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Laboratory investigation on chemical and rheological properties of bio-asphalt binders incorporating waste cooking oil

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HIGHLIGHTS

- The potential use of waste cooking oil as a new modifier for petroleum asphalt is discussed.
- The chemical and rheological effects resulted from bio-oil addition are characterized.
- The addition of bio-oils soften the control asphalt but increase the binder fatigue resistance.

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ABSTRACT

Recent efforts are being conducted to develop alternative asphalt binders from various bio-mass resources for future flexible pavements construction due to their renewability and the increasing costs of conventional petroleum-based asphalt. The objective of this paper is to investigate the potential of using the waste cooking oil (WCO) based bio-oil as a modifier for petroleum based neat asphalt binder and Styrene-Butadiene-Styrene (SBS) modified binder by means of chemical and rheological approaches. A series of tests were conducted for such purpose, including the infrared spectroscopy test, frequency sweep rheological test, multiple stress creep recovery test, and linear amplitude sweep test. The infrared spectroscopy results indicate identical chemical functional groups between the bio-oil and the petroleum asphalt binder though acid, ether, ester and alcohol compounds were also observed within the bio-oil. The bio-oil modified binders display increased carbonyl index with increasing the bio-oil percent weight whereas the sulfoxide index almost exhibits the same level as that of the control asphalt. Frequency sweep tests show that the bio-oil addition obviously decreased the binder stiffness according to the dynamic shear modulus master curve. Due to this softening effect from the bio-oil modifier, the weakened rutting resistance of bio-binders are demonstrated for both neat and SBS binders at the high temperature range. The fatigue life of bio-binders at intermediate temperature under cyclic fatigue loading are found to be significantly improved by increasing bio-oil content but the binder yield energy simultaneously decreased. It can be preliminarily concluded that the WCO based bio-oil tested in this study could be used as a potential bio-modifier to produce a sustainable asphalt binder.

1. Introduction

The conventional asphalt binders for producing the hot mix asphalt (HMA) is derived from petroleum refining process. However, the non-renewable resource and increasing costs of petroleum are also reflected in the prices of paving asphalt and thus, it becomes more urgent to explore possible alternative binder material to entirely or partly replace the petroleum-based asphalt for the sustainable developments of flexible pavements. Recently the bio-mass materials, which can be obtained from various bio-resources as waste wood, corn stroke, animal waste and waste cooking oil, are gaining increasing interests from the asphalt pavement industry. Currently a continuing effort is being made to generate the bio-asphalt that utilizing the bio-oil as a new kind of asphalt modifier.

Several research work has been conducted on performance evaluation of various bio-asphalt materials. Williams et al. investigated the rheology and other properties of the bio-asphalt, in

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Table 1
Physical properties of control asphalt.

Properties	Standard test methods	Test results
Penetration (0.1 mm) at 25 °C	ASTM D5	75
Softening point (°C)	ASTM D36	49
Ductility (mm) at 5 °C	ASTM D113	35.5
Viscosity (Pa s) at 135 °C	ASTM D4402	0.35

which the bio-oil was derived from red oak wood wastes using the fast pyrolysis method. The bio-asphalt was found to have an approximate stiffness levels with conventional asphalt binder and bio-asphalt mixtures also showed identical performance with the conventional asphalt mixtures [1]. Further a corn based bio-derived warm mix asphalt additive was verified for reducing the mixing and compaction temperature by 30 °C and improving the low temperature properties of asphalt binder [2]. Fini et al. employed a thermal-chemical liquefaction process on the animal waste of swine manure to generate the bio-oil as a rejuvenator for recycled asphalt shingles (RAS). The utilization of the bio-oil was shown to effectively reduce the viscosity in the RAS modified binder, which leads to decrease the mixing and compaction temperature of the RAS mixtures. Besides, the ductility and fracture energy of bio-oil based RAS binder was also improved [3–4]. Mills-Beale et al. also verified the use of bio-oil derived from swine manure enhanced the thermal cracking performance of conventional binder by increasing creep rate and decreasing creep stiffness from the bending beam rheometer (BBR) tests whereas the bio-asphalt showed a decreased complex modulus value based on dynamic shear rheometer tests [5]. Yang et al. evaluated the rheological performance of bio-oil modified asphalt binders in which the bio-oil was derived from waste wood resources and the binder rutting resistance can be improved while the low temperature performance would be sacrificed by addition of bio-oil [6,7]. Zhang et al. compared the low temperature performance of petroleum binder and two oil-modified binders, which consisted of bio-oil from wood plant and refined waste oil. The BBR and single edge notched beam tests demonstrated the better thermal cracking resistance of the oil-modified binders and further verified from the thermal stress restrained specimen tests of asphalt mixtures [8]. Another bio-oil resource extracted from spent coffee grounds was also utilized to rejuvenate the aged binders from the reclaimed asphalt pavements (RAP), indicating the rutting resistance of RAP binders were enhanced from bio-oil addition [9]. Audo et al. investigated the microalgae byproducts as a potential route for the production of road binders from renewable sources [10]. Recently the bio-materials derived from various biomass were used together with reclaimed asphalt to restore some of the properties of the aged asphalt within RAP mixtures [11–12].

