Behaviour of Synthetic Polymer-Modified Warm Mix Asphalt Under Oven Ageing Simulation

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Abstract

This research evaluates the mechanical properties and fracture behaviour of ethylene-vinyl acetate (EVA) polymer-modified warm mix asphalt under the influence of ageing simulated through oven heating at 85ºC in two different durations of 2 and 8 days. EVA contents of 4 - 6% of binder weight were employed, and the effect was measured through the semi-circular bending (SCB) test. Volumetric properties measurement showed negligible effect of polymer addition, with the difference in air void ratio ranging from 0.5% to 8% compared to the control mix. Meanwhile, the density and void in mineral aggregate (VMA) differed by a maximum of 2% compared with the control mixture. Moreover, the increase in the heating period was found to enhance the tensile strength, with a maximum difference of 81.72% exhibited by the mix with 0.5% EVA, corresponding to its tensile strength from the 8-day ageing conditioning by 28% larger than the control mix. Moreover, crack resistance and flexibility indexes (CRI and FI) were inversely proportional to the increase of polymer dosages for both 2- and 8-day aged specimens from being 20.5% and 52% to 6.4% and 18.3% larger than the control mixture, respectively, with the 8-day aged specimens having the CRI of 8% larger and FI of 8.7% smaller than the 2-day aged samples, indicating a brittle behaviour in respect to the ageing duration. Conclusively, the heating ageing simulation results in a brittle asphaltic mixture modified with EVA, displayed with higher strength and lower flexibility, particularly at 5% to 6% w/t.

Keywords

Warm-mix asphalt, Ethylene-Vinyl Acetate, Semi-Circular Bending, Ageing, Oven heating

INTRODUCTION

Ageing is a mechanism commonly known to affect the chemical composition of bitumen as the bonding agent in an asphalt concrete (AC) mixture. The ageing process can be divided into two stages. Short-term ageing occurs during the mixture production and the field compaction processes, whereas long-term ageing incorporates the interaction between the mixture with external exposure, such as temperature change and UV light radiation over time. Generally, the ageing process in bitumen modifies the equilibrium of its composition, which initially consists of the emulsion of the large molecular weight, elastic asphaltene and viscous maltene classified into saturated, aromatic and resin, especially the decreased saturated and aromatic fractions and increased asphaltene content due to the loss of its volatile component in the maltene fraction that results in a higher glass transition temperature and decreased thermal stability Meanwhile, the effect of ageing on binder chemical composition has displayed an increased sulfoxide during the short-term ageing process and carbonyl formation during the second stage; this is linked to the lower phase angle and higher complex modulus from the DSR test on the bitumen. [1]–[4]. Other impacts of ageing on bitumen have been documented to increase the stiffness and viscosity of the binder, as well as diminish the ductility and elastic recovery properties, leading to brittle behaviour [5]–[8]. Overall, the various types and chemical constitutions of the binder material, as well as the use of various aggregate gradation and absorption, have a significant impact on the rate of bitumen ageing [9]–[11]. The aged binder has been discovered to affect the bituminous mixture heavily, mainly in terms of the bonding between the mix constituent that can lead to the stripping phenomenon and the brittle cracking behaviour [12], [13]. Similar phenomena are also found to occur in the warm mix asphalt (WMA), though the production temperature is visibly lower than the standard hot mix asphalt (HMA), with the use of certain types of warm mix additives could contribute to reducing the sensitivity to the ageing effect [14]–[17]. Moreover, modifications to the mixture using polymeric products, particularly on the binder, have generated various effects, with most studies reporting that the application of elastomeric SBS products could reduce the ageing effect on the binder, leading to higher fatigue life, resilient modulus, and strain recovery properties [18]–[20]. Meanwhile, the application of the plastomeric ethylene-vinyl acetate (EVA) has shown a marginal impact on the ageing properties of the modified binder under high strain and low temperature due to its low susceptibility to degradation from thermal ageing [21]–[25]. The studies presented in this section have highlighted the effect of the polymer when being utilised to modify the bitumen, known as the wet mix method, as opposed to the dry mix method, in which the polymer is directly applied to the mixture during the blending stage [26]. Hence, this research attempts to evaluate the effect of the EVA-modified WMA when incorporated using the dry mix method, proceeding with the previous studies that have shown the positive impact of such application on the mechanical properties and environmental impact of bituminous mixtures [27]–[29].

