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Low-Temperature Fatigue Performance of Polymer-Modified Asphalt Mixtures Evaluated by Cyclic SCB Testing

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Abstract: Fatigue cracking is one of the most critical deterioration mechanisms affecting the service life of asphalt pavements. This study investigates the fatigue crack propagation behavior of asphalt mixtures modified with styrene-butadiene-styrene (SBS), Enprene 611, Enprene 701, and crumb rubber (CR) under low-temperature conditions. Semi-Circular Bending (SCB) specimens with notch depths of 10, 20, and 30 mm were subjected to cyclic loading at -20°C . Static SCB tests were first conducted to determine the reference load levels, and the resulting values were used to establish the loading protocol for the cyclic experiments. The deformation-load cycle relationships obtained from the cyclic SCB tests were analyzed to evaluate fatigue resistance and crack propagation characteristics. The results showed that all modifiers improved fatigue performance compared with the virgin and control mixtures by reducing deformation accumulation and delaying crack growth. Among the additives, Enprene 611 exhibited the highest fatigue resistance, particularly at a dosage of 4%, providing the greatest number of load cycles and the lowest deformation growth rate. SBS also significantly enhanced fatigue performance, while Enprene 701 and CR provided moderate improvements. Increasing notch depth accelerated crack propagation and reduced fatigue life for all mixtures. Based on the overall performance, the mixtures were ranked as Enprene 611 > SBS $\approx$ Enprene 701 > CR > Control > Virgin mixture. The findings indicate that polymer modification, particularly with Enprene 611, is an effective approach for improving the low-temperature fatigue crack resistance of asphalt mixtures and extending pavement service life.

Keywords: Asphalt mixture, Fatigue cracking, Cyclic SCB test, Fracture mechanics, Polymer modification

Introduction

Fatigue cracking is one of the major distress mechanisms in asphalt pavements, together with rutting and low-temperature cracking. It develops when pavement structures lose their ability to resist repeated traffic loading, eventually leading to functional failure and the need for rehabilitation or replacement (Roberts, 1996). Fatigue damage generally consists of two stages: crack initiation and crack propagation. Two main approaches are commonly used to evaluate this phenomenon: the phenomenological approach and fracture mechanics. In the phenomenological approach, smooth specimens are tested under controlled stress or strain conditions, and fatigue life is defined as the number of load cycles required for crack initiation and subsequent growth until failure. Fracture mechanics, however, assumes that materials contain inherent defects prior to loading. Accordingly, fatigue life is described as the number of cycles required for an existing flaw to propagate to a critical size. Crack growth behavior is commonly characterized using the Paris law equation (Paris, 1963; Huang, 2013).

The selection of an appropriate testing method is critical for accurately assessing fatigue performance. Although the Semi-Circular Bending (SCB) test effectively distinguishes asphalt mixtures based on fracture resistance, the

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fracture energy parameter (J_c) alone may not fully represent fatigue behavior. Repeated loading tests provide a more realistic simulation of damage accumulation in pavement structures; therefore, cyclic SCB testing combined with Paris law analysis has become a widely adopted approach for evaluating fatigue crack growth (Huang, 2013; Paris, 1963; Cheng, 2022; Walubita, 2012). However, determination of Paris law parameters requires accurate crack length measurements, which cannot be directly obtained using conventional devices such as strain gauges, extensometers, or LVDTs. To address this limitation, Digital Image Correlation (DIC) has emerged as a non-contact optical technique capable of monitoring surface deformations and crack development during testing (Chu, 1985). Previous studies have successfully applied DIC to investigate crack propagation in asphalt mixtures, demonstrating its effectiveness in fracture characterization (Birgisson, 2009; Chehab, 2007; Al-Qadi, 2022; Xing, 2017).

