

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2026

Volume 42, Pages 11-18

ICBASET 2026: International Conference on Basic Sciences, Engineering and Technology

Evaluation of the Crack Resistance of Hot Mix Asphalt Mixtures Modified with Enprene 611 Elastomer

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Abstract: In this study, the crack resistance of Hot Mix Asphalt (HMA) mixtures prepared using neat bitumen and bitumen modified with Enprene 611 elastomer was experimentally investigated through the Semi-Circular Bending (SCB) test. Asphalt mixtures were produced by incorporating 2%, 3%, and 4% Enprene 611 elastomer, by weight of the binder, into B70/100 penetration-grade bitumen. The compacted cylindrical specimens were cut into two equal halves, and artificial notches with depths of 10, 20, and 30 mm were introduced at the center of each semi-circular specimen to obtain SCB test samples. The SCB tests were conducted at 20°C and 40°C to evaluate the combined effects of temperature and notch depth on the fracture behavior of the asphalt mixtures. The experimental results demonstrated that the mixtures containing 4% Enprene 611 consistently exhibited the highest maximum fracture load (P_{max}) at all notch depths and test temperatures, significantly outperforming both the neat and the other modified mixtures. Furthermore, increasing the Enprene 611 content considerably enhanced the deformation resistance, cohesive bonding strength, and crack propagation resistance of the asphalt mixtures. Overall, the findings indicate that Enprene 611 is an effective polymer modifier for improving the fracture performance and mechanical durability of hot mix asphalt mixtures.

Keywords: Hot mix asphalt (HMA), Enprene 611 elastomer, Semi-circular bending (SCB), Crack resistance, Polymer-modified bitumen

Introduction

Road transportation is currently the most widely used mode of transportation worldwide. Among the various pavement systems, Hot Mix Asphalt (HMA) is the most preferred pavement type due to its cost-effectiveness, ease of construction, and satisfactory service performance. However, one of the most common forms of distress observed in HMA pavements is cracking, which significantly reduces pavement durability and service life. To minimize crack initiation and propagation, various modifier additives are incorporated into asphalt binders to enhance their adhesive and mechanical properties. These additives improve the rheological characteristics of bitumen, thereby extending the service life of flexible pavements.

The modification of neat bitumen using polymeric additives has become one of the most effective approaches for improving binder performance. Modified asphalt binders exhibit superior resistance to permanent deformation, fatigue damage, and thermal cracking compared with conventional binders. Consequently, Hot Mix Asphalt (HMA) technology utilizing polymer-modified binders has been widely adopted in pavement engineering applications (Zhao et al., 2025). In recent years, considerable attention has been devoted to the use of polymer- and elastomer-based modifiers for asphalt binder modification. These modifiers effectively improve rutting resistance at elevated temperatures while significantly reducing crack susceptibility caused by traffic loading and environmental conditions at intermediate and low temperatures.

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Among the available polymer modifiers, Enprene 611 elastomer has emerged as a promising additive for enhancing the engineering performance of asphalt binders and Hot Mix Asphalt mixtures. Recent studies have compared the performance of Enprene 611 with conventional modifiers such as Styrene–Butadiene–Styrene (SBS), Enprene 701, crumb rubber (CR), and various chemical additives, demonstrating its considerable potential for asphalt modification (Utku Tiryaki & Yalcin, 2025). Furthermore, Enprene 611 has been reported to significantly improve the high-temperature performance of asphalt binders by increasing their stiffness and resistance to permanent deformation (Seza Deveci & Yilmaz, 2025). To characterize the crack propagation behavior of asphalt mixtures under laboratory conditions, the Semi-Circular Bending (SCB) test has become one of the most widely accepted fracture testing methods because of its simplicity, repeatability, and ability to simulate crack initiation and propagation under controlled loading conditions.

