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Optimizing the mixing procedure of warm asphalt rubber with wax-based additives through mechanism investigation and performance characterization

Zhen Leng *, Huayang Yu [1], Zeyu Zhang, Zhifei Tan

Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

HIGHLIGHTS

- The effects of different mixing procedures to produce WAR were evaluated.
- Rheological and chemical characterizations were conducted on the liquid phase of warm asphalt rubber.
- Direct mixing causes worse workability of WAR compared with conventional procedure.
- Direct mixing leads to less wax content in liquid phase of WAR.

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ABSTRACT

Wax-based additives can be used as flow improvers to enhance the workability of asphalt rubber (AR). Conventionally, warm asphalt rubber (WAR) is produced by preparing AR first and then blending it with warm mix asphalt (WMA) additive. However, directly mixing WMA additive, base asphalt and crumb rubber together may save more energy since the early incorporation of WMA additive also helps decrease the production temperature of AR. To assess the feasibility of incorporating wax-based additives at an earlier stage, this study investigates the influence of the mixing procedure on WAR prepared by two wax-based additives, i.e., commercial Sasobit and conventional paraffin wax. Rheological tests on WAR revealed no significant difference between WARs prepared by different procedures. However, the direct mixing method led to worse WAR workability compared to the traditional mixing procedure. Chemical analysis on the liquid phase of WARs (crumb rubber removed) indicated that independent of the type of wax-based additive, there is less wax in the liquid phase of WARs when the additive is added earlier, which may be caused by the absorption of wax by crumb rubber during the interacting process. Thus, it is not recommended to replace the traditional mixing procedure with the direct mixing method.

1. Introduction

Asphalt rubber (AR), which is defined as raw bitumen modified by no less than 15% of crumb rubber modifier (CRM) by total binder weight [1], has gained increasing interest due to its excellent mechanical performance and tyre-road noise reduction function [2,3]. During its preparation process at elevated temperature, CRM absorbs the light fractions of base binder and releases polymer chains, such as natural rubber and styrene-butadiene rubber, resulting in higher percentage of heavy molecules in asphalt, thus higher viscosity [4–7]. Although the high viscous behavior enhances the rutting resistance of asphalt, it brings the concerns of worse pumpability, mixability and workability. In general, the production temperature of AR is 20–30 °C higher than that of base binder, leading to more energy consumption and higher construction emission [8]. During the past decade, warm-mix asphalt (WMA) technology has been successfully applied to alleviate the workability concern of AR [9,10]. Warm asphalt rubber (WAR) binders with lower viscosities at mixing and compacting temperatures can be prepared by incorporating WMA additives into AR binder before mixing it with aggregates. A 15–30 °C reduction can be achieved by using different WMA additives [8,10–15]. Among various types of WMA additives, organic additives, in most

* Corresponding author.
E-mail addresses: zhen.leng@polyu.edu.hk (Z. Leng), huayang.yu@connect.polyu.hk (H. Yu).
[1] Co-corresponding author.

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cases wax-based additives, have been reported to be effective in improving AR's workability without compromising its mechanical properties [11–13].

Attributed to its low melting point and good flowability at elevated temperature, wax is usually recognized as flow improver of asphalt binder. Various studies have shown that commercial wax product prepared by Fischer-Tropsch (FT) synthesis process positively affects not only workability, but also rutting and fatigue resistance of asphalt [2,7,8,10,11,15,16]. Meanwhile, despite its potential negative effect on low-temperature cracking resistance, traditional paraffin wax was found to be a potential WMA additive for AR binders, since its adverse effect on low-temperature performance can be compensated by CRM [13]. To prepare WARs with wax additives, the following two procedures can be adopted: 1) conventional method: mixing CRM and base binder first and then adding wax additive; 2) direct mixing method: directly mixing CRM, base binder and wax additives together. Between these two methods, the direct mixing method may save more energy as the preparing temperature of AR can also be reduced due to the earlier incorporation of WMA additive. Once the wax is incorporated, the viscosity of binder decreases, which brings positive effect on homogenous distribution of crumb rubber in base binder and makes the mixing work easier. However, it is still unclear that whether these two mixing procedures may lead to different interactions among CRM, raw binder and WMA additive, thus different final workability and rheological properties of WAR.

The performance of WAR with wax additives prepared by the conventional method has been well studied, while the research on the direct mixing method is relatively limited [12,17]. Thus, this study aims to evaluate the feasibility and effectiveness of incorporating wax-based WMA additives at an earlier stage of WAR production. To achieve this objective, the rheological properties, including penetration, softening point, viscosity, Superpave rutting parameter, and Superpave fatigue parameter of WAR binders were characterized and compared. In addition, to reveal the interaction mechanism, chemical analyses including Differential Scanning Calorimeter (DSC) test, Gel Permeation Chromatography (GPC) test and wax content test were also conducted.

