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Experimental investigation of physical properties and accelerated sunlight-healing performance of flake graphite and exfoliated graphite nanoplatelet modified asphalt materials

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HIGHLIGHTS

- Measure the viscosity, light absorbance, thermal conductivity of graphite modified asphalt binder.
- Capture the infrared image of samples during healing process to study the temperature distribution.
- Analyze the displacements of sample particles during cyclic light healing processes by digital image correlation.
- Evaluate the healing capacity of graphite modified asphalt mixture beams by fracture-light healing tests.

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ABSTRACT

This presented research investigated the physical properties and accelerated sunlight-healing performance of graphite modified asphalt materials. Two types of graphite materials, flake graphite and exfoliated graphite nanoplatelets (xGNP), were added to asphalt with different contents by weight. Asphalt binder tests were conducted to evaluate the performance of modified asphalt, including rotational viscosity, light absorbance, and thermal conductivity. The tests results of graphite modified asphalt showed increased viscosities, decreased activation energies, and increased light absorbance and thermal conductivity in comparison to the control asphalt. Afterwards, the graphite modified asphalt mixture beams (5% flake graphite and 2% xGNP) were prepared and used for cyclic fracture-light healing tests. The digital image correlation (DIC) was utilized to characterize the displacement changes in the fracture zone during the light healing process. The DIC results indicated that the improved healing performance of graphite modified asphalt mixtures and decreased healing displacement with light healing cycles. Finally, the measured recovered strength after each cycle was used to evaluate the healing performance of both the graphite modified and control samples. The results of cyclic fracture-light healing tests indicated that the graphite modified asphalt materials have significantly improved healing performance and therefore these materials have promises in promoting new light healing applications.

1. Introduction

In the United States, 94% of the pavement's surface was constructed using an asphalt mixture material [1]. Asphalt mixture consists of asphalt, graded aggregates and air voids [2]. The temperature-dependent asphalt binder behaves as viscous flow at high temperatures and as viscoelastic solid at low temperatures [3]. Increasing traffic loads and changing climatic conditions impose challenges to the pavement's durability and service life. In addition, the pavement performance can be quickly weakened with microcrack developments and combined pavement distresses [4]. For instance, raveling can be initiated by the abrasive action of vehicle wheels on the pavement surface. The moisture transport or freeze-thaw cycles can greatly increase further damage development, and lead to removal and loss of stones due to weaker bonding [5]. With all the combined damage factors, the wearing courses need to be maintained and repaired frequently.

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Asphalt mixture, as a self-healing material, has limited ability to repair its own damage after placed in service [6]. There are two key factors that impact the healing process, temperature and test periods [7,8]. Cracks developing in the asphalt mixture due to factors such as traffic loads or freeze-thaw cycles can be healed when the external activation energy is input into the system. If the energy or time is sufficient to complete this process, cracks could almost disappear [6]. It is concluded that the crack healing was mainly related to the Newtonian binder flow or the related creep flow of asphalt mastic through the cracks at elevated temperatures [9]. To initiate this process, the asphalt's temperature needs to be heated higher than the transition one. Then the binder behaves as a Newtonian fluid. The transition temperature level depends on the types and components of asphalt, normally in the range of 30–70 °C [10–13]. According to the study of Shen et al. [14], the healing behavior was a self-recovery capability of the asphalt binder which involved loading and environmental conditions. Self-healing can be considered a complex behavior, involving activation energy and capillary flow of asphalt at the micro or meso scale, and intermolecular diffusion and wetting of asphalt molecules at crack surfaces. The healing behavior is affected by the crack size, material mixture types and modification [9,15,16]. For example, Qiu et al. [15] showed that the healing ability of asphalt mastic modified by Styrene-Butadiene-Styrene polymer has been weakened compared to the unmodified control asphalt mastic.

The visible/near-field infrared lights are considered to be a type of easily obtained solar energy. The energy could be potentially used to heat and heal microcracks in the surface layer of pavement. However, the light absorption and thermal conductivity of asphalt mixture are relatively low [17,18]. Currently there is no effective method to employ the light energy (specifically the near-field infrared light energy) directly. Therefore, graphite materials that have the ability to increase the light absorbance and thermal conductivity of composites are necessary to be combined with asphalt mixture. Kim et al. [19] found that exfoliated graphite nanoplatelets (xGNP) can be used to improve the thermal conductivity of the material as an effective heat-diffusion promoter. In a study by Liu et al. [20], it was concluded that the manufactured flake graphite has high thermal conductivity through the graphite layers. Luo and Lloyd [21] found that the thermal energy transport in graphite-polymer was affected by graphite particle size and the graphite-matrix, interfacial bonding strength.

