was enhanced by 4%, 32%, 35%, and 65%							
Aramid fiber + polyolefin fiber	0.05% by wt. of mix.	19 mm	60–70 pen grade	—	ITFT	25°C	Controlled stress	Takaikaew et al. [57]
	The incorporation of fibers had a more significant impact on deformation value and enhanced resistance to fatigue cracking							
Aramid fiber + polyolefin fiber	—	19 mm	PG 70-16	—	4PBT	21°C	Controlled strain	Klinsky et al. [58]
	The fatigue life was higher for the HMA with fibers at moderate to low strain. However, the fatigue behavior at the highest strain levels needs further evaluation							
PET, Crumb PET	PET: 0.5, 1.0%, 1.5%, and 2.0% by wt. of asphalt binder Crumb PET: 1% and 2% by wt. of asphalt binder	10 and 20 mm	60–70 pen grade	PET:1% Crumb PET: 2%	4PBT	20°C	Controlled strain	Dehghan and Modarres [59]
	Utilizing of 20 mm long PET fiber at the rate of 1% demonstrated greater effectiveness than 10 mm long fiber. The fatigue lives of modified specimens with 1% and 2% crumb PET were 148% and 163% of the reference one, respectively							

Table 3: Continued.

Materials	Dosages	Fiber cut length	Type of asphalt binder	Optimum content based on fatigue results	Fatigue test	Test temp	Mode of loading	References
Polyester fiber	0.25%, 0.50%, and 0.75% by wt. of mix.	6.35 and 12.70 mm	40–50 pen grade	0.50%	3PBT	20°C	Controlled strain	Ismael and Taher [60]
	The addition of fibers really enhanced the fatigue resistance since the repetitions to failure increased by 9.40% for the 0.50% of 12.70 mm fibers length							
Polyester fiber	0.20%, 0.35%, and 0.50% by wt. of mix.	6 mm	AH-90	0.35%	3PBT	20°C	Controlled strain	Xu et al. [61]
	The improvement of fatigue characteristics is due to the three-dimensional networking influence of fibers in asphalt mixture and stabilization of asphalt binder on the aggregate surface							
Polyester fiber	0.3% by wt. of asphalt binder	6 mm	AH-70	—	ITFT	15°C	Controlled stress	Wu et al. [62]
	Fatigue behavior of the asphalt mixture was improved by the addition of fiber, particularly at lower stress levels							
Bamboo fiber–polyester fiber	0.3% by wt. of mix.	6 mm	PG 52-22	—	DTCFT	18°C	Controlled strain	Jia et al. [63]
	Compared with the polyester fiber asphalt mixture, the bamboo fiber asphalt mixture showed a smaller fatigue performance after long-term aging, due to the higher oil absorption and weak dispersion							

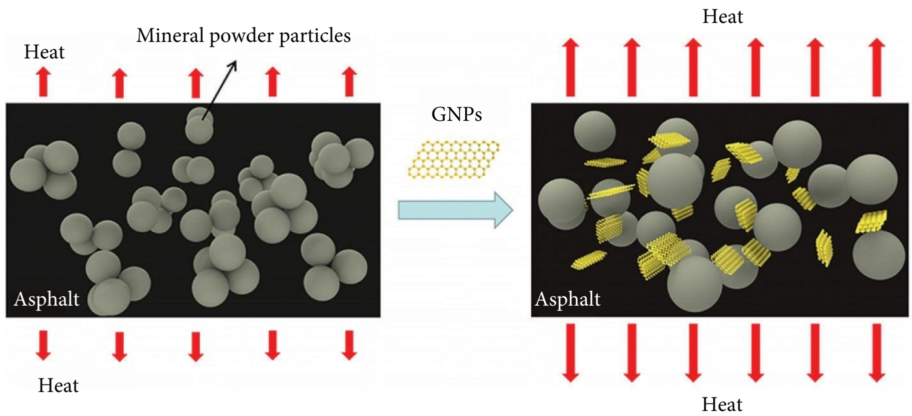


Figure 4: Antifatigue mechanism of GNPs-modified asphalt mastics [76].

asphalt mixtures by up to 44% and 20%, respectively. In another study, the effect of using nanomaterial, namely zycosoil, on the fatigue behavior of asphalt mixtures in dry and wet conditions was assessed by Nejad et al. [73]. It was figured out that the ratio of wet/dry values of indirect tensile fatigue for the mixtures modified by nanomaterial was higher than that of the control mixture.

In a study performed by Taherkhani and Afroozi [74], the fatigue behavior of asphalt mixtures modified by different percentages of nanosilica (i.e., 1%, 3%, and 5% by weight of asphalt binder) was evaluated. The fatigue life of the mixtures was calculated using a developed regression model obtained from the resilient modulus test [75]. The results showed that the fatigue resistance of the asphalt mixture improved by increasing the nanosilica content, so that the calculated fatigue life of the mixture containing 5% of nanosilica was nearly 160% higher than that of the control mixture. Li et al. [76] investigated the effect of graphene nanoplatelets (GNPs) on the fatigue resistance of asphalt mastics prepared with filler–asphalt ratios of 0.8, 1.0, and 1.2. The asphalt mastics were subjected to the time-sweep test and controlled stresses of 0.15 and 0.2 MPa. It was found that GNPs have a beneficial impact on the fatigue life of asphalt mastics. As demonstrated in Figure 4, the mechanism behind this can be due to the interaction between GNPs and asphalt, lubricity, and high thermal conductivity of grapheme [76].

In spite of the significant contributions to the improvement of the fatigue damage resistance of asphalt mixtures, some researchers realized that the nanomodified mixtures showed worse fatigue behavior than the control mixture. Research carried out by Ghile [77] exhibited that nanoclay modifications negatively affect the fatigue resistance performance of asphalt mixture, especially at low temperatures. Van de Ven et al. [70] added 6% nanoclay to a reference mixture and concluded that the modified mixture had lower fatigue damage resistance in comparison to the control mixture at low temperatures. Yarahmadi et al. [78] studied the impact of nano-$CaCO_3$ on the fatigue resistance of SMA mixtures. They incorporated varying nano-$CaCO_3$ ratios (0.3%, 0.6%, 0.9%, and 1.2% by weight of asphalt) and found that integration improved the fatigue life. This improvement stemmed from delayed crack initiation and propagation. Notably, 0.9% nano-$CaCO_3$ content yielded the best fatigue performance. A summary of findings obtained from other previous studies on the effect of nanomaterials on the fatigue performance of asphalt mixtures is presented in Table 4.

5.3. Polymers. Several studies have been conducted to evaluate the influence of polymers on the fatigue behavior of asphalt mixtures. Styrene–butadiene–styrene (SBS), styrene–butadiene rubber latex (SBR), polyethylene (PE), and ethyl vinyl acetate (EVA) are the most used polymers in asphalt technology since they can augment the mechanical performance of asphalt mixture [89, 90]. Comparing to others, SBS as an elastoplastomeric material is the most widely used polymer, which enhance the cracking resistance by increasing the elasticity of asphalt binder [91, 92]. Ahmedzade et al. [93] evaluated the fatigue performance of asphalt mixture made by different percentages of SBS (3%, 6%, and 9%) through ITFT. The results revealed that loading 6% of SBS led to the superior fatigue endurance at 25°C. Kim et al. [94] investigated the fatigue resistance of SBS-modified asphalt mastic using 4PBT and ITFT. The results disclosed that modified mixtures represented considerable enhancement in crack resistance at 20°C by a factor of 1.18 and 1.32 at 10°C. Furthermore, it was found that SBS was more effectual in retarding fatigue crack growth than preventing crack initiation when ITFT was conducted. Moreover, Kim et al. [95] figured out that SBS had the capacity to reduce the rate of micro damage accumulation contributing to an improvement in the cracking resistance and thus fatigue life of asphalt mixture.

In a research conducted by Ameri et al. [96], the effect of using SBR and poly butadiene rubber (PBR) polymers on the fatigue resistance of asphalt mixtures was assessed. The samples were subjected to 4PBT and ITFT. The ratio of dissipated energy change (RDEC) and the energy ratio methods were employed to analyze the fatigue results. Based on the results, the elastomers used in the study considerably enhanced the fatigue behavior of asphalt mixtures, and the performances of modified mixtures were comparable with that of the control specimen.

In another study, the fatigue life of asphalt mixtures modified with the compound of polypropylene (PP) and SBR polymers in different proportions was investigated. Besides, nanoclay was utilized to stabilize the polymers in the asphalt binder. The results obtained from ITFT revealed

Table 4: Impact of nanomaterials on the fatigue performance of asphalt mixture.

Nanomaterial	Dosages	Type of asphalt binder	Optimum content based on fatigue results	Fatigue test	Test temperature	Mode of loading	References
Nanoclay: Cloisite 15-A and Cloisite 30-B	2%, 4%, and 6% by wt. of mix.	60–70 pen grade	—	4PBT	5, 25°C	Controlled stress	Ameri et al. [79]
	Nanoclays did not have a significant effect on fatigue performance at low temperatures. Cloisite 15-A was more impressive at both temperatures in terms of fatigue life						
Nanoclay: Cloisite-15A Nanofill-15	0.7% by wt. of asphalt binder	60–70 pen grade	—	ITFT	5, 25°C	Controlled stress	Jahromi [80]
	Nanoclays had a negative effect on the fatigue performance of the asphalt mixture at low temperatures for all loading conditions						
Nanoclay	3% by wt. of asphalt binder	PG 64-22	—	DTCFT	18°C	Controlled strain	Miglietta et al. [81]
	The use of binders containing nanoclays augmented the fatigue properties of asphalt mixtures						
Nano-TiO_2	1%, 3%, and 5% by wt. of asphalt binder	60–70 pen grade	5%	ITFT	5, 25, 40°C	Controlled stress	Shafabakhsh et al. [82]
	Nano-TiO_2 improved the fatigue performance of asphalt mixes by preventing crack generation and hindering the propagation of microcracks						
Nano-TiO_2	3% and 6% by wt. of asphalt binder	85–100 pen grade	6%	ITFT	5°C	Controlled stress	Azarhoosh et al. [83]
	The nano-modified asphalt mixture presented higher fatigue life than the control mixtures due to the improvement of cohesion energy and higher resistance to fatigue cracking in asphalt film						
Nanocalcium carbonate (NCC)	2% and 4% by wt. of asphalt binder	85–100 pen grade	4%	ITFT	15°C	Controlled stress	Nejad et al. [84]
	The fatigue life improved 41.4% and 55.8% for 2% and 4% NCC, respectively						
Nanozinc oxide (ZnO)	1%, 3%, 5%, and 7% by wt. of asphalt binder	85–100 pen grade	7%	ITFT	5°C	Controlled stress	Azarhoush et al. [85]
	The asphalt mixtures containing ZnO had higher fatigue life than the control mixtures due to increased adhesion energy between the asphalt binder and aggregate						
CNT	0.3%, 0.6%, 0.9%, 1.2%, and 1.5% by wt. of asphalt binder	60–70 pen grade	1.5%	4PBT	25°C	Controlled strain	Ziari et al. [86]
	CNT increased the fatigue life of the asphalt mixture. In other words, using CNT led to an increase in cumulative dissipated energy and a decrease in the average rate of damage propagation						
CNT	0.2%, 0.5%, 0.8%, 1.2%, and 1.5% by wt. of asphalt binder	60–70 pen grade	1.5%	4PBT	25°C	Controlled strain	Ameri et al. [87]
	By increasing the CNT content, the plateau value (PV) decreased considerably, implying that CNT has a beneficial effect on the fatigue resistance of asphalt mixtures						
Graphene nanoplatelets (GNPs)	0.5% by wt. of asphalt binder	60–70 pen grade	—	ITFT	25°C	Controlled stress	Shamami et al. [88]
	The fatigue life improved by 55% due to the high specific surface area of GNPs and the high adhesion between the bitumen and aggregates						

that adding a polymer blend increased the fatigue performance of the asphalt mixture. Specifically speaking, the incorporation of 5% polymer blends comprising 50% and 70% SBR improved the fatigue life by more than 50% in comparison to the SBS-modified mixture [97].

