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# Extended FEM modelling of crack propagation using the semi-circular bending test

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## HIGHLIGHTS

- The semi-circular bend test was modelled using the extended finite element method.
- Small asphalt specimens were used to determine viscoelastic asphalt properties.
- Fractional calculus was used to model creep and relaxation of asphalt.
- Mode I crack propagation was successfully modelled.
- Good correlation was found between model predictions and laboratory experiments.

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## ABSTRACT

The semi-circular bend (SCB) test has been frequently utilised due to its straightforward sample preparation, ease of test execution and applicability to studies of asphalt crack resistance. Further, the eXtended Finite Element Method (XFEM) is particularly well suited to the modelling of discontinuous features such as inclusions and cracks. In this regard, an XFEM model of the SCB test is developed herein to model crack propagation and the results are compared to laboratory SCB testing of unmodified and polymer modified asphalts. To capture the time dependant viscoelastic properties of asphalt within the XFEM model, a fractional viscoelastic element is successfully used in place of traditional springs and dashpots. Inter-conversion between creep and relaxation is accomplished by use of fractional calculus, and is validated by comparison with laboratory results where higher stiffness and enhanced elasticity are observed with increasing polymer content. The results presented in this paper demonstrate the truly promising opportunities offered by the XFEM in conjunction with a fractional calculus framework for modelling cracking in asphalt efficiently.

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## 1. Introduction

Cracking of asphalt pavements is a significant failure mechanism for pavement engineers to contend with as it affects the ride quality and the long term durability of the pavement. Especially if the cracks are present in layers below the binder course then the cost of repairing the structure would be high. Therefore, a thorough understanding of the binder and mixture properties and their influence on cracking is crucial during pavement design, with the temperature and time dependent nature of asphalt further complicating the analysis.

Many practical laboratory tests have been utilised to assess the fracture properties of asphalt such as the two, three, and four-point bending tests, the disk-shaped compact tension test (DCT), the indirect tension (IDT) test, and the semi-circular bending test (SCB). The SCB geometry is practically more conducive to testing laboratory and field specimens than traditional beams. As a consequence it has been successfully applied to the analysis of rock [1], ice [2], and asphalt [3], and for asphalt, it has been formalised in an EU testing protocol [4]. Compared to traditional beam testing, the SCB geometry has a short span, and the more complex geometry and loading pattern introduces problems with boundary conditions. However, repeatability and reproducibility data [4] has demonstrated that the test has analytical value, and the relative ease of sample preparation from using cores rather than beams encourages further use of the SCB approach.

As part of the evaluation by Molenaar et al. [3] the Finite Element Method (FEM) was used to examine the stresses within the SCB specimen. Their modelling demonstrated that failure was

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primarily due to fracture and hence, the laboratory test results would be valuable in gauging asphalt fracture resistance. Many practical studies using the SCB geometry have since been performed under both monotonic and cyclic loadings [5–11]. Linear elastic fracture mechanics (LEFM) is limited to the study of materials with a small fracture process zone (FPZ) located at the crack tip. Asphalt is a heterogeneous quasi-brittle viscoelastic material and, within a cracking asphalt specimen, the FPZ is relatively large compared to brittle elastic materials. In order to resolve this, researchers have successfully applied cohesive zone modelling to produce FEM models of cracking in asphalt [12–16].

Most previous models adopted the classical FEM approach to depict cracking in asphalt. However, extensions of FEM developed to model discontinuous features, such as cracks and inclusions, have been recently employed to investigate asphalt crack initiation and propagation. For instance, Ozer et al. [17] used the generalised finite element method (GFEM) to investigate crack development under repeated wheel loading. Further, Peng et al. [18] applied the related eXtended finite element method (XFEM) to model crack propagation in a notched three point bending beam under fatigue loading conditions. The capability of XFEM to propagate cracks without re-meshing operations and to allow the crack to propagate in any direction based on the physics of the model makes this approach particularly efficient for asphalt crack modelling. Recently, XFEM has been used to model the mode I and II stress intensity factors and crack propagation paths of the SCB geometry [19].

As bitumen and asphalt are time dependent viscoelastic materials, it is essential to include these features in any dynamic model of their behaviour. Multiple combinations of springs and dashpots are traditionally used to create models of creep behaviour requiring a large number of model coefficients, which can be demanding to identify and handle. Recently, alternative viscoelastic models based on a fractional calculus framework have been proposed [20,21], which provide a more physically realistic model for material behaviour whilst requiring only two parameters to be identified.

