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Workability and mechanical property characterization of asphalt rubber mixtures modified with various warm mix asphalt additives

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HIGHLIGHTS

- All selected WMA additives improve the workability of AR mixture.
- Except for Sasobit, all WMA additives compromise rutting resistance of AR mixture.
- Effects of WMA additives on AR mixtures' moisture susceptibility are insignificant.
- Among selected additives, only Evotherm-DAT enhances the fatigue resistance of AR.
- Effects of WMA additives on AR binders and mixtures' performance follow similar trend, except for fatigue resistance.

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ABSTRACT

Warm mix asphalt (WMA) technology offers a promising solution to address the workability concern of asphalt rubber (AR) mixture. Warm asphalt rubber (WAR), the combination of AR and WMA, is expected to be a sustainable paving technology that integrates energy conservation, waste management, noise reduction, and performance optimization. This study aims to characterize and compare the engineering properties of WAR mixture prepared with various WMA additives. To achieve this goal, WAR mixtures were prepared with 40-mesh crumb rubber and five different WMA additives, including Evotherm-DAT, Evotherm-3G, Sasobit, 56# paraffin wax and Aspha-min. Comprehensive laboratory tests were conducted to characterize their workabilities and engineering properties, including moisture susceptibility, stiffness modulus, dynamic modulus, and rutting and fatigue resistance. According to the experimental results, by using WMA additives, a 16 °C reduction in construction temperature can be achieved without significantly deteriorating the mixtures' compactability. WMA additives influenced both the stiffness modulus and dynamic modulus of AR mixture. All WMA additives compromised the rutting resistance of AR mixture except for Sasobit, and the influence of WMA additives on the moisture susceptibility was insignificant. In terms of the fatigue performance, only Evotherm-DAT provided a positive effect. Finally, effects of WMA additives on AR binders and mixtures' properties followed the similar tendency, except for the fatigue performance.

1. Introduction

Asphalt rubber (AR) is a modified asphalt binder, which is composed of raw asphalt binder and no less than 15% of crumb rubber modifier (CRM) by total binder weight [1]. The high consumption of crumb rubber helps address the environmental concern on the disposal of waste vehicle tires [2]. Moreover, AR pavement is environmentally beneficial due to its tire-road noise reduction effect [3]. It was also reported that mixtures with AR binder provide superior rutting resistance and fatigue cracking resistance [4,5]. Despite the attractive merits of AR, there is one inherent problem which limits its wide application. Incorporation of crumb rubber significantly increases the asphalt binder viscosity, which in turn increases the required blending and compacting temperatures, resulting more energy consumption and emissions during pavement construction [6]. One potential solution is to use warm mix asphalt (WMA) technology to address the workability concern, making AR more sustainable [7]. If the production temperature for AR mixtures can be reduced by using WMA technologies without compromising their engineering performance, their overall benefits to both environment and society will be significant.

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The engineering performance and working mechanism of both AR and WMA have been well studied [8–10]. The interaction of CRM and base asphalt is reported to be a component exchange process [11]. At elevated temperature, CRM particles absorb asphalt fractions during swelling and release rubber components during depolymerization and devulcanization, which makes the modified binder stiffer and more elastic [12]. Compared to base asphalt, AR binder exerts improved performance in rutting, fatigue and low temperature cracking [13,14]. When used together, WMA additives are expected to enhance mixtures' workability while CRM is expected to provide superior mechanical properties. Due to their different physical natures and working mechanisms, WMA technologies may have different effects on binder properties and mixture performance [15].

When WMA and AR are used together, WMA is expected to influence both the component interaction and engineering performance of AR. Recent studies indicated that chemical and organic additives promote the dissolution of CRM in base asphalt [11], in addition, during the mixing process, CRM particles not only absorb light fractions of raw asphalt, but also certain amount of WMA additives [16]. In terms of the engineering performance, previous studies have proven that most WMA technologies can effectively reduce the viscosity of AR binder at elevated temperatures, resulting in enhanced mixture workability [17–19]. However, the effects of WMA technologies on mixtures' mechanical performance vary. Several studies have reported that the moisture damage resistance of WAR mixture is slightly poorer than that of hot AR mixture as less moisture from aggregate evaporates at lower production temperature [20,21]. This finding was also supported by a study on surface free energy, showing that AR with Rediset, Sasobit and Advera displayed poorer moisture resistance than hot AR [22]. However, Oliveira et al. hold the opposite view because they observed that surfactant additives enhance water sensitivity as the bond between aggregates and binder can be improved by surfactant [4]. Jones et al. concluded that the warm-mix technology by itself is unlikely to influence moisture sensitivity; however, problems are more likely caused by aggregate condition and construction quality [23]. In terms of fatigue performance, Xiao et al. reported that among Sasobit, Evotherm and Aspha-min, only Aspha-min led to poorer fatigue cracking resistance [24]. With respect to rutting resistance, WAR mixtures with Sasobit and surfactant-type additives were reported to provide better performance than hot AR [4,25]. Moreover, the effects of both foaming additives and foaming process on rutting resistance of rubberized asphalt mixtures were found insignificant [21].

