Construction and Building Materials 145 (2017) 42–51

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Evaluation of bio-binder modified asphalt's adhesion behavior using sessile drop device and atomic force microscopy

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HIGHLIGHTS

- Bio-binder would induce different influences on different asphalt's adhesion properties.
- Adhesive forces obtained by using different AFM tips are different.
- Some connections are found between SFE data and AFM data.
- AFM can be regarded as a powerful method complementary to current contact angle measurement.

ARTICLE INFO

Article history:
Received 7 November 2016
Received in revised form 27 February 2017
Accepted 12 March 2017

Keywords:
Adhesion
Bio-binder
Asphalt
Sessile drop device
Atomic force microscopy

ABSTRACT

Bio-binder is a renewable material which can be derived from natural resources. Applications of bio-binder in enhancing asphalt's properties have gained profound progresses in past several years. However, limitation still exists in our knowledge on adhesion property of asphalt blended with bio-binder. This study aims to characterize adhesion behavior of bio-binder modified asphalt using sessile drop device (SDD) and atomic force microscopy (AFM). Relationship between the two test results is also investigated. It is shown that addition of bio-binder would introduce different impacts on surface properties for different base asphalts (Pen30 and Pen70 asphalts in this paper), which may be attributed to distinct compatibilities between bio-binder and different asphalts. And the work of adhesion data demonstrates that the bio-binder enhances the interaction between basalt and bio-binder modified Pen70 asphalt binders while depress the interaction between basalt and bio-binder modified Pen30 asphalt binders. It is also found that AFM adhesive force is tip-dependent which may be interpreted using different contact mechanics. In this paper, the high coefficient of variation in soft tip's data may result from the capillary force and contamination during scanning. Interestingly, dispersive surface free energy and AFM results show some reasonable agreements for modified Pen70 asphalts, though there is still a gap between these two methods' results. It is speculated that the variations between surface free energy method and AFM measurement can be attributed to the differences in probe substance, test scale and measured components. Findings in this paper not only promote the development of bio-binder modified asphalt, but also shed lights of the application of AFM in characterization of asphalt's adhesion property.

1. Introduction

As a residue of petroleum industry, asphalt binder has long been used to bond aggregates in pavement engineering. However, petroleum is a non-renewable resource and may be exhausted in near future. In order to address this energy crisis, bio-binder has been developed to fully or partly replace traditional petroleum asphalt. In the past few years, efforts have been done to develop bio-binder from swine [1], wood waste [2,3], waste cooking oil [4,5] and other biomass [6]. It has been reported that incorporating bio-binder into asphalt not only lowers the construction cost, but also reduces the emission of greenhouse gas, which is both economical and environmental friendly [7]. Generally, bio-binder

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http://dx.doi.org/10.1016/j.conbuildmat.2017.03.114
0950-0618/

can be incorporated into asphalt in three ways: (1) as asphalt modifier (<10% asphalt replacement); (2) as asphalt extender (25–75% asphalt replacement) and (3) as direct alternative binder (100% asphalt replacement) [3]. Currently, research mainly focuses on using bio-binder as a modifier.

Previous research has provided thorough understanding on chemical and physical properties of bio-binder modified asphalt [1–6]. It is found that bio-binder can be blended with asphalt homogeneously due to their similar elemental compositions. Compared with base asphalt, the performances of bio-binder modified asphalt have been significantly changed. The addition of bio-binder to conventional asphalt will reduce binder viscosity, which results in enhancing its workability [8]. Bio-binder also has the potential to improve the low-temperature properties of asphalt mixture, while the high-temperature properties will be deteriorated at the same time [9–11]. Besides, the addition of bio-binder will also significantly increase the asphalt mixture's fatigue and cracking resistance, but slightly impact the tensile strength [11,12]. Moreover, anti-aging performance of asphalt will also be improved using bio-binder modifier due to its functional groups [3]. Nevertheless, only a few researches have been conducted to investigate the adhesion behavior of bio-binder modified asphalt [13]. Surface free energy (SFE) method has been developed to characterize the adhesion work of asphalt binder-aggregate interface. And the atomic force microscopy is recommended as a feasible way to characterize adhesion because the contact between asphalt surface and tip can be used to simulate the interaction within asphalt-aggregate interface [14,15]. Previous study also found that SFE results may have some correlations with AFM results [16]. However, no sufficient work has been conducted to look into this correlation. To this end, this paper prepared bio-binder modified asphalt samples using different dosages of additives. And contact angles between bio-binder modified asphalt samples and three probe liquids were measured using sessile drop device (SDD). Atomic force microscopy was also employed to acquire adhesive forces from each sample using silicon nitride tip to fabricate aggregate. Surface free energy and adhesive force data were then compared and the difference between these two methods was discussed herein.

2. Objectives and scope

This study focuses on characterization of adhesion behavior of bio-binder modified asphalts. SFE data are used to compute surface energy of modified asphalt. Adhesive forces are acquired with AFM test. Relationship between these two methods is analyzed to detect the difference between macro and micro test on asphalt's adhesion behavior. The objectives are as follows:

(1) Evaluate the adhesion property of bio-binder modified asphalt;
(2) Investigate the relationship between SFE method and AFM method.

