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Review

The use of fibres in asphalt mixtures: A state of the art review

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ABSTRACT

The various acknowledged benefits given by the use of fibre for construction materials made this component essential for specific applications, including asphalt pavements. Fibres in asphalt mixtures usually play two important roles: acting as an asphalt stabilizer to decrease the drain-down effect; and as a reinforcing additive to enhance the mechanical performance of asphalt mixtures. To better understand their use, this paper aims to review the various uses of different types of fibres in asphalt pavements. The main variables that influence the effectiveness of fibres and the reinforcing mechanism of using fibres are discussed. Furthermore, a state-of-the-art of the combined use of fibres and other additives, such as crumb rubber, polymer modifiers, and nano-size modifiers, is presented. Results from relevant studies confirmed the effectiveness of using fibres in asphalt pavements and the significance of optimizing the mixing method, size and dosage of fibres to achieve more suitable performance. Additionally, the latest research findings and experimental applications are discussed, with a specific focus on waste and recycled materials. Exploring feasible recycled alternatives to natural and traditional fibres, optimizing the use of fibres from wastes, and combining the use of fibres with other sustainable technologies, could maximize the environmental benefits of using fibres in asphalt pavements.

1. Introduction

Nowadays asphalt concrete is the most widely used material in pavements, with different applications such as highways, footpaths, runways, harbours, and parking lots. It is estimated that above 90% of pavements in Europe are paved with bituminous materials [1]. Depending on the adopted mixture of asphalt binder, aggregates and fillers, asphalt pavements can show great benefits including high skid resistance, low noise emissions, low roughness, safety, and durability. Nevertheless, the issue of pavement distresses (such as rutting, thermal and fatigue cracking, ravelling, and similar) cannot be ignored. It should be noted that, in recent years, the increasing traffic loads and volumes, as well as global warming (sustained high temperatures in some regions) intensified pavement distresses, especially the premature deterioration of pavements [2]. Particularly, asphalt, which plays a key role in asphalt concrete's behaviour, predominantly determines the pavement performance and its service period. Especially, the aging of asphalt during the service period worsens the low-temperature and fatigue performance, resulting in the shorter pavement service life [3]. Therefore, using asphalt with enhanced properties can be a good option for constructing high-performance asphalt pavements. Researchers and practitioners have been making great attempts to achieve this objective. According to several studies, different types of additives including polymers [4,5], fibres [6,7], anti-stripping agents [8], plastics [9], rubber [10,11], rejuvenators [12,13], nanomaterials [14], etc., are added either into the asphalt binders or in the asphalt mixtures to improve the ultimate performance of asphalt pavements.

Fibres, one of the most commonly used additives in asphalt mixtures, their application has been investigated and developed in the research field of paving materials for many years. Nowadays, fibres are still of great attention in the pavement industry due to their variety and significant improvements for specific purposes. For instance, one of the major shortcomings of asphalt mixtures is the weak tensile strength, which leads to the formation and development of cracking [6]. In this case, the application of fibres with high tensile strength could be a valid solution. When the fibres are incorporated into the asphalt mixtures, they work as reinforcing material and increase the cohesion of the mix, decreasing the reflective or fatigue cracking and increasing the resistance to permanent deformations [15–17]. Fibres can be also used as stabilizers, reducing the drain-down effects of asphalt mixtures, especially for SMAs (Stone Matrix Asphalts) and porous asphalt mixtures, which are traditionally rich in asphalt binders [7,18–20]. Under this circumstance, the inclusion of fibres is similar to the addition of very fine aggregates into the asphalt mixtures [17]. This also contributes to the

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prevention of asphalt bleeding.

Overall, adding fibres can alter the viscoelasticity of asphalt [21], increase the dynamic modulus [22] and creep compliance [23], and improve the rutting performance [23], water stability [24], freeze–thaw resistance [25], and cracking resistance [26]. Furthermore, fibres can be used in other forms when incorporated into asphalt mixtures. Some research works presented the combined use of fibres with SBS (styrene–butadienestyrene) [27], rubber [28], nanomaterials [29], and anti-rutting agents [30]. In the last years, in order to realize the sustainability of construction materials, fibres produced with waste materials or industrial by-products, like waste tires and carpets [16], cigarette butts [7] and face masks [31], have been applied into asphalt mixtures mainly to improve their performance.

Based on the constituent materials, two main categories of fibres are used in asphalt pavements: natural and synthetic fibres. In this review paper, various fibres from these two classes and fibres from waste or by-products will be discussed, as well as the most relevant variables related to their application (mixing methods and dimensions) and the reinforcing mechanism of using fibres. Besides, the combined use of fibres and other materials (such as rejuvenators in the RAP, some modifiers, etc.) will also be illustrated, together with the latest findings in the development of innovative fibres. Furthermore, some recommendations for further studies will be suggested.

2. The utilization of fibres in construction materials

The use of fibres in construction materials could be traced back to remote ancient times. The earliest use of fibre goes back to a 4000-year-old arch in China, which was built with clay earth added with fibres [17,32]. Also, the Great Wall, constructed over 2000 years ago, is an example of reinforced earth with fibre [17,32]. During the Ancient Egyptian periods, early residents in Egypt and Mesopotamia used straw as a component of the mud bricks to construct durable buildings [33]. Straw as one of the natural fibres, was a commonly used reinforcement material during the early times. Normally, natural fibres like straw, bamboo, coconut, and jute have a long history as they come from nature and are easily usable. The number of fibre types suitable for construction materials significantly increased as more and more different kinds of fibres have been found, tested and applied. Nowadays, almost all construction materials (including concrete, earth materials, blocks, bricks, asphalt and asphalt mixtures) can encompass the use of fibres [34]. Research studies have presented the use of steel, synthetic polypropylene, glass, and other fibres in concrete structures [35–37]. Among them, the application of steel fibres is very common in concretes [35]. Using fibres in soils is much earlier than their use in concrete, which acted as reinforcing components in a soil mass and led to increased shear resistance [38]. Various natural or synthetic fibres are also used to reinforce other earth materials, blocks, and bricks [39].

Apart from the abovementioned construction materials, fibre is also a very common additive in bituminous pavements. The thought of using fibres as a reinforcing material in bituminous mixtures originated from the fibre reinforcement in concrete materials [40]. The earlier application can be found in the patents published by Warren Brothers Company of Boston in 1917 and 1918 [41]. In their patents, asbestos fibres were used in sheet asphalts to prevent asphalt bleeding at high temperatures. In cold-laid asphalt pavements, asbestos fibres with a small amount can reduce the segregation of aggregates during the placement procedure [41]. Kietzman [41] found that adding asbestos fibres in asphalt mixtures resulted in an increase in plastic strength. Considering the healthy and environmental issues, this application only continued until the 1960s [42]. In the 1930s, cotton fibres were used in asphalt mixtures, but the degradation over time weakened the fibre reinforcement [43]. Since then, other types of fibres have been introduced into asphalt pavements. In recent years, ongoing research in the field of pavement engineering is focusing on the exploration of eco-friendly approaches or materials, including the use of fibres in paving materials. Using natural fibres is a good sustainable alternative due to the lower energy consumption and cost, renewability and biodegradability [44–47]. Fibres from waste materials or by-products also have great recycling value. In the following sections, the use of different types of fibres in asphalt pavements is discussed and reviewed.

3. Different types of fibres in asphalt pavements

This section presents the two main categories of fibres used in asphalt pavements: natural and synthetic fibres, then those from waste and by-products. Afterwards, the most relevant variables to be considered in the paving industry and the reinforcing mechanism of fibres in asphalt mixtures are elaborated. Fig. 1 listed the two main categories of fibres that are described in the following section.

3.1. Natural fibres

Natural fibres are produced from raw materials in nature and can be classified into three main groups according to their origin: plant-based, animal-based and mineral-based natural fibres [48,49]. In this section, the use of plant-based fibres (bamboo, coconut/coir, jute and sisal) and mineral fibres in bituminous mixtures is described.

3.1.1. Bamboo fibres

Bamboo is a giant woody plant that belongs to the grass family Poaceae. This wood plant has a surprisingly growing speed and can grow continuously even after cutting. Most bamboos have been found in tropical, subtropical, and temperate regions, like Southeast Asia and South America [50,51]. Bamboo can be used for buildings, furniture, textiles and as a food resource. It also provides a natural ligno-cellulosic fibre, which can be extracted from the bamboo culm. The major components of bamboo are cellulose, hemi-cellulose, and lignin, taking up above 90% of the whole weight, whereas the remaining minor parts are soluble polysaccharides, waxes, resins, tannins, proteins and ashes [52,53]. Chemical and mechanical processing methods are the two main manufacturing ways to manufacture bamboo fibres [54,55]. In the chemical processing, crushed bamboo is soaked in alkali hydrolysis (NaOH) solution, and then alkali-treated cellulose fibres are passed through carbon disulphide (CS_2) via multi-phase bleaching. Comparing the chemical process, the mechanical method requires higher labour and costs but is more environmental-friendly [55]. It uses natural enzymes on the crushed bamboo wood fibres, and the washed fibres can then be washed and mechanically spun into yarn.

