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Performance of asphalt binder blended with non-modified and polymer-modified nanoclay

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ABSTRACT

This study investigated the rheological properties of asphalt binders modified with nanomaterial additives. The additives used are non-modified nanoclay (NMN) and polymer modified nanoclay (PMN). They were added to the control PG 58-34 asphalt binder at concentrations of 2% and 4% by the weight of the asphalt binder, respectively. Superpave™ binder tests were employed to evaluate the characteristics of the nano-modified binders. Rheological properties of nano-modified asphalt were analyzed by use of asphalt binder tests such as Rotational Viscosity (RV), Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR). In addition, the short- and long-term aging properties of nano-modified asphalt were analyzed, with the aging process simulated by Rolling Thin Film Oven (RTFO) and the Pressure Aging Vessel (PAV). The dissipated work per load cycle of all asphalt binders was examined, in order to better understand the properties of nano-modified asphalt. The results reveal that both viscosity and complex shear modulus of asphalt binder remarkably increase when the NMN is added into the control asphalt, and decrease slightly when the PMN is added. In addition, from the dissipated work perspective, the overall performance of PMN modified asphalt binder is improved in terms of rutting and fatigue cracking resistance relative to the NMN modified asphalt binder.

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1. Introduction

Asphalt mixture is composed of asphalt, graded aggregates and air voids. Asphalt is a time–temperature viscoelastic material and its behaviors depend on both temperature and loading time. The components of asphalt are rather complex and they contain carbon, hydrogen, nitrogen, sulfur, oxygen, etc. Researchers have been trying to use different kinds of additives to modify the base asphalt in order to increase the resistance to pavement distress. In general, fibers and polymers are two main materials used in the asphalt modification [1–5]. Fiber was one of the most widely used additives to enhance the bonding between asphalt and aggregates or within asphalt since 4000 years old ago [6–12]. In addition, scientist and engineers tried to use the polymer Styrene Butadiene Styrene (SBS) to improve pavement fatigue and rutting resistance of asphalt [13–16]. Performance of asphalt binder modified with SBS was investigated using different test methods. Properties such as the asphalt composition, reaction between the modifier and asphalt or within asphalt, asphalt microstructure and rheology features, were evaluated by Fourier transform infrared (FTIR), atomic force microscopy (AFM) and Dynamic Shear Rheometer (DSR). Results show that SBS modified asphalt mixture can significantly improve the asphalt binder performance under both high and low temperatures [14,15,17–20].

Recently, nanomaterials for asphalt mixture have been developed rapidly as they have extensive and unique properties such as the quantum effects, structural features, high surface work, spatial confinement and large fraction of surface atoms. Nanomaterials possess an extraordinary potential for improving the performance of asphalt binders and mixtures. It is anticipated that these may enhance or modify the properties of asphalt pavement. You et al. presented that nanoclay modified asphalt could increase the shear complex modulus and reduced the strain failure rate of base asphalt. Furthermore, the addition of nanoclay would decrease the moisture damage of asphalt mixture [21,22].

In this study, two types of nanomaterials were used as additives to modify the control asphalt PG 58-34: (1) non-modified nanoclay (NMN); and (2) polymer modified nanoclay (PMN), both obtained from Nanocor Inc. (USA). The binder tests of Superpave™ were conducted, including Rotational Viscosity (RV), Dynamic Shear Rheometer (DSR), Bending Beam Rheometer (BBR), Rolling Thin

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Film Oven (RTFO) and Pressure Aging Vessel (PAV), and the performance of nanomaterials modified asphalt (NMA) was investigated. Based on the results of these tests, it can be concluded that the addition of NMN and increases the complex shear modulus ($|G^*|$) of asphalt significantly, and improve the high-temperature performance of asphalt from the rutting and fatigue dissipated energy perspective. Compared with the NMN modified asphalt binder from the BBR test, the low-temperature properties of PMN modified asphalt binder are slightly better.

2. Preparation and tests of nanomaterials modified asphalt

Nanoclay is widely used in the modification of polymer. It could improve the mechanical properties, heat resistance and biodegradability of hybrid materials [21]. The raw nanoclay (NMN) is montmorillonite; a 2-to-1 layered smectite clay mineral with a plate structure. The major sodium ions constitute the layer and this structure has high expansion pressure. It readily leads to exfoliation and dispersion of crystal in the form of micro-particles or layer [23]. NMN microstructure images are observed by Hitachi S-4700 field emission scanning electron microscope (FE-SEM) (Fig. 1). Polymer modified nanoclay is used as a polymeric photosensitizer [24]. The PMN is normally produced from the hydrophilic nanoclay with the organic cation exchange. Through the modification, the permeability of composite material is reduced; tear and compression strength is improved [25]. PMN FE-SEM microstructure images are shown in Fig. 2. Obviously, the agglomeration phenomena happened in both NMN and PMN. In addition, in this study, two nanoclay materials (NMN is hydrophilic and PMN is hydrophobic and organophilic via the modification by polysiloxane) were applied to modify the control asphalt. The PMN and NMN feature a bulk density of is 0.251 g/cm^3 and 0.678 g/cm^3 respectively and both feature a maximum size of 200–400 nm in terms of aspect ratio [26]. Asphalt graded PG 58-34 from a project site in Gladstone Michigan was used as the control asphalt. It is noted that the control asphalt was pre-modified with acrylonitrile butadiene styrene (ABS) in order to improve the compatibility between the asphalt and polymer, and meet the low temperature grade requirement.

