

Investigation on Ageing Behaviour of Bio-Extended Bituminous Binders and Asphalt Mixtures for Sustainable Road Infrastructure

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Abstract. This paper investigates the use of a plant-based bio-oil in bituminous binders as a partial replacement of petroleum-based bitumen for asphalt mixtures. Its effects on the ageing behaviour of bituminous binders and asphalt mixtures are studied. A total of six bituminous binders and their asphalt mixtures were prepared and analysed in laboratory, including three different binder formulations with varying percentages of bio-oil and their respective reference binders. Both the bituminous binders and asphalt mixtures were subjected to ageing protocols in laboratory. Softening point test, rheological and dynamic mechanical analyses were conducted to evaluate the changes in properties of the materials before and after ageing. The results indicate that the mechanical properties of aged binders and mixtures show very similar relationships as between the fresh materials, but the relationships after ageing are at changed levels due to the laboratory conditioning. This supports further studies to verify their functional performance in asphalt pavements.

Keywords: Asphalt Pavement, Bio-Bitumen, Bio-Asphalt, Ageing, Pavement Material, Road Infrastructure.

1 Introduction

The road network is an essential and integrated part of the transport infrastructure. Nowadays, most roads are paved with asphalt mixtures. The petroleum-based bitumen is used as a binder to hold the asphalt mixture together. As a petroleum-derived product, bitumen has a relatively high environmental impact and carbon footprint. For a green transition, the use of bio-based materials in asphalt mixtures from renewable resources, such as plant-based biomass, has been investigated as a potential next-generation solution [1]. Despite some promising results so far, knowledge gaps still exist in understanding the fundamental material behaviours and properties of the new bituminous binders and asphalt mixtures containing bio-based components. This is mainly because the bio-based components have different chemical compositions compared to bitumen and they may affect the binder behaviour and mixture performance in a different way, particularly the long-term performance.

This paper investigates a specific type of bio-based material, a plant-based bio-oil, for its use in bituminous binders and asphalt mixtures as a partial replacement (extender) of petroleum-based bitumen. The study focuses on a specific and significant knowledge gap, namely understanding how the presence of bio-oil affects the ageing behaviour of bituminous binders and asphalt mixtures. Ageing is an important aspect to consider when evaluating the long-term performance of asphalt materials, which undergo ageing due to various factors, including exposure to sunlight, air, temperature fluctuations, etc. This ageing process can significantly affect the mechanical properties of pavement materials and thus the durability of roads. This paper presents an experimental investigation into the ageing behaviour of bio-extended bituminous binders and asphalt mixtures, aiming to enhance our understanding of their long-term performance and durability.

2 Experimental Plan

2.1 Materials

In this study, a total of six bituminous binders were analysed. These binders are classified into three different grades based on their conformity to EN 12591:2009 and EN 14023:2010 standards. Specifically, the study included two penetration grade 70/100 binders, two penetration grade 160/220 binders, and two polymer-modified bitumen (PMB) grade 40/100-75 binders. Within each grade, there were two types of binders: one bio-extended binder formulated with the investigated plant-based bio-oil predominantly composed of high-boiling esters and free acids (partial replacement of bitumen up to 21% – the bio-160/220 binder contains more bio-oil than the bio-70/100 binder), and the other binder sourced commercially, serving as a reference for comparative evaluation. All the six binders were used to prepare dense graded asphalt mixtures: Swedish ABT16 mixtures with the 70/100 and PMB binders, and AG16 mixtures with the 160/220 binders. For each binder grade, the mix design procedure was the same and the basic characteristics such as volumetric parameters of mixtures were kept as close as possible between the bio-extended variant and reference counterpart.

2.2 Test Methods

The binder samples were subjected to laboratory ageing protocols, including the Rolling Thin Film Oven Test (RTFOT) according to EN 12607-1:2014 and the Pressure Ageing Vessel (PAV) test according to EN 14769:2023, to simulate the short-term and long-term ageing, respectively. For assessing the changes in binder properties due to ageing, the Ring and Ball softening point of binder was tested according to EN 1427:2015 and rheological testing was conducted using a Dynamic Shear Rheometer (DSR) according to EN 14770:2023. In addition, the compacted asphalt mixture specimens were aged in laboratory according to CEN/TS 12697-52:2017 (Procedure B.1 at 65 °C for 15 days) and subsequently tested using dynamic mechanical analyses according to EN 12697-26:2018+A1:2022 (Annex F cyclic indirect tensile test) to evaluate the changes in their mechanical properties due to ageing.