Sheng et al. [56] explored the possibility of using bamboo fibres to enhance the performance of asphalt mixtures. Different amounts of bamboo fibres were added into dense-graded (DG) and stone matrix asphalt (SMA) mixtures. Thermal stability test results showed that bamboo fibres exhibit sufficient thermal properties when they are subjected to high temperatures during the mixing and compaction processes. From mechanical test results, bamboo fibre mixtures showed satisfying moisture stability according to Marshall stability and freeze–thaw cycling tests, similar or even better properties compared with the polyester or lignin fibre mixtures. The rutting performance and low-temperature cracking resistance also improved. This study recommended the optimal contents of bamboo fibre in DG and SMA mixtures, 0.2–0.3% and 0.4% respectively (by weight of asphalt mixtures). The comparison in the study from Xia et al. [57] also showed that bamboo fibre is a good alternative to lignin fibre due to the improved low-temperature performance and moisture stability, although the mechanical property was better for the latter one. This study also concluded that bamboo fibres with a rough surface and good oil absorption properties contribute to the enhancement of the ductility and adhesion properties of asphalt mastic, while their higher density and toughness are responsible for the increased flexibility of mixtures and cracking resistance. Jia et al. [58] investigated the influence of laboratory aging on the stiffness and fatigue cracking of asphalt concrete produced with

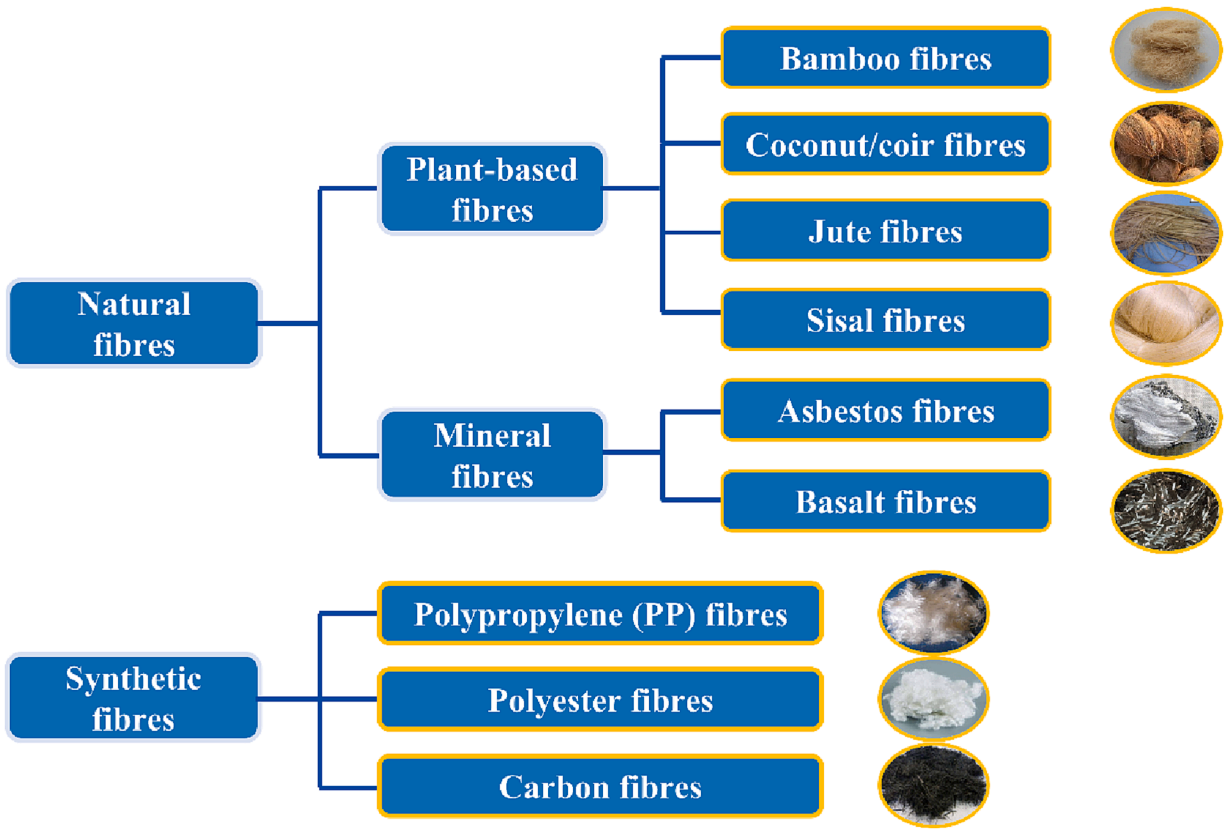

Fig. 1. Natural and synthetic fibres.

bamboo fibres. Compared to polyester fibre mixtures, similar results were obtained. It was also found that the interfacial adhesion between bamboo fibre and asphalt matrices was poor due to the high hydrophilicity of this fibre and the hydrophobicity of asphalt [59].To improve the interfacial adhesion, Yu et al. [60] modified bamboo fibres with melamine–formaldehyde copolymer before the incorporation into asphalt mixtures. Besides the increased stability and tensile strength of mixtures, good adhesion between the modified bamboo fibres and asphalt matrixes was observed through SEM images.

3.1.2. *Coconut/coir fibres*

Coconut fibre (also named coir fibre) is a lignocellulose-based fibre extracted from the husk of the coconut, a type of fruit basically grown in tropical regions, especially the Southeast of Asia. Coconut fibre can be divided into two different fibres according to the colour, namely white coir and brown coir. The fibres with white colour are obtained from the unripe coconuts, while the brown ones come from the rape coconuts [61]. In terms of the chemical composition of coconut fibre, it contains cellulose (32 to 50 %), hemicellulose (0.15–15%), lignin (30–46%) and pectin (3–4%) according to a review by Adeniyi et al [61]. This means that cellulose and lignin are the major components in this natural fibre, thus making the material durable, weather resistant and waterproof [62,63]. Besides, coconut fibre shows clear advantages in low cost, low density, high elongation at failure and biodegradability [61,64].

Indian researchers [65] used coconut fibres in SMA mixtures with two different asphalt binders (virgin 30 grade asphalt binder and crumb rubber modified binder). To select the optimal asphalt content and fibre concentration, the Marshall mix design was followed. The results showed that 0.3% of ripe coconut fibre can bring a significant improvement in Marshall properties. From the drain-down, static indirect tensile, repeated load indirect tensile and tensile strength ratio (TSR) tests, the addition of coconut fibre contributed to better asphalt absorption properties (especially in SMA mixtures that use the virgin asphalt), higher mechanical properties, improved fatigue life and reduced moisture damage. In Brazil, Oda et al. [66] also applied coconut fibres into the SMA mixtures containing asphalt rubber binders. Besides, three types of fibres (sisal, cellulose, and polyester) were used, to make a comparison of their effects on the mechanical properties of mixtures. From the obtained results, mixtures made with coconut or sisal fibres showed better results in drain-down tests than those using cellulose or polyester fibres. A general increase in the tensile strength and the resilient modulus was registered, but without a relevant difference between the adopted fibres. In the study from Vale et al. [67], two design methods (Marshall and Superpave) were used to investigate the effects of adding coconut fibres in SMA mixtures, taking the cellulose fibre mixture as reference. It was confirmed that coconut fibre can be a good option for replacing the cellulose fibre, as it provides excellent drain-down properties. However, the fatigue life was lower than that of mixtures containing cellulose fibres or no fibres. The possible reason given by the authors was that the incorporation of hard coconut fibre stiffens the mixtures, making them brittle. In Norhidayah and Haryati's study [68], both coconut shells and fibres were used in porous asphalt mixtures. Coconut shells in their studies were used as a partial replacement of 5 mm coarse aggregates according to the 0%, 5%, 10% and 15% of the total weight of aggregates. Coconut fibres were added with the dosage of 0.3% and 0.5%. Unlike the abovementioned studies, coconut shells and fibres were treated by soaking them in sodium hydroxide (NaOH) for one hour because of their high absorption property. The results showed that the incorporation of 10% coconut shells and 0.3% coconut fibres could substantially increase the stability and rutting resistance of asphalt concretes.

3.1.3. *Jute fibres*

Jute is a kind of bast fibre that belongs to family Tiliaceae. Most of the jute in the world is produced in countries like India, Pakistan, China, Bangladesh, and Brazil [69,70]. Jute fibre has been widely used in the fields of textile, construction and automotive because of its fine texture, low thermal conductivity, and low cost [71]. Like other natural fibres, cellulose, hemicellulose and lignin are the major components of jute fibres [72].

In the research study conducted by Rashid et al. [73], jute fibre as a reinforcing material in asphalt mixtures was investigated. Stability results from Marshall stability and flow tests showed that the 0.5% and 1% of jute fibre led to an increase in stability by 29% and 10% respectively. The optimal asphalt content increased from 4 to 5%. Jute fibre modified mixtures presented better deformation resistance than the unmodified ones and the content of jute fibre, 0.5%, was recommended by the authors. Ismael et al. [74] investigated three different fibres (jute, polyester, and carbon fibres) with varying contents (0.25%, 0.5% and 0.75%) and lengths (5, 7.5 and 10 mm) in SMA mixtures through drain-down, Marshall, wheel tracking tests. All three types of fibres with a content of 0.5% and a length of 7.5 mm can effectively improve the rutting resistance and stability of the SMAs. Among them, carbon fibres showed the greatest improvement (increasing the rutting resistance and dynamic stability by 53% and 100% respectively), followed by polyester fibre, then jute fibre (34% and 63% respectively). However, jute fibres exhibited the best drain-down properties. Apart from the hot mix asphalt (HMA) mixtures, jute fibre is also used as a reinforcing material in warm mix asphalt (WMA) [75] and cold mix asphalt (CMA) mixtures [76]. As for the application in WMA [75], the fracture resistance of WMA mixtures under the mode I (opening or tension mode) can be largely improved by adding jute fibres, indicating the reinforcement of tensile strength of WMA mixtures. It is also concluded that the optimum content of jute fibre in WMA was 0.3% by weight of the whole mixtures.

3.1.4. Sisal fibres

Sisal fibres are natural fibres obtained from the leaves of the sisal plant. This flower plant is native to Southern Mexico and now it can be found in many tropical and subtropical countries. The two methods of extracting sisal fibres from sisal plants include retting and then scrap or mechanical method through decortication [77]. The mechanical methods could provide higher-quality fibres than the former ones. The percentage of chemical components of sisal fibres changes with the growth of plants. From several studies [78–80], cellulose, lignin and hemicellulose are the three major components. All these studies showed that cellulose has the highest concentration in sisal fibres. Considering its advantages in low cost, low density, good strength, and high modulus [81], sisal fibres have various uses, including the use for paper, cloth, carpets, rope and geotextile. Besides, it is an important reinforcing material in composites and construction industries.

