Impact of Warm-Mix Additives on Viscosity Reduction in Virgin and Aged Bitumen with Polymer Modification

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ABSTRACT: Combining warm-mixing and recycling technologies in asphalt pavement is essential for reducing energy consumption, lowering greenhouse gas emissions, and decreasing material costs, providing both economic and environmental benefits. This study examines how warm-mix additive types and dosages, bitumen aging levels, and bio-oil addition impact the viscosity of virgin bitumen, polymer-modified bitumen (PMB), and their aged binders. The results indicate that wax-based and chemical-based warm-mix additives impact viscosity differently: Wax-based additive reduces viscosity in virgin bitumen more effectively, while chemical-based additive lower viscosity in PMB significantly. Polymer presence increases viscosity compared to virgin bitumen, but PMB demonstrates superior aging resistance, especially beyond 40h aging. Moreover, bio-oil consistently provides a greater viscosity reduction than Sasobit, which tends to be less effective in aged virgin bitumen but becomes more effective in aged PMB over time. Using a warm-mix additive with a bio-rejuvenator is an effective way to rejuvenate aged bitumen, though the effectiveness of each additive depends on the presence of polymer and the aging level of the bitumen.

Keywords: Warm-mixing additive; Viscosity reduction; Bio-rejuvenator; Aging level; SBS-modified bitumen

1 INTRODUCTION

Bitumen is an important material in road construction, serving as the primary binder in asphalt mixtures [1, 2]. However, its high viscosity at typical production temperatures poses challenges in mixing and compaction, often necessitating elevated temperatures during asphalt production. While this practice ensures workability, it also leads to high energy consumption and greenhouse gas emissions, raising environmental concerns [3].

To address these issues, warm-mix asphalt (WMA) technologies have emerged as a sustainable alternative, allowing asphalt production and paving at lower temperatures without sacrificing performance [4, 5]. This is achieved through the use of warm-mix additives, which reduce the viscosity of bitumen, making it easier to mix and compact at reduced temperatures. These additives offer the potential to lower emissions, conserve energy, and enhance the long-term performance of asphalt pavement [6].

While warm-mix additives have been shown to improve workability, their effects on bitumen viscosity, particularly in aged or polymer-modified bitumen, require further exploration [7, 8]. Aged bitumen often experiences increased stiffness due to oxidation, while polymer-modified bitumen, known as its enhanced durability and deformation resistance, presents additional viscosity challenges [9]. Understanding how warm-mix additives influence both virgin and aged bitumen, with and without polymer modification, is crucial for optimizing WMA technologies.

This study aims to study the impact of warm-mix additives on viscosity reduction of virgin and aged bitumen, both with and without polymer modification. By comparing these effects, the research seeks to provide valuable insights into the use of warm-mix technologies in the high-efficient rejuvenation process of bituminous materials.

2 MATERIALS AND METHODS

2.1 *Bitumen and warm-mixing additives properties*

A 70/100 grade bitumen was chosen with its fundamental properties detailed in Table 1. Two commercial warm-mixing additives, Sasobit (wax-based) and Rediset (chemical-based), were utilized to prepare the warm-mix bitumen. The basic properties of these two WMA additives are presented in Table 2.

Table 1 Chemo-physical properties of bitumen

Properties		value
25°C Penetration (1/10 mm)		91
Softening point (°C)		48
Chemical fractions (wt%)	Saturate, S	3.6
	Aromatic, A	51.6
	Resin, R	30.2
	Asphaltene, As	14.6
Element compositions (wt%)	Carbon, C	80.1
	Hydrogen, H	10.9
	Oxygen, O	0.6
	Sulfur, S	3.5
	Nitrogen, N	0.9

Table 2 Basic property of WMA additives [10, 11]

Properties	Sasobit	Rediset
Appearance		
25°C Density (g/cm^3)	0.900	-
20°C Solubility in water	Insoluble	-
40°C viscosity (cP)	-	135
40°C Density (g/cm^3)	-	0.962
Flash point (°C)	285	230
Initial boiling point (°C)	271	215

Meanwhile, the bio-oil was used as rejuvenator for viscous performance recovery of aged bitumen. The bio-oil is the rapeseed oil with a pale-yellow color. Its density and viscosity at 25°C are 0.911 g/cm^3 and 50 cP, respectively. The main molecular components of the bio-oil are methyl oleate, methyl linoleate, and methyl palmitate [13].