Graphite, as a super thermal conductor that can be applied in an asphalt mixture and pavement study, has attracted the interest of many researchers. Wu et al. [22] utilized asphalt mixtures within microcrystal graphite powders to collect solar energy for the heating and cooling of buildings and to keep the pavements ice-free. A study by Chen et al. [23] found that graphite powders could improve the thermal conductivity of asphalt mixtures and be a better method to counteract problems that arise from snow. Wang et al. [24] employed a finite element model to predict the thermal response of asphalt pavements with added graphite conductive media. Pan et al. [25] concluded that the thermal conductivity and diffusivity of graphite asphalt increased with the added graphite. In this research, two types of graphite materials, flake graphite and exfoliated graphite nanoplatelets were used as mixture modifiers to improve the visible/near-field infrared light healing effects.

The digital image correlation (DIC) is an effective optical technique that measures the full-field surface deformation of sample [26]. Essentially, two digital images are compared by DIC, one is the reference image regarded as an undeformed case and the other is the deformed image. The DIC algorithm could detect the two locations of one selected point (pixel) in the reference image and in the deformed image by matching the gray value of that point. Afterwards, the displacement (pixels) of the selected point can be calculated [27]. Some researchers have put efforts to use the DIC techniques in civil engineering, e.g., Kuntz et al. [28] utilized digital image cross-correlation to measure the displacement of a shear crack in a reinforced concrete beam during a bridge load test. Chehab et al. [29] studied the fracture process zone strains of asphalt mixtures by DIC. Rastiello et al. [30] established the relationship between the crack surface and the mid-height crack opening displacement using DIC techniques.

This research aims to evaluate the sunlight heating and accelerated self-healing performance of graphite modified asphalt and mixture materials. In the first place, flake graphite and exfoliated graphite nanoplatelets (xGNP) were added into asphalt with weight percentages for preparing the graphite modified asphalt binder. Then asphalt binder tests were conducted to evaluate the performance of graphite modified asphalt, including rotational viscosity, light absorbance and thermal conductivity. Afterwards, the graphite modified asphalt mixture beams (5% flake graphite and 2% xGNP) were prepared and used for cyclic fracture-light healing tests. The measured recovered strength after each cycle was used to evaluate the healing performance of both graphite modified and control samples. In addition, during the light healing process, the temperature distribution of tested beams was analyzed by capturing the infrared images. The DIC was utilized to evaluate the displacements of pixels in the fractured zone inside the sample, containing the average, maximum and median displacements.

2. Control and graphite modified asphalt binder preparation

In this research, five types of asphalt samples were prepared, including the control asphalt (PG 58-28), exfoliated graphite nanoplatelets (xGNP) modified asphalt (2% and 4% by binder weight) and flake graphite modified asphalt (5% and 7% by binder weight), respectively. The flake graphite was obtained from Asbury Carbons with a density of 2.25 g/cm^3. The particle sizes of flake graphite focus on two meshes, No. 100 (75%) and No. 200 (25%). The minimum layer thickness is 0.11 mm. The xGNP was manufactured by XG Sciences with a bulk density of 0.03–0.1 g/cm^3, particle diameter of 25 μm and an average thickness of approximately 15 nm. The flake graphite or xGNP graphite modifiers were added into control asphalt based on selected weight percentages and mixed by a high speed mixer at 120 °C for about 1 h. The prepared and control asphalt binder were used for following binder performance tests.

3. Asphalt binder tests and property measurement

3.1. Viscosity measurement and activation energy calculation

The viscosity as a basic rheological property of control and graphite modified asphalt samples was measured by a BROOKFIELD MODEL DV-II viscometer. The measured viscosity results of control, 5% flake graphite modified and 2% xGNP modified asphalt are exhibited in Fig. 1(a). The testing temperatures were selected as 100 °C, 125 °C, 135 °C, 150 °C, and 175 °C, separately. It can be observed that the 2% xGNP modified asphalt has a higher viscosity than the 5% flake graphite modified asphalt. The viscosity of the control asphalt is lower than those of the 2% xGNP and 5% flake graphite modified asphalt.

The concept of an activation energy barrier for starting viscous liquid flow was used [31]. The viscous flow process can be considered as a thermal process where atoms, molecules and groups of molecules should overcome an energy barrier to move [32]. The asphalt self-healing process was regarded as a viscous Newtonian flow process in this study. Therefore, the activation energy was used to evaluate the healing performance of control asphalt,