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Effect of Polymer-Modified Bitumen and Reclaimed Asphalt Pavement on The Physical Properties of Bitumen

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Abstract. The high cost of road construction due to the energy required for new material production and the environmental impact necessitates the use of reclaimed asphalt pavement (RAP) and other waste materials. This paper examined the effect of using RAP with a PET additive as a rejuvenator. PET additive (2%) was added to the virgin binder (VB) of 60/70 penetration grade to form a Polymer modified bitumen (PMB). RAP percentages used were 30, 40, and 50%, respectively. The physical properties were examined using the penetration, softening point, and ductility. The results show that the physical properties of RAP were improved by utilizing Rap binder (RB) and PMB mix ratio. The penetration and ductility values increased by 46.4% and 66.7%, respectively, with the PMB (30): RB (70) ratio blend, compared to RB: VB blend. This suggests a reduction in brittle behavior and less stiffness with the addition of PMB in the blend, enhancing the flexibility of the RAP. Although both mixtures blended with RB exhibited softening points within the acceptable range, improved performance was observed with RB/PMB mix blend over RB/VB blend when used in hot asphalt mixture.

1. Introduction

Road network development is significant in any nation's socioeconomic development and urbanization. The high cost of road construction due to the energy required for new material production and the environmental impact necessitates the search for cheaper alternative materials, such as waste materials. An increase in waste products sadly accompanies the increasing growth in population and improved standard of living. In line with the Sustainable Development Agenda of the United Nations Millennium Development Goals (2000) repeated in 2030, the sustainability of a better environment can be achieved through the use of recycled solid waste to aid road durability and transportation systems [1]. As a result, the crucial need for incorporating recycled discarded materials in road paving industries is being initiated to reduce the waste materials being discarded in the environment [2]. It is also apromient topic of discussion in today's society [3].

However, a major global challenge is the effective utilization of recycled solid waste in improving the quality of roads. To improve the ecological and environmental performance of road infrastructure, the development of environmentally friendly functional pavement materials poses challenges as well as opportunities for road engineers and researchers. In terms of environmental considerations, Spray et al. [4] have conducted research on pavement sustainability, life cycle cost (LCC), and)life cycle assessment (LCA). They define LCA as the environmental aspects and potential environmental impacts (e.g. resource consumption and environmental repercussions of releases) [4]. It occurs throughout the life cycle of a product, from raw material acquisition to production, usage, end-of-life treatment, recycling, and final disposal. Carbon footprint, a subset of greenhouse gas (GHG) emissions from product life cycles frequently used to evaluate global warming potential. Molenaar [5], suggested that employing recycled materials from asphalt pavements, demolition trash, and durable pavements could reduce the carbon impact of road construction by 20 -28% [6, 7]. Recently, recycled asphalt pavement (RAP) materials with other waste and byproducts were used on road pavements [8,9]. In study by Kamali et al. [3], reclaimed asphalt pavement (RAP) was employed to decrease the quantities of virgin asphalt and aggregates utilized in road construction.