Brovelli et al. [98], compared the fatigue performance of asphalt mixtures prepared by different additives, namely cellulose and synthetic fibers, amorphous polyolefin, and a polymer made by combining low-density polyethylene (LDPE) and EVA with those of conventional mixtures. ITF test was employed and the results were analyzed using classic approaches and energetic methods (dissipated energy (DE) and plateau value (PV)). It was found that amorphous polyolefin-modified mixtures had the best fatigue performance among others. Table 5 presents a comprehensive summary of findings from previous studies investigating the impact of polymers on the fatigue performance of asphalt mixtures.

Chegenizadeh et al. [105], investigated the fatigue life of SMA mixtures, which were modified with different proportions (0%, 2%, 4%, and 6% by weight of asphalt binder) of ethylene propylene diene monomer (EPDM). 4PBT was utilized, and the findings were analyzed using the DE approach. Results revealed that all samples with modified binder had improved performance concerning the cumulative DE compared to the control sample. In addition, samples containing 4% EPDM demonstrated the highest overall fatigue resistance.

5.4. Nonocomposites. Nanocomposite materials are composite materials that include at least one phase in the nanoscale range. These materials are formed by combining a nanoscale filler material with a macroscale, continuous matrix material. The filler material generally has greater strength compared to the matrix material. Nanocomposites are present in various fields such as materials science, engineering, and chemistry [106]. Polymer nanocomposites (PNCs) represent an innovative category of modifiers employed to enhance the performance and rheological characteristics of asphalt binders. PNCs are generated by the combination of polymers and nanomaterials. The great surface area of nanomaterials leads to convoluted interactions, which result in a new category of materials named PNC, exhibiting a distinct set of physical properties [107].

It has been reported that the incorporation of SBR/NC can improve the adhesion between the aggregate and asphalt binder [108, 109]. Therefore, in a research carried out by Salehfard et al. [110], the fatigue properties of SBR/NC-modified asphalt mixtures were evaluated by performing ITFT. For this purpose, SBR latex was prepared with a 40% concentration, and the solution method was employed for making nanocomposite. It was shown that the 5% SBR/NC-modified asphalt mixture had the best fatigue performance which was even more than the SBR modified asphalt mixture. This is because nanoclay facilitates the dispersion and stabilization of SBR in the asphalt matrix, which significantly affects the adhesive and cohesive properties of asphalt-aggregate systems.

5.5. Waste and Biomaterials. Different types of waste material are made every day, and the volume of waste generation is increasing annually as consumption grows. The finest way to cope with these wastes is by recycling and reusing them as raw materials or modifiers [111]. Among waste materials, waste tires and recycled polymers are the most consumed materials as modifier in asphalt technology [112–114].

Daghighi and Nahvi [115] used different percentages of modifiers, including CR, reclaimed rubber (RR), and SBS, to promote the fatigue resistance of the asphalt mixture. The samples were subjected to 4PBT using a stress-controlled mode. It was found that 5% SBS modification represented the best results, followed by 10% CR and 12% RR, whilst 10% CR and 12% RR-modified mixtures demonstrated a high deformation rate since initial cracking.

In another study, Moreno-Navarro et al. [116] assessed the potential of incorporating acrylic fibers and CR additives as a modifier to enhance the mechanical response of high-modulus asphalt mixtures (HMAM). Figure 5 and Table 6 depict the results obtained from the 4PBT, which were compared to the sample constructed with SBS polymer. It is clear that the incorporation of acrylic fibers (HMAM-AF) led to improvements in the fatigue resistance of HMAM at any strain level. Nevertheless, a negative effect was observed at a high strain level when CR was added to HMAM, which arises from premature failure caused by high deflections.

In recent years, numerous studies have been conducted to assess the impact of waste ethylene–propylene–diene-monomer (EPDM) on the performance of asphalt mixtures. The results have demonstrated significant improvements in various aspects, including the flexibility of mixtures [117], rutting resistance [118], and moisture susceptibility [119]. While several studies have shown enhanced fatigue performance of modified binders with waste EPDM [118, 120, 121], there is currently a lack of comprehensive research that has specifically examined the effect of this waste material on the fatigue properties of asphalt mixtures. This presents an opportunity for further investigation into the potential benefits of incorporating waste EPDM into asphalt mixtures to improve their fatigue characteristics.

Some studies have been performed on the performance evaluation of biobinders from a fatigue behavior and healing potential point of view. The results demonstrated promising results which highlighted no particular disadvantages and even enhanced responses were reported in some cases [122–125].

In research carried out by Gaudenzi et al. [126], the fatigue resistance of asphalt mixtures produced with a biobinder containing 30% lignin under different aging conditions was analyzed. The resistance to fatigue cracking was evaluated by conducting ITFT in controlled stress mode, and a repeated haversine load was applied with 0.1 s loading time and 0.4 s rest time. It was found that the bio-based mixtures were less susceptible to stress/strain levels. Moreover, apart from the aging condition, the use of lignin penalized the fatigue response of the asphalt mixture, but comparable behavior was found in the aged sample, implying that biomixtures mitigate the aging effects on it.

Zhang et al. [127] investigated the effects of two types of lignin, namely lignin powder (LP) and LF on the mechanical properties of asphalt mixtures, such as fatigue resistance. A

Table 5: Impact of polymers on the fatigue performance of asphalt mixture.

Polymer	Dosages	Type of asphalt binder	Optimum content based on fatigue results	Fatigue test	Test temperature	Mode of loading	Reference
SBS, Styrene ethylene Butylene–Styrene (SEBS), SBR latex, Elvaloy, CR	1%, 3%, 5%, and 10% by wt. of asphalt binder	AC-5, AC-10, and AC-20	—	ITFT	25°C	Controlled stress	Khattak et al. [99]
	The fatigue life of modified mixtures has a strong correlation with both the rheological properties of the binders and the engineering characteristics of the mixtures						
Polymerized pellets (PP), SBS	4% by wt. of asphalt binder	PG 64-16	—	DTCFT	20°C	Controlled strain	Sahebzamani et al. [100]
	The utilization of both polymers resulted in enhanced performance characteristics of asphalt mixtures. However, the aging process significantly deteriorated the fatigue and low-temperature cracking resistance of asphalt mixtures, particularly when they were modified with SBS						
Recycled polyethylene PE and CR	0.2% and 0.3% by wt. of mix.	60–70 pen grade	0.2%	4PBT	20°C	Controlled strain	Zhang et al. [101]
	The addition of PE reduced the fatigue life of the asphalt mixtures; the CR improved the PE-modified mixtures' fatigue resistance						
SBS, epoxy	—	60–70 pen grade	—	4PBT	10°C	Controlled strain	Nguyen and Tran [102]
	Epoxy asphalt mixtures exhibited superior fatigue resistance compared to polymer-modified asphalt mixtures						
SBS	2%, 3%, and 4% by wt. of asphalt binder	PG 58-28 and PG 64-28	3%	4PBT	20°C	Controlled strain	Qabur [103]
	The addition of polymers to both binders resulted in an increase in the fatigue life of the asphalt mixtures at all strain levels The presence of certain inconsistencies in the damage results, particularly for PG 64-28 at 3%, can be attributed to the non-homogeneous nature of the 4PBT						
SBS	—	PG 64-22 and PG 70-28	—	4PBT	20°C	Controlled strain	Ghabchi et al. [104]
	The utilization of a polymer-modified binder was found to significantly improve the fatigue life and counteract the detrimental effects caused by the inclusion of RAP and RAS in the asphalt mixture						

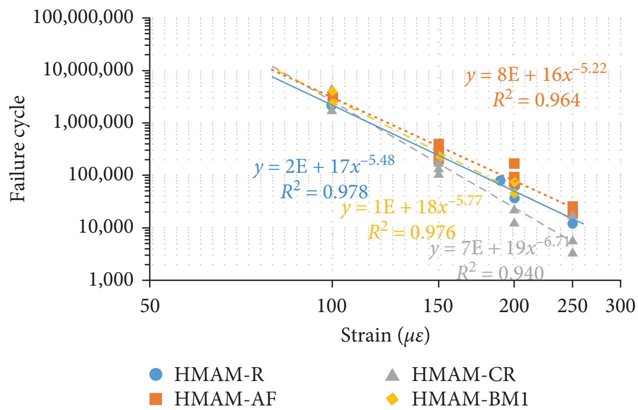


Figure 5: Fatigue life law obtained from 4PBTs [116].

Table 6: The results of the fatigue 4PBTs [116].

	HMAM-R	HMAM-AF	HMAM-CR	HMAM-BM1
$\varepsilon.10^6$	115	122	115	120
$\varepsilon.10^6$ max.	120	129	121	126
$\varepsilon.10^6$ min.	109	116	110	114
a	2×10^{17}	8×10^{16}	7×10^{19}	1×10^{18}
b	−5.487	−5.222	−6.713	−5.773
R^2	97.85%	96.64%	94.01%	97.60%

controlled-strain (300, 400, 500, 600, and 700 μ/m) mode and haversine loading were adopted at a frequency of 10 Hz and a temperature of 20°C. It was figured out that contrary to LP, LF had a negative effect on the fatigue resistance of asphalt mixtures, which could be ascribed to the incompatibility of asphalt binder and LF, which significantly affects aggregate bonding. Omran and Hesami et al. [128] used waste oil and SBS to enhance the fatigue behavior of the asphalt mixture. 4PBT and chromatography methods were employed to measure the mixture fatigue responses and analysis the asphalt chemical makeup, respectively. The results demonstrated that using oil and SBS/oil increased the fatigue resistance of the mixture by 6 and 3.5 times, respectively. Moreover, a strong correlation was reported between the fatigue life of the asphalt mixture and asphalt chemical indices.

