Construction and Building Materials 154 (2017) 310–322

Contents lists available at ScienceDirect

Construction and Building Materials

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

# Characterization of fume composition and rheological properties of asphalt with crumb rubber activated by microwave and TOR

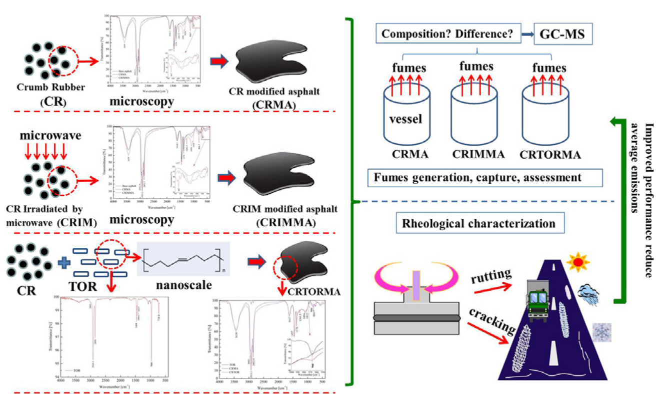
Ming Liang [a,b], Shisong Ren [a], Weiyu Fan [a,*], Hao Wang [b], Wenyao Cui [a], Pinhui Zhao [c]

[a] State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Qingdao 266580, China
[b] Department of Civil and Environmental Engineering, Rutgers University, Piscataway, NJ 08854, USA
[c] Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences, Qingdao 266101, China

## HIGHLIGHTS

- CR activated by microwave and TOR reduces PAHs and sulfur compounds in asphalt fumes.
- Microwave treatment on CR enhances relaxation performance of modified asphalt.
- TOR greatly improves viscoelastic behavior of CR modified asphalt at high temperatures.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 3 May 2017
Received in revised form 10 July 2017
Accepted 29 July 2017
Available online 5 August 2017

*Keywords:*
Asphalt fume
CR modified asphalt
TOR
Microwave
Rheology

## ABSTRACT

This paper studied asphalt fume chemical composition, rheological properties and microstructure of asphalt with crumb rubber (CR) activated by microwave and trans-polyoctenamer (TOR). To that end, asphalt fume was trapped through laboratory fume generation and capture system, which was subsequently analyzed by Gas Chromatography-Mass Spectrometry system (GC–MS). Moreover, the rheological behavior and microstructure of CR modified asphalt (CRMA) were characterized by dynamic shear rheometer (DSR) and FTIR. The GC–MS results indicated that CR activated by microwave and TOR reduces the contents of PAHs and sulfur compounds, implying the lower toxicological potential of fume. TOR has the greater effect of reduction in the toxicological species. The rheological results indicated that CR activated by TOR significantly improves modulus, zero shear viscosity (ZSV), and recovery ability of CRMA at high temperatures, which cause asphalt binder having the stronger resistance to rutting. The enhancement in thermo-mechanics is due to chemical cross-linking among TOR, rubber, and asphalt, which was verified by FTIR results. On the other hand, microwave treatment on CR affects high temperature performance of CRMA negatively in comparison to the untreated CRMA. However, microwave treatment leads to the faster stress relaxation response of CRMA, indicating the stronger resistance to thermal cracking.



* Corresponding author.
*E-mail addresses:* liangmingupc@126.com (M. Liang), fanwyu@upc.edu.cn (W. Fan).

http://dx.doi.org/10.1016/j.conbuildmat.2017.07.199
0950-0618/© 2017 Elsevier Ltd. All rights reserved.

## 1. Introduction

The recycling and reutilization of waste tires are attracting increasing attention in recent years, because the disposal of discarded tires (such as stockpile and landfill), poses adverse impacts on environment (potential fire hazardous, breeding grounds for rats, mosquitoes) [1]. The recycle of post-consumer tires is the most popular route to produce crumb rubber (CR) [2]. Generally, crumb rubber is produced by mechanical grinding at the ambient or cryogenic condition, resulting in different properties of rubber powders [3,4]. The relative high surface/volume ratio, irregular shape can be achieved for CR produced from ambient grinding while CR particles produced from cryogenic grinding have the flat and edgy surface [5,6]. One of the most cost-effective applications for crumb rubber is used as asphalt modifier in paving and roofing industry, which can improve asphalt rheology and also solve solid waste problems [7]. Previous studies have developed two general methods to prepare crumb rubber modified asphalt (CRMA), i.e. dry process and wet process [8–11]. In dry process, CR is mixed with aggregates and asphalt, as the filler of asphalt mixtures. Very limited interactions between asphalt and rubber exist in dry process. On the contrary, asphalt blended with CR at elevated temperatures for several hours in wet process has an advantage over dry process. Viscoelastic properties of asphalt can be improved significantly by the chemical and physical interactions among asphalt and rubber particles [12,13]. Therefore, wet process is the preferred one for producing CR modified asphalt.

