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Multi-parametric characterization of mode I fracture toughness of asphalt concrete: Influence of void and RA contents, binder and aggregate types

Saannibe Ciryle Somé [a,*], Montassar Abdhelack Fredj [a], Mai-Lan Nguyen [b], Arnaud Feeser [c], Alexandre Pavoine [a]

[a] Cerema, Laboratoire ÉcoMatériaux, 120 rue de Paris, 77487 Provins Cedex, France
[b] IFSTTAR/MAST, CS4 F-44344 Bouguenais Cedex, France
[c] Cerema, Laboratoire Strasbourg, 11 rue Jean Mentelin BP 9, 67035 Strasbourg Cedex 2, France

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Abstract

This study aims to evaluate the fracture toughness (K_{Ic}) in mode I cracking using semi-circular bending test (SCB). Experiment has been performed to investigate the influence of bitumen grade (using P15/25 and P50/70 bitumens), reclaimed asphalt (RA) content (using 0%, 20% and 40% RA contents) and temperature (using −20 °C, −5 °C, 10 °C test temperatures), through ANOVA. Additional investigations have been performed: (i) to evaluate the effect of the use of polymer modified bitumen (PMB), (ii) to evaluate the effect compactness using 5% and 8% air void contents, (iii) to evaluate the effect of aggregate type using siliceous-limestone and porphyry aggregates. The results show an important decrease in K_{Ic} when temperature increases from −5 °C to 10 °C and a slight decrease between −20 °C and −5 °C. The results also show that increasing RA content increases slightly the K_{Ic}. It was found from the ANOVA that the influent parameters can be ranked as follows: temperature, RA content and binder grade. The investigations show that PMB increases the K_{Ic} value than pure bitumens. Porphyry aggregates increase the K_{Ic} by about 16% than silica-limestone aggregates at low temperatures between −20 °C and −5 °C. However, this ranking is slightly inverted at 10 °C. In addition, K_{Ic} decreases by about 12% at 10 °C with an increase in air voids (by 5% to 8%). Void content effect is more significant at −5 °C and 10 °C, and negligible at −20 °C.

Keywords: Fracture toughness; SCB; Bituminous mixture; Reclaimed asphalt

1. Introduction

Cracking is one of the factors inducing early deterioration of the asphalt pavement structures in cold regions. It is caused by the combination of mechanical loads and climatic factors such as temperature cycles, freeze-thaw cycles and water infiltration. Cracking is a phenomenon which occurs in two steps: the initiation of microcracks and their propagation. Microcracks initiation has several causes: thermal shrinkage, joints cracking, fatigue, debonding, poor laying of mixtures, differential swelling of sub-base soils due to freeze. Traditionally, thermal cracking can be reduced using soft asphalt. This approach which gained successful results reaches its limits due to the use of hard bitumen to support the heavy weight traffic increasing and the use of reclaimed asphalt (RA) [1]. Moreover, because of the climate changes and the potential increase of temperature, the use of soft bitumen becomes

* Corresponding author.
E-mail address: ciryle.some@cerema.fr (S.C. Somé).
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Nomenclature

a	crack length, mm	P	class of penetration, 0.1 mm
B	specimen thickness, mm	RA	reclaimed asphalt
D	specimen diameter, mm	SBS	Styrene-Butadiene-Styrene
e	notch width, mm	T	temperature, °C
F	load, N	T_{RB}	softening temperature, °C
F_{max}	maximum load, N	u	displacement, mm
$f\left(\frac{a}{w}\right)$	dimensionless geometrical factor	w	specimen width, mm
$f^*\left(\frac{a}{w}\right)$	geometrical factor, $m^{1/2}$		
K_{IC}	critical stress intensity factor, $N \cdot mm^{-3/2}$	*Greek symbols*	
LA	Los Angeles abrasion test, %	α, β	proportion of fresh and recover binder
MDE	Microdeval abrasion test, %	σ	stress, MPa
p	percentage of RA, %	σ_{max}	maximum stress, MPa
PMB	polymer modified bitumen		

inappropriate because of the risk of rutting [2]. Furthermore, the deteriorations that occured on the national roadways in France during the cold winters in 2009–2010 and 2010–2011, proved the fragility of road networks and the limits of the historical test methods (water sensitivity, permanent deformation, stiffness modulus, fatigue) [3,4]. Among the factors identified as potential root causes, there are: cracking due to freeze–thaw cycles, debonding, water sensitivity and the frequency of temperature cycles around 0 °C [3] [5]. One way to improve pavement structures durability consists of a better selection of the constituents to prevent early cracking in winter periods.

Three test methods are commonly used to characterize fracture toughness of bituminous mixes: the semi-circular bend (SCB) historically used for rocks materials [6–9], the single-edge notched beam (SENB) [10,11] and the disk-shaped compact tension (DCT) tests. The two first methods are versatile, they have been used to evaluate the mode I and mixte modes I/II and I/III fracture toughness by several authors [12–15].

Numerous investigations have been performed on the experimental level to evaluate the effect of mixes' formulation on the fracture toughness. Aliha et al. [16] carried out investigations in mixte mode I/II to evaluate the effect of SBS modifier. They found that SBS modifier improves fracture toughness of the mixes. They also investigated the influence of mixes compactness on the fracture toughness. They found that increasing the air void content by 3% to 7%, decreases the mixte mode I/II fracture toughness. The influence of the binder content has been studied by Biligiri et al. [17] considering 4.4% and 5.4% binder content. Their investigations have been performed on very dense mixes containing 1% and 2% air void content. They found that increasing the binder content decreases the fracture toughness. A comparative study between granite and limestone aggregates has been reported by Li et al. [18]. They showed that granite aggregates increase the fracture peak than limestone aggregates. Their conclusions regarding the influence of void content and modifier are consistent with the results obtained by Aliha et al. [16]. The effect of the bitumen grade on the fracture toughness has been also investigated by Li et al. [18]. According to their conclusion, soft bitumen (PG 58) leads to lower fracture peak than hard bitumen (PG 64). Recently, Saha et al. [19] investigated the effect of binder content, void content, temperature and specimens' thicknesses and provided a relationship between the fracture toughness K_{IC} and these parameters.

Unlike the previous works whose results are globally consistent, the investigations performed to quantify RA content influence lead to contradictory results. Shu et al. [20] shows that increasing RA content increases the tensile strength and decreases the post-failure tenacity, so the J-integral decreases and therefore the cracking resistance of the mixes. Their results have been confirmed by Aurangzeb et al. [21], while Huang et al. [22] and Tang [23] reported contrary results. According to Tang [23] the fracture toughness performed on asphalt mixes containing 30, 40 and 50% RA content reveals the ranking list changes with varying temperatures. None of the asphalt mixtures evaluated in his research preserves its own advantage for the entire temperature range from −30 to −10 °C.

The influence of the SCB specimen size has been investigated by Molenaar [24] and Saha et al. [25]. Their studies allows to define the dimensions of the SCB specimen permitting to fulfill the plane strain conditions and to consider the measured fracture toughness as a material property. They provided a set of size effect conditions to be fulfilled and the dimensions (width, crack length) for the classical specimen diameters (100 mm, 150 mm, 225 mm).

The influence of temperature and loading rate on the fracture energy have been investigated by several authors [24]. Their results are consistent and tend to confirm that increasing the loading rate or reducing the test temperature