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Impacts of water content on rheological properties and performance-related behaviors of foamed warm-mix asphalt

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HIGHLIGHTS

- Unmodified and SBS modified asphalt binders respond differently to foaming as well as the amount of water used for foaming.
- Unmodified binder performs better in rutting with 1% of foaming water while modified one performs better with 3% of water.
- Unmodified binder performs better in low temperature with 1% of water while modified one performs better with 3% of water.
- 1% of water reduces unmodified binder's temperature sensitivity (TS) but foaming increases the TS of modified binder.
- Unmodified binder performs better in fatigue with 1% of water while modified one performs better with 2–3% of water.

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ABSTRACT

It has been shown from existing studies that foamed Warm Mix Asphalt (WMA) can effectively improve the workability of asphalt mixtures at relatively low temperature. However, there is limited research into the influence of the amount of water used to foam WMA on the rheological properties and performance-related characteristics of the foamed asphalt. In this study, different amount of water was used to foam non-modified and styrene–butadiene–styrene triblock copolymer (SBS) modified bitumen to create foamed bitumen specimens. They were subsequently tested for high temperature performance, low temperature performance, temperature sensitivity, and fatigue resistance properties. Test results indicate that water content in the foamed asphalt has significant impacts on its various properties and there is an interactive effect between asphalt type and water content. In general, it appears that better results can be achieved if one per cent of water is used to foam the unmodified asphalt, and three per cent of water is used to foam the modified asphalt. The findings may assist controlling experimental variations and improving foamed WMA production.

1. Introduction

Warm Mix Asphalt (WMA), produced at a temperature lower than that required for Hot Mix Asphalt (HMA), has gained much popularity around the world due to its energy saving and other environmentally friendly features. Several types of technologies have been developed to produce WMA, including the use of foaming additives such as Aspha-min®, Advera®, and WAM-FOAM®; organic additives such as Sasobit® and Asphaltan B; chemical packages such as Evotherm®; and surfactants such as Cecabase RT® [1–4]. Compared to these WMA technologies, foamed WMA by water does not require the use of chemical additives. This makes it less expensive to produce in many places of the world, even after factoring in one-time plant modification cost [5]. An early study by Castedo-Franco et al. suggests that any asphalt can be foamed under appropriate conditions [6], although it was later reported by Kendall et al. that silicones in some asphalt produced in Australia inhibits its foaming potential [7].

A large number of laboratory and field studies have been performed to characterize the properties and performance of foamed WMA mixtures. A study conducted by Middleton and Forfylow suggests that the use of foamed WMA can result in 10% reduction in CO, CO_2 and NO_x emissions and 24% reduction in energy consumption, and in the meantime, rutting and moisture susceptibly performance remains the same as the conventional HMA [8]. Punith et al. found that the indirect tensile strength (ITS) of foamed WMA mixture is much lower than those of the conventional mixtures, but the ITS increases after long-term aging [9]. Xiao et al. found that the aggregate source significantly affects the ITS and rutting resistance of foamed WMA mixture, regardless of the added water content for foaming and aggregate moisture content [10]. Shu et al. evaluated the performance of plant-produced, foamed WMA mixture containing high percentages of recycled asphalt

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pavement (RAP). The research results indicate that the foamed WMA with RAP is expected to perform as well as HMA in terms of moisture susceptibility [11]. Shen et al. evaluated the performance of HMA and WMA mixes from field extracted samples and concluded that the foamed WMA's fatigue resistance is comparable to that of the HMA control mixes, while its resistance to rutting is reduced [12]. As can be seen from the existing literature, although the experience of using foamed WMA is generally positive, there are some inconsistent conclusions on certain aspects of WMA performance.

A further literature review suggests that the application rate of water used to foam asphalt binder varies greatly in existing studies and practices. As shown in the examples in Table 1, water added in those studies ranges from 1% to 5%. Existing studies also suggest that water content affects the expansion ratio and half-life (time lapse between which the foamed binder shrinks from its maximum volume to half of the maximum volume) of the foamed binder [17,18]. Under the same production condition, the amount of residual water in the foamed asphalt may also be different. Its effect on the behavior of asphalt binder remains unknown.

As there is currently no guidance on the application rate of foaming water, two questions are raised: (1) if the variation in foaming water content affects the binder and mixture properties, (2) if there exists a foaming water content at which better engineering properties of the foamed asphalt binder can be achieved. The answer to the second question would also have practical values. The aim of the study, as presented in this paper, is to answer these two fundamental questions. In this study, Styrene–Butadiene–Styrene (SBS) polymer modified and unmodified asphalt binders were foamed under various water contents and subsequently tested for high temperature performance for rutting potential, low temperature performance for thermal cracking potential, temperature sensitivity, and fatigue resistance properties. It is anticipated that the research results will benefit the engineering practices of using foaming technology to produce WMA.

2. Material preparation and research methodology

2.1. Material preparation

This study used unmodified bitumen and SBS modified asphalt produced in Jiangsu Province, China for the generation of foamed asphalt binders and subsequent testing. Table 2 summarizes the various properties of the asphalt binders, tested in accordance to the Superpave® mix design specifications and the Chinese standard JTJ 052-2000 [19,20].