3. Materials and methods

3.1. Materials

3.1.1. Base asphalts

Base asphalts used in this study are penetration grade 30 and 70 (denoted as Pen30 and Pen70) asphalts. Research on the interaction mechanism between these two asphalts and bio-binder may contribute to an appropriate application of bio-binder in aforementioned areas.

Basic properties of these two asphalts are listed in Table 1.

3.1.2. Bio-binder

Bio-binder is a black sticky liquid which is derived from natural bean oil (see Figs. 1 and 2). Boiling point of this binder is higher than 400 °C. Its acid value ranges from 40 to 50 (mgKOH/g). And its density is 0.95 g/cm^3. Its components are listed in Table 2. This study further conducted Fourier Transform infrared spectroscopy test to offer chemical information of this binder. Spectra of the two base asphalts are also displayed as reference in Fig. 3.

Table 1
Basic properties of Pen30 and Pen70 asphalts.

Property	Unit	Pen30	Pen70
Penetration(25 °C,100 g,5 s)	0.1 mm	32	66
Ductility(10 °C,5 cm/min)	cm	0	52
Softening point	°C	76	46
Viscosity(135 °C)	Pa.s	1.87	0.59
Mass loss after RTFOT	%	−0.3	−0.2
Ductility after RTFOT(10 °C)	cm	0	8

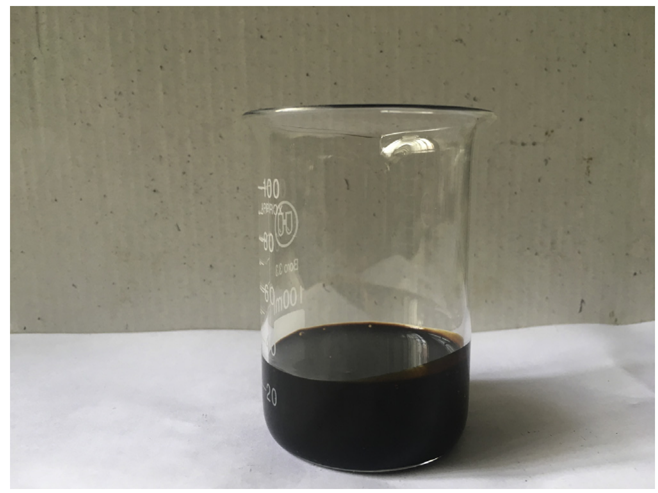

Fig. 1. Image of bio-binder.

It can be seen from Fig. 3 and Table 3 that Pen30 and Pen70 asphalt have similar functional groups while bio-binder has distinct peaks around wavenumber of 1745, 1164, 968 and 724 cm^{-1}. Wavenumber around 3007 cm^{-1} demonstrates that bio-binder has alkene structures. Among all three binders, obvious peaks can be found at 2927, 2854, 1463 and 1377 cm^{-1} which are corresponding to $-CH_3$ and $-CH_2$. This indicates that all three binders are hydrocarbon mixtures. However, particular peaks at wavenumber of 1745, 1710 and 1164 cm^{-1} reveal that bio-binder may contain more oxygen functional groups than base asphalts and these groups mainly come from aliphatic structure and fatty acid derivatives in bio-binder. The trace of $R-SO_2-OH$ may stem from the addition of concentrated sulfuric acid in production process. Overall, significant differences can be found from spectra of asphalts and bio-binder. Since bio-binder used in this study was produced from natural oil, functional groups from derivatives of saturated fatty acid are clearly shown in FTIR results.

3.1.3. Bio-binder modified asphalt

Bio-binder was incorporated into two base asphalts using high shear mixer at dosages of 1%, 2% and 3% (by weight of base asphalt mass percentage) respectively. High shearing mixing process lasted for 10 min using a shearing speed of 5000 rpm.

3.2. Methods

3.2.1. Contact angle measurement

Optical Contact Angle Measuring Device (Type OCA40) was used to determine the contact angle at 25 °C in this study. Samples were prepared using same method in our previous study [16]. And the contact angle was an average value of 6 duplicates.

Three probe liquids were used in present study. Surface free energy data of probe liquids are illustrated in Table 4.

Surface free energy of asphalt binder is determined using Eq. (1) [17,18].

$$1 + \cos\theta = 2\sqrt{\gamma_s^d}\left(\frac{\sqrt{\gamma_l^d}}{\gamma_l}\right) + 2\sqrt{\gamma_s^p}\left(\frac{\sqrt{\gamma_l^p}}{\gamma_l}\right) \quad (1)$$

Where θ (°)represents the contact angle between asphalt binder and liquids, γ_l (mJ/m^2) represents the surface free energy of liquid, γ_l^d (mJ/m^2) is the dispersion component of liquid, γ_l^p (mJ/m^2) is the polar component of liquid, γ_s^d (mJ/m^2) is the dispersion component of solid, γ_s^d (mJ/m^2) is the polar component of solid.