Evaluating the long-term cracking resistance of asphalt binder modified with bio-based softeners using poker-chip test

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ABSTRACT: Bio-based softeners, or bio-additives, are increasingly utilized as sustainable solutions for adjusting asphalt performance grading or rejuvenating aged binders in reclaimed asphalt pavements. However, comprehensive studies on the bio-based softener family remain limited, and their long-term effects on asphalt binder cracking performance are not well understood. This study evaluates four softeners with varying origins to examine their type- and dosage-dependent impacts on asphalt binder. Aging conditions, including RTFO, PAV20, PAV40, and PAV60, were employed to simulate long-term oxidative aging, while the poker-chip test was used to assess binder cracking performance. Results demonstrate the long-term effectiveness of bio-based softeners in enhancing cracking resistance, with significant improvements in poker-chip ductility under extended aging conditions. Additionally, the performance of bio-based softeners was found to be dosage-sensitive, with even a 1% dosage significantly improving cracking resistance, while higher dosages yielded further enhancements. This study highlights the potential of bio-based softeners as sustainable materials for significantly improving the long-term cracking performance of asphalt binders.

1 INTRODUCTION

Cracking is one of the most predominant distresses in asphalt pavement, which is accelerated by the oxidative aging of asphalt binder. It is widely recognized that long-term oxidative aging is detrimental to the service life of asphalt pavement, as it induces significant chemical transformations in the binder, including the polymerization and oxidation of its molecular structure, resulting in increased stiffness and brittleness. This stiffening compromises the binder's ability to relax stresses and accommodate deformations, thereby exacerbating the susceptibility of the pavement to cracking under thermal and mechanical loads. Consequently, maintaining adequate viscoelasticity and ductility in asphalt binders after long-term aging is essential for mitigating premature load-related and thermal cracking.

Since the introduction of the aging protocols and Performance Grading (PG) system by the Strategic Highway Research Program (SHRP), low-temperature PG grade has been used as a reliable predictor of thermal cracking performance of asphalt binders. Recognizing that regions with diverse climatic conditions and traffic loads require tailored PG specifications to ensure optimal pavement performance, asphalt binder producers have increasingly turned to modifiers and additives to achieve the desired low-temperature PG grade. Concurrently, the growing emphasis on sustainability and recyclability in pavement engineering has driven the widespread adoption of bio-based modifiers.

Bio-based softeners, or bio-additives, are additives derived from natural oils or synthesized from renewable resources and have been widely marketed and used to adjust and optimize the PG grades of asphalt binders. They can also be used as rejuvenators adding in Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingle (RAS) to soften the severely aged binders and restore the PG grades. Regardless of the mode of application, the main function of softeners is to improve the rheological and engineering properties of asphalt binder after long-term aging. In response to the growing demand for sustainable and recyclable materials in the pavement industry, bio-based softeners have increasingly been adopted for asphalt modification and rejuvenation.

Existing studies on bio-based softeners have primarily focused on individual softener types, lacking a comprehensive comparison across different softener types and dosages. Additionally, the influence of bio-based softeners on the intermediate-temperature cracking performance of asphalt binders remains unclear, largely constrained by the absence of a standardized and reliable fatigue cracking test for asphalt binders. Current fatigue cracking evaluation methods predominantly rely on rheological approaches, such as fatigue factors or the Glover-Rowe parameter (GRP) within the linear viscoelastic range, or shear strain fatigue tests like the Linear Amplitude Sweep (LAS). However, these methods have notable

limitations: fatigue factors often fail to correlate with field cracking performance (Zhou, Karki and Im, 2017), GRP shows varying results with modified binders (Glover *et al.*, 2005), and LAS-derived fatigue life can exhibit poor sensitivity to aging while being prone to edge flow issues (Gulzar *et al.*, 2024). Furthermore, fatigue cracking in asphalt pavements, typically driven by tensile loading, cannot be accurately captured in traditional DSR tests.