The length and content of fibres are the most significant variables when discussing the application of sisal fibres in asphalt mixtures. Effects of different lengths (5, 10, 15 and 20 mm) and concentrations (0.05, 0.1, 0.2 and 0.3%) of sisal fibres on the performance of asphalt mixtures were studied in the research conducted by Ramalingam et al. [82]. It was found that adding a small amount of sisal fibre could improve the fatigue resistance and moisture sensitivity of asphalt mixtures, while the stability of asphalt mixtures decreased with the increase in fibre content. When 15 mm sisal fibres at 0.05% concentration were added into asphalt mixtures with the optimum asphalt content of 5.4%, the best performance was achieved. In Kar et al.'s research [83], sisal fibres were used as a stabilizer in SMA and dense-graded asphalt mixtures. Expectedly, the introduction of sisal fibres in both two mixtures led to an increase in Marshall stability and tensile strength, and a decrease in flow value, air voids content and drain-down value. The comparison between the two different gradation mixtures demonstrated that with adding sisal fibres at the content of 0.3% as the stabilizer, SMA could achieve higher mechanical properties than the dense-graded mix. The study conducted by Razahi and Chopra [84] compared two types of natural fibres (sisal and coir fibre) in SMAs. According to the results, 0.3% was considered as the most suitable content for both fibres. Under the fibre content of 0.3%, SMA mixtures with coir fibre showed higher Marshall stability and tensile strength, and lower drain-down value than the one with sisal fibre. Kumar and Ravitheja [85] also obtained the same results from their study. Coir fibres exhibited the best effect when added into SMA mixtures. Like coconut fibres described before, sisal fibres have also been used in SMA mixtures with asphalt rubber [66]. Both natural fibres showed better potential in improving the mechanical performance (tensile strength and resilience modulus) of mixtures compared with bituminous mixtures produced with polyester and cellulose fibres.

3.1.5. Mineral fibres

Asbestos is exclusively used as a textile mineral fibre coming from fibrous reins of serpentine or amphibole rock [86]. The effects of using asbestos fibres in asphalt mixtures were usually compared with other types of fibres in most studies. Chen et al. [87] evaluated the utilization of four different fibres (polyester, polyacrylonitrile, lignin, and asbestos fibres) in their study. All fibres have the ability to increase the optimal asphalt content, air void content, void content in mineral aggregate and Marshall stability, while decreasing the bulk specific gravity. Asphalt mixtures reinforced with polymer fibres displayed higher stability because of the network formed, but the addition of lignin and asbestos fibres led to higher optimal asphalt content and VFA (voids filled with asphalt) due to the better absorption property.

Basalt fibre is also a type of mineral fibre that is obtained from natural volcanic rock and ore after melting at the high temperature [88]. Zhao et al. [89] conducted a series of mechanical tests to investigate the reinforcing effects of basalt fibres. Results showed that these fibres are beneficial for the improvement of mechanical properties, low and high-temperature performance, and water susceptibility. Taking the pavement performance and cost-saving into consideration, the most appropriate content of basalt fibre given in this study is around 0.3%. At this optimum content, the increase of Marshall Stability, dynamic stability, maximum bending strain and tensile strength ratio were higher if compared with the asphalt concrete with no fibres. Also, this study noted that basalt fibre had the better potential to enhance low-temperature performance than lignin and polyester fibres. Research conducted by Qin et al. [90] focused on reinforced asphalt mastics using basalt fibres. The stable three-dimensional network formed in asphalt mastics due to the addition of basalt fibres improved the ability of dispersing the stress and alleviated the crack propagation.

In the "natural fibres" section, the use of four plant-based fibres and mineral fibres in asphalt mixtures was elaborated. The plant-based fibres are abundantly available as they are extracted from different plants that grow naturally in the world. So, this type of fibre is one of the renewable and environmental sources of materials in engineering applications. They are also cost-saving and sustainable materials, requiring low or no energy to produce. Regarding the chemical components of plant-based fibres, they generally contain three main constituents, i.e., cellulose, lignin and hemicellulose. The weight percentage of each major constituent is different based on the plant origin. The chemical composition of the major constituents from the four plant-based fibres is displayed in Table 1 [49]. Considering that they are lignocellulosic materials, biodegradability is an unavoidable challenge in their practical application. Specifically, their thermal degradation or decomposition over time is detrimental to the performance of asphalt mixtures modified by these fibres. In Fig. 2, the degradation time of plant-based fibres is shown [91]. Chemical treatment (such as esterification, transesterification,

Table 1
Major chemical composition of plant-based fibres.

Type of plant-based fibres	Cellulose (%)	Lignin (%)	Hemicellulose (%)
Bamboo	26–73.83	10.15–36.88	12.49–31
Coconut/coir	32–43	40–45	0.15–0.25
Jute	41–48	21–24	18–24
Sisal	47–78	7–11	10–24

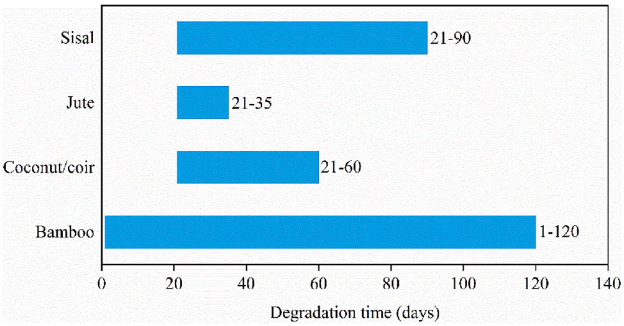

Fig. 2. Degradation time of plant-based fibres.

etherification, and silane treatment) has been proven to be effective to improve the durability and degradation resistance of these lignocellulosic fibres, when they are used to produce durable engineering composites [92]. In the cementitious environment, modified sisal fibres that were coated with a graphene oxide-based membranes on their surface can be used to enhance the resistance to degradation [93]. However, the decomposition of plant-based fibres in asphalt mixtures needs more exploration for an appropriate solution, ensuring long-term durability improvement. Also, the cost and environmental issues of these chemical treatments or coating methods deserve a deep investigation. Another problem is the interfacial bonding between plant-based fibres and asphalt. The plant-based fibres with strong hydrophilic properties and the hydrophobic asphalt result in poor fibre adhesion. Apart from the surface modification on bamboo fibres using melamine–formaldehyde copolymer [60], treatment methods such as mercerization, acetylation and silylation are utilised to reduce the hydrophilicity of fibres and increase the adhesion properties [94]. Different from the origin of plant-based fibres, mineral fibres are derived from inorganic natural sources with a high thermal property. Among mineral fibres, the use of asbestos fibres has been diminished or banned due to health concerns [95]. The other type of mineral fibre, basalt fibre, is cost-effective and eco-friendly like plant-based fibres, and shows additional advantages in acid and alkali resistance and resilience to both high and low temperatures [96], becoming an excellent option in pavement engineering.

3.2. *Synthetic fibres*

Different from natural fibres that are derived from plants or animals, synthetic fibres are human-made materials through spinning, polymerization and filament processing [94]. Three major categories of synthetic fibres were considered by Rajak et al. [97]: organic fibres (polyamides, polyesters, polyolefins, etc,), inorganic fibres (glass, carbon, boron, etc.), and other fibres. Three main synthetic fibres (polypropylene, polyester and carbon fibres) and their application in asphalt mixtures are described in this section.

3.2.1. *Polypropylene fibres*

Due to the great advantages of low production cost, good dimensional stability, and excellent mechanical performance, polypropylene (PP) fibres are one of the most important components in construction materials today. The wide application of PP fibres as a reinforcing agent in concrete has been reported in many studies [98–100]. These fibres can improve the toughness and durability of concrete because of the three-dimensional reinforcement provided by their application [101]. Not just limited to the application in the concrete field, also the use of PP fibres in asphalt mixtures has been studied by many researchers.

As for the use of PP fibres in asphalt mixtures, the Ohio State Department of Transportation (ODoT) proposed specific technical guidelines for their applications in HMAs [102], including the mixing, compaction and production of the asphalt concrete with PP fibres. In the guidelines, the amount of PP fibres added into asphalt mixtures is approximately 2.7 kg/ton. In Tapkin's research [103], it was concluded that the PP fibres reinforced asphalt mixtures at the optimal binder content displayed increased Marshall stability, decreased flow value, prolonged fatigue life, and better resistance to rutting and reflection cracking. With the inclusion of 1% of PP fibres, Marshall stability and fatigue life of specimens increased by 58% and 27% respectively. The study also noted that the physical alteration of asphalt mixtures is related to the physical properties of PP fibres (specific gravity and size distribution), thus influencing the mechanical behaviour of asphalt mixtures. Different from this study based on the Marshall compaction method [103], Tapkin used gyratory compaction to prepare the PP fibre reinforced specimens in his following research [104]. The results from static creep tests, standard physical properties, Marshall stability and flow analyses showed that both compaction methods gave the same optimal content of PP fibres (0.55% by the weight of aggregates). With the gyratory compaction method, it was also found that the physical and mechanical properties were improved by adding fibres in asphalt mixtures. Bayat and Talatahari [105] discussed the impact of PP fibres with different lengths and amounts in the mix. The results of the Marshall stability and flow value showed that the optimal length and amount of PP fibres were 19 mm and 0.5% respectively. Apart from HMA, PP fibres with a short length of 10 mm and a 0.15% content by the weight of asphalt mixtures were also used in recycled foamed asphalt (RFA) mixtures [106]. RFA mixtures with fibres showed higher Marshall stability and indirect tensile strength, better permanent deformation resistance, and lower temperature susceptibility compared to the reference mixture without fibres. The rutting performance was also better than that of recycled hot-mix asphalt (RHMA) mixtures. Though the moisture susceptibility was improved by adding PP fibre, the indirect tensile strength (IDT) ratio was still low, around 30%. This is because the RFA mixture is susceptible to failure when subjected to water immersion, with an IDT ratio of 20%. In another study, Mohammed and Ismael [107] found that the addition of PP fibres can enhance the moisture susceptibility of asphalt mixtures according to the increase of Tensile Strength Ratio (TSR) and Index of Retained Strength (IRS) values. When 6% PP fibres on the weight of asphalt binder were used, the TSR was increased from 77% to 92%.

