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Semi-circular bend – based extended finite element modeling analysis of epoxy asphalt fracture behaviour under variable temperatures

Shuwen Zhang[1], Ince Mutolo Mumba[1*]

[1] Department of Civil Engineering, Zhengzhou University, Henan, China
* Corresponding author's e-mail: ince246mumba@gmail.com

ABSTRACT

Cracking in asphalt pavements remains a significant challenge in road infrastructure worldwide. Epoxy asphalt concrete (EAC), known for its superior mechanical properties compared to conventional asphalt mixtures, is commonly used in high-performance applications such as bridge decks and airport runways. Understanding the fracture behavior of EAC across a range of temperatures is essential for optimizing pavement design and performance. This study employs a 2D semi-circular bend (SCB) simulation using Abaqus, incorporating extended finite element modeling (XFEM), to evaluate the fracture response of EAC at four different temperatures: −15 °C, −5 °C, 5 °C and 15 °C. The results show that peak load capacity decreases from 8,625.79 N at −15 °C to 4,099.57 N at 15 °C, while peak displacement increases from 1.07 mm to 2.73 mm, indicating a shift from brittle to ductile behaviour. These results emphasize the importance of accounting for thermal effects in fracture design and demonstrate XFEM's capability to accurately model temperature-sensitive crack propagation in epoxy asphalt concrete. This property can be useful in design scenarios where flexibility is needed to accommodate thermal or traffic-induced strain.

Keywords: XFEM, SCB test, epoxy asphalt concrete, fracture behavior, Abaqus.

INTRODUCTION

In China, epoxy asphalt concrete is widely used as a pavement material for steel bridge decks due to its excellent mechanical and thermal stability (1). However, fatigue cracking is one of the most prevalent forms of damage in such pavements (2). Stress concentrations develop at the crack tips under repeated loading, which accelerates crack propagation and may ultimately compromise the integrity of the entire bridge deck system. Recent studies have shown that some EAC layers are especially vulnerable to cracking under cyclic loads, particularly in cold environments (1).

The tough-brittle transition temperature of raw materials like steel and asphalt has been the subject of the majority of research on the subject, and the tough-brittle transition temperature of epoxy asphalt mixture has not been examined (1). Furthermore, based on the research findings, the design theory for epoxy asphalt mixture cracking resistance is still not flawless, and the research instruments require further development. Some study results design the epoxy asphalt mixture cracking resistance is not ideal, and the real engineering usage of a certain difference (3). The epoxy asphalt binder is a two-phase chemical system, with a thermosetting epoxy in the continuous phase and a combination of specialty asphalt and epoxy cross-linker in the discontinuous phase (4). Fuel resistance, water stability, anti-cracking, and high temperature stability are all provided by the thermosetting epoxy binder for EAC (5).

To simulate the fracture behaviour of EAC, this study employs the extended finite element method (XFEM) in Abaqus, a proven numerical technique effective in modelling crack propagation and other discontinuities in materials (6). The cracking process was modelled through SCB tests at multiple temperatures, and the load-displacement behaviour was analysed to understand the material's thermorheological response.

LITERATURE REVIEW

Epoxy asphalt concrete (EAC) is a high-performance pavement material known for its excellent fatigue resistance, rutting resistance, and durability under traffic loads (7). Its unique composition – combining thermosetting epoxy resin with conventional asphalt – yields superior mechanical performance compared to traditional hot mix asphalt (8). However, the mechanical response of EAC is highly temperature-dependent; at low temperatures it tends to exhibit brittle failure, while at higher temperatures it behaves in a more ductile manner (9).

Experimental investigations have provided insights into this temperature-sensitive behavior, especially through tests such as the semi-circular bending (SCB) test (10). For instance, Zhang et al., 2023 reported that the fracture toughness and fracture energy of epoxy asphalt mixtures vary significantly across different temperature regimes (1). Nonetheless, such experiments are often resource-intensive and time-consuming, limiting their practicality for parametric or sensitivity studies.

To overcome these limitations, numerical methods like the extended finite element method (XFEM) have emerged as powerful tools for fracture simulation (11). XFEM enables the modeling of crack initiation and growth without the need for remeshing, making it ideal for problems involving discontinuities (12). Its application in asphalt research has gained traction in recent years (13). Lou et al., 2023 employed XFEM to simulate thermally induced cracking in flexible pavements, demonstrating the method's ability to capture complex fracture behavior under thermal stresss (14).