3 Results and Discussion

3.1 Softening Point of Bituminous Binders

The softening point results of the investigated binders are listed in Table 1. The bio-extended binders without polymer exhibit smaller increases in their softening points after ageing than the reference binders. This means that these bio-extended binders harden less due to ageing than their reference binders. As for PMB binders, not only the hardening of the binder but also the eventual degradation of the polymer modifier may affect the softening point after ageing. Table 1 shows that the softening point of the bio-PMB decreases after ageing while that of the reference PMB increases significantly after short-term ageing by RTFOT and then decreases slightly after long-term ageing by PAV. Assuming the same ageing effect due to polymer degradation for both PMB binders, the test results suggest that the bio-PMB hardens significantly less due to ageing than the reference PMB.

Table 1. Softening point results (°C) according to EN 1427:2015.

| Ageing status | Bio 70/100 | Ref 70/100 | Bio 160/220 | Ref 160/220 | Bio PMB 40/100-75 | Ref PMB 40/100-75 |
|-----------------|---------------|---------------|----------------|----------------|----------------------|----------------------|
| Original | 47.2 | 46.8 | 40.4 | 38.8 | 86.5 | 81.5 |
| After RTFOT | 51.2 | 52.8 | 43.6 | 45.0 | 85.5 | 88.5 |
| After RTFOT+PAV | 57.8 | 62.4 | 50.4 | 53.8 | 81.5 | 86.0 |

3.2 Rheological Properties of Bituminous Binders

The DSR temperature sweep results at 1.59 Hz (10 rad/s) of the investigated binders are presented in Fig. 1-3, including the dynamic shear modulus $|G^*|$ and phase angle δ . The results indicate that the bio-extended binders have higher phase angle than their reference binders. After ageing, for binders without polymer, the phase angle decreases and the bio-extended binders without polymer still exhibit higher phase angle than their reference binders after long-term ageing by PAV. As for the PMB binders, the phase angle reaches a plateau in the high-temperature range. The bio-PMB shows very similar ageing effect as the reference PMB but with higher δ values.

For each binder grade, the $|G^*|$ curves of the two RTFOT-aged binders are almost identical, although there are some slight differences between the original binders. After long-term ageing by PAV, the $|G^*|$ increases, which means that the binder becomes stiffer. However, the bio-extended binders exhibit smaller increases in $|G^*|$ after long-term ageing than their reference binders, especially in the high-temperature range. This agrees with the conclusion drawn in the previous sub-section based on the softening point results. Meanwhile, the bio-extended binders without polymer appear to show slightly higher $|G^*|$ values after long-term ageing than their reference binders at the low-temperature end, which suggests that their $|G^*|$ is slightly more sensitive to temperature changes after experiencing the PAV ageing.

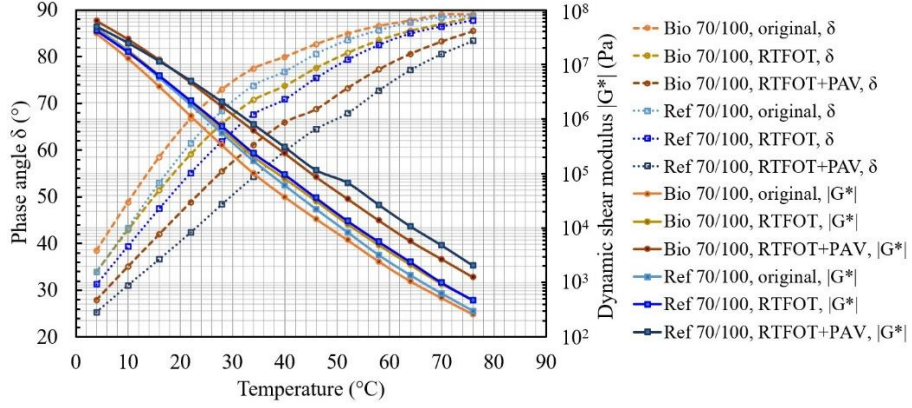


Fig. 1. DSR temperature sweep results at 1.59 Hz (10 rad/s) of 70/100 binders.