Yang et al. [129] in their research studied the effect of using three types of bio-oil namely original bio-oil (OB) which is derived from waste wood, dewatered bio-oil (DWB), and polymer-modified bio-oil on fatigue performance of asphalt mixtures. Figure 6 demonstrates the fatigue life of control and bio-oil modified (BOM) asphalt mixtures obtained from 4PBT. It is shown that BOM asphalt mixtures had higher fatigue life than the control sample at both strain levels. A considerable difference was observed at the higher strain level, in which the average fatigue life corresponding to BOM mixtures was 680% higher than that of the control mixture. The higher fatigue life of BOM asphalt mixtures could be due to lower flexural stiffness and lower initial DE.

In another study, Gaudenzi et al. [130] evaluated the fatigue response of asphalt mixtures produced by bio-oils derived from a by-product of the paper industry. The

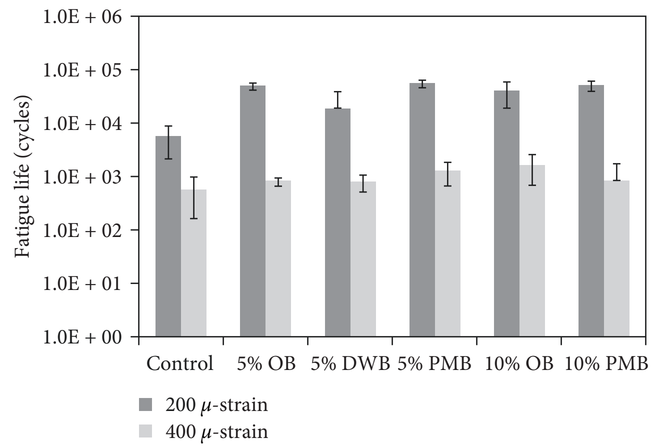


Figure 6: 4PBT results for control asphalt mixture and bio-oil modified (BOM) asphalt mixtures [129].

biobinder used in this study was made by adding 10% (by weight) bio-oil to 50–70 penetration grade of asphalt binder. The specimens were subjected to ITFT in dry, wet, and long-term aged conditions. Figure 7 shows the comparison between the fatigue behavior of bio-based and control asphalt mixtures at different conditions. It should be mentioned that control and bio-based asphalt mixtures were assigned as MB120 and MB50/70 + A10, respectively. It can be seen that the specimens with the same binder content have similar fatigue responses. Furthermore, in dry and aged conditions, the fatigue curve representative of the biobinder mixture is comparable to that of the control specimen, whilst, considerable improvement in the fatigue behavior can be observed in wet conditions, implying the mixture's low water sensitivity due to the presence of biobinder. The results of other research on the fatigue performance of asphalt mixtures modified with waste and biomaterials are tabulated in Table 7.

6. Impact of Freeze–Thaw Cycles

Freeze–thaw (F–T) cycles significantly impact the performance of road pavement, particularly in seasonal frozen regions. Some studies have explored the combined effects of F–T cycles and fatigue on asphalt mixtures. Kavussi et al. [138] assessed the fatigue behavior of polymeric sulfur modified asphalt mixtures under F–T conditioning using the ITFT test. Their investigation revealed that the presence of solid crystalline particles of polymeric sulfur in asphalt mixtures decreased flexibility, resulting in a more brittle behavior and reduced fatigue life. However, incorporating CR-modified binder in polymeric sulfur-modified mixtures could enhance the performance against fatigue failure during F–T cycles. In another study conducted by Guo et al. [139], the fatigue damage characteristics of composite crumb rubber modified asphalt mixture (CCRMA) and styrene–butadiene–styrene-modified asphalt mixture (SBSMA) under F–T cycles were analyzed using the semicircle bending fatigue test. The parameter PV of the stiffness modulus degradation ratio curve served as the analysis parameter to investigate damage evolution. The results indicated that F–T cycles accelerate the fatigue damage rate of asphalt mixtures. Furthermore, CCRMA demonstrated better F–T resistance and

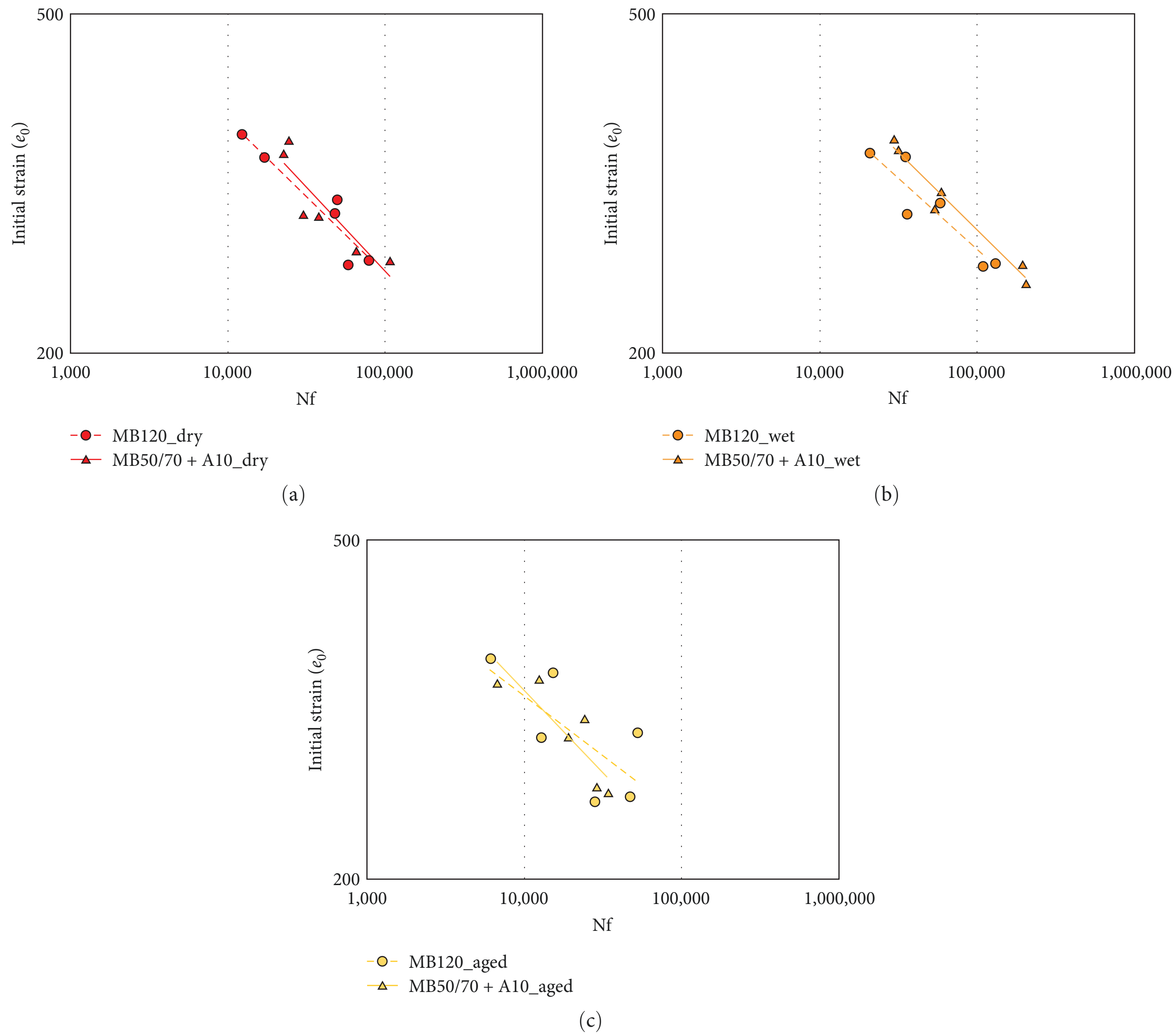


Figure 7: Fatigue laws corresponding to control and bio-based asphalt mixtures: (a) dry conditions, (b) wet conditions, and (c) aged conditions [130].

fatigue resistance than SBSMA, which is consistent with the findings of Cui et al. [140].

7. Cost-Effectiveness and Environmental Consequences

Although numerous studies have reported the improved performance of asphalt mixtures containing additives, the cost-effectiveness of modified asphalt mixtures and their environmental impacts must be considered. Due to their high cost, the use of additives such as nanomaterials could make their use uneconomical in high dosages and increase the production costs of asphalt pavement. However, given their potential to enhance resistance to aging, they may reduce lifecycle costs [141].

A comprehensive cost analysis revealed that the production of a nano-modified binder with carbon nanotubes is more expensive compared to other nanomaterials, whereas nanotitanium dioxide is the most economical option. In addition to the expense of nanomaterials, there are additional indirect expenses related to nano modification, including equipment expenses and the employment of experienced employees [69].

On the other hand, using waste materials can help achieve environmental goals and potentially lower production costs for asphalt mixtures [142] but it is essential to ensure that the utilization of mixtures containing waste materials does not have adverse effects on human health or local ecosystems, particularly through the potential run-off of these mixtures. In research carried out by Fernandes et al. [143], the environmental effect of SMA mixtures containing SBS, waste motor oil, CR, and waste high-density polyethylene was assessed. They measured the amount of heavy metals found in the asphalt mixture leachates and compared them with the prespecified thresholds. It was found that the utilization of waste materials in asphalt mixtures may not entail

Table 7: Impact of waste and biomaterials on the fatigue performance of asphalt mixture.

