Construction and Building Materials 152 (2017) 520–528

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effect of aggregate gradation on the cracking performance of wearing course mixtures

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HIGHLIGHTS

- The CMD and the DASR model significantly affect the cracking resistance of mixtures.
- Mixtures with low $CMD_{area\text{-}DASR}$ values have high J_c values and high K_{Ic} values.
- The J_c and K_{Ic} values of a mixture increase as the *GCI* of aggregate gradation increases.
- The *GCI* parameter is most strongly correlated with the J_c value.
- The $CMD_{area\text{-}DASR}$ parameter is most strongly associated with the K_{Ic} value.

ARTICLE INFO

Article history:
Received 15 February 2017
Received in revised form 21 May 2017
Accepted 2 July 2017

Keywords:
HMA mixtures
Cracking
Index
Aggregate gradation
Notched semi-circular bending test
Dominant aggregate size range
Continuous maximum density

ABSTRACT

Cracking is one of the main failure mechanisms of asphalt pavements. This study investigates the effects of aggregate gradation on the cracking performance of hot mix asphalt (HMA) mixtures at two stages, i.e., the cracking initiation and cracking propagation stages. Based on the continuous maximum density (CMD) of aggregate gradation and the dominant aggregate size range (DASR) model, a novel cracking performance index—designated the gradations-based cracking resistance index (*GCI*)—was developed to easily evaluate the cracking resistance of wearing course mixtures. This simple index was applied to comparatively investigate cracking resistance in a variety of dense-, coarse-, and fine-graded mixtures with 12.5-mm nominal maximum particle size. Seven blends of different aggregate gradations were developed using the conventional Marshall mix design method. This study employed the notched semi-circular bending test to evaluate the cracking resistance of the HMA mixtures. The experiments demonstrated a strong relationship between *GCI* and cracking resistance at the cracking initiation stage. In addition, cracking resistance was observed to increase with increasing *GCI* value. These findings indicate that the novel index has potential applications for evaluating the cracking performance of wearing course mixtures.

1. Introduction

Wearing course mixtures with low cracking resistance at normal service temperatures are susceptible to ductile fracture [1]. In Vietnam, a rise in the traffic volume of heavy vehicles in combination with high ambient temperature has increased the incidence of premature cracking in wearing course mixtures of asphalt pavements. However, current Vietnamese guidelines do not stipulate any evaluation procedures to ensure adequate cracking resistance for these mixtures. There is therefore a need to conduct rational evaluation tests for cracking performance under these conditions. These tests should have the ability to assess the tensile fracture characteristics of wearing course mixtures.

The notched semi-circular bending (SCB) test has been applied to evaluate the cracking behavior of hot mix asphalt (HMA) mixtures. Two main parameters have been specified for analyzing cracking performance of HMA mixtures at two distinct stages. The first stage is cracking initiation, which occurs when a load reaches the bonding strength of the mixture's component materials [1]. Based on the concept of elastic-plastic fracture mechanics (EPFM), the J-integral (J_c) parameter was established to determine the cracking resistance of HMA mixtures during the cracking initiation stage [1,2]. As this parameter describes the accumulated fracture energy at the point where a crack originates in an HMA

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http://dx.doi.org/10.1016/j.conbuildmat.2017.07.009
0950-0618/

mixture, it is therefore applicable for examining ductile fracture in HMA mixtures during cracking initiation [1]. Previous research has shown that the J_c value is closely associated with the field cracking rate at construction sites [2]. The second stage for assessing cracking performance is cracking propagation. During the propagation stage, the crack length increases until the applied load decreases to the failure limit [1]. A fracture toughness parameter (K_{Ic}) was developed to assess the potential for cracking propagation [3].

During the HMA mixture design process, cracking resistance may be improved through the specification of an appropriate level of aggregate gradation. Aggregate interlock plays a critical role in preventing premature cracking. When backbone aggregate particles are in close contact with one another, aggregate interlock can occur more effectively and improve a mixture's frictional strength [1]. Because aggregate gradation can strongly influence aggregate interlock, there is a need for an in-depth examination of the relationship between the characteristics of aggregate gradation and the cracking resistance of HMA mixtures. However, to the best of our knowledge, the effects of aggregate gradation on cracking resistance in HMA mixtures have yet to be discussed in detail. Previous studies have generally focused on the influence of coarse aggregates, asphalt binders, and temperature on the cracking resistance of HMA mixtures [1,4,5].

The objectives of this study were to develop a simple cracking performance index and to investigate the effects of aggregate gradation on the cracking performance of HMA mixtures with a 12.5-mm nominal maximum particle size (NMPS) at the cracking initiation and propagation stages. The notched SCB test was applied to evaluate cracking resistance in seven blends of HMA mixtures that were designed in accordance with Vietnamese guidelines for wearing course mixtures. In addition, the study examined the relationship between the parameters J_c and K_{Ic}.

