Effects of Tire Pyrolysis Oil (TPO) on the Rheological Properties of Bitumen

Abdulnaser Al-Sabaei1*, Madzlan Napiah1, Muslich Sutanto1, Wesam Alaloul1 and Nura Bala2

1 Department of Civil & Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia.
2 Department of Civil and Environmental Engineering, Universiti of Alberta, Edmonton, Canada.
*corresponding e-mail: abdulnaser_17005477@utp.edu.my

Abstract. Millions of tires are produced worldwide every year and after a short time become waste. This is considering a massive waste need to be incorporated in various sustainable applications such as in a bitumen modification. In this study, tire pyrolysis oil-modified bitumen was prepared at 0%, 5%, 10%, and 15% by total weight of the blend. The influence of tire pyrolysis oil (TPO) on the conventional and high-temperature rheological properties of bitumen was evaluated by conducting penetration grade, ring and ball, dynamic viscosity, complex modulus, phase angle, and rutting resistance evaluations. Results show that the addition of TPO into base bitumen reduces the penetration values and slight reduction in softening points of modified bitumen which indicating the consistency and applicability of the TPO as a bitumen modifier. Based on the dynamic viscosity and temperature sweep test performed by a dynamic shear rheometer, it was observed that overall, TPO improved the viscosity, complex modulus, phase angle, and permanent deformation of bitumen at the temperature range of 40 to 76 °C, particularly at lower TPO content. Furthermore, TPO-modified bitumen exhibits rutting resistance better than base bitumen which could be attributed to the improvement in the elastic behaviour of bitumen with the addition of TPO. 15%TPO-modified bitumen show adequate rheological properties to be used as an alternative for base bitumen in hot regions pavement applications.

1. Introduction

Bitumen is one of the oldest engineering materials that mainly used as a binder for aggregate particles in pavement industries. It plays an essential role in the performance of asphalt mixtures. The asphalt pavement performance can be affected by various kinds of failures over time due to the change in traffic loading, environmental conditions, and axial loads. Three main distresses are most common which are rutting, fatigue, and thermal cracking. All these distresses are directly related to the rheological properties of bitumen [1-2]. The industries and researchers always looking for the enhancement of the performance of bitumen and asphalt mixtures through various bitumen modification techniques [3-5]. Polymers are one of the most common modifiers that have been investigated to improve the performance of bitumen for high and low-temperature pavement applications [6-7]. Thermoplastic elastomers are one of the uses of the widely known polymer to enhance the rheological properties of base bitumen. Styrene-butadiene styrene (SBS) and crumb rubber (CR) are the most known elastomers applied for bitumen
modification particularly to improve the high-temperature rheological characteristics as a result of improving the elasticity of bitumen and reduction the temperature susceptibility [8, 9].

On the other hand, the application of conventional crumb rubber in bitumen modification has its drawbacks such as poor storage stability, low workability, and high emission during the bitumen modification and paving process due to the high operating temperature required (equal or above 180 °C) [10-11]. Therefore, tire pyrolysis oil (TPO) was used as an alternative for conventional crumb rubber to overcome the above-mentioned problems [10-11]. TPO is an elastic and semi-solid liquid rubber consist of high percentages of recycled tire rubber and other oils produced through pyrolysis [11-12]. Presti et al. and Wu et al. [11, 13] claimed that the application of liquid rubber in bitumen modification resulted in increasing the rubber amount incorporation in bitumen with adequate stability at hot storage temperatures. Also, the manufacturing temperature reduces by 30 °C to prepare liquid rubber-modified bitumen with excellent low and intermediate-temperature rheological properties. High-temperature rheological properties were enhanced only at low strain. Although, Malaysia has one of the highest reservation of natural rubber that considered the main raw materials of rubber used in the manufacturing of tire rubber which at the end becomes waste [14], this research area of incorporating TPO instead of conventional CR still very few or no studies conducted in this regard in Malaysia so far. Thus, incorporate such materials in bitumen could open a new research line for researchers and industries that are interested in rubberized bitumen technology toward reduction of the final cost of rubberized bitumen products and contribute to reducing environmental pollutions. Therefore, in this study, the effects of tire pyrolysis oil as a modifier on the high-temperature rheological properties of 60/70 pen-grade base bitumen was investigated.

2. Materials and modification process

2.1. Materials
The base bitumen binder 60/70 pen-grade supplied by PETRONAS refinery, Malacca, Malaysia used in this study. Tire pyrolysis oil (TPO) was obtained from the sludge of waste tire pyrolysis operation in bio-fuel manufacturers that conversion tire script into bio-gas. TPO was supplied by Tyre Oil (M) Sdn. Bhd Manufacturer, Perak, Malaysia used as a modifier for petroleum-based bitumen at 0%, 5%, 10% and 15% by total weight of the blend.

2.2. Modification process
The base bitumen was kept in an oven at a temperature of 160 °C to ensure sufficient fluidity before mixing with TPO. The specific content of TPO added gradually into the base bitumen binder and manually mixed for 2 minutes and the blend left for 20 minutes to maintain the temperature at 140 °C. The final blends were prepared using a shear mixer at 1000 rpm and 140 °C for 60 minutes to ensure the homogenous mixture.