Waste/Biomaterials	Dosages	Type of asphalt binder	Optimum content based on fatigue results	Fatigue test	Test temperature	Mode of loading	References
CR + low-density polyethylene (LDPE)	CR: 15% by wt. of asphalt binder. LDPE: 2.5%, 5%, 7.5%, and 10% by wt. of asphalt binder	40–50 pen grade	—	4PBT	20°C	Controlled strain	Almaali et al. [131]
	The addition of 7.5% and 10% LDPE, along with 15% CR, has been found to achieve the best fatigue life for the asphalt mixtures						
CR	5%, 7%, 9%, and 11% by wt. of asphalt binder	60–70 pen grade	9%	ITFT	32°C	Controlled stress	Vishnu and Lakshman [132]
	Compared to conventional asphalt mixture, the fatigue life of asphalt mixtures incorporating light, medium, and heavy automobile waste tires exhibited increases of 62%, 71.1%, and 95.68%, respectively						
Recycled plastic	6% by wt. of asphalt binder	40–60 pen grade	—	4PBT	20°C	Controlled strain	White and Magee [133]
	The fatigue life of asphalt mixtures containing recycled plastic did not exhibit a significant difference when compared to the control mixtures						
CR + WMA additive	10% by wt. of asphalt binder	PG 64-22	—	4PBT	5°C	Controlled strain	Xiao et al. [134]
	The fatigue life values of the control mixtures were generally lower than those of other rubberized mixtures, regardless of the presence or absence of WMA additives						
CR	20% by wt. of asphalt binder	PG 64-22	—	DTCFT	25°C	Controlled stress	Asgharzadeh et al. [135]
	The addition of crumb rubber to railway asphalt mixtures significantly enhances their fatigue life by up to 7.2 times compared to unmodified mixtures. The aged crumb rubber modified mixture demonstrated the lowest fatigue life among the tested samples						
CR + WMA additive	15% and 20% by wt. of asphalt binder	PG 64-22	20%	ITFT	—	Controlled stress	Yazdipanah et al. [136]
	The enhanced fatigue resistance observed in asphalt mixtures modified with CR at both stress levels can be attributed to the combined effects of the polymer modification caused by the soluble components of CR and the particle effect resulting from the presence of insoluble parts in CR The inclusion of rejuvenator has proven to be effective in extending the fracture of rubberized asphalt mixtures under two stress levels						
Waste styrene butadiene rubber (WSBR) and waste poly butadiene rubber (WPBR)	3% and 5% by wt. of asphalt binder	60–70 pen grade	5% WSBR	4PBT ITFT	15, and 25°C	Controlled strain on the 4PBT and controlled stress on the ITFT	Ameri et al. [96]
	The fatigue life of waste polymer-modified mixes is considerably greater than that of mixes with neat binder and is remarkably close to the original polymer-modified mixes						
Rapeseed oil	1.25%, 2.5%, 3.75%, and 5.0% by wt. of asphalt binder	35–50 pen grade	2.5%	4PBT	10°C	Controlled strain	Kowalski et al. [137]
	The addition of a bioagent mitigates the stiffening effect of RAP and enhances the fatigue resistance of the asphalt mixture through its fluxing action						

the risk of producing harmful leachates that could impact the environment or human health.

Fiber addition to asphalt mixtures enhances the strength and longevity of road pavement, leading to a reduction in maintenance costs [144, 145]. Incorporating waste PF into asphalt mixtures can extend the lifespan of road pavement and contribute to the disposal of end-of-life tires, which is beneficial for both the economy and the environment [146]. On the other hand, polymer fibers such as polyacrylonitrile, polyamide, and polyester contribute to environmental pollution [28].

The use of plant fibers in asphalt mixtures can reduce the cost of pavement construction and produce environmentally friendly asphalt mixtures with improved road performance [147].

Martinez-Soto et al. [148] carried out a life cycle assessment (LCA) to assess the environmental impact of several fibers. The study found that the use of end-of-life tires (FiTyre) and cellulose fibers is more advantageous than traditional fibers (fiberglass, PF, and aramid fiber).

Natural fibers, compared to synthetic fibers, provide environmental advantages and are cost-effective. The incorporation of waste fibers also provides environmental benefits for pavement engineering. However, further research should concentrate on waste fiber processing methods and determining the optimal fiber content [29].

Several types of polymers have been studied as modifiers; however, only a few number of them have proven to be satisfactory in terms of both performance and cost-effectiveness. Within the category of polymer additives, SB copolymers are relatively costly compared to other additives. However, the expense can be mitigated by partially substituting these copolymers with alternative modifiers such as ground tire rubber (GTR), thereby reducing costs while preserving necessary characteristics [90]. Nevertheless, the utilization of PMB asphalt mixtures enhances pavement performance, leading to a reduction in the frequency of maintenance and rehabilitation activities. Consequently, significant environmental benefits can be achieved irrespective of the type of PMB used in the asphalt mixture and subsequent maintenance and rehabilitation activities of the pavement structure [149, 150]. Souliman et al. [151] compared the cost-effectiveness of asphalt mixtures prepared by asphalt rubber (AR) and polymer additives with control mixtures based on fatigue performance. The 4PBT test was used, and the fatigue lives were calculated using a 3D-Move model. It was found that the fatigue performance of the AR mixtures was greatly higher than that of the polymer-modified and control mixtures. AR mixtures demonstrated considerable cost-effectiveness in comparison to the control mixtures. Overall, the cost-effectiveness of the polymer-modified mixtures and AR mixtures was 2.6 times and 4.1 times greater than the control mixtures, respectively.

Since fatigue cracks are one of the most common failures in asphalt pavements, leading to additional repair and maintenance costs and the loss of initial capital, assessing the environmental impact and the costs of modified asphalt mixtures based on fatigue performance can significantly contribute to the asphalt pavement industry. Therefore, future research is necessary to conduct a comprehensive life cycle analysis of modified asphalt mixtures utilizing various categories of additives to verify their sustainability.

8. Summary of Findings and Discussion

Based on the literature and a comparison of the key results presented in the tables, the findings can be summarized and discussed as follows:

Generally, the incorporation of fibers in asphalt mixtures has been shown to improve fatigue life by dissipating energy and bridging cracks during fatigue loading. Among the different types of fibers discussed in this study, BF has demonstrated superior performance due to its ability to delay fatigue crack propagation through its coating effect. The fiber content, length of fibers, and the mixing methods used are important parameters that significantly influence the fatigue behavior of asphalt mixtures. However, there are exceptions such as in the case of GF, where fiber length does not have a significant effect on fatigue resistance. The incorporation of two different types of fibers can have a synergistic effect on fatigue performance, as one type of fiber can mitigate the disadvantages of the other. The optimum fiber content in asphalt mixtures varies depending on factors such as fiber type, size, aggregate type and size, and binder content and grade, making it challenging to define a universal optimum amount. Upon summarizing the literature, the optimal fiber percentage ranged from 0.35% to 0.8% by weight of the mixture and from 1% to 10% by weight of the asphalt binder. Given the observed decrease in fatigue resistance at higher stress levels in multiple studies, further evaluation is warranted in this area.

Upon comparing the results obtained from various research studies on the usage of nanomaterials in asphalt mixtures, it is evident that NC has been the most commonly used nanomaterial. The ITFT and control stress have emerged as the most prevalent testing method and mode of loading, respectively, predominantly conducted within the temperature range of 5−25°C. In terms of the optimum content determined from fatigue results, it varied between 1.5% and 7% by weight of asphalt binder. In general, the application of nanomaterials to improve the fatigue performance of asphalt mixtures can yield significant benefits. This is primarily attributed to the distinct structure of nanomaterials, which effectively combats crack initiation and propagation by enhancing adhesion and cohesion energy. However, the fatigue performance of asphalt mixtures modified with nanomaterials at lower temperatures poses significant challenges. The poor compatibility between the nanomaterial and asphalt binder, coupled with an inhomogeneous microstructure, can have a detrimental effect on the fatigue performance of asphalt mixtures. It is important to address these challenges in order to fully leverage the potential benefits of nanomaterials for improving the fatigue resistance of asphalt mixtures.

Regarding polymers, SBS has been extensively utilized in numerous studies, demonstrating its wide applicability in enhancing the fatigue life of asphalt mixtures. This can be attributed to its remarkable elasticity, durability, and ability to improve the mechanical properties of asphalt. Notably, SBS exhibits exceptional performance at low temperatures, making it a preferred choice. However, further investigation is required to understand the impact of aging on the fatigue behavior of SBS-modified asphalt mixtures. In terms of testing methodologies, the use of ITFT and controlled strain mode has been more prevalent among researchers. Most studies have conducted their tests at temperatures ranging from 20 to 25°C. No specific range for optimal content based on fatigue results was identified, attributed to the insufficient information provided by the authors. Nevertheless, considering the significant role of polymers in enhancing the fatigue performance of asphalt mixtures, it is crucial to conduct additional research to explore the effect of polymers under lower temperature conditions.

The use of CR is common in asphalt mixtures to enhance fatigue resistance, although it is generally less effective than prevalent polymers like SBS. Nevertheless, the combination of CR with other additives in asphalt mixtures holds promise for improved fatigue behavior, especially when exposed to F–T cycles. However, the performance of waste materials, particularly under high-stress levels and aging conditions, is still a subject of debate. Biomaterials play a significant role in the performance of asphalt mixtures, and their effectiveness is highly dependent on the condition under which the fatigue test is conducted. Among biomaterials, asphalt mixtures modified with bio-oils exhibit superior performance at higher strain levels due to their lower stiffness. Moreover, the incorporation of biomaterials, including bio-oils, in RAP mixtures shows promising results in enhancing the overall performance of the asphalt mixture. However, it should be noted that the compatibility between biomaterials and asphalt binder can have a negative effect on the fatigue performance of the asphalt mixture, and this issue is still a topic of debate and further research. The optimal content of waste and biomaterials ranged from 2.5% to 20% by weight of asphalt binder, a range highly influenced by various factors.

9. Challenges and Recommendations for Future Work

The current findings highlight the potential of additives in improving the fatigue performance of asphalt mixtures, aligning with sustainability requirements in road construction. However, to comprehensively evaluate the applicability of these modifiers, further investigations and future work can be conducted in the following areas.

9.1. Fibers

(i) The influence of fiber orientation and distribution on asphalt mixture fatigue performance remains an unsettled area of research. While some studies have explored this relationship, further investigation is crucial to comprehensively understanding the mechanisms at play. Employing imaging techniques such as SEM can hold significant promise in elucidating the connections between specific fiber distribution patterns and key fatigue parameters of the mixture.

(ii) There is limited research on the effect of fatigue damage evolution of fiber-modified mixtures under aging conditions, indicating a need for further investigation in this area. Additionally, more research is needed on the fatigue performance of fiber-modified mixtures at high stress levels due to their vulnerability.

(iii) Limited information exists regarding the utilization of fibers in porous mixtures, indicating the need for further exploration and study in this area.

(iv) It is worth considering the application of principles from composite science to model the effect of fiber reinforcement on the fatigue performance of asphalt mixtures.

9.2. Nanomaterials

(i) Given the poor dispersity of nanomaterials, such as graphene oxide (GO), in the asphalt matrix, directly affecting the fatigue performance of asphalt mixtures, it is recommended to employ different modification techniques, such as surface functionalization, for various nanomaterials. By comparing the results, a better understanding can be gained regarding the modification mechanism and its impact on enhancing fatigue resistance.

