Biomass valorization toward sustainable asphalt pavements: progress and prospects

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Abstract: To cope with the global climate crisis and assist in achieving the carbon neutrality, the use of biomass materials to replace fully or partially petroleum-based products and unrenewable resources is expected to become a new solution. Based on the analysis of the existing literature, this paper firstly classified the biomass materials with potential application prospects in pavement engineering according to the application form and summarized their respective preparation methods and characteristics. The pavement performance of asphalt mixtures with biomass materials was analyzed and summarized, and the economic and environmental benefits of bio-asphalt binder was evaluated. The analysis shows that pavement biomass materials with potential for practical application can be divided into three categories: bio-oil, bio-fiber, and bio-filler. Adding bio-oil to modify or extend the base asphalt binder can mostly improve the low temperature performance of asphalt binder. Adding styrene-butadiene-styrene (SBS) or other preferable bio-components for composite modification will have a further improved effect. Most of the asphalt mixtures prepared by using bio-oil modified asphalt binders have improved the low temperature crack resistance and fatigue resistance of asphalt mixtures, but the high temperature stability and water stability may decrease. Adding bio-fiber could significantly improve the high temperature stability, low temperature crack resistance and water stability of asphalt mixtures. There are relatively few studies on bio-fillers, and some bio-fillers can improve the high temperature stability and fatigue resistance of asphalt binders. Through calculation, it is found that the cost performance of bio-asphalt has the ability to surpass the ordinary asphalt and has better economic benefits. The use of biomass materials for pavement not only reduces pollutants, but also reduces the dependence on petroleum-based products. It has extremely high environmental benefits and development potential.

Key words: asphalt pavement; biomass material; bio-oil; bio-fiber; bio-filler

Contents

List of abbreviations

SBS	Styrene-Butadiene-Styrene
SLR	Systematic Literature Review
CNKI	China National Knowledge Infrastructure
OGFC	Open Graded Friction Course
HHV	Higher Heating Value
HTL	Hydrothermal liquefaction
MSCR	Multiple Stress Creep Recovery
BBR	Bending Beam Rheometer
DSR	Dynamic Shear Rheometer
SCB	Semi-circular Bending

TSRST	Thermal Stress Restrained Specimen Test
BHT	2,6-Di-tert-butyl-4-methylphenol
SMA	Stone Mastic Asphalt
OBC	Optimum Binder Content
TSR	Tensile Strength Ratio
IRS	Immersion Residual Stability
ITS	Indirect Tensile Strength
HL	Hydrated Lime
RHA	Rice Husk Ash
IPCC	Intergovernmental Panel on Climate Change
C	Carbon
Ca	Calcium
Cu	Copper
K	Potassium
N	Nitrogen
S	Sulphur
H	Hydrogen
O	Oxygen
FSP	Fish Scale Powder
ERB	European Rock Bitumen
WCO	Waste Cooking Oil

WMA	Warm Mix Asphalt
MD	Molecular Dynamics
SEM	Scanning Electron Microscope
AFM	Atomic Force Microscope
TLA	Trinidad Lake Asphalt

1 Introduction

In recent years, the growing energy crisis and environmental problems have attracted great attention from various industries and all parts of the world, leading to more and more efforts made to understand and improve the concomitant relationship between technology and environment and the concept of sustainable development (Wu et al., 2021). The road industry is not an exception. According to the International Road Federation, the transport industry accounts for nearly 15% of global greenhouse gas emissions, and more than 20% of energy-related carbon dioxide (CO_2) emissions are generated by the transport sector (Albuquerque et al., 2020). In addition, worldwide, more than 90% of the roads are paved with asphalt mixture, of which the asphalt binder is usually produced by crude oil distillation (Porto et al., 2021). However, some data show that with the continuous exploitation and use of non-renewable oil, the remaining reserves is expected to last for 46 years only (Penki and Rout, 2021). To address the shortage of resources and the environmental pollution caused by the processing of petroleum products, the development and utilization of renewable energy and resources has become an urgent task (Schipfer et al., 2017). It is also a weathervane for the road industry to change to green and sustainable solutions.

To overcome these challenges, many countries and regions have begun to pay increased attention to the development and utilization of renewable resources in road construction. The U.S. Department of Energy stressed that biomass is the second largest renewable energy in the United States after hydropower (U.S. Department of Energy, 2010), providing the road industry with possibilities of cleaner energy and new raw materials. To achieve the goal of carbon emission reduction, the road industry in the Netherlands has put forward a plan to find alternative products of petroleum asphalt, in which bio-asphalt represented by lignin has the potential for industrialization (Oliveira and Silva, 2022; Elsamny and Gianoli, 2023). In New Zealand, woody biomass has been regarded by the government as a promising renewable resource for the future transport fuel and the production of bio-asphalt through various conversion processes (Kolokolova, 2013). Many researchers have also summarized the application of some biomass in some aspects of the road, some of which are shown in Table 1.

[Table 1 here.]

In this context, based on the latest development status of biomass materials, this paper focuses on the overall classification of biomass materials used in asphalt pavement, and clarifies the three major categories of biomass materials used in pavement: bio-oil, bio-fiber and bio-filler. At the same time, the definition and preparation method of each type of material are explained, the latest application status of each type of material is reviewed, and the advantages and disadvantages of their performance are summarized. Finally, the economic and environmental benefits of using biomass materials for pavement are discussed and the future development direction of pavement biomass materials is proposed.

2 Methodology

In this paper, a systematic literature review (SLR) approach (Tranfield et al., 2003) was employed to summarize the application of biomass materials in pavement. SLR collects relevant information comprehensively and systematically through several steps for review (Zahoor et al., 2021). Firstly, for the determination of the problem and theme, this paper set the overall objective of the research as the application of biomass materials on pavement, and the focus was on the classification and exploration of the existing and new applications of biomass materials in pavement. Then some commonly used databases were used in the literature survey, including Web of Science, Google Scholar, Wanfang Data and China National Knowledge Infrastructure (CNKI). Keyword searches were conducted on each database, including bio-oil, bio-fiber, bio-filler, bio-asphalt, biomass, etc. In addition, further adjustment and screening were carried out during the retrieval process to ensure that its application scope is related to pavement. Finally, the literature was classified and reviewed, including bio-oil, bio-fiber, and bio-filler. The structure of this review paper is shown in Fig. 1.

[Fig. 1 here.]

This paper particularly focuses on the following aspects: (a) The source and application classification of pavement biomass materials; (b) The impacts of bio-oil, bio-fiber, and bio-filler on the performance of asphalt binder and asphalt mixture; (c) Economic and environmental benefits of biomass materials in pavement applications.

3 Biomass materials for pavements: definition, classification, and composition characteristics

3.1 Biomass materials and wastes

3.1.1 Generalized biomass materials

[Fig. 2 here.]

Biomass refers to an organism in which animals, plants, and microorganisms convert solar energy into energy stored in the body through direct photosynthesis or indirect use of it. Biomass can convert the stored solar energy into conventional solid, liquid, gas, and other substances through renewable carbon cycle (Wang, 2016). In essence, it is another form of solar energy (Fig. 2). Therefore, in a broad sense, all living or having lived organic substances can be referred to as biomass.

3.1.2 Agricultural and forestry by-products and wastes

The by-products and wastes of agricultural production mainly include straw, algae, fruit shells, plant debris, corncobs, bagasse, vegetable waste, etc. Forestry waste mainly includes plants (including plant appendages) and forestry processing waste, such as bark, fallen leaves, roots, animal and plant shells, lignin, tall oil, etc. Every year, countries around the world generate large amounts of usable agricultural and forestry wastes (Duque-Acevedo et al., 2020). However, at present, many extensive treatment methods not only fail to effectively utilize these resource-based agricultural and forestry wastes, but also cause great pollution issues. For example, 2/3 of the potassium in the straw will be lost when the straw is burned and returned to the field, and 9/10 of the energy in the straw will be lost when the straw is used as firewood (Wei, 2013).

As typical lignocellulosic biomass, agricultural and forestry wastes are mainly composed of cellulose, hemicellulose, and lignin. Compared with fossil energy, it has the advantages of renewable, low pollution and wide sources (Cao et al., 2017). The contents of cellulose, hemicellulose and lignin in common agricultural wastes are summarized in Table 2.

[Table 2 here.]

3.1.3 Livestock manure

Due to the development of animal husbandry, animal manure becomes concentrated and difficult to deal with (Wang et al., 2021). As a large country in animal husbandry, China discharges more than 3 billion tons of livestock and poultry manure every year (Ministry of Ecology and Environment of China, 2009). While many countries around the world have developed animal husbandry, there is a lack of effective and environmentally friendly means for the treatment and utilization of livestock and poultry manure. For example, in the United States, a large amount of pig manure is dumped into lagoons every year, which causes a hidden danger of water pollution and produces a large amount of greenhouse gases, emitting methane (CH_4) and nitrous oxide (N_2O), causing serious damage to the environment, while only 5% of farmland uses livestock manure to fertilize (Samieadel et al., 2018). The same is true for China. Even if more pig manure is used as fertilizer, in the case that the manure contains trace amounts of heavy metals, long-term use will also lead to land and crop pollution. A study on the corn farmland with long-term application of pig manure, around 7 large pig farms in Jilin Province, China, found that the contents of As, Cd, Cr, Cu, Hg, Ni, Pb and Zn in soil and corn seeds exceeded the standard (Cui et al., 2022). Therefore, the long-term use of these livestock and poultry manure with high content of heavy metals has potential risks to agricultural products and the ecological environment. However, bio-oil produced by thermochemical treatment of pig manure can be a solution with potential use in asphalt pavement, which not only effectively utilizes waste biomass, but also greatly reduces the adverse impact on the environment (Fini et al., 2011). There are many animal manures similar to pig manure, as listed in Table 3. The transformation of animal manure into bio-oil through thermochemical treatment technology has opened a new market for traditional agricultural wastes like manure.

[Table 3 here.]

3.1.4 Kitchen wastes

In recent years, with the growth of the world population, the global kitchen waste has risen sharply. South Africa and the European Union generate 9 million tons and 89 million tons of kitchen waste each year respectively (Tian et al., 2020). China produces about 195 million tons of kitchen waste every year (Hafid et al., 2017). Improper handling can cause serious problems to society and the environment. For instance, if dumped randomly, kitchen waste will quickly deteriorate, leading to the growth of bacteria and viruses (Yin et al.,2016). Watery food waste landfills occupy a large area and produce a large amount of malodor and leachate. Some even risks being redirected back into the market as raw materials for “swill-cooked dirty oil” and “garbage pigs” (Wang et al., 2019). Therefore, how to clean and effectively utilize kitchen waste is of great significance. For pavement engineering, the waste oil obtained from the preliminary treatment of kitchen waste usually contains many long-chain fatty acids with good compatibility with asphalt binders (Sindhu et al., 2019). They can be used to prepare bio-asphalt binders and can improve the low temperature crack resistance and fatigue performance of asphalt mixtures to some extent (Dong et al., 2019b; Li et al., 2019; Nie et al., 2021). If it can be widely used in the field of pavement engineering, it will provide a new option for clean and effective use of kitchen waste.

3.2 Classification, composition, and characteristics of biomass materials for pavements

3.2.1 Classification of biomass materials for pavements

There are many kinds of complex biomass materials, and their products by different processing technologies may have significantly different uses in asphalt pavements. For example, the bio-oil prepared from crop straw through rapid thermal cracking can be used to prepare modified asphalt binder, while the lignin fiber can be extracted to replace other pavement fibers to prepare asphalt mixture. As shown in Fig. 3, biomass materials can be classified into three categories by their uses in asphalt mixtures: bio-oil, bio-fiber, and bio-filler. Most bio-oils are added to the base asphalt binder as modifier, and a few are used as extender. The goal of completely replacing petroleum-based asphalt binder has so far not reached but could become more realistic in the future. Bio-fibers and bio-fillers can be used as stabilizing additives and are thus mostly added in the mixing stage of asphalt mixture. In addition, several bio-fillers are ground into fine powders and used for modifying asphalt binder. An overview of different uses of biomass materials in asphalt pavement is also presented in Fig. 3.

[Fig. 3 here.]

3.2.2 Composition and characteristics of biomass materials for pavements

(1) Bio-oil

Bio-oil is usually a dark brown oily liquid prepared by rapid thermal cracking. It has many similarities with the petroleum-based asphalt binder in appearance and internal structure. Relatively speaking, the definition of bio-asphalt binder is not clear at present. Considering the three application modes of bio-oil in asphalt binder: as modifier (bio-oil content ≤ 10%), as extender (25% < bio-oil content ≤ 75%), and completely replacing petroleum-based asphalt binder (Alamawi et al., 2019). Therefore, bio-asphalt binder refers to the asphalt binder material containing a certain proportion (0%-100%) of bio-oil.

Bio-oil is a mixture of complex organic components with high oxygen content. Its main elements include C, H, O, N, and S. The biggest difference between bio-oil and petroleum-based asphalt binder is that bio-oil usually contains more water, making the H and O elements significantly higher than petroleum-based asphalt binder, while the lower content of N and S elements reduces the potential impact on the environment (Penki and Rout, 2021). Bio-oil is mainly composed of organic compounds with very large molecular weight, such as various alcohols, organic acids, ethers, aldehydes, esters, phenols, and other oxygenated organic compounds, which also lead to its low chemical or thermal stability (Kumar et al., 2020). Depending on the type of raw materials, the properties of the bio-oil produced also vary to some extent (Table 4).