RESEARCH SIGNIFICANCE

This research attempts to evaluate the effect of thermal ageing on the mechanical properties of the polymer-modified warm mix asphalt, namely strength and resistance to crack. In this research, the polymer was incorporated directly into the mixture using the dry blending method, as opposed to the standard wet mix method, in which the polymer was mixed into the bitumen prior to blending with the aggregates. Moreover, this research presents the study on the mixture level to accurately examine the polymer, which is supposed to act at that stage.

METHODOLOGY

A. MATERIALS EVALUATION – VOLUMETRIC AND PHYSICAL PROPERTIES

Several materials were employed as the constituents of the warm AC mix evaluated herein, namely bitumen with penetration grade 60/70 by Shell, coarse and fine aggregates, warm mix asphalt additive in the liquid state with the brand name Rediset MX, and EVA polymer in the granular shape with the brand name Superplast (Figure 1 and Figure 2). The binder and aggregates were subjected to rheological, physical, and volumetric properties evaluations, such as penetration, softening and flash point, specific gravity tests for the bitumen, and specific gravity and absorption tests for the aggregates.

(a)

(b)

Figure 1 (a) PEN 60/70 bitumen and (b) aggregates

(a)

(b)

Figure 2 (a) WMA additive and (b) EVA polymer

The mixture composition was designed according to the national Bina Marga 2018 standard for the AC wearing course (AC-WC) [30] shown in Figure **3**, and the binder content was determined later by the Marshall test.

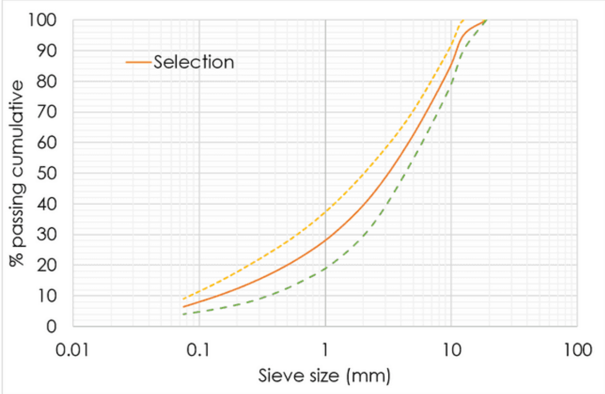

Figure 3 Mix design of AC mix specimens

B. SPECIMEN PRODUCTION

The specimen production was performed according to the following steps. Firstly, the materials were heated in an oven at 135°C, except the binder, which was heated at 160°C for 30 minutes. Afterwards, the binder was mixed with the warm mix additive with a 1% bitumen weight dosage before being placed with other materials for another 15 minutes. The total heating stage took approximately 45 minutes. Then, the aggregates were poured and blended inside a mixer for another 2 minutes, after which the binder was put into the mixer and the process continued for another 2 minutes until the aggregates were fully coated with the binder and there was no part of the aggregate that remained visible. Before the compaction commenced, the mixture was put back inside the oven at 135°C for 5 minutes to ensure the compaction temperature did not fall below the standard of 110ºC. Only after that will the mixture be poured inside the desired mould, depending on the specimen size, for further compaction. There were two types of samples produced in this research. The first type of specimen was the standard cylindrical Marshall of 100mm diameter and 63mm height, whereas the second one was the Semi-Circular Bending (SCB) sample with a diameter of 150mm and height of 50mm. Both types of AC mix specimens were subjected to a compaction effort of 75 blows for each side, following the Bina Marga 2018 standard for the heavy-duty mixture [30]. After being stored at room temperature for 24 hours inside the mould, the specimens could be released for further phases of this study. The optimum binder content for this study, out of three contents: 5, 5.5 and 6% of mix weight, was determined by the result of the standard Marshall test. On the other hand, the SCB cylinders needed to be split to follow the desired geometry of half-cylinders with a notch fabricated at the centre part of the specimen in the largest diameter location with a thickness of 1mm, which was developed according to Eurocode NEN 12697:44; the sample image is shown in Figure 4.