This study aims to characterize and understand the effects of bio-based softeners on the cracking performance of asphalt binders under long-term aging conditions. To achieve this, four bio-based softeners of varying origins were evaluated for their type- and dosage-dependent effects on asphalt binders. Aging durations from RTFO to PAV60 were used to simulate long-term oxidative aging, and the thin film direct tensile test, poker-chip test, was employed to assess cracking performance, providing a more representative evaluation of asphalt binder behavior under tensile loading conditions.

2 MATERIAL AND METHODS

2.1 *Raw Materials*

In this study, the unmodified asphalt binder with known performance grading, PG 67-22, was selected as the base binder. To fabricate the bio-based softener modified binders, four additives, including three commercially available bio-based softeners with diverse sources and compositions, as well as one petroleum-based softener, were employed. These additives, designated as S1 through S4, include various types of bio-based products, except for S1 which was a petroleum based product included as a reference.

2.2 *Blending and aging procedures*

Two blending strategies were employed to evaluate the long-term cracking and oxidation resistance of bio-based softeners. In the first strategy, the effect of different bio-based softeners was examined by modifying PG 67-22 with four softeners at similar dosage levels to achieve a target grade of PG 58-28. The second strategy investigated the influence of bio-based softeners dosage, where PG 67-22 was modified with S3 at four dosage levels (1%, 2%, 4%, and 6% by weight of binder). The details of all the binders, along with the corresponding nomenclature used in this study, are presented in Table 1. It is important to note that PG 58-28 S3 and PG 67-22 S3 4% refer to the same binder. Consequently, a total of eight binders were prepared for the following aging.

Table 1. Details of binders used in the study.

Name	Group	Nomenclature
PG 67-22	I, II	B1
PG 58-28 S1	I	B1-1
PG 58-28 S2	I	B1-2
PG 58-28 S3	I	B1-3
PG 58-28 S4	I	B1-4
PG 67-22 S3 1%	III	B1-1%
PG 67-22 S3 2%	III	B1-2%
PG 67-22 S3 4%	III	B1-4%
PG 67-22 S3 6%	III	B1-6%

Following blending, the binders were short-term aged using the rolling thin-film oven (RTFO) aging procedure at 163 ℃ for 85 min as per ASTM D2872. Subsequently, the pressure aging vessel (PAV) aging procedure at 100 ℃ for 20 h, 40 h, and 60 h, were used to simulate the long-term aging of asphalt binders, as per ASTM D652.

2.3 *Experimental methods*

The poker-chip test method (Filonzi *et al.*, 2022) consists of a two-part specimen mold and a simple loading frame, as shown in Figure 1.

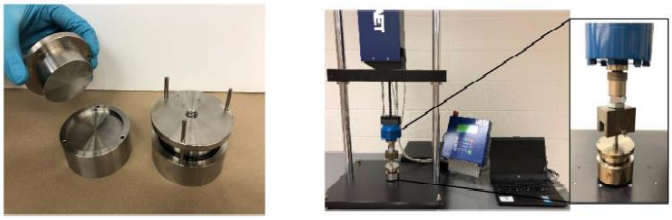

Fig. 1. Poker-chip mold (left) and simple loading frame (right)

A sample (4.5 ± 0.05 g) of the binder is poured into the bottom part of the mold that is preheated to approximately 165°C. Three dowel pins (1.589 ± 0.005 mm thick and 3.176 ± 0.25 mm long) are dropped in the binder to control the thickness of the specimen. The top of the mold (also preheated to 165°C) is then placed face down over the film of the asphalt binder. The top and bottom plates are aligned using three rods. The test specimens are allowed to cool to the test temperature, 25°C. Two replicates were prepared for each sample.

The poker-chip test is load-controlled and is performed by applying a constant loading rate of 2 N/s on a specimen that is 50.84 mm in diameter. This constant rate of load is applied after preloading the sample to 40 N. The test can be conducted using any

feedback-controlled load frame that is capable of applying a constant rate of load up to 3 kN and a motor that can displace at a rate of at least 160 mm/min. The load was applied until failure, and the load and displacement were recorded. The results from the test include: i) tensile strength of the binder, and ii) elongation or percentage strain of the binder when it reached 80% of post peak stress. In the context of this test and study, the second parameter is also referred to as ductility, which is used as the cracking parameter.