2. Experimental program

2.1. Preparation of AR and WARs

Asphalt with a penetration grade of 60/70 (Pen 60/70), a common type of asphalt in Hong Kong, was used as the base binder. Crumb rubber with 40-mesh size was used and the content was 18% by weight of base binder. Two different types of wax additives were selected and used, namely Sasobit (commercial WMA additive produced by the Fisher-Tropsch process) and 56# paraffin wax (conventional wax), and their dosages were determined as 3 wt% and 1.5 wt%, respectively, based on the manufacture's recommendation and preliminary test results [13]. Both the conventional and direct mixing methods were applied to produce WARs, leading to in total four WARs. These WARs are labeled as ARS, ARW, ARSD and ARWD, representing AR with Sasobit prepared by conventional method, AR with Wax prepared by conventional method, AR with Sasobit prepared by direct mixing method, and AR with Wax prepared by direct mixing method, respectively. Table 1 provides detailed description on the sample IDs and the corresponding mixing conditions of each test binder.

Both Sasobit and 56# paraffin wax can be completely dissolved in asphalt, while CRM remains in small particulate form in asphalt after interaction. To investigate the interaction among different components of AR and WARs, the liquid phase of AR and WARs were extracted by passing the hot binders through a mesh #200 sieve [5]. Right after they were prepared, the AR and WARs were dropped onto the sieve which was placed on top of a custom-designed container. Then the whole extraction system was placed into an oven at 150 °C for 30 min to drain the liquid phase through the sieve. The extracted liquid phase was stored at 0 °C to prevent further ageing or reaction. Each extraction process could produce approximately 50 g extracted liquid phase from 400 g AR or WAR binders. The liquid phases of WARs were labeled as L-WAR in this paper.

Table 1
Description of Prepared Binders.

Sample ID	Description
Pen 60/70	Base binder, obtained from Anderson Co., Ltd, Hong Kong
AR	Blending 18% of 40-mesh crumb rubber by the total weight of AR with base asphalt at 176 °C and 4000 rpm /min for one hour using a high shear mixer
ARS	Adding 3% of Sasobit into AR binder and high shear mixing for 10 min at 160 °C right after the mixing process of AR
ARW	Adding 1.5% of 56# paraffin wax into AR binder and high shear mixing for 10 min at 160 °C right after the mixing process of AR
ARSD	Directly high shear mixing Sasobit, crumb rubber and base binder together (same mass ratio as ARS) at 160 °C for one hour
ARWD	Directly high shear mixing 56#paraffin wax, crumb rubber and base binder together (same mass ratio as ARW) at 160 °C for one hour

2.2. Testing program

Conventional binder property tests conducted in this study included penetration, softening point and ductility tests [18–20].

Viscoelastic properties of the AR and WAR binders as well as their liquid phases were characterized by the dynamic shear rheometer (DSR) test. The high- and intermediate-temperature performances were characterized by the Superpave rutting parameter and fatigue parameter, respectively [21]. 2 mm gap was used for all DSR tests to reduce the influence of CRM particles [5,22,23]. Unaged binders were used for Superpave rutting parameter measurement (with 25 mm-diameter plates) and Pressure Aging Vessel (PAV) aged binders were used for Superpave fatigue parameter measurement (with 8 mm-diameter plates). Besides, the complex modulus and phase angle were recorded for rheological analysis. For each test, two replicates were prepared.

The workabilities of AR and WARs were evaluated by three parameters, including rotational viscosity [24], air void content of Marshall Specimen (SMA10, 4.0% design air void) corresponding to each binder [25,26], and number of gyrations of Superpave Gyratory Compactor (SGC) samples (SMA 10, 7.0% air void) to achieve the same specimen height [26]. The mixing and compaction temperatures of the samples with AR were 176 °C and 160 °C, respectively, while the samples with WARs were mixed at 160 °C and compacted at 144 °C. Three replicates were prepared and tested.

The interaction among asphalt, CRM and WMA additives was investigated through chemical analyses, including Differential Scanning Calorimeter (DSC) test, Gel Permeation Chromatography (GPC) test, and wax content test [27]. All these tests were performed on the extracted liquid phases of the test binders.

The thermal properties of L-WARs were measured using the Mettler Toledo instruments DSC3. The melting temperatures (T_m) of the binder components were determined by heating the samples from −20 °C to 150 °C at a rate of 5 °C/min.

The molecular weight distribution of L-WARs was evaluated by GPC test. A P230 Elite GPC with three columns (M, NT and NN) was used to separate the constituents of asphalt binder based on