Cold Regions Science and Technology 110 (2015) 149–159

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Asphalt concrete resistance against fracture at low temperatures under different modes of loading

S. Pirmohammad, M.R. Ayatollahi *

Fatigue and Fracture Laboratory, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran University of Science and Technology, Narmak, Tehran 16846, Iran

ARTICLE INFO

Article history:
Received 27 June 2013
Received in revised form 13 August 2014
Accepted 4 November 2014
Available online 11 November 2014

Keywords:
Asphalt concrete
Low temperature
Aggregate gradation
Binder
Air void
Fracture resistance

ABSTRACT

Asphalt concrete components including binder, aggregate and air void play important roles in the fracture mechanism of asphalt pavements in cold regions. In this research, effects of different binders, aggregate gradations and air void contents on the fracture behavior of asphalt concretes were studied by performing three-point bend tests at −10 °C using an improved semi-circular bend (SCB) specimen under pure mode I, pure mode II and mixed mode I/II loading. Results showed that as the binder in the asphalt concrete softens, the resistance of asphalt concrete against fracture increases. Coarser aggregates lead to higher fracture resistance, and the mixture containing the finest aggregates was found to resist poorly against fracture under pure shear loading. Meanwhile, it was found that as the air void content increases, the fracture resistance of asphalt concrete at low temperature decreases. Moreover, all the studied asphalt concretes were significantly sensitive to the loading modes, and by increasing shear load, the fracture resistance first decreased and then increased.

1. Introduction

Asphalt concretes are considered as composite materials making up of aggregates, binders and air voids. Binders constitute about 5% by weight and 15% by volume of hot mix asphalt (HMA) mixture, and play a significant role in the performance of the mixtures. Binders are known to be temperature dependant materials. At high temperatures, binders show viscoelastic behavior for which the dynamic modulus (E^*) test is often proposed for describing the performance of the HMA concretes (Tran and Hall, 2004). At hot temperatures, asphalt concrete is more susceptible to rutting deterioration due to heavy vehicle traffic on pavements. However, by decreasing the temperature particularly at cold climate regions, the binder in HMA mixture becomes brittle and loses its ductility. Therefore, the resistance of asphalt concrete against rutting improves, although fracture becomes the more likely mode of deterioration. Fracture at low temperatures is one of the major sources of deterioration in asphalt pavements imposing significant costs on the pavement rehabilitation agencies annually. Many efforts have been devoted in the past to characterize the mechanical properties of HMA and to improve the performance of HMA pavements at low temperatures (see for example: Arslan et al., 2013; Edwards et al., 2006; Tan et al., 2012). At high temperatures, binders in the HMA mixtures are able to flow; hence, the resulting relaxation mechanism prevents the crack formation in the HMA mixture (Hesp et al., 2002). An ideal HMA concrete should have good performance at both high and low temperatures. Therefore, depending on the region average temperature conditions, appropriate binders must be used in producing HMA mixtures. Binder modifiers such as SBS (styrene–butadiene–styrene), EVA (ethylene-vinyl acetate), PE (polyethylene) are frequently used in preparation of HMA mixtures in order to improve their resistance against both deterioration mechanisms of rutting and fracture (see e.g. Al-Hadidy, 2001; Bates and Worch, 1987; Casey et al., 2008; Punith and Veeraragavan, 2007). Among these modifiers, SBS has been used more frequently by asphalt manufactures (Stastna et al., 2003). Moreover, aggregates (as a major component used in the preparation of HMA mixtures) and air voids can also affect fracture behavior of the asphalt concretes. Previous investigations have shown that a HMA mixture containing larger aggregates has a higher rutting resistance, and also requires less binder content compared with that containing smaller aggregates (see e.g. Kim, 2006).

The mechanical behavior of HMA mixtures containing different binders was investigated both at high temperatures and at low temperatures. However, these studies address the HMA concrete behavior only under mode I loading conditions. Meanwhile, a review of literature reveals that the effect of aggregate size on the asphalt fracture toughness has received little attention. Many efforts have been devoted in the past to study the fracture behavior of asphalt concretes under mode I loading (see e.g. Kim et al., 2003; Li and Marasteanu, 2004; Molenaar and Molenaar, 2000; Molenaar et al., 2003); while, depending on the vehicle position relative to the crack plane, the crack very often can experience

* Corresponding author. Tel.: +98 21 7724 0201; fax: +98 21 7724 0488.
E-mail address: m.ayat@iust.ac.ir (M.R. Ayatollahi).

http://dx.doi.org/10.1016/j.coldregions.2014.11.001

Nomenclature

R	Radius of the SCB specimen
T	Thickness of the SCB specimen
P	Applied load
A	Crack length in the SCB specimen
K_I	Mode I stress intensity factor
K_{II}	Mode II stress intensity factor
Y_I	Mode I geometry factor
Y_{II}	Mode II geometry factor
L	Crack distance from the middle of SCB specimen
S_1, S_2	Distances of the lower supports from the middle of SCB specimen in the three-point bend loading
M^e	Mixity parameter
K_{If}	Mode I critical stress intensity factor (critical SIF)
K_{IIf}	Mode II critical stress intensity factor (critical SIF)
K_{eff}	Effective critical stress intensity factor (effective critical SIF)
P_{cr}	Fracture load

mode II and mixed mode I/II deformation (Ameri et al., 2011; Graf and Werner, 1993; Molenaar, 1993). Therefore, it is important to study the fracture behavior of asphalt concretes containing different types of binders, aggregate sizes and air voids under different loading modes to better understand the fracture mechanisms.