Several laboratory test methods have been developed to evaluate the cracking resistance of asphalt mixtures, including the four-point bending test (Zhang et al., 2023), uniaxial fatigue push–pull test (Soltani & Anderson, 2005), Texas Overlay Test (Walubita et al., 2021), and indirect tensile fatigue test (Haggag et al., 2011). Depending on the loading protocol, these methods generally employ either monotonic or cyclic loading conditions. Among them, the SCB test has become one of the most frequently adopted techniques for evaluating the fracture behavior and cracking resistance of asphalt mixtures (Meng et al., 2023). Historically, asphalt fracture has been investigated through laboratory experiments, numerical simulations, and field observations. Over the past decades, laboratory investigations supported by analytical and numerical approaches have substantially improved the understanding of fracture mechanisms in asphalt mixtures (Saha & Biligiri, 2016). Although extensive research has been conducted on monotonic SCB testing, fatigue-based SCB investigations remain relatively limited and require further improvements regarding loading protocols and fracture characterization parameters (Meng et al., 2023). Recent studies have combined the SCB test with digital image correlation (DIC) to evaluate the low-temperature fracture and damage behavior of asphalt concrete. Such full-field deformation measurements allow damage to be monitored throughout the crack propagation process, providing a more comprehensive understanding of fracture evolution in asphalt mixtures (Zhu et al., 2025). In general, the cracking resistance of asphalt materials is primarily evaluated using two categories of testing methods: repeated-loading fatigue tests and monotonic fracture tests (Shi et al., 2025).

In the present study, the crack resistance of Hot Mix Asphalt mixtures produced with B70/100 penetration-grade bitumen modified by 2%, 3%, and 4% Enprene 611 elastomer was experimentally investigated. The crack propagation behavior of both neat and modified mixtures was comprehensively evaluated using the Semi-Circular Bending (SCB) test at 20°C and 40°C with notch depths of 10, 20, and 30 mm. The effects of polymer content, testing temperature, and notch geometry on the fracture performance of asphalt mixtures were systematically examined.

Materials and Methods

Materials

In this study, B70/100 penetration-grade neat bitumen, produced by the Batman TÜPRAŞ Refinery (Türkiye), was used as the asphalt binder. Considering the climatic and environmental conditions of Türkiye, B70/100 penetration-grade bitumen is one of the most commonly used binders in flexible pavement applications. The specific gravity of the neat bitumen used in this study was determined to be 1.033 g/cm³. The fundamental physical properties of the neat asphalt binder are summarized in Table 1 (Yalcin et al., 2026).

Table 1. Physical properties of the B70/100 penetration-grade neat bitumen			
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

Enprene 611 elastomer, supplied by Mpolimer Co., was used as the polymer modifier for bitumen modification. For the production of Hot Mix Asphalt (HMA) mixtures, limestone aggregate, which is characterized by its high abrasion resistance, was selected as the mineral aggregate.

Bitumen Modification

The modified asphalt binders were prepared by incorporating Enprene 611 elastomer into the B70/100 penetration-grade neat bitumen at concentrations of 2%, 3%, and 4% by weight of the binder. The modification procedure was carried out according to the following steps: Initially, the neat bitumen was heated in a laboratory oven at $180 \pm 5^\circ\text{C}$ for approximately 30 min until it reached a sufficiently fluid state. Subsequently, 800 g of the heated bitumen was transferred into a metallic mixing container and maintained at $180 \pm 5^\circ\text{C}$ until thermal equilibrium was achieved.

The predetermined amount of Enprene 611 elastomer was gradually added to the bitumen. The mixture was then blended using a high-speed mechanical mixer operating at 2700 rpm for 4 h to ensure the homogeneous dispersion of the polymer throughout the binder. At the end of the modification process, the polymer-modified asphalt binders were obtained and subsequently used for the preparation of the Hot Mix Asphalt (HMA) specimens.

Preparation of Hot Mix Asphalt (HMA) Specimens

The limestone aggregates used in the preparation of the asphalt mixtures were separated into individual size fractions according to the aggregate gradation specified for the Semi-Circular Bending (SCB) specimens. Each aggregate fraction was weighed using a precision balance to satisfy the target gradation limits presented in Table 2 (Yalcin et al., 2026).

Table 2. Aggregate gradation used in the hot mix asphalt (HMA) mixtures

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

Based on the preliminary mix design analyses, the optimum bitumen content (OBC) for the control mixture was determined to be 4.67%. Subsequently, 1975 g of the aggregate–bitumen mixture was thoroughly blended using a laboratory-scale Hot Mix Asphalt (HMA) mixer to ensure a homogeneous mixture. The prepared mixture was then placed into the mold of a Superpave Gyratory Compactor (SGC) and compacted to produce cylindrical HMA specimens. The specimen preparation procedure is illustrated in Figure 1 (Yalcin et al., 2026).

