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Physical–chemical properties of aged asphalt rejuvenated by bio-oil derived from biodiesel residue

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HIGHLIGHTS

- Bio-oil could be used to rejuvenate aged asphalt.
- Rejuvenation effects are different for base and polymer modified asphalts.
- Physical properties of aged asphalt are enhanced after mixing with bio-oil.
- Anti-moisture performance of rejuvenated asphalt need to be further investigated.

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ABSTRACTS

Use of bio-binder could address depletion of petroleum oil, pollution from residue waste, greenhouse gases emissions, and development of sustainable asphalt pavement that is both economically and environmentally friendly. This study investigated the physical and chemical properties of bio-oil rejuvenated asphalt with a series of test. A pre-treatment procedure was introduced to upgrade the biodiesel residue produced from waste cooking oil. Aged asphalt was prepared with a laboratory short-term aging method. The optimal content of the bio-oil was determined by conventional tests and related index, such as penetration, softening point, and ductility, to rejuvenate aged asphalt to its virgin level. Rheological properties, including viscosity, high-temperature rutting resistance, and low-temperature cracking resistance, of virgin, aged, and bio-oil rejuvenated asphalts were then investigated. Afterward, asphalt fraction components, functional groups, and microstructures of virgin, aged and bio-oil rejuvenated asphalts, together with the molecular information of bio-oil, were analyzed with the aid of micro testing techniques. Finally, the moisture susceptibilities were evaluated by conducting micro mechanical experiments. Results clearly demonstrate that bio-oil could soften aged asphalt and improve its low-temperature cracking resistance. Workability was improved due to the reduction of viscosity. Moreover, bio-oil was found to be a complex organic mixture with low molecular weight. Bio-oil was able to compensate aged asphalt for the loss of light components and may also interact with polymer in modified asphalt. Meanwhile, the aggregation of polar components after aging can be mitigated. Thus, the properties of aged asphalt would be enhanced with the addition of bio-oil rejuvenator. However, the anti-moisture performance of bio-oil rejuvenated base (Pen50) asphalt needs to be further improved due to the presence of hydrophilic functional groups and components. In sum, this paper presents the superiorities and potential application challenges of using biodiesel-residue-based bio-oil to rejuvenate aged asphalt.

1. Introduction

Conventional asphalt binders used in pavement are derived from fossil fuels. However, with petroleum oil reserve becoming depleted, increasing construction costs and strong demand for asphalt have encouraged the development of alternative binders to modify or even replace conventional binders [1–7].

Recently, through comprehensive research on and significant development toward converting renewable resources into bio-oil, great efforts have been made to build an eco-friendly energy system [8–11]. However, only a few studies address the specific issues of building sustainable asphalt pavement with bio-oil based binders [12–14].

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Essentially, bio-oil is a kind of dark brown organic liquid, which consists of various highly oxygenated compounds [3]. Bio-oil can be produced from various raw materials, such as swine manure, soy, and different kinds of vegetable oil [1,2,15]. In China, waste cooking oil, which can cause serious social and environmental problems, has been converted into bio-fuel and widely used. This technology not only disposes of a hazardous waste, but also produces low-cost clean energy. However, dealing with the residue from the biodiesel production process is problematic. Biodiesel residue contains complex compounds and can't be used as a fuel because of its low combustion value.

At the same time, asphalt pavement maintenance has become a critical issue in China. Highly oxidized asphalt treated by a rejuvenator can be reused in pavement reconstruction, and reuse has significant economic and environmental benefits. Many types of rejuvenators have been successfully applied to asphalt pavement projects in various countries. However, the feasibility of applying biodiesel residue-based oil, bio-oil namely, to rejuvenate asphalt has not been well investigated. From a technical perspective, bio-oil and asphalt are expected to be compatible due to their similar chemical compositions [2]. Furthermore, bio-oil may compensate for the loss of light components due to volatilization and oxidation of asphalt, and thus reverse the imbalance of asphalt fractions. If the performance of bio-oil rejuvenated asphalt could meet the pavement requirement, this technology would not only take advantage of waste biodiesel residue and waste asphalt, but also build sustainable asphalt pavement that is renewable and environmentally friendly. Greenhouse gas emission and energy consumption would also be reduced.