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(a) (b)

Figure 4 (a) Split cylindrical specimens for SCB preparation and (b) an SCB specimen with a notch in the middle

C. OVEN AGEING CONDITIONING AND SCB TEST

The half-cylindrical specimens were subjected to oven-based ageing simulation (Figure 5a) to accelerate the ageing condition, starting from a short-term simulation for 4 hours in the oven at 135ºC proceeding with two different heating durations of 2 and 8 days at 85ºC. These treatments were conducted following AASHTO R 30-02 [31] with a modification in the ageing duration. The samples were then subjected to the SCB test protocol performed in a standard universal testing machine (UTM) with a loading rate of 5 mm/min (Figure 5b), and the outcomes were the data series of force-displacement curve (Figure 6) that would be converted to several mechanical properties using equations (1) to (5), such as tensile strength, fracture energy, crack resistance and flexibility indexes (CRI and FI). CRI can be defined as the ratio between fracture energy and maximum force that indicates the ability of the mix to deform until its breaking point, and FI is the ratio between the fracture energy and the post-peak slope of a force-displacement curve, which was developed to evaluate the behaviour of an AC mix specimen after the crack started to propagate [32], [33].

(a) (b)

Figure 5 (a) Oven ageing simulation and (b) SCB samples subjected to the evaluation

$$\sigma_{max} = \frac{4.263P_{max}}{2rt} \quad (1)$$

$$G_f = 10^3 \, x \frac{W_f}{A_{lig}} \quad J/m^2 \quad (2)$$

$$A_{lig} = (r-a)t = t \, x \, L \quad (3)$$

$$CRI = \frac{G_f}{P_{max}} \quad (4)$$

$$FI = \frac{G_f}{|m|} x 0,01 \quad (5)$$

Where:

W_f : work of fracture (Nmm)
A_{lig} : ligament area (mm^2)
r : specimen radius (mm)
a : notch depth (mm)
t : specimen thickness (mm)
L : ligament length (mm)
$|m|$: slope at post-peak point of inflection (kN/mm)

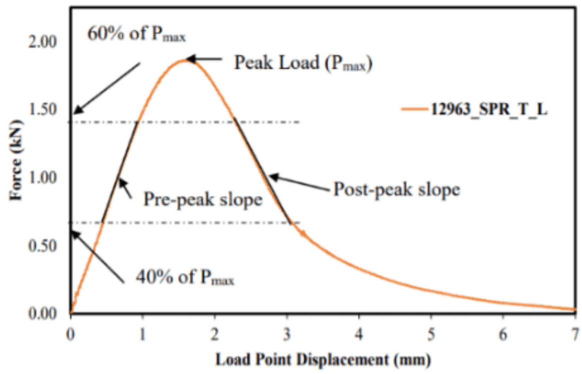

Figure 6 Typical force-displacement curve from SCB test

RESULTS AND DISCUSSIONS

A. MATERIAL PROPERTIES TEST

The list of material physical, volumetric and rheological properties as the result of the tests is presented in Figure 7 and Table 1. It can be concluded that the materials herein could be employed for further stages according to the Bina Marga 2018 standard.