The bio-oil derived from agricultural and forestry by-products and wastes, commonly known as plant fiber bio-oil, is a kind of bio-oil with the most abundant raw materials and the most widely used in asphalt pavements. As shown in Table 4, the main component of this kind of bio-oil is water, which is due to the incompletely dried water in biomass raw materials and the water generated by polycondensation reaction of biomass during preparation such as thermal cracking. Bio-oil usually has poor thermal stability and many components with low boiling point. Thus, it is difficult to remove water by conventional heating methods. However, the excessive moisture content of bio-oil will lead to the instability of asphalt. On the one hand, water reduces the calorific value of bio-oil, resulting in the separation of water phase from oil phase in bio-oil. On the other hand, water can reduce the high viscosity of bio-oil itself, and the hydroxyl group (-OH) from water can effectively inhibit the production of carbon black and accelerate its oxidation during combustion. Therefore, compared with the production and preparation of petroleum-based asphalt binder, the addition of bio-oil can reduce the generation of nitrogen oxides and the emission of gaseous pollutants. As with the petroleum-based asphalt binder, the apparent acidity of bio-oil may strongly corrode ordinary metal materials, but it is not corrosive to polymers, which ensures the stability of bio-oil when combined with other additives for asphalt mixtures.

Compared with bio-oils derived from plant fiber, the compositions of bio-oil derived from animal husbandry manure and kitchen waste are relatively simple. Animal husbandry feces are mainly pig feces, while kitchen waste is mainly waste cooking oil. Bio-oil prepared by hydrothermal liquefaction of pig manure contains more water. The composition of bio-oil from waste cooking oil is relatively complex. It comes from food waste oil, "gutter oil" and other kitchen waste, mainly consisting of lauric acid, myristic acid and other components (Su et al., 2013). It is difficult to separate them through laboratory tests. Specifically speaking, it is necessary to produce such bio-oils through industrialized treatment.

[Table 4 here.]

(2) Bio-fiber

Bio-fiber refers to the fiber extracted from biomass, which can be divided into primary biological fiber, regenerated biological fiber and biosynthetic fiber according to the production process. According to the source, primary biological fiber can be divided into plant fiber and animal fiber (Vinod et al., 2020), while regenerated biological fiber and biosynthetic fiber belong to man-made fiber, which is the secondary processing of primary biological fiber. The specific classification is shown in Fig. 4. As an example, in China, a large amount of straw is burned or abandoned in the field every year because of its loose nature, large volume, inconvenient transportation, and poor fuel characteristics, which causes environmental pollution and wastes a lot of biomass resources at the same time (Feng et al., 2022).

[Fig. 4 here.]

At present, many bio-fibers have been used in asphalt pavement, such as lignin fiber as a regenerated biological fiber and polyester fiber as a biosynthetic fiber. Like conventional pavement fiber, its main functions include toughening, crack resistance, stability and so on (Yi et al., 2016). Comparing with mineral fiber, it is found that lignin fiber has strong adsorption capacity to asphalt binder, while polyester fiber has the worst absorption performance. Basalt fiber has the characteristics of high elasticity, high modulus, and high strength. Secondly, basalt fiber is a kind of inert material. Its physical and chemical properties are not easy to change, and its stability is excellent. The comprehensive performance of mineral fiber is better than that of the other two kinds of fibers (Table 5), but its cost is higher. The basic properties of other bio-fibers, such as straw fiber and fast-growing grass fiber, are similar to lignin fiber, which improve the high temperature stability and low temperature crack resistance of asphalt mixture (Lei et al., 2016; Liu et al., 2020; Nie et al., 2021; Qiang et al., 2013; Xue et al., 2013). Their cost is relatively low, and the processing is relatively simple. Therefore, trying to add bio-fiber to asphalt mixture can not only make effective use of waste biomass resources, protect the environment, but also can improve the road performance of asphalt mixture. It is thus foreseen that the application of bio-fiber in asphalt pavement has a good prospect.

[Table 5 here.]

(3) Bio-filler

Bio-fillers mainly include animal and plant shells, natural rubber, and other materials. Most of the animal and plant shells come from biomass waste, while natural rubber is mostly biomass raw materials. They are generally processed into powder or particles by physical processing, added to asphalt binder for modification or mixed in asphalt mixture.

Natural rubber is a kind of green, environmentally friendly, clean, and renewable elastomer biopolymer. Natural rubber can be divided into two categories: solid natural rubber and latex. At present, natural rubber is mainly used as asphalt modifier. The most common way is that natural rubber is broken into crumb rubber and directly put into asphalt binder to produce modified asphalt. The addition of crumb rubber improves the penetration, ductility, viscosity, and other properties of asphalt binder (Yang et al., 2018). Rubber-modified asphalt technology has become mature. More and more researchers began to use bio-oil as rubber asphalt additive and put it into asphalt binder together with crumb rubber for shear mixing (Dong et al., 2019b; Yang et al., 2018). It is found that bio-oil can reduce the processing temperature of rubber asphalt, accelerate the swelling rate of rubber, and improve the fatigue resistance and low temperature stability of rubber modified asphalt.

Animal and plant shell materials mainly include oyster shell, crayfish shell, palm shell, etc. Most of the discarded shells of animals and plants come from food waste. According to statistics, China produces more than 8 million tons of crustacean waste every year, and most of the waste is not effectively utilized, but directly landfilled (Zhang et al., 2018). Chitin is the main substance in the waste shell of crustaceans, which is a long-chain polymer like plant cellulose with six-carbon monomer. The molecular weight of chitin can be more than 1000 kDa. Its strong adsorption capacity makes it a promising asphalt bonding material. Additionally, most waste nut shells have certain strength and high temperature resistance. Many tests show that the addition of such materials can effectively improve the high temperature stability of asphalt mixture (Zhang et al., 2018).

4 Use of bio-oil in asphalt binder and asphalt mixture

4.1 Preparation of bio-oil and bio-asphalt binder

4.1.1 Preparation of bio-oil

[Fig. 5 here.]

At present, biomass conversion and utilization can be divided into three categories (Fig. 5): biotransformation method, chemical treatment and thermochemical conversion. The biotransformation method is mainly based on anaerobic digestion and special enzyme technology (Cong et al., 2020). The energy form provided is biogas, and the main component is methane, which has significant environmental benefits, but the energy output is low, and the investment is large. The chemical treatment method is mainly aimed at hemicellulose in biomass, and chemical raw materials are obtained by heating and hydrolysis in different environments. Bio-oil is mainly prepared by thermochemical conversion, including hydrothermal liquefaction and thermal cracking pyrolysis (Cong et al., 2020).

(1) Pyrolysis technology

Biomass pyrolysis (thermal cracking) is essentially a thermochemical conversion process (Rolland et al., 2020a, 2020b). It reacts in a closed space (without oxygen or part of oxygen) at more than 300 °C for 15-45 minutes to obtain biochar, bio-oil, gas, and other substances.

The main equipment of thermal cracking can include an ablation reactor, a fluidized bed, a circulating fluidized bed, a vacuum moving bed, a rotating cone, or a drainage bed (Demirbas and Arin, 2002). Among them, the fluidized bed is most commonly used due to its simple operation. As shown in Fig. 6, its circulation process can provide heat through the generated by-product gas and biochar to effectively produce bio-oil. Biomass pyrolysis gained popularity in the 1970s in European and American countries, and now has widely adopted in many other countries. The research on biomass pyrolysis in China is relatively late and has not yet formed systematic large-scale production. According to process parameters and conditions, the pyrolysis process can be divided into two types: fast pyrolysis and slow pyrolysis.

[Fig. 6 here.]

Fast pyrolysis (Fig. 7) refers to the fast heating of biomass to 800-1300 °C within 1-10s and maintaining the heating rate of 10-200 °C/s. Fast pyrolysis can quickly decompose biomass to obtain bio-oil. The other two by-products are biochar and gas. The outputs of fast pyrolysis include liquid products (60%-75%), non-condensable gas (10%-20%), and biochar (15%-20%). Fast pyrolysis is a method with high yield of bio-oil. Increasing the temperature rising rate in fast pyrolysis greatly limits the formation of unnecessary biochar.

[Fig. 7 here.]

Slow pyrolysis is a traditional thermal cracking method, which greatly reduces the holding temperature and heating rate compared with fast pyrolysis and has a longer residence time. Generally, the biomass is heated to 400-500 °C, and the heating rate is maintained at 0.1-1 °C/s for 5-30 min. Due to the long heating time and low heating rate, slow pyrolysis is conducive to biochar formation, while the yields of gas and bio-oil are relatively low. At the same time, it also reduces the emission of harmful gases and can flexibly handle different types of raw materials and different operating conditions to produce the required final products.

(2) Hydrothermal liquefaction technology

Hydrothermal liquefaction refers to the process of depolymerization and liquefaction of biomass under the action of solvent, atmosphere (inert gas, hydrogen, or carbon monoxide, etc.) and catalyst under certain pressure and temperature conditions, finally obtaining biochar, liquefied products, and small molecular gases (Geantet et al., 2022; Velandia et al., 2021). Different chemical products and bio-oils can be obtained by separating the liquefied products. Fig. 8 shows the ideal transformation cycle system of biomass hydrothermal liquefaction. In the process of hydrothermal liquefaction, firstly, biomass macromolecules undergo physical and chemical reactions such as depolymerization under the action of solvent to produce highly active and unstable small molecules or molecular fragments, which is followed by the reorganization and polymerization of small molecules or molecular fragments to produce more stable liquefied products, and finally the target products are obtained by separation and purification. Compared with thermal cracking technology, hydrothermal liquefaction technology has the following advantages: (a) the reaction conditions are mild – the reaction temperature of hydrothermal liquefaction is mostly in the range of 200-400 °C, with reaction pressure 5-25 MPa, and no higher heating rate is required; (b) the process has the advantages of simple operation, low energy consumption and high energy utilization rate; (c) the equipment is simple. Due to mild reaction conditions, the equipment required for hydrothermal liquefaction is simpler. Complex reactors are not required, and it is easier to carry out industrialized production.

[Fig. 8 here.]

4.1.2 Preparation of bio-asphalt binder

[Fig. 9 here.]

Fig. 9 show that the bio-oil prepared by thermal cracking or hydrothermal liquefaction needs to be processed after separating carbohydrates, phenols, and acids by distillation, extraction, and oxidation. Finally, the processed bio-oil is mixed into petroleum-based asphalt binder and sheared at high speed to obtain bio-asphalt binder. In terms of composition, bio-asphalt and petroleum-based asphalt binders contain four fractions, namely, saturates, aromatics, resins and asphaltenes. Studies have shown that bio-asphalt binder usually contains more resins and asphaltenes, which can improve the compatibility between bio-asphalt and petroleum-based asphalt binders (Cao et al., 2015). However, due to the heterogeneity of biomass, the composition of bio-oil may be different, and the conditions required to prepare bio-asphalt binder are also different (Table 6). In general, it is recommended that the shear temperature should not be lower than 150 ℃ when preparing bio-asphalt binders, and the blending speed should not be lower than 4000 r/min under the condition of 30 min shear time. The specific parameters should be adjusted according to the content of bio-oils.

[Table 6 here.]

4.2 Types, properties, and technical parameters of bio-asphalt binders

The types of different bio-asphalt binders depend on the content of mixed bio-oil: complete replacement of petroleum-based asphalt binder (substitution rate is 100%), as an extender (substitution rate is usually 25%~75%) and as modifier of petroleum asphalt (substitution rate is usually less than 10%). The biomass rapid pyrolysis reactor developed by Raouf and Williams (2009) produces the bio-oil from corn, straw, oak sawdust and switchgrass. The bio-binder obtained by modifying bio-oil with polyethylene modifier can completely replace the petroleum asphalt. However, due to various limitations of bio-oil itself, few other researchers have succeeded in completely replacing petroleum-based asphalt binder with bio-asphalt binder, and most of them were limited to indoor laboratory tests. The current technology is not yet mature enough to completely replace petroleum-based asphalt binder. It is generally used as an extender or modifier of petroleum-based asphalt binder in pavement engineering (Lei et al., 2012). However, based on different raw materials, they can be divided into three categories: plant fiber bio-asphalt binder (including agricultural and forestry biomass materials), animal husbandry manure bio-asphalt binder, and kitchen waste bio-asphalt binder.

[Table 7 here.]

It can be found from Table 7 that: (1) plant fiber bio-asphalt binder is the most studied type among the listed at present, because it has many kinds of available materials and is rich in resources, and the treated bio-oil has good compatibility with petroleum-based asphalt binder; (2) when using biomass mainly containing lignin, cellulose and hemicellulose as raw materials to prepare bio-oil and bio-asphalt binder, it is necessary to maintain a high shear rate and a high reaction temperature, so it is recommended that the reaction temperature of rapid pyrolysis is not lower than 150 °C and the shear rate is 4000 r/min; (3) when the content of bio-oil is 5%-15% as modifier, the performance of bio-asphalt binder is better; (4) most bio-oils can improve the low temperature performance and viscosity of asphalt binder, but whether it can improve the high temperature performance of asphalt is still controversial; (5) livestock manure materials are mainly transformed into bio-oil by hydrothermal liquefaction technology; (6) compared with the preparation of plant fiber bio-asphalt binder, the shear rate for preparing livestock manure bio-asphalt binder is lower; (7) livestock manure bio-asphalt binder generally improves the high temperature stability and low temperature crack resistance of binder and reduces the viscosity of asphalt; (8) at present, livestock manure raw material for preparing bio-asphalt binder is mainly pig manure, and there is little research on other manure materials; (9) kitchen waste materials are mostly used as modifiers or extenders of asphalt binder; (10) the shear rate (for 30 min blending) of kitchen waste bio-asphalt binder is mostly maintained between the shear rates of the other two kinds of bio-asphalt binders; (11) kitchen waste bio-asphalt binder has good performance in improving ductility and low temperature crack resistance but has little improvement in other performance.

To sum up, although different kinds of bio-asphalt binders have improved performance, it has not achieved ideal binder performance as a whole. The instability of the performance of petroleum-based asphalt binder mixed with bio-oil can be improved in two ways: (1) it is recommended to add SBS with a mass fraction of about 5% for composite modification to improve the high and low temperature performance of bio-asphalt; (2) it is suggested to improve the performance of bio-asphalt binder by means of composite bio-modification. The existing research combinations include waste oil and corn straw, waste oil and crumb rubber, corn straw and oak chips, corn straw and grass chips, etc. (Cong et al., 2020; Lei et al., 2012; Nie et al., 2021; Rasman et al., 2018). However, the optimal content of each specific bio-oil needs to be verified by the test performance of the modified bio-asphalt binder with different mixing proportions.