(ii) Extensive research is needed to investigate this aspect and develop a versatile apparatus capable of accommodating various mixing methods while ensuring dispersion homogeneity. Such a development can potentially contribute to reducing the production costs associated with nano-modified binders.

(iii) The life cycle cost analysis, encompassing operational costs, maintenance, rehabilitation, energy consumption, and other factors, remains largely unexplored in this field. It is imperative to conduct a comprehensive life cycle cost analysis and disseminate the findings through publication. This analysis will facilitate the development of specifications and recommendations to enhance decision-making processes.

9.3. Polymers

(i) It is recommended to investigate the compatibility and synergistic effects of polymer modifiers with other additives commonly used in asphalt mixtures, such as fibers, rejuvenators, and warm mix asphalt additives, to optimize their combined impact on fatigue resistance.

(ii) Exploring the feasibility of incorporating sustainable and environmentally friendly polymer modifiers, such as bio-based or recycled polymers, can be beneficial to enhance the fatigue resistance of asphalt mixtures while reducing the environmental impact.

(iii) Limited polymer compatibility, dispersibility, and storage stability remain significant challenges, directly impacting the fatigue performance of asphalt mixtures. Further research is crucial to develop and evaluate strategies that improve these aspects, ultimately enhancing the fatigue resistance of polymer-modified asphalt.
(iv) There is a lack of knowledge about the effect of the morphological and micromechanical properties of polymer-modified asphalt binder on the fatigue behavior of mixtures. It is advised to analyze the microstructural changes of the binder and its interfacial interactions with aggregates using advanced characterization techniques, such as atomic force microscopy (AFM). Correlating these results with the fatigue life of asphalt mixtures, including parameters such as roughness, adhesion force, and Derjaguin–Muller–Toporov (DMT) modulus, can provide a better understanding of the underlying mechanisms of fatigue improvement.

9.4. Waste and Biomaterials

(i) Further research is needed to address the aging issues associated with asphalt mixtures modified with waste and biomaterials, aiming to improve their long-term performance.
(ii) The homogeneity problem of coating between waste materials and aggregates needs to be solved to improve the fatigue behavior of asphalt mixture.
(iii) It is important to evaluate the impact of domestic biomaterials on the fatigue performance of asphalt mixtures and explore opportunities to maximize the incorporation of biowaste materials in pavement applications.
(iv) It is recommended to investigate the correlation between the fatigue performance of asphalt mixtures and the chemical composition of biomodified asphalt binder due to the existing lack of knowledge in this area.
(v) It is advisable to embrace the utilization of a combination of two or more biomaterials in asphalt pavement applications, as research has shown that each biomaterial can have either a negative or positive influence on the fatigue resistance of asphalt mixtures.
(vi) Conducting a comprehensive comparison of the environmental impacts and LCA between asphalt mixtures made with bio and waste materials and those with conventional asphalt binders is necessary.
(vii) Establishing a clear performance relationship between the fatigue behavior of biomodified asphalt binder and the bioasphalt mixture is essential.

10. Conclusion

In recent years, the use of additives in asphalt technology has garnered significant attention due to their potential to enhance the mechanical properties and durability of asphalt mixtures. The main types of additives are encompass fibers, nanomaterials, polymers, and waste/biomaterials. Extensive research has been conducted on different types of fibers, including natural, synthetic, and mineral fibers, revealing their effectiveness in improving asphalt mixture performance concerning cracking resistance and fatigue behavior. Likewise, nanomaterials like nanosilica and CNTs have exhibited potential in enhancing fatigue resistance, but their high cost and lack of standardization present challenges. Polymers, particularly SBS and EVA, have been extensively used and evaluated in various research studies, showing promising results; however, their performance under different aging conditions requires further investigation. The utilization of waste and biomaterials, such as CR and bio-oils, has also yielded encouraging outcomes in enhancing fatigue life and contributing to improved environmental sustainability. Overall, the integration of additives in asphalt mixtures holds immense potential for enhancing the durability and longevity of road surfaces. Further research is necessary to optimize their utilization, address production, and implementation challenges in asphalt technology, and ensure their practical viability in real-world applications [152, 153].

Conflicts of Interest

The authors declare that there are no conflicts of interest.

References

[1] M. Arabani and S. M. Mirabdolazimi, "Experimental investigation of the fatigue behaviour of asphalt concrete mixtures containing waste iron powder," *Materials Science and Engineering: A*, vol. 528, no. 10-11, pp. 3866–3870, 2011.
[2] M. Arabani and S. A. Tahami, "Assessment of mechanical properties of rice husk ash modified asphalt mixture," *Construction and Building Materials*, vol. 149, pp. 350–358, 2017.
[3] E. H. Fini, I. L. Al-Qadi, Z. You, B. Zada, and J. Mills-Beale, "Partial replacement of asphalt binder with bio-binder: characterisation and modification," *International Journal of Pavement Engineering*, vol. 13, no. 6, pp. 515–522, 2012.
[4] G. Rusbintardjo, M. R. Hainin, and N. I. M. Yusoff, "Fundamental and rheological properties of oil palm fruit ash modified bitumen," *Construction and Building Materials*, vol. 49, pp. 702–711, 2013.
[5] D. Daryaee and M. Vamegh, "Effect of chemical components of asphalt binders on fatigue resistance of binder and asphalt mixtures in high reclaimed asphalt pavement mixtures," *Journal of Testing and Evaluation*, vol. 50, no. 1, pp. 340–352, 2022.
[6] Z. Suo and W. G. Wong, "Analysis of fatigue crack growth behavior in asphalt concrete material in wearing course," *Construction and Building Materials*, vol. 23, no. 1, pp. 462–468, 2009.
[7] H. Wang, Z. Dang, L. Li, and Z. You, "Analysis on fatigue crack growth laws for crumb rubber modified (CRM) asphalt mixture," *Construction and Building Materials*, vol. 47, pp. 1342–1349, 2013.
[8] M. Elkashef, R. C. Williams, and E. Cochran, "Investigation of fatigue and thermal cracking behavior of rejuvenated

reclaimed asphalt pavement binders and mixtures," *International Journal of Fatigue*, vol. 108, pp. 90–95, 2018.
[9] M. Sol-Sánchez, A. Fiume, F. Moreno-Navarro, and M. C. Rubio-Gámez, "Analysis of fatigue cracking of warm mix asphalt. Influence of the manufacturing technology," *International Journal of Fatigue*, vol. 110, pp. 197–203, 2018.
[10] M. Fakhri, *Laboratory Methods for Controlling Cracking of Asphalt Pavement Loading and Predictive Modeling of Fatigue Cracks in the Road*, Institute for Transportation, Tehran, 2010.
[11] M. Arabani, M. Haghi, A. K. Mirabdolazimi, and S. M. Haghgoo, "Increment of fatigue resistance of HMA by waste tire thread," in *7th International Congress on Civil Engineering*, Tehran, Iran, 2006.
[12] S. Abo-Qudais and I. Shatnawi, "Prediction of bituminous mixture fatigue life based on accumulated strain," *Construction and Building Materials*, vol. 21, no. 6, pp. 1370–1376, 2007.
[13] Q. Ma, Z. Guo, P. Guo, L. Sun, F. Yang, and H. Li, "Research on fatigue prediction model of asphalt mixture with high RAP content," *Sustainability*, vol. 13, no. 14, Article ID 7995, 2021.
[14] A. Chen, G. D. Airey, N. Thom, and Y. Li, "Characterisation of fatigue damage in asphalt mixtures using X-ray computed tomography," *Road Materials and Pavement Design*, vol. 24, no. 3, pp. 653–671, 2023.
[15] N. Sudarsanan and Y. R. Kim, "A critical review of the fatigue life prediction of asphalt mixtures and pavements," *Journal of Traffic and Transportation Engineering*, vol. 9, no. 5, pp. 808–835, 2022.
[16] A. K. Kuchiishi, K. "Caleb" Lee, and B. S. Underwood, "Simplified protocol for fatigue cracking characterization of asphalt mixtures using the direct tension cyclic fatigue test," *Construction and Building Materials*, vol. 363, Article ID 129828, 2023.
[17] G. N. King and H. W. King, *Polymer Modified Asphalts: An Overview*, pp. 240–254, American Society of Civil Engineering, 1986.
[18] L. H. Lewandowski, "Polymer modification of paving asphalt binders," *Rubber Chemistry and Technology*, vol. 67, no. 3, pp. 447–480, 1994.
[19] H. U. Bahia, D. Perdomo, and P. Turner, "Applicability of superpave binder testing protocols to modified binders," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1586, no. 1, pp. 16–23, 1997.
[20] H. Taherkhani and H. Amini, "Investigating the properties of nylon fiber reinforced asphalt concrete," *International Journal of Science and Engineering Investigations*, vol. 5, no. 48, pp. 6–11, 2016.
[21] M. Mohammed, T. Parry, and J. Grenfell, "Influence of fibres on rheological properties and toughness of bituminous binder," *Construction and Building Materials*, vol. 163, pp. 901–911, 2018.
[22] F. M. Nejad, M. Vadood, and S. Baeetabar, "Investigating the mechanical properties of carbon fibre-reinforced asphalt concrete," *Road Materials and Pavement Design*, vol. 15, no. 2, pp. 465–475, 2014.
[23] M. Vadood, M. S. Johari, and A. Rahai, "Developing a hybrid artificial neural network-genetic algorithm model to predict resilient modulus of polypropylene/polyester fiber-reinforced asphalt concrete," *The Journal of the Textile Institute*, vol. 106, no. 11, pp. 1239–1250, 2014.
[24] K. Zhang, J. Lim, S. Nassiri, K. Englund, and H. Li, "Reuse of carbon fiber composite materials in porous hot mix asphalt to enhance strength and durability," *Case Studies in Construction Materials*, vol. 11, Article ID e00260, 2019.
[25] M. Enieb, A. Diab, and X. Yang, "Short- and long-term properties of glass fiber reinforced asphalt mixtures," *International Journal of Pavement Engineering*, vol. 22, no. 1, pp. 64–76, 2021.
[26] C. J. Slebi-Acevedo, P. Lastra-González, D. Castro-Fresno, and M. Bueno, "An experimental laboratory study of fiber-reinforced asphalt mortars with polyolefin-aramid and polyacrylonitrile fibers," *Construction and Building Materials*, vol. 248, Article ID 118622, 2020.
[27] A. M. Alnadish, N. S. S. Singh, and A. M. Alawag, "Applications of synthetic, natural, and waste fibers in asphalt mixtures: a citation-based review," *Polymers*, vol. 15, no. 4, Article ID 1004, 2023.
[28] H. Jia, Y. Sheng, P. Guo et al., "Effect of synthetic fibers on the mechanical performance of asphalt mixture: a review," *Journal of Traffic and Transportation Engineering*, vol. 10, no. 3, pp. 331–348, 2023.
[29] Y. Guo, P. Tataranni, and C. Sangiorgi, "The use of fibres in asphalt mixtures: a state of the art review," *Construction and Building Materials*, vol. 390, Article ID 131754, 2023.
[30] C. J. Slebi-Acevedo, P. Lastra-González, P. Pascual-Muñoz, and D. Castro-Fresno, "Mechanical performance of fibers in hot mix asphalt: a review," *Construction and Building Materials*, vol. 200, pp. 756–769, 2019.
[31] A. Sharma, R. Choudhary, and A. Kumar, "Laboratory investigation of draindown behavior of open-graded friction-course mixtures containing banana and sugarcane bagasse natural fibers," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2678, no. 1, pp. 366–380, 2024.
[32] R. Choudhary, V. Kumar, A. Kumar, S. Pathak, and A. Kumar, "Use of banana natural fiber as a stabilizing additive in open graded friction course," in *Recent Developments in Sustainable Infrastructure (ICRDSI-2020)—GEO-TRA-ENV-WRM: Conference Proceedings from ICRDSI-2020*, vol. 2, pp. 371–382, Springer, 2022.
[33] A. Sharma, R. Choudhary, and A. Kumar, "Stabilization of open graded asphalt friction course mixes with plant-based natural fibers," *Materials Today: Proceedings*, 2023.
[34] N. L. N. K. Kumar and A. Ravitheja, "Characteristics of stone matrix asphalt by using natural fibers as additives," *Materials Today: Proceedings*, vol. 19, pp. 397–402, 2019.
[35] S. Oda, J. L. Fernandes Jr, and J. S. Ildefonso, "Analysis of use of natural fibers and asphalt rubber binder in discontinuous asphalt mixtures," *Construction and Building Materials*, vol. 26, no. 1, pp. 13–20, 2012.
[36] L. Ferreira da Costa, L. Lucena, A. Lucena, and A. Grangeiro de Barros, "Use of banana fibers in SMA mixtures," *Journal of Materials in Civil Engineering*, vol. 32, no. 1, Article ID 04019341, 2020.
[37] C. S. Bindu and K. S. Beena, "Comparison of shear strength characteristics of stone matrix asphalt mixture with waste plastics and polypropylene," *International Jourbal of Structural and Civil Engineering Research*, vol. 2, no. 4, pp. 13–21, 2013.
[38] S. Wang, R. B. Mallick, and N. Rahbar, "Toughening mechanisms in polypropylene fiber-reinforced asphalt mastic at low temperature," *Construction and Building Materials*, vol. 248, Article ID 118690, 2020.
[39] M. J. Khattak, A. Khattab, H. R. Rizvi, and P. Zhang, "The impact of carbon nano-fiber modification on asphalt binder rheology," *Construction and Building Materials*, vol. 30, pp. 257–264, 2012.

