Fuel 192 (2017) 18–26

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Combustion mechanism of four components separated from asphalt binder

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HIGHLIGHTS

- Combustion mechanism of four components separated from asphalt binder are discussed.
- Thermal effects during the combustion of four components are different from each other.
- The dynamic evolution and constituents of volatiles from each component are different.
- Heteroatom contents of combustion residues become more from saturates to asphaltenes.
- Combustion properties of asphalt binder are further understood from its components.

ARTICLE INFO

Article history:
Received 3 October 2016
Received in revised form 28 November 2016
Accepted 30 November 2016

Keywords:
Asphalt binder
Four components
Thermal effects
Released volatiles
Combustion mechanism
Combustion residues

ABSTRACT

To study the combustion mechanism of four components separated from asphalt binder, combustion properties of each component and their dynamic evolution of released volatiles were discussed, respectively, and then the morphology and chemical compositions of combustion residues were analyzed. Results indicated that combustion reactions of saturates, aromatics and resins include thermal decomposition of each component and oxidation combustion of charring layer, but asphaltenes only includes oxidation combustion of charring layer. Further, four exothermic volatilizations and endothermic reactions occured alternately during combustion of both saturates and aromatics. Combustion reactions of aromatics were more intense and its thermal effects were more obvious than those of saturates. However, only two and one exothermic peaks were found during the combustion of resins and asphaltenes, respectively. The total heat release amount of each component was increased from saturates to asphaltenes. Additionally, the dynamic evolution and constituents of released volatiles from each component were different. CO_2 and H_2O were the most important products during the combustion of each component. Gram–Schmidt analysis also further validated the dynamic evolution of released volatiles during the combustion of each component. All these were benificial to further understand the multi-stage combustion characteristics of asphalt binder. Finally, the morphologies of combustion residues of four components are different due to complicated endothermic volatilizations and exothermic reactions. Combustion residues of saturates, aromatics and resins mainly contained C, O and a small amount of heteroatoms, while combustion residues of asphaltenes contained less C and more O and heteroatoms. Combustion properties of asphalt binder are better understood from a new perspective of its component combustion.

1. Introduction

Asphalt binder has been widely utilized in civil engineering, waterproof membranes for the roofing industry and energy source of metallurgical furnaces and kilns [1]. It is well known that asphalt binder is composed of hydrocarbons and heteroatoms [2]. Gong et al. [3] studied the thermal decomposition characteristics of asphalt binder used as a fuel of industrial furnaces. However, more asphalt binder was utilized in pavement engineering on highway and urban road [4]. Asphalt pavement is also widely used in road tunnel due to such advantages as driving comfort, low noise, good skid resistance, short construction period, and maintenance convenience [5].

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http://dx.doi.org/10.1016/j.fuel.2016.11.110
0016-2361/

However, many traffic accidents often occur in road tunnel, easily leading to a fire [5]. Asphalt material is combustible when it is exposed to a higher temperature [6]. When a fire happens, a great deal of fumes is released because of thermal decomposition of asphalt binder, including inorganic gases, volatile organic compounds as well as the aerosols and mists resulting from their condensation after volatilization [7]. These are harmful to human health and environments. It was reported that 85% of deaths in a fire were because of inhaling toxic smoke [8].

Therefore, many studies have been conducted on the thermal decomposition properties of asphalt binder to reveal its combustion mechanism. Wu et al. [9] found that the combustion process of asphalt binder was approximately divided into two stages, including primary volatile combustion and fixed carbon combustion. Xu and Huang [10] investigated the combustion mechanism of asphalt binder in a mixed gas environment. Zhang et al. [11] reported that the mass loss process of asphalt binder was divided into three stages, including the devolatilization and oxidation first, then the ignition and combustion of volatiles, and the combustion of formed char in finally. Zhao et al. [12] studied combustion behaviors of asphalt binder, and calculated its activation energy to reveal the combustion mechanism of asphalt binder.

Currently, it is known that chemical compositions of asphalt binder are very complicated. Four generic components, including saturates, aromatics, resins and asphaltenes were usually separated from asphalt binder to study its properties [13]. Of course, the components of asphalt binder primarily depend on the crude oil source and the processing procedure [14]. There were obvious differences among four components of asphalt binder in chemical compositions, molecular structures and thermal properties [15]. Hence, it is necessary to further study the combustion mechanism of four components in asphalt binder.