The stiffness of RAP, on the other hand, is one of its most important drawbacks in road construction. RAP usage introduces a number of unwanted qualities into the bituminous mixture, the majority of which are caused by the brittleness of the original pavement as it ages. It is critical to develop a design that can alleviate the stiffening effect of RAP asphalt when the RAP content is between 25% and 100% [10]. Polymer-modified bitumen is increasingly used in road pavement and highways over conventional bitumen due to its lower susceptibility to temperature variations and higher resistance to deformation at elevated pavement temperatures [11]. Polymers such as styrene-butadiene-styrene (SBS), ethyl vinyl acetate, polyvinyl chloride, polyethylene, polyoctenamer, and polyethylene terephthalate (PET) have been investigated and shown promising results [12]. PET, a thermoplastics polyester that accounts for 18% of total polymer production worldwide, is extensively used in the production of plastic bottles [12]. The performance of the mixes, including RAP, has also been effectively improved by using bitumen which is softer and bitumen-treated polymers [13]. Umar Hayat et al. [14] used PET at 2, 4 and 6% to modify virgin bitumen and with various ratios of RAP and concluded that PET enhanced the performance of the asphalt mixture. Although some studies have shown the feasibility of using PET plastic in HMA, the use of recycled PET in asphalt pavements will also improve performance. Including recycled PET into HMA has been reported via two main methods; (i) recycled crushed PET used in asphalt in various particle sizes and (ii) chemically processed PET used as an asphalt binder modifier. The outcome of the resulting mix's behavior varies in previous literature due to the different polymers combined with RAP. It has also been demonstrated that the inclusion of RAP leads to greater rutting resistances at lower levels of polymer modification. However, at higher levels of polymer modification, the addition of RAP has no significant influence on the rutting resistance of the HMA mix [15]. In this study, a PET-derived additive was used for the modification of the virgin asphalt. The physical properties of RAP content were evaluated upon the addition of the PET additive to the virgin binder to form a polymer-modified binder (PMB).

2. Methodology

2.1 Extraction of RAP binder

The reclaimed asphalt pavement (RAP) was obtained from the mill and paved road construction in Skudai, Johor Baharu. The aged binder was extracted from RAP using methylene chloride solvent according to ASTM D-2172 [16] and was recovered using a rotary evaporator. The extraction results are very operator-sensitive, and the residual solvents present may affect the binder test results. Therefore, to minimize the error, all extraction was carried out by a single extraction device. After the extraction, the RAP binder was recovered by separating the methylene chloride using a rotary evaporator per ASTM D5404 [17].

The recovered RAP binder was placed in an oven at 90 °C for 30 min and stirred at intervals. After which the recovered RAP binder was kept for five days, on the fifth day the recovered RAP binder was placed in the oven again at 90 °C for 30min and stirred for the remaining methylene chloride to evaporate.

2.2 PET additive

The PET- derived additive utilized in this research was produced by aminolysis of waste PET bottle using TETA solvent.

2.2.1 Synthesis of PET additive

The aminolysis procedure was used to chemically transform the PET waste into benzamide derivatives using a non-catalytic method as a synthon [18]. In the presence of nitrogen gas, 30 g of PET which was cut into smaller sizes of 1 cm × 1 cm with 100 ml of TETA were charged into a one-necked, 500 ml round bottom beaker with an overhead stirrer was placed in an oil bath (Figure 1 A, B, and C). TETA has been chosen as the solvent due to its high yield and degradation time [18]. The combination was heated to reflux for six hours at 135-140oC. As the PET degradation process finished, the flask disappeared, and the mixture became homogeneous (Figure 1 D). The polyamines and glycols were recovered under pressure after the reaction was completed using the filtration aeration vacuum method shown in Figure 1 E and final product PET–derived additive (Figure 1 F).