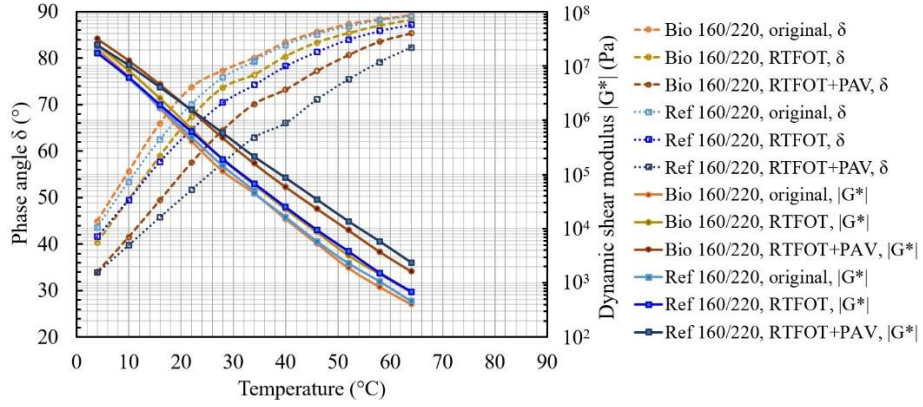


Fig. 2. DSR temperature sweep results at 1.59 Hz (10 rad/s) of 160/220 binders.

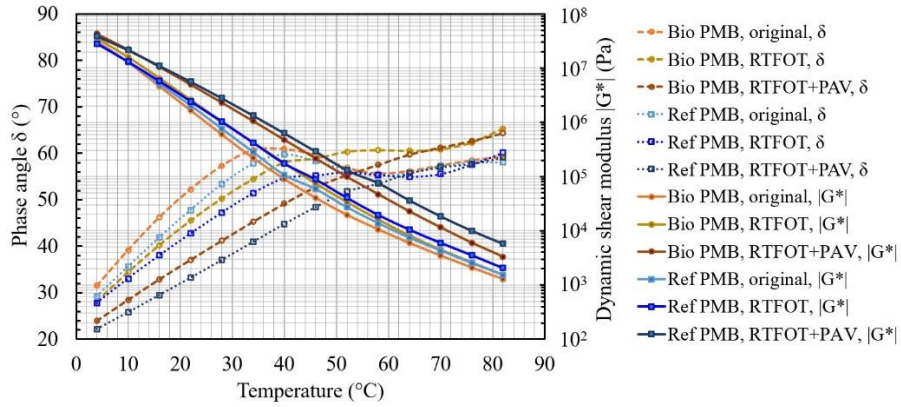


Fig. 3. DSR temperature sweep results at 1.59 Hz (10 rad/s) of 40/100-75 PMB binders.

3.3 Dynamic Mechanical Properties of Asphalt Mixtures

The master curves for dynamic modulus $|E^*|$ and phase angle ϕ of the investigated asphalt mixtures are presented in Fig. 4-6. The $|E^*|$ and ϕ values were measured at different temperatures and frequencies by a cyclic indirect tension test on cylindrical specimens and the master curves were constructed at reference temperature 10 °C.

In the low-frequency (corresponding to high-temperature) range, the asphalt mixtures with bio-extended binders have higher ϕ values than their reference mixtures. At very high frequencies (corresponding to very low temperatures), however, the bio-extended binders lead to lower ϕ values of asphalt mixtures than the reference binders, especially when the bio-oil content is high (e.g., the AG16 mixtures with 160/220 binders). After ageing, the ϕ of asphalt mixtures decreases and its peak value (the maximum [2]) moves towards to the low-frequency end. The aged mixtures show very similar relationship of ϕ as the fresh mixtures but at a reduced level.

