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Improved microwave heating and healing properties of bitumen by using nanometer microwave-absorbers

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HIGHLIGHTS

- Microwave-absorbers can be used to improve the healing property.
- Microwave-absorbers can enhance the high-temperature resistance.
- CNTs modified bitumen shows better healing efficiency than graphene does.
- The exothermic rate of bitumen with microwave-absorbers reaches to 0.2 °C/s.
- Microwave-absorbers can double the exothermic rate of bitumen.

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ABSTRACT

Two nanometer microwave-absorbers named as carbon nanotubes (CNTs) and graphene, were firstly used to improve the microwave heating and healing properties of bitumen under microwave irradiation. Surface textures of two nanometer microwave-absorbers, low-temperature cracking resistance and high-temperature rheological properties of modified bitumen during heating process were characterized. Initial self-healing temperature based on flow behavior index, exothermic rate and healing effects of bitumen were also tested. Results illustrated that CNTs and graphene improved the high-temperature rheological properties of basis bitumen, while they presented a worse effect on low-temperature cracking resistance. Exothermic rate of basis bitumen was only a quarter of that of graphene modified bitumen and one third of that of CNTs modified bitumen. After 12 h of rest time, the healing indexes of basis bitumen, graphene modified bitumen and CNTs modified bitumen were 13.89%, 69.15% and 75.20% respectively. Nanometer microwave-absorbers significantly accelerated the heating process and modified bitumen had better healing effects than basis bitumen.

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1. Introduction

Asphalt mixtures have been widely applied in transportation infrastructure, especially in many high-grade pavements [1–4]. Nevertheless due to the impacts of traffic circulation and environmental factors (temperature variation, moisture damage, solar radiation, oxidation effect), bitumen would become stiffener during its service life, even losing the capacity of adhesion and cohesion in bitumen gradually, and consequently causing the potential of cracks [5–8]. Initially, generated cracks are in micro dimensions and able to be healed by capillary flow, molecules wetting and intermolecular diffusion in bitumen at ambient temperature [9–11]. However, the healing process must be conducted without any traffic loads during a prolonged period, until cracks have completely disappeared and recovered material has the same strength as the original one [5,12,13]. In actual situation, the cracks haven't disappeared entirely yet while pavements must be used under continuous traffic load. This condition may cause more serious damages to road performance, and it is crucial to seek solutions to promote the healing efficiency of asphalt mixtures.

Researchers have found that the healing rate can be accelerated when subjected to a higher temperature heated by induction or microwave [14,15]. When exposed to an alternating electromagnetic field during induction heating process, the conductive materials blended in asphalt mixtures, can release heat through the joule effect of eddy currents [5,16]. Sun studied the exothermic effects of steel fiber on asphalt mixtures, and found that the temperature of upper surface was almost 50 °C higher than that of bottom [17]. This phenomenon can be expressed by the skin effect

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caused by the eddy current, but will lead to high surface temperature and low internal temperature. The inhomogeneous temperature distribution can result in the aging of external mixtures and decrease of healing efficiency [18–20].

Microwave heating is another proceeding way applied in the healing of asphalt mixtures, but the novel technique meets obstacle of promotion due to the low absorption of microwave in asphalt materials [21]. At present, considerable efforts have been conducted for improving the sensitivity of microwave in asphalt materials, such as (1) iron based materials and (2) binder-based conductive materials. For iron based materials, Gonzalez et al added metal waste to increase the temperature of bituminous materials through microwave radiation heating, and found that the temperature of asphalt samples after microwave heating was 20.85 °C higher than induction heating [22]. Miguel et al used steel filler to generate heat through microwave irradiation and indicated that the application of microwaves was an efficient way of controlled quick heating for asphalt mixtures [23]. Norambuena-Contreras and Gonzalez-Torre studied the Influence of the microwave heating time on the self-Healing properties of asphalt mixtures contained steel wool fibers. Results indicated that cracks can be sealed while heating times was more than 30 s, and 40 s was the optimum heating time, asphalt mixtures could achieve a balance between the highest healing levels and the lowest damage at 40 s [24]. For binder-based conductive materials, Jahanbakhsh and Karimi added carbon black and activated carbon to asphalt binder to increase the microwave absorption of asphalt materials. The heating rate of carbon black modified asphalt concrete samples contained limestone and siliceous aggregate was 47% and 25% more than the neat asphalt concrete, respectively [25]. Additionally, activated carbon is recognized as viable and robust binder-based conductive component for induced heating and healing of asphalt concrete [26].