A Wirtgen WLB10 laboratory plant was used to create foamed asphalt, with ordinary tap water used as the foaming agent. Foamed WMA with 1%, 2%, and 3% of water by mass of asphalt binder was prepared and then used in the tests. For unmodified asphalt binder, the foaming temperature was 150 °C for asphalt and 30 °C for water, while for SBS modified asphalt, the foaming temperature was 170 °C for asphalt and 30 °C for water. Although the amount of water added to the asphalt binder was carefully controlled, the amount left after the foaming process was unknown.

2.2. Test and evaluation methods

The experiment was designed to evaluate the rheological properties and aging behaviors of foamed WMA created at different water contents. Zero shear viscosity (ZSV) was chosen to characterize the behavior of asphalt binders at relatively high temperature for rutting potential; creep stiffness and "m value" in the Bending Beam Rheometer (BBR) tests were used to characterize their low temperature properties; logarithms of shear storage and loss moduli at different temperatures were chosen to evaluate temperature sensitivity; and ultimate fatigue temperature based on the dynamic shear rheometer (DSR) test was selected to characterize fatigue resistance. Fig. 1 summarizes the test and evaluation methods used in this study. Three replicate tests were conducted for each experiment.

Table 1
Percent of foaming water by mass of asphalt binder reported in existing literature.

Percent of foaming water	Existing literature
1–5%	Button et al. [13]
1.5%	Prowell and Hurley [14]
<2%	Thompson [15]
2–5%	Middleton and Forfylow [8]
2%, 3%, 4%	Xiao et al. [10]
4%	Fu et al. [16]

Table 2
Properties of asphalt binders used in this study.

Properties	Types of asphalt binder			
	Unmodified bitumen		SBS modified asphalt	
	Requirements	Test results	Requirements	Test results
Penetration (25 °C,100 g, 5 s)/0.1 mm	60∼80	62.7	50∼70	53.6
Penetration index PI	⩽0	−1.1	⩽0	−0.23
Ductility ((15 °C, 5 cm/min)/cm	⩾40	>100	⩾25	34.3
Softening point (TR&B)/°C	⩾46	47.2	⩾65	68.7
Density (15 °C)/(g/cm^3)	N.A.	1.034	N.A.	1.037
Solubility (trichloroethylene)/(%)	⩾99.5	99.9	⩾99	99.7
After RTFOT (163 °C, 85 min)				
Mass loss/(%)	⩽0.8	0.3	⩽1	0.5
Penetration ratio (25 °C)/(%)	⩾58	78	⩾65	69.1
Ductility (5 cm/min 5 °C)/(cm)	⩾15	39	⩾20	20.5
PG grade	–	PG64-22	–	PG70-22

2.2.1. Zero shear viscosity of non-foamed and foamed asphalt

Zero shear viscosity (ZSV) is considered to be one of the most fundamental indicators for rutting potential of asphalt binders at relatively high service temperature (60 °C) [21]. Existing studies suggest that the ZSV values of unmodified binders can be obtained by extrapolating the plots of the frequency sweep tests, while the ZSV values of polymer modified binders cannot be obtained from frequency sweep tests because the frequency is not sufficiently low [22]. Anderson et al. proposed that the ZSV values of modified binders can be determined indirectly from the creep recovery tests [21]. Hence, in this study, the ZSV values of unmodified binders were obtained from the frequency sweep tests, while the ZSV values of foamed SBS modified binders were derived based on the creep recovery tests using Burger's model. In addition, existing studies suggest that, for the Newtonian liquid region, stress for the creep test should be no more than 30 Pa [23]. Therefore, stress for the creep recovery test was kept at 25 Pa and the test temperature was set at 60 °C. The creep and creep recovery times were chosen at 16.4 min and one hour, respectively.

2.2.2. Low temperature properties of non-foamed and foamed asphalt

The foamed and non-foamed, unaged asphalt binders were also evaluated for low temperature performance by using the bending-beam rheometer (BBR) test. In the test, the creep stiffness and m-values of the binders at −12 °C, 18 °C, −24 °C were determined and compared.

2.2.3. Temperature sensitivity of non-foamed and foamed asphalt

Temperature sensitivity is closely related to the performance of asphalt binder. There are several evaluation criteria for temperature sensitivity of asphalt binder, including penetration index (PI), penetration-viscosity number (PVN), viscosity-temperature susceptibility (VTS), modulus temperature susceptibility (GTS), etc. In this study, both the shear storage modulus (Eq. (1)) and loss modulus (Eq. (2)) of the foamed asphalt binders at various temperatures were assessed, and regression equations were developed to depict the relationships between the logarithms of the shear storage and loss moduli and temperatures.

$$G' = G^* \cdot \cos\delta \tag{1}$$

$$G'' = G^* \cdot \sin\delta \tag{2}$$

Shear storage modulus measures the elastic portion of an asphalt binder while shear loss modulus measures its viscous portion [24–26]. Slopes of the linear regression equations were used to assess the foamed binders' temperature sensitivity.

2.2.4. Fatigue characteristics of non-foamed and foamed asphalt

Foamed asphalt binders prepared with different water content were artificially aged in rolling thin film oven (RTFO) and pressure aging vessel (PAV) to simulate both short-term and long-term aging. During the experiments, water bubbles were observed in reheating the specimens after RTFO, indicating that the aging process