Considering the mixing methods of adding PP fibres in asphalt mixtures, two different procedures have been discussed by Habib et al. [108]. They are wet method (fibres are blended with asphalt first before being mixed with aggregates) and dry method (fibres are mixed with aggregates before the incorporation of the asphalt). When using the wet method, specimens displayed better performance regarding density, stability, and stiffness with the increasing content of fibres (1%, 2%, and 3% by the weight of asphalt). Results were different when using the dry method. Conversely, 1% of fibres with the dry method reinforced the mixture conferring better performance. The study also concluded that the wet method is preferred in terms of improving the stiffness of asphalt mixtures. This is because the fibres in the dry method play a similar role of aggregates in the mixture, without influencing the viscosity and rheological properties of the asphalt.

3.2.2. *Polyester fibres*

Another organic-based synthetic fibre, polyester, has also been widely used in asphalt mixtures as a reinforcing agent to enhance the resistance to fatigue and plastic deformation [109]. Wu et al. [110] reported the effects of polyester fibres on the rheological properties of asphalt binders and the fatigue performance of asphalt mixtures. The dry method was used to prepare modified asphalt mixtures. Decreased complex shear modulus and loss modulus of asphalt binders were observed with the increasing polyester fibre content, while no significant change in the phase angles among the binder samples with or without fibres. The results from the asphalt mixtures showed that 0.3% of polyester fibres (by weight of the asphalt mixture) led to the reduction of dynamic modulus and phase angle, thus decreasing the fatigue parameter. It means increased resistance to fatigue damage due to the addition of fibres. The fatigue resistance improvement can also be observed from the increasing cycles to failure, especially at low stress levels. Ye et al. [111] did the same dynamic modulus tests on fibre modified asphalt mixtures, and three different fibres (0.3% cellulose fibre, 0.3% polyester fibre, and 0.4% mineral fibre) were chosen. According to the results, all the fibre modified specimens displayed better fatigue performance than the control one, while the one with polyester fibres had the greatest improvement in fatigue resistance. Another study from Chen et al. [87] focused on the volumetric and mechanical properties of fibre-reinforced asphalt mixtures with four different fibres (polyester, polyacrylonitrile, lignin, and asbestos fibres). The inclusion of fibres led to the higher optimum asphalt content, air void, Void in Mineral Aggregate and Marshall stability, but lower specific gravity. With the fibre content increasing, optimal asphalt content, Marshall stability, and dynamic stability showed a rising trend first and then decreased. Among the four fibres, better stability was reported from the mixtures containing the polyester and polyacrylonitrile fibres because of their stronger network effect. Furthermore, higher optimal asphalt content and VFA (voids filled with asphalt) values were obtained in lignin and asbestos fibres samples due to their ability to absorb asphalt. With polyester fibres, the use of 0.35% by weight of aggregates was suggested in this study. According to Anurag et al. [112], polyester fibres also have a positive effect on enhancing the wet tensile strength and tensile strength ratio (TSR), as well as improving the stiffness in both dry and wet conditions. The application of polyester fibres has been also successfully verified in field sites [113,114]. One of the experimental applications promoted by the Pennsylvania Department of Transportation concluded that the resistance to reflective cracking can be improved by introducing polyester fibres [114].

3.2.3. Carbon fibres

As carbon fibres and asphalt (mainly hydrocarbons) are both carbon-based materials, the inherent compatibility is a great advantage compared to the use of other fibres in bituminous mixtures [17]. The high melting point and tensile strength of carbon fibres are also good advantages of using this type of fibre in asphalt mixtures. According to the different sizes of carbon fibres, the mixing methods are either wet or dry. The carbon nanofibres (CNFs) are usually blended with asphalt using the wet method [115], whereas the mixing of larger size (micro or macro) carbon fibres is normally made through the dry method [116].

The research conducted by Jahromi used the dry method to investigate the reinforcing effects of 12.5 mm and 20 mm carbon fibres on asphalt mixtures [117]. Expectedly, the incorporation of carbon fibres led to an increase in stability and air voids content, while a reduction of flow value was observed. With the optimum fibre content of 0.4% (by weight of total mix), the improvement in stiffness, resistance to permanent deformation and fatigue performance was the most significant. Besides, this study also noted that the length of fibres is a critical factor when using fibres in asphalt mixtures, considering the "balling" phenomenon caused by the clumping of fibres and uniform dispersity. Different from Jahromi's study, Nejad et al. [118] used the wet method to produce carbon fibre-reinforced asphalt mixtures. Various fibre lengths and contents were selected, then fatigue and Marshall tests were carried out to find the optimum length and content. The results showed that asphalt mixtures with 3 cm long carbon fibres with a content of 0.025% by weight of total mixtures have the best performance in fatigue resistance and Marshall stability. With these fibres, the carbon fibre-reinforced sample showed an increase of 24.5% in tensile stiffness modulus compared with the sample without fibres. The fatigue life of the fibre-reinforced samples was 2.4 times higher than the ones without fibres, and the resistance to permanent deformation also improved, especially at low temperatures. Another attractive point of using carbon fibres in asphalt mixtures is that they can improve the thermal and electrical conductivity to the pavement, which could be beneficial as a de-icing method for cold weather roads [119,120].

The different use of natural and synthetic fibres and their effect are summarized in Table 2. According to the summarized information in Table 2, the recommended content of added fibres is generally from 0.2% to 0.5% by the weight of the asphalt mixture. Some few research confirmed the effectiveness of using fibres with a content below 0.1% [82,118]. The Optimal Asphalt Content (OPC) for the hot mix is usually around 5% for dense-grade mixtures and around 6% for SMA. It is also found from Table 2 that the addition of fibres led to the higher OPC, but the alteration of Air Void (AV) content was not identical due to the different type of fibres. The reason for the reduction in AV content might the filling of voids by a minority of fibres [82]. The increased AV content could be the result of the fibres absorbing asphalt when adding fibres in asphalt mixtures, which provides a solution to the bleeding of the pavements in the hot regions [117]. The mechanical reinforcement due to the incorporation of fibres is also clear in Table 2. Considering that the asphalt, aggregates and mix design were different in the reviewed studies, the comparison of using different fibres to improve the mechanical properties of asphalt mixtures was not given.

3.3. Fibres from waste or by-products

Some discarded materials from industries can be seen as an origin of fibres, often identified as waste fibres. These materials are usually disposed of in landfills, increasing the demand for more landfill space and causing potential environmental problems. If fibres produced from waste materials could be effectively used, it will be both beneficial from an economic and environmental point-of-view. Some waste fibres have been applied in asphalt pavements to achieve this aim.

Putman and Amirkhanian explored the possibility of using waste tire and carpet fibres in SMA in their study [16]. Compared with cellulose and polyester fibres, the mixtures with waste tire and carpet fibres showed similar resistance to permanent deformation and moisture susceptibility. But waste tire and carpet fibres, as well as polyester fibres led to a higher increase in stiffness than cellulose fibres. Waste nylon wire is another source of fibres and its application in SMA mixtures was investigated by Yin and Wu [121]. The advantages of waste nylon wire include lower density and cost compared with inorganic fibres, while higher strength properties and better ability to disperse in asphalt mixtures than organic fibres. Results from this study demonstrated the positive impacts of using waste nylon wire, including improving the high temperature performance, cracking resistance at low temperatures and moisture susceptibility.

Cigarette butts (CBs) or cigarette filters (CFs) are one of the common wastes, which can be easily found in the industry. The cellulose fibres contained in CBs moved some researchers to investigate the use of CBs in asphalt pavements. Mohajerani et al. recently investigated the feasibility of using CBs in asphalt mixtures [122–124]. In their first attempt, CBs encapsulated with asphalt and paraffin wax were added into dense grade asphalt mixtures [122]. From the volumetric and mechanical tests, using the amount of 10 kg/m^3 and 15 kg/m^3 of CBs encapsulated with asphalt showed satisfying results, enabling the mixtures to meet the performance and requirements of road pavements for light, middle and heavy traffic conditions. But with the utilization of CBs encapsulated with paraffin wax at 10 kg/m^3, asphalt mixtures only met the demand for light traffic conditions. Mohajerani et al. further studied the application of asphalt encapsulated CBs in SMA [123]. In this study, asphalt encapsulated CBs were used to replace the coarse aggregates (1%, 2%, and 3% by weight). Results showed that the inclusion of up to 2% of asphalt encapsulated CBs can improve the stability and resistance to permanent deformation. The leachate test also indicated that the used encapsulation method can decrease the leaching of heavy metals by 96% on average. They also conducted a further study to explore the possibility of using CBs as a fibre modifier in asphalt [124]. To obtain modified asphalt, shredded CBs were blended with asphalt at the temperature of 160 °C and a rotation speed of 500 rpm. Test results showed that the penetration, softening point and viscosity values of asphalt were changed due to the incorporation of different amounts (0.2%, 0.3%

Table 2
Different use of natural and synthetic fibres in asphalt mixtures and their effects.