Iron based materials as microwave-absorbers showed ideal exothermic effects by microwave heating, but they would also increase the mass of asphalt mixtures and be rusted gradually under the erosion of water and oxygen. Binder-based conductive materials like carbon black and activated carbon showed more ideal effects, and can be beneficial to improve the mechanical and rheological characteristics of asphalt concrete. Carbon nanotubes (CNTs) and graphene are also nanometer binder-based conductive materials, and because of small size effect, surface and boundary effect, quantum size effect, these two nanometer materials have a high relative complex permittivity ($\varepsilon_r = \varepsilon' - j\varepsilon''$), resulting in high reflection loss of microwave [27–29]. High reflection loss of microwave can transfer more microwave energy to thermal energy by dielectric dissipation in the microwave field, and lead to the exothermic phenomenon in asphalt materials. Therefore, this research demonstrated on the application feasibility of nanometer microwave-absorbers (CNTs and graphene) in bitumen, especially the feasibility to enhance exothermic and self-healing properties during microwave heating. Firstly, morphological characteristics of two nanometer microwave-absorbers were characterized by Scanning Electron Microscope (SEM). Then two types of modified bitumen were obtained by mixing basis bitumen with different nanometer microwave-absorber whose volume amounted to 10% volume of basis bitumen. Bending Beam Rheometer (BBR) and Dynamic Shear Rheometer (DSR) were used to characterize the rheological properties of modified bitumen, including low-temperature rheological performance which represents the ability to resist cracking, and high-temperature rheological performance which reflects anti-rutting performance and flow behavior during heating process. Initial self-healing temperature, which can reflect the response to the reaction into self-healing process, was determined based on flow behavior index. In order to evaluate the heat release of different bitumen under microwave irradiation, exothermic rate during heating process was supervised through Forward Looking Infrared Radiometer (FLIR) systems. Finally, three-point bending test at −20 °C was used to appraise the self-healing effects of different bitumen after microwave irradiation, and the effects of different rest time periods on self-healing effects were also analyzed.

2. Materials and methods

2.1. Materials

Basis bitumen was supplied by Guochuang Co., Ltd., Hubei, China, and its basic properties were shown in Table 1. CNTs and graphene were supplied by Hengqiu Science and Technology Co., Ltd., Jiangsu, China, whose density was 0.15 g/cm^3 and 0.42 g/cm^3 separately.

2.2. Preparation of modified bitumen

Nanometer microwave-absorber was added into bitumen with 10% by volume ratio, and Fig. 1 shows the preparation of modified bitumen. Sample vessel was placed in oil bath pan which was heated by an electric furnace. Meanwhile the temperature sensor

Table 1
Basic properties of basis bitumen.

Properties	Values	Requirements
Penetration (25 °C, 0.1 mm)	68.3	60 ~ 80
Softening point (°C)	49.4	≥42.0
Ductility (15 °C, mm)	> 1000	> 1000
Density (15 °C, g/cm^3)	1.025	–
Wax content (%)	1.89	≤3.00
Flash point (°C)	304	≥260
Solubility (%)	99.8	≥99.5

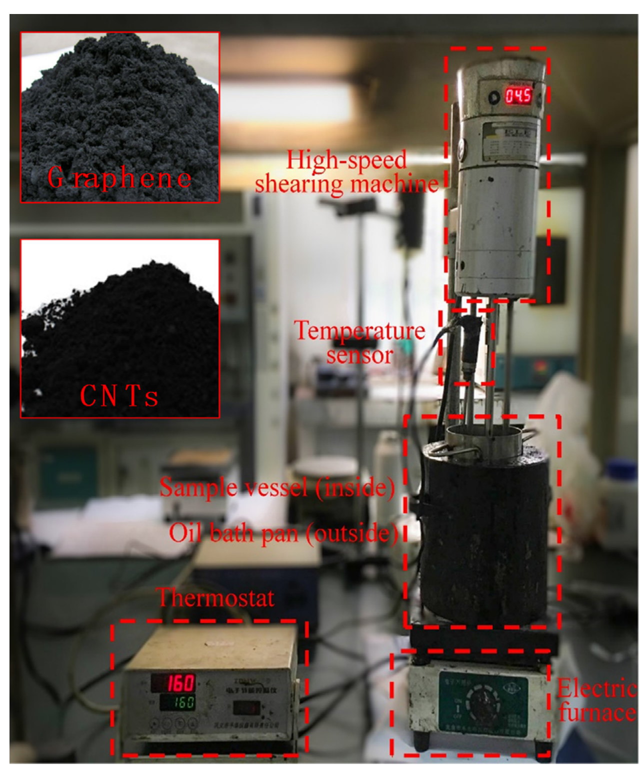

Fig. 1. Preparation of modified bitumen.

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