3. Experimentation method

3.1. Penetration test
The penetration test was conducted at 25 °C in accordance with the ASTM D5-13 standard. The penetration values of the base and modified bitumen samples were measured as the penetration depth recorded under 100g and a period of 5 seconds.

3.2. Softening point temperature test
The softening point temperature test was carried out based on ASTM D36-12 to measure the softening point temperatures of base and TPO-modified bitumen binders. The temperature that the bitumen sample cannot longer resist under 3.5g steel ball at uniform heat of 5 °C recorded as a softening point temperature.
3.3. Temperature susceptibility
Temperature susceptibility for the base and TPO-modified bitumen binders was evaluated based on the penetration index (PI) parameter. The PI value was calculated according to Equation (1).

\[
PI = \frac{1952 - 500 \times \log\text{Pen} - 20 \times SP}{50 \times \log\text{Pen} - SP - 120}
\]

When pen is the penetration at 25 °C and SP is the softening point in °C.

3.4. Dynamic shear viscosity
In order to evaluate the resistance of the bitumen for flow under shear stress and various temperatures, the dynamic shear viscosity test of base and TPO-modified bitumen was carried out at testing temperatures of 76, 82 and 88 °C using Malvern Kinexus rheometer at 500 Pa shear stress. The diameter of the plate and gap used in this test are 25 mm and 0.5 mm respectively in accordance with the steady shear flow (SSF) method [15].

3.5. Dynamic shear rheometer test
High-temperature rheological properties of base and TPO-modified bitumen binders were evaluated based on the ASTM D7175 standard using a Malvern Kinexus dynamic shear rheometer. In order to determine the viscoelastic behaviour of base and modified bitumen at a wide temperatures range, a temperature sweep test at controlled strain loading mode was performed at a standard load frequency of 10 rad/s and testing temperatures between 40 °C to 76 °C at the step of 6 °C. The plates geometries of 25 mm diameter and 1 mm gap were used to fulfil the standard requirements and according to the main objective of this study to investigate the high-temperature rheological properties of base and TPO-modified bitumen binders.

4. Results and discussions

4.1. Penetration test
The effect of tire pyrolysis oil on the penetration of control and rubberized bitumen binders is shown in Figure 1. It can be seen that the penetration values of TPO-modified bitumen decrease as the content of TPO increases up to 5% and then turn to increase. The lowest penetration value of 50 dmm showed for modified bitumen with 5% TPO which is 16.7% below the penetration value of base bitumen. On the other hand, rubberized bitumen modified with 15% TPO exhibit a penetration value similar to base bitumen of 60 dmm. Such results indicate an enhancement of the hardness and consistency of TPO-modified bitumen compared to base bitumen with replacement at most 15%. This finding might reveal the improvement in the intermediate temperature behaviour of TPO-modified bitumen which leads to durable rubberized asphalt pavement.

4.2. Softening point test
The softening point temperatures of base and TPO-modified bitumen are presented in Figure 2. It can be observed that the addition of TPO leads to reduce softening point temperatures compared to base bitumen. It was also noted that the softening point values decreases as the TPO content increases and the lowest softening point showed at 15% TPO. These results in agreement which those observed by Fini et al. [16]. The reduction in softening point of TPO-modified bitumen indicates the sensitivity of modified bitumen for temperature which might result in lower stiffness that will enhance the TPO-modified bitumen behaviour against fatigue cracking.
4.3. Temperature susceptibility
The change in the temperature susceptibility of base and TPO-modified bitumen in terms of penetration index values are presented in Figure 3. It can be seen that with the addition of TPO, the PI value decreases. Such behaviour indicates that the temperature susceptibility of TPO-modified bitumen is higher than that for base bitumen, however up to 5% TPO the PI maintains a value below -2 which fulfills the range of +2 and -2 that recommended being used for bitumen to ensure the sol-gel structure for pavement applications. These findings are considered a preliminary indicator for the applicability of using TPO as a modifier for asphalt pavement in road construction, however, the advanced characterization using a dynamic shear rheometer is more accurate and can predict the performance of modified bitumen better than the aforementioned conventional tests.

