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Influence of graphite on the thermal characteristics and anti-ageing properties of asphalt binder

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HIGHLIGHTS

- Graphite improves anti-ageing properties of asphalt.
- Thermal conductive and diffusivity increases with increasing of graphite content.
- Specific heat decreases with the increasing of graphite content.
- Thermal properties of asphalt depend largely on the amount of graphite particles.
- Graphite is a potential material to improve energy efficiency of hydronic pavement.

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ABSTRACT

Hydronic asphalt pavement (HAP) is an emerging technology for the purpose of harvesting solar energy in the summer and deicing the pavement in the winter. Increasing the thermal conductivity of pavement material is a fundamental technology to improve the operation efficiency of such novel system. In this paper, the influences of graphite on the thermal characteristics and anti-ageing properties of asphalt binders were experimentally investigated. A control asphalt binder (CAB) sample was prepared by the same weight ratio of asphalt and mineral filler. Experimental results indicated that the thermal conductivity and diffusivity increased linearly with the increasing of graphite content, while the specific heat presented a descending trend correspondingly. Although the storage stability of asphalt binders with graphite were better than the CAB sample, binders with mineral filler or graphite showed bad high temperature storage stability. Differences between the physical and rheological properties of the original asphalt binders and the aged samples illustrated that graphite improved the anti-ageing properties of asphalt binders.

1. Introduction

Asphalt pavement surface temperature can reach to 70 °C in summer due to its high absorption coefficient to solar radiation [1]. On the one hand, this phenomenon consequently degrades the durability of asphalt pavement. High temperature will induce the permanent deformations of asphalt pavement with the effect of traffic. It can also accelerate the thermal oxidative, which will result in degradation of the pavement performances [2]. One the other hand, higher surface temperature on the pavement leads to environment problems. The high surface temperature plays an important role on contributing to the development of urban heat island effect (UHIS), which means the temperature of urban area close to asphalt pavement is higher than the temperatures of surrounding suburban and rural areas [3]. Therefore, in order to prolong the service life of asphalt pavement and mitigate the UHIS problem, it is necessary to develop a method to cool the asphalt pavement during the hot period.

In addition, cold weather with the accumulation of snow and the ice formation on the road surface can lead to the transportation safety problems, especially on some sections like bridges and ramps. How to remove such snow/ice effectively and keep the asphalt pavement with acceptable pavement behaviors are the primary concerns by the transportation managers. The use of deicing agent is a traditional method to melt the snow and ice. Unfortunately, it can result in concrete corrosion and environmental pollution [4,5]. Some mechanical method, which can be used to remove the snow and ice, will surely lead to the surface damages and high maintenance cost for mechanical devices [6]. In recent decades,

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many studies have been conducted on exploiting a most efficient, convenient, safe and environmental conservative method to remove snow and ice.

To solve these problems, one of the most promising methods is the application of hydronic asphalt pavement (HAP). HAP consists a series of serpentine or parallel pipes embedded in the pavement, below the surface layer. The HAP system has two main parts: cooling the warm pavement by the circulated groundwater and deicing (and/or heating) the pavement by the extracted energy from the pavement [7,8]. What makes this type of pavement more enticing is that HAP can extract solar energy in the summer and provide heat for snow melting in the winter. Numerous researches have been investigated in the hydronic asphalt pavement with laboratory measurements and numerical simulations [9–11]. It is commonly believed that improving the thermal conductivity of asphalt concrete can facilitate the energy transfer process occurring in the asphalt concrete. Previous studies testified that the addition of graphite powder is helpful to improve the thermal conductivity and electrical conductivity of asphalt concrete [12–14]. Compared to conventional asphalt concrete, graphite modified asphalt concrete shows better permanent deformation resistance and fatigue resistance, but worse moisture stability [15].

However, the long-term performance of graphite modified asphalt concrete is still not reported. Factors that can influence the long term performance of asphalt mixture can be classified in three main categories, including realistic traffic loading, environmental loading, material properties and compositions [16]. It is well known that the HMA behaviors subject to the asphalt mastic, which consists of an intimate homogeneous mixture of fine aggregate, filler and bitumen. The asphalt can be easily get aged under the heat, sunlight, oxygen or combination of these factors. The ageing of the asphalt binder would cause serious degradation in the performance of asphalt binder, and hence attenuates the durability of pavement [17,18]. The influence of ageing on the rheological and physical properties of asphalt binder with graphite is not reported as well. Moreover, although the incorporation of graphite can improve the thermal conductivity of asphalt concrete/binder, the effect of graphite on the other related thermal characteristics of asphalt concrete/binder is still unknown. The other related thermal characteristics of asphalt binder are thermal diffusivity and specific heat. The thermal diffusivity indicated the heat transfer ability of asphalt binder. Pavement materials with high thermal diffusivity could improve the heat transfer efficiency of hydronic asphalt pavement. For the same amount of heat, pavement materials with low specific heat implied large temperature variation. This may result in bigger temperature gradient between the pavement and heat transfer pipes, which improve the heat transfer behavior of hydronic asphalt pavement. Therefore, thermal diffusivity and specific heat are as important as the thermal conductivity.