Reference	Fibre name and characteristics				Effects of fibres on asphalt mixtures (compared to mixtures without fibres)										
	Name	Length or recommended optimum length by authors	Diameter	Content or recommended optimum content by authors (by weight of mixture)	Optimal Asphalt content, OPC (%)	Air void (AV) content (%)	Marshall stability	Flow value	Moisture Susceptibility	Rutting performance	Cracking resistance	Freeze-thaw cycle durability	Fatigue performance	Drain-down property	Indirect tensile strength
[56]	Bamboo	6 ± 2 mm	20–60 μm	0.2–0.3% in dense-grade mixtures	5.21 (0.2% fibre), 5.31 (0.3% fibre)↑	4.1 (0.2% fibre), 4.0 (0.3% fibre)↓	↑	↑	↑	↑	↑	–	–	–	–
[57]	Bamboo	4–8 mm	15–20 μm	0.4% in dense-grade mixtures	5.3 in AC 13, 5.2 in AC 16	–	↑	–	–	–	↑	↑	↑	–	–
[65]	Coconut/coir	3–5 mm	0.2–0.6 mm	0.3% in SMA mixtures	Around 4	3↓	↑	↓	↑	–	–	–	↑	↑	↑
[66]	Coconut/coir	N/A	N/A	0.3% and 0.5% in SMA mixtures	6.8 (not stated whether it was OPC)	4.2 (0.3% fibre), 4.1 (0.5% fibre)↓	–	–	–	–	–	–	No significant impact	↑	–
[73]	Jute	N/A	N/A	0.5%	4.73↑	↓	↑	↓	–	–	–	–	–	–	–
[74]	Jute	7.5 mm	31 μm	0.5% in SMA mixtures	6.5	4	–	–	–	↑	–	–	–	↑	–
[82]	Sisal	15 mm	0.1–0.2 mm	0.05%	5.40↑	4↓	↓	↓	↑	–	–	–	↑	–	–
[83]	Sisal	10 mm	0.2 mm	0.3% in dense-grade mixtures and SMA mixtures	5.2 in dense-grade mixtures and 6 in SMA mixtures	4↓	↑	↓	↑	–	–	–	–	↑	↑
[84]	Sisal	8 mm	0.02–0.04 cm	0.3% in SMA mixtures	6.1	3.91↓	↑	↓	–	–	–	–	–	↑	↑
[103]	Polypropylene	10 ± 2 mm	N/A	0.3%, 0.5% and 1%	5.5	8.98 (0.3% fibre), 10.02 (0.5% fibre), 11.03 (1% fibre) ↑	↑	↓	–	↑	↑	–	↑	–	–
[105]	Polypropylene	19 mm	19 μm	0.5%	5	–	↑	↓	–	–	–	–	–	–	–
[106]	Polypropylene	10 ± 2 mm	N/A	0.15% in recycled foamed asphalt	7.8↑	–	↑	–	–	↑	–	–	–	–	↑
[110]	Polyester	6 mm	20 μm	0.3%	5.0	3.0	–	–	–	–	–	–	↑	–	–

(continued on next page)

Table 2 (*continued*)

Reference	Fibre name and characteristics				Effects of fibres on asphalt mixtures (compared to mixtures without fibres)										
	Name	Length or recommended optimum length by authors	Diameter	Content or recommended optimum content by authors (by weight of mixture)	Optimal Asphalt content, OPC (%)	Air void (AV) content (%)	Marshall stability	Flow value	Moisture Susceptibility	Rutting performance	Cracking resistance	Freeze-thaw cycle durability	Fatigue performance	Drain-down property	Indirect tensile strength
[87]	Polyester	6.35 mm	0,02 mm	0.35% in dense-grade mixtures	Around 4.63↑	Around 4.35↑	↑		↑	↑	–	–	–	–	–
[117]	Carbon	20 mm	7.5–7.8 µm	0.4%	5.9↑	Around 6↑	↑	↓	–	↑	–	–	↑	–	–
[118]	Carbon	1, 2 and 3 cm	8 µm	0.02%, 0.025% and 0.03%	5.7 (0.02% fibre), 5.75 (0.025% fibre), 5.8 (0.03% fibre) ↑	–	↑	–	–	↑	–	–	↑	–	–
[87]	Mineral (Asbestos)	5.5 mm	N/A	0.4%	Around 4.81↑	Around 4.30↑	↑	↑	↑	↑	–	–	–	–	–
[89]	Mineral (basalt)	1.5 mm	11–13 µm	0.3% in dense-grade mixtures	5↑	Around 4.38 ↑	↑	–	↑	↑	↑	–	–	–	–

"N/A" or "-": not available.
"↑": increase of value or improvement of performance compared to mixtures without fibres; "↓":decrease of value or negative effect on performance compared to mixtures without fibres.
Column "Optimal Asphalt content (%)" and "Air void content (%)": the corresponding values of the fibre reinforced asphalt mixtures are presented.
AC 13 or AC 16: the term "AC" is "Asphalt Concrete", "13" or "16" is the maximum particle size of aggregates.

Table 3
Different uses of waste fibres in asphalt and asphalt mixtures.

Type of waste fibres	Processing methods	Shape or dimension	Used content	Application
Tire and carpet fibres [16]	Tire fibres: from the cryogenic processing of scrap tires; carpet fibres: torn into smaller tufts	Tire fibres: from 3 to 13 mm in length; carpet fibres: like smaller tufts of mineral fibres	0.3% by weight of total mixture	In SMA: Comparable resistance to permanent deformation and moisture susceptibility, compared with cellulose and polyester fibres.
Nylon wire [121]	N/A	Length: 20 mm, diameter: 0.2 mm	0.5%, 1.0%, 1.5%, and 2.0% by weight of total mixture mass of asphalt mixtures	In SMA: Adding waste nylon wire can improve the high temperature performance, cracking resistance at low temperatures and moisture susceptibility.
Cigarette butts (CBs) [122]	CBs were dried and then encapsulated with asphalt and paraffin wax	Original shape of the waste CBs	CBs encapsulated with asphalt: 10 kg/m^3 and 15 kg/m^3; CBs encapsulated with paraffin wax: 10 kg/m^3	In Dense-grade mixtures: CBs encapsulated with asphalt: meet light, middle and heavy traffic conditions. CBs encapsulated with paraffin wax: only meet light traffic conditions.
Cigarette butts (CBs) [123]	CBs were dried and then encapsulated with asphalt	Original shape of the waste CBs	Replace the coarse aggregates (1%, 2%, and 3% by weight).	In SMA: 2% of encapsulated CBs can improve the stability and resistance to permanent deformation. The encapsulation method can decrease the leaching of heavy metals by 96% averagely.
Cigarette butts (CBs) [124]	CBs were dried and then shredded before removing the tobacco.	Ground fibre	0.2%, 0.3% 0.4%, and 0.5% by weight of asphalt	As a fibre modifier in asphalt: Improving physical and rheological properties of asphalt.
Single-use face masks [31]	Disinfection, removal of the nose metal strips and ear-loops, melting, cooling, then being shredded into particles	Size of shredded particle size: 40x5 mm	0.25%, 0.5%, 0.75%, 1%, 1.25%, and 1.5% by weight of the mixtures	In HMA: Increased stiffness, rutting resistance and the adhesion between aggregates.

0.4%, and 0.5%) of shredded CBs. The results concluded that the CBs can be used as a fibre modifier because of the improved physical and rheological properties of asphalt containing CBs. 0.3% shredded CBs can be used to modify asphalt without compromising the performance required during the construction of asphalt pavements. Different from this study [124], Tataranni and Sangiorgi evaluated the use of shredded electronic CFs in SMA and made a comparison with cellulose fibres [7]. Results confirmed the possibility of using shredded electronic CFs as stabilizing fibres in SMAs. The authors suggested that using waste CFs could be a valid recycling approach based on the positive outcomes obtained with new shredded CFs. In this way, a sustainable alternative to cellulose fibres can be used and promoted as paving material.

The plastic waste pollution from the increasing use of single-use face masks due to the Covid-19 pandemic is also a serious and current environmental issue. Wang et al. [31] made an attempt to recycle this type of waste in asphalt pavements, since the polypropylene (PP) fibres from the masks can be used as an additive in asphalt mixtures. Brand new masks were used in this study. The following procedures were conducted before adding masks into HMA: simulation of disinfection, removal of the nose metal strips and ear-loops; melting process and following cooling at ambient temperature. Once hardened, the masks were shredded into particles (40 × 5 mm). Then, various contents of shredded face masks (SFM) were used to produce asphalt mixtures. From the results, the resistance to rutting was improved with the SFM content rising. Moreover, the stiffness of mixtures and the adhesion between aggregates were enhanced due to the addition of SFM. This preliminary research also proposed the future direction of the study, such as increasing the contents of face masks, and evaluating other mechanical properties.

Table 3 concluded the different uses of waste fibres in asphalt and asphalt mixtures. The origins of the waste fibres should be considered when designing and adopting the processing methods to collect usable fibres. Fig. 3 displayed some waste materials after the processing procedures. Like natural and synthetic fibres, the content of waste fibres can be around 0.2%–0.5% when they are used to reinforce asphalt mixtures. Apart from the encapsulated CBs that were used to replace aggregates, the application of other waste fibres can be considered a potential alternative for the frequently used natural or synthetic fibres. More aspects of using waste fibres need to be further explored, such as their processing methods, the determination of their dosages in asphalt mixtures, and the environmental effects.

3.4. Significant variables when using fibres in asphalt pavements

According to the application of various fibres in bituminous mixtures discussed in previous sections, the method of mixing fibres and asphalt and the dimensions of fibres are usually considered. This section refers to these two main variables that influence the effectiveness of using fibres.

3.4.1. Mixing method

As discussed in the previous parts, the mixing methods of adding fibres into asphalt mixtures can be different. Regarding how to introduce fibres into asphalt mixtures, no specific standards were proposed so far [125]. The mixing methods can be classified into the wet process and dry process, which have been briefly described in the aforementioned part. In the wet process, the fibre is incorporated into asphalt biners before the mixing of asphalt and aggregates. To ensure the uniformity of the blended binders without the presence of clumps or aggregation, the melting point of the selected fibres is required to be lower than the adopted temperature during the blending. Thus, the wet method is more suitable for the application of some synthetic fibres with melting points below 160 °C like low-density polyethylene (LDPE), high-density polyethylene (HDPE) and polypropylene (PP) fibres [126]. The wet method can also be effectively used for nano-sized fibres, such as carbon nano-fibres, as incorporating carbon nano-fibres via wet method can achieve a uniform dispersion between fibres and asphalt [115]. The major goal of using the wet method is to bring rheological modification. It was reported that fibres can influence the rheological parameters of frequency sweep tests and rutting parameters, resulting in improved permanent deformation resistance and elasticity of asphalt [127]. Like other modifiers (such as crumb rubber and polymers), the main concern is to determine and control the mixing temperature, time and shear speed as it is extremely critical to the properties of the final resulting binders. Insufficient blending or unmolten fibres in the asphalt cause clumps or aggregation and the higher mixing temperature leads to the aging of asphalt. Bellatrache et al. also demonstrated that the longer mixing time and higher shearing speed contribute to the increased

