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Fracture damage evaluation of asphalt mixtures using Semi-Circular Bending test based on fracture energy approach

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ABSTRACT

This research investigated fracture damage of conventional dense and modified gap- and open-graded asphalt mixes using Semi-Circular Bending test. Fracture damage parameters were formulated and deduced from load-crack mouth opening displacement relationship and used to estimate fracture damage based on Elastic Plastic Fracture Mechanics. Dissipated energy for modified mixes were 1.5–2 times greater than conventional mixes. Damage parametric models were developed based on material properties' energy based behaviour. It was clearly found that Semi-Circular Bending test is a truly promising quality control tool, and the Elastic Plastic Fracture Mechanics concept is a potential numerical approach towards comprehensively understanding fracture mechanism.

1. Introduction

Fatigue cracking phenomenon is one of the most challenging distresses in flexible pavements due to its complexity during performance prediction. Heterogeneous matrix, nonlinear viscoelastic material properties, wide range of temperatures and loading conditions, and stress dependent rheology of asphalt binders and mixtures have posed complications to deal with this problem using simple analyses and techniques. Therefore, the basic approach to comprehensively address the cracking associated problems in the ambit of flexible pavements is through fracture mechanics. In this context, fundamental underlying principles illustrate that if energy stored near the crack tip exceeds the crack resistance of the material, then cracking initiates in the vicinity of the crack tip. Research studies [1–6] have investigated asphalt cracking phenomenon and associated material properties mainly using Linear Elastic Fracture Mechanics (LEFM) concept. In LEFM, crack initiation starts with the Fracture Plastic Zone (FPZ) in the vicinity of the crack tip (or weak zone), which is produced by plastic deformation in the material. FPZ for an elastic material is generally smaller in magnitude and does not contribute much during fracture analysis process. However, in the case of asphaltic material that is quasi-brittle, fracture process is mainly governed by FPZ that has higher magnitude, thereby, questioning the applicability of LEFM to explain cracking phenomenon accurately.

In another direction, several attempts are ongoing to investigate cracking mechanism using Elastic Plastic Fracture Mechanics (EPFM) through experiments and numerical approach [7–18]. Fracture energy release rate (also called *J* integral) and stiffness are being used as candidate parameters to explain fatigue cracking in asphalt mixes. In the last few years, Semi-Circular Bending (SCB) test has received significant attention since it offers a great deal of flexibility in terms of repeatability, consistency, and simplicity to estimate fracture resistance of asphalt mixes. Many researchers [2–9,11–13, 15–25] have used SCB test to assess fracture resistance of asphalt materials using fundamental fracture mechanics

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Nomenclature

ζ	$= \frac{3/4^{th}\ Damage}{Half\ Damage}$
ξ	$= \frac{Full\ Damage}{Half\ Damage}$
ρ_{200}	percentage of aggregates passing through sieve no. 200, %
ρ_{38}	percentage of aggregates retained on sieve on 3/8 in. sieve, %
V_{beff}	effective binder content, %
VFA	volume filled with asphalt, %
VMA	volume of mineral aggregates, %
η	viscosity of asphalt binder, centipoise (cP)
T	temperature, degree Celsius
Rubber	percentage of rubber, %
Polymer	percentage of polymer, %
K_{IC}	fracture toughness, N/mm$^{3/2}$
α and β	fracture damage parameters
E	modulus of the material, MPa
μ	Poisson's ratio of material
J_{IC}	critical fracture energy
SCB	semi-circular bending
LEFM	linear elastic fracture mechanics
EPFM	elastic plastic fracture mechanics
FPZ	fracture plastic zone
CMOD	crack mouth opening displacement

parameters. These parameters include fracture toughness, stress intensity factor, stiffness, compliance, fracture energy, and J integral using LEFM and EPFM concepts. Based on the success of using SCB test effectively in asphalt mix fracture characterization, the methodology has become a full-fledged European standard protocol EN 12697-44: 2010 [26].

Some of the major flexible pavement design guidelines [27–33] predict fatigue performance chiefly pivoting the modulus of asphalt materials which basically limits the tensile strain at the bottom of the asphalt layers. Although higher tensile strain ends up inducing a crack into the asphalt material, it is inadequate to entirely sketch the fatigue performance without relating fracture phenomenon and associated time span for crack propagation. Furthermore, the current designs consider only the elastic behaviour although asphalt mix fatigue damage due to fracture is mainly dictated by the materials' viscous behaviour. Thus, it is very important to understand fracture damage evaluation of asphalt mixes mainly based on two aspects: (a) to comprehensively understand fracture cracking mechanism of asphalt mixes from fracture mechanics approach; and (b) to estimate dissipated fracture energy of the cracked asphalt materials based on different levels of fracture damage. Therefore, a set of parametric indices are needed to evaluate fracture damage in asphalt mixes inclusive of dissipated fracture energy components accounting for crack initiation and propagation mechanisms simultaneously.

Thus, the main objective of this study was to formulate and deduce a new set of fracture damage parameters from load-crack mouth opening displacement (CMOD) relationship in order to estimate fracture energy of nineteen asphalt mixtures based on fracture mechanics principles. The approach taken in this study was first of its kind since it considered synergizing LEFM and EPFM concepts in respect of pre-crack initiation and post-crack initiation periods within the regime of asphalt fracture cracking research. Experimental investigation in this study encompassed evaluation of: ten conventional dense-graded (DG), four polymer-modified gap-graded (PGAP), four rubber-modified gap-graded (ARGAP), and one rubber-modified open-graded (AROP) mix. The scope of the research included (Fig. 1):

- Conduction of SCB test on asphalt mixes at varying temperatures to obtain load-CMOD characteristics.
- Estimation of fracture damage parameters based on dissipated fracture energy.
- Evaluation of fracture properties at different levels of damage at varying temperatures.
- Development of fracture toughness (K_{IC}) and damage parametric predictive models based on material properties.
- Simulation of experimental observations through numerical modelling using ABAQUS®.

2. Theoretical background

FPZ is caused due to plastic deformation, which is more pronounced for quasi-brittle viscoelastic materials such as asphalt mixes in comparison with elastic materials. FPZ is found to influence the cracking process significantly [34] and schematically illustrated in Fig. 2(a). In addition, laboratory measured fracture toughness designated as K_{IC} for quasi-brittle material is highly dependent on geometry of the specimen and length of the crack (notch depth). Hence, high scale yielding (HSY) and geometric dependency of K_{IC} does not aid in a complete understanding of asphalt cracking mechanism with just LEFM concept. In contrast, EPFM explains the fracture process with the help of fracture energy considering