



REVIEW



Mechanical Performance and Design Considerations of Bituminous Mixtures Incorporating Recycled Fibers: A Systematic Review

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Abstract

Recycled fibers in bituminous mixtures are increasingly recognized for their potential to modify and reinforce asphalt mixtures, enhancing durability and reducing environmental impacts. This paper reviews the influencing themes and factors related to the incorporation of recycled fibers into bituminous mixtures, based on a systematic bibliometric analysis. A bibliometric study was conducted covering the evolution of document publications, sources, authors, countries, and the clustering of influential keywords, which frame the main themes explored in a systematic literature review. Results reveal a growing interest in case studies assessing the mechanical performance of bituminous mixtures incorporating recycled fibers, highlighting sustainability and reinforcement design development. The review discusses the main factors influencing mixture reinforcement design, the processing methods and characterization of recycled fibers, and the mechanical performance of different fiber types including plastic, plant-based, textile, and glass fibers. Overall, this work provides insights into the key factors in the literature influencing the performance of recycled fiber-reinforced bituminous mixtures and serves as a preliminary guide and reference for researchers entering this field of study.

Keywords Recycled fibers · Reinforced bituminous mixtures · Mechanical performance · Bibliometric analysis · Systematic review

Abbreviations

BM	Bituminous mixtures
CMA	Cold mix asphalt
ELT	End-of-life tires
GFRP	Glass fiber reinforced polymer
HMA	Hot mix asphalt
ITSR	Indirect tensile strength ratio
LDPE	Low density polyethylene
OBC	Optimum bitumen content
OGFC	Open-graded friction course
PA	Porous asphalt
PET	Polyethylene terephthalate

PP	Polypropylene
PS	Polystyrene
SBR	Styrene-butadiene rubber
SMA	Stone mastic asphalt
WTB	Wind turbine blade

1 Introduction

Asphalt pavements are designed to withstand varying traffic loads and climate conditions to prevent deterioration and structural distress over time [1]. To meet these demands, researchers have developed reinforcement approaches for bituminous mixtures (BM) aimed at enhancing their mechanical performance and durability. The incorporation of modifying polymers and reinforcing additives such as fibers into BM has shown promising results, improving resistance to common distresses including rutting [2, 3], cracking [4], and moisture damage [5, 6]. However, in addition to ongoing challenges related to temperature variations and fluctuating load levels due to increasing urbanization, the sector also faces the issue of high raw material

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consumption, as the asphalt pavement construction industry remains one of the most material and energy intensive sectors [7]. As a sustainable approach, various studies have promoted the use of recycled fibers for the reinforcement of BM in substitution of conventional fibers [8–12]. This approach contributes to reducing the environmental burden both by diverting fiber waste from disposal [13–18] and by reducing the carbon footprint associated with the production of asphalt mixtures [8].

Various types of recycled fibers have been investigated for their potential use in BM, including plastic fibers (such as Polyethylene terephthalate (PET), Polypropylene (PP), and Polystyrene (PS)) [19–27], plant-based fibers [28–34], textile fibers [9, 35–38], and glass fibers (including glass fiber reinforced polymer (GFRP)) [2, 39–41]. Prior to their incorporation into BM, some of these fibers can be subjected to certain chemical or physical treatments to remove impurities and modify their surface properties [35, 39, 42]. Such treatments are intended to enhance fiber–bitumen adhesion and promote the formation of a thick asphalt–fiber film structure [31]. Subsequently, during the mixing and compaction processes involved in BM production, some fiber properties may degrade. To assess the stability of these properties, several studies have conducted chemical, mechanical, and thermal characterizations, examining parameters such as humidity resistance, adhesion to asphalt, and oil absorbency [35, 40–43]. When fiber properties remain stable or are enhanced, they can be used to improve stiffness, fracture resistance, and interfacial adhesion within the mixture [2, 44, 45]. Their incorporation into mixtures, either as fine aggregates or additives, has been shown to reduce asphalt bleeding and provide a stabilizing effect to the mixture [13, 16, 46–48]. Moreover, they also provide a reinforcing mechanism to the structure of the mixtures [42, 43, 49–51], delaying crack propagation and improving pavement durability [25, 52, 53]. Building on these mechanisms, most studies showed that adding recycled fibers improved the mechanical properties of asphalt mixtures, increasing strength properties [24], rutting and cracking resistance [4, 54], and enhancing moisture stability [5, 55]. Overall, the use of such fibers generally enhances the mechanical performance of mixtures or, at minimum, has a neutral effect [56].

In addition to the overall mechanical improvements observed with the incorporation of fibers, the extent of these benefits strongly depends on the optimization of key mixture design parameters, including fiber size [25, 30], bitumen and fiber content [29, 57], and the fiber addition method to the mixture [14, 56, 58]. Moreover, the optimization of these parameters allows for controlling and balancing the potential loss of workability that may occur during the mixing and compaction of fiber-reinforced asphalt mixtures [59–62]. In fact, the method of fiber incorporation

significantly affects fiber dispersion and the overall consistency of the mixture, which are key practical aspects related to workability [63]. For this reason, most studies begin with preliminary tests to determine the most appropriate fiber incorporation method [58, 64], typically comparing wet and dry addition procedures to ensure proper dispersion and avoid fiber clustering, along with optimizing the other mixture design parameters.

This paper presents a status quo of the research field addressing the use of recycled fibers in BM based on a systematic bibliometric analysis. As an initial step, a bibliometric analysis was performed, providing the evolution of document publications and their sources, countries and authors mapping, as well as the evolution of keywords. Based on the findings, the most influential themes were determined to guide the systematic literature review discussions in the following sections: sustainability and BM reinforcement design, recycled fibers, mechanical characterization of BM with recycled fibers, and finally, the specific characteristics of stone mastic asphalt (SMA) and porous asphalt (PA). Furthermore, the main conclusions were drawn.

2 Materials and Methodology

This review is based on a systematic bibliometric analysis. According to the flowchart displayed in Fig. 1, the research was performed using the platforms Scopus and Web of Science (WOS). The identification of the search strings is a crucial step in this process, which should reflect aspects of the incorporation of recycled fibers into bituminous mixtures, reflecting the objective of this study. For this purpose, four search expressions were used: (“Bituminous mixtures” OR “Asphalt pavements” OR “Pavement reinforcement”) AND “Recycled fibers”, with a timeline up to 2024. The search returned 135 records found in Scopus and 98 records found in WOS. The retrieved documents included peer-reviewed articles, review papers, book chapters, and conference papers. The duplicates were removed, and then all titles and abstracts of the resulting sample were individually checked and screened to remove the non-relevant documents, including non-English publications, studies evaluating conventional fibers, and other studies addressing entirely different research fields. Moreover, additional studies from 2025 were added to enrich the discussions. Finally, the sample was refined to 113 documents.

To compile the different external characteristics of the sample determined for this review and identify the research status and trends, a bibliometric analysis was performed assessing the evolution of document publications and their sources, and the clustering networks of countries, authors,

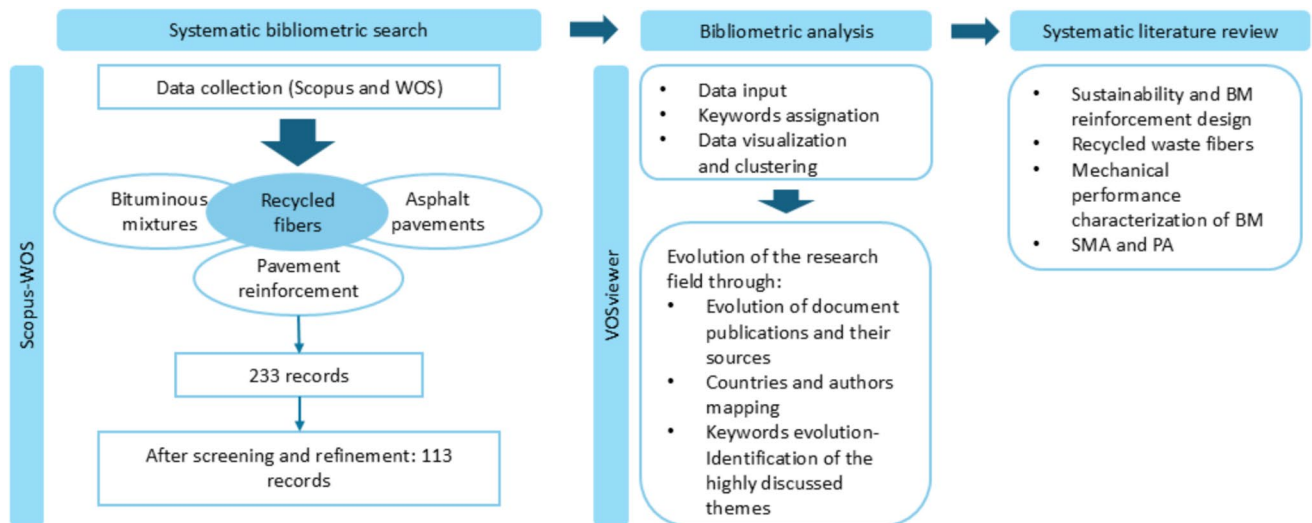
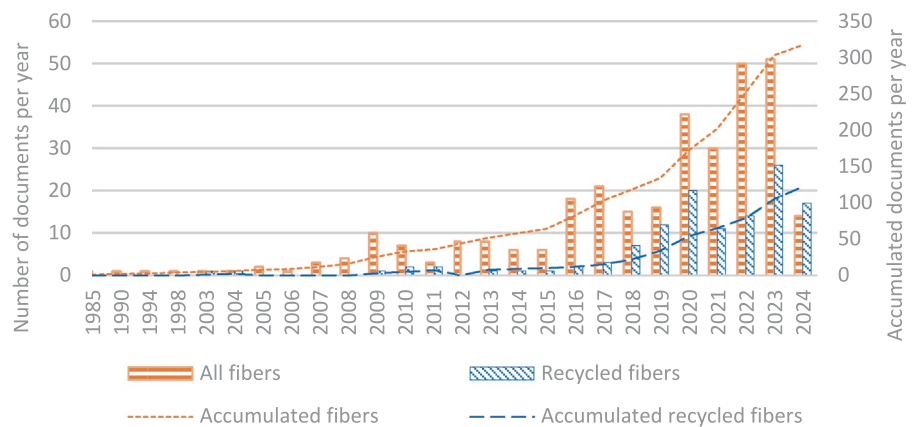