4.3 Research progress on preparation of asphalt mixture with bio-asphalt binder

4.3.1 Microscopical characteristics of asphalt binder

As the development of modern testing tools and technologies, it has become possible to observe the microstructure of asphalt binder and study the microscopical characteristics. The commonly used technical tools are Atomic Force Microscope (AFM), Scanning Electron Microscope (SEM) and so on. Meng et al. (2022) added 25% Trinidad Lake Asphalt (TLA) to different amounts of modified bio-asphalt binder to prepare bio-asphalt/TLA composite modified asphalt binder to improve its aging resistance. The microscopic characteristics of modified asphalt were studied by scanning electron microscope (Fig. 10).

[Fig. 10 here.]

Fig.10 (a) shows that the surface of the unaged base asphalt binder is flat and shiny, while the surface of the composite modified bio-asphalt in Fig.10 (b) has smooth particles slightly raised, which are the ashes exposed to the asphalt binder surface. These phenomena show that bio-asphalt has the function of lubrication. It is also proved that the blend of bio-asphalt, TLA and petroleum asphalt can combine stably and have good compatibility on the micro-scale. Fig.10 (c) shows that, after short-term aging (the base asphalt is aged), the gloss is dim and the surface is rough due to the volatilization of light components and the reaction of asphalt binder molecules with oxygen. The existence of ash in Fig.10 (d) slows down the volatilization of light components in asphalt binder and reduces the contact area between asphalt and oxygen, while bio-asphalt can supplement light components. Fig.10 (e) shows that the surface of base asphalt binder blackens and cracks appear after long-term aging. This shows that the colloidal structure of asphalt binder has been destroyed. Macroscopically, the asphalt binder becomes hard and brittle. However, in Fig.10 (f), the wrinkle degree of bio-asphalt/TLA composite modified asphalt binder deepens, but it does not crack. Bio-asphalt and ash play a role with their respective characteristics to slow down the aging process of asphalt binder. By observing the microscopic characteristics of asphalt binder, we can effectively analyze the modification mechanism and explain the macroscopic phenomena.

Cao et al. (2019) used sawdust as raw material to prepare biomass heavy oil by hydrothermal liquefaction. It was found that the substances contained in biomass heavy oil were hydrocarbons, esters, and aromatic hydrocarbons, which was similar to the base asphalt, indicating that the two have good compatibility. In addition, Wu et al. (2017) used pine kraft lignin powder to add into a SK 70# base asphalt binder (penetration grade around 70) and sheared it at high speed 4500 r/min at 165 °C to prepare bio-asphalt binder. The functional groups of lignin, petroleum-based asphalt binder and lignin-modified asphalt binder were compared by infrared spectrum test. It was found that the addition of lignin did not change the chemical structure of asphalt and did not form new functional groups. The addition of bio-oil in asphalt binder does not significantly change the internal structure of asphalt and cause other changes. On the contrary, bio-oil shows good compatibility with petroleum-based asphalt materials.

4.3.2 Rheological properties of bio-asphalt binder

The temperature range of viscous behavior of bio-oil is usually about 30-40 °C, lower than that of asphalt binder. Compared with traditional binder, unmodified bio-asphalt binder with bio-oil may have certain different rheological properties, temperature and shear sensitivity. Especially, after adding polymer modifier to bio-asphalt binder, the rheological properties of the bio-asphalt binder change significantly (Lei et al., 2018). To explore the technology and mechanism of composite modification technology to improve the road performance of bio-asphalt binder, Dong et al. (2019a) prepared composite modified bio-asphalt binder. Rubber powder (CR) and SBS additives were added to mixture of petroleum asphalt and castor oil bio-asphalt to prepare composite modified asphalt binder. The rheological properties of composite modified bio-asphalt binder were evaluated by Multiple Stress Creep Recovery (MSCR), Bending Beam Rheometer (BBR) and Dynamic Shear Rheometer (DSR) testes. The results show that the castor oil bio-asphalt modified by SBS and CR has the best high and low temperature performance compared with the single modified asphalt. At the same time, by using the master curves and other parameters, it is found that the rheological property of the composite modified bio-asphalt is almost homogeneous at 20 ℃ and temperature dependence occurred at 80 ℃.

Gao et al. (2017) mixed 5%, 10%, 15% and 20% bio-oil into a 50# base asphalt (penetration grade around 50) to obtain bio-asphalt binder. Through MSCR test, it was found that the addition of bio-oil decreased the high temperature performance of bio-asphalt, and the addition of bio-oil could increase the rutting resistance of aged asphalt. But with the increase of temperature, the creep recovery rate of bio-asphalt decreased, and the deformation resistance decreased. Most bio-asphalt is more significantly affected by aging because there are more oxygen-containing components in bio-oil than asphalt. They are more likely to "oxidize" with oxygen in the environment, resulting in changes in structure and composition, resulting in embrittlement and hardening. Therefore, bio-oil cannot be treated at a temperature higher than 120 ℃, because high oxygen content and high temperature will lead to the occurrence of a large amount of oxidation in the oil. Warm mix asphalt may be a good way to resist aging (Ma et al., 2015).

4.3.3 Properties of bio-asphalt mixture

Previous research mostly focused on the performance and preparation of bio-asphalt binder, especially with wood chips, pig manure, castor oil and other materials as raw materials, while there has been very little research on bio-asphalt mixture. In addition, a unified technical specification has not formed for bio-asphalt mixture. The existing research shows that the optimum content of bio-oil should be determined according to the asphalt mixture performance test, and the initial content should be 5-15%. The main conclusions of some comprehensive studies on the pavement performance of bio-asphalt mixture are shown in Table 8.

[Table 8 here.]

(1) High temperature stability

High temperature stability of asphalt mixture is an important index of asphalt performance test, which reflects the ability of mixture to resist permanent deformation. It can be seen from the above Table 8 that the addition of most bio-oils reduces the high temperature stability of asphalt mixture, mainly due to the low viscosity and poor deformation resistance of bio-oil itself. Yang and You (2015) also found that the addition of sawdust oil slightly reduced the high temperature performance of bio-asphalt mixture, because sawdust oil promoted the movement of asphalt binder molecular chain. Fig. 11 shows the dynamic stability values of different bio-asphalt mixtures (Gao et al., 2017; Liu and Dong, 2019; Ma, 2020; Zeng et al., 2017). The wheel tracking test is used to evaluate the high temperature stability of bio-asphalt mixtures, and the test temperature is 60 °C. Among them, "sawdust oil + 50# base asphalt" and "plant bio-oil + 50# base asphalt + SBS" are AC-16C mixtures; "castor oil + 50# base asphalt" is AC-20C mixture; and "sawdust oil + 90# base asphalt" and "sawdust oil + 90# base asphalt + SBS" are AC-16 mixtures. The mixture dynamic stability of sawdust oil modified asphalt binder (50# base asphalt) is maintained at about 2500 times/mm when the content of bio-oil is 10%, and the dynamic stability is reduced to about 2000 times/mm when the content of bio-oil is 20%. The dynamic stability of bio-asphalt mixture with castor oil decreases significantly, but it meets the requirements of dynamic stability value of asphalt mixture (1000 times/mm according to JTG D50-2017) when the content is 10%. The mixture dynamic stability of sawdust oil modified asphalt binder (90# base asphalt) reaches about 1500 times/mm when the content of sawdust oil is 10%. The addition of SBS modifier improves the high temperature stability of bio-asphalt mixture. Among the above bio-asphalt mixtures, except for the 20% castor oil bio-asphalt mixture, the high temperature performance of the rest is better than that of the conventional asphalt mixture and meets the specification requirements. From the comparison within the group, it is found that, with the increase of bio-oil content, the dynamic stability value of bio-asphalt mixture gradually decreases, and the dynamic stability value of high-content bio-asphalt mixture (20% castor oil + 50# base asphalt) cannot meet the requirements for warm and humid areas. Therefore, it is recommended that the upper limit of bio-oil content is set at 10%-20%. The specific value needs further tests to verify according to the specific application conditions. However, the upper limit of bio-oil content can be further extended for other areas, for example, the hot-summer, warm-winter and semi-dry area.

[Fig. 11 here.]

(2) Low temperature crack resistance

Low temperature cracking is due to the thermal stress in the asphalt pavement when the temperature decreases, while the stress relaxation of the asphalt pavement is poor at low temperature. When the thermal shrinkage stress exceeds the tensile strength of the asphalt mixture and the thermal shrinkage stress cannot be released through stress relaxation, cracks will occur in the pavement. The Thermal Stress Restrained Specimen Test (TSRST) is a common test method for low temperature test of asphalt mixtures, including bio-asphalt mixture. The research of most scholars shows that the addition of bio-oil can improve the low temperature crack resistance of asphalt mixture. Zhao et al. (2020) firstly determined the optimal content of bio-oil, SBS and nano silica through orthogonal test. From the low temperature test results, it was found that the composite modified bio-asphalt mixture has the best low temperature performance compared with base asphalt mixture and SBS asphalt mixture. Mohammad et al. (2013) used pine sawdust as the raw material to prepare bio-oil and added SBS modifier together. They found that bio-oil can improve the water stability and low temperature crack resistance of asphalt mixture. Similarly, researchers (Lei et al., 2018; You et al., 2011; Zhang and Zhang, 2018) also found that the addition of bio-oil greatly improves the low temperature crack resistance of asphalt mixture. The flexural tensile strength of different bio-asphalt mixtures (Liu and Dong, 2019; Ma, 2020; Zeng et al., 2017) is presented in Fig. 12. The low temperature crack resistance of asphalt mixture is evaluated by trabecular bending test (three-point). The test temperature is -10 °C. In Fig. 12, the "sawdust oil + 50# base asphalt" and "factory bio-oil + 50# base asphalt + SBS" are AC-16C mixtures; "sawdust oil + 90# base asphalt" and "sawdust oil + 90# base asphalt + SBS" are AC-16 mixtures. With the increase of bio-oil content, it has little effect on the flexural tensile strength of asphalt mixture and tends to be stable. The addition of SBS modifier improves the low temperature crack resistance of bio-asphalt mixture to a great extent.

[Fig. 12 here.]

(3) Water stability

The water stability of asphalt mixture is the ability of asphalt concrete pavement to resist the damage of potholing and raveling caused by water damage (Gao et al., 2017a). To evaluate the pavement performance of pine wood bio-asphalt mixture, Mohammad et al. (2013) conducted a comprehensive experimental study by using Hamburg wheel tracking test, modified Rotman test, Semi-circular Bending Test (SCB) and TSRST. It was found that the addition of bio-oil helps to improve the water sensitivity of the mixture. Yan et al. (2022) studied the effect of European rock bitumen (ERB) and waste cooking oil (WCO) composite modified asphalt on the macroscopic mechanical properties of asphalt mixture. Four kinds of ERB/WCO modified asphalt combinations were used for freeze-thaw splitting test (18%ERB+0%WCO, 2%WCO+18%ERB, 4%WCO+18%ERB and 4%WCO+12%ERB). The freeze-thaw splitting test results of five groups of asphalt mixtures are shown in Fig. 13, and the TSR and immersion residual stability (IRS) of asphalt mixtures have similar trends. The addition of ERB and WCO has a positive effect on improving the water stability of asphalt mixture.

[Fig. 13 here.]

Zeng et al. (2017) conducted pavement performance tests on bio-asphalt mixtures with 5%, 10%, 15% and 20% castor oil content respectively. The results showed that, with the increase of bio-oil content, the water stability decreased significantly, and the water stability improved significantly after adding hydrated lime as an anti-stripping agent. Lei et al. (2018) claimed that the addition of bio-oil can reduce the loss of asphalt modulus and increase asphalt viscosity, so as to improve water stability.

(4) Fatigue resistance

The fatigue resistance of bio-asphalt mixture can be studied by four-point bending fatigue test, direct tensile test, and indirect tensile test. Zhang and Zhang (2018) selected catering waste oil as the raw material and prepared bio-oil by thermochemical liquefaction method. They prepared 3%, 5% and 7% bio-asphalt mixtures respectively for pavement performance test. It is found that there is not a universal linear relationship between the content of bio-oil and fatigue performance. A small amount of bio-oil can significantly improve the fatigue resistance of asphalt mixture under medium and low load, but too much bio-oil cannot improve the fatigue resistance of asphalt mixture. Under the action of high strain, the fatigue resistance of asphalt mixture can be improved only when the content of bio-oil is high (> 7%). Lei et al. (2018) found that the stiffness of asphalt binder was reduced after modification with bio-oil and the low temperature performance and fatigue resistance of asphalt mixture were improved. Yang and You (2015) found through the four-point bending fatigue test that the addition of bio-oil significantly improves the fatigue performance of polymer-modified asphalt mixture.

To sum up, the addition of bio-oil can significantly improve the low temperature performance and fatigue resistance of asphalt mixture, while the effects of high temperature stability and water stability are quite various. It depends on the chemical characteristics of different kinds of bio-oils.

5 Use of bio-fiber in asphalt binder and asphalt mixture

5.1 High temperature stability

It can be seen from Table 9 that the addition of most bio-fibers can improve the high temperature stability of asphalt mixture, which is mainly because the existence of bio-fibers will adsorb free asphalt binder. So, the structural asphalt binder in asphalt mixture increases, and it binds aggregate in the mixture to form skeleton support, which enhances the deformation resistance of asphalt pavement. Moreover, the bio-fibers are dispersed in the asphalt mixture to form a grid structure and connect with each other. When the pavement is subjected to load, the bio-fibers can transfer the load and prevent the structural damage caused by stress concentration (Li et al., 2019). Zhou and Lu (2020) respectively mixed lignin fiber, polyester fiber, and basalt fiber into SBS/crumb rubber composite modified asphalt mixture for test and comparison. The high temperature rutting test results show that when the content of lignin fiber was around 0.3% of the asphalt mixture, the dynamic stability reached the highest, and the improvement effect on the high temperature stability of asphalt mixture was slightly lower than that of polyester fiber and basalt fiber.

[Table 9 here.]