Although the performance of WAR mixtures has been investigated by various studies, comprehensive studies covering all three types of WMA technologies and WAR mixtures' engineering properties in full spectrum, are still very limited. To this end, this study aims to evaluate the overall engineering performance of WAR mixtures by characterizing the mixtures' workability, modulus, moisture susceptibility, rutting resistance and fatigue resistance. This study is expected to provide extensive information for selecting appropriate type of WMA technology for field application of WAR.

2. Experimental program

2.1. Materials and sample preparation

The raw bitumen (with penetration grade of 60/70) used in this study was supplied by Anderson Asphalt Ltd., a local asphalt company in Hong Kong. AR binder was prepared by high shearing mixing of CRM and raw asphalt for one hour. The mixing temperature was 176 °C and the mixing rate was set as 4000 rpm, following the previous AR studies [13,26,27].

In total, five representative WMA additives were selected, including: two chemical additives (Evotherm-DAT and Evotherm-3G), two organic additives (Sasobit and 56# paraffin wax), and one foaming additive (Aspha-min). Evotherm-DAT and Evotherm-3G are chemical additives, which act as surfactants between asphalt binder and aggregates. Sasobit (commercial WMA additive produced by the Fisher-Tropsch process) and 56# paraffin wax (conventional wax) are organic additives, which act as flow improvers for viscous binder due to their low viscosities after melting. The purpose of using 56# paraffin wax was to evaluate whether the negative influence of the conventional wax on low-temperature properties can be compensated by CRM when they are used together [13,27]. Aspha-min is a special type of synthetic zeolite, which contains approximately 19–21 wt% of water which can be released during the asphalt blending process. Table 1 presents the basic information of the five WMA additives used in this study.

The WAR binders were prepared by blending WMA additives into hot binder right after the preparation of AR. The blending process was conducted at 160 °C, with a shearing speed of 800 rpm, and lasted for 10 min. Based on our previous experience and studies, the WMA additives can be completely dissolved in AR binder. A reaction procedure of 1-h storing was conducted for AR and WAR binders. The prepared WAR binders were labelled as ARE, ARE3G, ARS, ARW and ARMIN, representing those using Evotherm-DAT, Evotherm-3G, Sasobit, 56# paraffin wax and Aspha-min, respectively. The rheological properties of Pen 60/70 virgin binder, and the prepared AR and WAR binders are shown in Table 2.

The mixture design for the 10 mm aggregate size stone mastic asphalt (SMA10, Table 3), which is commonly used in Hong Kong, was selected for mixture preparation. The optimum asphalt

Table 1
Properties of WMA additives.

Properties	Evotherm-DAT	Evotherm-3G	Sasobit	56# paraffin wax	Aspha-min
Ingredients	Fatty amine derivatives, Alkylamines	Fatty amine derivatives, Alkylamines	Solid Saturated hydrocarbons	Solid saturated hydrocarbons	Zeolite, Water
State	Liquid	Liquid	Solid	Solid	Solid
Color	Caramel	Light-orange	Milky-white	Light-white	White
Odor	Amine-like	Amine-like	None	None	None
Density	>1.0 g/cm^3	>1.0 g/cm^3	0.622 g/cm^3	0.85 g/cm^3	1.57/cm^3
PH value	9–10	8–9	N/A	N/A	N/A
Boiling point	150–170 °C	150–170 °C	N/A	N/A	N/A
Melting point	N/A	N/A	105–110 °C	54 °C-58 °C	N/A
Water solubility	Partially soluble	Partially soluble	Insoluble	Insoluble	Insoluble
Dosage	5 wt% of AR binder	0.5 wt% of AR binder	3 wt% of AR binder	1.5 wt% of AR binder	0.3 wt% of mixture