However, it is noticed that asphalt binder was often regarded as a homogeneous entirety when the combustion mechanism of asphalt binder was discussed. Few studies were conducted to discuss the combustion mechanism of asphalt binder based on thermal decomposition properties of its four components. Combustion properties of each component in asphalt binder were seldom involved in, and constituents of released volatiles during each component combustion were rarely identified [16]. As a result, it is difficult to reveal the combustion nature of asphalt binder without understanding combustion properties of each component. The objective of this study is to further understand combustion properties of four components separated from asphalt binder, and identify their released volatiles, and study remained combustion residues, providing a deep insight into the combustion properties of asphalt binder.

In addition, the combined technique of thermogravimetry/differential scanning calorimetry-Fourier transform infrared spectroscopy (TG/DSC-FTIR) was usually applied to evaluate pyrolysis and combustion properties of different materials. Michelle et al. [17] analyzed the thermal behaviors of two heavy crude oils based on the TG/DSC-FTIR technique. Chen et al. [18] characterized pyrolysis characteristics of petrochemical wastewater sludge based on TG/DSC-FTIR experiments. Worzakowska et al. [19] used the TG/DSC-FTIR technique to study the thermal behaviors of phenyl methacrylate copolymers. Also, the releasing behaviors of volatile products from polymers were characterized using the TG/DSC-FTIR technique [20]. It is concluded that the TG/DSC-FTIR technique has become one of important methods to analyze thermal decomposition properties and released volatile evolution of various materials.

In this study, four components were first separated from asphalt binder. Then thermal effects such as endothermic volatilizations and exothermic reactions at different combustion stages of each component were discussed based on TG/DSC test results. Also, the dynamic evolution of released volatiles during each component combustion were characterized using three dimensional (3D) FTIR and Gram– Schmidt (G–S) intensity, respectively. Finally, the field emission scanning electron microscopy (FESEM) and energy dispersive spectrometer (EDS) were used to observe the microscopic morphology and identify chemical compositions of combustion residues after each component combustion, respectively. This is conductive to further find out the combustion mechanism of four components. It is believed that combustion properties of asphalt binder are also better understood from a new perspective of component combustion.

2. Experimental

2.1. Material

Asphalt binder was obtained from SK Corp., Republic of Korea. The basic physical properties of asphalt binder were tested as shown in Table 1.

2.2. Method

2.2.1. Preparation of four components

In this study, four components were separated from asphalt binder sample according to the standard ASTM D4124–09, including saturates, aromatics, resins and asphaltenes. The principle of separation method was based on the different component to dissolve in different solvents and the different adsorption capacity of alumina to different components. The contents and appearances of each component were given in Table 2.

2.2.2. TG/DSC-FTIR test

Combustion properties of each component were studied using a TG/DSC (NETZSCH STA 409 PC/PG) test system coupled with a FTIR spectrometer (TGA/FT-IR Nicolet-IZ10). The spectrometer was equipped with an IR gas cell and DTGS KBr detector through a short transfer tube heated at a constant temperature of 225 °C. In this work, the inputted gas was composed of 21% oxygen and 79% nitrogen at a flow rate of 120 ml/min. Approximately 15 mg sample of each component was placed in alumina crucible of TG/DSC test sysytem. Each sample was heated from room temperature to 800 °C at a heating rate of 10 °C/min. The purge gas was nitrogen at a flow rate of 40 ml/min. Simultaneously, the emitted volatiles from each component were directly introduced into the gas cell for FTIR analysis, and constituent changes in released gaseous products were monitored by FTIR spectrometry as the temperature rose. The 3D FTIR and G–S intensity were recorded with 16 scans per spectrum at a resolution of 4 cm^{-1}.

Table 1
Basic physical properties of asphalt binder sample.

Physical properties	Standard	Test results
Penetration (25 °C, 0.1 mm)	ASTM D5-06	54.2
Softening point (°C)	ASTM D36-06	87.2
Ductility (5 °C, cm)	ASTM D113-07	35.1
Brookfield viscosity (135 °C, Pa s)	ASTM D4402-06	2.2
Wax content (%)	ASTM D3344-90	1.82
Flash point (°C)	ASTM D92-02	325
Tests after TFOT		
Mass loss (%)	ASTM D2872-04	0.08
Penetration ratio (25 °C, %)	ASTM D5-06	76.2
Ductility (5 °C, cm)	ASTM D113-07	28.2