Lei et al. (2016) compared the effects of cotton straw fiber and lignin fiber on the performance of asphalt mixture. Through high temperature rutting test, it was found that the dynamic stability of asphalt mixture mixed with cotton straw fiber was greatly improved, by more than 30%, which is slightly higher than the lignin fiber. This is mainly because the length of cotton straw fiber was generally 3-6 mm and had certain strength, toughness, as well as good adhesion with asphalt binder, which leads to better "bridging reinforcement" effect than the lignin fiber.

[Table 10 here.]

Cui et al. (2022) modified the asphalt binder by adding 1.5% content bamboo fibers which were treated by four methods respectively (Table 10). Through the MSCR test results, it is found that the asphalt binder with Silane coupling agent Treated Bamboo Fibers (STBF) has better elasticity under two stress levels, while under the stress level of 3.2 kPa, the addition of fiber has little effect on the creep recovery ability of asphalt binder. In addition, the $J_{nr}3.2$ of a fiber asphalt binder is lower than that of base asphalt, indicating that the addition of fiber can improve the rutting resistance of asphalt binder, and the improvement effect of STBF is the best.

5.2 Low temperature crack resistance

Chen et al. (2019) found that the addition of a small amount of corn straw fiber (< 2%) led to the decrease of asphalt binder stiffness and the improvement of low temperature performance. Nie et al. (2021) extracted and made fast-growing grass fiber from bamboo, and they determined that the optimal fiber content was 0.4% of the asphalt mixture and conducted mixture test. Through three-point bending test, the low temperature crack resistance of fiber-reinforced asphalt mixture was evaluated. The maximum flexural tensile strength and flexural stiffness modulus of fast-growing grass fiber asphalt mixture were 9.78% and 9.39% higher than lignin fiber asphalt mixture respectively. It shows that the fast-growing grass fiber asphalt mixture has better low temperature crack resistance. Li et al. (2019) compared the low temperature cracking performance of fiber-free asphalt mixture, lignin fiber asphalt mixture and corn straw fiber asphalt mixture. The low temperature bending test results show that the addition of bio-fiber can significantly improve the low temperature cracking resistance of asphalt mixture, and the tensile strength of lignin fiber asphalt mixture and corn straw fiber asphalt mixture is about 6% higher than that of fiber-free asphalt mixture. Corn straw fiber asphalt mixture shows better low temperature crack resistance. Thus, the addition of bio-fiber can better improve the low temperature crack resistance of asphalt mixture, which is mainly because the bio-fiber has rough surface as well as a certain tensile strength and length diameter ratio. While adsorbing asphalt binder, it is very easy to form a grid structure, which plays a better role in reinforcement and bridging.

5.3 Moisture damage resistance

The water damage of asphalt pavement is mainly due to the water entering the mixture through the air voids, which reduces the bonding performance between asphalt binder and aggregate. The driving of vehicles will generate internal stress in the pavement. The stress accelerates the stripping of pavement material, and further cause the water damage. The addition of bio-fiber can improve the consistency of asphalt mortar, make the contact between asphalt and aggregate closer, and improve the ability of water resistance. Xue et al. (2013) independently developed the incorporation of straw composite fiber (raw materials were crop straw and modified bentonite) into SMA asphalt mixture. Through immersion Marshall test and freeze-thaw indirect tensile strength (ITS) test, it is found that the incorporation of bio-fiber significantly improves the water stability of asphalt mixture, and the water stability of straw composite fiber asphalt mixture is better than that of lignin fiber asphalt mixture. Liu et al. (2020) have studied the water stability of fiber-free asphalt mixture, cotton straw fiber asphalt mixture and cellulose fiber asphalt mixture. Through the test results, it was found that the addition of cotton straw fiber has a more significant effect on the improvement of water stability of asphalt mixture.

To sum up, bio-fiber can be added to the mixture without changing the gradation. Because bio-fiber has certain strength and strong adsorption capacity for free asphalt binder, it strengthens the bonding between asphalt binder and aggregate and plays the role of “bridging and reinforcement”. So, the addition of bio-fiber can significantly improve the high temperature stability, low temperature crack resistance and water stability of asphalt mixture.

6 Use of bio-filler in asphalt binder and asphalt mixture

Compared with conventional mineral fillers for asphalt mixture, most bio-fillers are alkaline materials with certain strength, such as shell powder, crayfish shell powder, etc. As a "temperature sensitive" material, asphalt binder directly affects the service life of asphalt pavement through its viscoelastic properties (Liu, 2014). The use of alkaline materials is one of the main means to improve the water damage resistance of asphalt pavement (Xie, 2011). In fact, resin and asphaltene in asphalt are polar molecules, which have certain activity themselves. At the same time, the two components are weakly acidic. When in contact with the aggregate, there is not only physical adsorption on the surface, but also chemical adsorption with strong adhesion (Zhou et al., 2005).

However, there is little research on the application of bio-filler in asphalt pavement, and there is also a lack of engineering trial cases. There is almost no relevant research on bio-filler asphalt mixture, and the potential of bio-filler needs to be further explored. At present, the application of bio-fillers is mainly focused on cement concrete materials. Yang et al. (2010) have shown that shells can replace limestone to manufacture shell cement. It is found that adding 10% shell powder into long-term high-strength concrete will not affect the long-term strength of concrete and can significantly improve the freeze-thaw resistance and water permeability of concrete. Wang et al. (2013) used shells to replace some natural sand in cement mortar, which effectively improved the compressive strength of cement mortar. For asphalt mixture, Guan (2018) selected conventional limestone mineral filler and waste shell powder as the fillers for SMA-13 asphalt mixture and compared the influence of waste shell powder on the related properties of asphalt mixture. It was found that the mixture dynamic stability (test temperature 60 ℃) of SMA-13 with waste shell powder as filler was higher than that of limestone mineral filler sample, indicating that waste shell powder better filled and stabilized the skeleton structure of SMA mineral materials. Additionally, the water stability has also been improved. Lv et al. (2020) carried out experimental research on asphalt binder with crayfish shell powder. The crayfish shell powder was added with mass fractions of 5%, 10% and 15% to the base asphalt binder under high-speed shear. It was found that the addition of crayfish shell powder increased the softening point of asphalt binder and reduced the penetration. Compared with crumb rubber, crayfish shell powder can more effectively improve the high temperature mechanical properties of asphalt binder.

Tahami et al. (2018) partially replaced the limestone filler with 0%, 25%, 50% and 100% rice husk ash filler respectively. Through the mixture test results, it was found that, in comparison with the limestone filler, the dynamic stability of asphalt mixture increased with the increase of the replacement amount of rice husk ash filler, indicating that the replacement of rice husk ash filler could improve the high temperature stability of asphalt mixture. The effect was the best when the replacement amount was 75% of the total filler. Al-Hdabi (2016) found that with the increase of the replacement amount of rice husk ash filler, the dynamic stability of asphalt mixture first increased and then decreases. The highest stability was reached when the replacement amount was 50% of the total filler, indicating that the replacement of rice husk ash filler significantly improved the high temperature stability of asphalt mixture. Kang (2019) compared the high temperature performance of conventional asphalt mixture and rice husk ash modified asphalt mixture through high temperature rutting test. The results show that the dynamic stability of rice husk ash modified asphalt mixture was 3.4 times that of conventional asphalt mixture. It is indicated that the high temperature stability of asphalt mixture was greatly improved by using rice husk ash as filler, which is mainly due to the three-dimensional network connection system formed by rice husk ash and asphalt binder. The system reduced the air void and improved the internal friction of asphalt mixture, so as to improve the high temperature performance. Lv et al. added 4%, 8%, 12% and 16% fish scale modified bio-asphalt to base asphalt respectively. It was found that fish scale powder (FSP) improved the adhesion, viscoelasticity, temperature sensitivity and permanent deformation resistance of the asphalt. In addition, through the aging index (Table 11), it is found that the low content of FSP has little effect on the aging of asphalt, so it is necessary to control the content.

[Table 11 here.]

Arabani et al. (2015) grinded seashell into powder and added it into hot mix asphalt mixture as filler. Through the indirect tensile fatigue test, it is found that the best replacement amount of seashell powder filler (replacing granite filler) was 100% (namely total replacement of the filler), because the surface of shell powder was rougher and has better mechanical strength, which improved the fatigue life of asphalt mixture. Kang (2019) sieved the activated rice husk ash after high temperature treatment through a 0.075mm sieve and prepared modified asphalt binder and asphalt mixture under the shear rate of 5000 r/min. The high temperature stability, low temperature crack resistance, and water stability of the mixture were tested, respectively. The results showed that rice husk ash could improve the strength, deformation resistance, water stability, and high temperature stability of asphalt mixture. By the significance of influence of rice husk ash on the properties, the ranking was as follow: high temperature stability strength > deformation resistance > water stability. Although rice husk ash would slightly reduce the low temperature crack resistance of asphalt mixture, it still met the requirements and needs of practical engineering. Mistry et al. (2019) used rice husk ash as filler instead of hydrated lime to study its influence on the high temperature performance and water stability of dense graded asphalt macadam mixture. They added different amounts of hydrated lime (HL) filler and rice husk ash (RHA) filler (2%, 4%, 6%, 8%) into asphalt mixture for comparison. The results (Table 12) show that when rice husk ash was used as the filler of asphalt mixture, its performance was significantly better than that of hydrated lime filler. When the amount of rice husk ash filler was 4% of the asphalt mixture, its ITS value reached 1540 kPa, which greatly improved the water stability of asphalt mixture.

[Table 12 here.]

To sum up, among bio-fillers, the animal and plant fruit shell materials are rarely studied in asphalt mixture other than use for binder modification. In only a few studies on replacing conventional fillers with bio-fillers, it is found that rice husk ash and shell powder bio-fillers could improve the high temperature stability and fatigue resistance of asphalt mixture, while the research on other pavement performance focused on the modified asphalt mixture. As for the application of bio-fillers in asphalt mixture, there are few examples at present. The above conclusions cannot represent the performance of most bio-fillers.

7 Application potential, economic and environmental benefits of bio-asphalt binder and asphalt mixture

The production of asphalt binder, cement, aggregate, and various additive materials in pavement engineering consumes not only a lot of energy but also many non-renewable raw materials. This has a very adverse impact on the sustainable development of social economy and environmental protection. Towards the further societal development, the construction of an environment-friendly and sustainable society has been advocated globally, which promotes more and more attention and application of biomass materials with green, renewable, and degradable characteristics (Yi et al., 2016). In this regard, scientific research plays an important role. Fig.

14 shows the quantity of scientific articles published in the field of biomass-containing asphalt materials in different countries in recent years. The statistical results show that China, the United States, and Malaysia published the most articles recently. This is likely because the three countries are rich in domestic biomass resources. China and the United States are dominated by straw biomass, while Malaysia is dominated by natural rubber biomass. Similarly, as a country vigorously develops the infrastructure industry and transportation industry, there would likely be many scientific studies on the use biomass in asphalt materials. In this area, it is found that most of the research on bio-asphalt binder and bio-asphalt mixture investigated sawdust, straw, pig manure, "gutter oil" etc. as raw materials. Among these, the performance of bio-asphalt binder and bio-asphalt mixture with straw, pig manure and "gutter oil" as raw materials is controversial in terms of high and low temperature properties. Compared with the other popular materials, bio-asphalt binder and bio-asphalt mixture with sawdust as raw materials are better in pavement performance. The combination with SBS and other modifiers can make the performance of the asphalt binder and asphalt mixture even better. Although the research on pavement biomass materials is still in its infancy, the problems such as resource shortage, environmental pollution and carbon emission caused by traditional petroleum-based asphalt materials have affected the global pavement paving industry. The research on biomass materials is urgent, which will also be the "revolution" of pavement engineering.

[Fig. 14 here.]

7.1 Economic benefits

7.1.1 Cost analysis

On the one hand, the price of biomass raw materials and wastes is relatively low. Replacing petroleum-based asphalt binder for pavement construction not only reduces the dependence on non-renewable resources, but also saves the high cost of petroleum-based asphalt binder. On the other hand, due to the limitation of biomass material properties, in some cases, it cannot achieve the absolutely high performance of asphalt mixture in some aspects. Therefore, it is necessary to evaluate the economic benefits of bio-asphalt binder and asphalt mixture (Khan et al., 2022). Due to the lack of research on bio-filler in asphalt binder and asphalt mixture, the specific suitable dosage and performance are not clear. The low content of bio-fiber (0.3%-0.5%) has little impact on the overall price. Therefore, the remainder of this section mainly focuses on the comparison between bio-asphalt binder and base asphalt binder. We compare the following two binders: bio-asphalt binder using sawdust as raw materials and 70# base asphalt binder. In addition, it should be noted that the following analysis is based on price collected from China's asphalt and biomass markets in 2021.

The content of sawdust-derived oil in the binder should be selected in the range of 5%-15%, and the contents of 5%, 10% and 15% are selected for comparison. According to the collected price trend of China's 70# baes asphalt (Fig. 15), the annule average price is calculated to be 4118 RMB/ton. Therefore, the average 4118 RMB/ton is taken as the reference price. The price of sawdust oil is about 1400 RMB/ton.

[Fig. 15 here.]

[Table 13 here.]

Factors such as mixing time, mixing method and mixing energy consumption are not considered (as it is already a common industrial practice to mix different grades of asphalt binders now), and only the influence of raw material cost and price is considered. Taking 70# base asphalt binder's 4118 RMB/ton as the relative price 1, it is calculated that the price of sawdust oil bio-asphalt binder with 5% content is 3982 RMB/ton. The price of sawdust oil bio-asphalt binder with 10% content is 3846 RMB/ton, and the price of sawdust oil bio-asphalt binder with 15% content is 3710 RMB/ton. The relative cost proportion coefficients of the three types of asphalt binders are 0.967, 0.943 and 0.901 respectively.

