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Laboratory performance of warm mix asphalt binder containing polyphosphoric acid

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HIGHLIGHTS

- Rheological and morphological properties of WMA-PPA binders were studied.
- Viscosity, Temperature and frequency sweep, creep stiffness, etc. were tested.
- The 1.5% of PPA was found to be the optimum content.
- The modification effect of PPA on WMA asphalt is a chemistry process.

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ABSTRACT

In this study, the objective was to conduct a laboratory investigation of rheological and morphological properties of warm mix asphalt containing polyphosphoric acid (WMA-PPA). The Superpave binder tests (i.e., rotational viscosity test, dynamic shear rheometer (DSR) test and bending beam rheometer (BBR) test) as well as microscopic tests (i.e., Fluorescence microscopy, Fourier transform infrared spectroscopy (FT-IR) and Differential Scanning Calorimetry and Thermogravimetry (DSC/TG) test) were performed to determine the influences of polyphosphoric acid (PPA) on warm mix asphalt binders. The experimental design included six binders and four different polyphosphoric acid dosages (by weigh of neat asphalt). The test results indicated that, the addition of PPA into warm mix asphalt binders exhibited an increase in the viscosity at different test temperatures, giving clear indication of the modification effects of PPA on the warm mix asphalt binders' high-temperature performances. Temperature and frequency sweep tests show that the WMA-PPA binders demonstrate lower value of phase angle and higher value of complex modulus compared with the WMA binder regardless of aging state, the WMA-PPA asphalt containing more PPA has higher values of complex modulus (lower values of phase angle) than the WMA-PPA asphalt with less PPA in original state and after RTFO aging state. Bending beam rheometer (BBR) test illustrates that the addition of PPA making the low temperature rheological properties of the WMA binder worse. Furthermore, the amount of PPA has a great effect on the microstructures and hot storage stability of WMA-PPA asphalts, and the modification effect of PPA on WMA asphalt is a chemistry process. The 1.5% of PPA was found to be the optimum content between the studied percentages due to the warm mix asphalt binder containing 1.5% PPA achieved comparative good intermediate and high temperature rheological properties and at the same time is considered economical.

1. Introduction

Energy consumption is one of the principal factors in pavement construction that significantly contributes to the entire construction cost. In conjunction with that, it is important to control the entire construction cost and to meet increasingly stringent environmental regulation using a green and energy saving technology, which is known as warm mix asphalt (WMA). The technology of WMA began in Europe aimed to reduce the greenhouse gases in response to Kyoto agreement [1,2]. WMA technologies reduce binder viscosity as well as mixing and compaction temperatures by 20–30 °C during asphalt mix production and laydown [3]. By now, many efforts have been made to reduce the mixing and compaction temperature and considerable research on WMA has been conducted in many countries [4–9]. Jamshidi et al. [10] proposed a methodology to characterize the changes in the rheological properties of unaged and aged asphalt binders incorporating various Sasobit and Rediset contents at high and intermediate

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temperatures. Guo et al. [11] evaluated the laboratory performance of warm mix asphalt containing reclaimed asphalt pavement (WMA–RAP) materials and the WMA mixtures containing 0% and 40% RAP were produced using Evotherm-DAT and S-I WMA additives. Xiao et al. [12] explored the utilization of the conventional fatigue analysis approach in investigating the fatigue life of rubberized asphalt concrete mixtures containing the WMA additive and the fatigue beams were made with one rubber type (−40 mesh ambient crumb rubber), two aggregate sources, two WMA additives (Asphamin and Sasobit), and tested was carried at 20 °C. Xiao et al. [13] also investigated the rheological behaviors of various WMA binders after long term UV aging and conventional PAV aging procedures and the complex shear modulus, phase angle, elastic modulus, viscous modulus at an intermediate service temperature, and deflection, stiffness, and m-value at a low temperature were tested and evaluated. Zhao et al. [14] investigated and characterized the effects of various warm additives on the rutting performance of asphalt concrete with different binders and mixing temperature applications. Compared with hot mix asphalt (HMA), WMA have many advantages as follows [15]:

In environmental: lower emissions, fumes and odors.
In production: reduced aging of bitumen.
In paving: lower bitumen viscosity at paving temperature and longer haul distances and reduced time of pavement cooling.
In economic: reduced energy consumption, less wear on asphalt plant due to reduced temperature.

Three technologies have been primarily used for the production of WMA, the first technology is foaming techniques (which are divided into water-based and water containing), the second technology is the use of organic or wax additives, and the last technology is the use of chemical additives. In this study, a type of chemical additive, Evotherm DAT, was used to form the WMA. Evotherm DAT is a surfactant based chemical additive that depends on foaming for lowering mixing and compaction temperatures. However, Evotherm is a chemistry package that could improve workability, adhesion promoters of the mixtures. At a small concentration of the additive, the properties of the bitumen remain mainly unchanged. The mechanical properties of the bitumen are not influenced by adding Evotherm DAT [16,17].