Fig. 1 Bibliometric research flowchart

Fig. 2 Evolution of publications and accumulated documents per year addressing the use of fibers in BM



and keywords using the VOSviewer software tool [65]. Before the generation of the keyword clustering networks, a manual pre-processing of the imported data was performed, creating groups of principal keywords by merging synonyms and removing generic terms. This step allowed us to define the conceptual boundaries of the clusters. Consequently, the automatic clustering was performed based on co-occurrence networks, which allowed the visualization and the identification of the highly discussed themes. Finally, a systematic literature review was conducted based on the discussion of five main themes, carefully reviewing documents related to each theme to extract relevant data such as fiber size, fiber and bitumen content, fiber addition method, recycling and properties of fibers, etc. It is worth mentioning that not all studies explicitly reported mixture design parameters, testing methods, or the same performance indicators. Consequently, studies with incomplete or inconsistent reporting were selectively excluded from analyses of certain topics, for example, fiber and bitumen content, but were retained for discussions of other themes. This approach ensured that

the conclusions reflect the methodological quality and reliability of the available literature.

3 Influencing Bibliometrics

3.1 Evolution of Document Publications and Their Sources

Figure 2 shows the evolution of the published documents addressing the use of recycled fibers in BM, within a broader context representing the evolution of studies using fibers in general (recycled and non-recycled). The graph shows the growing research interest in the development of BM engineering using sustainable materials through the introduction of recycled fibers. This increased interest is driven by the need to address environmental concerns in the construction sector in general and to promote the use of recycled materials.

Table 1 Publication sources with at least 5 documents addressing the use of recycled fibers in BM

Sources	Documents	Citations
Construction and Building Materials	19	1039
Applied sciences (Switzerland)	7	69
Journal of Cleaner Production	6	167
Case studies in construction materials	6	65
Journal of Materials in Civil Engineering	5	77
Materials	5	160
Sustainability (Switzerland)	5	39

Regarding the sources of publications addressing the use of recycled fibers, Table 1 shows the first seven journals with the highest number of publications. The relevance of the scope of these leading sources to the research topic lies in their focus on new materials and up-to-date technologies, including the use of recycled materials in BM, that promote sustainability and clean production.

3.2 Countries and Authors Mapping

Figure 3a presents the mapping of countries, identifying six countries connected to the same network, each with a minimum number of five documents. Based on the size of the circles, China and Malaysia lead the ranking in terms of the number of publications. Meanwhile, the United States has the highest number of total citations (Table 2), reflecting its role as the leading country with the longest involvement in the field. On the other hand, China and Australia, which are considered emerging countries in the field, present the highest average normalized citations of 1.08 and 1.75, respectively, making them the most influential countries in the research field.

Figure 3b shows the author network visualization with at least five publications, where only three of them are connected in one network, showing a low collaboration rate. The results show that Liu Q. [18] and Sangiorgi C. [17], who are affiliated with China and the United States, respectively, have the highest number of citations with 152 and 66,

Table 2 List of the six leading countries in terms of publications count addressing the use of recycled fibers in BM

Position	Country	Number of documents	Total citations	Average normal citations
1	China	33	517	1.08
2	Malaysia	18	305	0.90
3	United states	16	583	1.05
4	India	12	248	0.74
5	Nigeria	8	61	0.47
6	Australia	7	263	1.75

respectively. They are considered the most prolific contributors to the research field.

The research themes analyzed by Liu Q. focused on the self-healing performance of asphalt mixtures [66] and the incorporation of recycled materials in BM, including plastic and plant-based fibers such as medical masks [18] and recycled kapok fiber [67]. On the other hand, Sangiorgi's contribution mainly investigated the use of recycled cigarette butts as stabilizing fibers for SMA mixture [13, 16, 17]. Moreover, other authors carried out investigations on a wide range of recycled fibers, including, in addition to plastic fibers [16, 21] and plant-based fibers [5, 29], textile fibers [36, 68] and glass fibers [40, 49] such as end-of-life tires (ELT) fibers and GFRP, which are widely studied in this review.

3.3 Evolution of Keywords

To identify the evolution of the research field and the highly discussed themes, the clustering network displayed in Fig. 4 shows seven clusters with a total of 37 highly relevant keywords. Each cluster represents a group of strongly related keywords connected through co-occurrence links.

Table 3 presents the highly influential keywords of each cluster and themes assigned to each cluster based on average normal citations and average publication year. The highly influential keywords of the seven clusters allowed

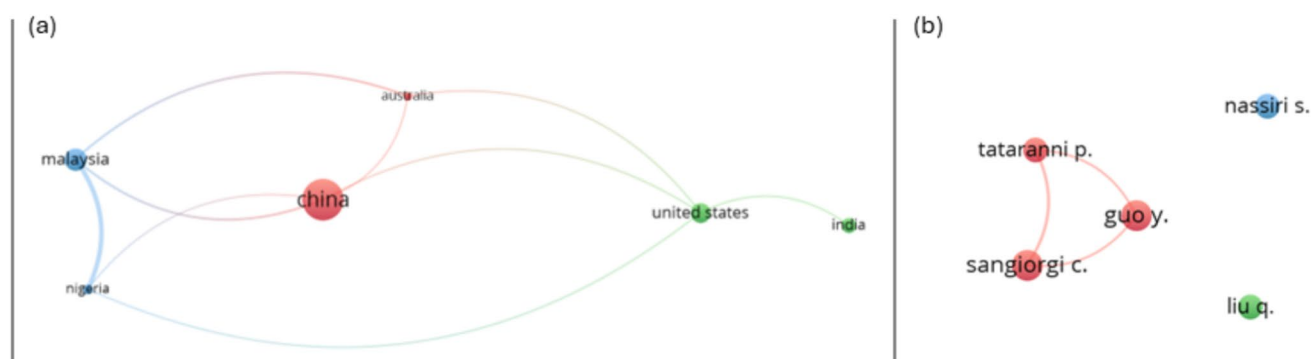


Fig. 3 Network visualization of: (a) leading countries in terms of total documents, and (b) authors with a minimum of five documents published addressing the use of recycled fibers in BM

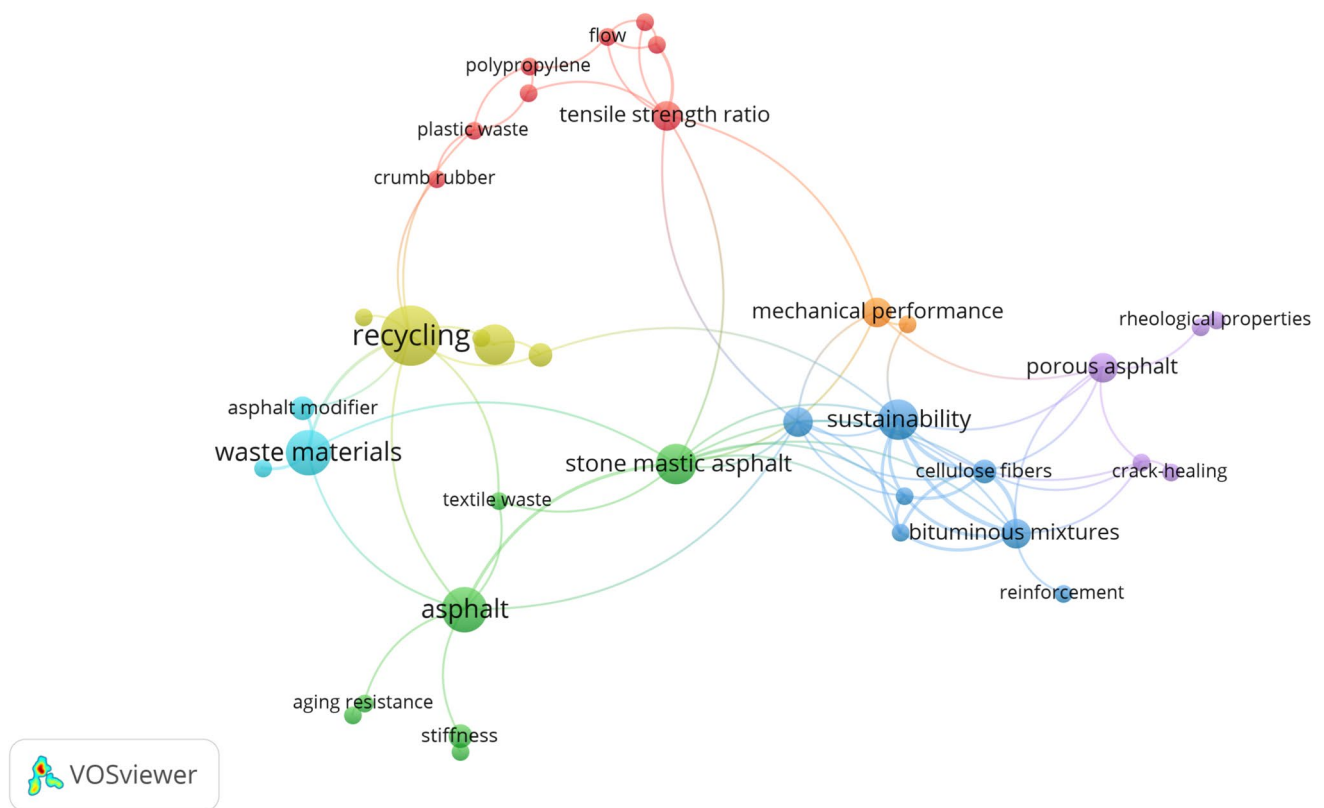


Fig. 4 Visualization network of the author keywords in terms of average citations with a minimum of five occurrences