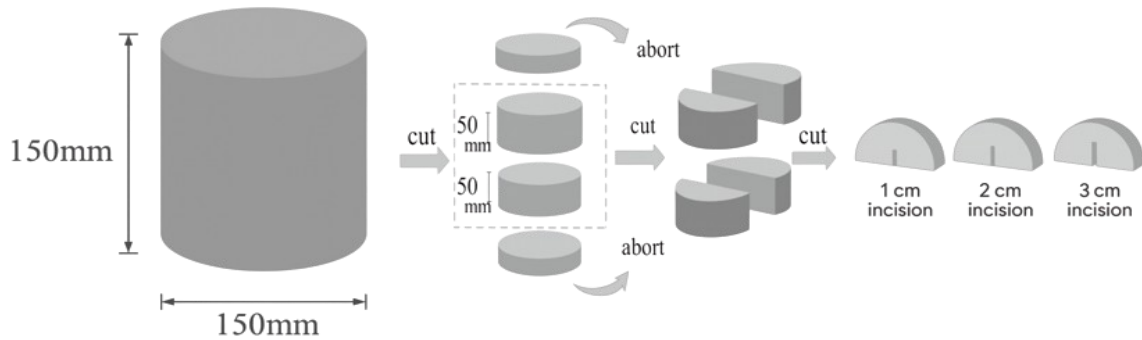


Figure 1. Schematic diagram of the preparation process of semi-circular bending specimen

Semi-Circular Bending (SCB) Test

The Semi-Circular Bending (SCB) test was employed to evaluate the cracking resistance of the asphalt mixtures, which represents one of the most critical distress mechanisms affecting flexible pavements throughout their service life. The compacted cylindrical HMA specimens with a diameter of 150 mm were cut into two equal halves to obtain semi-circular test specimens. Artificial notches with depths of 10, 20, and 30 mm were then introduced at the midpoint of the flat edge of each specimen to ensure controlled crack initiation during the SCB tests. The semi-circular specimens prepared using both neat and Enprene 611-modified bitumen were conditioned at 20°C and 40°C to investigate the influence of temperature on crack propagation behavior and specimen stiffness. The SCB tests were performed under three-point bending using a constant displacement rate of 50 mm/min under monotonic loading conditions. Throughout the tests, the applied load and the corresponding crack mouth opening displacement (CMOD), measured at the notch mouth, were continuously recorded using a computerized data acquisition system until complete failure of the specimens. The SCB test specimens and the experimental setup are shown in Figure 2.



Figure 2. Semi-circular bending (SCB) test specimens and experimental setup

Results and Discussion

The crack propagation behavior of the neat and Enprene 611-modified Hot Mix Asphalt (HMA) mixtures was evaluated under different testing temperatures (20°C and 40°C) and notch depths (10, 20, and 30 mm) using the load–Crack Mouth Opening Displacement (Load–CMOD) curves obtained from the Semi-Circular Bending (SCB) tests. The corresponding maximum fracture load (P_{max}) values obtained from the experiments are summarized in Table 3.

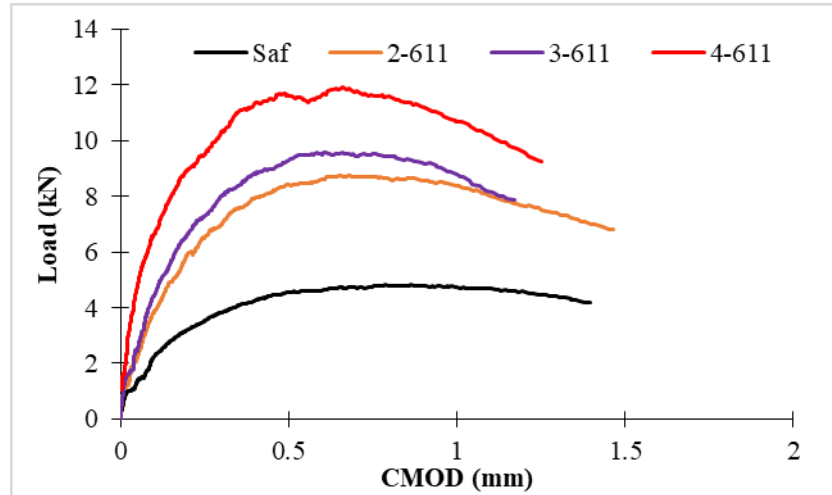
Table 3. Maximum fracture load values obtained from the SCB tests for neat and enprene 611-modified hot mix asphalt (HMA) mixtures

