Construction and Building Materials 187 (2018) 865–875

Contents lists available at ScienceDirect

Construction and Building Materials

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

Microwave-healing performance of modified asphalt mixtures with flake graphite and exfoliated graphite nanoplatelet

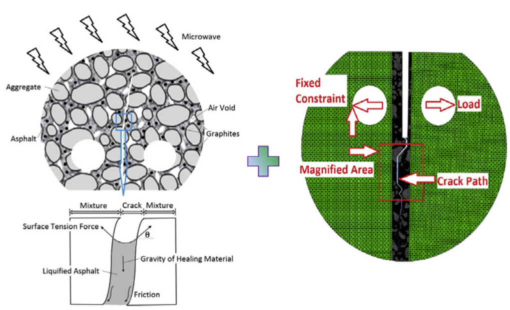
Zigeng Wang [a], Qingli Dai [b,*], Shuaicheng Guo [b]

[a] College of Architecture and Civil Engineering, Beijing University of Technology, No. 100 Pingleyuan, Chaoyang District, Beijing 100124, PR China
[b] Department of Civil and Environmental Engineering, Michigan Technological University, 1400 Townsend Dr., Houghton, MI 49931-1295, United States

HIGHLIGHTS

- The fracture energy of control and graphite modified asphalt mixture was measured.
- The original fracture strength of control and modified asphalt mixture was analyzed.
- The self-healing performance of asphalt mixture with cyclic fracture-microwave healing tests was evaluated.
- The DIC calibration of relative strain ratio was used to evaluate the healed fracture energy.
- The cohesive finite element model with a crack path was established to accurately simulate facture behavior.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 10 October 2017
Received in revised form 6 June 2018
Accepted 26 June 2018

Keywords:
Microwave healing of asphalt mixture
Flake graphite
Exfoliated graphite nanoplatelet
Fracture energy
Disk-shaped compact tensile test
Cohesive fracture simulation

ABSTRACT

This paper computationally and experimentally investigated the microwave healing performance of graphite (flake graphite and exfoliated graphite nanoplatelet (xGNP)) modified asphalt mixture. The original fracture energy and strength were first measured for the modified asphalt mixture through the disk-shaped compact tension test. Then the micro-wave healing performance (recovered fracture energy and strength) were further examined. All these were enhanced with the added carbon materials. The recovered fracture strengths were also compared with FE cohesive zone model (CZM) simulation with digital image correlation (DIC) calibrated parameters. The predicted recovered fracture strength had good agreement with the experimental measurement.

1. Introduction

The asphalt materials have self-healing behaviors [1] when the environmental temperature reaches above its transaction temperature [2,3], which involves the capillary flow, wettability and intermolecular diffusion, crack size and material type [4–7]. However, due to the insufficient external energy in natural field [8], the self-healing ability of the normal asphalt mixture is limited during its service life [9,10]. Hence, it is necessary to develop materials and methods to improve the self-healing process of asphalt, like the sunlight and induction methods proposed by Wang et al. [11–13].

* Corresponding author.
E-mail addresses: zigengw@bjut.edu.cn (Z. Wang), qingdai@mtu.edu (Q. Dai), sguo3@mtu.edu (S. Guo).

https://doi.org/10.1016/j.conbuildmat.2018.06.210
0950-0618/

As known, the microwave irradiation method has also been applied to enhance the self-healing performance of asphalt concrete. Gallego et al. [14] used the microwave oven to heat asphalt mixture with steel wool and studied how the microwaves influenced the healing process. Norambuena-Contreras et al. [15] evaluated the asphalt mixture with added steel wool fiber. Moreover, it was found by Wang et al. [8] that the asphalt mixture containing electrically conductive carbon fibers could be better healed with microwave radiation. In addition, microwave radiation was employed by Wang el al. [16] to improve the carbon fibers/matrix interfacial properties with developing the morphology, structure and composites. The study by Norambuena-Contreras and Gonzalez-Torre [17] demonstrated the microwave irradiation can generate universal temperature distribution when the added carbon materials were evenly dispersed.

Besides the application of carbon fiber [18], the graphite based materials has also been applied on the construction material reinforcement [19]. Wu et al. [20] utilized the microcrystalline graphite powders to collect solar energy for heating pavement surface. Pan et al. [21] proposed that the graphite could increase the thermal conductivity and diffusivity of asphalt binder. Additionally, a study by Guo et al. [22] demonstrated the adhesion between the exfoliated graphite nanoplatelet (xGNP) and the asphalt material can be enhanced with the synthesized carbon nanotubes on the xGNP surface.

The fracture energy has been used widely to evaluate the material crack resistance [23,24]. Vavrick et al. [25] evaluated the contour J integral and energy dissipated in the fracture process zone. Yang et al. [26] tried to relate the maximum fracture load of a notched concrete beam to the local fracture energy at the cohesive crack tip region with the tri-linear model. In order to predict the fracture behavior of civil engineering structure, the cohesive zone model (CZM) can be used with material properties. Alberti et al. [27] proposed a numerical model of fracture processes of macro-polymer fiber reinforce concrete based on the cohesive fracture approach with good understanding of the material behavior to fracture under Mode I. The core idea of the CZM is to define the relation between crack surface traction and crack opening displacement [28], such as exponential model [29] and bilinear model [30].

