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Characterization of temperature- and rate-dependent fracture properties of fine aggregate bituminous mixtures using an integrated numerical-experimental approach

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ABSTRACT

This paper employs an integrated numerical-experimental approach to evaluate the temperature- and rate-dependent fracture characteristics of four fine aggregate bituminous matrices. Two bending tests (semicircular bending, and single-edge notched beam) and one tension test (disk-shaped compact tension) were performed in the laboratory at three temperatures (−10 °C, 10 °C, and 25 °C) and three loading rates (0.5 mm/min, 1.0 mm/min, and 2.0 mm/min). The fracture tests were further simulated using a computational model based on the finite element method that is incorporated with material viscoelasticity and cohesive zone fracture. Two cohesive zone fracture parameters, i.e., cohesive strength and fracture energy, were determined via a calibration process between experimental and numerical results. The results obtained indicated that temperature- and rate-dependent fracture characteristics are obvious in viscoelastic bituminous mixtures, and an accurate identification of such characteristics is a key step towards the implementation of successful computational microstructure predictive models. This would lead to core insights into the effects of constituents on the overall mixture performance, with significant savings in experimental costs and time.

1. Introduction

Among the several types of distresses that cause damage to asphalt mixtures, cracking is probably the most challenging to be predicted and controlled. Modeling the initiation and coalescence of microcracks and the propagation of the resulting macrocracks is a very complicated task due to several complex characteristics of the mixture components.

In an attempt to model the complex fracture process in asphalt mixtures, many researchers have adopted the microstructural modeling approach as an efficient and promising tool [8,17,19,28–30,20,9,12,13,2,3,6].

Unlike other modeling methodologies, the microstructure models allow the consideration of various key material characteristics, such as heterogeneity, volume fraction, random shape, and spatial distribution of aggregate particles within the

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mixture microstructures, temperature- and rate-dependence of the mechanical responses, among others. In addition, the microstructure models can simulate the damage-dependent behavior of the mixtures considering realistic scales because the global macroscopic material responses are characterized based on the analysis of the local microscopic behavior.

In addition to the consideration of relevant material characteristics, the microstructural approach does not require a large number of expensive and time-consuming laboratory experiments because it typically uses constituent characteristics instead of mixture-level testing results. Such constituent-level testing protocols need to be well-designed because the accuracy of the model inputs obtained from the analysis of the experimental data directly affects the predictive capabilities of the microstructure models.

In that sense, among the main testing protocols proposed in the literature for the characterization of the fracture-related damage behavior of asphalt mixtures, the most commonly used are probably: (a) disk-shaped compact tension test, DC(T) [24,26,1]; (b) indirect tension test, IDT [27,10,20]; (c) semi-circular bend test, SCB [16,14,15,23,4,5]; and (d) single-edge notched beam test, SE(B) [25,20,11].

To simulate the mechanical behavior of asphalt concrete (AC) mixtures with the computational microstructure modeling approach, researchers have regarded such mixtures as composite materials comprised of coarse aggregates, fine aggregate matrix (FAM), i.e., asphalt cement + fine aggregate particles + mineral fillers + entrained air voids, and optional additives [31,18,7,13].

FAM has been typically regarded as a main component in microstructure models that attempt to characterize the mechanical behavior of AC mixtures. The presence of FAM results in several complexities to the overall behavior of the asphalt concrete, which is intensified if highly nonlinear responses are expected due to microstructural cracking. Thus, the proper understanding and characterization of the fracture process in FAM becomes a key step towards the development of successful microstructure models [12,3,13].

Some authors have recently adopted the testing protocols mentioned before in their attempts to obtain fracture properties of the primary FAM phase. For instance, Aragão and Kim [4] investigated the rate-dependent fracture characteristics of FAM for intermediate temperature conditions (21 °C). In that work, the fracture properties of the material were determined based on the calibration of cohesive zone fracture properties during simulations of real SCB tests conducted in the laboratory.

Although relevant information regarding the rate-dependence of the fracture properties of FAM could be obtained from the approach, it was later observed that the control of the displacement of the machine actuator in the fracture tests did not result in constant crack propagation speeds within the microstructures of the samples. Alternatively, Aragão et al. [5] proposed the use of clip-on gauges installed on the tip of the initial notch of the specimens to allow a more accurate control of the crack propagation speed. An iterative loop was programmed in the software of the testing machine so that the displacement of the actuator was continuously adjusted during the fracture tests to guarantee a constant opening rate at the notch tip. Aragão et al. [5] also demonstrated that the updated version of the numerical-experimental procedure could generate fracture properties that were independent of the testing configurations evaluated (DC(T), SCB, and SE(B)) for the testing conditions adopted in their study, i.e., −10 °C and crack-tip opening displacement (CTOD) rate of 1.0 mm/min.

In an attempt to advance the understanding on the complex viscoelastic fracture process of asphalt mixtures, this paper adopts the numerical-experimental approach proposed by Aragão et al. [5] for the determination of fracture properties at different temperatures and CTOD rates. More specifically, the validity of the methodology is investigated based on comparisons among the fracture properties determined from model simulations of the three different experimental testing configurations, i.e., DC(T), SCB, and SE(B), for the different temperatures, CTOD rates, and FAMs.

2. Materials and sample fabrication

In this study, the complex temperature- and rate-dependent fracture characteristics of four FAMs were evaluated. The FAMs were designed using two aggregates with different characteristics: Aggregate 1, composed of fine limestone and hydrated lime CH-I; and Aggregate 2, composed of a mix of sand (particles between 0.15 mm and 0.60 mm), fine limestone (particles smaller than 0.15 mm), and hydrated lime CH-III. The limestones in Aggregates 1 and 2 had different mineralogy and were obtained from different quarries in the state of Rio de Janeiro. Three asphalt binders, typically used in the state of Rio de Janeiro, two unmodified and classified as PG 64-22S and a PG 64-22H, and one SBS modified, classified as PG 70-22H, were also used in the composition of the FAMs.

FAM 1 was composed of Aggregate 1 and binder PG 64-22S. FAMs 2, 3, and 4 were produced with a combination of Aggregate 2 and binders PG 64-22S, PG 64-22H e PG 70-22H, respectively. Table 1 summarizes the materials adopted in the compositions of the FAMs.

Table 1
Composition of the four FAMs evaluated in this study.

Asphalt binder		Aggregate 1	Aggregate 2
Binder 1	PG 64-22 S	MAF 1	MAF 2
Binder 2	PG 64-22 H	–	MAF 3
Binder 3	PG 70-22 H	–	MAF 4