Even though WMA has shown promising results in energy savings and emission reduction, however, only limited studies and laboratory tests have been conducted to date. Further detailed studies and tests are needed to evaluate the performance of WMA, especially the performance of WMA containing PPA (WMA-PPA), PPA is the abbreviation of polyphosphoric acid which is one kind bitumen modifier permits to significantly harden bitumen in an easily controllable way [18–23]. After PPA modification, the high temperature rheological properties of bitumen can be improved remarkably without affecting the low temperature grade [18]. Edwards et al. observed that adding PPA especially to a non-waxy bitumen, showed considerable positive effects on the rheological behavior at higher, medium and low temperatures [24,25]. Some researchers even reported that addition of 1% by weight of PPA to an asphalt binder improves the high-temperature performance by approximately 10 °C and the low-temperature performance by approximately 2 °C [26–28].

The primary objective of this study was to characterize the rheological and morphological properties of WMA-PPA asphalts through some laboratory tests. Rotational viscosity, complex modulus (G^*), phase angle (δ), stiffness and m-value tests were performed to explore the rheological behaviors of various aged and unaged WMA-PPA binders in this study. In addition, Fluorescence microscopic image analysis, infrared spectroscopic analysis, and thermogravimetric and differential scanning calorimetry analysis were carried to investigate the morphological properties of WMA-PPA asphalts in this study.

2. Research significance

During the last decades, an increasing concern for the preservation of natural resources has led to the pursuit of alternatives to reduce the production of harmful emissions and energy consumption in several industries, and warm mix asphalt (WMA) technologies are the result of several efforts directed to identify more sustainable technologies that can be used for the construction of road infrastructure. What's more, as mentioned above, PPA is one kind bitumen modifier permits to significantly harden bitumen in an easily controllable way, and the considerably lower cost of PPA compared with polymer modifiers has made PPA modification a popular choice for pavement applications. Therefore, investigating the rheological and morphological properties of WMA binders containing PPA is an important aspect in the construction of road infrastructure. In this study, an attempt was made to conduct a laboratory investigation of rheological and morphological properties WMA binders containing PPA. The testing procedures such as viscosity, DSR, BBR, Fluorescence microscopy, Fourier Transform Infrared Spectroscopy and thermogravimetric and differential scanning calorimetry (TG/DSC) were performed to determine the influences of PPA on WMA binders.

3. Materials and test program

3.1. Materials

3.1.1. Neat asphalt

In this work, one commercial asphalt binder, AH50 (Whose penetration grade is 50#), was used as the neat asphalt. 50 means the penetration of the asphalt binder at 25 °C ranging from 40 to 60 (units in 0.1 mm), according to the Chinese specification, JTG F40-2004 [29]. Table 1 presents their main characteristics including penetration, ductility, softening point (R&B). Table 1 also shows the properties of RTFO residue including mass-loss, penetration ratio, and ductility.

3.1.2. WMA additive

Evotherm DAT, the second generation of Evotherm WMA technology, is applied as a WMA additive, which uses a chemical additive technology and a "Dispersed Asphalt Technology" delivery system. By using the technology, a unique chemistry customized for aggregate compatibility is delivered into a dispersed asphalt phase, i.e., emulsion. During production, the asphalt emulsion with Evotherm® chemical package is used in place of conventional asphalt binder. The emulsion is then mixed with the aggregate in the plant. It is indicated that the chemistry provides aggregate coating, workability, adhesion, and improved compaction with no change in materials or job mix formula required [30]. Besides, the properties of Evotherm DAT were presented in Table 2.

3.1.3. Modifier

Polyphosphoric acid (PPA) was used as asphalt modifier in this study. PPA is a kind of colorless transparent sticky liquid, and $H_6P_4O_{13}$ is its molecular formula. In this study, the PPA was provided by Beijing bashine chemical technology co., LTD, and the index parameter of PPA was presented in Table 3.

3.2. Sample preparation

In this study, one Evotherm DAT concentrations (5%, which was based on the recommendation of the manufacturer) and four PPA concentrations (0.5%, 1.0%, 1.5%, 2.0%), with respect to the weight of neat asphalt, were selected. The high shear

Table 1
Basic performance index of neat asphalt.

Index		Units	Test values	Code values
Penetration (25 °C, 5 s, 100 g)		0.1 mm	55.1	40–60
Ductility at 15 °C		cm	>150	⩾80
Softening point		°C	48.3	⩾46
After RTFOT	Mass loss	%	0.36	⩽±0.8
	Penetration ratio	%	61.5	⩾60
	Ductility at 15 °C	cm	51.2	