The integration of cyclic SCB testing and fracture mechanics has attracted considerable attention in recent years. Hofman et al. monitored crack growth during cyclic SCB tests using digital image analysis and mortar displacement methods (Hofman, 2003). Similarly, Paris law has been applied together with cyclic SCB testing to characterize crack propagation by relating strain energy release rates obtained from load–displacement hysteresis loops to fatigue crack growth behavior (Mull, 2005). Saha et al. developed a fatigue prediction model based on crack mouth opening displacement (CMOD) measurements obtained from cyclic SCB experiments (Saha, 2017). Zhang et al. employed DIC to establish a relationship between crack length and CMOD, enabling crack length estimation throughout fatigue testing (Zhang, 2018). Teixeira et al. demonstrated that cyclic SCB testing provides fatigue results comparable to indirect tensile fatigue tests while offering improved repeatability and shorter testing durations (Teixeira, 2023). Huang et al. combined SCB fatigue testing with finite element analysis and reported that binder modifiers significantly influenced fracture resistance, while the obtained Paris law parameters were consistent with previous studies (Huang, 2013). Ma et al. proposed an optimized cyclic SCB procedure and showed that Paris law coefficients were less sensitive to notch depth and loading frequency than fatigue life measurements (Ma, 2024). Furthermore, Saha and Biligiri related modulus degradation to fracture characteristics obtained from dynamic SCB tests and developed a nomograph to predict stiffness reduction as crack growth progressed (Saha, 2018). The novelty of this study lies in the comparative evaluation of SBS, Enprene 611, Enprene 701, and crumb rubber-modified asphalt mixtures using cyclic SCB tests under low-temperature conditions. By investigating fatigue crack propagation behavior at different notch depths, the study provides insight into the effectiveness of these modifiers in improving the low-temperature fatigue resistance of asphalt mixtures.

Method and Testing

In this study, B70/100 penetration-grade bitumen supplied by Batman Refinery was used as the base binder. The density of the reference binder was measured as 1.033 g/cm³, and its basic properties are presented in Table 1. Four modifiers were used to modify the base binder: SBS, Enprene 701, Enprene 611, and crumb rubber (CR). CR was obtained from waste vehicle tires and sieved through a No. 40 sieve before use. The remaining modifiers were supplied by their respective manufacturers. The technical properties of SBS, Enprene 701, and Enprene 611 are summarized in Table 2 based on the manufacturers' data sheets.

Table 1. Physical properties of the base binder

Properties	Unit	Standard	Results
Penetration	0.1mm	EN 1426	87.4
Softening point	°C	EN 1427	52.6
Flash point	°C	EN ISO 2719	230
Viscosity at 135°C /165°C	cP	ASTM D4402	562.5/162.5

Table 2. Properties of the polymer modifiers used in the study

Properties	SBS	701	611
Molecular structure	Linear	Linear	Radial
Styrene/butadiene ratio	31/69	33/67	31/69
Density (g/cm ³)	0.94	0.93	0.94
Oil content	None	None	None
Viscosity (5%, cps)	-	14	24
Tensile strength (kgw/cm ²)	324	220	200
Hardness	70	80	83
Ash content	-	0.2	0.2
Elongation at break (%)	880	600	700

Preparation of Modified Bitumen and Asphalt Mixtures

Modified binders were produced by incorporating SBS, 611, 701, CR, into the base bitumen. The base binder was first heated to $180 \pm 5^\circ\text{C}$ and then blended with the selected modifiers at dosages of 2%, 3%, and 4% for SBS, Enprene 611, and Enprene 701, and 4%, 6%, and 8% for CR, by mass of the base binder (Yalcin, 2022; Sayedzada, 2024).

In the figures, C denotes the asphalt mixture prepared with the untreated base binder. MC denotes the control mixture prepared with the base binder subjected to the same heating and mixing procedure used for modification ($180 \pm 5^\circ\text{C}$, 2700 rpm, 4 h), without adding any modifier. This control was included to distinguish the effects of modifier addition from those of the heating and mixing procedure. The notation used for modified mixtures consists of two parts. The first number indicates the additive dosage by weight of binder (e.g., 2, 3, and 4 correspond to 2%, 3%, and 4%, respectively), whereas the second part identifies the type of modifier used. For example, 2-611, 3-611, and 4-611 represent asphalt mixtures modified with 2%, 3%, and 4% Enprene 611, respectively. This naming convention is adopted throughout the study to facilitate comparison of the effects of additive type and dosage on the fatigue and fracture performance of asphalt mixtures.