2.2 *Preparation of polymer modified bitumen*

The Styrene-Butadiene-Styrene (SBS) modified bitumen was produced using 70/100 penetration grade bitumen as the base binder, with 4% by weight of Kraton D1102 SBS added. The SBS polymer is a linear block copolymer containing 28.5% styrene [12]. It should be noted that the abbreviation of virgin bitumen and polymer modified bitumen is VB and PMB, respectively.

2.3 *Aging protocols*

In this study, both bitumen and SBS-modified bitumen were subjected to short-term and long-term aging to prepare the aged binders. The Thin-Film Oven test (TFOT) and Pressure Aging Vessel (PAV) were used to age the samples. The temperature and duration of TFOT test is 163°C and 5 hours. The PAV test was run at 100°C and 2.1MPa with variable aging times of 20h, 40h, and 80h to investigate the effect of aging level. The abbreviations for aged bitumen are 1PB, 2PB, and 4PB, while the abbreviations of aged SBS-modified bitumen are 1PMB, 2PMB, and 4PMB.

2.4 *Preparation of warm-mix and rejuvenated bitumen*

The virgin bitumen and SBS-modified bitumen were heated in an oven at 140°C to ensure flowability. Afterwards, the warm-mixing additives (Sasobit and Rediset) are added in bitumen. The Sasobit dosages were 0%, 1%, 2%, and 4% by weight of bitumen, while the Rediset concentration was 0%, 0.3%, 0.6%, and 0.9%. To obtain a homogenous warm-mixing bitumen binder, the bitumen and the added warm-mix additives were mixed at 140°C for 30min. Considering the practical application of asphalt mixture warm-recycling, the aged bitumen and aged polymer modified bitumen were mixed with Sasobit additive (4wt%) first at 140°C for 30min, and then the bio-oil rejuvenator (10wt%) was incorporated to prepare the warm-mixing rejuvenated binders.

2.5 *Viscosity measurement*

The rotational viscometer (RV) was utilized to measure the dynamic viscosity values of all bitumen binders according to the standard of AASHTO T316-13. The temperature was set as 120°C and the rotor spinning rate was 20 rad/s.

3 RESULTS AND DISCUSSION

3.1 *Effect of WMA additives on viscosity of bitumen and PMB*

The viscosity variations of fresh and polymer modified bitumen as a function of WMA dosage are displayed in Fig.1. It is evident that increasing the dosage of WMA additives leads to a substantial reduction in viscosity, which is consistent with the goal of these additives in improving workability at lower temperatures. For all bitumen, the viscosity shows a linear reduction trend as the increase in Rediset dosage, while an exponential decline law is observed for the Sasobit case. Compared to Rediset, Sasobit appears to be more effective in achieving a sharper drop in viscosity in virgin bitumen.