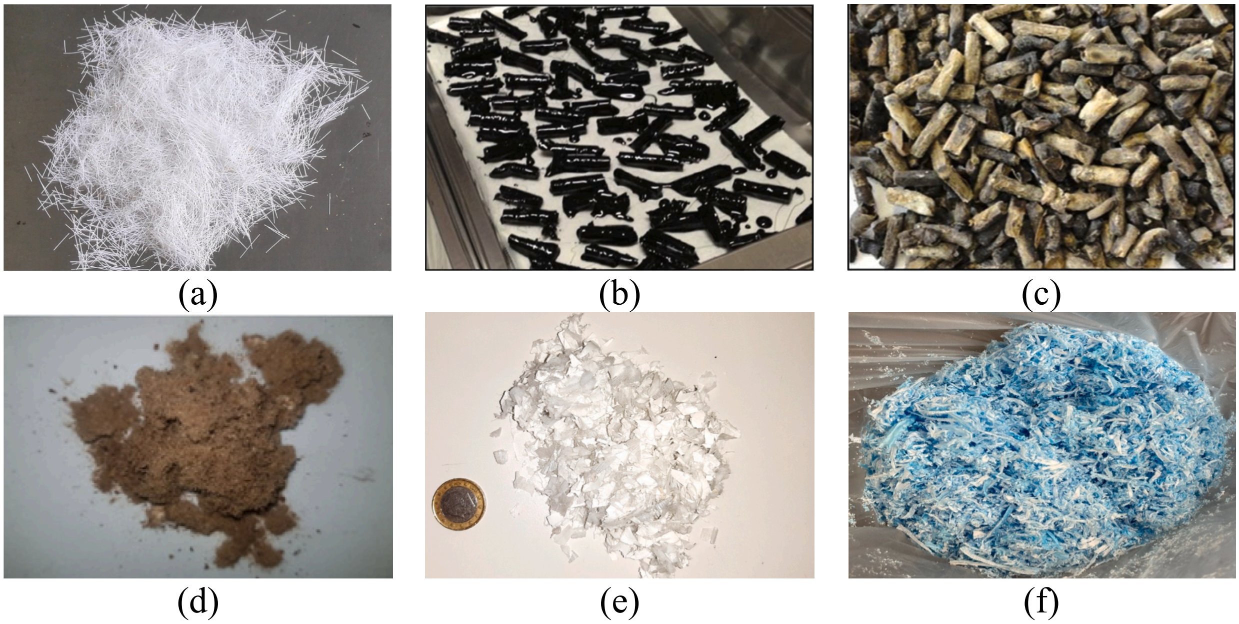

Fig. 3. Processed waste fibre materials used for asphalt and asphalt mixtures: (a) waste nylon wire [121]; (b) asphalt encapsulated CBs [122]; (c) paraffin wax encapsulated CBs [122]; (d) shredded CBs [124]; (e) shredded new CBs [7]; (f) shredded single-use face masks [31].

stiffness of the binders [128]. In their research, with the same mixing time of 30 min, the increase of the shear speed from 600 rpm to 1200 rpm led to decreased penetration and increased softening point. The penetration and softening point can be maintained at a stable level when the blending time was increased to 60 min. This is because the asphalt was exposed to air and the volatile components were evaporating during the blending. The dimension and the amount of fibres can be important factors affecting the formation of a homogenous blending [129]. Storage stability is also an issue deserving of attention for the use of modified asphalt, especially using plastic fibre as a modifier. It was reported that recycled PP with a content less than 2% can meet the stability requirement under mild agitation, while for recycled HDPE and LDPE, the proposed contents were below 4% and below 6% respectively [130].

In the dry process, fibres are mixed with aggregates before the asphalt is added into the blend. Unlike the fibre modified asphalt, the fibres are not required to be melted in mixtures when adding fibres into asphalt mixtures with the dry method. The dry method is preferably used due to the following advantages: easier operation during production, better distribution of fibres in the asphalt mixture, and minimized issues of clumping or balling of fibres in the mixture [17,131]. Like using the wet method, the key point is to obtain a homogenous mix which requires the fibres to be distributed uniformly in the asphalt mixtures. To reduce the aggregation of fibres in the asphalt mixtures, Pirmohammad et al. adopted a procedure of adding fibres into asphalt mixtures after the aggregates coated by asphalt biners and then mixing for 5 min, but the longer fibres (above16 mm) or the higher dosages (above 0.4%) is negative to the distribution of fibres [132]. To guarantee sufficient adhesion to the asphalt and avoid stripping issues due to the introduced water, the critical point is to make sure that the fibres are correctly dried [133,134]. As introduced before, the surface modification and chemical treatment of plant-based fibres are also useful in terms of the adhesion improvement. In Table 4, the advantages, disadvantages, and applicable conditions of the wet and dry methods are summarized.

3.4.2. Fibres dimensions

The size (length, diameter) and length/diameter ratio of fibres also have a great influence on the final performance of asphalt mixtures [135–138]. Compared to the diameter of fibres, length is more often discussed in studies, as the diameter is normally provided by the manufacturers and depends on specific industrial procedures [24,139]. Fibres with excessive length might lead to the "balling" issue (lumps of fibres), which is detrimental to the adequate mixing with asphalt, thus causing adverse effects on the stability and reinforcing properties. Relatively shorter fibres do harm to the uniform distribution, leading to the formation of agglomerations. Through the literature review of natural and synthetic fibres, the frequently used fibre length is from 5 to 20 mm, among which the lengths from 5 to 10 mm are more commonly used. To determine the optimum fibre length, Guo et al. conducted the mesh-basket drain down test and cone penetration test on the use of different lengths (6, 9, and 15 mm) of basalt fibre [24]. The results showed that 6 mm basalt fibre was the optimal option. In another study by Wang et al. [139], the use of chopped basalt fibres with different contents (3% and 4%) and lengths (3, 6, 9, and 12 mm)) in porous asphalt mixture was evaluated via drain-down test and a series of mechanical tests. Based on the results, the recommended dosage and length for chopped basalt fibres are 0.3% and 9 mm respectively.

The length/diameter ratio (also called aspect ratio) is another important index that influences the mechanical properties, low temperature performance and moisture sensitivity [26,138,140,141]. The increasing of the aspect ratio is beneficial for the formation of the network, improving the cohesion between aggregates and bituminous mastic [135,138]. Xu et al. [138] compared the use of four types of fibres (polyester, polyacrylonitrile, lignin and asbestos) in asphalt concrete. It was reported that the use of polymer fibres (polyester and polyacrylonitrile) has better improvement in rutting performance, fatigue life and split indirect tensile strength compared with the other two fibres. This is because of the higher aspect ratios and tensile strength of the polymer fibres (see Table 5), improving the networking function when they were incorporated in asphalt mixtures. Zhang et al. found that with the increasing aspect ratios (20, 30, 40, and 50), the viscoelastic equivalent creep behaviour of basalt fibre-reinforced asphalt mixtures can be improved [142]. At the aspect ratio of 50, viscoelastic parameters in the IDT (indirect tensile) mesostructural specimen model showed the highest value.

3.5. Reinforcing mechanism of fibres in asphalt materials

The reinforcing mechanism is also a significant aspect of studying the use of fibres in asphalt pavements. The macro experimental techniques

Table 4
Advantages, disadvantages and applicable conditions of two mixing methods of incorporating fibres.

Mixing methods	Advantages	Disadvantages	applicable conditions
Wet method	Bring rheological modification (improved permanent deformation resistance and elasticity of asphalt).	Uniformity issue of the blend (clumps or agglomerations); the determination of mixing conditions (time, temperature, and shear speed); storage stability.	Working as an asphalt modifier; synthetic fibres are more preferred.
Dry method	Improve the stabilizing effect; reinforcing the mechanical properties; easier operation, better distribution of fibres in the asphalt mixture, and minimized issues of clumping or balling of fibres in the mixture.	The adhesion issue, especially when using plant-based fibres.	Working as a stabilizer or reinforcing agent to the asphalt mixture.

are widely used for the mechanical characterization of reinforcing effects, while the testing methods on the micro or nano scale are effectively utilized for the understanding of the reinforcing mechanism. SEM microstructures of lignin, basalt, asbestos, polyester, and polyacrylonitrile fibre are shown in Fig. 4. The microstructure of fibres and fibre-modified asphalt can be characterized by SEM. Fibres like basalt and asbestos with round shapes and smooth surfaces are not able to absorb asphalt binders [23,143], while lignin fibre which has more surface areas due to the porous structure shows high absorption property [143]. The surface area size relating to the absorption closely has a significant influence on the adhesion property. The mesh-basket draindown test reported the lowest results of the lignin fibre compared with asbestos fibre, polyester fibre, and polyacrylonitrile fibre [143]. This result can relate to the surface area found in SEM tests, indicating that the higher surface areas contribute to higher asphalt absorption. Not like lignin fibres, the improvement in stabilizing effect and interface adhesion by adding polyester fibres is explained by the spatial network effect. The antenna features of polyester fibres provide stronger connections and joints which is beneficial to the formation of spatial network. The three-dimensional network in the asphalt mix consequently contributes to the stronger mastic coating and enhances the cracking resistance [143]. The distribution of fibres in the asphalt also can be detected using SEM, helping to analyse the mixing efficiency or state [23]. Apart from the physical characterization of the microstructure of fibres, the mechanical properties of fibres can help to understand the reinforcing mechanism. Xing et al. explained that the reinforcing effect of aramid fibres is attributed to the high strength and modulus and the network structure formed by adding this fibre [144]. Chen and Qin et al. also explained the mechanism using the three-dimensional network [90,135]. Another identification method, X-ray CT scanning was used by Long et al. to investigate the action mechanism of basalt fibres in hydraulic asphalt concrete [145]. They studied the effect of fibre length and contents on the porosity property of the asphalt concrete. It is reported that the negative effect of the higher porosity was significant when the fibre content increased from 0.3% to 0.4%. The excessive amount of fibre led to the aggregation of fibres and the surface area of fibres cannot be sufficiently used to absorb asphalt binders. Such phenomenon resulted in the decreased bonding ability between materials, then the increased porosity weakened the bridging and stress dispersing function of using fibres in asphalt concrete.