This paper aims to provide some insight into assessing the anti-ageing properties of graphite modified asphalt binder. At the same time, the effect of graphite on the thermal characteristics of asphalt binder was investigated by Thermal Constants Analyzer. The changes on rheological and physical properties of asphalt binders with or without graphite were investigated through short-term ageing test (thin film oven test, TFOT), long-term ageing test (pressurized ageing vessel, PAV) and ultraviolet radiation ageing test (UV).

2. Materials and experimental

2.1. Materials

AH-70 paving asphalt, obtained from the Hubei Guochang Hi-tech Material Co., Ltd., with a softening point of 47.2 °C (ASTM D36) [19], a ductility of 156 cm (25 °C, ASTM D113) [20], a penetration of 73 dmm (deci-millimetre, 25 °C, ASTM D5) [21] and a thermal conductivity of 0.17 W/(m K), was used for this research. Limestone powder, with a particle size of lesser than 0.075 mm, a density of 2.699 g/cm^3 and a thermal conductivity of 2.92 W/(m K), was used as the mineral filler. Graphite was used as thermal conductive filler. It has a density of 2.1 g/cm^3 and a thermal conductivity of 59.32 W/(m K), consists of carbon (98.9%), ash (0.2%), and iron (0.03%) by weight. Its particle size was less than 150 μm.

2.2. Preparation of modified asphalt binders

Table 1 shows the composition of graphite modified asphalt binders. For each type of modified binder, the weight sum of mineral filler and graphite were the same with that of asphalt. As shown in Table 1, the weight fractions of graphite were 0 wt.% (CAB), 10 wt.% (GMAB-10), 20 wt.% (GMAB-20), 30 wt.% (GMAB-30) and 40 wt.% (GMAB-40) respectively. The asphalt binders were mixed using a high shear mixer (made by Weiyu Machine Co., Ltd., China). Asphalt binder (500 g ± 5 g) was first heated to 165 ± 5 °C in an oil-bath heating container. Secondly, the mineral filler and graphite were separately added slowly within 10 min, while the shear speed was kept at 2500rp/m. After all the mineral filler and graphite were added, the asphalt binder was sheared for another 30 min to make sure the homogenously dispersing of additive in the asphalt.

2.3. Storage stability test

The storage stability of modified asphalts was specifically used to evaluate the high temperature storage stability of modified asphalt binders. Due to the differences in the density of asphalt and graphite or mineral filler, additives sedimentation would take place in the graphite modified asphalt binder during storage at high temperatures. Therefore, it is necessary to investigate the storage stability of graphite modified asphalt binders. There were simply three steps to conduct the storage stability test. Firstly, a certain amount of specimen was poured into an aluminum toothpaste tube (32 mm in diameter and 160 mm in height). The tubes were then sealed and stored vertically in an oven at 163 °C for different storage time of 0.5 h, 1 h, 4 h, 8 h, 24 h and 48 h. Secondly, the tubes were taken out of the oven, cooled at 5 °C for 4 h ± 5 min and cut into three equal sections. Thirdly, the differences in the softening point of the samples, which were taken from the top and bottom sections, were used to evaluate the storage stability of the asphalt binders. Lower differences in softening point indicates better high-temperature storage stability.

2.4. Thermal characteristics analysis

The thermal properties of asphalt binders were measured by Thermal Constants Analyzer (TPS 2500S, Hot Disk, Sweden). In this study, three test repetitions were tested and the average value was used. The thermal conductivity and thermal diffusivity were measured by the thermal constant analyzer. And the heat specific is calculated by the following equation:

$$c_v = \frac{\lambda}{\alpha} \tag{1}$$

where c_v is the specific heat, MJ/(m^3 K), λ is the thermal conductivity, W/(m K), α is the thermal diffusivity, mm^2/s. Rapid cooling of asphalt binders could mitigate the sedimentation of graphite and mineral filler. The effect of graphite on the thermal conductivity, thermal diffusivity and specific heat were investigated. Fig. 1 illustrates the schematic representation of the thermal properties measurement for asphalt binders. The test sensor connected to the thermal constant analyzer. The test temperature was 20 °C. The modified asphalt binders were heated to 150 °C and poured into the container with a dimension of 120 × 60 × 60 mm. As soon as the test sensor was vertically immersed into the asphalt binder, the container was put in the oil-bath. The temperature of asphalt binder was 145 °C and the temperature of oil bath was 0 °C. When the asphalt binder became a solid state, the temperature of oil-bath was set to 20 °C. Then, the container should be kept in the oil-bath for 4 h, to make sure the temperature in asphalt binder remaining uniform.

2.5. Standard ageing procedure

In this study, accelerated ageing of asphalt binders were performed by the thin film oven test, TFOT (ASTM D1754), pressurized ageing vessel, PAV (ASTM D6521), and ultraviolet radiation (UV) ageing test. The TFOT simulates short-term ageing

Table 1
Composition of graphite modified asphalt binders.

Asphalt binder	Composition (g)				
	CAB	GMAB-10	GMAB-20	GMAB-30	GMAB-40
Asphalt	501.1	502.4	499.1	500.5	501.8
Mineral filler	501.1	452.2	399.3	350.4	301.1
Graphite	0.0	50.2	99.8	150.1	200.7