In this research, a large number of mixed mode fracture tests were conducted on the cracked semi-circular bend (SCB) specimens made

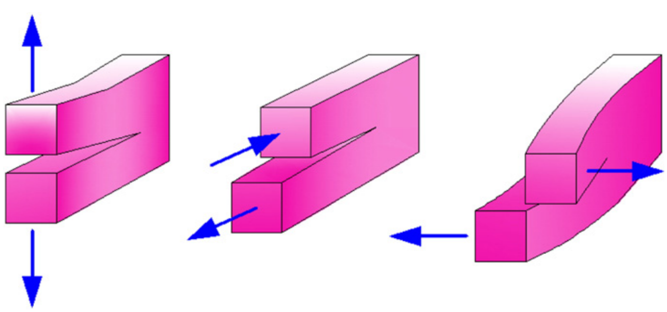

Fig. 1. Three different modes of loading in a cracked body.

of HMA mixtures containing different types of binders, aggregate gradations and air voids at low temperatures. The stress intensity factors K_I and K_{II} were calculated from finite element analysis for the test specimen. Using the finite element results and the fracture loads obtained from the experiments, the effects of binder type, aggregate gradation and air void on the mixed mode fracture resistance of tested HMA mixtures were studied.

2. Finite element analysis

Fracture can occur under different modes of loading including mode I, mode II, mode III or a combination of them as shown in Fig. 1. Mode I (known also as opening mode) occurs when crack faces open without any sliding. Mode II (or sliding mode) takes place when the crack faces slide normal to the crack front without any opening, and mode III (or tearing mode) takes place when the crack faces slide parallel to the crack front without any opening. Different test specimens such as single edge notched beam (SENB), disc-shaped compact tension (DC-T), semi-circular bend (SCB), etc have been used in the past by researchers (Molenaar et al., 2003; Tekalur et al., 2008; Wagoner et al., 2005) to study the fracture behavior of asphalt concretes. In the present research, an improved SCB specimen was employed to conduct fracture tests under mixed mode I/II loading (see Fig. 2a). Unlike the conventional SCB specimen (Lim and Johnston, 1994), the crack in the improved SCB specimen is always vertical and its position is not fixed at the center line. Different loading modes from pure mode I to pure mode II can be achieved using this SCB specimen by changing the positions of crack and lower supports (i.e. the parameters L, S_1 and S_2 illustrated in Fig. 2a). For describing the relative contributions of mode I and mode II, a mixity parameter M^e is used here as:

$$M^e = \frac{2}{\pi}\tan^{-1}\left(\frac{K_I}{K_{II}}\right) \quad (1)$$

where M^e is one for pure mode I and zero for pure mode II. For any other mixed mode loading conditions, M^e varies between zero and one. In order to conduct the experiments for the full range of mode mixities, the experiments were planned for $M^e = 0, 0.2, 0.5, 0.8$ and 1, and then a large number of finite element analyses were performed to find the corresponding values of L, S_1 and S_2. In the finite element analyses, crack length *a*, specimen radius R, specimen thickness t and the reference load P were assumed to be 20 mm, 75 mm, 32 mm and 1000 N, respectively. These dimensional parameters are the same as those of the test specimens used later for fracture experiments. Cracked SCB specimens were

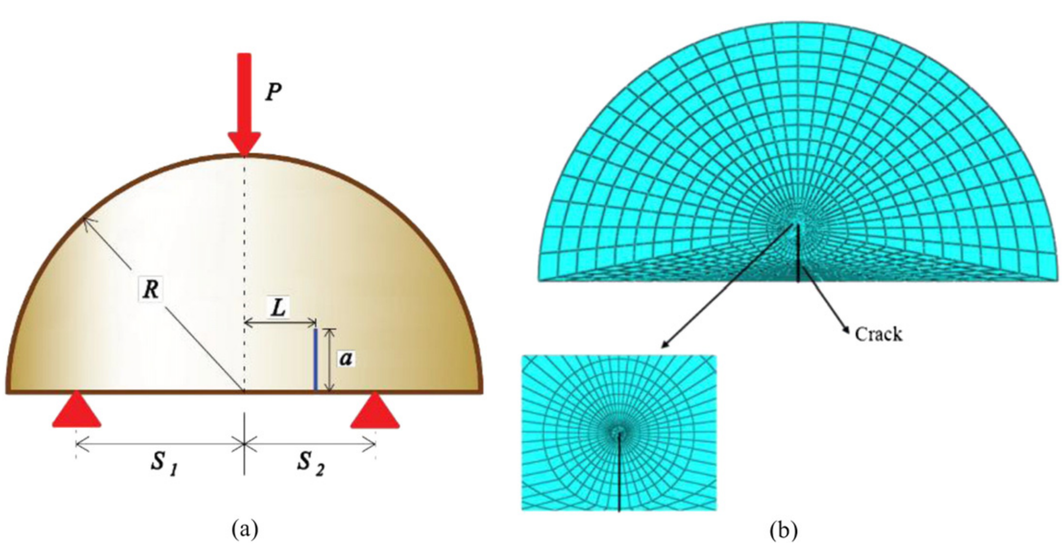

Fig. 2. a) The SCB specimen used for conducting fracture tests under mixed mode loading. b) Typical mesh used for finite element modeling of SCB specimen.