7.1.2 Analysis of pavement performance excellence

The relative evaluation index of pavement performance is used to calculate the excellence of pavement performance (*n*) of asphalt mixture (*m*) among all analyzed mixtures. The calculation method is shown in Equation (1):

$$a_{mn} = \frac{n_{m1}}{n_{1\max}} \quad （1）$$

Where: a_{mn} is the relative evaluation index of pavement performance (*n*) for asphalt mixture (*m*) among all mixtures; n_{m1} is the measured value of pavement performance (*n*) of asphalt mixture (*m*); n_{1max} is the maximum measured value of pavement performance (*n*) among all analyzed mixtures.

The overall performance of asphalt mixture *m* is quantitatively evaluated by the excellence (T_m) of the asphalt mixture, which is defined as in Equation (2):

$$T_m = \sum(a_{mn} \times c_k) \quad （2）$$

Where: c_k is the weight of each individual pavement performance. Three target pavement performance parameters are considered in this study, including the 60 °C dynamic stability (high temperature property), maximum strain by three-point bending test (low temperature property), and freeze-thaw TSR (water sensitivity) of the asphalt mixture. They are all specification parameters in China and have same weights for the evaluation of excellence in this study. So for each individual pavement performance, $c_k = \frac{1}{3}$. For all three parameters, a higher value means a better pavement performance.

Based on the pavement performance test results of a 70# base asphalt mixture and three sawdust oil bio-asphalt mixtures (Oliveira et al., 2011), the overall performance excellence values were calculated by Equations (1) and (2) and the results are presented in Table 14. The pavement performance excellence values of the four types of asphalt mixtures are 0.952, 0.933, 0.795 and 0.759 respectively.

[Table 14 here.]

7.1.3 Economic benefit analysis

The cost-performance ratio of asphalt mixture is the ratio of pavement performance excellence to relative cost. The cost-performance ratio values of the analyzed ordinary asphalt mixture and bio-asphalt mixtures were obtained by calculation and are presented in Table 15. It can be seen from Table 15 that when the content of sawdust oil was 5%, the performance cost ratio was the highest. With the increase of sawdust oil content to 10% and 15%, the performance cost ratio gradually decreased and became lower than that of ordinary asphalt mixture. Although the cost of bio-asphalt binder with high-content bio-component can be significantly lower than a 70# base asphalt binder, it may greatly affect the pavement performance of asphalt mixture. Considering that there are currently very few field trials with bio-asphalt mixture and lack of corresponding cost data of bio-asphalt pavement during the whole service life, only the initial design and construction cost was considered here in this study. With this regard and the performance, 5% sawdust oil bio-asphalt mixture led to good economic benefits. In many aspects, the performance of single bio-oil modified asphalt is often not as good as that of the composite modified asphalt mixture with bio-oil and other modifiers, like SBS polymer. However, due to the lack of comparable test results and evaluation indicators of composite modified bio-asphalt binders, it is difficult to evaluate and analyze the economic benefits of these types of bio-asphalt binders and their mixtures.

[Table 15 here.]

7.2 Environmental benefit

The road transport industry traditionally has high energy consumption and generates high carbon emission. In terms of energy consumption and carbon emission intensity, the asphalt pavement construction process is particularly a large contributor. The carbon emission of asphalt mixture is mainly caused by the consumption of fuel and energy such as coal and diesel, and the high construction temperatures also affect the greenhouse gas emission. According to the Intergovernmental Panel on Climate Change (IPCC), 13.1% of global greenhouse gases come from the road transport industry (Oliveira et al., 2011). According to surveys, the United States consumes about 350 million tons of raw materials in the construction and maintenance of pavements every year. In Europe, the overall consumption of asphalt binder remains high, ranging from 12.89 million tons in 2016 to 10.74 million tons in 2019 (Weir et al., 2022). According to the International Pavement Federation, the greenhouse gas emissions of the transportation industry account for 13% of the global greenhouse gas emissions, of which the CO_2 emissions account for 23%, while the CO_2 emissions from the highway sector are as high as 74% (Huang et al., 2009). Moreover, asphalt fume is also generated during hot processing of asphalt binder. Asphalt fume is a special pollutant, which is mainly composed of liquid hydrocarbon particles and gaseous hydrocarbons and their derivatives. It mainly contains substances such as sulfur dioxide (SO_2), carbon dioxide (CO_2), nitrogen oxides and benzopyrene, some of which may be hazardous for health and the environment, like polycyclic aromatic hydrocarbons. Many researchers are committed to the development of warm mix asphalt (WMA) technology. The production temperature of WMA can be controlled under 130 °C by solvent or surfactant, which will effectively avoid the generation of asphalt fume. However, this technology also has problems such as high cost and is still seeking large-scale field trial and application (Ma et al., 2015). Furthermore, when the asphalt mixture gets into contact with the surface or ground water, a small part of water-soluble components will be leached and enter the water body and possibly cause water pollution.

Bio-asphalt binder contains components from biomass resources, which can be regenerated and recycled in a relatively short time (Manke et al., 2021; Sotoodeh-Nia et al., 2021; Weir et al., 2022). The renewable biomass resources can be converted into cleaner bio-asphalt binder that can partially replace petroleum-based asphalt binder and some can even reduce the construction temperature. In this way, we can reduce dependence on limited oil resources, but also greatly reduce the emission of pollutants and greenhouse gases, improving the environment and protecting the ecology. At the same time, the utilization of biomass resources reduces the pollution and carbon emission associated with disposal of waste biomass materials, such as the combustion of waste straw, pollution of livestock manure, etc. The transfer of carbon from the atmosphere and storage to the highway pavement have been preliminarily verified.

To sum up, bio-asphalt and asphalt mixture have economic and environmental benefits while ensuring certain pavement performance, which also confirms that biomass materials have a good potential to be used in pavements. However, at present, bio-asphalt binders and their mixtures are rarely used in the pavement industry. Most of the existing trials are indoor tests and there is a lack of data from the field. Therefore, it is necessary to strengthen the research, especially the field research and studies on bio-asphalt binders with high-content of bio-components. Related test processes need to be designed and formulated and evaluation indicators proposed. All these efforts will assist in improving the cost-effectiveness of asphalt pavements and maximizing environmental benefits by promoting the large-scale application of bio-asphalt binders and their mixtures.

8 Conclusions

This paper reviewed existing research literature on road biomass materials and classified road biomass materials according to the application form. The preparation methods and applications of different kinds of road biomass materials emerging in recent years were compared, and the performance effects of biomass materials used in asphalt binder and asphalt mixture were summarized. Meanwhile, the economic and environmental benefits of road biomass materials were analyzed. Based on the above-mentioned discussions and analyzes, the following conclusions can be drawn:

(1) According to the application form, biomass materials with great potential for practical application in pavements can be divided into three major categories: bio-oil, bio-fiber, and bio-filler. Their main sources are agricultural and forestry by-products and wastes, livestock manure, and kitchen waste. The existing literature shows that bio-oil is mainly used as asphalt binder modifier at present and the dosage does usually not exceed 15%. Bio-fiber is mainly used as asphalt mixture stabilizer and bio-filler is mainly used as a substitute for commonly used fillers

in asphalt mixture.

(2) Fast pyrolysis is still the most mature and stable method for preparing bio-oil from solid biomass materials, while hydrothermal liquefaction is suitable for the preparation of bio-oil from biomass materials containing a large amount of liquid components. The preparation process of bio-fiber and bio-filler is not uniform and relatively simple, depending on raw materials and actual needs.

(3) On the basis of summarizing recently conducted studies, it is recommended to set the shear temperature at 150-180 °C, the shear rate at 4000-5000 r/min, and the shear time at 30 min as control parameters in most bio-asphalt binder preparation processes. Most bio-oils can improve the low temperature performance and fatigue resistance of asphalt binders, but their effects on high temperature performance and water stability are still controversial. It is recommended to add SBS or other materials (polymer or biomaterials) for compound modification to obtain bio-asphalt binders with better performance.

(4) The bio-fiber can absorb the free binder in the asphalt mixture to form a network structure and connect with each other, which greatly improves the mechanical strength of the asphalt mixture and improves the high temperature stability, low temperature crack resistance and water resistance of the asphalt mixture. Bio-fibers have the advantages of being renewable and degradable, helping to meet the environmental protection requirements of pavements.

(5) The bio-filler can be used to modify asphalt mixtures and replace some fillers. Certain bio-fillers can improve pavement performance to some extent. However, there are few studies on bio-fillers at present, and no systematic research has been conducted yet, and its potential remains to be discovered.

(6) The calculation in this study shows that the cost performance ratio of bio-asphalt binder has the potential to surpass that of ordinary asphalt binder. Due to the environmental benefits from biomass materials, bio-asphalt binder is expected to become a substitute for petroleum-based asphalt binder from non-renewable resources in the future. At the same time, it provides a reference for related authorities on the application prospect of biomass materials in pavements.

9 Future work

This paper is a comprehensive review of the application and effects of biomass materials on pavement. The application of biomass materials in pavement has been proven feasible and the research efforts have been fruitful in all aspects, but there are still difficulties in the distance hindering from completely replacing petroleum-based asphalt binder in pavement. Therefore, there are some recommendations for future study:

(1) Due to the variety of biological wastes and other factors, the properties of the produced bio-oil are very different. At present, there are few manufacturers that specialize in providing pavement bio-oil. At the same time, most of the bio-oil obtained by research is a by-product of other oil products, which contains many impurities. If the joint preparation system of bio-oil and asphalt binder can be established, and the specific properties of bio-oil can be controlled according to the performance needs of bio-asphalt binder, the usability and research value of bio-asphalt binder will be significantly improved.

(2) At present, the research on bio-oil asphalt binder is mostly limited to the macro-scale, and the micro-mechanism of bio-asphalt modification is rarely investigated. Modern analysis and testing techniques and numerical simulations, such as time-of-flight secondary ion mass spectrometry, infrared microscopy, phase-filed modeling, and molecular dynamics (MD)

simulation, should be further used to study the interaction behavior between components of bio-oil molecules at the microscopic and molecular scales, and establish numerical models to provide theoretical support for further research.

(3) Composite modification is currently an effective way to increase the content and utilization of biomass materials in pavements. It is particularly important to explore suitable composite combinations of materials and related preparation and evaluation methods. The existing literature has shown the effectiveness of using SBS together with bio-oil in asphalt binder. Due to the high carbon footprint of SBS co-polymer, however, the overall environmental performance of such binders is still questionable. The search for a fossil-free alternative to SBS could be a research direction for future studies. Meanwhile, the use of different types of biomass materials in a single binder has not been researched very much. This could be an approach leading to firstly increased amount of bio-based materials in the binder and eventually a complete replacement of the petroleum-based asphalt binder. Life cycle analysis of bio-based modification of asphalt pavements will be helpful to inform the design for optimal content that take into account durability and circularity, but will need to address challenges such as cross-sector boundary setting.

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Table 1

Some previous summary and comparison of pavement biomass materials.

Keywords	Main efforts	Reference
Characterization of biomass, biochar, bio-oil	The biomass characterization, elements, structural components were analyzed. The effects of bio-oil and biochar on asphalt were analyzed.	Penki and Rout, 2021
Waste oil, modification, rejuvenation	The state of the art, preparation process and property comparison, aging and asphalt rejuvenation, and modified asphalt were reviewed.	Yan et al., 2022
Application of lignin	This paper summarized the application of lignin and its derivatives in sustainable construction and pointed out the future development direction of lignin.	Jędrzejczak et al., 2021
Thermochemical conversion technology, road bio-binder	The relationship between biomass thermochemical conversion technology and their respective products was reviewed, with emphasis on the introduction of road bio-binder.	Weir et al., 2022
Bio-oil, aging	This paper summarized the changes of chemical composition, physical and chemical properties and multiphase behavior of bio-oil with aging, and the methods to improve the anti-aging ability of bio-oil.	Cai et al., 2021
Bio-oil and asphalt additives	Bio-oil and its application, and effect as asphalt additive were reviewed.	Zhang et al., 2021
Waste cooking oil, recycling	The latest research on asphalt rejuvenation with waste cooking oil and the effect of waste cooking oil on the properties of asphalt binder were summarized and reviewed.	Zahoor et al., 2021

Table 2

Cellulose, hemicellulose, lignin content of different typical agricultural and forestry biomass (wt % dry basis).

Biomass	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	References
Rice straw	37.8	25.3	23.3	Jung et al., 2008
Rice husk	34.7	17.4	25.5	Cao et al.,2017
Wheat straw	41.2	27.7	18.5	Cao et al.,2017
Corn stover	38.8	23.5	20.2	Cao et al.,2017
Bamboo	26.0	30.0	21.0	Vinod et al.,2020

Table 3

Chemical composition of common animal manure (d.w.%)[a].

	Crude fats	Crude protein	Hemicellulose	Cellulose	Lignin	Reference
Swine manure[b]	20.3±1.5	24.5±1.8	27.3±2.2	3.8±1.4	3.6±1.3	Chen et al., 2014
Cattle manure	0.8	16.78	0.04	12.84	18.28	He et al., 2021
Cattle manure	1.1	-	19.4	13.2	12.5	Fang et al., 2021
Fish sludge	13.06	47.19	-	-	-	Conti et al., 2020

[a] Dry weight basis.

[b] Average values.

Table 4

Basic properties of different types of bio-oils.