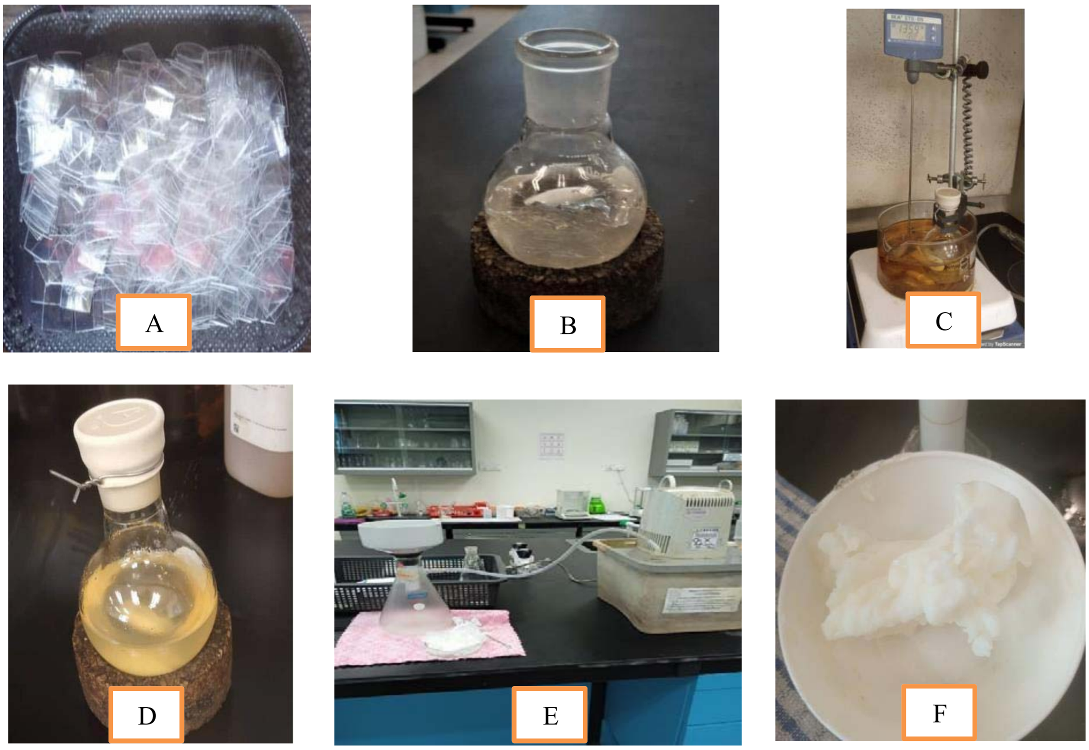

Figure 1. Process of Aminolysis (A) Pet cut into 1cm by 1cm, (B) PET and TETA solvent and (C) Aminolysis process in reflex (D) TETA after Aminolysis (E) Filtering using filtration aeration vacuum method (F) PET- derive additive.

2.3 Production of Polymer Modified Binder (PMB)

The optimum percentage of PET additive used in this study was 2%, chosen based on extensive antistripping test by Rabindra K. Padhan et al. [19] as shown in Table 1. The virgin asphalt was heated in the oven at 150 ℃ until a semi-viscous liquid state was obtained. The asphalt binder with the 2% PET additive was then added and stirred with a lab mixer set at 60 rpm and 165 ℃ for 2 h [20].

Table 1. Selection criteria for % of PET additive used based on hot water stripping tests [19].

Binder Composition	Percentage [%] of Antistripping Characteristic
100% RAP binder	40 to 45
25% RAP binder + PET [1%] modified binder	65 to70
25% RAP binder + PET [1.5%] modified binder	75 to 80
25% RAP binder + PET [2%] modified binder	85 to 90
15% RAP binder + PET [2%] modified binder	90 to 95
40% RAP binder + PET [2%] modified binder	75 to 80

2.4 Physical properties of RAP binder

The mix ratios for the RAP Binder (RB), Virgin Binder (VB), and PET-Modified Binders (PMB) are indicated in Table 2. Varied proportions of RB were employed in this research, specifically 30%, 40%, and 50%. These ratios were selected guided by literature suggesting that incorporating RB beyond 25% would enhance the stiffness of the asphalt mixture [10].

Table 2. Mix ratio for the samples.

Blend Mix Ratio	VB	RB	PMB	TOTAL
VB100	100	-	-	100
RB	-	100	-	100
RB30/VB70	70	30	-	100
RB40/VB60	60	40	-	100
RB50/VB50	50	50	-	100
PMB100	-	-	100	100
RB30/PMB70	-	30	70	100
RB40/PMB60	-	40	60	100
RB50/PMB50	-	50	50	100

Several physical tests were conducted on each prepared sample, including the penetration test, softening point test, and ductility test. The penetration test is a common method used to determine the consistency and hardness of bituminous materials. This test has been conducted based on ASTM D5 [21]. Another consistency test involved was softening point test. The softening point test was conducted to determine the temperature at which a bituminous material undergoes a significant change in its physical state from solid to semi-solid or viscous. The test was carried out following the guidelines of ASTM D36 [22]. The ductility test assesses the plastic deformation properties of bituminous materials at elevated temperatures. It measures the distance a standard briquette of bitumen can be stretched before it breaks under specified conditions. This test was performed based on ASTM D113 [23]