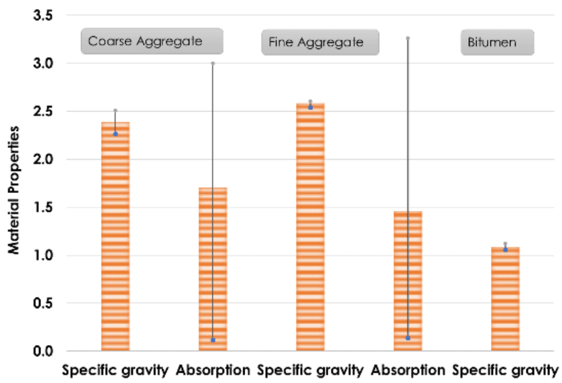

Figure 7 Constituent material properties

Table 1 Rheological properties of bitumen

Parameter		Value
Penetration	dmm	60.83
Softening Point	ºC	48
Flash Point	ºC	340
Burning point	ºC	347

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Table 2 Marshall Test result

Parameter		Bitumen content (%)			Requirement
		5.5	6	6.5	
Density	kg/m^3	2075.24	2122.24	2100.77	-
VIM	%	6.45	4.34	5.30	3 - 5.5
VMA	%	22.86	21.12	21.92	$\geq$ 15
Stability	kg	986.71	1179.95	1092.11	$\geq$ 800
Flow	mm	3.31	3.68	3.96	2 - 4

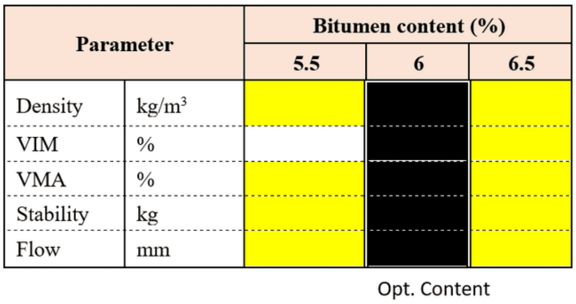

Figure 10 Optimum bitumen content determination

B. OPTIMUM BINDER CONTENT DETERMINATION

The bitumen content used for the further phase was determined by means of the standard Marshall compression test, where the outcomes would be compared with the Bina Marga 2018 requirement. The result is presented in Table 2 and the determination is shown by Figure 10. Evidently, the binder content of 6% was chosen for the next stage.

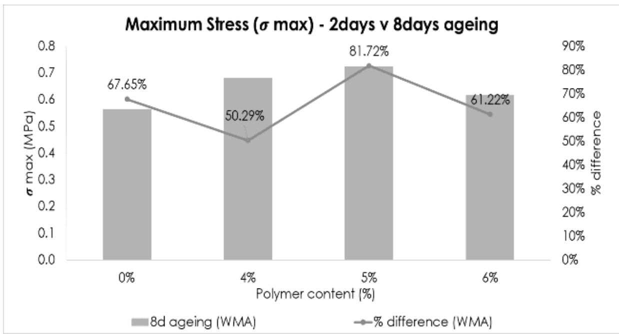

Figure 8 Tensile strength of 2-day and 8-day oven-aged specimens with various EVA contents

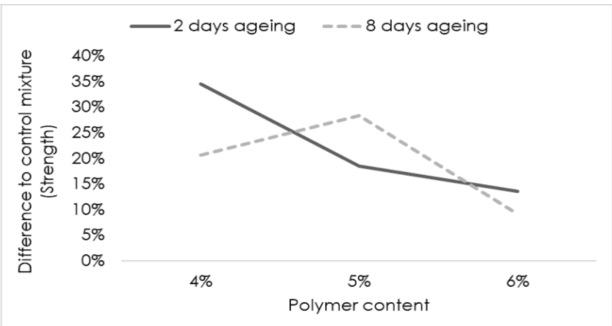

Figure **9** Variation of tensile strength of 2-day and 8-day oven-aged specimens with various EVA contents

C. SEMI-CIRCULAR BENDING TEST RESULTS

The outcomes from the SCB test are tensile strength, fracture energy, CRI and FI. The effect of adding various polymer contents and ageing duration will be presented in this section, shown in Figure 8 to Figure 16.