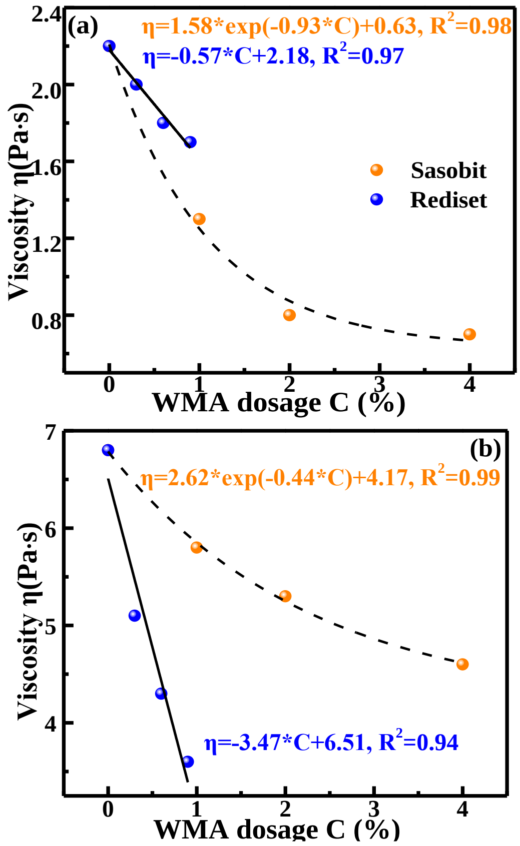

Fig.1. Influence of WMA additives on viscosity of bitumen (a) and PMB (b)

For polymer modified bitumen (PMB), all viscosities are higher than the virgin bitumen due to the presence of SBS polymer. An opposite phenomenon can be observed in the reduction of viscosity of PMB compared to virgin bitumen that the addition of Rediset has a greater impact on the reduction compared to the addition of Sasobit in PMB. The phenomenon may be attributed to the effective reduction function of Rediset on the interfacial tension between polymer and bitumen, and thus improving the flowability of whole PMB. Moreover, the addition of Sasobit can reduce the viscosity of PMB, but less effective than virgin bitumen. Therefore, the Sasobit is more useful for the warm-mixing production of virgin bitumen, while the Rediset is more effective for PMB case. From the results, the need for selection of WMA additives, based on the specific type of bitumen and desired workability during construction, should be considered carefully.

3.2 *Aging effect on viscosity of bitumen and PMB*

Figure 2 illustrates the effect of aging on the viscosity of virgin and SBS-modified bitumen. The relationship between aging time and viscosity is captured through exponential equations, highlighting how both materials respond to oxidative aging. The viscosity of virgin bitumen increases significantly with aging time. The steep rise in viscosity, particularly at longer aging times (80 h), suggests that virgin bitumen undergoes substantial hardening due to oxidation. This result underscores the susceptibility of virgin bitumen to aging, which can lead to reduced flexibility and potential cracking in pavement over time.

In contrast, the viscosity of PMB increases more gradually. Initially, PMB has a higher viscosity (6.8 Pa·s) compared to VB, due to the presence of polymers. Even after 80h aging, the viscosity of PMB only reaches 16.2 Pa·s, a much smaller increase compared to VB. The result highlights the superior resistance of PMB to aging, likely due to the stabilizing effect of the polymer, which mitigates the hardening process.

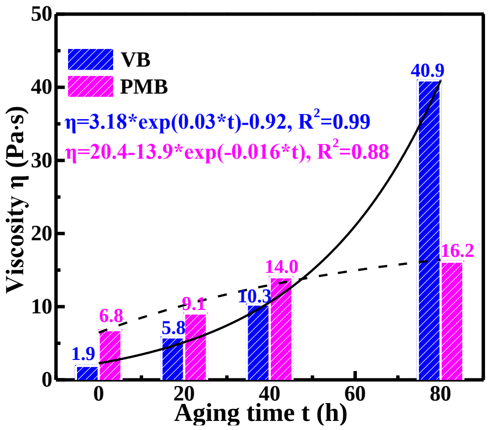

Fig.2. Aging effect on viscosity of bitumen and PMB

3.3 *Effect of WMA and bio-oil rejuvenator on viscosity of aged bitumen and PMB*

Sasobit and bio-oil were added to aged bitumen and aged polymer-modified bitumen (PMB) with varying aging durations to achieve the dual objectives of warm-mixing and rejuvenation. Fig.3 shows the changes in viscosity after the addition of Sasobit (WMA) and a Sasobit/bio-oil blend (WMA-BO). The results indicate that both Sasobit and bio-oil effectively reduce the viscosity of both virgin and aged bitumen with different mechanisms, with bio-oil consistently achieving a greater percentages reduction than Sasobit. This trend holds true for both VB and PMB, although the relative effectiveness of these additives decreases with increasing aging, especially for Sasobit. Notably, the impact of Sasobit on viscosity reduction in virgin bitumen declines as the aging level rises. At an aging level of PAV80h, the reduction efficiency is only 9.1%. For PMB, the effectiveness of Sasobit first increase slightly and then declines. Although the initial effect of Sasobit on viscosity reduction is lower in PMB than in VB, it becomes relatively more effective for PMB after prolonged aging, particular at 20-hour and 40-hour aging intervals.