3. Results and discussion

3.1 Penetration

The penetration value for different samples is shown in Figure 2. The VB penetration value falls within the range of penetration grade (PG) of 60/70. Upon the addition of RB the penetration value decreased from 66.4 dmm (VB100) to 28 dmm (RB30/VB70), 23 dmm (RB40/VB60), and 22 dmm (RB50/VB50) as shown in Figure 2. This can be attributed to the introduction of RAP binders in the mix blend. The resulting blends became less responsive to temperature due to the high level of asphaltene in the sample, which decreased penetration depth values caused by the higher-aged asphalt component. As the asphalt ages, its light chemical components transform into heavy chemicals, increasing the ring-like structures that are packed and condensed, like asphaltene [24]. Due to the larger quantity of heavy components, penetration was consequently reduced, and the softening point was raised [25]. However, the usage of PMB/RB instead of VB/RB has led to higher penetration values, the main disadvantage of RAP in HMA is that it reduces low-temperature cracking performance, which is caused by oxidation, volatilization, and exudation which is the primary phenomena linked to asphalt binder ageing which causes the stiffness of the mixed blend. PMB on the other hand, can improve both the fatigue resistance and the low-temperature cracking resistance of HMA mixes. This occurs as a result of the polymers' ability to reinforce the link between the components, resulting in the new pavement's long-term durability [26]. As expected a decrease in penetration values was also observed with the addition of the RB from 57 dmm (PMB100) to 41dmm (RB30/PMB70), 33 dmm (RB40/PMB60), and 23 dmm (RB50/PMB50).

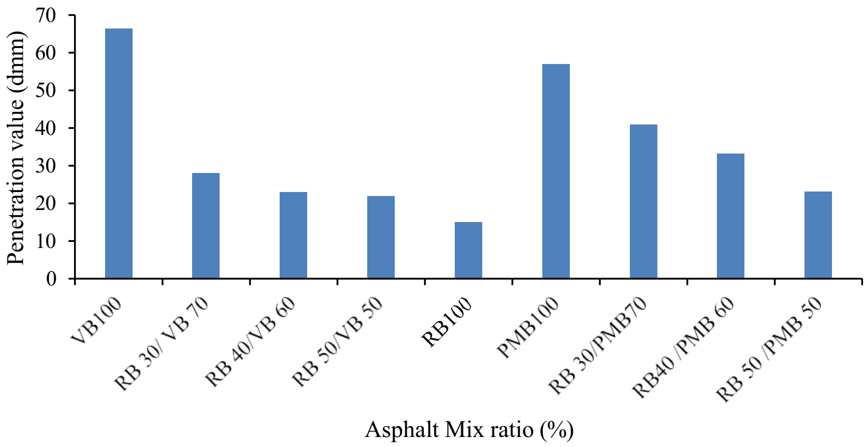

Figure 2. Penetration Value results.

3.2 Softening Point

The softening point values for different samples are shown in Figure 3. From the result, RB100 has the highest softening point compared to VB100 and PMB100. This can be attributed to the presence of a larger quantity of heavy components in the RB due to the aged asphalt [27]. A decrease in softening point was observed as the concentration of RB decreases in the mix ratio blend of RB/VB from 71 °C (RB100) to 55.5 °C (RB50/VB50), 55°C (RB40/VB60) and 51.5°C (RB30/VB70). While RB/PMB blend reduced from 58.5°C (RB50/PMB50), 53.5°C (RB40/PMB60) and 51°C (RB30/PMB70) respectively. This shows that VB and PMB have a positive impact on improving the softening point of RB from 71°C to 51°C (RB30/PMB70), in terms of temperature variation. However, no significant difference was observed between the respective blends of RB/VB and RB/PMB.