Table 3 Description of keywords clusters in terms of average normal citations and average publication year

Cluster number	Color	Influential keywords		Theme assigned	Average publication year	Average normal citations
		Keyword	Average normal citation			
1	Blue	Sustainability	1.78	Sustainability and BM reinforcement design	2020	0.94
2	Yellow	Recycling	1.37			
3	Red	Plastic waste	1.49	Recycled fibers	2018	1.06
4	Light blue	Waste materials	1.15			
5	Orange	Mechanical performance	0.83	Mechanical characterization of BM with recycled fibers	2021	1.93
6	Green	Stone mastic asphalt	1.71			
7	Purple	Porous asphalt	1.29	Porous asphalt	2020	1.31

the identification of the main themes by merging closely related influential keywords to represent a single relevant topic. Consequently, the main themes reflecting the most influential keywords in the reviewed studies were identified as follows: Sustainability and BM reinforcement design, Recycled fibers, Mechanical characterization of BM with recycled fibers, and SMA and PA.

Moreover, Fig. 5 shows the overlay network in which the color of an item is determined by the average publication year, where colors range from blue (earliest) to green to yellow (most recent). This overlay allows us to see the temporal evolution of the research themes. Accordingly, most of the identified themes were discussed throughout

the entire time horizon. Nevertheless, the overlay network indicates a growing research interest in sustainability, recycling, PA, and cellulose fiber-related topics. This suggests that the development of BM designs in the last five years has increased concern for the use of recycled materials and the sustainable production of mixtures. Furthermore, the prominence of recycling, PA, and cellulose fibers themes indicates that the research field is recently paying attention to PA, which is characterized by high air void content and susceptibility to asphalt draindown. The emergence of cellulose fibers in recent studies supports this observation, as they are widely recognized for their stabilizing effect within asphalt mixtures.

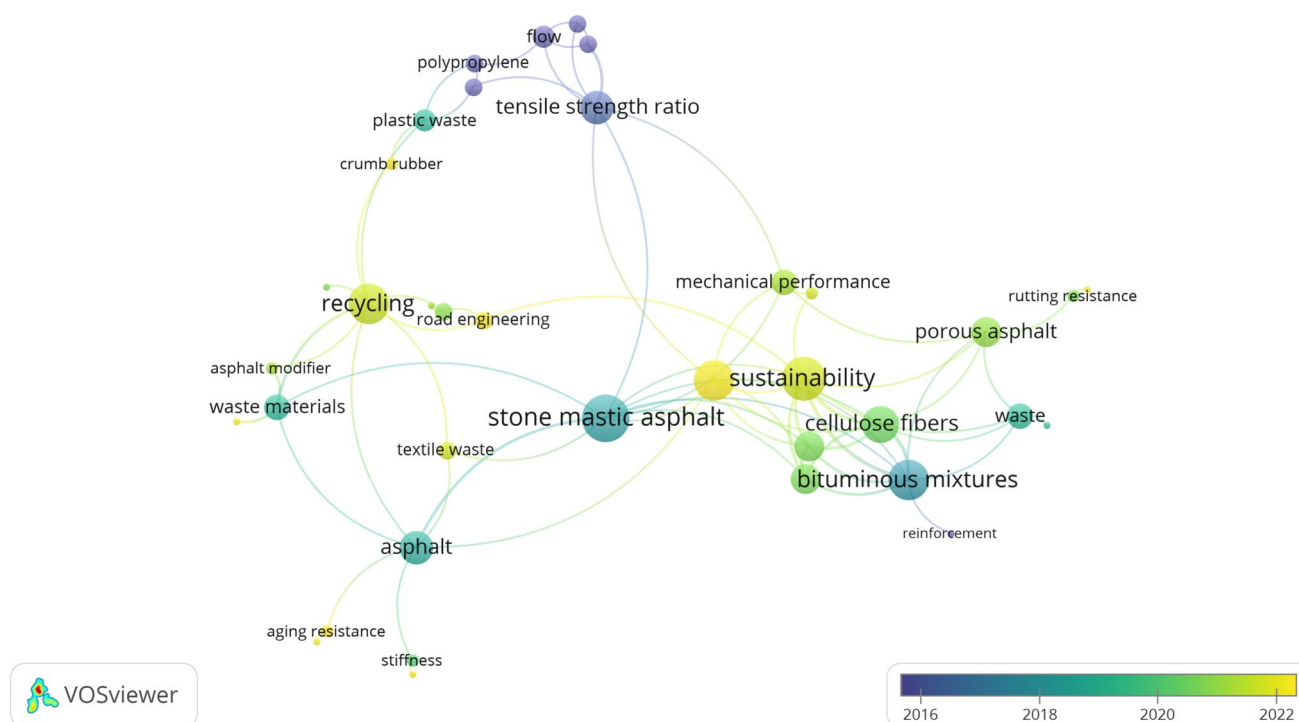


Fig. 5 Overlay network of the highly discussed themes in the research field in terms of average publication year

Finally, the documents related to each of the main themes were reviewed and discussed in the following sections.

4 Sustainability and BM Reinforcement Design

Ensuring sustainability has become essential in the development of construction materials due to increasing environmental concerns and resource depletion. The use of recycled fibers for the modification and reinforcement of BM reduces environmental burdens and waste disposal [8, 9, 69, 70]. Moreover, these fibers enhance the durability performance of asphalt pavements, extending service life and decreasing the need for additional raw materials [9, 67, 69]. According to the bibliometric results, sustainability has appeared as an influential keyword. However, most studies evaluated mechanical performance (addressed in Sect. 6) without an environmental assessment. In these studies, the use of recycled fibers was highlighted as an eco-friendly solution contributing to sustainable asphalt pavements. Nevertheless, the environmental assessment of asphalt mixtures incorporating recycled fibers has recently emerged in literature, as a significant validation mechanism for the feasibility of these fibers. The comparative life cycle assessment (LCA) approach has been widely used for this purpose. According to Martinez-Soto et al. [8], the incorporation of ELT textile fibers and cellulose fibers in HMA/

SMA showed lower environmental impacts than fiberglass, polyester fiber, and aramid fiber. The LCA included material collection for fiber production and processing stages. In another study conducted by Landi et al. [9], ELT fiber-reinforced HMA mixtures showed increased pavement service life and reduced environmental impacts in terms of energy demand and climate change compared with cellulose fibers. This study adopted broader system boundaries, including raw material extraction, mixtures production, pavement construction, and maintenance. Investigating the environmental effects of waste chopped basalt and polyester fibers through a cradle-to-gate LCA, Xu et al. [69] found that waste chopped basalt fibers provided better environmental performance, reducing global warming potential and fossil resource depletion by 15% each, achieving energy savings of 12.4%, and extending service life by 35%.

On the other hand, limited environmental benefits were observed when recycled fishnets were used during the production stage, highlighting the need for comprehensive LCAs to capture potential environmental benefits [71]. In some cases, the recycling processes required before incorporating fibers into asphalt mixtures may generate relatively high environmental burdens [61], similar to findings in fiber-reinforced concrete LCAs [72]. Overall, the environmental assessment of asphalt mixtures incorporating recycled fibers remains limited, and comprehensive comparative evaluations of different fiber types are still needed to better understand their overall sustainability performance.

In BM design, understanding whether fibers act primarily as modifiers or reinforcements is essential, as these functional roles directly influence pavement mechanical performance. The incorporation of fibers can be considered a modification approach aimed at improving the rheological properties and stability of the bitumen [73–75]. In this case, fibers may melt if the asphalt mixing temperature reaches or exceeds their melting point, or they may blend with the binder, as occurs with most fiber types, often exhibiting a tendency to absorb bitumen and thereby reduce asphalt draindown [76]. This mechanism changes the viscoelastic behavior of the bitumen, which can enhance both high and low temperature performance [77], or improve high temperature rutting resistance with limited effects on low temperature cracking and fatigue resistance, as reported by T. Xie et al. [77]. Moreover, an interface modification occurs when the fibers are coated with the binder, promoting binder-aggregates adhesion [78].

