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Mechanical performance of asphalt mixtures modified by bio-oils derived from waste wood resources

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HIGHLIGHTS

- Effect of bio-oils on mechanical performance of asphalt mixture is investigated.
- Bio-oil can improve asphalt mixture fatigue performance significantly.
- Polymer modified bio-oil performs better than original and dewatered bio-oils.
- Statistical analysis are conducted for the laboratory results.

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ABSTRACT

Bio-oils derived from waste wood resources are thought to be potential alternatives for petroleum asphalt binders used in asphalt pavement. This study aims to evaluate the effect of bio-oils on asphalt mixture performance after blending bio-oil (5% and 10% by weight, respectively) into the traditional asphalt binder. Three types of bio-oils are used – the original bio-oil (OB), dewatered bio-oil (DWB) and polymer-modified bio-oil (PMB). The asphalt pavement analyzer (APA) test, four-point beam fatigue test, dynamic modulus ($|E^*|$) test and indirect tensile (IDT) strength test were conducted to evaluate the rutting resistance, fatigue performance, dynamic stiffness, and tensile strength, respectively. The test results showed that the addition of bio-oils significantly improves the asphalt mixture fatigue performance, has no significant effect on the rutting performance and dynamic modulus, but slightly impacted the tensile strength. In addition, polymer in the bio-oil was observed to improve the asphalt mixture performance as the PMB modified asphalt mixtures performed better than the two other mixtures. Further, statistical analysis on the laboratory test results are conducted and found to be consistent with the findings above. The study shows that the bio-oils derived from waste wood resources can be a good extender and modifier for petroleum asphalt binders in the pavement industry.

1. Introduction

The asphalt industry is facing increasing price challenges and potentially shorter supply because of the limited reserves of crude oil. Researchers and engineers have been seeking approaches to reduce the use of new petroleum asphalt. Using alternative materials is one of the most effective and environmentally friendly ways to solve this problem. Recently researcher have found that bio-oils can be generated from such biomass materials as microalgae [1], animal waste [2,3], cornstover [4], urban yard waste [5], tea and coffee residue [6,7], rapeseed and soybean [8,9], etc. Some of these bio-oils have been used to modify or partially replace the petroleum asphalt binders in the asphalt pavement structure [2–4,10,11].

A number of innovative technologies have been developed for the generation of bio-oil from biomass materials [12–16]. Most of the effective yield technologies involve a pyrolysis, which is a thermal–chemical process that converts organic materials into solids (biochar) and volatiles (bio-oil and gases) by heating in the absence of air [17]. Pyrolysis can be divided into fast, intermediate and slow pyrolysis according to the residence time of the solid phase in the reactor [18]. Sometimes, pressure, vacuum, catalysis, or some other material is used to help the decomposition of the biomass. It is found that a fast pyrolysis process is an effective approach to generate high bio-oil fractions compared to other pyrolysis technologies [19,20]. For a fast pyrolysis process, the biomass is preheated to reduce the water content first and then rapidly heated to 450–600 °C in the absence of air. A mixed vapor and biochars will be generated during this process. The vapors are separated as liquid bio-oil and gas with a condensation. The gases

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produced can be the energy source to heat the biomass in return while the biochar and the liquid bio-oils are stored.

Compared to petroleum asphalt, all of the bio-oils generated from various biomasses have much higher oxygen (O) element. Generally, the fractions of oxygen element in bio-oils vary from 10% to 45% according to the bio-oil resources while the oxygen element content in petroleum asphalt is only about 1% [7,21–25]. The chemical composition difference may result in different chemical and physical properties. For instance, some previous research indicates that the bio-oil is more susceptible to aging due to high temperature [26–28]. In addition, the variances of the bio-oil resources and pyrolysis condition may yield bio-oil fractions of different properties. It is found that bio-oil generated from swine waste is liquid while that derived from waste wood resources is solid at room temperature. Many previous studies investigated the techniques of generating bio-oils and the chemical and physical properties as well as the effect of them on petroleum asphalt. It is well revealed that bio-oils generated from many resources have similar thermo-dependent behavior comparable to petroleum asphalt [1–3,8,9]. Zofka and Yut [29] investigated the rheological and aging properties of traditional asphalt binders modified with waste coffee grounds and found that the coffee beans can serve as a solvent in the traditional asphalt binders. Fini et al. [30] and Mills-Beale et al. [3] found that bio-oils generated from swine waste can enhance the low temperature performance of asphalt binders and save the cost. Raouf and Williams [4] studied the rheology of bio-oils from cornstover and found that the rheological properties of cornstover bio-oils are similar and comparable to bitumen binders and can be a renewable alternative for traditional asphalt binders. Raouf et al. [24] proceeded further to add polymers into the bio-oil and investigated the properties of bio-oils modified by polymers. Asphalt binders modified or partially replaced by bio-oils together with other normal modifiers such as nanomaterial and crumb rubber are also investigated [27,31,32].

