Construction and Building Materials 114 (2016) 423–433

Contents lists available at ScienceDirect

Construction and Building Materials

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

Homothetic behaviour investigation on fracture toughness of asphalt mixtures using semicircular bending test

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HIGHLIGHTS

- Investigated homothetic behaviour of asphalt mixtures' fracture properties.
- Determined fracture toughness of 216 dense graded asphalt specimens using SCB test.
- Evaluated the effect of specimen thickness using mixed-level factorial design.
- Recommended specimen thickness range to obviate geometric dependency on fracture.

ARTICLE INFO

Article history:
Received 19 January 2016
Received in revised form 17 March 2016
Accepted 29 March 2016
Available online 4 April 2016

Keywords:
AASHTO TP 105-13
Asphalt mix
Fracture toughness
Fracture behaviour
Thickness
Semicircular bending test
Material properties

ABSTRACT

The objective of this study was to investigate the homothetic behaviour of asphalt mixes in respect of fracture toughness. A total of 216 samples encompassing six dense graded asphalt mixes were tested at three temperatures with four replicates per mix type using static semicircular bending test based on the AASHTO TP 105-13 protocol. A mixed-level factorial design was employed to understand the effect of variables: asphalt content, air voids, temperature, and thickness. Statistical analyses showed that the change in the thickness from 40 to 50 mm produced an insignificant change in the fracture toughness. It was also found that the selection of the specimen thickness to evaluate fracture toughness in the range of 40–50 mm was not significantly dependent on asphalt mix material properties and temperature.

1. Introduction

Cracking is a fundamental failure mechanism of asphalt pavements. It plays a deciding role towards the evaluation of pavement performance in fatigue and low temperature cracking of asphalt mixtures. Although the causes of these distresses are distinctive, the elementary mechanism of cracking in terms of their analysis and investigation methodologies is better understood using fracture characterization.

In the last few decades, extensive research studies have been made to understand the fracture behaviour of asphalt binder [1–8] and mixtures [9–18] using empirical and mechanistic-empirical methods. In general, the conventional approach to assess the cracking performance of asphalt mixes in the ambit of material characterization employs indirect diametral tensile (IDT) [19], and beam fatigue [20] tests. Although the test methodologies have been commonly used as fundamental performance test, very limited information can be obtained regarding the fracture cracking behaviour of asphalt mixes. The non-homogenous and anisotropic material structure of asphalt material has encouraged the researchers to apply fracture mechanics principles to characterize cracking behaviour [21–28]. Since fracture mechanics employs the evaluation of the material's behaviour with the presence of the flaw in the material, it renders a rational approach to evaluate fracture properties accounting for the inherent anisotropy of the asphalt mixes. In this direction, semicircular bending (SCB) test has received a growing interest in assessing fracture properties of asphalt mixes due to its simplicity and repeatability [26,29–34].

Although various fracture parameters such as fracture toughness (K_{IC}), fracture energy, and J integral have been used for cracking performance evaluation, the determination of K_{IC} constitutes the major share in the mainstream fracture analyses of asphalt mixes. In linear elastic fracture mechanics (LEFM) approach, K_{IC} is defined as the resistance of a material against cracking. Further,

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http://dx.doi.org/10.1016/j.conbuildmat.2016.03.169
0950-0618/

K_{IC} is considered as the intrinsic material property when plane strain conditions are met [35,36]. In this context, the specimen geometry, especially thickness plays a vital role by demarcating the plane stress and plane strain conditions. Therefore, the specimens having the same shape but different dimensions produce different magnitudes of fracture toughness. This phenomenon is called ''homothetic" or geometrically similar specimen behaviour [37].

Although the static SCB standard protocols [38,39] that determine fracture toughness prescribe a certain set of geometry to ensure its repeatability; time-and-temperature dependency of asphalt mix characteristics in association with nonlinear viscoelastic properties question the applicability of the same set of specifications being used for various combinations of temperature. Furthermore, the effects of mix variants such as air voids, asphalt content, and geometric dependency of specimens also complicate the evaluation process of K_{IC}. Therefore, there is certainly a need to comprehensively understand the associated variable effects on K_{IC} at various temperatures for two reasons: (a) to deduce a specific specimen geometry which curtails geometric dependency, and (b) to analyze the interaction effect of geometry with the mix compositions in order to understand the geometric impact on fracture resistance of asphalt mixes.

Thus, the main objective of this study was to investigate the homothetic behaviour of asphalt mixes in respect of the major cracking assessor: fracture toughness (K_{IC}). The research effort encompassed fracture toughness evaluation of six asphalt mixtures at three temperatures with varying asphalt contents, air voids levels, and specimen thicknesses. The approach taken in this study was first of its kind since it included in-depth factorial analysis of the geometric variation over the rational range of material properties at various temperatures, which accounted for low and intermediate levels of fracture cracking. The scope of the work included:

- Determination of K_{IC} for different asphalt mixes with varying thicknesses and temperatures using AASHTO TP 105-13 protocol [39] to conduct monotonic SCB tests.
- Design of a mix-level factorial analysis and evaluation of main and interaction effects of the various factors.
- Evaluation of geometric dependency of K_{IC} at varying temperatures and mixture properties.
- Recommendation of a rational design range of specimen thicknesses to minimize the geometric dependency on fracture toughness evaluation.