On the other hand, fiber reinforcement of BM focuses on enhancing structural integrity through stress transfer and crack-bridging mechanisms [10, 17, 25, 42, 50]. In fact, fibers can delay crack initiation and propagation by redistributing stress within the three-dimensional network formed by aggregates and mastic. However, the concepts of reinforcement and modification may overlap, as fibers can simultaneously provide structural reinforcement and stabilization of BM [13, 14]. In other words, reinforcing fibers may also induce a certain modifying effect within the mixture, while primarily enhancing mechanical performance by improving the cracking and rutting resistance [15, 29, 79]. In contrast, fibers used mainly as modifiers primarily provide mixture stabilization through bitumen absorption, leading to reduced draindown [47]. A reinforcing effect may also be observed, however, it is generally secondary.

To fully benefit from the incorporation of fibers, whether for mixture modification or reinforcement, it is important to consider the optimization of several factors that include fiber size, fiber and bitumen content, and the fiber addition method.

4.1 Fiber Size

Figure 6a illustrates the proportion of publications investigating each fiber type in the reviewed studies, while Fig. 6b summarizes the optimum fiber size reported in the literature for each fiber type, along with the corresponding fiber content and OBC. According to the records that include fiber size information, the median optimum size varies depending on the fiber type. Textile and plant-based fibers exhibit the smallest dimensions, measuring 1.50 mm × 0.25 mm and 4.50 mm × 0.16 mm, respectively. In contrast, plastic and glass fibers have dimensions measuring 10 mm × 0.78 mm and 10.75 mm × 0.30 mm, respectively. These findings suggest that textile and plant-based fibers may be used to provide a similar mechanism within asphalt mixtures, with smaller fiber size primarily interacting with the binder to improve stabilization and resistance to micro-cracking. On the other hand, plastic and glass fibers are typically used in larger sizes to primarily enhance reinforcement through the micro-bridging mechanism.

Moreover, fiber size is recognized as an influential factor in the performance of BM [25], and achieving the right balance between fiber length and fiber dispersion within the mixture is crucial. Fiber length must be carefully selected: if it is too long, it may cause balling and affect fiber dispersion in the mixture, while if it is too short, it may fail to provide the desired reinforcement effect [25, 30].

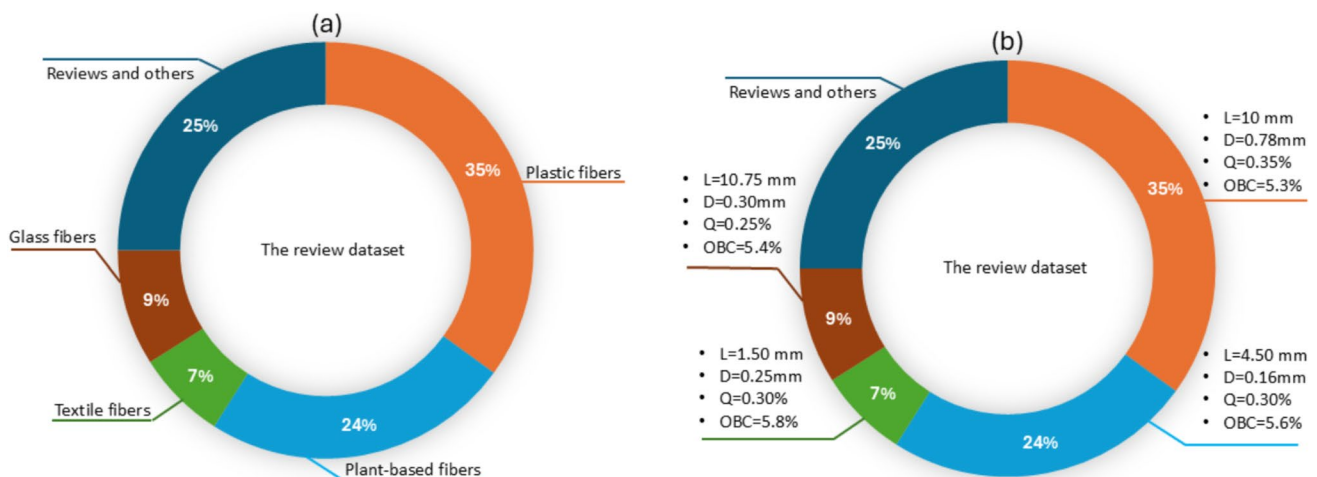


Fig. 6 **a** Proportions of publications investigating each fiber type, and **b** median characteristics of fibers including length (L), diameter (D), fiber content (Q), and optimum bitumen content (OBC)

Table 4 Size and content of various types of fibers with the corresponding OBC and mixture type

Fiber type	Fiber length (mm)	Fiber diameter (mm)	Fiber content (%)	OBC (%)	Mixture type or design method	Ref
Cigarette butt fiber (cellulose + plastic)	< 15	—	0.3 *	6 *	SMA	[17]
PET fiber	1.18–2.36	—	0.5 *	5	Superpave system	[11]
Cigarette butt fiber (cellulose diacetate)	12–19	0.0105	0.4 **	6	SMA	[85]
Cigarette butt fiber	≤ 10	—	0.4 *	6 *	SMA	[13]
Waste nylon fiber	20–30	0.2	0.1; 0.2	5; 5.5	SMA	[42]
PET fiber	10	0.78	0.3; 0.5	4.7; 4.9	Superpave system	[22]
Waste Nylon wire	20	0.2	1.5 **	6	SMA	[15]
PET fiber	—	—	0.5	4.7	Superpave system	[12]
PET fiber	10	0.78	0.5	4.9	Superpave system	[80]
LDPE fiber	2	—	0.3	5	OGFC	[86]
Roofing PET waste fiber	6.35	—	0.5	6.4	Marshall design	[24]
Coconut fiber	50	—	0.6	6.5	SMA	[46]
Sugarcane bagasse fiber	6	—	0.3	5.58	SMA	[87]
Sugarcane bagasse fiber	5	1–3	0.3	6.5	SMA	[5]
Coconut fiber	—	—	0.3	5	PA	[29]
Lignin fiber	3–6	—	0.38	6.2	SMA	[82]
Cotton straw fiber	4–8	—	0.2	5	AC-13	[30]
Palm oil fiber	5–25	0.16–0.5	0.3	6.34	SMA	[10]
Corn stalk fiber	3	0.05–0.425	0.6	5.6	SMA	[57]
ELT	3–13	—	0.3	10.11	SMA	[83]
ELT	1–2.5	0.005–0.04	0.3	5	Dense graded	[36]
ELT	11–40	0.256	1.5; 3.5 ***	4.8; 5	—	[66]
ELT	2–5	—	2	5.85	Superpave system	[35]
Textile waste	—	≤ 1.7	0.3	6.5	SMA	[68]
GFRP	0.075–9.5	—	0.1; 0.3 *	—	Dense graded	[39]
Cellulose-based mineral fiber (glass)	—	—	0.3	5.6	SMA	[81]
Glass fibers chips	10–12	0.5–0.71	5 **	—	—	[49]
Glass fibers	12	—	0.15	5.26	Dense graded	[89]
GFRP	6	0.006	3 **	—	—	[90]
GFRP	—	0.15–0.3	2 **	—	—	[41]

*Percentage on aggregates weight

**Percentage on binder weight

***Percentage on binder volume

All other content values are expressed relative to the total weight of the mixture

“—”Not available

4.2 Fiber and Bitumen Content

The choice of the appropriate fiber content in bituminous mixtures is crucial, as studies have shown that excessive fiber content affects mixture performance at both high and low temperatures [29, 57]. Based on the findings presented in Fig. 6, the median optimum fiber content by weight of the total mixture was found to be approximately 0.30%, with specific values of 0.35% for plastic fibers, 0.30% for plant-based fibers, 0.30% for textile fibers, and 0.25% for glass fibers.

The OBC, which is a key parameter in asphalt mix design, reflects how much binder is needed to coat the aggregates while accounting for the absorption capacity of the fibers. Table 4 shows how different fiber types affect this parameter.

For plastic fibers, such as PET, studies report a consistently low OBC, ranging from 4.7% to 5%, which suggests low binder absorption [11, 12, 22, 80]. Textile fiber shows an OBC of about 5.8%, consistent with the high surface area of the fibers [35, 36, 68, 81]. Regarding plant-based fibers, they tend to increase the OBC due to their high absorbency and irregular shapes, for example, sugarcane bagasse and coconut fibers exhibit values ranging from 5% to 6.5%, depending on the fiber origin [10, 29, 46, 57, 82, 83]. Although it is often not reported, the OBC for BM containing glass fibers is approximately 5.4%. Overall, within the common OBC range of 5% to 6.5%, the relationship between fiber content and bitumen content primarily depends on fiber type.

4.3 Fiber Addition Method

The mixing process and the order in which the components are added to the BM affect particle distribution, mixture homogeneity, and the ability of bitumen to adequately coat the aggregates (a phenomenon known as active adhesion) [84]. According to the literature, two methods of fiber addition are used: the dry method, where the fibers are mixed with the aggregates before adding the binder; and the wet method, in which the fibers are either initially mixed with the binder or added to the mixture at the end. In the sample studied in this work, only 27% of the records specified the fiber addition method, of which 58% used the dry method.

In general, the dry method has shown better results than the wet method in terms of homogeneity and distribution, and it is also considered easier to implement compared to the wet method [25]. Moreover, if the added fibers are not meant for the modification of bitumen, the dry method is more efficient, as it can minimize the clumping of fibers in the mixture [14, 56, 58].