Despite these significant research advancements in bio-oil development and application, little existing research is directly related to the performance evaluation of asphalt mixtures modified or partially replaced by bio-oils. Thus, this study makes a comprehensive investigation of the mechanical performance of hot mix asphalt (HMA) mixtures modified by bio-oils through laboratory evaluation. The mechanical performance behaviors evaluated include stiffness, tensile strength, rutting resistance, indirect tensile strength and fatigue performance. Relevant laboratory characterization tests used for the performance evaluation are: (1) Asphalt Pavement Analyzer (APA) test; (2) Indirect Tensile (IDT) Strength Test; (3) Dynamic modulus ($|E^*|$) test; (4) Flow Number (F_N) test; and (5) Four-point bending beam fatigue test.

2. Material preparation

2.1. Asphalt binders

The asphalt binder used in this study is performance grading asphalt PG 58-28 resourced from Detroit in the United States. Table 1 shows some detailed properties of PG 58-28 binders. The rotational viscosity and $G^*/\sin\delta$ values met the Superpave PG 58-28 requirements.

Table 1
The properties of asphalt binder PG 58–28.

Test properties	Test results	Specification
Specific gravity	1.03	–
Rotational viscosity @135 °C (Pa S)	0.320	<3.0
$G^*/\sin\delta$ @ 58 °C for virgin binder (kPa)	1.218	>1.0
$G^*/\sin\delta$ @ 58 °C for RTFO residue (kPa)	2.916	>2.2

2.2. Bio-oils

The bio-oils used in this study are generated through fast pyrolysis from waste wood resources collected in the upper Michigan region in the United States. Three types of bio-oils were used in this study: the original bio-oil (i.e., OB), dewatered bio-oil (i.e., DWB) and polymer-modified bio-oil (i.e., PMB). The original bio-oil is the bio product yield directly from the waste wood resources. The water content of this type of bio-oil is about 15–30% by weight. The high water content is from the biomass feed stock. The dewatered bio-oil is prepared through the process of reducing the water content of the bio-oil to about 5% [26]. The polymer-modified bio-oil is a product in which 4% of polyethylene by weight is added. The physical properties of original bio-oil from waste wood resources are shown in Table 2. The original bio-oil has elemental compositions (C, H, N) of 59.5%, 6.6%, and 0.37%, respectively, while the elemental compositions (C, H, N) in the base asphalt PG 58-28 are 81.6%, 10.8%, and 0.9%, respectively.

2.3. Aggregates and gradation

The aggregates used in this study were a mix of natural sand, washed natural sand and ¼ minus screen, collected from Eagle River, Wisconsin, United States. The detailed gradation of the HMA mixtures in this study is shown in Table 3. Three aggregate stockpiles were used to meet the Superpave™ gradation requirements for 12.5 mm nominal maximum aggregate size for the asphalt mixture. No reclaimed asphalt pavement (RAP) material was used.

2.4. Preparation of bio-oil modified asphalt binder

In this study, the bio-oil was firstly blended into the petroleum asphalt binder PG 58-28. Then, the asphalt mixture is prepared by mixing the aggregate with the bio-oil blended asphalt binders. The petroleum asphalt binder in this study is also the control asphalt binder. To prepare the bio-oil modified (BOM) asphalt binders, the control asphalt binders were blended with 5% and 10% OB, 5% and 10% DWB, and 5% and 10% PMB, respectively. Thus, a total of seven asphalt binder blends are investigated in this study. These seven asphalt binders were subsequently mixed with the same aggregate to make asphalt mixtures. The procedures of preparing the BOM asphalt binders were of two folds. Firstly, the control asphalt binder and the three types of bio-oils were heated to 130 °C and 110 °C, respectively. Secondly, the control asphalt binder and the bio-oil modifier were mixed for 20 min at 130 °C using a high shear mixer. The shearing rate of the mixing was 5000 rounds per minute (RPM).

2.5. Preparation of asphalt mixture

Before the preparation of the asphalt mixtures, the rotational viscometer (RV) test for asphalt binders was conducted to determine the mixing and compaction temperatures according to Superpave™ specification. The mixing and compaction temperatures were determined where the rotational viscosities were 0.17 and 0.28 Pa S, respectively. HMA samples in this study were prepared according to the Superpave™ mixture preparation process from Michigan Department of Transportation (MDOT) [33]. After the mixing, the loose asphalt mixtures were aged in the oven for 2 h before compaction. The mixture design for the asphalt mixtures followed MDOT specification for E3 mixtures, which is designed for traffic level between 1 and 3 million equivalent single axle loads. The asphalt concrete specimen is prepared in a Superpave™ gyratory compactor. Some design information of the asphalt mixture is shown in Table 4.

3. Experimental evaluation of asphalt mixtures

The tests conducted in this study are to evaluate the effect of the bio-oils on the asphalt mixture performance behavior. The performance evaluation approaches and the associated tests are shown as following.

Table 2
Physical properties of original bio-oil from waste wood.

Physical property	Test value
Specific gravity	1.2
pH	2.5
Moisture content (wt%)	15–30
Rotational viscosity at 135 °C (Pa S)	0.10
Distillation residue (wt%)	42.94