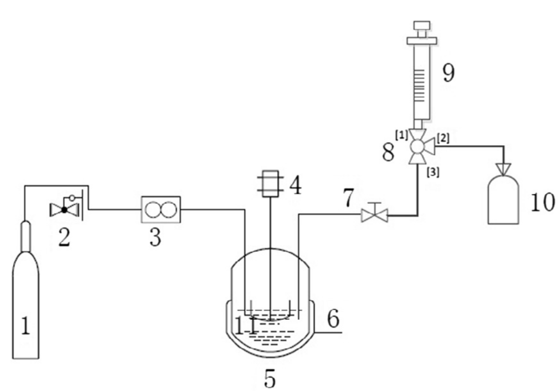
However, the extent of enhancement of performance in wet process is mainly determined by the interfacial properties of rubber particles and the interactions between asphalt component and particles [14,15]. Since rubber molecules are vulcanized, their three-dimensional networks are hardly cleaved in asphalt even blending for long time and at elevated temperatures. This leads to incompatibility problems and the sedimentation of rubber particles at the bottom of bulk asphalt phase and further affects the performance of CRMA negatively [16,17]. Many attempts [18–22] have been taken to break the C—S or S—S bonds in rubber chemical linking networks (devulcanization) and to improve compatibility of CR with asphalt. Those approaches include high-speed shear disintegration, pre-blending process with matrix, microwave treatment and plasticization. It is noted that microwave treatment [23–25] was found being an effective method to break the cross-linked S—S or C—S bonds among the three-dimensional networks of rubber molecules. Yu et al. (2011) reported that CR irradiated by microwave improves conventional properties and storage stability of modified asphalt [26]. Poyraz (2013) analyzed crumb rubber treated by microwave through FT-IR characterization and indicated that short-term microwave irradiation (four minutes) can devulcanize the scrap GTR particles effectively [27]. In addition, various additives, cross-linking agent [28], polyphosphoric acid [29], polymeric reactants with conjugated diene [30], etc., were also incorporated in the rubber/asphalt blends to retard the separation process of rubber particle from bulk asphalt phase. Among the above-mentioned additives, trans-polyoctenamer (TOR) is a polymeric reactive rubber with double-bond structures in molecules [30,31]. TOR is prepared by a metathesis polymerization of cyclooctene monomer and synthesized from 1, 3-butadiene and 1, 5-cyclooctadiene. When TOR was mixed with CR/asphalt blends, it improves workability of blends and allows blends with lower viscosity owing to its low glass transition temperature. More importantly, the fairly good compatibility exists with CR/asphalt blends after adding TOR, which can facilitate the interaction between CR and asphalt through crosslinking of sulfur components in rubber and asphaltene [32,33].

Although CRMA shows advantages such as the better resistance to rutting and cracking, low noise at tire-pavement surface, and so on, it demands the high processing temperature in plant and the high mixing temperature with aggregate in construction due to its higher viscosity as compared to conventional asphalt [10]. This contributes the higher energy consumption and more hazardous gaseous emissions. It is a fatal disadvantage for CRMA because more emphasis is put on environmental protection as well as occupational health. Several studies [34–36] have investigated the composition and quantity of fume released in production plant or construction area.

Some researches [37–40] compared gaseous emissions from the production, mixing, and paving of CRMA with those generated from conventional asphalt. The findings revealed that the increased

**Table 1**
The traditional test results and chemical compositions for base asphalts.

| Items | Results | |
|---|---|---|
| | Q | K |
| Penetration (25 °C, dmm) | 65 | 67 |
| Softening point (R&B, °C) | 47.9 | 48.8 |
| Ductility (10 °C, cm) | 45.0 | 68.5 |
| Viscosity (135 °C, Pa·s) | 0.524 | 0.609 |
| Saturates (%) | 22.7 | 27.3 |
| Aromatics (%) | 42.1 | 32.7 |
| Resins (%) | 26.7 | 39.1 |
| Asphaltenes (%) | 8.5 | 0.9 |




1-$N_2$ cylinders, 2-reducing valve, 3-flowmeter, 4-agitator, 5-fume generator, 6-electric jacket, 7-valve, 8-three-way valve, 9-glass syringe, 10-aluminum foil collecting bag

**Fig. 1.** Laboratory modified asphalt fumes generation and capture system.