Despite these advancements, the use of XFEM for simulating the fracture behavior of EAC remains underexplored, especially in studies lacking experimental validation. Existing XFEM-based studies primarily focus on traditional hot mix asphalt (HMA) systems or rely on laboratory data for calibration. Consequently, there is a critical research gap in applying SCB-based XFEM modeling to simulate epoxy asphalt fracture under variable thermal conditions using entirely numerical frameworks. This study addresses that gap by developing a temperature-dependent XFEM model to simulate crack evolution in epoxy asphalt, offering a computational approach to assess its fracture performance across a range of temperatures.

SCB TEST SETUP IN ABAQUS

The SCB simulation was implemented in Abaqus 2023 using a 2D plane strain model with the XFEM to simulate crack initiation and propagation. The model setup is based on the AASHTO TP105 standard with modifications suitable for numerical simulation.

Geometry and dimensions and material properties

The SCB specimen is modelled as a semi-circular disk with the following dimensions:

- Radius (R): 75 mm
- Thickness (t): 50 mm (used as out-of-plane depth for post-processing energy)
- Initial notch depth (a): 25 mm
- Support span (distance between rollers): 2 s = 60 mm

The notch is centrally located at the flat edge of the semi-circle. A reference point is created at the top of the specimen to apply the vertical displacement, simulating loading via a loading pin (Figure 1 and Table 1).

XFEM implementation

The SCB model utilized the built-in XFEM module in Abaqus 2023 to simulate crack initiation and propagation without predefined paths. The mesh was constructed using CPS4R (4-node bilinear plane strain) elements, with two degrees of freedom per node. Geometric nonlinearity was enabled. Crack initiation was defined using the maximum principal stress criterion, while crack growth followed a damage evolution law based on fracture energy.

The phase-field level set method (PHILSM), as shown in Figure 3, was used to track crack development spatially within the XFEM framework. The model was analyzed under quasi-static

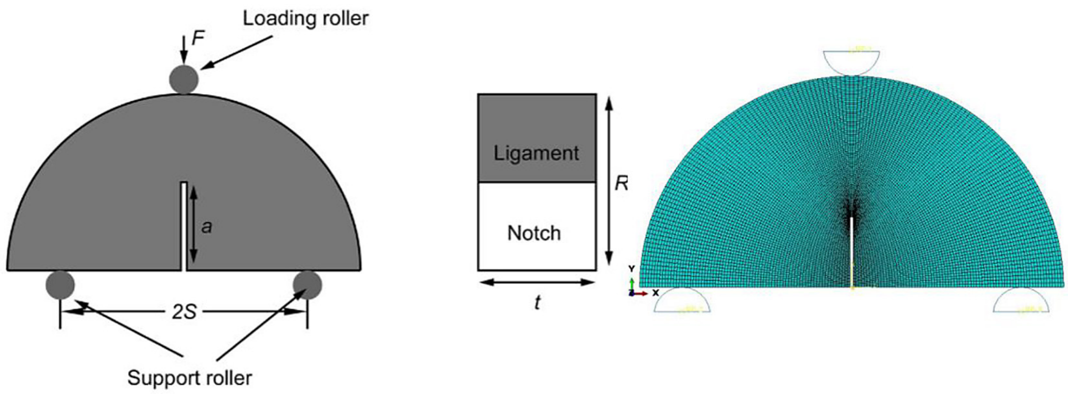

Figure 1. Geometry and boundary setup for the SCB model in Abaqus. The semi-circular disk (R = 75 mm, notch depth = 25 mm, thickness = 50 mm) is supported at two points (span = 60 mm), with load applied vertically at the top centre

Table 1. Parameters of epoxy asphalt material at different temperatures

Temperature (°C)	Elastic modulus (MPa)	Critical tensile strength (MPa)	Fracture energy (N·m^{-1})
−15	3165	7.19	444
−5	1982	6.49	610
5	989	4.66	1536
15	459	2.72	2180

loading, with temperature-specific material properties assigned for each case. Due to the brittle-elastic nature of EAC at lower temperatures, only linear elastic material definitions were used, as validated in previous fracture simulations. Although temperature-dependent properties were considered through elastic modulus and fracture energy variations, thermal expansion or heat transfer effects were not included, which is noted as a limitation.

RESULTS AND DISCUSSION

Crack evolution process

Using XFEM in Abaqus, Figure 2 shows the crack propagation process of the EAC specimen at 15 °C. The simulation successfully captures important stages: (a) crack initiation occurs at the notch tip as the maximum principal stress criterion is met; (b) crack propagation follows an unpredictable path, demonstrating the advantage of XFEM in handling discontinuities without predefining crack trajectories; and (c) complete fracture occurs as the crack reaches the boundary, resulting in loss of load-carrying capacity. These stages demonstrate that XFEM can accurately model both the initiation and unstable growth of cracks in quasi-brittle materials like EAC.