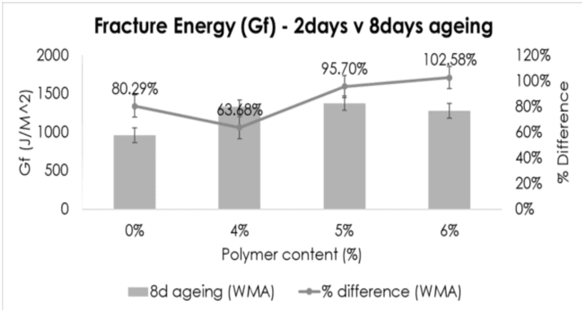

Figure 11 Fracture energy of 2-day and 8-day oven-aged specimens with various EVA contents

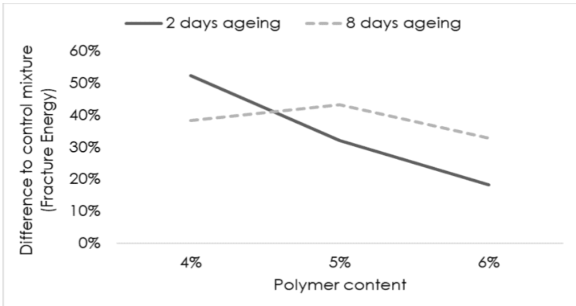

Figure 12 Variation of fracture energy of 2-day and 8-day oven-aged specimens with various EVA contents

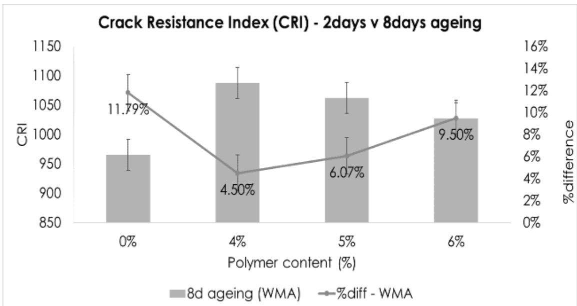

Figure 13 Crack resistance index of 2-day and 8-day oven-aged specimens with various EVA contents

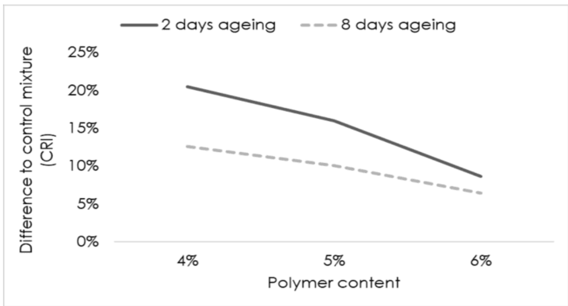

Figure 14 Variation of CRI of 2-day and 8-day oven-aged specimens with various EVA contents

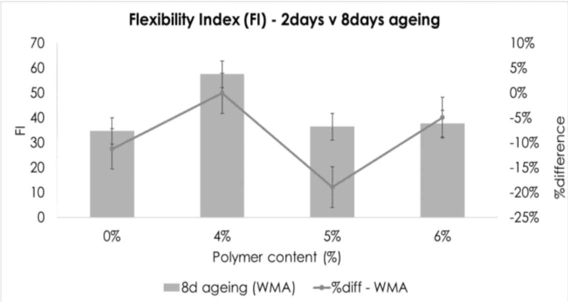

Figure 15 Flexibility index of 2-day and 8-day oven-aged specimens with various EVA contents

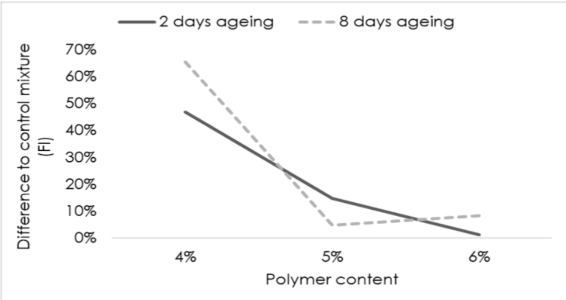

Figure 16 Variation of FI of 2-day and 8-day oven-aged specimens with various EVA contents