Biomass/ Petroleum asphalt	Elemental analysis (wt%)				Fuel properties						Reference
	C	H	N	O	Viscosity	Water content (wt%)	HHV (MJ/kg)	pH	Density (g/ml)	Acid value (mg of KOH/g)	
Oak wood	59.99	7.18	0.92	31.91	173.35^{a}	15.15	24.87	-	-	-	Kumar et al., 2020
Pine wood	42.60	8.47	0.08	48.85	175^{a}	-	19.5	-	-	-	Kumar et al., 2020
Corn stover	-	-	-	-	1.60^{c}	54.7	2.66		1.08	85.8	Kumar et al., 2020
Softwood	39.96	7.74	0.11	52.19	67.39^{a}	28.05	15.27	-	1.20	79.23	Kumar et al., 2020
Bamboo	41.39	7.03	2.01	49.55	-	35	17.47	-	-	-	Jung et al., 2008
Rice straw	49.19	5.55	1.83	43.10	-	8	18.6	2.73	-	-	Jung et al., 2008
Chlorella protothecoides	62.07	8.76	9.74	11.24	-	-	29-41	-	-	-	Li et al., 2019
Spirulina	67.52	9.82	10.71	11.34	-	-	29.3	-	-	-	Li et al., 2019
Cyanobacteria	67.58	8.95	7.75	14.48	-	-	31.9	-	-	-	Li et al., 2019
Food waste	51.26	7.65	4.46	36.22	-	-	-	-	-	-	Chen et al., 2019
Cattle manure	38.53	5.28	2.03	54.16	-	-	10.87	-	-	-	Fang et al., 2021
Swine manure	72.58	9.76	4.47	13.19	843^{b}	-	36.05	-	-	-	Xiu et al., 2010
Petroleum asphalt	80-88	8-12	0-2	0-2	-	-	-	-	-	-	Mortazavi and Moulthrop, 1993

Units of viscosity, a-mPa·s; b-cP; c-cSt; d-mm^{2}/s.

Table 5

Comparison of the properties of bio-fiber and mineral fiber.

Selection of fiber	Main findings	Reference
Basalt fiber, polyester fiber, lignin fiber	1) Lignin fiber has better lipophilicity. 2) Lignin fiber has better bonding with asphalt. 3) Basalt fiber mixed with asphalt mixture has the best road performance.	Cai, 2019
Basalt fiber, polyester fiber, lignin fiber	1) Basalt fiber can improve the high temperature stability, low temperature crack resistance and water sensitivity of asphalt mixture. 2) Lignin fiber has stronger asphalt adsorption and water absorption. 3) Lignin fiber has poor thermal stability.	Guo et al., 2020
Mineral fiber, flocculent lignin fiber, granular lignin fiber	1) The oil absorption rate of flocculent lignin fiber is the highest. 2) The road performance of mineral fiber is better after adding to mixture. 3) The fatigue resistance of mineral fiber is better.	Liu, 2018
Basalt fiber, polyester fiber, lignin fiber	1) Basalt fiber is the best to improve the road performance of asphalt mixture.	Kong and Li, 2020

Table 6

Preparation parameters and conditions of bio-asphalt binder.

Biomass	Reference	Process
Poplar sawdust	Ding et al., 2018	High speed shear at 165 °C, 4500 r/min
Pine kraft Lignin	Wu et al., 2017	High speed shear at 165 °C, 4500 r/min
Lignin	Batista et al., 2018	High speed shearing for 60 min at 160 °C and 5000 r/min
Catering waste oil	Zhang et al., 2018	High speed shear for 30 min at 135 °C and 5000 r/min
Waste engine oil	Fernandes et al. 2017	High speed shearing at 180 °C and 7200 r/min for 20 min

Table 7 Performance of bio-asphalt binders.

Plant fiber materials.

Biomass	Reference	Preparation process		Performance
		Bio-oil	Bio-asphalt	
Sawdust	Cao et al., 2019	Sawdust liquefaction	Shear rate 2500r / min, shear temperature 250 ℃	The ductility does not meet the requirements when the content is 20%.
Poplar sawdust	Ding et al., 2018	Liquefy at 160 ℃, add sodium hydroxide and formaldehyde and keep it at 90 ℃ for 40 min to obtain thermoplastic phenolic resin	Shear rate 4500r / min, shear temperature 165 ℃	Good high temperature rutting resistance.
Pine kraft lignin	Wu et al., 2017	-	Shear rate 4500r / min, shear temperature 165 ℃	The high temperature stability is improved, and the low temperature crack resistance is not ideal, which can effectively delay the aging of asphalt.
Castor seed	Zeng et al., 2019	-	The bio-modified asphalt was prepared at 105 ℃ and 1500 r/min	Bio-asphalt and composite modified asphalt have good high temperature stability.
Wheat stalk	Guo and Liu, 2019	① Slow pyrolysis method: react at 400 ℃ for 6h to obtain 33% bio-oil and 28% biochar	-	The increase of pyrolysis temperature and long time are conducive to the rupture of lignin ether bond to form phenol, and the

Biomass	Reference	Preparation process		Performance
		Bio-oil	Bio-asphalt	
		② Fast pyrolysis method: pyrolysis at 500 ℃/1s, 500 ℃/2s, 600 ℃ /1s and 600 ℃/ 2s, and the yield of bio-oil is 30%, 37%, 42% and 40% respectively	-	rapid pyrolysis product is better.
Lignin	Xu et al., 2017	-	The shear rate is 1500r/min, the shear temperature is 163 ℃, and the shear time is 30min	The addition of lignin significantly improves the high temperature rutting resistance of asphalt binder.
Corn straw, oak chips, etc	Ding et al., 2018	-	Add 3%, 6%, 9%, 12% wood resin to base asphalt at 140℃ and perform high-speed shearing	Adding wood resin can improve high temperature performance, anti-aging performance and temperature sensitivity.
Corn straw, oak chips, etc	He et al., 2015	-	Add 3%, 6% and 9% bio-oil into the base asphalt	When mixed with bio-oil, the high temperature grade decreases slightly, but not significantly.

Livestock manure.

Biomass	Reference	Preparation process		Performance
		Bio-oil	Bio-asphalt	
Pig manure	Fini et al., 2011	Hydrothermal liquefaction	-	With the increase of bio-oil content, the asphalt pavement has better low temperature performance.

Biomass	Reference	Preparation process		Performance
		Bio-oil	Bio-asphalt	
Pig manure	Hill et al., 2018	-	The shear rate is 1000r/min, the shear temperature is 200 °C, and the shear time is 30min	High temperature viscosity of asphalt decreases, high temperature performance decreases and low temperature performance improves.
Pig manure	Fini et al., 2011	-	The shear rate is 1600r/min, the shear temperature is 120 °C, and the shear time is 30min	Improve asphalt complex modulus, high temperature performance and aging resistance.
Pig manure	Hill et al., 2018	Hydrothermal liquefaction	-	Significantly improve low temperature performance.
Pig manure	Zhang et al., 2017	Hydrothermal liquefaction	-	The viscosity of asphalt is reduced, and the low temperature performance is improved.

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1408 Kitchen waste materials.

Biomass	Reference	Preparation process		Performance
		Bio-oil	Bio-asphalt	
Catering waste oil	Zhang and Zhang, 2018	-	3%, 5%, 7% bio-oil blending ratio, shear rate 2000r/min, shear temperature 135 °C, shear time 30min	Low content of bio-oil improves the high temperature stability and low temperature performance of asphalt.
Catering waste oil	Cong et al., 2020	-	The shear rate is 1800r/min, the shear temperature is 145 °C, and the shear time is 30min	The ductility of asphalt is increased, the softening point is reduced, and the low temperature crack resistance is improved.

Biomass	Reference	Preparation process		Performance
		Bio-oil	Bio-asphalt	
Catering waste oil	Rasman et al., 2018	-	1%, 2%, 3% bio-oil blending ratio, shear rate 1000r/min, shear temperature 163 °C, shear time 1h	The viscosity of asphalt is reduced, and the high temperature performance is poor.
Catering waste oil	Wang et al., 2013	Add 10% and 15% crumb rubber into the bio-oil	-	It can completely replace petroleum asphalt.

Table 8

Pavement performance of bio-asphalt mixture.

Bio-oil raw materials	Content (wt%)	High temperature performance	Low temperature performance	Water stability	Fatigue resistance	Reference
Factory bio-oil	5%, 10%, 15%, 20%	Reduce	-	-	-	Gao et al., 2017
Straw and fruit shell	-	Increase	Reduce	Reduce	-	Tang, 2017
Mixed bio-oil	5%, 7%, 9%	Increase	Increase	Increase	-	Zhao et al.,2020
Castor seed	5%, 10%, 15%, 20%	Reduce	Increase	Reduce	-	Zeng et al., 2017
Waste cooking oil	10%, 30%, 60%	Reduce	Increase	-	Reduce	Wang et al.,2015
Waste cooking oil	3%, 5%, 7%	Reduce	Increase	-	Increase	Hill et al.,2018
Castor seed	12.5%, 22%, 30%, 36%	Increase	Reduce	Reduce	-	Zeng et al.,2019
Sawdust	5%, 10%	Reduce	-	Reduce	Increase	Yang and You, 2015
Pine	20%, 25%, 25.5%, 30%	Increase	Reduce	Increase	-	Mohammad et al.,2013

Table 9

Pavement performance of bio-fiber asphalt mixture.

Reference	Bio-fiber	Content in asphalt mixture	High temperature performance	Low temperature performance	Water stability
Zhou and Lu, 2020	Lignin fiber	0.2%, 0.3%, 0.4%	Increase	Increase	Increase
Lei et al., 2016	Cotton straw fiber	0.2%, 0.3%	Increase	Increase	Increase
Nie et al., 2021	Fast growing grass fiber	0.4%	Reduce	Increase	Increase
Li et al., 2019	Corn straw fiber	0.27%	Increase	Increase	Increase
Xue et al., 2013	Straw composite fiber	0.2%, 0.3%、 0.4%, 0.5%、 0.6%, 0.7%	Increase	Increase	Increase
Liu et al., 2020	Cotton straw fiber	0.20%	Increase	Reduce	Increase

Table 10

MSCR parameters of different asphalt binders with bamboo fibers (Cui et al., 2022; Copyright source: Elsevier).

Binder type	R0.1 (%)	R3.2 (%)	R_{diff} (%)	$J_{nr}0.1$ (kPa^{-1})	$J_{nr}3.2$ (kPa^{-1})	$J_{nr\text{-}diff}$ (%)
Base asphalt	4.33	0.01	99.77	2.7112	3.1479	8.88
UBF asphalt	4.45	0.02	99.55	2.6681	2.9049	16.11
STBF asphalt	7.16	0.35	95.11	1.7749	2.4060	35.56
ATBF asphalt	4.82	0.10	97.93	2.1741	2.5078	15.35
HTBF asphalt	3.97	0.08	97.98	2.3827	2.7185	14.09

Note: alkali treated bamboo fibers (ATBF); silane coupling agent treated bamboo fibers (STBF); heat treated bamboo fibers (HTBF); untreated bamboo fibers (UBF).

Table 11

Aging index of the asphalt binders with fish scale powder (Lv et al., 2021; Copyright source: Elsevier).

Binder types	58℃	64℃	70℃	76℃
base binder	2.50	2.36	2.36	2.11
FS4	2.47	2.31	2.31	2.03
FS8	2.56	2.38	2.19	1.88
FS12	3.24	3.22	3.05	3.02
FS16	4.19	3.99	3.64	3.23

FS4: 4% fish scale powder modified bio-asphalt was added to the matrix asphalt.

Table 12

Test results of asphalt mixtures with rice husk ash (RHA) as filler, compared to hydrated lime (HL), (Data source: Mistry et al., 2019).

Item	Temperature	2% HL	4% HL	6% HL	8% HL	2% RHA	4% RHA	6% RHA	8% RHA
OBC(%）	-	5.21	5.18	5.33	5.59	5.14	4.9	5.33	5.42
ITS (kPa)	60℃	1068	810	930	1000	1100	1540	1330	1265
Freeze-thaw TSR (%)	60℃	95.3	84.7	81.3	67.3	90.3	97.4	86.8	81.7

OBC: optimum binder content; ITS: indirect tensile strength of asphalt mixture; TSR: tensile strength ratio

Table 13

Cost analysis of different types of asphalt binders with sawdust oil.

Types	Price (RMB/ton)	Relative cost proportion coefficient
70# base asphalt binder	4118	1
5% sawdust oil bio-asphalt binder	3982	0.967
10% sawdust oil bio-asphalt binder	3846	0.934
15% sawdust oil bio-asphalt binder	3710	0.901

Table 14

Overall evaluation index of pavement performance of bio-asphalt mixtures with sawdust oil.

Type	Individual pavement performance			Overall pavement performance excellence
	Dynamic stability	Maximum strain	Freeze-thaw TSR	
70# base asphalt mixture	1	0.857	1	0.952
5% sawdust oil bio-asphalt mixture	0.917	0.913	0.970	0.933
10% sawdust oil bio-asphalt mixture	0.536	0.97	0.881	0.795
15% sawdust oil bio-asphalt mixture	0.576	1	0.702	0.759

Table 15

Cost performance ratio of bio-asphalt mixtures with sawdust oil.