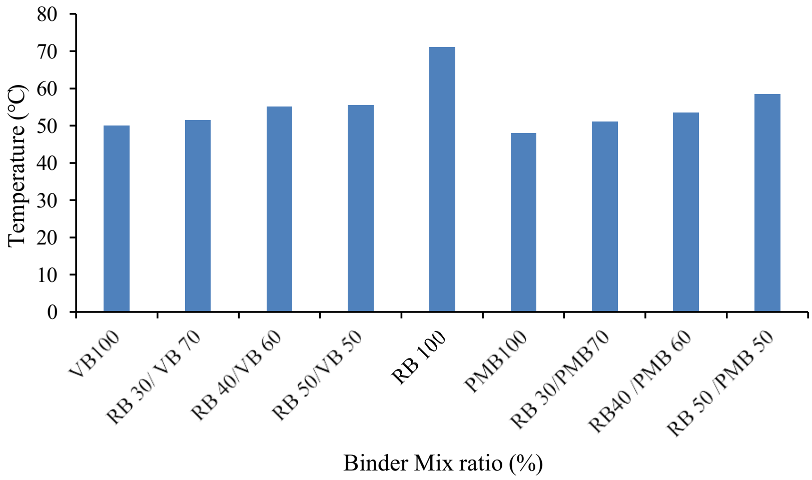

Figure 3. Softening point results.

3.3 Penetration index (PI)

The penetration index (PI) signifies a quantitative measure of the response of asphalt to the difference in temperature. It was calculated using the penetration value and softening point values. Knowing the PI of a particular asphalt, it is possible to envisage its behavior in an application. Thereby, the temperature susceptibility of the asphalt is given by the penetration index (PI). The following expression was used to calculate the PI.

$$PI = \frac{(1951.4 - 500 \log P - 20SP)}{(50 \log P - SP - 120.14)} \tag{1}$$

Where,P = penetration value (mm),SP = softening point value (°C).

A greater penetration index signifies reduced temperature sensitivity, indicating that the bitumen possesses enhanced resistance to higher temperatures. Conversely, a lower penetration index suggests heightened temperature sensitivity, leading to decreased resistance of the bitumen against temperature elevation. The results in Figure 4 show that all samples are within the acceptable normal range of bitumen for paving works which is between -2 to + 2 for conventional paving bitumen [28]. VB100 shows a PI value of -0.51 and it increased to 0.43 for RB100. An increase in PI indicates low temperature cracking susceptibility for RB100. This could result from the steric hardening process, which occurs as the asphaltene structure formulates over time, leading to an increased rate of oxidative hardening and the development of a gel-like structure [29]. Nevertheless, it's evident that PMB100 and RB/PMB combinations have notably reduced the PI values ranging from -1.42 to -0.89, signifying enhanced resilience to temperature sensitivity. Simultaneously, it also demonstrates superior temperature resistance when compared to VB100 and RB/VB combinations. This can be attributed to the PMB whose main purpose is to improve asphalt mixtures' resilience to high-temperature cracking while having no adverse effects on their low-temperature qualities [30]. It has also been demonstrated that adding PMB to RAP mixes increased the binder's stiffness and enhanced its temperature susceptibility [31].

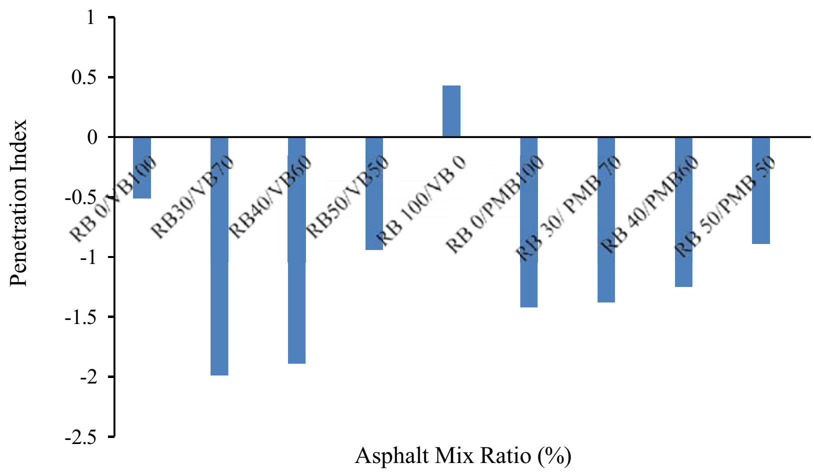

Figure 4. Penetration Index result.