[40] S. M. Hejazi, *Mechanical Reinforcement of Hot Mix Asphalt Using Textile Materials*, Department of Textile Engineering, Isfahan University of Technology, Iran, 2007.
[41] S. M. Abtahi, M. Sheikhzadeh, and S. M. Hejazi, "Fiber-reinforced asphalt-concrete—a review," *Construction and Building Materials*, vol. 24, no. 6, pp. 871–877, 2010.
[42] C. Gao and W. Wu, "Using ESEM to analyze the microscopic property of basalt fiber reinforced asphalt concrete," *International Journal of Pavement Research and Technology*, vol. 11, no. 4, pp. 374–380, 2018.
[43] D. Wang, L. Wang, X. Gu, and G. Zhou, "Effect of basalt fiber on the asphalt binder and mastic at low temperature," *Journal of Materials in Civil Engineering*, vol. 25, no. 3, pp. 355–364, 2013.
[44] X. Qin, A. Shen, Y. Guo, Z. Li, and Z. Lv, "Characterization of asphalt mastics reinforced with basalt fibers," *Construction and Building Materials*, vol. 159, pp. 508–516, 2018.
[45] K. Lou, P. Xiao, A. Kang, Z. Wu, and P. Lu, "Suitability of fiber lengths for hot mix asphalt with different nominal maximum aggregate size: a pilot experimental investigation," *Materials*, vol. 13, no. 17, Article ID 3685, 2020.
[46] Y. Cheng, D. Yu, Y. Gong, C. Zhu, J. Tao, and W. Wang, "Laboratory evaluation on performance of eco-friendly basalt fiber and diatomite compound modified asphalt mixture," *Materials*, vol. 11, no. 12, Article ID 2400, 2018.
[47] Q. Ye, S. Wu, and N. Li, "Investigation of the dynamic and fatigue properties of fiber-modified asphalt mixtures," *International Journal of Fatigue*, vol. 31, no. 10, pp. 1598–1602, 2009.
[48] A. Shen, H. Wu, X. Yang, Z. He, and J. Meng, "Effect of different fibers on pavement performance of asphalt mixture containing steel slag," *Journal of Materials in Civil Engineering*, vol. 32, no. 11, 2020.
[49] M. Arabani and A. Shabani, "Evaluation of the ceramic fiber modified asphalt binder," *Construction and Building Materials*, vol. 205, pp. 377–386, 2019.
[50] M. Abdelaziz, M. R. Karim, and H. Y. Katman, "Fatigue and deformation properties of glass fiber reinforced bituminous mixes," *Journal of the Eastern Asia Society for Transportation Studies*, vol. 6, pp. 997–1007, 2005.
[51] M. Shukla, D. Tiwari, and K. Sitaramanjaneyulu, "Performance characteristics of fiber modified asphalt concrete mixes," *International Journal on Pavement Engineering & Asphalt Technology*, vol. 15, no. 1, pp. 38–50, 2014.
[52] H. Ziari and A. Moniri, "Laboratory evaluation of the effect of synthetic Polyolefin-glass fibers on performance properties of hot mix asphalt," *Construction and Building Materials*, vol. 213, pp. 459–468, 2019.
[53] Q. Guo, L. Li, Y. Cheng, Y. Jiao, and C. Xu, "Laboratory evaluation on performance of diatomite and glass fiber compound modified asphalt mixture," *Materials & Design (1980–2015)*, vol. 66, pp. 51–59, 2015.
[54] Z. Liu, S. Luo, Y. Wang, and H. Chen, "Induction heating and fatigue-damage induction healing of steel fiber-reinforced asphalt mixture," *Journal of Materials in Civil Engineering*, vol. 31, no. 9, 2019.
[55] Y. Paluri, V. Noolu, H. Mudavath, and R. Kumar Pancharathi, "Flexural fatigue behavior of steel fiber-reinforced reclaimed asphalt pavement-based concrete: an experimental study," *Practice Periodical on Structural Design and Construction*, vol. 26, no. 1, Article ID 4020053, 2021.
[56] H. Behbahani, V. N. M. Gilani, R. Salehfard, and D. Safari, "Evaluation of fatigue and rutting behaviour of hot mix asphalt containing rock wool," *International Journal of Civil Engineering*, vol. 18, no. 11, pp. 1293–1300, 2020.
[57] T. Takaikaew, P. Tepsriha, S. Horpibulsuk, M. Hoy, K. E. Kaloush, and A. Arulrajah, "Performance of fiber-reinforced asphalt concretes with various asphalt binders in Thailand," *Journal of Materials in Civil Engineering*, vol. 30, no. 8, Article ID 4018193, 2018.
[58] L. M. G. Klinsky, K. E. Kaloush, V. C. Faria, and V. S. S. Bardini, "Performance characteristics of fiber modified hot mix asphalt," *Construction and Building Materials*, vol. 176, pp. 747–752, 2018.
[59] Z. Dehghan and A. Modarres, "Evaluating the fatigue properties of hot mix asphalt reinforced by recycled PET fibers using 4-point bending test," *Construction and Building Materials*, vol. 139, pp. 384–393, 2017.
[60] M. Q. Ismael and H. M. Al-Taher, "Reinforcement of asphalt concrete by polyester fibers to improve flexural bending fatigue resistance," *Journal of Engineering*, vol. 21, no. 1, pp. 115–130, 2015.
[61] Q. Xu, H. Chen, and J. A. Prozzi, "Performance of fiber reinforced asphalt concrete under environmental temperature and water effects," *Construction and Building Materials*, vol. 24, no. 10, pp. 2003–2010, 2010.
[62] S. Wu, Q. Ye, and N. Li, "Investigation of rheological and fatigue properties of asphalt mixtures containing polyester fibers," *Construction and Building Materials*, vol. 22, no. 10, pp. 2111–2115, 2008.
[63] H. Jia, H. Chen, Y. Sheng et al., "Effect of laboratory aging on the stiffness and fatigue cracking of asphalt mixture containing bamboo fiber," *Journal of Cleaner Production*, vol. 333, Article ID 130120, 2022.
[64] J. Teizer, M. Venugopal, W. Teizer, and J. Felkl, "Nanotechnology and its impact on construction: bridging the gap between researchers and industry professionals," *Journal of Construction Engineering and Management*, vol. 138, no. 5, pp. 594–604, 2012.
[65] J. Yang and S. Tighe, "A review of advances of nanotechnology in asphalt mixtures," *Procedia—Social and Behavioral Sciences*, vol. 96, pp. 1269–1276, 2013.
[66] P. Nazir, R. Choudhary, A. Kumar, and A. Kumar, "Characterization of nano-alumina modified asphalt binders and mixtures," in *Proceedings of the Fifth International Conference of Transportation Research Group of India: 5th CTRG*, vol. 1, pp. 275–287, Springer, 2022.
[67] M. E. Abdullah, K. A. Zamhari, R. Buhari et al., "A review on the exploration of nanomaterials application in pavement engineering," *Jurnal Teknologi*, vol. 73, no. 4, pp. 69–76, 2015.
[68] K. Debbarma, B. Debnath, and P. P. Sarkar, "A comprehensive review on the usage of nanomaterials in asphalt mixes," *Construction and Building Materials*, vol. 361, Article ID 129634, 2022.
[69] S. Iftikhar, P. M. Shah, and M. S. Mir, "Potential application of various nanomaterials on the performance of asphalt binders and mixtures: a comprehensive review," *International Journal of Pavement Research and Technology*, vol. 16, no. 6, pp. 1439–1467, 2023.
[70] M. F. C. Van de Ven, A. A. A. Molenaar, and J. Besamusca, "Nanoclay for binder modification of asphalt mixtures," in *Proceedings of the 7th International RILEM Symposium on Advanced Testing and Characterization of Bituminous Materials*, pp. 133–142, Rhodes, Greece, 2009.
[71] E. Santagata, O. Baglieri, F. Miglietta, L. Tsantilis, and P. P. Riviera, "Impact of nanosized additives on the fatigue