Figure 3 shows the PHILSM contour plots representing full crack propagation at different temperatures. The crack path remains relatively straight at −15 °C and −5 °C due to the brittle fracture mode, while more curved or diffuse crack paths appear at 5 °C and 15 °C, indicating ductile fracture behaviour.

Load displacement behavior

The load–displacement curves for EAC at -15 °C, -5 °C, 5 °C, and 15 °C are shown in Figure 4, where several significant patterns are noted:

- Peak Load – as the temperature rises, the maximum load falls. The specimen can support a maximum load of 8,625.788 N at -15 °C, which decreases to about 4099.565 N at 15 °C. This decrease is explained by the temperature-dependent decrease in EAC's tensile strength and stiffness.
- Peak Displacement – the displacement at which peak load occurs rises from 1.066 mm at −15°C to 2.733 mm at 15 °C. This demonstrates higher deformation before failure as temperature rises, implying increased ductility at hotter temperatures.

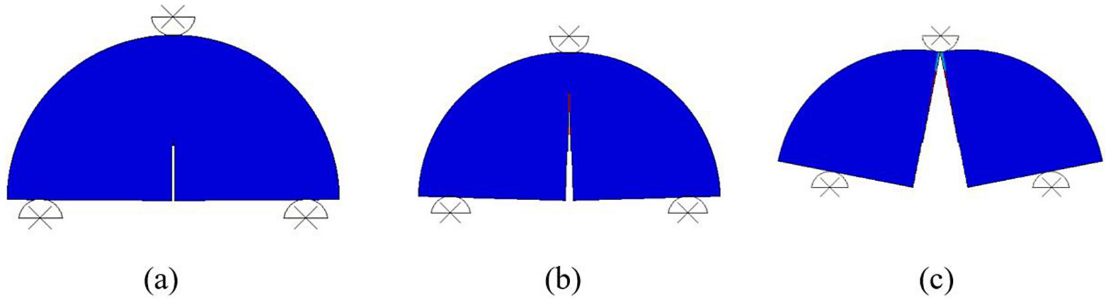

Figure 2. Crack evolution stages in the SCB simulation using XFEM in Abaqus of EAC at 15 °C: (a) crack initiation; (b) crack propagation; (c) full crack propagation and fracture

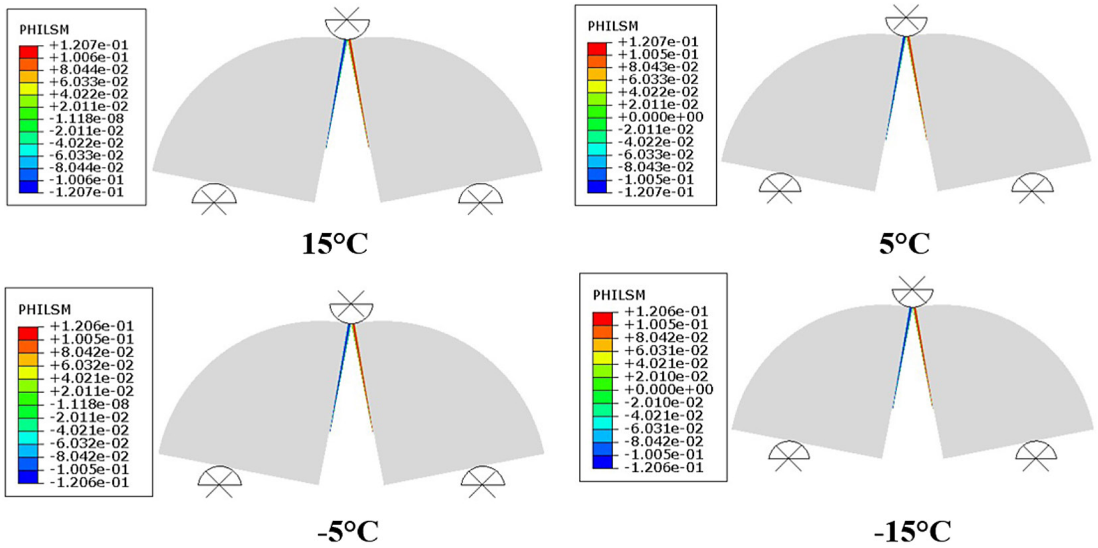

Figure 3. Full crack propagation and fracture of EAC at different temperatures (PHILSM Contour)