3.4 Ductility Test.

According to Figure 5, VB100 has the highest ductility value of 150 cm, while that of RB100 had the least ductility value of 20 cm. The addition of RB to VB resulted in a decrease in ductility values to 42 cm (RB30/VB70), 39 cm (RB40/VB60), and 24 cm (RB50/VB50), indicating the brittleness of the aged asphalt. The ductility of PMB100 is the same as that of VB100. The addition of PMB to RB blend resulted in increased ductility compared to the RB/VB blend. The corresponding aged asphalt samples indicate that the addition of PMB can increase the asphalt flexibility. This can be attributed to PMB restoring the lost oils and resins due to the treatment conditions and revitalizing the worn-out asphalt. The brittleness of the asphalt increased as the RB ratio increased, negatively affecting the sample's behavior, which was dependent on the aged asphalt component in the blend. Heat, pressure, air, humidity, rain, and UV rays are other factors linked to the brittleness feature of aged asphalt [32]. These elements result in oxidation and dehydrogenation, which ultimately cause the asphalt's ductility to deteriorate. Studies by Pereira L et al. [33] and Gong M., et al. [34] directly correlated the asphalt ductility and in-service pavement performance. This is due to the effect that ductility has on asphalt's resilience to fatigue and its ability to shatter at low temperatures. Thus, asphalt should be firm to maintain a good matrix and a relaxed state under the applied loads. The increase in ductility, which resulted in the rejuvenation of the chemicals in the aged asphalt, observed in this study is consistent with other researchers [34].

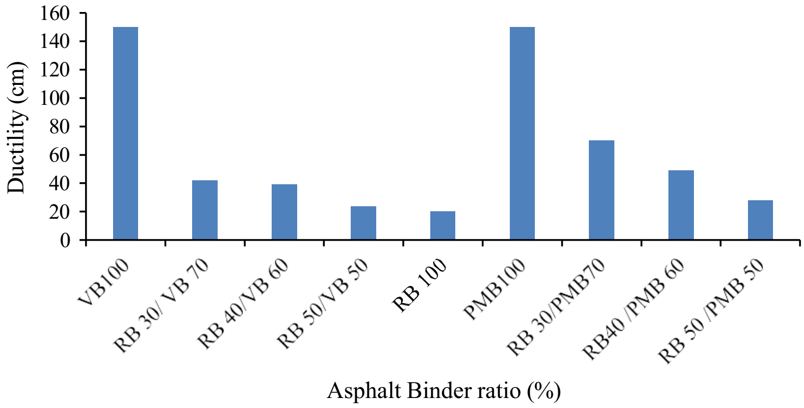

Figure 5. Ductility result.

4. Conclusion

The physical characteristics of asphalt binder made with 2% PET-derived additives show improved performance compared to conventional binder when used with reclaimed asphalt pavement binder. The addition of PMB to the blend (compared to the RB/VB blend) resulted in an increase in penetration and ductility. This indicates a shift towards less brittle behavior and reduced stiffness, enhancing the flexibility of the RAP blend. The primary function of PMB is to strengthen the resistance of asphalt mixes to high-temperature cracking while having no negative effects on the low-temperature properties as can be seen in the PI result in Figure 4, which is beneficial in road construction, in our opinion. The use of non-biodegradable plastic also provides a convenient and affordable means of disposal, promoting sustainability in road construction. However, more research is required to fully understand the complicated behavior of binders modified with recycled asphalt pavement and polyethylene terephthalate for long-term deformation, fatigue, and lower-temperature cracking.

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