Numerical simulation or modelling is also an efficient tool for exploring the reinforcing mechanism of fibres. Zhang et al. used ABAQUS software to construct a two-composite model containing fibres and mastic matrices and simulate the shear creep test [146]. The creep behavior of the mastic model was analyzed based on the Burgers model. Simulation results from the displacement contour of the FAM model showed that the overall displacement of the mastic was reduced with the addition of fibre. According to the stress contour of the FAM model, the incorporation of fibres led to the decrease of the stress value of the edge part and a shift of stress concentration to the fibre region of the model, implying that fibre is capable of absorbing the stress that appeared in the mastic. These phenomena are in line with laboratory testing. For the effect of testing temperature, fibre content and its modulus on the viscoelastic parameters of materials, the temperature can make a significant difference, then fibre content, followed by the modulus. Furthermore, a three-dimensional model constructed by the finite element model (FEM) method can be used to predict the rutting behavior of cold mix asphalt (CMA) mixtures with two natural fibres (jute and coir fibre), based on the viscoelastic response of CMA subjected to different temperatures and stress conditions [147]. In another study by Cheng et al., three-dimensional models were used to analyze the influence of fibre dispersion and distribution on the flexural tensile property of the asphalt mixtures. The simulation results show that the well-dispersed basalt fibres led to lower peak tensile stress of the asphalt mixture beam, while the poor dispersion of fibres with larger size of fibre bundles increased the peak stress. For the spatial distribution of basalt fibres, the effect of the horizontal distribution on the tensile property was more significant compared to the vertical distribution. These studies confirmed the effective use of simulation methods that can help strengthen the understanding of the function and reinforcing mechanism of fibres in asphalt materials. Relevant research works need to be further conducted, especially the in-depth analysis of the interfacial bonding, adhesion property, and cracking behavior with the assistance of simulation techniques.

Table 5
Aspect ratios and tensile strength of the used fibres in the research by Xu et al. [138].

Fibre types	Aspect ratio	Tensile strength (MPa)
Polyester fibre	300	531
Polyacrylonitrile fibre	385	>910
Lignin fibre	24	–
Asbestos fibre	–	30–40

4. Combined uses of fibres and other materials in asphalt mixtures

4.1. Fibres and rejuvenator used in RAP (Reclaimed asphalt Pavement)

The recycling of RAP for the production of new bituminous mixtures shows great benefits like decreasing the cost of raw materials, addressing the problem of disposing of a large quantity of RAP, and making the road more sustainable. The issues of using higher contents of RAP should be also considered, such as the cracking and the poor low temperature performance because of the higher stiffness of aged asphalt from the RAP [148]. The addition of fibres can be a good solution to this problem. Ziari et al. [149] investigated the crack resistance of HMA containing different contents of RAP, rejuvenator, and glass fibre. It was found that the inclusion of 0.12% glass fibres led to a great improvement in crack resistance. This amount of glass fibres was also suitable for the mixtures containing 100% RAP because no significant decrease in cracking resistance was found from the semi-circular bending (SCB) Fracture tests. Metal fibres have also been applied in asphalt mixtures containing RAP [150]. Apart from the possible increase of the air void content, the incorporation of metal fibres can enhance the crack-healing ability of asphalt mixtures through induction heating.

In WMA mixtures with a larger amount of RAP, adding glass fibres

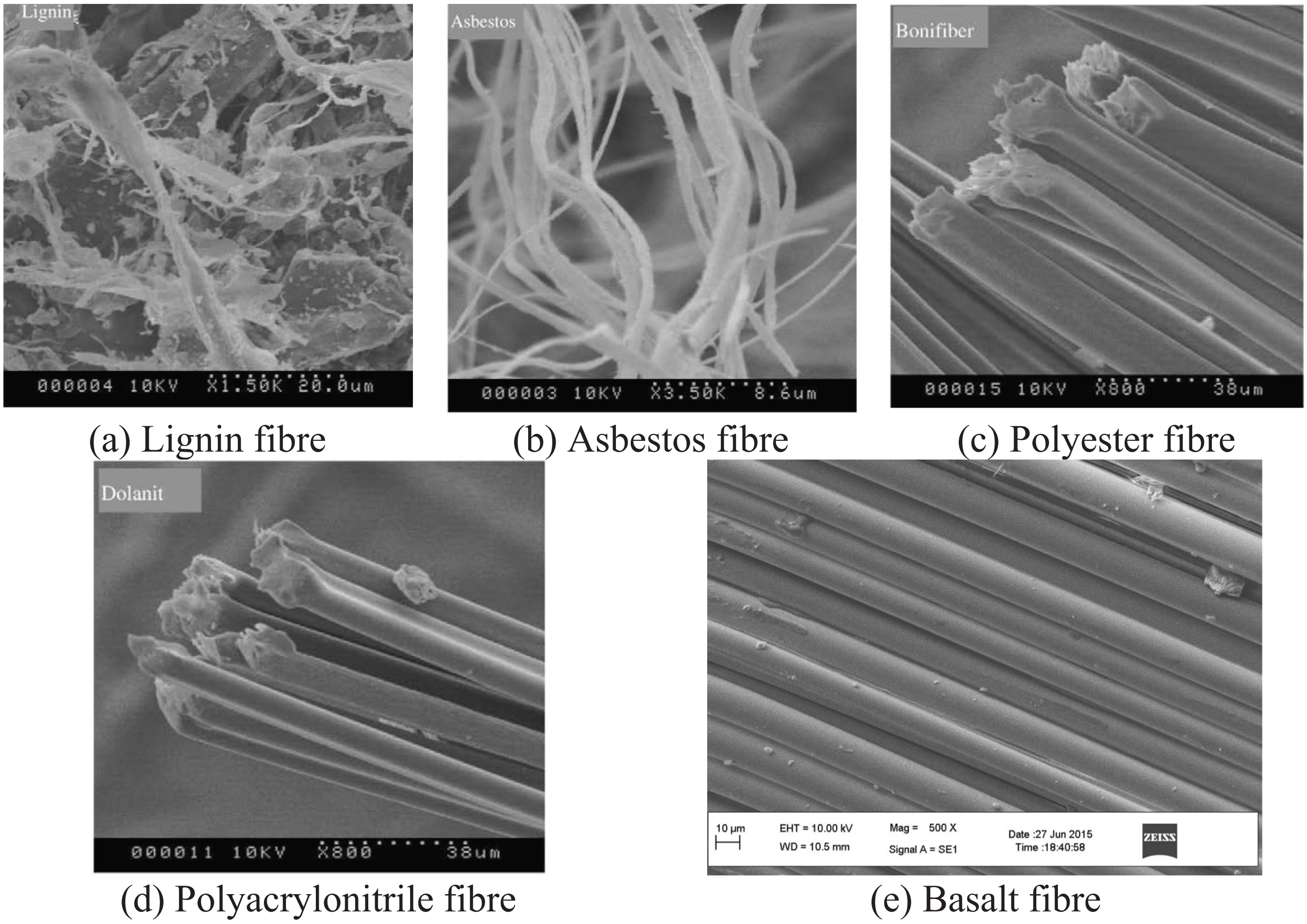

Fig. 4. SEM micro-structures of lignin, basalt, asbestos, polyester, and polyacrylonitrile fibre [23,143].

can also improve the resistance to rutting and water susceptibility [151]. CMA mixtures mixed with RAP are recognized to have significant benefits including saving energy consumption, decreasing construction costs, and reducing the environmental effects of pavement maintenance and repair [152]. Du investigated the impacts of five different fibres (polyester, polypropylene, polyacrylonitrile, lignin, and basalt fibres) on the performance of cold recycled mixtures with asphalt emulsion [153]. The inclusion of different fibres was reported to influence the optimum pre-mixing water (OPW) content and optimum emulsion content (OEC) of cold recycled mixtures. With fibre content increasing, the OPW and OEC increased due to the enlarged surface area of emulsion recycled mixtures. Among these fibres, polyester fibre shows the greatest effect in enhancing the fatigue life of mixtures and is recommended as the best solution for improving the performance of cold recycled mixtures with asphalt emulsion.

4.2. Fibres and other modifiers used in asphalt mixtures

In some studies, fibres and other modifiers including recycled crumb rubber modifier (CRM), and styrene butadiene styrene (SBS) have been applied in asphalt mixtures to combine the advantages of each additive. CRM is obtained from waste tire rubber and has been used as an effective modifier in asphalt for above 50 years [10]. Using CRM as an asphalt modifier has significant advantages including increasing the service life and durability of asphalt pavement, replacing part of asphalt, and recycling the waste tires to achieve better sustainability of roads [154]. Oda et al. [66] investigated the use of natural fibres and rubberized asphalt (containing 20% of ground tire rubber) in SMA. The results demonstrated that the employed natural fibres (coconut and sisal) worked better than cellulose and polyester fibres in improving the draindown property. In terms of fatigue tests, SMA mixtures made of asphalt rubber binder and with no fibres showed the best results, while the effect of fibres was not obvious. In another research, Wang et al. [155] explored the effect of adding eco-friendly diatomite and basalt fibre in waste crumb rubber modified asphalt mixtures. Same as in Oda's study [66], the mixing of rubber was done through the wet process, i.e., the crumb rubber was mixed with asphalt first at high shear speed. The diatomite used in this study was a nature-based inorganic modifier with good adsorption property and high micro-porosity. Results displayed superior performance of crumb rubber modified asphalt with diatomite and basalt fibres, including rutting resistance, low-temperature cracking resistance splitting, and water susceptibility. Furthermore, noise and vibration absorption properties were registered for the experimental mixtures. This could be attributed to the microporous structure of diatomite and to the spatial network structure formed by basalt fibres, which was also beneficial in terms of reinforcing effect.