Each nanomaterial, PMN or NMN were added to the base asphalt at concentrations of 2% and 4% by the weight of control asphalt, respectively. The modified asphalt binder was mixed with high shear mixing equipment at the condition of 4000 rpm rotational speed and of around 130 °C temperature. All samples were mixed for around 2 h prior to the Superpave™ binder tests. In addition, microstructure images of 4% NMN and PMN modified asphalt binder were also obtained by using a Hitachi SU6600 FE-SEM with a cryogenic stage and shown in Figs. 1 and 2. The SU6600 images showed that the NMN was mainly found in conglomerates, which ranged in size from 50 to 15 μm. The dispersion of the PMN was slightly better with an average conglomerate size of 4 μm, but there were a few extremely large conglomerates (∼80 μm). From the figures, it can be seen that agglomeration phenomena of nanomaterials also occured in the asphalt binder and nanomaterials were melted uniformly in the control asphalt binder. It is possible that chemical reaction was undertaken between the nanomaterials and control asphalt binder.

3. Results and discussion: rotational viscosity test

The rotational viscosity is the measurement of a fluid's resistant to flow. Asphalt samples were measured with the Brookfield viscometer at 100 °C, 125 °C, 135 °C, 150 °C, 175 °C, and 190 °C. The 27# spindle was selected and test temperatures covered the range of mixing and compaction temperatures (AASHTO, 2006). The test results are shown in Fig. 3.

Fig. 3 shows that with the addition of NMN in the control asphalt binder, the viscosity of the modified asphalt increases by an average of 250% within 100 °C to 190 °C temperature range. However, the addition of PMN in the base asphalt does not result in significant improvement in viscosity values and maintain the same level with the control asphalt. Fig. 1 illustrates that all viscosity data under 135 °C pass the specification of Superpave™ Standard, and are lower than the limit of 3 Pa s. The asphalt viscosity determines the pumpability, mixability and workability of asphalt binder. The high viscosity leads to the high mixing and compaction temperature. It will cost more heating work for asphalt pavement construction. In light of the viscosity, the PMN modified asphalt binder has more advantage relative to the NMN modified asphalt binder. In addition, non-modified nanoclay was melted into the asphalt binder and increases the viscosity for the mechanical, thermal, and barrier properties. Polymer modified nanoclay has the excellent temperature resistance due to the polysiloxanes modification. That is the reason for lower viscosity.

4. Results and discussion: Complex shear modulus ($|G^*|$) test

Dynamic Shear Rheometer (DSR) is used to characterize the viscous and elastic behavior of asphalt binder at the medium and high temperatures. It measures the complex shear modulus ($|G^*|$) and phase angle (δ) of asphalt binder. The $|G^*|$ is used to evaluate the rutting potential of asphalt binder at unaged or short-term aging condition and the phase angle represents the time lag between the applied shear stress and the resulting shear strain. When the phase angle is zero, the subject asphalt binder is a purely elastic material, and when the phase angle is 90°, it is a purely viscous material. High $|G^*|$ means stiffer in the asphalt binder at high temperature. It has potential to resist the deformation of asphalt pavement. Simultaneously, for rutting dissipated work per load cycle, the calculation equation is shown in the following equation:

$$\text{Rutting}: Wc = \pi\sigma_0^2\left[\frac{1}{G^*/\sin\delta}\right] \quad \text{(stress-controlled)} \tag{1}$$

And for fatigue cracking dissipated work per load cycle, the calculated equation is shown in the following equation:

$$\text{Fatigue cracking}: Wc = \pi\sigma_0^2(G^*\sin\delta) \quad \text{(strain-controlled)} \tag{2}$$

where Wc = work dissipated per load cycle, σ = stress applied during load cycle, ε = strain during load cycle, G^* = complex shear modulus, δ = phase angle.

Permanent deformation resistance is conducted on the unaged and RTFO-aged asphalt binder and the fatigue cracking is conducted on the PAV-aged asphalt binder. In addition, with each cycle, when the load is applied, the work from each load is transferred into the pavement. A portion of the work is absorbed by the pavement and reflected as elastic rebound. The remaining work is converted into damage in the form of rutting, fatigue cracking and crack propagation. Therefore, the low dissipated energies per load cycle indicate that an asphalt binder has good resistance ability to rutting and fatigue cracking.

4.1. NMN modified asphalt binder

From Fig. 4, the complex shear modulus master curves of NMN modified asphalt binder and control asphalt binder are displayed. It can be described that the complex modulus ($|G^*|$) values of 2% and 4% NMN modified asphalt binder are more than the control asphalt binder, and the complex shear modulus ($|G^*|$) values of 2% NMN modified asphalt binder are close to that of control asphalt binder

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