Asphalt mixtures were prepared using the aggregate gradation shown in Table 3. Specimens were compacted with a gyratory compactor under a pressure of 600 ± 18 kPa, an internal angle of $1.25 \pm 0.02^\circ$, and 100 gyrations to achieve approximately 4% air voids. The control mixture was mixed and compacted at 171°C and 158°C , respectively. Volumetric properties of the reference mixture included 3.78% air voids (Va), 74.3% voids filled with asphalt (VFA), 14.7% voids in mineral aggregate (VMA), and a bulk specific gravity (Gmb) of 2.292.

For cyclic SCB testing, 150-mm-diameter gyratory-compacted specimens were cut into semicircular specimens. Notches with depths of 10, 20, and 30 mm were introduced at the midpoint of the straight edge. These three notch depths were used to investigate the influence of initial notch depth on the cyclic response of the mixtures.

Table 3. Aggregate gradation used in asphalt mix

Sieve Size (mm)	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing (%)	100	95	88	65	35	23	14	10	8	6

SCB Experiment

To determine the loading levels applied in the cyclic SCB tests, the maximum load values obtained from the static SCB experiments were first considered. These values provided the reference stress levels representing the load-carrying capacity of the mixtures under monotonic loading for each temperature and initial notch depth. At -20°C , the average maximum loads were measured as 13,420 N, 8,221 N, and 5,901 N for notch depths of 10 mm, 20 mm, and 30 mm, respectively.

At -20°C , the average maximum load decreased from 13,420 N at a notch depth of 10 mm to 8,221 N at 20 mm and 5,901 N at 30 mm. This corresponds to an approximately 56% reduction between the 10 and 30 mm notch depths, demonstrating the influence of initial notch depth on the load-carrying capacity of the specimens.

As the notch depth increased from 10 mm to 30 mm, the maximum load capacity decreased substantially, confirming the significant effect of specimen geometry on fracture behavior. These findings demonstrate that the fracture behavior of asphalt mixtures is highly sensitive to both temperature and specimen geometry. The average maximum load values obtained from the static SCB tests were subsequently used to establish the loading protocol for the cyclic SCB experiments. In this way, loading levels appropriate to the static strength of the material were selected for each testing condition, ensuring a consistent and reliable evaluation of fatigue crack propagation behavior.

Results and Discussion

Figure 1 presents the deformation–load cycle curves obtained at -20°C with a 10 mm notch depth. The results clearly show that all modified mixtures outperformed the virgin and control mixtures by increasing fatigue life and reducing deformation accumulation. While the virgin and control mixtures failed after approximately 2,200–2,700 cycles, most modified mixtures survived between 6,000 and 14,000 cycles. All curves exhibited three typical stages: initial deformation settlement, a stable deformation accumulation phase, and a rapid

increase in deformation before failure. The modified mixtures displayed a considerably longer stable region, indicating slower damage development.

Among the additives, Enprene 611 provided the best performance. The 4% Enprene 611 mixture achieved the highest fatigue life, reaching approximately 13,500–14,000 cycles while maintaining low deformation levels. The 3% and 2% Enprene 611 mixtures also showed substantial improvements compared with the virgin mixture. SBS-modified mixtures exhibited similar behavior, with the 4% SBS mixture reaching approximately 11,500–12,000 cycles. Increasing SBS content consistently improved fatigue performance, although Enprene 611 produced slightly better results at comparable dosages.