Test Temperature	Notch Depth(mm)	Neat	2%Enprene611 (kN)	3% Enprene 611 (kN)	4% Enprene 611 (kN)
20 °C	10	4.85	8.70	9.60	11.90
20 °C	20	3.70	7.50	8.30	9.20
20 °C	30	2.60	6.80	7.45	8.45
40 °C	10	2.70	6.30	7.50	8.35
40 °C	20	1.70	3.85	5.15	6.75
40 °C	30	0.80	3.35	4.15	5.50

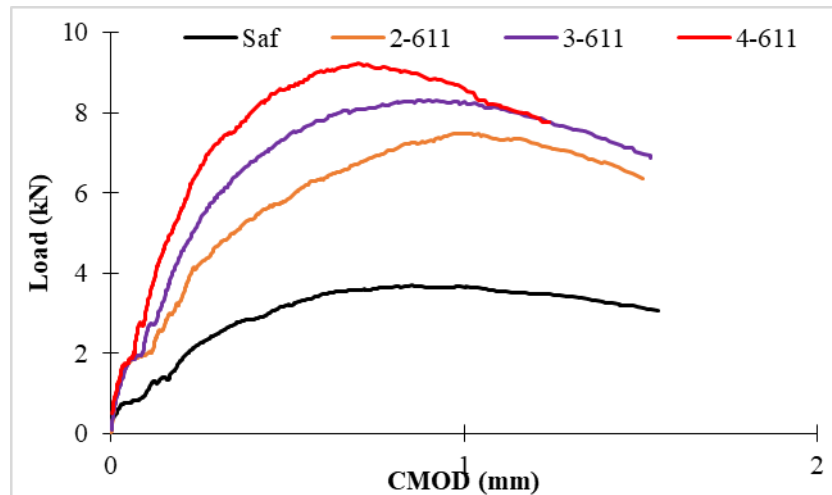
The SCB test results obtained at 20°C clearly demonstrated that the incorporation of Enprene 611 elastomer significantly enhanced the load-carrying capacity and crack initiation resistance of the asphalt mixtures, regardless of notch depth. For the specimens with a 10 mm notch, the neat HMA mixture exhibited a maximum fracture load of 4.85 kN. Incorporating 2%, 3%, and 4% Enprene 611 increased the maximum fracture load to 8.70 kN, 9.60 kN, and 11.90 kN, respectively. Among all mixtures, the specimen containing 4% Enprene 611 exhibited the highest mechanical performance, corresponding to an approximately 145% increase in fracture load compared with the neat HMA mixture. As the notch depth increased from 10 mm to 20 mm and 30 mm, a gradual reduction in the maximum fracture load was observed for all mixtures owing to the decrease in the effective load-bearing cross-sectional area. Nevertheless, despite this geometric reduction in the net ligament area, the beneficial effect of polymer modification remained evident. Even for the specimens with a 30 mm notch, the mixture modified with 4% Enprene 611 exhibited a load-carrying capacity more than three times greater than that of the neat HMA specimen (2.60 kN), demonstrating the effectiveness of the elastomer in improving fracture resistance under severe crack conditions.

The influence of elevated temperature became more pronounced during the SCB tests conducted at 40°C. Owing to the viscoelastic nature of the asphalt binder, increasing the test temperature significantly reduced both the stiffness and maximum fracture load of all HMA mixtures compared with those tested at 20°C. The maximum fracture load of the neat HMA specimen with a 10 mm notch decreased from 4.85 kN to 2.70 kN. Furthermore, the neat specimen containing a 30 mm notch, which represented the most critical notch geometry, exhibited the lowest fracture load of only 0.80 kN, indicating that the asphalt mixture became considerably more susceptible to crack propagation under elevated-temperature conditions. In contrast, modification with Enprene 611 elastomer remarkably improved the high-temperature stability and cohesive strength of the asphalt matrix. Under the test condition of 40°C with a 10 mm notch, the specimen containing 4% Enprene 611 achieved a maximum fracture load of 8.35 kN, corresponding to an approximately 209% increase compared with the neat