In their study evaluating the impact of the fiber mixing process on the cracking resistance of asphalt mixtures, Wang et al. [4] designed four distinct fiber mixing processes by changing the sequence of fiber addition during the mixing procedure. The results showed that the fiber mixing process had a significant effect on the cracking resistance, and the process that represented the dry method achieved the highest cracking resistance. Meanwhile, the process representing the wet method, in which the fibers were added separately at the end, showed weak cracking resistance. In another study using waste palm oil fiber for SMA mixtures, Yaro et al. [10] investigated the influence of traditional and sequential mixing processes. The traditional method represented the dry process, while the sequential method was carried out in three stages, with fibers and fine aggregates added at the final stage. Good performance was obtained using the sequential method, which was attributed to improved material dispersion within the mixture. Overall, studies comparing different fiber addition methods contribute to the development of a performance database. However, comprehensive parametric investigations considering variations in fiber size, fiber and bitumen content, and fiber addition methods across a full optimization window are still lacking.

5 Recycled Fibers

Various types of fibers have been tested and incorporated into BM. According to the studies reviewed in this work, these types include plastic waste [11–13, 15, 17, 22, 24, 42, 80, 85, 86], those derived from plant waste materials and

organic by-products [5, 10, 29–31, 46, 57, 82, 87], textile waste primarily from end-of-life tires [35, 36, 68, 83, 88], and glass fibers including GFRP [39, 41, 49, 81, 89, 90]. The reviewed studies evaluated the effectiveness of recycled fibers in BM using various characterization techniques, recycling and processing methods, and analyses of fiber properties.

5.1 Characterization Methodology of Recycled Fibers

The characterization of recycled fibers, including chemical, mechanical and thermal properties, is usually carried out to assess their ability to withstand the various conditions involved in BM fabrication. The commonly reported characterization methods for recycled fibers include chemical analysis [39, 40, 79], thermal stability testing [23, 31, 41, 42], humidity resistance evaluation [41], tensile strength testing [43, 80], adhesion testing [42], and oil absorbency analysis [42].

Chemical analysis, which provides the chemical composition and micromorphology of the particles, is typically performed through elemental analysis, X-ray fluorescence (XRF) tests [39, 79], and scanning electron microscopy (SEM) [39, 40].

Thermal stability is a critical property of recycled fibers, as their incorporation into BM requires high heat resistance [2, 47]. Differential thermogravimetric (DTG) and differential scanning calorimetry (DSC) analyses are commonly used. In the study by Nie et al. [41], a method based on Chinese specifications was employed, in which recycled glass fibers were tested by measuring their weight loss after heating at 210 °C for 1 h, and acceptable performance was defined as less than 6% weight loss with no signs of combustion. For the same type of fibers, Khaled et al. [91] exposed the samples to 162 °C for 5 h to evaluate mass loss. In another study by Yin J. [42], the heat resistance of waste nylon filaments was investigated by observing color changes after heating at temperatures of 190 °C, 200 °C, 210 °C, and 220 °C for 20 min. Similar oven-drying tests were also performed by Xue et al. [31] for straw composite fibers, where the fibers were heated at 193 °C for 5 h, and by Xia et al. [23] for recycled polyester fibers, which were heated at 210 °C for 2 h. These short-term aging tests assess whether fibers can endure asphalt mixing temperatures without significant mass loss, thereby ensuring their suitability for use in asphalt mixtures. However, the findings indicate that different temperatures and exposure times have been adopted across studies, and no specific standardized protocol is currently available.

Humidity resistance reflects how the fibers interact with water and maintain their structural and adhesive properties

under wet conditions. This property is typically assessed through an evaluation of the quality, shape, and color of the fibers after a conditioning phase. In a study carried out by Nie et al. [41], the weight stability and visual inspection of glass fibers derived from recycled wind turbine blades were monitored after 5 days under controlled conditions at 20 °C and 90% relative humidity [92].

Tensile strength testing is commonly conducted to determine the mechanical strength of the fiber and its capacity to withstand asphalt mixing and compaction processes [43, 80]. A uniaxial tensile test is typically used to measure the tensile strength of fibers, according to the ASTM C1557 standard [93] or similar protocols.

Adhesion tests help assess the susceptibility of the fiber-bitumen interface to moisture damage. This property plays a key role in the crack resistance, water stability, and fatigue life of fiber-reinforced pavements. According to Yin J. [42], this property refers to the ability of the fiber to resist asphalt stripping caused by water erosion. To evaluate this, a laboratory boiling test was conducted that consists of measuring the percentage of asphalt that remains attached to the fiber after it has been boiled in water.

Oil absorbency reflects the capacity of recycled fibers to absorb asphalt binder. This property contributes to the stabilization of mixtures and is typically evaluated by determining the oil absorbency rate of fibers, often through standardized laboratory tests such as the gravimetric immersion method [42], in which this property is expressed as the percentage increase in fiber weight after immersion in bitumen compared to its dry weight. A higher oil absorbency indicates that more binder is required to achieve proper coating.

5.2 Recycling, Processing, and Properties of Fibers

5.2.1 Plastic Fibers

As partial substitution for fine aggregates and mixture modifiers, the use of waste plastic fibers in BM enhances the adhesion and bonding effect between aggregates and improves the rheological properties of bitumen [20]. In this review, 35% of the studies addressed the influence of using plastic fibers in BM, with the most common polymeric waste discussed in the literature being PET, PP, and PS.

Depending on their melting points, plastics can be used either as partial aggregate replacements, in the case of high-melting-point rigid plastics such as PET, or as a plastic encapsulation for aggregates (mixture modifiers), when using low-melting-point plastics such as low-density polyethylene (LDPE) and high-density polyethylene [14, 86, 94, 95]. This latter approach is referred to in the literature as aggregate or mixture modification.

PET is the most widely recycled thermoplastic polymer, typically recovered from plastic bottles and containers [11, 21, 22]. It is recognized for its strong water and moisture resistance and a high melting point of 260 °C [80]. However, its thermal resistance is relatively low, which can restrict its performance in BM applications. To overcome this limitation, various modification techniques have been studied. For example, Xia et al. [23] investigated the surface modification of recycled PET through in situ grafting with nano-SiO₂ particles, and the results showed increased surface roughness and specific surface area, which led to improved heat stability and thermal resistance.

Compared to PET fibers, recycled PP and PS fibers have been less investigated to be used for the fabrication of flexible pavements. In the case of PP, which is characterized by its semi-crystalline structure, incompatibility with hot asphalt binder may occur due to the low melting point of the fiber [25]. Regarding PS, which has a primarily amorphous structure, it is characterized by a high melting point; however, its thermal resistance in asphalt mixtures is relatively low, as it might lose some of its mechanical integrity before reaching its melting point.

Other thermoplastic fibers that behave like synthetic plastic fibers are cellulose fibers derived from recycled cigarette butts [13, 16, 17, 74, 85]. The material is predominantly composed of cellulose acetate fibers (filter) wrapped in paper [13, 74], which is used as fiber stabilizers to prevent binder draindown in SMA mixtures. According to Liu et al. [85], these fibers are characterized by a tough surface texture and corrugated structure, which enhances the bonding mechanism with the asphalt binder, making them an efficient replacement for polyester and polyacrylonitrile fibers. To prepare the fibers for use, the material is disinfected and dried at 105 °C for 24 h, then separated from other components such as unburned tobacco, ash, and paper [85].

Another thermoplastic polymer fiber is waste nylon filament, derived from brush wire products such as toothbrushes, hairbrushes, or paintbrushes [15, 42]. This material has good heat resistance, allowing for its adhesion to asphalt and creating a binding effect in the asphalt mixture. It also has excellent tensile properties and a long stage of plastic deformation [42].

Overall, the application of plastic fibers is strongly dependent on melting point and thermal behavior, enabling their use either as partial aggregate replacements or as mixture modifiers. Among them, PET fibers are the most extensively studied, benefiting from high melting temperature and moisture resistance, although surface modification is often required to overcome limitations in thermal resistance. However, while recycled plastic fibers such as PET, PP, and PS show potential to improve adhesion, binder rheology,

and mixture stability, research remains limited for PP and PS.

5.2.2 Plant-Based Fibers

A variety of plant-based fibers were examined in the sample reviewed in this study, including coconut fibers [29, 46], sugarcane bagasse fibers [5, 87], lignin-containing fibers [82], cotton straw fibers [30], palm oil fibers [10], and corn stalk fibers [57].

Plant-based fibers are usually subjected to physical and chemical pretreatments before their incorporation into BM. The treatment process varies across studies, depending on the fiber's initial state and the desired fiber characteristics. For example, a basic process for coconut fibers consists of natural drying and cutting into small sizes of 5 cm, with a controlled heating step to remove moisture and ensure brittleness [46]. In another study, coconut fibers were treated with sodium hydroxide (NaOH) to reduce their water absorption ability [29]. For the use of cotton straw fibers, Liu et al. [30] adopted a simple physical/mechanical pulverization method to reduce the size of straw to fiber. In another study by Xue et al. [31], straw fibers were obtained by smashing the plant straw, followed by alkalizing and boiling; the fibers were then synthesized to fabricate a composite material modified with bentonite. These treatments help remove surface impurities and increase surface roughness and asphalt absorption, thereby leading to improved adhesion between fibers and asphalt. Overall, pretreatment procedures vary widely across studies, resulting in fragmented approaches and highlighting the need for standardized protocols tailored to each fiber type.