damage behaviour of asphalt mixtures," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 42, no. 12, pp. 2738–2746, 2019.
[72] S. A. Zangena, "Performance of asphalt mixture with nanoparticles," in *Nanotechnology in Eco-Efficient Construction*, pp. 165–186, Elsevier, 2019.
[73] F. M. Nejad, A. R. Azarhoosh, G. H. H. Hamedi, and M. J. Azarhoosh, "Influence of using nonmaterial to reduce the moisture susceptibility of hot mix asphalt," *Construction and Building Materials*, vol. 31, pp. 384–388, 2012.
[74] H. Taherkhani and S. Afroozi, "Investigating the performance characteristics of asphaltic concrete containing nano-silica," *Civil Engineering Infrastructures Journal*, vol. 50, no. 1, pp. 75–93, 2017.
[75] A. Mansoorian, *Using indirect tensile strength test for investigation of fatigue life of asphaltic mixtures*, PhD. thesis, University of Science and Technology, Tehran, Iran, 2006.
[76] K. Li, H. Ren, and W. Huang, "Effect of graphene nanoplatelets (GNPs) on fatigue properties of asphalt mastics," *Materials*, vol. 14, no. 17, Article ID 4864, 2021.
[77] D. B. Ghile, "Effects of nanoclay modification on rheology of bitumen and on performance of asphalt mixtures," 2006.
[78] A. M. Yarahmadi, G. Shafabakhsh, and A. Asakereh, "Laboratory investigation of the effect of nano $Caco_3$ on rutting and fatigue of stone mastic asphalt mixtures," *Construction and Building Materials*, vol. 317, Article ID 126127, 2022.
[79] M. Ameri, S. Nobakht, K. Bemana, H. Rooholamini, and M. Vamegh, "Effect of nanoclay on fatigue life of hot mix asphalt," *Petroleum Science and Technology*, vol. 34, no. 11-12, pp. 1021–1025, 2016.
[80] S. G. Jahromi, "Nanoclay-modified asphalt mixtures for eco-efficient construction," in *Nanotechnology in Eco-Efficient Construction*, pp. 108–126, Elsevier, 2013.
[81] F. Miglietta, B. S. Underwood, L. Tsantilis, O. Baglieri, K. E. Kaloush, and E. Santagata, "Fatigue properties of nano-reinforced bituminous mixtures: a viscoelastic continuum damage approach," *International Journal of Pavement Research and Technology*, vol. 11, pp. 766–773, 2018.
[82] G. H. Shafabakhsh, S. M. Mirabdolazimi, and M. Sadeghnejad, "Evaluation the effect of nano-TiO_2 on the rutting and fatigue behavior of asphalt mixtures," *Construction and Building Materials*, vol. 54, pp. 566–571, 2014.
[83] A. R. Azarhoosh, F. M. Nejad, and A. Khodaii, "Using the surface free energy method to evaluate the effects of nanomaterial on the fatigue life of hot mix asphalt," *Journal of Materials in Civil Engineering*, vol. 28, no. 10, Article ID 4016098, 2016.
[84] F. M. Nejad, E. Geraee, and A. R. Azarhoosh, "The effect of nano calcium carbonate on the dynamic behaviour of asphalt concrete mixture," *European Journal of Environmental and Civil Engineering*, vol. 24, no. 8, pp. 1219–1228, 2020.
[85] A. R. Azarhoosh, F. M. Nejad, and A. Khodaii, "Nanomaterial and fatigue cracking of hot mix asphalt," *Road Materials and Pavement Design*, vol. 19, no. 2, pp. 353–366, 2016.
[86] H. Ziari, H. Farahani, A. Goli, and T. Akbari, "The effect of carbon nano-tube on the fatigue life of asphalt mixtures," *International Journal of Transportation Engineering*, vol. 2, no. 1, pp. 81–96, 2014.
[87] M. Ameri, S. Nowbakht, M. Molayem, and M. R. M. Aliha, "Investigation of fatigue and fracture properties of asphalt mixtures modified with carbon nanotubes," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 39, no. 7, pp. 896–906, 2016.
[88] K. G. Shamami, M. Effati, and S. M. Mirabdolazimi, "Evaluation of the effects of graphene-nanoplatelets on the rutting, fatigue performance, and moisture sensitivity of hot-mix asphalt," *International Journal of Pavement Research and Technology*, pp. 1–14, 2023.
[89] O. González, J. J. Peña, M. E. Muñoz et al., "Rheological techniques as a tool to analyze polymer−bitumen interactions: bitumen modified with polyethylene and polyethylene-based blends," *Energy & Fuels*, vol. 16, no. 5, pp. 1256–1263, 2002.
[90] A. Behnood and M. M. Gharehveran, "Morphology, rheology, and physical properties of polymer-modified asphalt binders," *European Polymer Journal*, vol. 112, pp. 766–791, 2019.
[91] L. Cong, J. Peng, Z. Guo, and Q. Wang, "Evaluation of fatigue cracking in asphalt mixtures based on surface energy," *Journal of Materials in Civil Engineering*, vol. 29, no. 3, Article ID D4015003, 2017.
[92] R. Babagoli, M. Vamegh, and P. Mirzababaei, "Laboratory evaluation of the effect of SBS and Lucobite on performance properties of bitumen," *Petroleum Science and Technology*, vol. 37, no. 3, pp. 255–260, 2018.
[93] P. Ahmedzade, M. Tigdemir, and S. F. Kalyoncuoglu, "Laboratory investigation of the properties of asphalt concrete mixtures modified with TOP–SBS," *Construction and Building Materials*, vol. 21, no. 3, pp. 626–633, 2007.
[94] T. W. Kim, J. Baek, H. J. Lee, and J. Y. Choi, "Fatigue performance evaluation of SBS modified mastic asphalt mixtures," *Construction and Building Materials*, vol. 48, pp. 908–916, 2013.
[95] B. Kim, R. Roque, and B. Birgisson, "Effect of styrene butadiene styrene modifier on cracking resistance of asphalt mixture," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1829, no. 1, pp. 8–15, 2003.
[96] M. Ameri, S. Yeganeh, and P. E. Valipour, "Experimental evaluation of fatigue resistance of asphalt mixtures containing waste elastomeric polymers," *Construction and Building Materials*, vol. 198, pp. 638–649, 2019.
[97] M. Vamegh, M. Ameri, and S. F. C. Naeni, "Performance evaluation of fatigue resistance of asphalt mixtures modified by SBR/PP polymer blends and SBS," *Construction and Building Materials*, vol. 209, pp. 202–214, 2019.
[98] C. Brovelli, M. Crispino, J. C. Pais, and P. A. A. Pereira, "Assessment of fatigue resistance of additivated asphalt concrete incorporating fibers and polymers," *Journal of Materials in Civil Engineering*, vol. 26, no. 3, pp. 554–558, 2014.
[99] M. J. Khattak and G. Y. Baladi, "Fatigue and permanent deformation models for polymer-modified asphalt mixtures," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1767, no. 1, pp. 135–145, 2001.
[100] H. Sahebzamani, M. Z. Alavi, and O. Farzaneh, "Evaluating effectiveness of polymerized pellets mix additives on improving asphalt mix properties," *Construction and Building Materials*, vol. 187, pp. 160–167, 2018.
[101] J. Zhang, H. Li, P. Liu et al., "Experimental exploration of influence of recycled polymer components on rutting resistance and fatigue behavior of asphalt mixtures," *Journal of Materials in Civil Engineering*, vol. 32, no. 6, Article ID 4020129, 2020.
[102] Q. T. Nguyen and T. C. H. Tran, "Experimental investigation of fatigue behavior for polymer modified asphalt and epoxy asphalt mixtures," in *Proceedings of the 3rd International Conference on Sustainability in Civil Engineering: ICSCE 2020*, pp. 161–166, Springer, November, Hanoi, Vietnam, 2021.

[103] A. Qabur, *Fatigue Characterization of Asphalt Mixes with Polymer Modified Asphalt Cement*, University of Waterloo, 2018.

[104] R. Ghabchi, M. Zaman, D. Singh, M. Barman, and D. L. Boeck, "Effectiveness of using polymer-modified asphalt binders in enhancing fatigue life of asphalt mixes containing RAS and RAP," in *Challenges and Innovations in Geomechanics: Proceedings of the 16th International Conference of IACMAG*, vol. 125, pp. 213–219, Springer, 2021.

[105] A. Chegenizadeh, M.-O. Aung, and H. Nikraz, "Ethylene propylene diene monomer (EPDM) effect on asphalt performance," *Buildings*, vol. 11, no. 8, Article ID 315, 2021.

[106] O. V. Kharissova, L. M. Torres-Martínez, and B. I. Kharisov, *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications*, Springer, 2021.

[107] S. Gulzar and S. Underwood, "Use of polymer nanocomposites in asphalt binder modification," *Advanced Functional Textiles and Polymers*, pp. 405–431, 2019.

[108] R. Rajasekar, G. Heinrich, A. Das, and C. K. Das, "Development of SBR-nanoclay composites with epoxidized natural rubber as compatibilizer," *Research Letters in Nanotechnology*, vol. 2009, Article ID 405153, 5 pages, 2009.

[109] I. Ghasemi, M. Karrabi, M. Mohammadi, and H. Azizi, "Evaluating the effect of processing conditions and organoclay content on the properties of styrene-butadiene rubber/organoclay nanocomposites by response surface methodology," *Express Polymer Letters*, vol. 4, no. 2, pp. 62–70, 2010.

[110] R. Salehfard, A. Abdi, and B. Amini, "Effect of SBR/NC on the rheological properties of bitumen and fatigue resistance of hot mix asphalt," *Journal of Materials in Civil Engineering*, vol. 29, no. 5, Article ID 4016282, 2017.

[111] W. H. Chesner, R. J. Collins, M. H. MacKay, and J. Emery, "User guidelines for waste and by-product materials in pavement construction," *Recycled Materials Resource Center*, 2002.

[112] M. Arabani, S. M. Mirabdolazimi, and A. R. Sasani, "The effect of waste tire thread mesh on the dynamic behaviour of asphalt mixtures," *Construction and Building Materials*, vol. 24, no. 6, pp. 1060–1068, 2010.

[113] E. H. Fini, D. J. Oldham, and T. Abu-Lebdeh, "Synthesis and characterization of biomodified rubber asphalt: Sustainable waste management solution for scrap tire and swine manure," *Journal of Environmental Engineering*, vol. 139, no. 12, pp. 1454–1461, 2013.