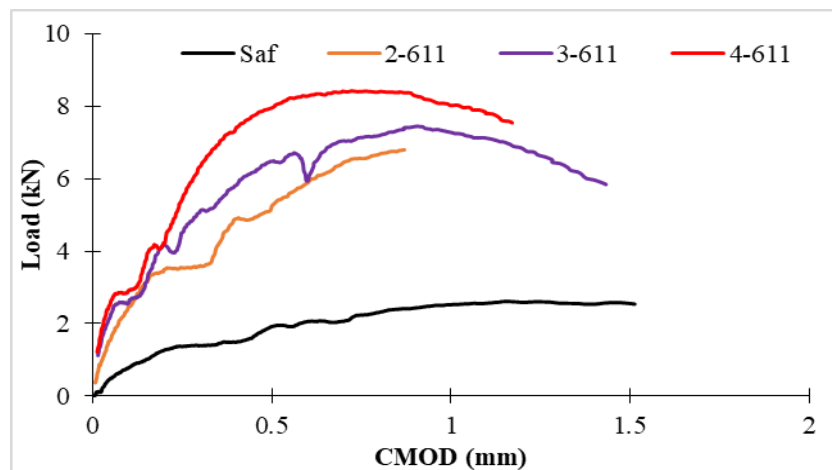
HMA mixture. Even under the most severe testing condition (40°C and a 30 mm notch), the 4% Enprene 611-modified specimen sustained a fracture load of 5.50 kN, which was nearly seven times greater than that of the neat HMA specimen (0.80 kN). These findings suggest that the three-dimensional polymer network formed by Enprene 611 effectively enhanced the aggregate–binder interaction and delayed the transition of microcracks into macrocracks, thereby significantly improving the fracture resistance of the asphalt mixtures under elevated-temperature conditions.