Figure 8 and Figure 9 illustrate the variation of tensile strength between non-modified and EVA-modified bituminous mix specimens subjected to both 2- and 8-day oven ageing simulation. Evidently, the increase in treatment duration has increased the strength of every sample, ranging from 50% to the maximum of 81.72% reached by the specimen employing 5% w/t EVA. This finding could be explained by the possible increased stiffness in the binder material, that leads to such occurrences, reinforced by the data presented in Figure 11 and Figure 12. Figure 11 mainly depicts a massive increase in fracture energy by 63% to more than 100% due to the additional six days of oven simulation. However, the crack resistance index (CRI) only marginally improved by 4.5 – 12% (Figure 13), and FI even decreased by almost 20% (Figure 15), thus solidifying the hypothesis of an elevated stiffness that has contributed to increased strength and fracture energy, but not necessarily to the resistance to crack. Moreover, it can be seen from Figure 9, Figure 12, Figure 14 and Figure 16 that the application of 5% w/t EVA has generated the highest tensile strength and fracture energy following the 8-day ageing treatment with a difference of 22% on average to the control mix; tensile strength improved by 28.4% and fracture energy improved by 43.4%, which was mostly affected by the increase of strength as opposed to the deformation capacity. Conversely, using 4% w/t EVA yielded the largest parameters for the 2-day and 8-day aged specimens with average differences of 38% and 34.2% to the control mix, respectively. In general, it can be seen that the enhanced polymer dosages resulted in decreased mechanical properties mainly due to the brittle bonding formed with the binder, except for the case of 5% w/t EVA at 8-day specimens, influenced by the brittle behaviour of the bituminous mixture under the ageing effect. The similar phenomenon of increased strength and decreased flow number, signifying more brittle behaviour, has been notable in previous research, where the tensile strength was found to elevate up to a specific heating period, but the flow decreased exponentially [34]. Lastly, the various trends occurring in the outcome can be linked to the variability of air voids, which need to be addressed in the future.

CONCLUSIONS

This study has attempted to evaluate the effect of incorporating EVA polymer and varying heating duration on the mechanical properties of the warm bituminous mixture. Three polymer contents of 4 – 6% w/t and two heating durations of 2 and 8 days at 85ºC were employed herein, and the effect was assessed utilising the semi-circular bending test (SCB). Firstly, the examinations of the physical, volumetric, and rheological properties of the material show that all materials could be used as constituents for the bituminous mixture. Moreover, the Marshall compression test indicates that a binder content of 6% is used for the SCB test specimen. Lastly, the SCB test outcome indicates that increasing the heating duration from 2 to 8 days has enhanced the stiffness of the asphalt mixture, leading to a stronger but brittle specimen, as depicted by the tensile strength, fracture energy, crack resistance and flexibility indexes (CRI and FI). The tensile strength is enhanced by 50 - 81.72%, fracture energy is improved by 63 - 102.6%, and CRI is slightly increased by 4.5 - 12%; whereas FI declines by the maximum of almost 20%. Moreover, the application of various EVA contents leads generally into decreased mechanical properties, judging from the total results that the mixture with 4% EVA generates the largest improvement to the control mixture in both 2- and 8-day aged specimens by the differences of 38% and 34.2% to the control mix, respectively. Nonetheless, an exception occurs in terms of the tensile strength and fracture energy of the mix added with 5% w/t EVA, with a difference of 28.4% and 38.4%, respectively. Conclusively, the increase in ageing duration influences the stiffness of bituminous mixtures, leading to stronger but brittle behaviour. Moreover, the mechanical properties of the EVA-modified bituminous mixture are inversely proportional to the increase of EVA content, where 4% EVA fraction yields the largest properties, except to the tensile strength, where the dosage of 5% w/t generates the highest outcome.

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