4.4. Dynamic shear viscosity
In order to evaluate the shear resistance of base and modified bitumen, the dynamic shear viscosity test was carried out. Figure 4 presents the dynamic viscosities of base and TPO-modified bitumen at 500 pa shear stress over the test temperatures of 76, 82, and 88 °C. It can be observed that most of the TPO-modified bitumen show dynamic viscosities better than or similar to base bitumen. TPO-modified bitumen with 5% TPO exhibits the highest viscosity value of 39.81 Pa.s at 76 °C which higher than base bitumen by 43.5%, however, a slight reduction in the viscosity was observed at high TPO content of 15%. Such results could be attributed to the physical and chemical interaction of rubber in the bitumen matrix particularly at low content of TPO. This enhancement in the viscosity of TPO-modified bitumen also indicates that TPO could improve the high-temperature rheological properties of TPO-modified bitumen.
4.5. Rheological properties
The complex modulus ($G^*$) and phase angle ($\delta$) of base and TPO-modified bitumen versus testing temperatures are shown in Figures 5 and 6 respectively. In general, it can be observed that the $G^*$ and $\delta$ of all base and modified bitumen decreases and increases respectively with the temperature increase. This result could be ascribed to the effect of temperature on the cohesion properties of bitumen which leads to reducing the stiffness and become more viscous than elastic. It can be also seen that the $G^*$ of TPO-modified bitumen significantly increased up to 5% TPO and beyond that decreased, however, all TPO-modified bitumen showed complex modulus higher than base bitumen. In addition, the $\delta$ showed a remarkable reduction of up to 5% TPO and then increased. This could be due to the ability of TPO to interact with bitumen and result in the stiffness enhancement of TPO-modified bitumen. This result also reflects the improvement of the permanent deformation resistance of TPO-modified bitumen. These findings are consistent with Presti et al. [11] which showed there was an improvement in the complex modulus and phase angle behaviour of liquid rubber-modified bitumen, particularly at the optimum dosage.

![Figure 5. Complex modulus versus temperature.](image)

![Figure 6. Phase angle versus temperature.](image)

4.6. Rutting parameters
The effects of testing temperatures on the rutting factor ($G^*/\sin\delta$) of base and TPO-modified bitumen is presented in Figures 7 and 8. The rutting factor is considered one of the most common parameters that can be used for evaluating the rutting performance of base and modified bitumen. From Figure 7, it can be shown that the $G^*/\sin\delta$ of base and modified bitumen decrease as the temperature increase, which is most commonly known due to the effects of temperature on the stiffness of bitumen and become softer at high temperatures. It can be also noted that the $G^*/\sin\delta$ of TPO-modified bitumen showed to be higher than that for base bitumen and the highest $G^*/\sin\delta$ values showed at 5% TPO. These results can be attributed to the enhancement of elastic properties of modified bitumen due to the addition of TPO which acts as an elastic binder [12]. Therefore, it can be said that the addition of TPO can partially replace the base bitumen with improving high-temperature stability.

Based on the Superpave requirements, the minimum rutting factor for unaged bitumen is 1 kPa to be able to resist the high-temperature deformations. From Figure 8, it can be noted that all base and TPO-modified bitumen have $G^*/\sin\delta$ values equal or higher than 1 kPa at 64 °C, which indicate that base and modified bitumen fulfilled the Superpave requirements to be used at a pavement service temperature of 64 °C with maintaining good deformation resistance. It can be also observed that the highest $G^*/\sin\delta$ showed for 5% TPO-modified bitumen of 2.12 kPa which reflects the almost 105% improvement compared to the base bitumen. The 15% TPO-modified bitumen exhibits $G^*/\sin\delta$ value at 64 °C of 1.15 kPa which higher than that for base bitumen by 11.7% with replacing a 15% of base bitumen. These findings indicate the applicability of TPO-modified bitumen for high-temperature bitumen applications. It can be concluded that tire pyrolysis oil could be considered for bitumen modification as an alternative for conventional crumb rubber with adequate rutting resistance. The observed results in this study seem to agree with previous studies that found the incorporation of TPO in bitumen modification could
enhance the intermediate-temperature performance of bitumen with maintaining at least the same high-temperature performance of bitumen particular at low content of TPO [10, 13].

![Figure 7. Rutting parameters versus temperature.](image)

Figure 7. Rutting parameters versus temperature.

![Figure 8. Rutting parameters at 64 °C versus WDF content.](image)

Figure 8. Rutting parameters at 64 °C versus WDF content.

5. Conclusions
This study evaluated the conventional and high-temperature rheological properties of base and tire pyrolysis oil-modified bitumen. Results of conventional properties showed decreasing in penetration values of TPO-modified bitumen compared to base bitumen which indicates the improvement in the hardness of modified bitumen, however, a slight reduction in the softening point was observed. Dynamic shear viscosity test results showed high dynamic viscosity of the TPO-modified bitumen up to 10% TPO, which reveals the improvement in temperature susceptibility. Rheological properties investigation showed an increase in the complex modulus and rutting factor of TPO-modified bitumen and a decrease in phase angle, particularly at low TPO content. That indicates the improvement of the viscoelastic properties of TPO-modified bitumen due to the addition of TPO which makes the TPO-modified bitumen applicable for high-temperature pavement applications. Rutting factor showed that the TPO-
modified bitumen is more resistant to permanent deformation which reveals the suitability of TPO-modified bitumen for high-temperature regions applications that are expected to expose for rutting distresses. Based on the results reported above, 5% TPO is the best concentration for improving the rutting resistance of base bitumen, however, 15% TPO is preferable for replacing the high amount of TPO and at the same time has adequate permanent deformation resistance at 64 °C (more than 1 kPa) which higher than that for base bitumen. To incorporate the high content of TPO, it is recommended to combined TPO with another modifier such as fibre.

6. References

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Acknowledgments
The authors would like to thank Universiti Teknologi PETRONAS for supporting this study.