Load-CMOD Curve of the HMA Mixtures with a 10 mm Notch Depth

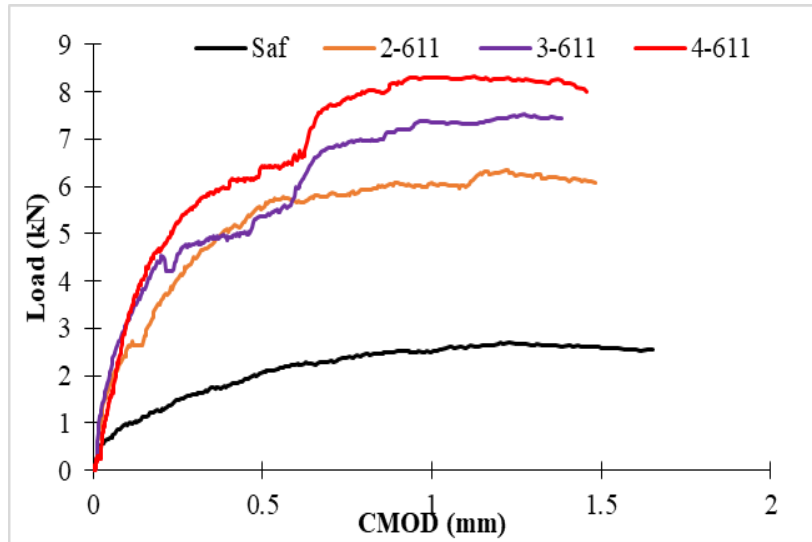


Load-CMOD Curve of the HMA Mixtures with a 20 mm Notch Depth

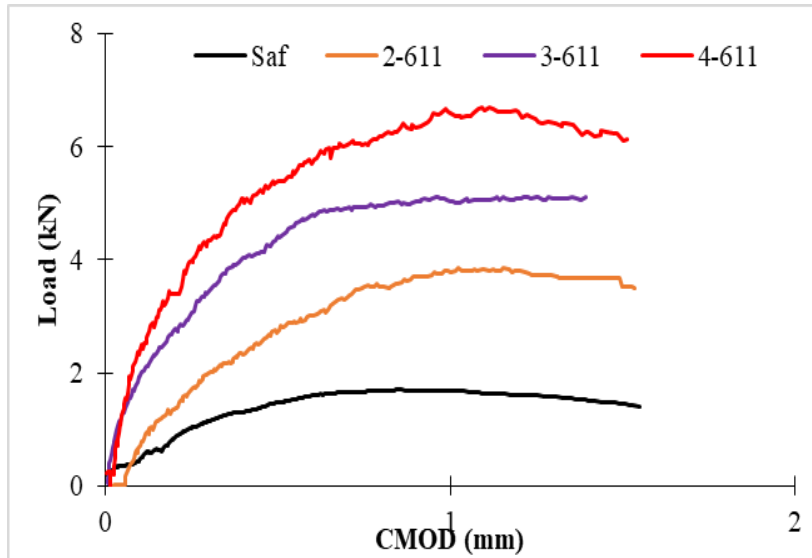


Load-CMOD Curve of the HMA Mixtures with a 30 mm Notch Depth

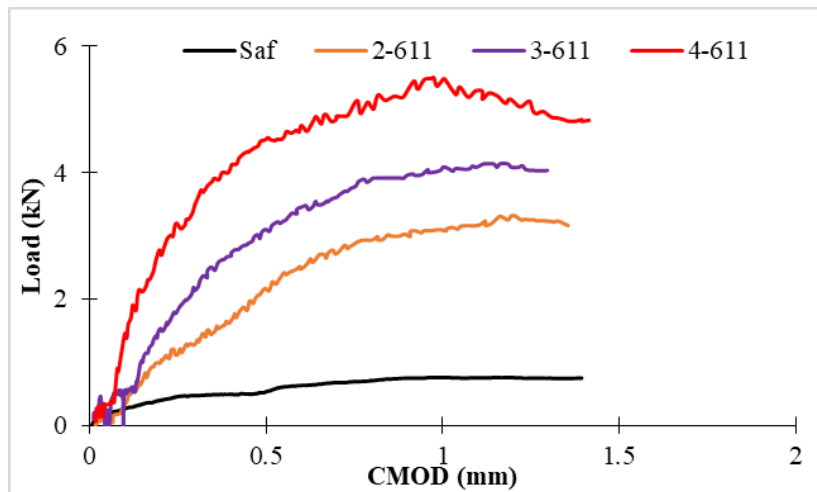
Figure 3. Load-CMOD Curves of HMA Mixtures with Different Notch Depths at 20°C



Load-CMOD Curve of the HMA Mixtures with a 10 mm Notch Depth



Load-CMOD Curve of the HMA Mixtures with a 20 mm Notch Depth



Load-CMOD Curve of the HMA Mixtures with a 30 mm Notch Depth

Figure 4. Load-CMOD Curves of HMA Mixtures with Different Notch Depths at 40°C

Conclusion

Based on the experimental findings obtained from the Semi-Circular Bending (SCB) tests, the following conclusions can be drawn:

Enprene 611 elastomer modification significantly improved the crack propagation resistance of the Hot Mix Asphalt (HMA) mixtures at both ambient (20°C) and elevated (40°C) temperatures across all notch geometries. The improvement became more pronounced with increasing polymer content. Among all experimental conditions, the HMA mixtures containing 4% Enprene 611 exhibited the highest crack resistance and load-carrying capacity, demonstrating the superior reinforcing effect of the elastomer within the investigated dosage range.

Increasing the notch depth from 10 mm to 30 mm reduced the maximum fracture load due to the decrease in the effective load-bearing cross-sectional area. Nevertheless, Enprene 611 modification effectively preserved the structural integrity of the asphalt matrix and mitigated brittle fracture, even under the most critical notch geometry.

Increasing the test temperature from 20°C to 40°C resulted in a noticeable reduction in fracture resistance owing to the thermal softening of the asphalt binder. However, the incorporation of Enprene 611 significantly enhanced the high-temperature stability of the asphalt mixtures by limiting viscous flow, thereby improving their resistance to permanent deformation and thermally induced cracking.

Overall, the findings of this study demonstrate that Enprene 611 is a promising polymer modifier for improving the fracture performance and long-term durability of Hot Mix Asphalt mixtures, providing valuable insights for the development of more durable and sustainable flexible pavement systems.

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.

Funding

* This study was supported by the Fırat University Scientific Research Project Management Unit (FUBAP) under Project No. MF.26.83. The authors would like to acknowledge the financial support provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under Project No. 123M648, as well as the support received through the TÜBİTAK 2224-B Domestic Scientific Event Participation Support Program.

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Basic Sciences, Engineering and Technology (www.icbaset.net) held in Istanbul/Türkiye on September 17-18, 2026.

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To cite this article:

Bakir, E. & Yalcin, E. (2026). Evaluation of the crack resistance of hot mix asphalt mixtures modified with enprene 611 elastomer. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM)*, 42, 11–18.