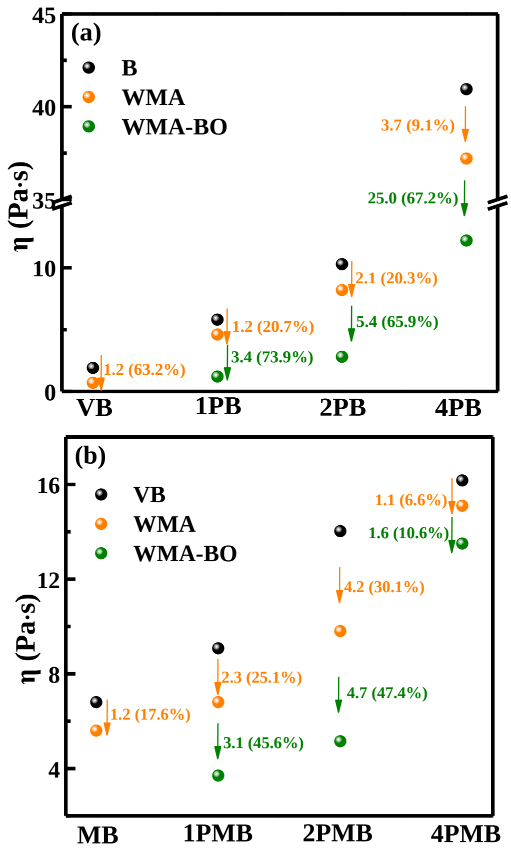

Fig.3. Effect of Sasobit and bio-oil on viscosity of bitumen (a) and PMB (b) with various aging levels

In highly aged bitumen and PMB, the superior performance of bio-oil suggests it may be more effective for restoring workability in severely-aged binders. This makes bio-oil a potentially more versatile and efficient rejuvenator for viscosity reduction of aged bitumen and PMB. Based on viscosity reduction percentages, the impact of bio-oil on aged bitumen is more pronounced than on aged polymer-modified bitumen. Overall, combining a warm-mix additive with a bio-rejuvenator provides an effective approach to achieving warm-mixing rejuvenation of aged bitumen. However, their effects are highly dependent on the aging level of both bitumen and polymer-modified bitumen.

4 CONCLUSIONS

This study investigates the effects of warm-mix additive types and dosages, aging level of bitumen, and bio-oil on the viscosity property of bitumen, polymer-modified bitumen, and their corresponding aged binders. The main findings are drawn as follows:

(1) The two warm-mix additives, Sasobit and Rediset, have distinct effects on reducing the viscosity of both virgin bitumen and polymer-modified bitumen. Sasobit shows a more pronounced viscosity-reducing effect on virgin bitumen, whereas the addition of Rediset results in a significant viscosity reduction in polymer-modified bitumen.

(2) Compared to virgin bitumen, the presence of polymer increases the viscosity of modified bitumen. However, the rate of viscosity increase due to aging is considerably lower in polymer-modified bitumen than in virgin bitumen, due to its superior aging resistance, particularly when aging time exceeds 40 hours.

(3) Both Sasobit and bio-oil reduce the viscosity of virgin and aged bitumen, with bio-oil consistently achieving a greater reduction. The impact of Sasobit lessens in virgin bitumen as aging progresses, but it becomes more effective for polymer-modified bitumen after 20h and 40h aging.

(4) Combining a warm-mix additive with a bio-rejuvenator offers an effective method for achieving rejuvenation of aged bitumen under warm-mixing conditions. However, the selection of warm-mix additive and its effectiveness on viscosity reduction is highly dependent on the presence of polymer and aging level of bitumen.

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