2. Theoretical background: geometry dependency of K_{IC}

It is important to note that K_{IC} can be considered as a true material property when plane strain conditions are met [35,36]. As the concept evolved based on the mechanics of metals and rock materials which exhibit high degree of homogeneity, the fracture process governed by the plane stress and plane strain conditions for those materials is significantly different. In case of thin specimens, plane stress fracture process employs the development of the maximum shear forces at 45° angle to the surface. Further, it drives the cracking plane 45° to one or another plane of maximum shear, and then fails the specimen by producing the shear lips. On the other hand, plane strain condition prevails for thick specimens where a state of the triaxial tensile action at the crack tip causes crack propagation into the same plane of crack, and failure occurs by producing the flat surface. Since the plane stress fracture absorbs more energy than that of the plane strain condition, the plane stress and plane strain proportions have strong influence towards the fracture resistance. Plane strain fracture toughness is considered as the intrinsic property of the materials due to the fact that the failure energy remains constant in this process. A typical fracture toughness variation of a metal with respect to sample thickness as a schematic is illustrated in Fig. 1.

However, asphalt mix, which is a blend of asphalt binder and aggregates, exhibits significantly a deviation from homogeneity in its structure when compared with the metals and rock materials. As a result, fracture process of asphalt mixes does not show any pronounced mechanism of neither plane stress nor plane strain condition, rather fracture occurs along the aggregate boundary. Thus, the characterization of the fracture properties of the asphalt mixes with respect to specimen geometry is notably different from the conventional methodologies of fracture evaluation.

3. Materials and experimental investigation

3.1. Experimental program

The study encompassed six dense-graded asphalt mixes prepared with viscosity graded VG-30 asphalt binder and mid-point dense gradation prescribed in [40]. Note that viscosity of the asphalt binder used in this study was in the range of 3000 ± 600 P as per the viscosity grading scale. Table 1 presents the aggregate gradation summary used in this study. At first, the optimum asphalt content (OAC) was determined using Superpave mix design methods [41], which were approximately equal to 4.5%. The compaction levels: N_{ini}, N_{des}, and N_{max} used for the mix design process were 9, 139, and 228, respectively.

As a next step, asphalt mixes were prepared with varying asphalt contents and air voids levels in order to understand the effects of these variables on fracture properties. Asphalt content was varied at three levels: OAC, and OAC ± 0.5 whereas two air voids levels were used: 4 and 7%. Aggregates and asphalt binders were blended and compacted to cylindrical specimens of height 110 mm and diameter 150 mm using Superpave gyratory compactor as per [41]. A total of 54 gyratory specimens were prepared with nine gyratory specimens per mix type. Then, thin layers from the top and bottom surfaces of the cylindrical specimens were trimmed off to obtain smooth surfaces on either end. Since the scope of the study included the understanding of the fracture behaviour with respect to the thickness of the semicircular specimen, the cylindrical gyratory specimens were sliced to the desired sample thicknesses of 30, 40, and 50 mm. Each specimen was cut into a combination of two thicknesses out of the three, and then, cut into semicircular geometry for SCB tests. Thus, a total of twelve SCB specimens were prepared at each level of thickness: 30, 40, and 50 mm per mix. Overall, a total of 216 SCB specimens were prepared as part of this study. Air voids of the SCB specimens were determined as per [42]. The samples having air voids exceeding the target air voids were discarded. Finally, a 15 mm notch was made at the specimen base along the thickness direction. Fig. 2 presents the sequential steps of the specimen preparation and the test setup.

3.2. Experimental investigation: K_{IC} determination

Static SCB tests were conducted on the specimens at three temperatures (5, 15, and 25 °C) using a Universal Testing Machine as per [39]. Note that the study attempted to focus on characterizing the homothetic behaviour on fracture toughness, where K_{IC} was used as the assessor. In this process, the upper temperature considered was 25 °C since the asphalt mix at this condition shows fatigue distress, which is governed by fracture phenomenon. Thus, the viscoelastic behaviour was considered instead of pure brittle response of the materials. The samples were conditioned at the test temperature in the environmental chamber for four hours prior to the test. The test sequence was completely randomized since it was a reliable method of ensuring homogenous treatment groups without involving any potential

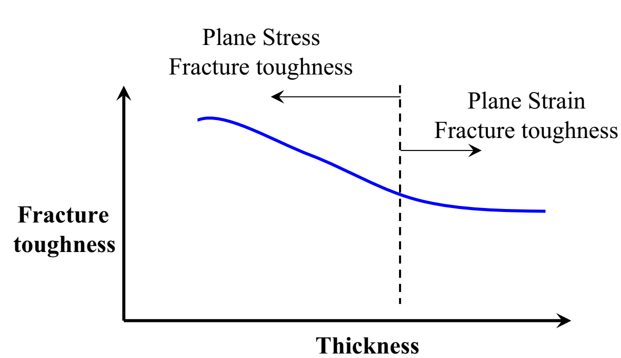

Fig. 1. Schematic variation of K_{IC} with thickness for brittle materials.