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Laboratory performance evaluation of both flake graphite and exfoliated graphite nanoplatelet modified asphalt composites

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HIGHLIGHTS

- Improve viscosity, modulus and thermal properties of asphalt materials with added graphite.
- Analyze chemical oxidation groups in modified binder.
- Evaluate low- and high-temperature performance of modified asphalt binder.
- Increase dynamic modulus and rutting resistance of modified asphalt mixtures.

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ABSTRACT

This paper presents a laboratory investigation of the thermal, electrical, rheological and mechanical properties and performance of control and graphite (flake graphite and exfoliated graphite nanoplatelet (xGNP)) modified asphalt binder and mixture. For the graphite modified asphalt binder, the rolling thin film oven (RTFO) test and pressure aging vessel (PAV) test were utilized to simulate the short-term and long-term aging process of control and graphite modified asphalt binder, respectively. The bending beam rheometer (BBR) test and dynamic shear rheometer (DSR) test were conducted to evaluate the rheological properties of the control and graphite modified asphalt binder at low and high temperatures, respectively. The Fourier transform infrared spectroscopy (FTIR) was used to evaluate the oxidation group content in these asphalt binders. The thermal conductivity of the graphite modified asphalt binder increased with graphite content. For the graphite modified asphalt mixtures, both thermal and electrical conductivities also increased with added graphite modifiers. The measured dynamic modulus results of mixture performance tests indicated that the added graphite particles were capable of increasing their moduli at both high and low temperatures. The Hamburg wheel tracking device (HWTD) test results also showed an improved rutting resistance. As a result, the graphite modified asphalt mixture can improve multiple physical properties and high-temperature performance as promising conductive materials for many applications.

1. Introduction

Asphalt mixture consists of asphalt, graded aggregates and air voids [1,2]. The temperature-dependent asphalt binder exhibits viscous flow at high temperatures and behaves as a viscoelastic solid at low temperatures [3,4]. 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 [5]. 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 induce further damage and lead to the removal and loss of stones due to weaker bonds [6]. With the combination of all these factors, the wearing courses need to be maintained and repaired frequently.

Recently, graphite as a superior thermal and electrical conductive filler has been applied in an asphalt mixture and pavement studies and has attracted the interest of many researchers. In the authors' accompanying research, the infrared light healing and microwave healing of graphite-modified asphalt mixtures were evaluated, and the results showed a promising potential for field

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applications [2,7,8]. Wu et al. [9] 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. [10] found that graphite powders could improve the thermal conductivity of asphalt mixtures and be a better method to resolve the pavement snow-melting problem. In addition, Wang et al. [11] employed a finite element model to predict the thermal response of asphalt pavements with added graphite conductive media. Pan et al. [12] concluded that the thermal conductivity and diffusivity of graphite asphalt increased with the addition of graphite. Added nanomaterials, such as nanoclay and nanosilica, can improve the performance of asphalt mixture in rutting and stiffness. The layer structures of nanoclay were intercalated and exfoliated when the nanoclay was high-speed mixed in the asphalt matrix. The rutting resistance and modulus significantly improved in the nanoclay modified asphalt mixtures [1,13,14]. In order to compare with the nanoclay modified asphalt mixtures, the exfoliated graphite nanoplatelets were added to asphalt binder and mixtures for performance evaluation in this presented paper.

In order to evaluate modified asphalt binder and mixture performance, the laboratory performance tests were conducted, which included binder rheological properties, mixture dynamic modulus and rutting performance tests. The dynamic modulus is one of the most important parameters for flexible pavement design [15]. It was found that the dynamic modulus was affected by asphalt stiffness and aggregate size distribution [16]. Clyne et al. [17] reported that the dynamic modulus of the mixture with softer asphalt was lower than those with stiffer asphalt. Birgisson et al. [18] proposed that the aggregate gradation had a crucial impact on the dynamic modulus of mixtures. A study by Chen et al. [19] presented that the asphalt mixtures using low percentages of flat and elongated aggregates resulted in a stable internal structure due to improved stone-on-stone contact, and thus increasing the dynamic modulus.