3 RESULTS AND DISCUSSIONS

The poker-chip test, a direct evaluation of binder cracking behavior, provides a ductility metric closely linked to field-scale pavement performance. A poker-chip ductility of 150% is regarded as the cracking threshold, with values above this benchmark signifying superior fatigue and thermal cracking resistance (Mohanraj *et al.*, 2023). In this section, poker-chip ductility was employed as the cracking index to evaluate the long-term cracking resistance of asphalt binders modified with bio-based softeners under two distinct mixing strategies

3.1 *Effect of different bio-based softeners on poker-chip ductility*

Fig. 2 illustrates the effect of different bio-based softeners on the long-term cracking performance of the non-modified base binder, B1. As shown, the poker-chip ductility of B1 decreases significantly with increasing aging duration, particularly from RTFO to PAV20, where a reduction of approximately 50% is observed, falling below the critical cracking threshold of 150%. This indicates that PAV20 already causes substantial loss of ductility and cracking resistance in the non-modified base binder. However, the addition of bio-based softeners substantially improves the ductility of the binder in two key aspects: (1) Enhance the poker-chip ductility after long-term aging. While the ductility of modified binders remains similar to that of the base binder under RTFO aging, all bio-based softeners exhibit significant improvement effects under PAV20, PAV40, and PAV60 conditions, with nearly double the ductility observed compared to the base binder. Notably, all modified binders maintain ductility above the 150% threshold at PAV40, and B1-2 even retains this characteristic under PAV60. (2) Mitigation of early ductility loss. From RTFO to PAV20, bio-based softeners effectively prevent rapid ductility reduction. Several binders, such as B1-2, B1-4, and B1-5, maintain ductility levels at PAV20 comparable to or even higher than those observed under RTFO aging. These findings demonstrate that bio-based softeners, regardless of their source, significantly enhance the cracking resistance of asphalt binders. They effectively mitigate ductility loss under long-term aging, ensuring superior resistance to cracking even under extended aging conditions

3.2 *Effect of bio-based softener dosages on poker-chip ductility*

Fig. 3 illustrates the impact of bio-based softener dosage on poker-chip ductility. Generally, higher dosages result in greater ductility, particularly under long-term aging conditions. Under RTFO, the non-modified base binder (B1) exhibits minimal sensitivity to softener dosage, with a slight decrease in ductility at higher dosages. However, under long-term aging conditions, ductility is highly responsive to increased softener dosage. Even at a low dosage of 1%, the softener nearly doubles the ductility of B1 under PAV60. At higher dosages (B1-6%), the ductility of binders under PAV40 surpasses that of the base binder under PAV60, with PAV40 ductility reaching 164.6%, exceeding the critical cracking threshold of 150%. These results demonstrate the sensitivity of asphalt cracking performance to bio-