Waste cooking oil (WCO) is another promising biomass resource for use as possible asphalt substitute and replace the conventional binder. China is a large producer of WCOs and generates over 5 million tons of WCOs each year, which may cause social and environmental problems if the WCOs are not efficiently recycled. Currently the collected WCOs are mainly re-used for the bio-diesel production, during which process about 10% bio-oil by-product is coproduced [13–15]. This black viscous liquid of bio-oil residue has been regarded as the potential bio-modifier for producing WCO based bio-asphalt. Several studies focused on the performance of bio-asphalt modified with the WCO based bio-oils have been recently performed. Wen et al. assessed the effects of bio-oil that obtained from WCO polymerization on conventional asphalt binders, in which the addition of bio-oil increased thermal cracking resistance but reduced resistance to rutting [16]. Sun et al. obtained the similar results that adding WCO based bio-oil could reduce the deformation resistance but improving the low temperature cracking resistance of control asphalt [17]. A recent study from Azahar et al. proposed that the acid value of the collected WCO is a critical parameter. The rutting resistance of the bio-asphalt could be increased when applying the chemical pre-treatments for WCO to reduce the acid values [18]. Other researchers also utilized the WCO based bio-oil as a rejuvenating agent for either laboratory aged asphalt binders or RAP aged binders from the field [19–24]. Studies to date demonstrate that the bio-asphalt is a promising alternative to conventional petroleum based asphalt. Meanwhile, the diversity problem of bio-oil in source and process needs further studies for practical application of bio-asphalt to pavement industry.

There are currently approximately one hundred thousand tons of WCOs produced every year in Beijing. Most of the bio-oil residue from the WCO based bio-diesel production are still not applicable for any further recycling. The objective of this paper is to investigate the possible application of this WCO based bio-oil by-product as a bio-modifier for the petroleum asphalt by means of chemical and rheological performance testing. The bio-oil effects on the fatigue cracking resistance of neat and SBS modified binder is especially characterized, which has been fewer addressed in the literatures.

2. Materials and testing

2.1. Materials

2.1.1. Asphalt binders

In this study, a 60/80 penetration grade asphalt was used as the control asphalt binder. This asphalt was obtained from Hebei

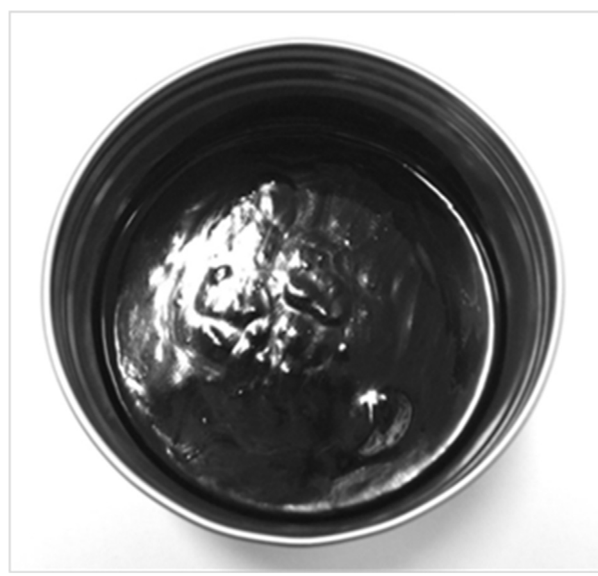

Fig. 1. WCO based bio-oil residue.

Table 2
Summary of tested asphalt binders.

Materials	Binder ID	Percent Weight of Bio-Oil Addition
Control 60/80 Asphalt Binder	70#	/
SBS Modified Asphalt Binder	SBS	/
Bio-Oil Modified Asphalt Binders	70# + 5%Bio	5% Bio-Oil
	70# + 10%Bio	10% Bio-Oil
	70# + 15%Bio	15% Bio-Oil
Bio-Oil Modified SBS Binders	SBS + 5%Bio	5% Bio-Oil
	SBS + 10%Bio	10% Bio-Oil
	SBS + 15%Bio	15% Bio-Oil