Although bio-oil has distinct advantages over traditional fuel, the knowledge about physical and chemical properties of biodiesel-residue-based oil rejuvenated asphalt is lacking. Moreover, few tests have been conducted to determine the moisture susceptibility of bio-oil modified asphalt binders. This limited knowledge has been the motivation for this investigation. The objectives of this research are as follows:

1. Determine the optimal content of bio-oil.
2. Investigate the viscosities, high temperature rheological properties and low temperature cracking resistances of virgin, aged and bio-oil rejuvenated (at optimal content) asphalts.
3. Characterize the chemical composition of bio-oil.
4. Analyze the composition transformations of virgin, aged and bio-oil rejuvenated asphalts.
5. Observe the microstructures and evaluate the moisture susceptibilities of virgin, aged and bio-oil rejuvenated asphalts.

It is anticipated that this study will fill the gap for using bio-oil to rejuvenate aged asphalt and promote wider application of sustainable resources produced from waste cooking oil.

2. Experimental section

2.1. Materials

2.1.1. Asphalt

The virgin asphalts used in this study were Pen50 asphalt and styrene–butadiene–styrene (SBS) modified asphalt, respectively. Aged asphalt was obtained by aging virgin asphalts using the thin-film oven test (TFOT) method. The basic properties of virgin and aged asphalts are present in Table 1.

Table 1
Properties of asphalts.

Property	Pen50		SBS modified	
	Virgin	Aged	Virgin	Aged
Penetration (25 °C, 5 s)/0.1 mm	53	37	66	50
Ductility (10 °C)/cm	32	Brittle failure	56	14
Softening point/°C	55	60	64	70

2.1.2. Bio-oil

Waste cooking oil is used to produce biodiesel, which mainly consists of esters and glycerol, by reacting with alcohol through esterification using catalyst, a practice that is financially supported by Chinese government policy. Since chemical companies dispose of their waste to meet environment protection guidelines, reducing their profit, companies were pleased to donate the biodiesel residue for us to incorporate into asphalt binder, rather than having it burned or landfilled, like scrap tires [16].

In our pre-experiment, we found that asphalt binder tended to flow at room temperature after it was mixed with 0.5 wt.% residue. In addition, this residue was likely to separate into two layers if it was left standing for 10 min. We concluded that the presence of water and volatile content were responsible for the upper layer. An upgraded procedure was adopted to dispose this layer, preventing it from separating.

The biodiesel residue was distilled until dark viscous liquid came out of the condenser pipe. The temperature of the liquid was approximately 100 °C, indicating the evaporation of water and volatiles.

After distillation, the beaker was cooled to room temperature and the remaining bio-oil was collected. The basic properties of bio-oil were tested; specific information is present in Table 2.

2.1.3. Bio-oil rejuvenated asphalt

Considering the similarities in the chemical compositions of asphalt and bio-oil, they were expected to be compatible. Liquid asphalt and bio-oil mixtures were stirred for 10 min at 130 °C for Pen50 asphalt and 160 °C for SBS modified asphalt to prepare a homogenous bio-binder.

2.2. Experimental scheme

The framework is illustrated in Fig. 1.

Using the weight of asphalt binder, the mass of bio-oil was calculated based on the desired percentages, from 0 wt.% to 3 wt.% respectively. Following the preparation procedure, the basic properties of rejuvenated asphalt were investigated using conventional laboratory performance tests, including penetration test, softening point test and ductility test. The concentration of bio-oil that restored aged asphalt to its virgin properties was considered the optimal bio-oil concentration.

Virgin, aged and bio-oil rejuvenated asphalt samples were also tested using the rotational viscometer (RV) and dynamic shear rheometer (DSR) to determine the high-temperature rheological properties related to mixing workability at 135 °C, and rutting resistance in the 52–82 °C range, respectively. The bending beam rheometer (BBR) was used to investigate the low temperature cracking resistances of asphalt samples at both −12 °C and −18 °C.

After that, gas chromatography–mass spectrometry (GC–MS) and Fourier transform infrared spectroscopy (FTIR) were conducted to analyze the chemical composition of bio-oil, which provide an important insight into the nature of this rejuvenator. The

Table 2
Properties of bio-oil.

Density (g/cm^3)	Flash point (°C)	Burning point (°C)	State
0.922	200	230	Viscous liquid