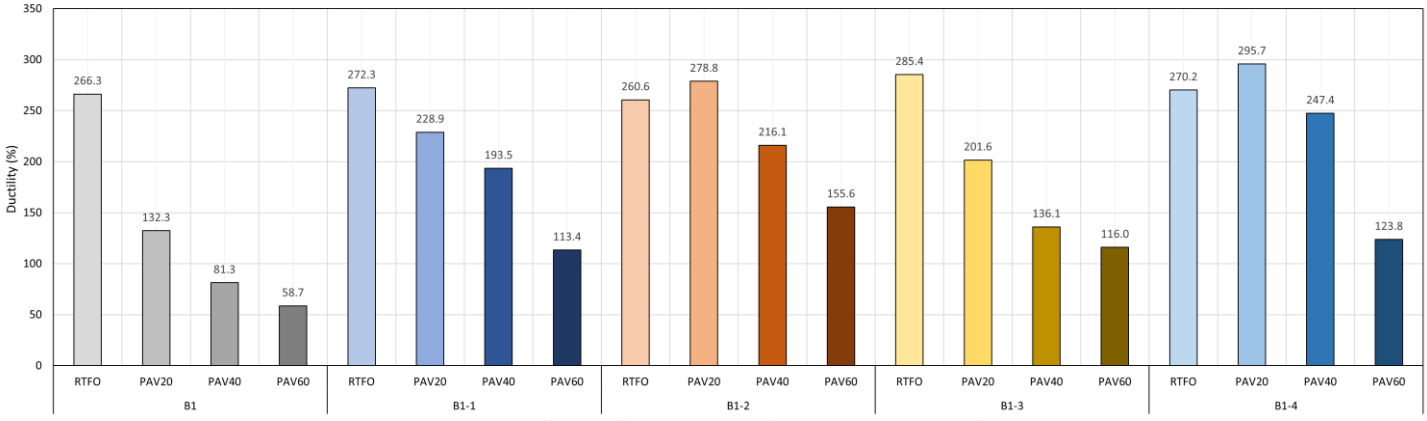

Fig. 2. Effect of different bio-based softeners on poker-chip ductility.

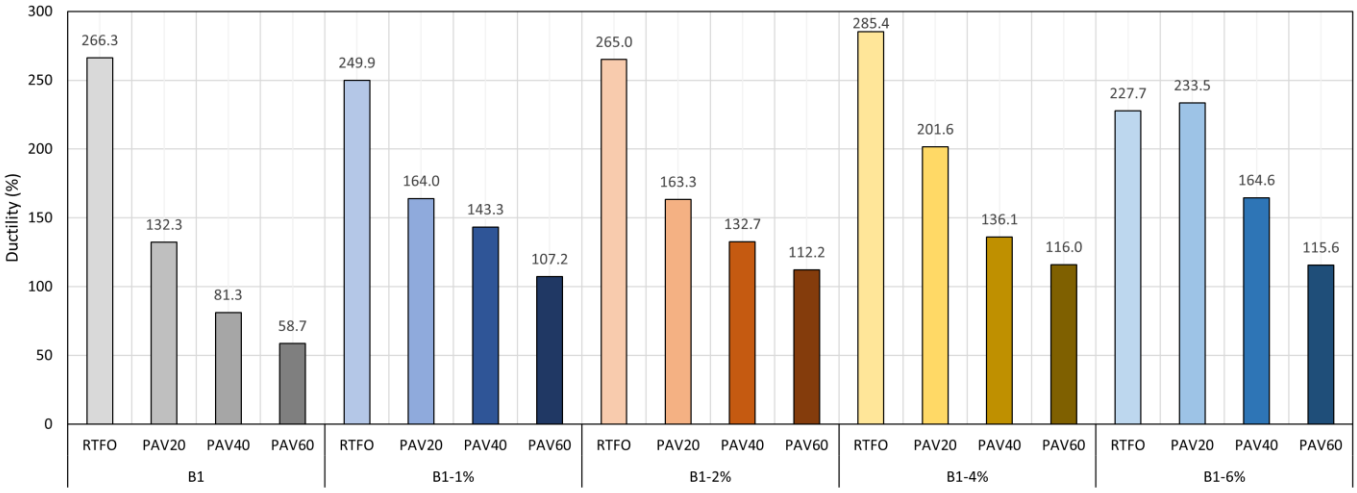

Fig. 3. Effect of bio-based softener dosages on poker-chip ductility.

based softener dosage, with higher dosages leading to significantly improved long-term cracking resistance

4 CONCLUSIONS

The poker-chip test demonstrates the effectiveness of bio-based softeners in improving the long-term cracking resistance of asphalt binders. They mitigate ductility loss during the transition from short-term to long-term aging and significantly enhance ductility under extended aging conditions. Moreover, the poker-chip ductility is highly sensitive to bio-based softeners dosage, with even small amounts significantly enhancing long-term cracking performance.

ACKNOWLEDGEMENTS

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