Regarding performance, Xue et al. [31] found that the use of straw composite fibers improved asphalt absorption in the mixtures, resulting in a thick structural asphalt-fiber film. Similar improvements in binder retention and mixture stabilization were achieved using palm oil fibers and sugarcane bagasse fibers [5, 10, 96]. For heat resistance, straw fibers showed better resistance compared to conventional cellulose fibers, which have a thinner diameter, making them more susceptible to heat damage [30, 31]. All the studies indicated that plant-based fibers exhibited promising potential for the reinforcement and stabilization of mixtures, with coconut fibers characterized by the highest toughness among them [29, 46].

5.2.3 Textile Fibers

In the sample reviewed in this study, the recycled textile fibers used for the reinforcement of BM were mostly derived from ELT, generally obtained by breaking down used tires into their constituent materials. One recycling method that

can be used is cryogenic processing, which consists of cooling the tires to very low temperatures until they can be mechanically broken down [83]. The composition of these materials varies between truck and car tires. Both contain 70% crumb rubber, while truck tires contain 27% steel wires and 3% fibers, compared to car tires, which contain 15% steel wires and 15% fibers [36, 97]. According to Bocci et al. [36], tire fibers are composed of polyester, characterized by a transparent appearance with a thin layer of black rubber powder resulting from the tire recycling process due to the incomplete separation of rubber from the fibers. Another source of textile fibers found in the sample is cotton fibers, which are sourced from waste generated in the cotton yarn spinning mill process [68, 98].

The incorporation of tire fibers into asphalt mixtures was often accompanied by recycled tire crumb rubber as styrene-butadiene rubber (SBR) modifier [35, 56], or combined with other fibers such as carpet fibers [83]. This incorporation was carried out using different processing forms. One approach included the use of granular additives, which were fabricated from tire fibers, rapid-setting cationic asphalt emulsion, water, and rubber powder added at the end to prevent agglomeration [37, 38]. Another approach involved the processing of tire fibers into pellets, fabricated from fibers and 10% by weight of paraffin wax through an industrial process [36]. This method was adopted to avoid filament balling during the mixing process and to ensure good dispersion of the fibers in the mixture. Regarding the incorporation of cotton fibers, they were added in loose form to the aggregates before mixing [68, 98].

In general, textile waste fibers were investigated as replacements for traditional cellulose fibers in BM [37, 38, 68, 98]. Their use has shown promising results, including reduced bitumen drainage and improved mixture stability [68, 98], leading to enhanced performance of asphalt pavements [35].

5.2.4 Glass Fibers

Glass fibers are primarily made from silica and are commonly used in the manufacturing of structural composite matrices such as GFRP which is appreciated in the reinforcement of BM. The concentration of fibers in the matrix of GFRP is typically found in the range of 12%–60% by volume [99], while the other inorganic fillers range from 0–20% by volume [3, 100]. In the studies reviewed in this work, GFRP was derived from aircraft cabin components [49], retired wind turbine blades (WTB) [39–41], and other GFRP composite wastes [54, 89, 90, 101].

Regarding the processing of these fibers, in their study investigating the use of glass fibers derived from aircraft cabins, Yang et al. [49] used a mechanical process to

recover the glass fiber chips by separating them from the plastic matrix. For the GFRP derived from retired WTB, the process included the mechanical crushing of the blades, resulting in several components: glass and carbon fibers, polymeric resins, lightweight balsa wood, and polyurethane [39]. When using GFRP, Li et al. [40] and Nie et al. [41], performed chemical treatments to remove surface impurities and improve adhesion, by soaking the fibers in acetone to remove the resin coating and then treating the surface of the fiber with a silane coupling agent (UP152).

The incorporation of glass fibers into mixtures has been carried out using different approaches. In the study of Yang et al. [49], glass fiber chips were uniformly mixed into bitumen, ensuring consistent distribution. For GFRP sourced from WTB, two incorporation methods were observed: one involved using GFRP without separating it from other components produced during blade crushing [40], while the other involved selectively incorporating GFRP separated from the other components [2, 39, 41].

GFRP provides a mix of glass strength and polymer flexibility, and it is known for its high strength, lightweight properties, and resistance to corrosion [99]. Serving different functions in the mixture, recycled GFRP acts as a reinforcing additive, forming a stable three-dimensional network with bridging effects and a specific pullout behavior [49]. It has also been used as a composite powder for mineral filler replacement, improving the performance of asphalt mastics [101], and as a substitution for fine aggregates [39]. Furthermore, glass fibers have been incorporated as composite modifiers in conjunction with SBR and waste tire rubber [39, 40, 81, 89, 101].

6 Mechanical Characterization of BM with Recycled Fibers

Three primary factors influence the performance of asphalt pavements: material characteristics, traffic loading, and environmental conditions. The mechanical characterization of BM consists of the assessment of the mixture response to different configurations of these three factors [80]. According to the literature, the mechanical performance of the mixtures is evaluated based on their behavior under varying temperature conditions and repeated traffic loadings [2, 3, 90]. At low temperatures, key performance indicators usually include thermal cracking resistance and stiffness modulus [4, 21]. Under high-temperature conditions, critical parameters involve rutting resistance, creep resistance, and high-temperature stiffness [2, 3, 11, 15, 87]. In addition, fatigue resistance is an important mechanical property, particularly for binder and base layers, where mixtures are subjected to repeated traffic loading that can lead to crack

initiation and propagation [22, 80]. Finally, the durability of asphalt mixtures is generally assessed through their resistance to moisture damage, aging-induced degradation, and raveling [5, 29, 67, 90].

Fibers have been actively investigated to enhance the complex response of mixtures and to balance their elastic, viscoelastic, and plastic characteristics. They are expected to impart viscoelastic behavior to the bitumen, helping prevent cracking at low temperatures and rutting at high temperatures [52].

6.1 Plastic Fibers

The incorporation of polymeric fibers derived from waste plastic into BM is expected to improve binder-aggregates bonding and provide better mechanical performance under temperature variations [20]. However, the effect of using such materials on the mechanical performance of mixtures varies across studies.

In the case of using PET fibers, the longer and thicker ones with a rough surface significantly improved the toughness of asphalt mixtures at different temperatures [21]. Characterized by a high melting point and lengths of 1.18–2.36 mm, the use of these fibers improved rutting resistance regardless of the test temperature [11]. However, the enhancement depended on the fiber content, as exceeding 0.5% by the weight of aggregates resulted in adverse effects [11]. Moreover, the use of PET fibers improved fatigue cracking at low and higher strains, using PET contents at 0.3% and 0.5% by weight of the mixture, respectively [22]. The authors of this study measured the stiffness modulus to evaluate the fatigue cracking of the asphalt mixture [22]. It is worth mentioning that it is critical to balance fatigue cracking and rutting resistance, as high stiffness of the mixture improves the rutting resistance, but excessive stiffness increases the brittle behavior of the mixture at low temperature, leading to low fatigue cracking resistance. In addition to the stiffness modulus, the resilient modulus is used as well to assess fatigue cracking and rutting resistance. Usman et al. [80] found that recycled PET fibers improved the resilient modulus of reinforced mixtures at both 25 °C and 40 °C, showing potential for improvement in fatigue and rutting resistance. Regarding moisture damage in BM, the use of 0.5% recycled PET enhanced stripping resistance, achieving an indirect tensile strength ratio (ITSR) of up to 90% [12]. Anurag et al. [24] found that homogeneously dispersed roofing waste PET fibers enhanced both the wet tensile strength and ITSR of the mixtures. These studies showed that PET fibers enhance the asphalt mixtures durability, showing improved resistance to fatigue cracking, rutting, and moisture damage. Furthermore, the surface of recycled PET fibers can be modified to improve the toughness of BM, for example, a

surface treatment with SiO₂ increased resistance to cracking, rutting, and fatigue by 10.3%, 19%, and 2.5%, respectively [23].

Similar performance was observed when LDPE was incorporated into open-graded friction course (OGFC) mixtures, resulting in improved resistance to permanent deformation, reduced moisture damage and aged abrasion loss, and consequently lower fatigue damage [86].

Regarding the use of other types such as PE, Lastra-Gonzalez et al. [56] found that the incorporation of PE in conjunction with ELT improved stiffness and permanent deformation resistance compared to conventional BM, whereas PP had a neutral effect.

For the case of recycled cigarette butt fibers (cellulose acetate, 15 mm), they were used to stabilize SMA mixtures as a substitute for conventional cellulose fibers [17]. The results indicate enhanced structural capacity and improved resistance to permanent deformation, as reflected by increased indirect tensile strength (ITS), indirect tensile stiffness modulus (ITSM), and rutting resistance. In another study, Liu et al. [85] investigated the use of recycled cellulose diacetate (rCDA) at 0.4% in SMA, in comparison with PS (0.3%) and polyacrylonitrile (PAN) fibers (0.3%). Their findings showed that the high-temperature stability and low-temperature cracking performance of rCDA were intermediate between those of PS and PAN, while all three fibers exhibited similar fatigue life under lower stress levels. On the other hand, Tataranni et al. [13] questioned the stabilization effect of recycled cigarette filters without surface treatment, as their direct incorporation into SMA did not significantly improve the mechanical performance of the mixture.

Finally, regarding the use of waste nylon filament for the reinforcement of BM, the results showed improved performance at both high and low temperatures. The reinforcing effect of the fibers was attributed to their ability to retard crack propagation in asphalt mixtures [15, 42].