Enprene 701 also improved fatigue resistance, but its performance remained below that of Enprene 611 and SBS. The 4% Enprene 701 mixture reached approximately 8,500–9,000 cycles, whereas lower dosages exhibited shorter fatigue lives. CR-modified mixtures showed higher initial deformation but relatively stable behavior during later loading stages. The 8% CR mixture achieved the best result within the CR group, reaching approximately 6,000–6,200 cycles. These findings suggest that CR primarily enhances ductility and deformation tolerance, whereas Enprene 611 and SBS are more effective in improving overall fatigue resistance.

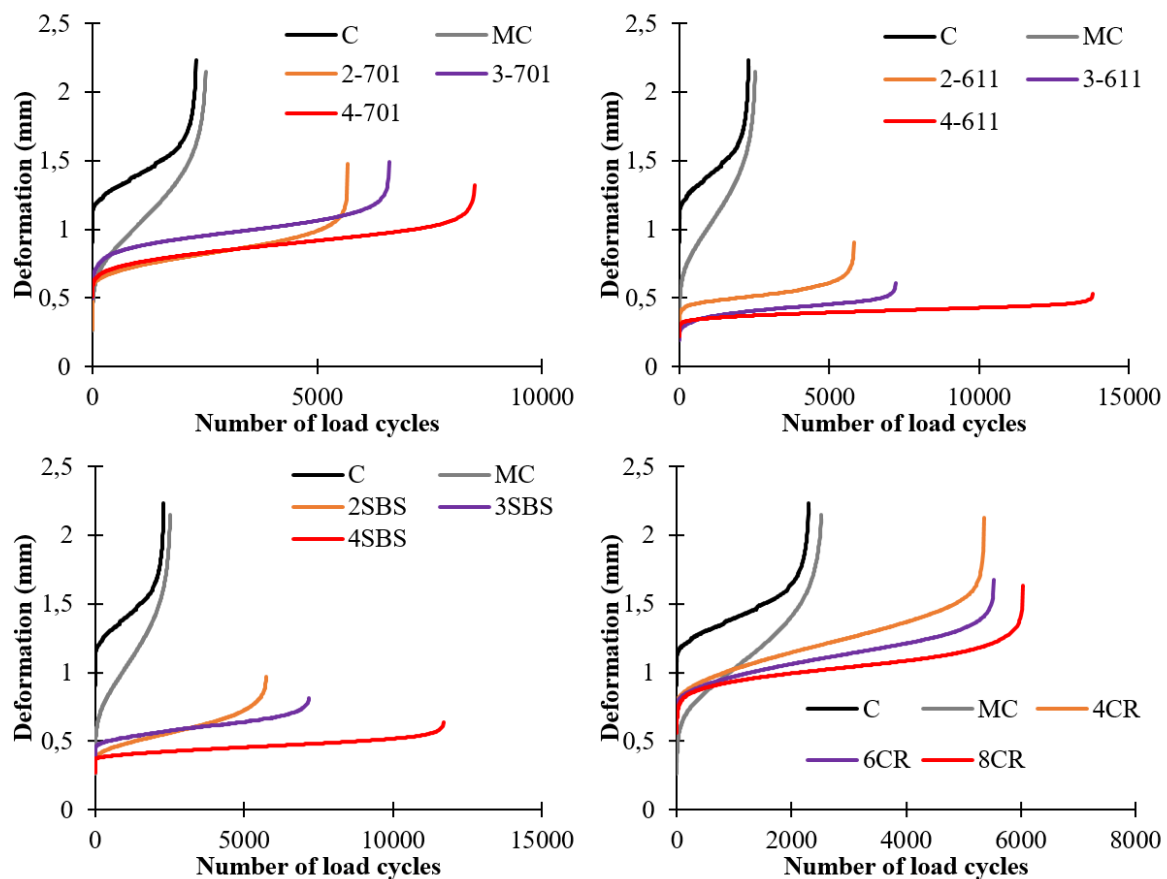


Figure 1. Deformation-load cycle count curves at -20°C and 10 mm notch

As shown in Figure 2, the virgin and control mixtures exhibited a rapid increase in deformation and reached failure at relatively low numbers of load cycles under the conditions of -20°C and a 20 mm notch depth. In contrast, the modified mixtures accumulated deformation more gradually, resulting in an improvement in fatigue life. Among the additives, Enprene 611 demonstrated the best performance, with deformation curves becoming flatter as the additive content increased, indicating delayed crack propagation. The 4% Enprene 611 mixture achieved the highest number of load cycles and the lowest rate of deformation growth. SBS-modified mixtures exhibited stable behavior and high fatigue resistance with moderate deformation accumulation, while Enprene 701 provided similar but slightly lower performance. Although CR-modified mixtures showed greater ductility and higher initial deformation levels, their fatigue performance remained lower than that of the other modifiers due to a faster increase in deformation during later loading stages. Overall, all additives improved fracture resistance and delayed crack propagation at low temperatures, with the performance ranking determined as: Enprene 611 > SBS ≈ Enprene 701 > CR > Control > Virgin mixture.