Type	Cost performance ratio
70# base asphalt mixture	0.952
5% sawdust oil bio-asphalt mixture	0.965
10% sawdust oil bio-asphalt mixture	0.851
15% sawdust oil bio-asphalt mixture	0.842

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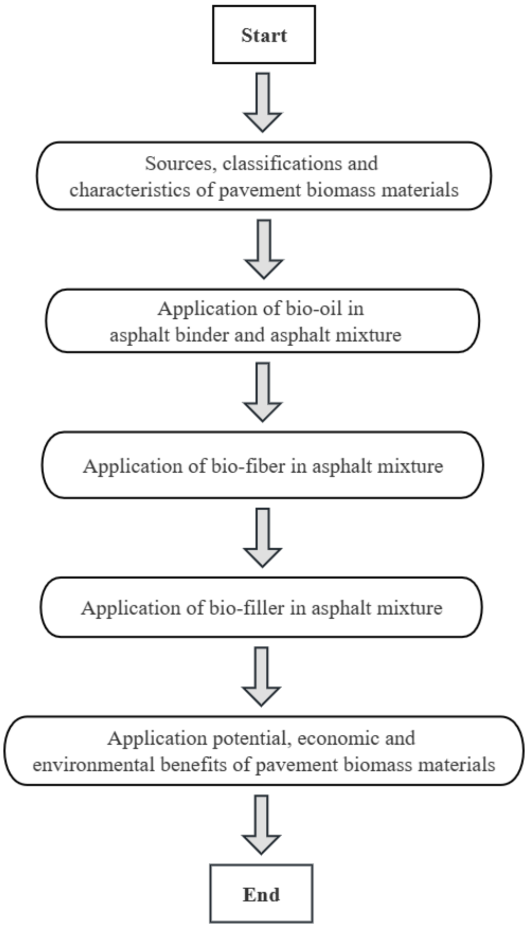

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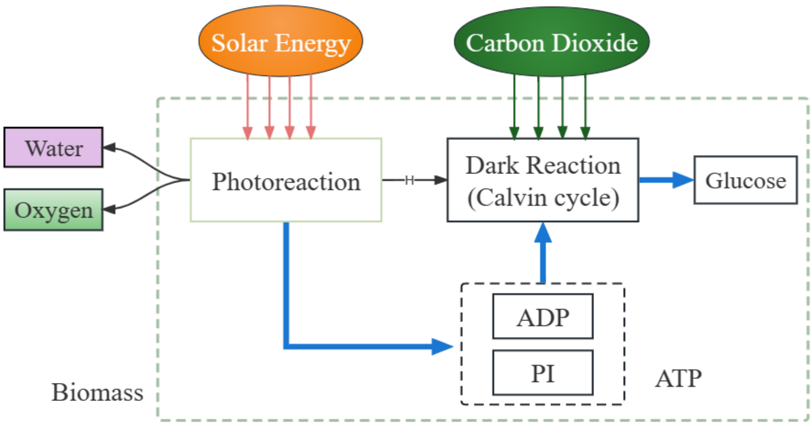
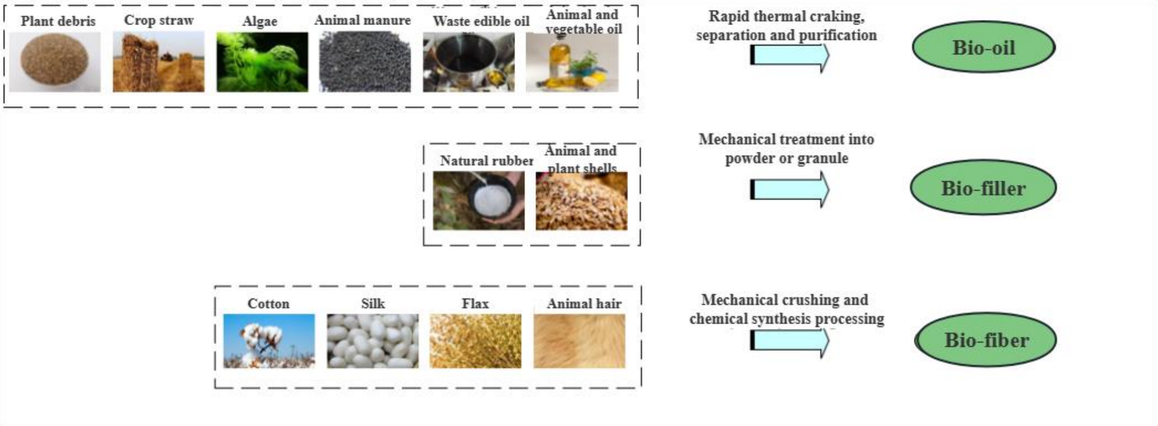
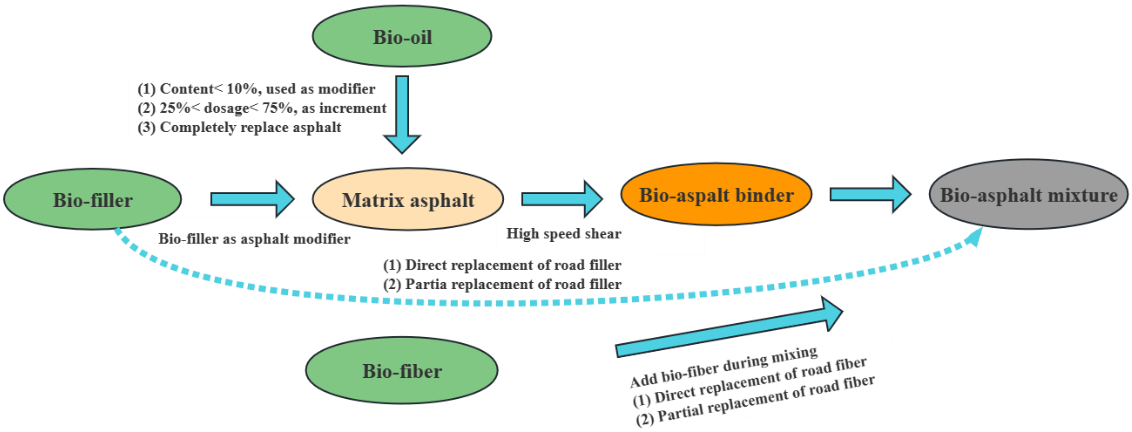


ATP: adenosine triphosphate $C_{10}H_{16}N_5O_{13}P_3$; PI: inorganic phosphate HPO_4^{2-};
ADP: adenosine diphosphate $C_{10}H_{15}N_5O_{10}P_2$

Fig. 2. Biomass energy conversion diagram.

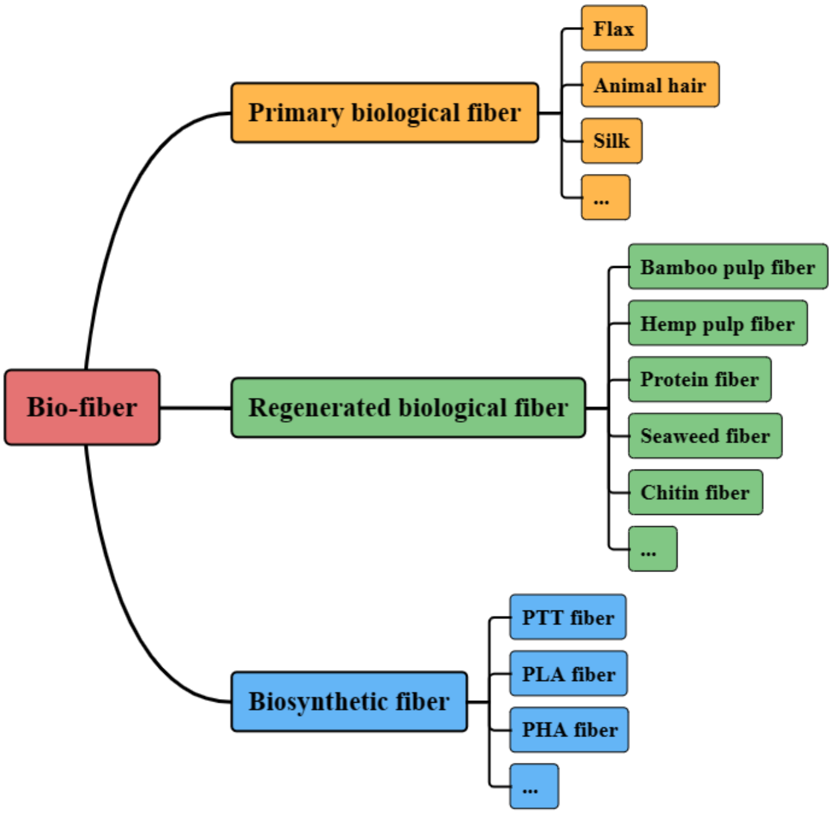


(a) Classification of pavement biomass materials.



(b) Application method of pavement biomass materials.

Fig. 3. Classification and application of pavement biomass materials.



PTT fiber: polyterephthalic acid 1,3 propylene glycol ester fiber
PLA fiber: polylactic acid fiber
PHA fiber: polyhydroxyl fatty acid ester fiber

Fig. 4. Classification of bio-fibers.

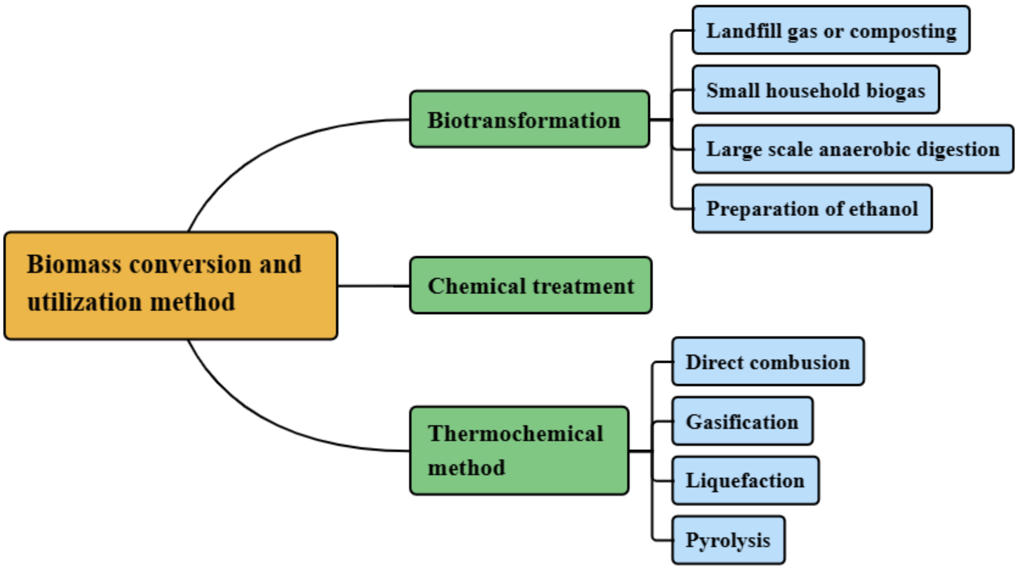
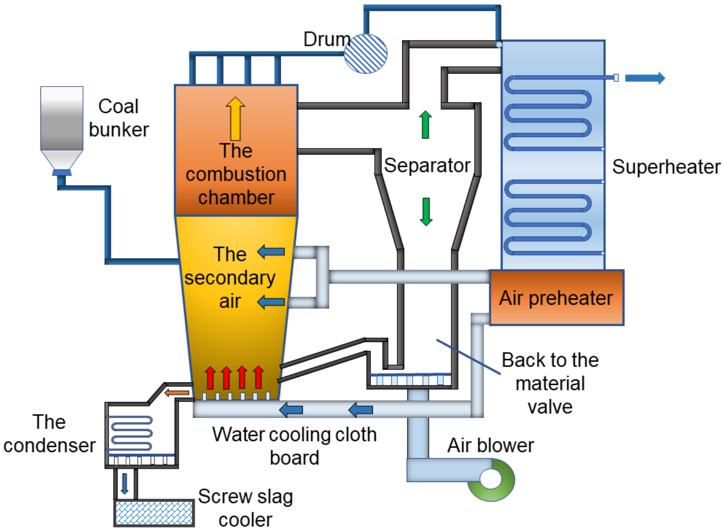


Fig. 5. Biomass conversion and utilization methods.



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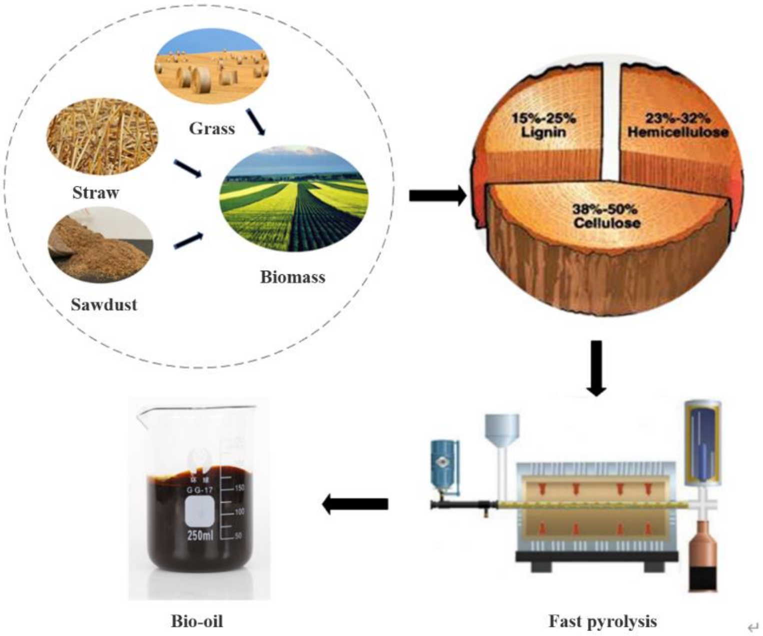

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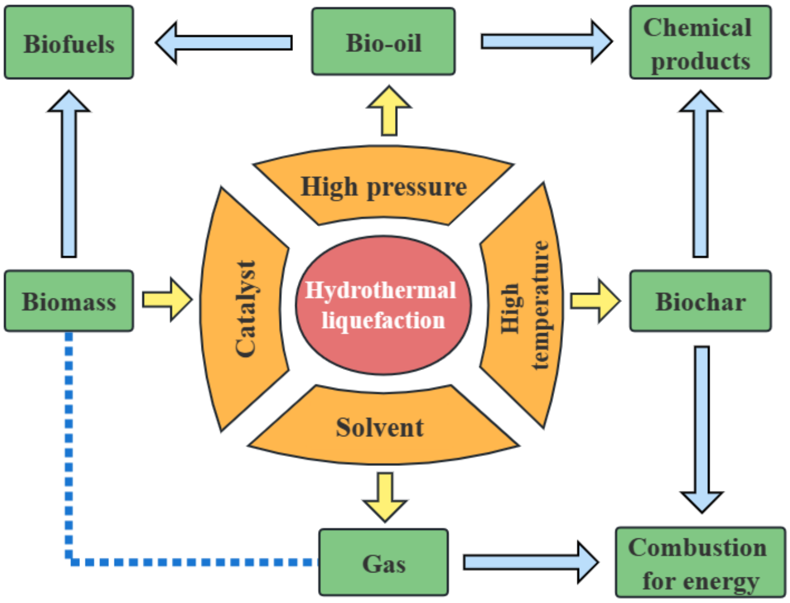