Overall, plastic fibers have demonstrated clear potential to enhance the mechanical performance, leading to improved durability of bituminous mixtures, with PET fibers showing the most consistent benefits. However, the reported effects are highly dependent on fiber type, size, content, surface treatment, and dispersion method, and exceeding optimal dosages can lead to adverse outcomes.

6.2 Plant-Based Fibers

The effectiveness of using plant-based fibers in BM depends like with other fibers on their type, dosage, and interaction with the asphalt binder and aggregates. These fibers mainly improve the toughness of bituminous mixtures (BM) through stabilization and enhanced cohesion, increasing resistance

to low-temperature cracking. However, their limited effectiveness as a reinforcement mechanism makes improvement in high-temperature performance more challenging [54]. Most of the studies included in the systematic review agree that plant-based fibers tend to enhance high-temperature stability of the mixtures [57, 82, 87, 102, 103]. According to Mansor et al. [87], using sugarcane bagasse fibers in SMA reduced rut depth from 1.945 mm to 1.635 mm and showed a higher dynamic modulus at 25°C, indicating better rutting resistance. In another study using corn stalk fibers, the results indicated an improvement in the high-temperature deformation resistance of the SMA due to their absorption capacity [57]. This shows that the stabilizing effect of plant-based fibers can help indirectly and moderately improve rutting resistance.

Regarding resistance to thermal cracking, fatigue cracking, abrasion, and moisture damage, Zhang et al. [82] found that incorporating lignin fibers into asphalt mixtures produced mixed effects on the BM performance. While rutting and thermal cracking resistance improved, fatigue cracking, abrasion, and moisture resistance decreased. The fibers enhanced performance at low and high temperatures, likely due to their stabilizing and relatively reinforcing effects. However, at moderate temperatures, they reduced fatigue and abrasion resistance, possibly because of rapid micro-crack accumulation under cyclic loading and the relatively large fiber size, which compromised mixture adhesion. The observed reduction in moisture resistance was attributed to increased air voids following fiber addition.

In addition to the fiber size effect on the abrasion resistance, Ting et al. [29] showed the influence of coconut fibers (CF) dosage on the mixture stiffness, observing a non-linear relationship between resilient modulus and fiber dosage. A dosage of 0.3% CF yielded the highest resilient modulus, whereas 0.5% CF resulted in a lower value. This improvement was observed only for unaged asphalt mixtures; no similar enhancement was seen after long-term aging [29]. Similarly, Nasir et al. [104] observed that higher CF contents affected the abrasion resistance and fuel spillage resistance of hot mix asphalt (HMA), despite improvements in stability and stiffness. Based on these findings, the authors recommended an optimal CF dosage in the range of 0.125–0.25% to achieve a balanced overall performance.

In the case of cotton straw fibers, their performance exceeded that of conventional cellulose fibers at high temperatures and provided equivalent performance in terms of low-temperature behavior and water stability [30].

Additionally, composite fibers can offer a more balanced improvement across multiple properties. In particular, a combination of corn stalk and basalt fibers provided a complementary effect, enhancing low-temperature performance, high-temperature resistance, and moisture damage

resistance in SMA [57]. These studies showed that although rutting resistance was improved, the reduction in fatigue performance at intermediate temperatures suggests a potential stiffness-induced brittleness effect. This indicates that durability improvements may be temperature-dependent and that fiber addition could introduce trade-offs between deformation resistance and crack resistance.

6.3 Textile Fibers

Most of the findings focused on the use of textile fibers recovered from ELT. Whether in loose or granular form, BM incorporating these fibers consistently met design specifications, demonstrating their mechanical viability and ability to replace traditional additives without compromising the core structural properties of asphalt mixtures [36, 83].

According to Putman et al. [83], mixtures containing textile ELT fibers or automotive carpet fibers showed no significant difference from those with traditional cellulose or polyester fibers in terms of permanent deformation and moisture damage resistance. However, the same study found that textile ELT, carpet, and polyester fibers each significantly improved the toughness of the SMA compared to cellulose fibers. In the same context, the use of cellulose-based commercial fibers in SMA is shown to be replaceable with granular additives based on ELT fibers [38]. Valdés-Vidal et al. [38] found that the cracking and rutting resistance, stiffness modulus, and moisture sensitivity results indicate that using granular additives based on ELT fibers did not compromise the mechanical durability of the SMA mixture compared with the mixture containing commercial cellulose fibers. This suggests that the ELT additives can function as a structurally equivalent alternative while maintaining key durability-related properties. Moreover, in HMA, the incorporation of ELT fibers improved fatigue resistance, Bocci et al. [36] attributed this result to the fiber's ability to reduce the propagation of microcracks, and limit their opening, which helps extend the pavement service life.

Furthermore, Jin et al. [35] reported that the combined use of rubber and textile ELT fibers led to enhanced pavement performance. These improvements were confirmed through both laboratory tests and field demonstrations, in which modified HMA incorporating ground tire rubber (GTR) and ELT fibers demonstrated better durability and aging resistance compared to both conventional HMA and GTR modified HMA. These findings show that textile ELT fibers can effectively replace traditional cellulose fibers, while combinations with rubber further enhance durability and aging resistance.

In addition to textile fibers, the incorporation of metallic fibers recovered from ELT was investigated for both their mechanical performance and self-healing capacity in

asphalt mixtures [66]. According to González et al. [66], the inclusion of metallic fibers led to a reduction in indirect tensile stiffness and strength with increasing temperature and fiber content. However, the ITSR remained within acceptable limits (>80%), confirming the mechanical viability. Regarding self-healing behavior, the metallic fibers exhibited electrically conductive behavior, with electrical resistivity decreasing as fiber content increased, which facilitated heat transfer and enhanced crack-healing capacity of the mixtures.

6.4 Glass Fibers

As described in Sect. 5.2.4, GFRP was incorporated in BM in the form of powder and fibers for the substitution of filler and fine aggregates [39], and as composite modifiers in conjunction with SBR or waste tire rubber [39, 40, 81, 89, 101]. The integration of GFRP aims to reinforce mixtures, reduce binder draindown, and improve adhesion.

To investigate the effect of the polymer coat of recycled glass fibers, Yang et al. [90] tested the use of glass fibers in mixtures, with or without a polymer coat. The results showed that in both cases the glass fibers improved resistance to moisture damage, whereas only GFRP enhanced the resistance to oxidative aging, which could be attributed to the adhesion between glass fibers and bitumen promoted by the polymer coat. According to Izaks et al. [89], aside from enhancing moisture damage resistance, using 0.15% glass fibers in dense-graded asphalt mixtures improved cracking and deformation resistance, while higher content (0.5%) reduced performance. Another study assessed the effect of recycled glass fiber chips on bitumen reinforcement [49]. The results demonstrated the ability to enhance bitumen's performance across a wide temperature range by improving high-temperature properties such as stiffness, rutting resistance, and creep-recovery behavior, while simultaneously mitigating low-temperature cracking and increasing moisture damage resistance in asphalt mixtures due to the bridging and pullout mechanism created by the three-dimensional fiber structure [49].

Derived from waste WTB, glass fibers were subjected to chemical treatment beforehand to improve the mechanical performance of mixtures [40, 41]. As in the case of the study conducted by Lan et al. [39], the crushed WTB was used in the form of powder and fibers for the substitution of filler and fine aggregates, respectively. The results showed an improvement in the mechanical performance of the mixture and highlighted the adverse effect of using excessive fiber content on flexural strength. Similar results were found using waste epoxy-based GFRP composite powder as a mineral filler alternative in asphalt mastics, improving medium and high-temperature performance, through rutting

and fatigue resistance, however, a decrease in low-temperature performance was reported due to the lower density of epoxy-based GFRP [101]. Most studies used the wet addition process for GFRP as a bitumen modifier, particularly when particle size was below 0.3 mm. Moreover, improved durability and performance were obtained with limited dosages, often <0.3 wt.% [41].

Regarding the use of glass fibers as composite modifiers, Li et al. [40] tested different configurations using GFRP-based powder derived from crushed WTB to prepare a composite powder modifier for the mixture. The process of the composite powder preparation included silane surface treatment and mixing with SBR. Results showed that GFRP-based composite modifier significantly improved moisture damage resistance, reaching 95.6% and contributing to asphalt pavement durability. In the same context, Eskandarsefat et al. [81] assessed the feasibility of replacing polymer-modified bitumen combined with conventional fibers by using neat bitumen in combination with composite modified fibers (made of glass and cellulose fibers). The results showed that modified fibers enhanced stiffness at high temperatures and improved moisture damage resistance but led to a reduction in fatigue life. While modified fibers mixtures can offer mechanical performance comparable to that of polymer-modified bitumen, the latter still demonstrates superior rutting and fatigue resistance. Overall, the studies indicate that recycled GFRP and glass fibers can enhance the mechanical durability of asphalt mixtures, particularly in terms of moisture damage resistance, high-temperature stiffness, rutting resistance, and oxidative aging. However, improvements are highly dependent on fiber content, particle size, and surface treatment. Excessive fiber dosage or improper processing can reduce low-temperature performance and fatigue life, highlighting the need to optimize mixture design to achieve a balanced durability profile.