This study aims to investigate the microwave healing performance of the graphite modified asphalt mixtures through the integrated experimental and simulation approach. The fracture energy and the original fracture strength of the control, flake graphite modified (5% and 7%) and xGNP modified (2%) asphalt mixture samples were measured with the disk-shaped compact tension (DCT) device under low-temperature. The detailed mixture design is shown in Table 1. Afterwards, the cyclic fracture-microwave healing tests were conducted to evaluate the microwave healing performance of the control and the modified asphalt mixture samples. Subsequently, the cohesive finite element model with a defined crack path and DIC calibrated fracture parameters was used to simulate the fracture behavior of the asphalt mixture samples during the fracture-microwave healing process. The predicted results and experimental results were compared to demonstrate the microwave healing performance of graphite-modified asphalt mixtures.

Table 1
Aggregate gradation of control asphalt mixture sample preparation.

Sieve number	Sieve size (mm)	Passing percentage (%)
3/4	19.0	100
1/2	12.5	94
3/8	9.5	86.3
No.4	4.75	68.2
No.8	2.36	49.2
No.16	1.18	38.4
No.30	0.6	27.8
No.50	0.3	15
No.100	0.15	6.7
No.200	0.075	4.5
Pan powder	<0.075	0

2. Materials and methods

2.1. Materials

In this research, two types of graphite materials, flake graphite and xGNP, were utilized to investigate the low-temperature properties and the self-healing performance of asphalt mixture. The flake graphite was obtained from Asbury Carbons with a density of 2.25 g/cm^3 and mesh sizes of No.100 (0.15 mm, 75% by weight) and No.200 (0.075 mm, 25% by weight). The minimum layer thickness was 0.11 mm. The xGNP was produced by XG Sciences with a bulk density of 0.03–0.1 g/cm^3, particle diameter of 25 μm and average thickness of approximately 15 nm. The asphalt binder was PG 58-28 with a density of 1.024 ton/m^3. The aggregates in the mixture came from Hancock, Michigan with an average density of 2.72 g/cm^3.

2.2. Test samples preparation

The flake graphite and xGNP modified asphalt binder were first prepared. The asphalt binder were mixed together with these carbon materials with a high speed mixer at 120 °C for 1 h. Then the asphalt mixture was prepared with 5.2 wt% of the modified asphalt, which was determined by conducting the optimum asphalt content test from the Superpave volumetric design guide. Particularly, the added flake graphite and xGNP were considered as similar-sized fine aggregates and pan powder (Below sieve size No.200) respectively in the asphalt mixture. Thus, for the 5% flake graphite modified mixture, 2.99 wt% of the No.100 aggregate and 3.76 wt% of the No.200 aggregate were replaced with the flake graphite particles. For the 7% flake graphite modified mixture, 4.17 wt% of the No.100 aggregate and 5.25 wt% of the No.200 aggregate were replaced. For the 2% xGNP modified mixture, 2.86 wt% of the pan powder of the aggregates were replaced.

The Hot Mix Asphalt (HMA) mixture was compacted in a cylindrical mold with a diameter of 150 mm using a Superpave gyratory compactor. The air void was maintained at 4%. The cylindrical sample was further cut into a half-disk shape with a middle-notched crack and two drilled out loading holes for the DCT test, shown in Fig. 1. Two knife edges were attached next to the notched crack with a distance of 5 mm to measure the crack mouth opening displacement (CMOD) during the DCT test.

2.3. Fracture energy measurement of asphalt mixture samples

In this research, the fracture energy was utilized to investigate the fracture toughness at low-temperature. The control, flake graphite modified and xGNP modified asphalt mixture samples were tested by following the ASTM E399 DCT test standard. The sample was installed on the frictionless loading pins in a temperature controlled chamber with the displacement gauge clipped on the knife edges. Fig. 2 (a) shows the experimental setup with the loading fixture, sample, clip-on gauge

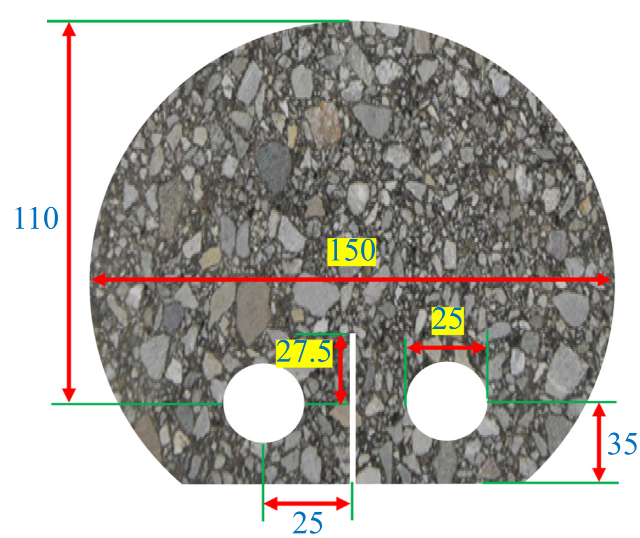


Fig. 1. Geometry (unit: mm) of asphalt mixture samples for DCT test.