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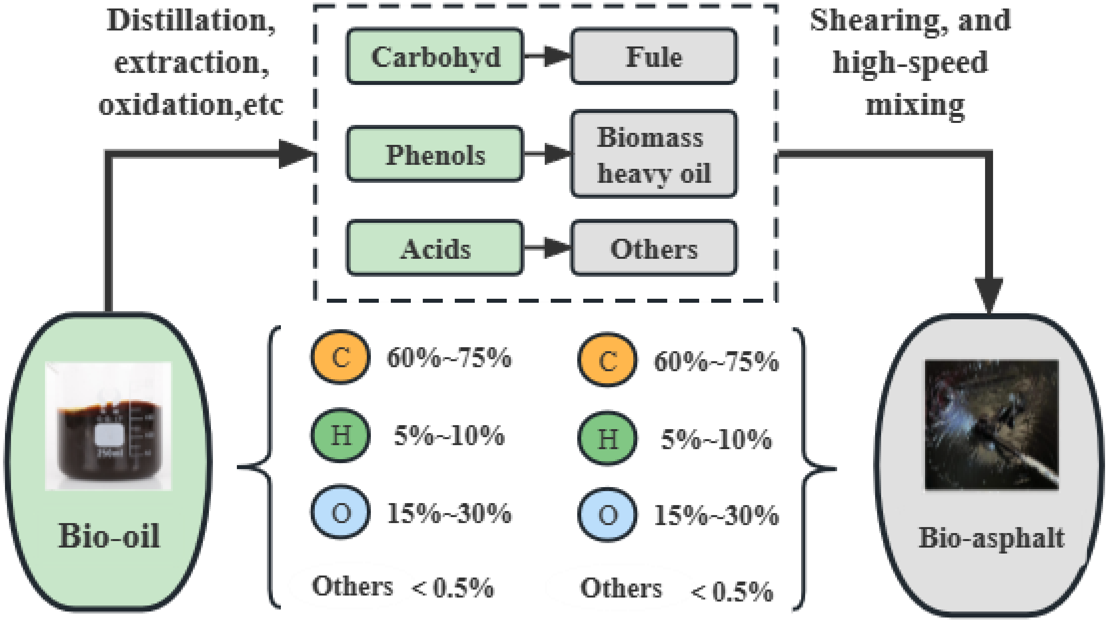

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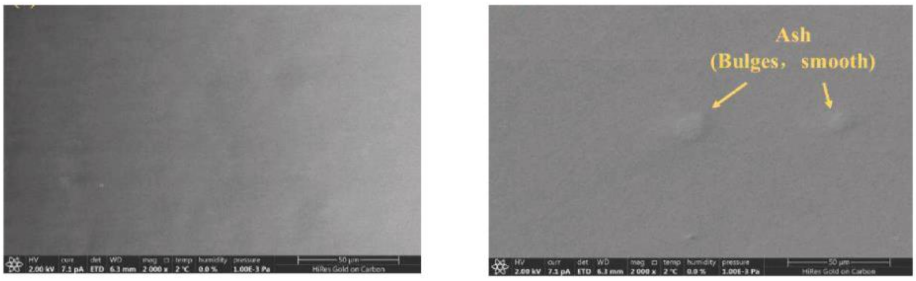
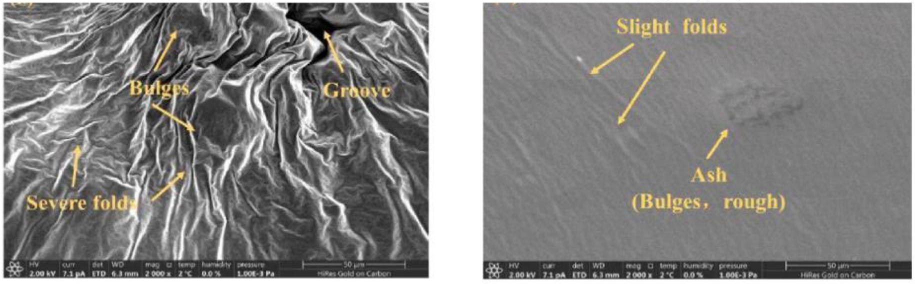


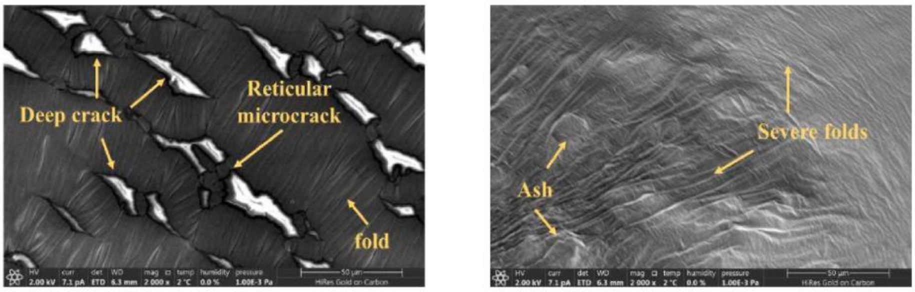
(a) Base bitumen (uaged)

(b) Composite modified bitumen (uaged)



(c) Base bitumen (short-term aging)

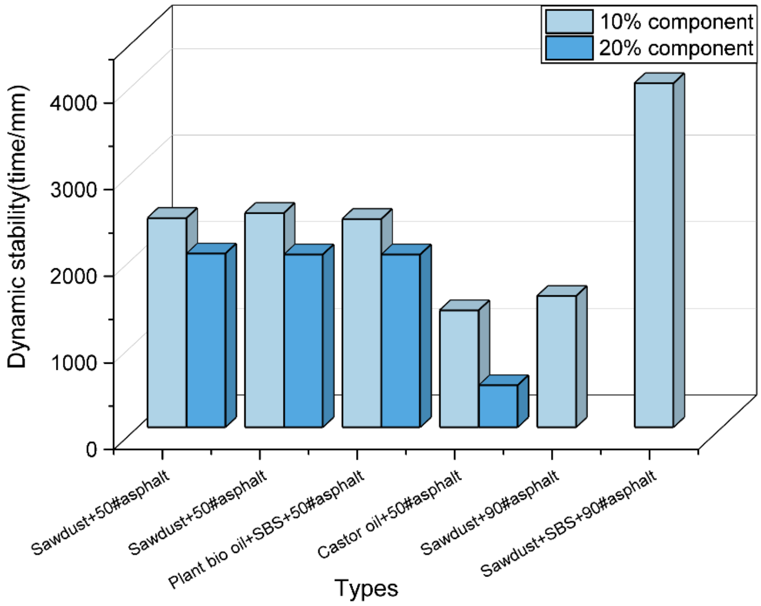
(d) Composite modified bitumen (short-term aging)



(e) Base bitumen (long-term aging)

(f) Composite modified bitumen (long-term aging)

Fig. 10. SEM of asphalt at different aging stages (Meng et al., 2022; Copyright source: Elsevier).



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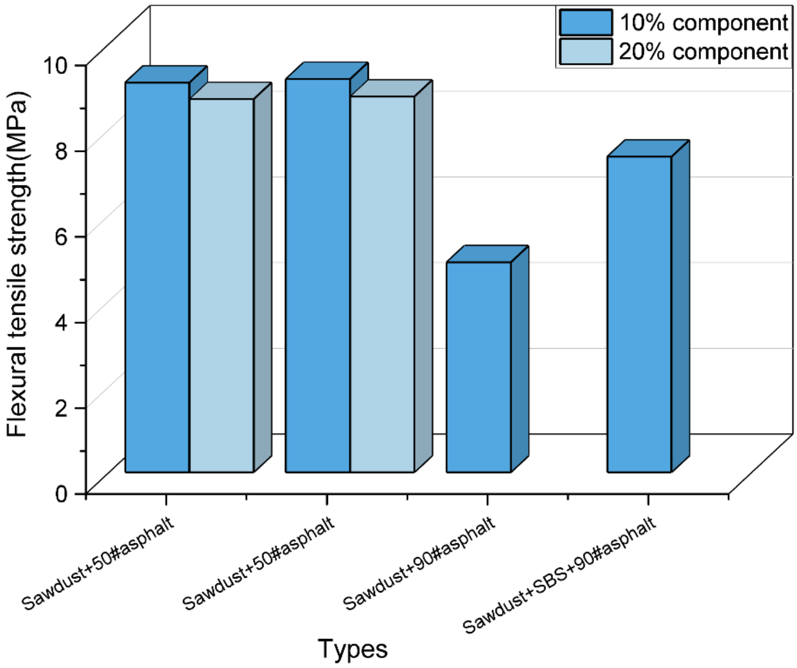

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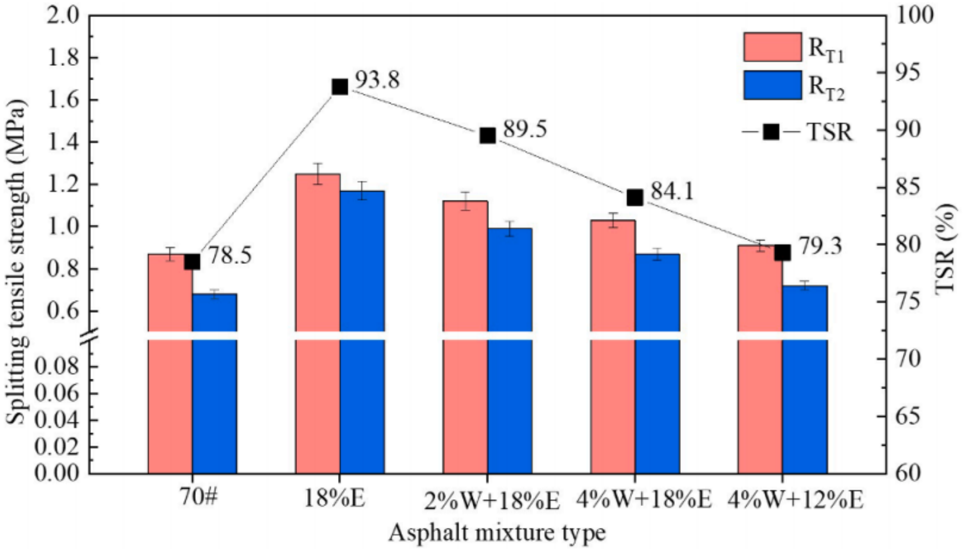

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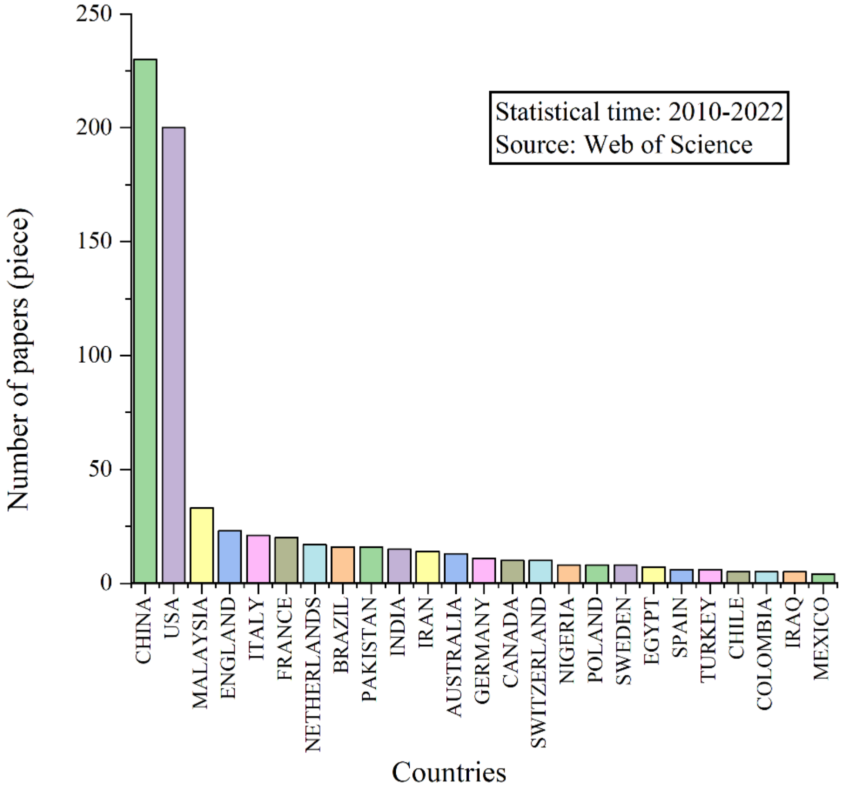

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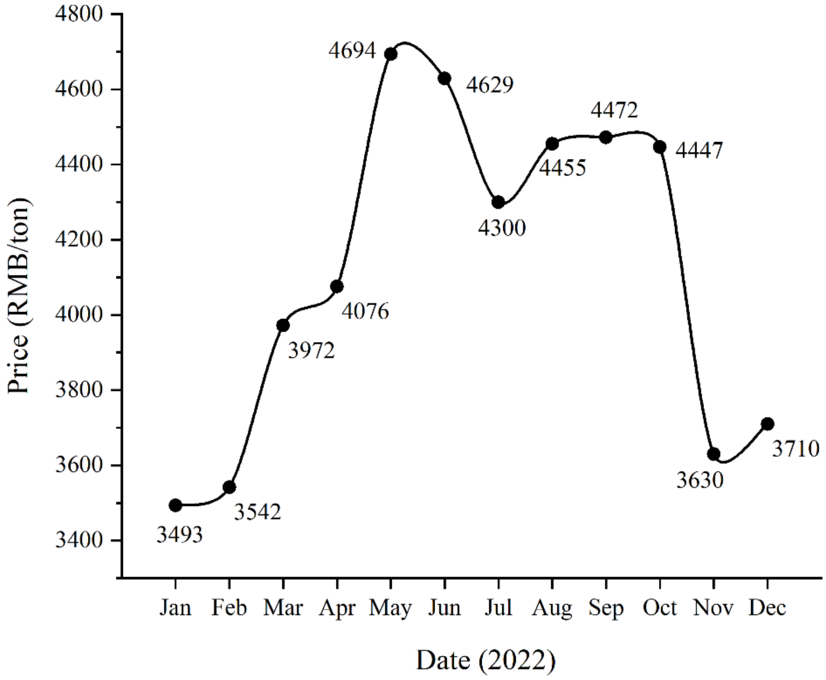

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