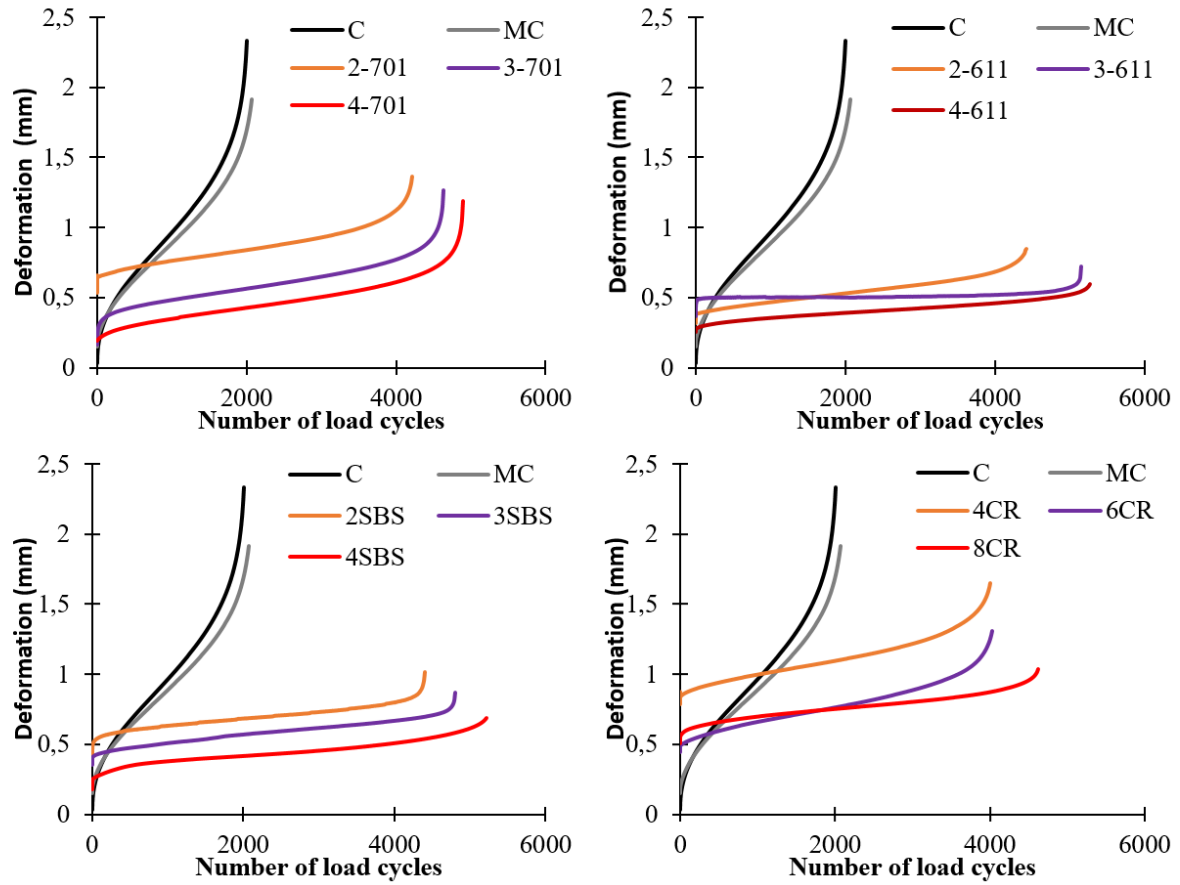


Figure 2. Deformation-load cycle count curves at -20°C and a 20 mm notch

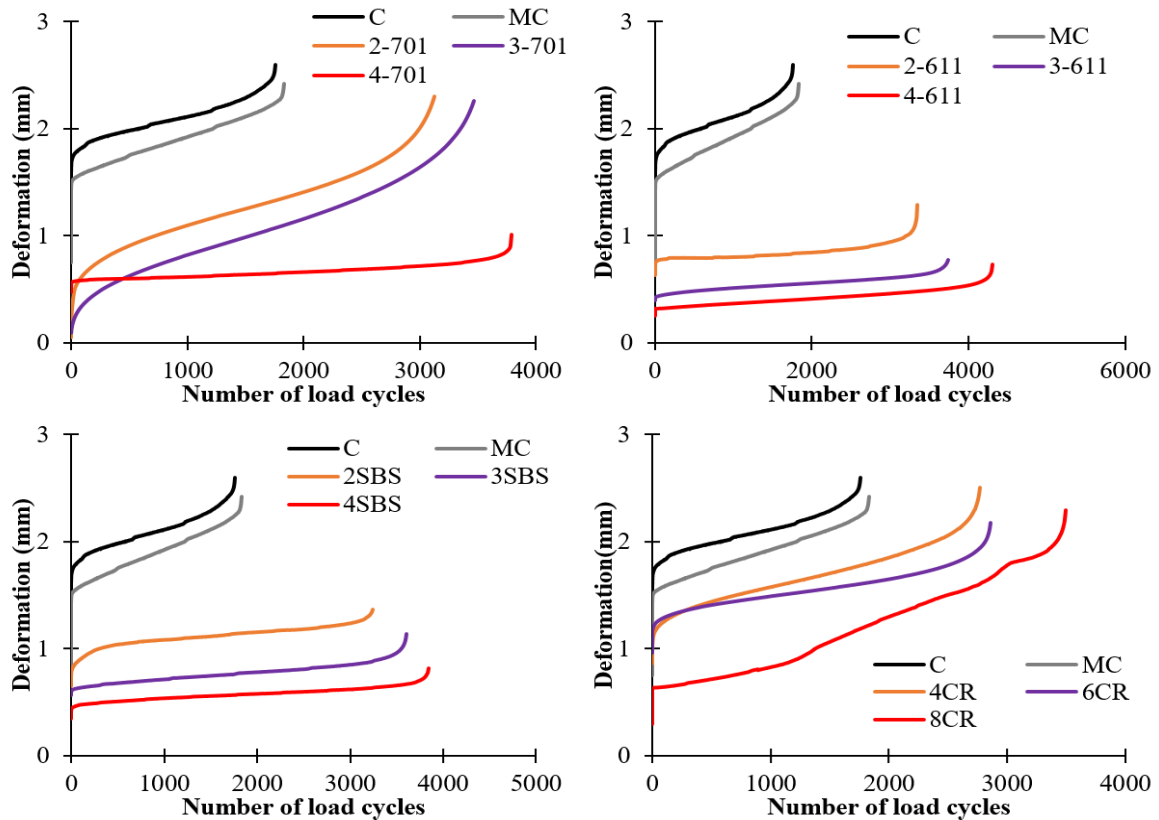


Figure 3. Deformation-load cycle count curves at -20°C and a 30 mm notch

As illustrated in Figure 3, the virgin and control mixtures exhibited a rapid increase in deformation and failed at relatively low numbers of load cycles under dynamic loading at -20°C with a 30 mm notch depth. The effect of notch depth became more pronounced, accelerating crack propagation and reducing fatigue life. In contrast, all modified mixtures reduced deformation accumulation and achieved higher load cycle numbers, indicating improved resistance to crack growth.