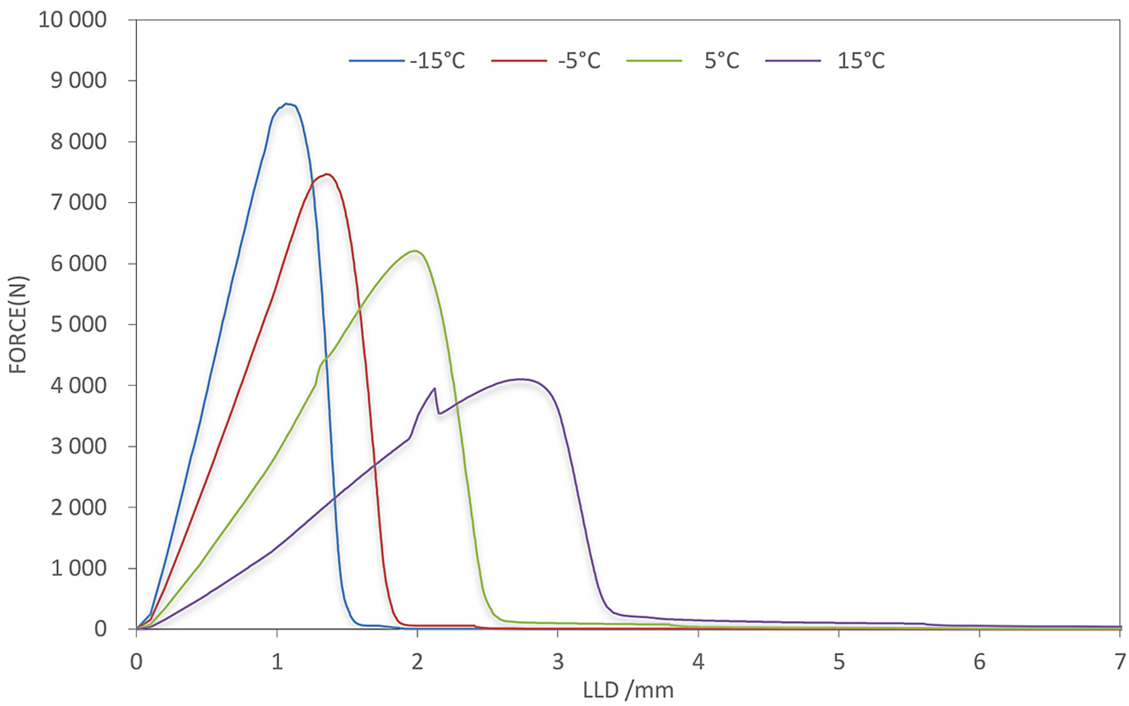

Figure 4. Load-Displacements curves of EAC from XFEM-SCB simulations at different temperatures

Table 2. SCB test summary of epoxy asphalt concrete at various temperatures

Temperature (°C)	Peak load (N)	Peak displacement (mm)	Fracture mode	Post-peak ductility
−15	8,625.788	1.066	Brittle	Very Low
−5	7468.793	1.351	Brittle	Low
5	6208.367	1.984	Semi-ductile	Moderate
15	4099.565	2.733	Ductile	High

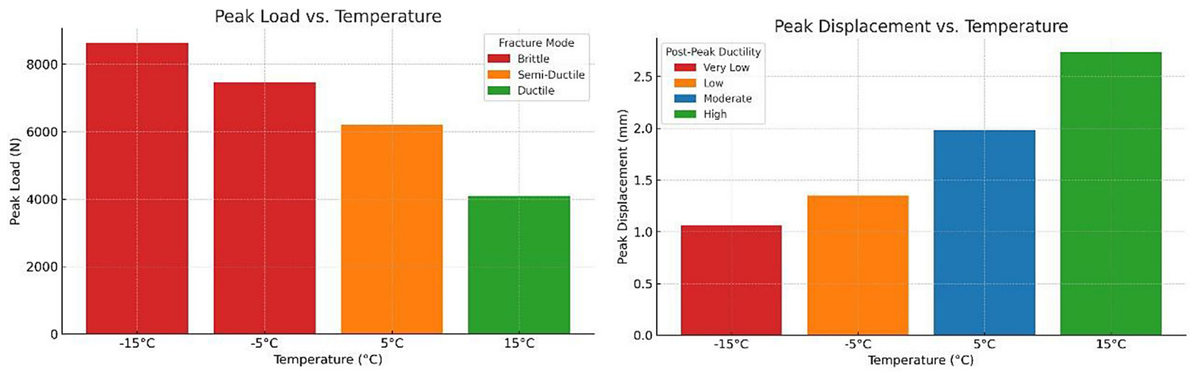

Figure 5. Shows the trends of peak loads and peak displacements at various temperatures