[114] D. Jin, D. Ge, X. Zhou, and Z. You, "Asphalt mixture with scrap tire rubber and nylon fiber from waste tires: laboratory performance and preliminary M-E design analysis," *Buildings*, vol. 12, no. 2, Article ID 160, 2022.

[115] A. Daghighi and A. Nahvi, "Effect of different additives on fatigue behavior of asphalt mixtures," in *Construction Materials and Structures*, pp. 601–607, IOS Press, 2014.

[116] F. Moreno-Navarro, M. Sol-Sánchez, M. C. Rubio-Gámez, and M. Segarra-Martínez, "The use of additives for the improvement of the mechanical behavior of high modulus asphalt mixes," *Construction and Building Materials*, vol. 70, pp. 65–70, 2014.

[117] A. Cetin, "Laboratory performance of porous asphalt mixtures containing ethylene propylene diene monomer-EPDM," *Građevinar*, vol. 74, Article ID 1, 2022.

[118] A. Kumar, R. Choudhary, and A. Kumar, "Characterisation of asphalt binder modified with ethylene-propylene–diene-monomer (EPDM) rubber waste from automobile industry," *Road Materials and Pavement Design*, vol. 22, no. 9, pp. 2044–2068, 2021.

[119] A. Kumar, R. Choudhary, and A. Kumar, "Utilization of waste ethylene-propylene-diene-monomer (EPDM) rubber modified binder in asphalt concrete mixtures," in *Proceedings of the Fifth International Conference of Transportation Research Group of India: 5th CTRG*, vol. 1, pp. 477–493, Springer, 2022.

[120] A. Kumar, R. Choudhary, and A. Kumar, "Composite asphalt modification with waste EPDM rubber and tire pyrolytic oil: rheological, chemical, and morphological evaluation," *Journal of Materials in Civil Engineering*, vol. 34, no. 12, Article ID 04022325, 2022.

[121] A. Kumar, R. Choudhary, and A. Kumar, "Composite asphalt binder modification with waste non-tire automotive rubber and pyrolytic oil," *Materials Today: Proceedings*, vol. 61, pp. 158–166, 2022.

[122] E. Gaudenzi, F. Cardone, X. Lu, and F. Canestrari, "Analysis of fatigue and healing properties of conventional bitumen and bio-binder for road pavements," *Materials*, vol. 13, no. 2, Article ID 420, 2020.

[123] L. P. Ingrassia, X. Lu, G. Ferrotti, and F. Canestrari, "Chemical and rheological investigation on the short-and long-term aging properties of bio-binders for road pavements," *Construction and Building Materials*, vol. 217, pp. 518–529, 2019.

[124] L. P. Ingrassia, F. Cardone, F. Canestrari, and X. Lu, "Experimental investigation on the bond strength between sustainable road bio-binders and aggregate substrates," *Materials and Structures*, vol. 52, pp. 1–14, 2019.

[125] C. Wang, L. Xue, W. Xie, Z. You, and X. Yang, "Laboratory investigation on chemical and rheological properties of bio-asphalt binders incorporating waste cooking oil," *Construction and Building Materials*, vol. 167, pp. 348–358, 2018.

[126] E. Gaudenzi, F. Cardone, X. Lu, and F. Canestrari, "Performance assessment of asphalt mixtures produced with a bio-binder containing 30% of lignin," *Materials and Structures*, vol. 55, no. 8, Article ID 221, 2022.

[127] Y. Zhang, X. Wang, G. Ji et al., "Mechanical performance characterization of lignin-modified asphalt mixture," *Applied Sciences*, vol. 10, no. 9, Article ID 3324, 2020.

[128] A. Molamohamadi Omran and S. Hesami, "Correlation between asphalt chemical indices and fatigue performance and healing of reclaimed asphalt mixture containing waste oil and polymer," *Journal of Transportation Infrastructure Engineering*, vol. 8, no. 2, pp. 55–70, 2022.

[129] X. Yang, Z. You, Q. Dai, and J. Mills-Beale, "Mechanical performance of asphalt mixtures modified by bio-oils derived from waste wood resources," *Construction and Building Materials*, vol. 51, pp. 424–431, 2014.

[130] E. Gaudenzi, F. Canestrari, X. Lu, and F. Cardone, "Performance assessment of asphalt mixture produced with a bio-based binder," *Materials*, vol. 14, no. 4, Article ID 918, 2021.

[131] Y. A. Almaali, S. Al-Busaltan, and M. A. Kadhim, "The effect of sustainable materials on fatigue cracking of thing overlay asphalt mixture," *Journal of Physics: Conference Series*, vol. 1895, no. 1, Article ID 012020, 2021.

[132] T. B. Vishnu and K. Lakshman Singh, "Experimental investigation on fatigue characteristics of asphalt mixes with different automobile waste tyres as modifiers," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, pp. 1–10, 2021.

[133] G. White and C. Magee, "Laboratory evaluation of asphalt containing recycled plastic as a bitumen extender and modifier," *Journal of Traffic and Transportation Engineering*, vol. 7, no. 5, pp. 218–235, 2019.

[134] F. Xiao, W. Zhao, and S. N. Amirkhanian, "Laboratory investigation of fatigue characteristics of rubberized asphalt mixtures containing warm asphalt additives at a low temperature," *Journal of Testing and Evaluation*, vol. 39, no. 2, pp. 290–295, 2011.

[135] S. M. Asgharzadeh, J. Sadeghi, P. Peivast, and M. Pedram, "Fatigue properties of crumb rubber asphalt mixtures used in railways," *Construction and Building Materials*, vol. 184, pp. 248–257, 2018.

[136] F. Yazdipanah, M. Ameri, M. Shahri, N. Hasheminejad, and H. F. Haghshenas, "Laboratory investigation and statistical analysis of the rutting and fatigue resistance of asphalt mixtures containing crumb-rubber and wax-based warm mix asphalt additive," *Construction and Building Materials*, vol. 309, Article ID 125165, 2021.

[137] K. J. Kowalski, J. B. Król, W. Bańkowski, P. Radziszewski, and M. Sarnowski, "Thermal and fatigue evaluation of asphalt mixtures containing RAP treated with a bio-agent," *Applied Sciences*, vol. 7, no. 3, Article ID 216, 2017.

[138] A. Kavussi, M. Azarnia, P. Ayar, and M. Pedram, "The fatigue behavior of polymeric sulfur-modified asphalt mixtures subjected to freeze–thaw conditioning," *Journal of Thermoplastic Composite Materials*, vol. 35, no. 4, pp. 467–486, 2022.

[139] Z. Guo, L. Wang, L. Feng, and Y. Guo, "Research on fatigue performance of composite crumb rubber modified asphalt mixture under freeze thaw cycles," *Construction and Building Materials*, vol. 323, Article ID 126603, 2022.

[140] S. Cui, N. Guo, L. Wang et al., "Effect of freeze-thaw cycles on the pavement performance of SBS modified and composite crumb rubber modified asphalt mixtures," *Construction and Building Materials*, vol. 342, Article ID 127799, 2022.

[141] J. Crucho, L. Picado-Santos, J. Neves, and S. Capitão, "A review of nanomaterials' effect on mechanical performance and aging of asphalt mixtures," *Applied Sciences*, vol. 9, no. 18, Article ID 3657, 2019.

[142] S. Salehi, M. Arashpour, J. Kodikara, and R. Guppy, "Sustainable pavement construction: a systematic literature review of environmental and economic analysis of recycled materials," *Journal of Cleaner Production*, vol. 313, Article ID 127936, 2021.

[143] S. Fernandes, H. M. R. D. Silva, and J. R. M. Oliveira, "Mechanical, surface and environmental evaluation of stone mastic asphalt mixtures with advanced asphalt binders using waste materials," *Road Materials and Pavement Design*, vol. 20, no. 2, pp. 316–333, 2017.

[144] H. Ziari, M. Orouei, H. Divandari, and A. Yousefi, "Mechanical characterization of warm mix asphalt mixtures made with RAP and Para-fiber additive," *Construction and Building Materials*, vol. 279, Article ID 122456, 2021.

[145] D. Scorza, R. Luciano, S. Mousa, and S. Vantadori, "Fracture behaviour of hybrid fibre-reinforced roller-compacted concrete used in pavements," *Construction and Building Materials*, vol. 271, Article ID 121554, 2021.

[146] E. Bocci and E. Prosperi, "Recycling of reclaimed fibers from end-of-life tires in hot mix asphalt," *Journal of Traffic and Transportation Engineering*, vol. 7, no. 5, pp. 678–687, 2020.

[147] Z. Li, K. Li, W. Chen, W. Liu, Y. Yin, and P. Cong, "Investigation on the characteristics and effect of plant fibers on the properties of asphalt binders," *Construction and Building Materials*, vol. 338, Article ID 127652, 2022.

[148] A. Martinez-Soto, G. Valdes-Vidal, A. Calabi-Floody, C. Avendaño-Vera, and C. Martínez-Toledo, "Comparison of environmental loads of fibers used in the manufacture of hot mix asphalt (HMA) and stone mastic asphalt (SMA) mixes using a life cycle assessment (LCA)," *Sustainability*, vol. 14, no. 21, Article ID 14246, 2022.

[149] T. D. K. A. Masri, R. Ferdaus, and P. J. Ramadhansyah, "Sustainable use of polymer in asphalt mixture: a review," *Construction*, vol. 2, no. 2, pp. 12–21, 2022.

[150] J. Santos, V. Cerezo, K. Soudani, and S. Bressi, "A comparative life cycle assessment of hot mixes asphalt containing bituminous binder modified with waste and virgin polymers," *Procedia CIRP*, vol. 69, pp. 194–199, 2018.

[151] M. Souliman, M. Mamlouk, and A. Eifert, "Mechanistic analysis and cost-effectiveness of rubber and polymer modified asphalt mixtures," *Advances in Civil Engineering Materials*, vol. 6, no. 1, pp. 106–118, 2017.

[152] V. N. M. Gilani, G. H. Hamedi, M. R. Esmaeeli, M. Habibzadeh, and M. H. Eshkiknezhad, "Presentation of thermodynamic and dynamic modules methods to investigate the effect of nano hydrated lime on moisture damage of stone matrix asphalt," *Australian Journal of Civil Engineering*, pp. 1–10, 2022.

[153] V. N. M. Gilani, S. M. Hosseinian, and M. Nikookar, "Presentation of a new deicer with the least moisture and fatigue failures in asphalt mixtures," *Arabian Journal for Science and Engineering*, vol. 46, no. 11, pp. 10457–10471, 2021.