Among the modifiers, Enprene 611 provided the best overall performance. As the additive content increased, the deformation curves became noticeably flatter, demonstrating slower crack propagation and enhanced fatigue resistance. The 4% Enprene 611 mixture exhibited the lowest deformation growth rate and the highest fatigue life. SBS-modified mixtures also showed stable and balanced deformation behavior, with performance improving as the SBS content increased, although their effectiveness remained slightly lower than that of Enprene 611. Enprene 701 exhibited a similar trend to SBS but generally showed higher deformation levels and lower fatigue resistance. CR-modified mixtures displayed greater initial ductility and higher initial deformation; however, deformation accumulated more rapidly at higher load cycles, resulting in lower fatigue performance compared with the other modifiers.

Overall, although increasing the notch depth to 30 mm accelerated crack propagation, all modifiers substantially mitigated this adverse effect. The performance ranking was determined as: Enprene 611 > SBS $\approx$ Enprene 701 > CR > Control > Virgin mixture.

Conclusion

The fatigue crack propagation behavior of asphalt mixtures modified with SBS, Enprene 611, Enprene 701, and crumb rubber (CR) was evaluated using cyclic SCB tests conducted at -20°C under different notch depths. The results demonstrated that all modifiers improved fatigue performance compared with the virgin and control mixtures by reducing deformation accumulation and delaying crack propagation. Increasing notch depth accelerated crack growth and reduced fatigue life, highlighting the significant influence of specimen geometry on fracture behavior. Among the additives, Enprene 611 exhibited the best overall performance, with the 4% Enprene 611 mixture providing the highest fatigue life and the lowest deformation growth rate under all test conditions. SBS also significantly enhanced fatigue resistance, although its performance remained slightly lower than that of Enprene 611. Enprene 701 improved fatigue behavior compared with the virgin mixture but was less effective than Enprene 611 and SBS. CR-modified mixtures exhibited greater ductility and improved fatigue resistance; however, their higher deformation levels resulted in lower overall performance than the polymer-modified mixtures. Based on all test results, the overall performance ranking was determined as Enprene 611 > SBS $\approx$ Enprene 701 > CR > Control > Virgin mixture. Under the investigated laboratory conditions, the mixture containing 4% Enprene 611 exhibited the most favorable cyclic SCB response at -20°C among the mixtures tested.

Recommendations

The laboratory results identify Enprene 611 as a promising modifier for improving the cyclic SCB response of asphalt mixtures at -20°C . Future studies should investigate the long-term aging performance of Enprene-modified mixtures and evaluate their behavior under different temperatures, loading frequencies, and environmental conditions. In addition, field-scale validation studies are recommended to confirm the laboratory findings and assess the practical applicability of these modifiers in pavement construction. Further research incorporating Digital Image Correlation (DIC) and fracture mechanics parameters is also suggested to provide a more comprehensive understanding of crack initiation and propagation mechanisms in modified asphalt mixtures.

Scientific Ethics Declaration

* The authors declare that this study complies with scientific research and publication ethics. All scientific, ethical, and legal responsibilities related to the content of this article belong to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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References