Table 3. Influence of temperature on key mechanical indicators

Parameter	Trend with increasing temperature
Peak load	Decreases
Peak displacement	Increases
Fracture energy	Increases
Brittleness	Decreases
Ductility	Increases

Fracture mode and post-peak behaviour

As illustrated in Figure 4, the load–displacement curves demonstrate a clear transition in fracture behaviour with temperature. At lower temperatures (−15 °C and −5 °C), the curves exhibit a steep and abrupt drop following the peak load, characteristic of brittle fracture with negligible

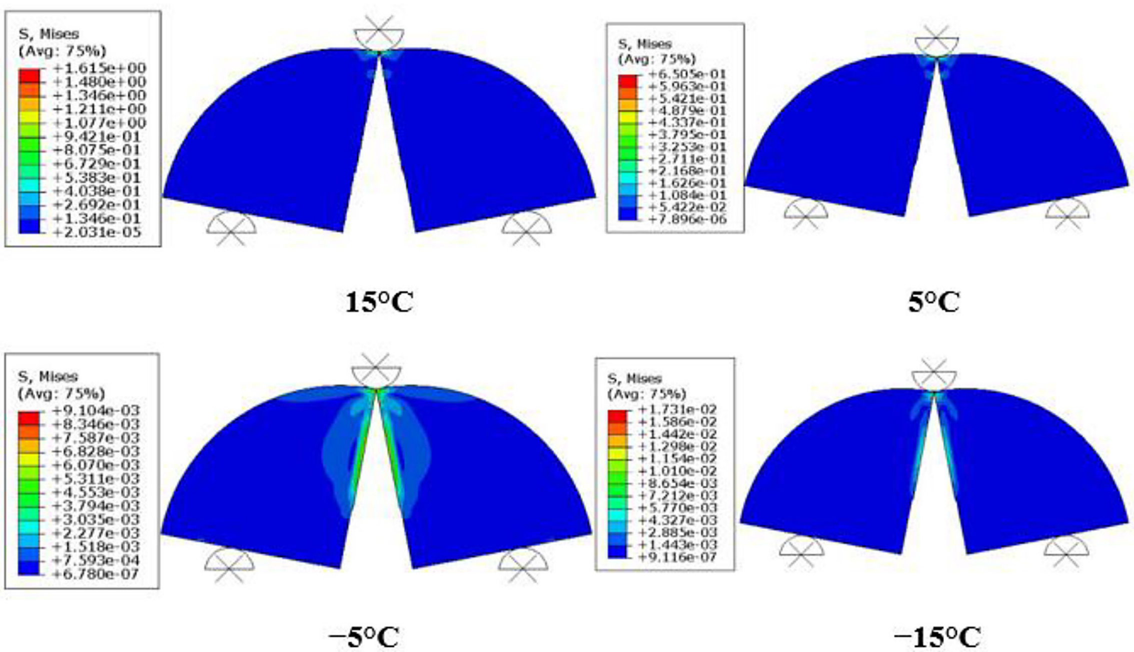

Figure 6. von Mises stress distribution in SCB specimens of epoxy asphalt at various temperatures

post-peak deformation. The short tail length of the curve in these cases indicates limited crack growth resistance and low energy dissipation after failure initiation.

In contrast, at elevated temperatures (5 °C and especially 15 °C), the curves show a more gradual post-peak decline. This is accompanied by a longer tail, signifying enhanced ductility, extended crack propagation, and increased fracture energy absorption. The extended tail length at 15 °C, in particular, suggests the material can sustain more deformation after crack initiation before complete failure. The kink observed at 15 °C in the load–displacement curve (Figure 4) may be attributed to local crack tip blunting and increased material ductility. The material at this temperature undergoes stable crack propagation with energy absorption, resulting in a more complex post-peak behaviour compared to abrupt failure seen at colder temperatures. These differences emphasize the strong influence of temperature on the fracture response of epoxy asphalt concrete. A summary of the key fracture parameters across the temperature range is provided in Table 2 and Figure 5. Table 3 shows how temperatures affect the key mechanical indicators of EAC.