FEM is widely used in engineering but encounters difficulty in modelling discontinuous elements such as cracks or inclusions. To model cracking in FEM, cohesive zone (CZ) element edges must be aligned with the crack path and the mesh must be refined around the crack tip to resolve the singularities that can occur in the model solution. This approach may lead to unrealistic crack propagation if the incorrect elements were included in the crack path, and a high computational demand as the crack path and crack tip would need to be continually remeshed as the crack propagates. To overcome these problems, the XFEM was developed by researchers [22,23] through use of the partition of unity [24] to produce a model where the crack location and propagation is independent of the mesh. The finite element nodes within the domain close to the discontinuity of interest, such as a crack, are enriched with additional degrees of freedom and shape functions which allow the state of the discontinuity to be modelled. Thus, the need is obviated for complex re-meshing adopted in traditional FEM crack propagation analysis, as shown in Fig. 1. The XFEM crack is then able to follow any arbitrary solution dependant path within the bulk of the material leading to a more physically realistic and versatile modelling approach. This makes XFEM particularly suitable for the modelling of asphalt, which often has complex geometries and loading patterns.

Specifically, the displacement vector field $\vec{u}$ in traditional FEM is defined as

$$\vec{u} = \sum_{i=1}^{N} N_i(x)\vec{u}_i \tag{1}$$

where $i$ is the set of all nodes in the domain, $N_i$ is the standard finite element shape function of node $i$, and $\vec{u}_i$ are the nodal displacement vectors.

To model a crack using XFEM additional enriched nodes are introduced as

$$\vec{u} = \sum_{i=1}^{N} N_i(x)\left[\vec{u}_i + H(x)\vec{a}_i + \sum_{\zeta=1}^{4} F_\zeta(x)\vec{b}_i^{\zeta}\right] \tag{2}$$

where $H(x)$ is the is the Heaviside function with value +1 on one side of the crack and $-1$ on the other, $\vec{a}_i$ and $\vec{b}_i^{\zeta}$ are vectors of additional nodal degrees of freedom, and $F_\zeta(x)$ is the elastic asymptotic crack-tip function.

This paper aims to utilise the advances of XFEM to model asphalt cracking in the SCB geometry. In combination with XFEM, it is aimed to capture asphalt's time dependency using a fractional viscoelastic element requiring only two parameters to model both the creep and relaxation of the asphalt. Polymer modified asphalt is often used to mitigate pavement cracking. Therefore, the effect of polymer modification on the creep and XFEM models is also explored.

## 2. Materials and methods

For the asphalt tests, an AC10 close surface course [25] recipe mixture was used as shown in Fig. 2, with limestone aggregate from the UK used to produce samples. All base binders were 50/70 penetration grade of Venezuelan origin, with the modified binders produced by the addition of a linear SBS polymer, with the binder physical properties reported in Table 1.

To produce the test specimens, a 150 mm diameter by approximately 120 mm high gyratory core was produced to the design target air void content. Each core was then sawn to produce two test samples of 150 mm diameter by 50 mm in height. The indirect tensile stiffness modulus (ITSM) of each core was measured in indirect tension (IT-CY) at 20 °C according to European Standard 12697-26 annex C. This test is standard in the UK as part of the QC process for HMA production. Each core was then halved to produce two semi circular samples, which were notched as

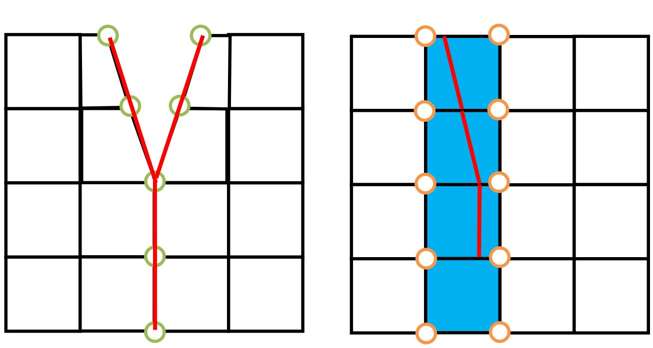

**Fig. 1.** Schematic of crack propagation modelling in FEM with CZ elements (left) and XFEM with enriched nodes (right).

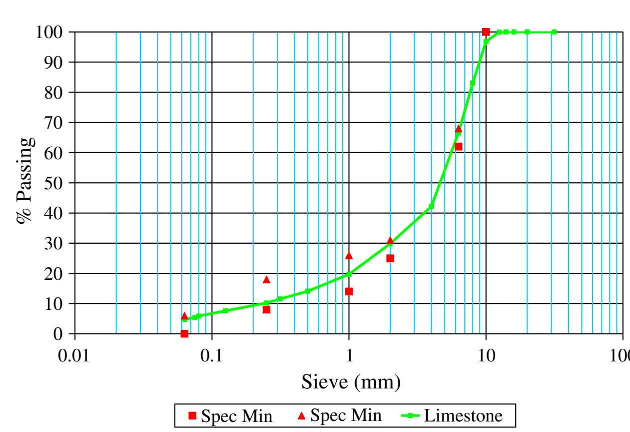


**Fig. 2.** "AC10 Close surface course" grading curves (PD6691 T B.14).

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