The commonly used polymer-modified asphalt mixture can also be reinforced with fibres. The investigation carried out by Ho et al. [156] focused on the comparison between the performance of polymer-modified asphalt concrete (PMAC) and fibre-reinforced polymer-modified asphalt concrete (FPMAC) via laboratory tests and field evaluations. The fibre used in SMA was a synthetic fibre blend containing polyolefin and aramid. Among them, polyolefin fibre can melt during the production of asphalt mixtures while the unmelted aramid fibres are able to create a three-dimensional structure reinforcing the tensile strength of the final mixture. Better results could be seen in the FPMAC samples based on the thermal cracking and dynamic modulus testing data. Most importantly, FPMAC showed less amount of cracks than PMAC during the two-year monitoring. The improvement of thermal cracking properties was related to the melted and plastically deformed polyolefin fibres during the production of FPMAC, which resulted in a higher relaxation modulus. Besides, with the fibre addition, FPMAC showed good abilities in freeze–thaw cycling and rutting resistance. Specifically, the unmelted aramid fibres offered three-dimensional reinforcement that improved rutting resistance and higher dynamic modulus. Wang et al. [157] used two compaction methods (Superpave gyratory compaction (SGC) and Marshall) to prepare SBS modified SMA mixtures with basalt fibres, and then evaluated their performance. Results from the asphalt binder tests demonstrated that the addition of basalt fibre led to an improvement in shear strength and viscosity, while a slight reduction of force ductility. The reason could be the spatial network structure formed by the incorporation of basalt fibres. It was also concluded that the SGC method was more appropriate for preparing SBS modified samples with basalt fibres, showing better workability and mechanical properties.

Recently, different composite fibres like asphalt-treated fibres, polymer-added fibres and rubberized fibres have been developed [158]. In this way, fibres acted as conveyors for asphalt modifiers to provide better absorption to binders. In terms of binder absorption, cellulose based-fibres are preferred when compared with mineral ones [135,159]. In the research work conducted by Eskandarsefat et al. [158], four novel composite cellulose-based poly-functional fibres with and without a plastomeric polymer and crumb rubber content were explored, which are listed in Table 6. It was found that adding rubber can decrease the softening point and viscosity and increase the penetration. Rheological data suggested that the presence of rubber in the modified fibres led to lower stiffness and higher elasticity for SBS Polymer modified Bitumen (PmB). Though the results demonstrated the advantages of the method of adding rubber through fibres to produce rubberized asphalt mixtures, some critical aspects such as the percentages of each component within the composite modified fibres, and the selection of modifiers and fibres should be considered.

Table 6
The composition of four novel composite cellulose-based poly-functional fibres [158].

Number	Components
1	Cellulose + glass fibre
2	Rubberized cellulose + glass fibre
3	Cellulose + Glass + Plastomeric polymer
4	Rubberized cellulose + glass fibre + Plastomeric polymer fibre

Apart from the above-mentioned modifiers, fibres have also been used with nanomaterials and antistripping agents in some studies [29,30]. The research conducted by Fu et al. [29] investigated the composite-modified asphalt binders with the combination use of basalt fibres and nano-TiO_2/ZnO. The analysis of FTIR (Fourier-transform infrared spectroscopy) tests identified that no chemical reaction was developed among asphalt binder, basalt fibre, and nano-TiO_2/ZnO modifier, and the modification effect was mainly in terms of physical change. A uniform distribution of nanoparticles and network structure formed by fibres can prevent the development of internal microcracks. According to mechanical tests, it was found that this composite-modified asphalt binder had great improvements in rutting resistance and fatigue life before aging or after different laboratory aging conditions (short-term, long-term, and ultraviolet). Fu et al. concluded that the optimal contents for basalt fibres and nano-TiO_2/ZnO were 6% and 4% by weight of asphalt binders. Double use of an anti-rutting agent and lignin fibre in asphalt mixtures also showed great potential in improving the dynamic stability, rutting resistance, low-temperature performance, and moisture stability, especially when using 0.40% anti-rutting agent and 0.36% lignin fibre [30].

Table 7 summarized the combination use of Fibres and other modifiers in asphalt mixtures. The common way of combining fibre and another modifier into the same mixtures is the modifier like rubber or SBS is modified with asphalt first and then modified asphalt is added into the mix of fibre and aggregates. Compared to this way, the method of using fibre to convey asphalt modifiers into the asphalt binders was unique, which requires the fibres to be pre-treated with the incorporation of polymers or rubbers. However, more work needs to be conducted to evaluate this type of pre-treated or composite fibres, like the storage ability of the asphalt after the modification of this fibre and the distribution of fibres in asphalt mixtures.

Table 7
Combination use of Fibres and other modifiers in asphalt mixtures.

Reference	Fibre type	Fibre content	Other modifiers	Mixing methods	Effects
[66]	Coconut, sisal, polyester, and cellulose fibre	0.3% and 0.5% on the weight of mixtures	Rubber	Rubber: wet method Fibre: dry method	Natural fibres led to improved drain-down property than cellulose and polyester fibres; no significant effect on the fatigue performance was recorded.
[155]	Basalt fibre	0.3% on the weight of mixtures	Crumb rubber	Rubber: wet method Fibre: dry method	Improve the rutting resistance, low-temperature cracking resistance splitting, and water susceptibility; fibres contribute to the formation of network structure, bringing noise and vibration absorption properties.
[156]	A synthetic fibre blend containing polyolefin and aramid.	–	polymer	–	Fibres enhanced the abilities to resist thermal cracking, freeze–thaw cycling, and rutting deformation.
[157]	Basalt Fibre	Into asphalt: not given; into asphalt mixture: 0.34% on the weight of mixtures	SBS	SBS: wet method Fibre: wet and dry method	To asphalt: higher shear strength and viscosity. To asphalt mixtures: better workability and mechanical properties.
[158]	Cellulose and glass fibre	7.5% on the weight of asphalt	Plastomeric polymer and waste tire rubber	Wet method: Composite fibres containing other modifiers were prepared before adding fibres into asphalt	Composite fibres containing rubber increased the penetration and elasticity, decreased the softening point, viscosity and stiffness.
[29]	Basalt fibre	6% on the weight of asphalt	Nano-TiO2/ZnO	Wet method: asphalt was mixed with nano-TiO2/ZnO first, then fibres were added into the blend	No chemical reaction was developed among asphalt, fibre, and the modifier. Great improvements in rutting resistance and fatigue life.
[30]	Lignin fibre	0.36% on the weight of mixtures	Anti-rutting agent	Anti-rutting agent: dry method Fibre: dry method	Great improvement in dynamic stability, rutting resistance, low-temperature performance, and moisture stability.

5. Conclusions

This article aims to review the different applications of various fibres in asphalt pavements and their impacts on asphalt binders and mixtures. Two main categories of fibres (natural and synthetic ones) are summarized in detail, with a specific focus on the use of fibres from waste and by-products, being a current topic considering their related environmental advantages. Furthermore, different variables that influence the use and performance of fibres in asphalt pavements are discussed. Then the importance of exploring the fibre-reinforcing mechanism is highlighted. The combined use of fibres with other materials including RAP, rejuvenators, polymer modifiers, and nano-modifiers is also reviewed in this paper.

The following critical conclusions can be inferred in light of the considered literature:

- The use of fibre as a construction material has a long history since the earliest use was in a 4000-year-old arch constructed with clay earth. Currently, fibres are widely used as a significant component in concrete, earth materials, blocks and bricks, and asphalt materials. Various uses of fibres in asphalt pavements have been investigated and are still worth being explored in the long run.
- From the review of natural and synthetic fibres used in asphalt mixtures, fibres can work as a stabilizer, preventing or reducing asphalt leakage and increasing the binder content in the mix design. Fibre is also an excellent reinforcing additive, improving the rutting performance, water sensitivity, low-temperature and reflective cracking resistance, freeze–thaw resistance, fatigue life, and overall durability of the asphalt mixture. The reinforcing effects are related to the characteristics of fibres and the formed network due to the addition of fibres.
- Though natural fibres have clear environmental benefits and are cost-saving in production, the thermal degradation or decomposition of plant-based fibres should be considered when using them. The chemical treatment or coating methods of plant-based fibres could be a good solution, but the evaluation of the resulting cost and environmental effects cannot be ignored.
- Using fibres from waste and by-products is attracting many researchers considering the value of recyclability and sustainability. Useable fibres obtained from the waste materials including waste tire and carpet, waste nylon, waste cigarette butts, and waste face masks showed great potential for substituting the normal fibres in terms of modifying asphalt or reinforcing the asphalt mixtures. Simultaneously, incorporating recycled materials brings environmental-friendly benefits to pavement engineering. But more work needs to be focused on waste materials processing methods and the determination of optimal fibre content.
- The mixing process of adding fibres and their size are important factors during their application in asphalt mixtures. The dry method brings simplified operating procedures during production and is also better for the distribution of fibres in mixtures, while the wet method is widely used to modify the physical and rheological properties of asphalt. In terms of size, length is a more critical parameter than diameter. To make the selected fibre work effectively, optimal length and content should be determined based on relevant experiments.
- Micro or nano identification techniques like SEM and CT are effective tools to investigate the reinforcing mechanism of fibres in asphalt materials. Additionally, with the utilization of numerical simulation, the understanding of how fibres reinforce asphalt materials can be strengthened, which is beneficial to the optimization of using fibres in asphalt pavement.
- Positive effects of using fibres combined with other materials have also been observed. This represents an innovative use of fibres, considering their function as conveyors for different additives. Fibres can improve the cracking resistance when used with RAP, solving the issues caused by the brittleness of aged asphalt. With other modifiers like crumb rubber, SBS, nano-particles, and anti-rutting agent, fibres can exert reinforcing effects, modifying the rheological properties of the asphalt.

For future studies, it is suggested to develop the various use of different waste fibres in asphalt mixtures and seek the best replacement for normal fibres. This follows the "3R (Reduce, Reuse, Recycle)" concept, making the road more sustainable. Furthermore, the study and evaluation of a new generation of fibres that act as conveyors for additives with different functions and purposes represent the emerging state of the current research that will be implemented and developed in the following years.

CRediT authorship contribution statement

Yunfei Guo: Writing – original draft. **Piergiorgio Tataranni:** Writing – review & editing. **Cesare Sangiorgi:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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