Figure 6 displays the von Mises stress distribution for each case. At lower temperatures, stress is highly concentrated near the notch, promoting abrupt failure. As temperature increases, stress redistributes more gradually across the specimen, supporting a more progressive crack propagation and energy dissipation.

CONCLUSIONS

The XFEM-based SCB simulations conducted in this study demonstrate that epoxy asphalt concrete exhibits a strong dependency on temperature with respect to its fracture behavior, consistent with observations reported in previous literature. The results confirm a transition from brittle fracture at lower temperatures (−15 °C and −5 °C) to ductile behavior at higher temperatures (5 °C and 15 °C), as evidenced by increasing peak displacements, rising fracture energy, and softening post-peak response.

These findings underscore the critical need to account for service temperature in pavement fracture design. XFEM effectively captured temperature-induced transitions in crack behavior and enabled simulation of realistic fracture processes without predefined paths. This research provides a foundational framework for thermally sensitive fracture modeling of EAC in transportation infrastructure.

However, the study is limited by its 2D plane strain approximation, assumption of elastic behavior, and lack of experimental validation. Future studies should incorporate 3D modeling, viscoelastic properties, and physical SCB testing at varying temperatures to validate and expand upon these findings.

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REFERENCES

1. Zhang S, Nie W, Sha A, Li W, Jiang W. Ductile–brittle transition temperature of epoxy asphalt concrete of steel bridge deck pavement based on impact toughness. Advances in Materials Science and Engineering. 2023;2023(1):4691529.
2. Zhang M, Qian Z, Xue Y, editors. Research on fracture performance of epoxy asphalt concrete based on double-K fracture criterion. IOP conference series: materials science and engineering; 2017: IOP Publishing.
3. Fan Y, Chen H, Yi X, Xu G, Cai X, Zhou Y, et al. Cracking resistance evaluation of epoxy asphalt mixtures with 100% reclaimed asphalt pavement (RAP). Construction and Building Materials. 2023;395:132320.
4. Yang S, Li R, Zhu H, Qin Y, Huang C. Review of the state-of-the-art techniques for enhancing the toughness of thermosetting epoxy asphalt. Construction and Building Materials. 2024;449:137660.
5. Cong P, Liu N, Shang H, Zhao H. Rheological and fatigue properties of epoxy asphalt binder. International Journal of Pavement Research and Technology. 2015;8(5):370.
6. Pirmohammad S, Ayatollahi MR, Pirmohammad S, Ayatollahi MR. Numerical Studies on Asphalt Concretes. Fracture Behavior of Asphalt Materials. 2020:17–76.

7. Chen Y, Hossiney N, Yang X, Wang H, You Z. Application of epoxy - asphalt composite in asphalt paving industry: a review with emphasis on physicochemical properties and pavement performances. Advances in materials science and engineering. 2021;2021(1):3454029.
8. Yin H, Jin H, Wang C, Sun Y, Yuan Z, Xie H, et al. Thermal, damping, and mechanical properties of thermosetting epoxy-modified asphalts. Journal of Thermal Analysis and Calorimetry. 2014;115:1073–80.
9. Huang W, Guo W, Wei Y. Prediction of paving performance for epoxy asphalt mixture by its time-and temperature-dependent properties. Journal of materials in civil engineering. 2020;32(3):04020017.
10. Chen X, Li H, Qian Z. On the fracture properties of epoxy asphalt mixture with SCB test. Advanced Testing and Characterization of Bituminous Materials, Two Volume Set: CRC Press; 2009;547–56.
11. Torabi A, Majidi H, Amani H, Akbardoost J. Implementation of XFEM for fracture prediction of VO-notched brittle specimens. European Journal of Mechanics-A/Solids. 2020;81:103970.
12. Zeng G, Zhou P, editors. Research on fracture parameters of asphalt mixture based on XFEM and J Integral method. Journal of Physics: Conference Series; 2021: IOP Publishing.
13. Alkaissi Z, editor Modelling of crack propagation in flexible pavement using X-FEM method. IOP Conference Series: Earth and Environmental Science; 2022: IOP Publishing.
14. Lou L, Xiao X, Li J, Xiao F. Thermal-mechanical coupled XFEM simulation of low temperature cracking behavior in asphalt concrete waterproofing layer. Cold Regions Science and Technology. 2023;213:103910.
15. Qian Z-d, Hu J. Fracture properties of epoxy asphalt mixture based on extended finite element method. Journal of Central South University. 2012;19(11):3335–41.