7 SMA and PA

Based on aggregate gradation, BMs are generally classified into dense-graded, gap-graded, and open-graded mixtures [105, 106]. Dense-graded mixtures are considered the most conventional mixture used in pavements, characterized by a well-graded aggregate structure, which minimizes air voids and ensures durability. Gap-graded mixtures, usually SMA, are characterized by a high content of coarse aggregates and bitumen; they are widely used as surface-course mixtures, providing stone-to-stone contact and great resistance to high-temperature deformation [46], which is considered well-suited for high traffic roads [13]. Open-graded mixtures, including OGFC and PA, are characterized by high porosity and designed to reduce surface runoff by

facilitating water drainage [107]. Similarly to SMA, open-graded mixtures require a high bitumen content, making them susceptible to excessive binder draindown, which can lead to mechanical performance degradation [25, 87].

As described in Sect. 3.5, SMA was frequently cited and received significant attention in the reviewed studies, unlike PA mixtures. Although the use of fibers was certainly also addressed in dense-graded mixtures, especially with plastic-derived waste polymers such as PET, PP, and PS for mixture reinforcement, the incorporation of fibers in SMA attracted more attention, particularly in studies investigating the feasibility of stabilizing this mixture [48], which generally consumes higher amounts of bitumen compared to dense-graded mixtures [108].

Cellulose and mineral fibers are commonly used for the stabilization of SMA [83]. Based on chapters 5.2.2 and 5.2.3, recycled textile and plant-based fibers offer a viable replacement for cellulose fibers, especially in SMA, enhancing the stability and durability of mixtures. On the other hand, PA incorporating plant-based fibers showed promising results, such as reducing binder drainage and abrasion loss, as well as increasing cracking resistance [32, 34]. However, the incorporation of coconut fiber showed limited enhancement, only improving the early-life performance of pavements [29]. Besides hot and warm mix asphalt types, cold mix asphalt (CMA) incorporating recycled fibers has emerged as a sustainable alternative [109]. The lower production temperatures in CMA are a key benefit compared to hot and warm asphalt, particularly when thermal stability is critical for recycled fibers, as discussed in Sect. 5.1. The cold process reduces the thermal degradation of plant-based fibers [110], preserving their integrity while still providing significant mechanical benefits [111]. Moreover, compared to HMA incorporating recycled polymeric fibers [112], cold mix asphalt reinforced with the same fibers has shown improved cracking resistance, although rutting resistance may be lower. However, studies evaluating the performance response of CMA with recycled fibers remain limited, as research in this area is still emerging.

Overall, existing studies remain fragmented and primarily focused on stabilization effects of recycled fibers in SMA, while a comprehensive understanding of the reinforcement potential of recycled fibers across different mixture types, particularly PA mixtures, and their long-term performance remains insufficiently addressed.

In addition, the wide range of mixture types, fiber characteristics, and performance indicators considered in these studies makes the identification of the optimal fiber option a multi-response problem [9, 61]. Consequently, several researchers have explored different approaches to compare and select optimal fibers, including direct property-by-property comparisons between fiber types [37, 113], the

application of statistical analyses [112], and the adoption of automated approaches, such as multi-criteria decision-making (MCDM) methods [114–117], to evaluate multiple criteria simultaneously. These approaches convert the multi-response problem into a single-response optimization problem. A typical MCDM workflow involves several steps [118–122], including the selection of statistically significant performance indicators (criteria), the assignment of weights to these criteria, and the ranking of different alternatives. Such approaches enable a more systematic evaluation of recycled fibers and support the identification of optimal fiber types according to specific design requirements and performance objectives.

8 Strategic Research Roadmap and Conclusions

8.1 Strategic Research Roadmap

- Studies should report complete mix design parameters, to enable reproducibility and comprehensive comparisons. Only 27% of the reviewed records explicitly reported the fiber addition method, leading to a limited and fragmented systematic knowledge on optimal fiber size, fiber and bitumen content, and fiber addition method. Moreover, despite the reported promising results of the mechanical performance, the studies reviewed use varying methods and performance indicators, making comparisons difficult. To enable consistent evaluation of durability in future research, a framework is needed that standardizes test methods, aging procedures, fiber dosages, and reporting metrics, particularly for rutting, fatigue, moisture susceptibility, and thermal cracking. This framework should also include the establishment of thresholds linked to field performance.
- A standardized pretreatment protocols of fibers should be defined, future research should explicitly report pretreatments procedures as they vary significantly among some studies, ranging from simple to complex processes and using different parameters (for instance, oven drying ranges from 210 °C for 20 min to 210 °C for 2 h).
- Future research should include more comparative studies assessing untreated vs. treated fibers from the same recycled fiber source, particularly with respect to their influence on long-term aging and durability performance.
- Future studies should perform more long-term durability characterization of BM incorporating recycled fibers, to enable widespread normalization and large-scale industrial implementation.
- Further comprehensive parametric investigations of open-graded mixtures incorporating recycled fibers should be performed, as they exhibit high sensitivity to binder content and stabilization mechanisms.

8.2 Conclusions

This study aimed to review the highly discussed key factors and themes in the literature related to the incorporation of recycled fibers into BM, based on a systematic bibliometric analysis. The following main conclusions were drawn:

- Recycled fibers are gaining attention as sustainable alternatives to commercial fibers in BM, aiming to enhance durability, extend pavement service life, and reduce their environmental footprint.
- Fibers can act as both modifiers, improving bitumen's rheological properties, and as reinforcement, strengthening the asphalt mixture, with these roles often overlapping to reduce binder loss, increase aggregate adhesion, and delay crack propagation.
- The performance of BM incorporating recycled fibers is significantly influenced by fiber size and content. Optimal reinforcement is often achieved with around 0.3% fiber content by total mixture weight, with specific fiber particle size depending on the fiber type. Moreover, the fiber addition method affects homogeneity and cracking resistance of the mixture. The dry method, where fibers are mixed with aggregates before binder addition, generally shows better results in terms of homogeneity of fiber distribution and performance. To assess the suitability of using recycled fibers in BM, a specific fiber characterization is necessary to ensure the fibers can endure fabrication conditions without compromising the performance of asphalt pavements.
- Plastic waste fibers, including PP, PE and PS, but especially PET, are widely studied for their positive impact on BM, improving rutting resistance, stiffness, and moisture damage resistance. Surface modifications have enhanced the thermal resistance of plastic fibers and the bonding of low-melting ones. Additionally, recycled cigarette butt fibers and waste nylon filaments have shown potential as stabilizers in SMA mixtures.
- Plant-based fibers such as coconut, straw, and bagasse fibers show strong potential as sustainable alternatives to cellulose fibers in BM, enhancing tensile strength (best performance with coconut fibers) and reducing binder drainage (best performance with straw and bagasse fibers). Inorganic fibers generally outperform natural ones in heat stability, though straw fibers show better performance than cellulose due to their thicker diameter. Pretreatment processes are crucial for optimizing

the adhesion and performance of plant-based fibers in BM. While certain fibers improve rutting and cracking resistance while reducing fatigue and moisture performance, combined fibers can overcome such limitations by enhancing both temperature and moisture resistance.

- Recycled textile fibers, mainly from ELT and cotton waste, can effectively replace traditional cellulose fibers in BM by reducing bitumen drainage and maintaining or improving the mechanical properties of asphalt mixtures, such as toughness, and rutting and fatigue resistance. They can be processed into granules or pellets to ensure proper dispersion and avoid clumping during mixing. Furthermore, when combined with ground tire rubber or other fibers, ELT textile fibers enhance the durability and aging resistance of the mixtures.
- GFRP has been effectively used in BM as a powder replacing mineral filler, as fibers replacing fine aggregates, or as a composite modifier combined with rubber. It has been shown to improve BM performance in high-temperature properties such as stiffness and rutting resistance, while also mitigating low-temperature cracking and enhancing moisture resistance, due to its bridging structure and reinforcing effect. Chemical and thermal treatments of such fibers enhance their adhesion and contribute to better moisture resistance and oxidative aging resistance. Optimal performance is generally achieved with limited GFRP dosages (<0.3 wt.%), as excessive fiber content can negatively affect mechanical properties such as flexural strength. Glass fibers in conjunction with rubber and cellulose fibers can replace polymer-modified bitumen with conventional fibers, offering comparable stiffness and durability at high temperatures, though polymer-modified bitumen still performs better in terms of fatigue and rutting resistance.
- The incorporation of recycled fibers into BM may create performance trade-offs, making it essential to select the appropriate fiber type based on the performance requirements prioritized by the designers. Plant-based fibers are mainly used for their modification effect, improving low temperature performance but may offer limited high temperature stability. Plastic and glass fibers enhance stiffness, rutting resistance, and overall stabilization. Textile fibers can replace commercial cellulose fibers, providing a structurally equivalent alternative, maintaining key durability-related properties.
- SMA and PA have received research attention for fiber stabilization compared to dense-graded mixtures, as they are more prone to binder draindown. Waste textile and plant-based fibers can effectively replace traditional cellulose fibers in SMA and PA, improving mixture stability, reducing binder drainage, and enhancing mechanical performance and durability.

Based on the conclusions, future research should focus on establishing unified reporting of mix design parameters (including fiber size, type, dosage, bitumen content, and method of addition) to improve reproducibility and enable meaningful comparisons. Standardized fiber pretreatment protocols are also needed to reduce variability, and further studies are required on comprehensive parametric investigations of PA mixtures incorporating recycled fibers. Additionally, research should address long-term performance and industrial scalability, while integrating environmental and sustainability assessments to support the practical implementation of recycled fibers in bituminous mixtures.

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