Since rutting is a primary traffic load-related distress on pavement [20], the rutting resistance of modified asphalt mixtures is measured to evaluate the high-temperature performance of pavement. The performance tests that were normally conducted to evaluate the rutting level of the asphalt mixture include the asphalt pavement analyzer (APA) test and Hamburg wheel tracking device (HWTD) test [21]. Zhao et al. [22] utilized APA and HWTD rutting tests to investigate rutting depths of the warm and hot mix asphalt mix containing reclaimed asphalt pavement. Rushing et al. [23] studied the rutting susceptibility of HMA designed for high tire pressure aircraft. Based on these studies, both the dynamic modulus and rutting resistance of control and graphite modified asphalt mixtures were tested in this study.

This research aims to evaluate the performance of asphalt binder and mixture modified by two types of graphite materials, flake graphite and exfoliated graphite nanoplatelets (xGNP). First, flake graphite and xGNP particles were added into asphalt with different weight percentages for preparing the graphite modified asphalt binder. Then asphalt binder tests were conducted to evaluate the performance of graphite modified asphalt, including the bending beam rheometer, dynamic shear rheometer, Fourier transform infrared spectroscopy and thermal conductivity. Afterwards, the electrical, thermal, and mechanical properties of graphite modified asphalt mixture were investigated, including the control, 5% flake graphite modified and 2% xGNP modified asphalt mixtures. Specifically, the electrical resistivity, thermal conductivity, rutting resistance and dynamic modulus of the graphite modified asphalt mixture were measured by using the Megohmmeter, thermal property analyzer, HWTD and UTM-100, respectively. The results showed that the small addition of micro or nano graphite particles can generally improve the physical properties and high-temperature performance of both asphalt binder and asphalt mixtures.

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 mainly included two meshes, No.100 (0.15 mm, 75%) and No.200 (0.075 mm, 25%). The minimum layer thickness was 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 and 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. Then the control and graphite modified binder were processed by the RTFO test and PAV test to obtain the short-term and long-term aged binder. The prepared and control asphalt binder were used for following binder performance tests. For each of binder performance test, at least three binder samples for each type were used for the property measurement. The presented data in the binder test results is the averaged value among these replicated samples.

3. Asphalt binder performance tests and property measurement

3.1. Bending beam rheometer test

The low temperature property of graphite modified asphalt binder was evaluated with the bending beam rheometer (BBR) test. The control, flake graphite modified (5% and 7% by binder weight), and xGNP modified (2% and 4% by binder weight) binder, processed by the rolling thin-film oven (RTFO) test and pressure aging vessel (PAV) test, were cast into a mold to make asphalt binder beams with a dimension of 101.6 mm × 12.7 mm × 6.35 mm. Three samples for each type of asphalt were prepared. The stiffness and m-value of the beam were measured by applying a loading on the top center with a testing temperature of −18 °C. Fig. 1 (a) and Fig. 1 (b) display the relationship between the testing time and average stiffness of the long-term aged control, 5% and 7% flake graphite modified, and 2% and 4% xGNP modified asphalt binders, respectively. It was observed that the graphite materials increase the stiffness of asphalt binder with graphite content. The obtained stiffness, m-values and standard deviations of the control and graphite modified asphalt binder at 60 s during the test are listed in Table 1. It was seen that all the stiffness of graphite modified binders increased compared to the control asphalt binder. In addition, all the m-values of graphite modified binders decreased compared with the control asphalt binder. Based upon the Superpave standard, the stiffness value should not exceed 300 MPa, and the minimum m-value is 0.3. Therefore, the graphite materials could slightly decrease the low temperature property of asphalt. The content of xGNP cannot go up to 4% of the asphalt by weight.

3.2. Complex shear modulus test

A dynamic shear rheometer (DSR) was used to measure the complex shear modulus of the control and graphite modified asphalt binders. The complex shear modulus described the resistance of the tested asphalt binder to the deformation induced by shear force. In this study, all the tested asphalt binders were divided into three groups, including virgin asphalt binder, RTFO