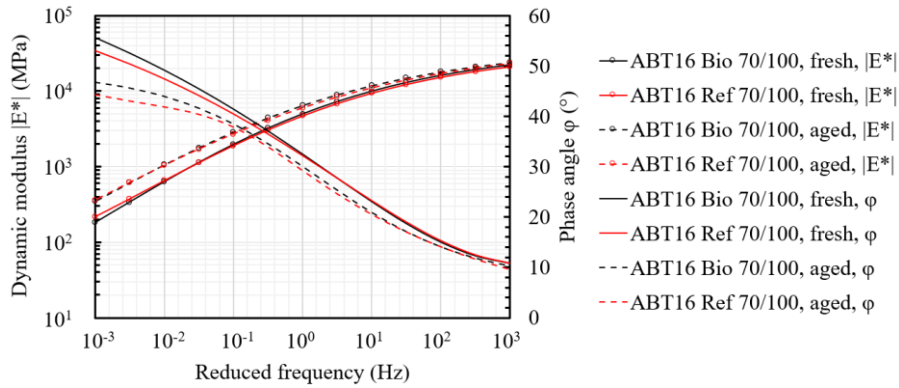


Fig. 4. Dynamic modulus $|E^*|$ and phase angle ϕ master curves at reference temperature 10 °C of ABT16 asphalt mixtures with 70/100 binders.

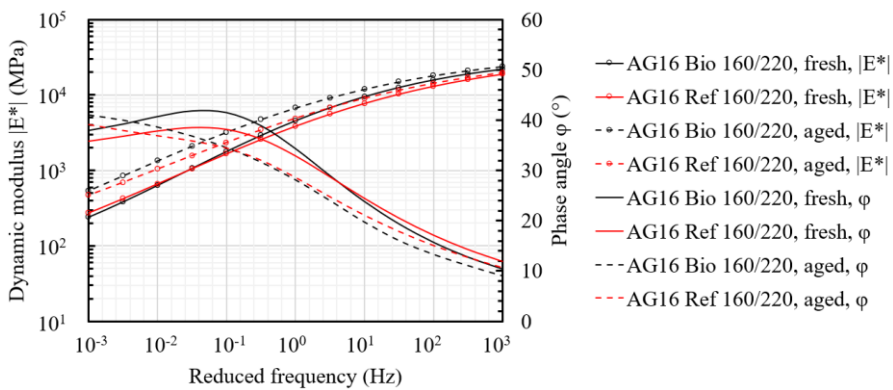


Fig. 5. Dynamic modulus $|E^*|$ and phase angle ϕ master curves at reference temperature 10 °C of AG16 asphalt mixtures with 160/220 binders.

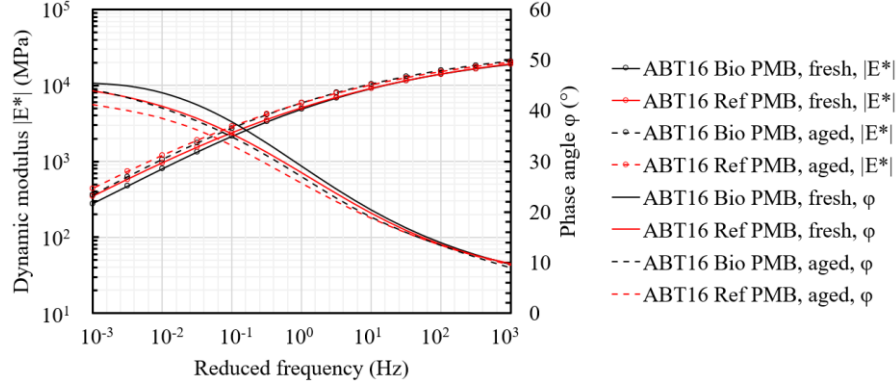


Fig. 6. Dynamic modulus $|E^*|$ and phase angle ϕ master curves at reference temperature 10 °C of ABT16 asphalt mixtures with PMB binders.

The asphalt mixtures with bio-extended binders have lower $|E^*|$ than their reference mixtures in the low-frequency range. However, as the frequency increases, the $|E^*|$ values of bio-asphalt mixtures surpass that of the references. This effect is the most significant in the case of high bio-oil content such as the AG16 mixtures with 160/220 binders. After ageing, the $|E^*|$ of asphalt mixtures increases. The aged mixtures show very similar relationship of $|E^*|$ as the fresh mixtures but at an increased level.

4 Conclusions

Using the investigated bio-oil as a bitumen extender results in increased phase angle and decreased modulus of the binders and asphalt mixtures at high temperatures and low frequencies. However, at very low temperatures and high frequencies, the bio-extended binders lead to decreased phase angle and increased modulus of the asphalt mixtures. The effects are more significant at a higher bio-oil content. Ageing hardens the materials. The mechanical properties of aged binders and mixtures show very similar relationships as between the fresh materials but at changed levels due to the ageing. This supports further studies to verify their functional performance.

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