- Al-Qadi, I. L., Said, I. M., Ali, U. M., & Kaddo, J. R. (2022). Cracking prediction of asphalt concrete using fracture and strength tests. *International Journal of Pavement Engineering*, 23(10), 3333–3345.
- Birgisson, B., Montepara, A., Romeo, E., Roncella, R., Roque, R., & Tebaldi, G. (2009). An optical strain measurement system for asphalt mixtures. *Materials and Structures*, 42(4), 427–441.
- Chehab, G. R., Seo, Y., & Kim, Y. R. (2007). Viscoelastoplastic damage characterization of asphalt–aggregate mixtures using digital image correlation. *International Journal of Geomechanics*, 7(2), 111–118.
- Cheng, L., Zhang, L., Liu, X., Yuan, F., Ma, Y., & Sun, Y. (2022). Evaluation of the fatigue properties for the long-term service asphalt pavement using the semi-circular bending tests and stereo digital image correlation technique. *Construction and Building Materials*, 317, 126119.
- Chu, T. C., Ranson, W. F., & Sutton, M. A. (1985). Applications of digital-image-correlation techniques to experimental mechanics. *Experimental Mechanics*, 25(3), 232–244.
- Hofman, R., Oosterbaan, B., Erken, S. M. J. G., & van de Kuilen, J. (2003). Semi-circular bend test to assess the resistance against crack growth. In *Proceedings of the Sixth International RILEM Symposium* (pp. 257–263). Zurich, Switzerland.
- Huang, B., Shu, X., & Zuo, G. (2013). Using notched semi-circular bending fatigue test to characterize fracture resistance of asphalt mixtures. *Engineering Fracture Mechanics*, 109, 78–88.
- Ma, Y., Mohammad, L. N., Liu, J., Asghar, M., Elnaml, I., Cooper, S. B., et al. (2024). Development of a cyclic semi-circular bending test protocol to characterize fatigue cracking of asphalt mixture at intermediate temperature. *Construction and Building Materials*, 443, 137669.
- Mull, M. A., Othman, A., & Mohammad, L. (2005). Fatigue crack propagation analysis of chemically modified crumb rubber–asphalt mixtures. *Journal of Elastomers and Plastics*, 37(1), 73–87.
- Paris, P., & Erdogan, F. (1963). A critical analysis of crack propagation laws. *Journal of Basic Engineering*, 85(4), 528–533.
- Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D. Y., & Kennedy, T. W. (1996). *Hot mix asphalt materials, mixture design and construction* (2nd ed.). NAPA Education Foundation.
- Saha, G., & Biligiri, K. P. (2017). Stato-dynamic response analyses through semi-circular bending test: Fatigue life prediction of asphalt mixtures. *Construction and Building Materials*, 150, 664–672.
- Saha, G., & Biligiri, K. P. (2018). Modulus prediction of asphalt mixtures using dynamic semicircular bending test: Estimation algorithm and nomograph development. *International Journal of Fatigue*, 109, 137–144.
- Sayedzada, S. E., Ozdemir, A. M., Yalcin, E., & Yilmaz, M. (2024). Investigation of mechanical properties of hot mix asphalts with modified binders with SBS, 611 and 701 polymers. *Polymer Bulletin*, 81, 3695–3724.
- Teixeira, J. E. S. L., Amaecing Junior, C. M., Rezende, L. R., Castelo Branco, V. T. F., & Kim, Y. R. (2023). Evaluation of asphalt concrete’s fatigue behavior using cyclic semi-circular bending test. *Construction and Building Materials*, 400, 132772.
- Walubita, L. F., Simate, G. S., Ofori-Abebresse, E., Martin, A. E., Lytton, R. L., & Sanabria, L. E. (2012). Mathematical formulation of HMA crack initiation and crack propagation models based on continuum fracture-mechanics and work-potential theory. *International Journal of Fatigue*, 40, 112–119.
- Xing, C., Tan, Y., Liu, X., Anupam, K., & Scarpas, T. (2017). Research on local deformation property of asphalt mixture using digital image correlation. *Construction and Building Materials*, 140, 416–423.

- Yalcin, E., & Demirbag, A. (2022). Effects of modified binders obtained from different polymers on conventional and rheological properties. *Construction and Building Materials*, 357, 129366.
- Zhang, J., Sakhaeifar, M., Little, D. N., Bhasin, A., & Kim, Y. R. (2018). Characterization of crack growth rate of sulfur-extended asphalt mixtures using cyclic semicircular bending test. *Journal of Materials in Civil Engineering*, 30(11).

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