2. Literature review

2.1. Previously identified parameters of HMA mixture cracking resistance

The cracking initiation stage occurs in an HMA mixture when the applied load reaches the mixture's bonding strength. J_c is defined as a path-independent line integral around the crack location, and has been used to measure the accumulated external energy required to form a new surface crack in an HMA mixture [1,6]. A high J_c value is indicative of high cracking resistance in a mixture [1,2]. In the notched SCB test, data on loads and deformation are continuously recorded to obtain J_c values. Based on a load-deformation curve, the following equation is applied to determine the critical value of J_c [1,2,5,7]:

$$J_c = \left(\frac{U_1}{b_1} - \frac{U_2}{b_2}\right) \times \frac{1}{a_1 - a_2} \quad (1)$$

where J_c is the critical J-integral value; U_1 and U_2 are strain energy failure values obtained from the load-deformation curve for specimens with notch depths of a_1 and a_2, respectively; and b_1 and b_2 indicate the thickness of the specimens with notch depths of a_1 and a_2, respectively. The strain energy value of an HMA specimen is determined as the area under the loading portion (from the initial load to the maximum load) of the load-deformation curve. Fig. 1 shows the configuration and dimensional information of the notched SCB test specimens.

The cracking propagation stage involves the increase in crack length after cracking initiation [1]. The European Standards utilize the notched SCB test to evaluate the cracking resistance of HMA mixtures during the cracking propagation stage. The tensile strength (or fracture toughness) parameter K_{Ic} is described by the following equations and other associated variables [3]:

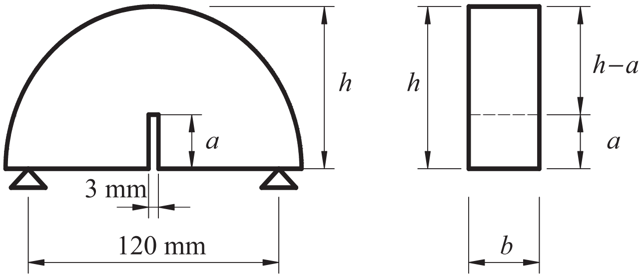

Fig. 1. Configuration of the notched SCB test specimens.

$$K_{Ic} = \sigma_{max} \times f\left(\frac{a}{h}\right) \quad (2)$$

$$\sigma_{max} = \frac{4.263 \times P_{ult}}{D \times b} \quad (3)$$

$$f\left(\frac{a}{h}\right) = -4.9665 + 155.58 \times \left(\frac{a}{h}\right) - 799.94 \times \left(\frac{a}{h}\right)^2 + 2141.9 \times \left(\frac{a}{h}\right)^3 - 2709.1 \times \left(\frac{a}{h}\right)^4 + 1398.6 \times \left(\frac{a}{h}\right)^5 \quad (4)$$

where K_{Ic} is the fracture toughness of the material; σ_{max} is the maximum horizontal stress at failure; P_{ult} is the maximum force; D is the diameter of the specimen; and $f\left(\frac{a}{h}\right)$ and h are the geometric factor and the height of the specimen, respectively.

2.2. Development of a novel parameter of HMA mixture cracking resistance

The presence of air voids within an HMA mixture can negatively affect its cracking resistance, and it has been reported that an increase in the amount of air voids reduces the fatigue life of a mixture [8]. Air voids are part of a mixture's voids in mineral aggregate (VMA). Because the characteristics of aggregate gradation greatly influence the amount of air voids in an HMA mixture, it may be possible to optimize the VMA by controlling these characteristics. A previous study investigated the relationship between VMA and the area of continuous maximum density (CMD), or CMD_{area}, which indicates the degree of total deviation from the CMD line [9]. The results of that study showed that the VMA of HMA mixtures increases with increasing CMD_{area} [9]. Another study reported that the K_{Ic} of HMA mixtures decreases with increasing VMA [10]. The K_{Ic} and J_c parameters are used to indicate the cracking resistance of HMA mixtures and are closely correlated: when the K_{Ic} of a mixture decreases, J_c also decreases [11]. An increase in CMD_{area} may increase the amount of air voids in the aggregate structure and reduce cracking resistance. The present study posited that CMD_{area} is a potential parameter that indicates a negative effect on the cracking resistance of HMA mixtures.

The dominant aggregate size range (DASR) refers to the interactive size range of particles that form the backbone of an aggregate structure. Dominant particles of coarse aggregate in the DASR create a structural network and produce voids. Interstitial components (IC) fill the void spaces between the DASR aggregate particles, and include fine aggregate, filler, and asphalt binder [12]. Among these, fine aggregate has a particularly substantial effect on cracking resistance [13]. Fig. 2 illustrates the effects of fine aggregate on a mixture's cracking performance. When the proportion of fine aggregate is low, there is inadequate interaction among the DASR particles. The fine aggregate does not support any load and does not contribute frictional strength to the DASR