Construction and Building Materials 150 (2017) 664–672

Contents lists available at ScienceDirect

Construction and Building Materials

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

Stato-dynamic response analyses through semi-circular bending test: Fatigue life prediction of asphalt mixtures

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HIGHLIGHTS

- Estimated crack propagation properties of eight asphalt mixtures using semi-circular bending test.
- Developed a novel methodology to characterize crack propagation properties using fracture mechanics principles.
- Established relationships between static and dynamic fatigue properties of asphalt mixtures.
- Found CMOD as a promising candidate parameter to quantify fatigue cracking phenomenon of asphalt mixtures.
- Formulated a synergistic approach to analyze stato-dynamic responses of fatigue-fracture mechanism of asphalt materials.

ARTICLE INFO

Article history:
Received 3 March 2017
Received in revised form 4 June 2017
Accepted 5 June 2017

Keywords:
Asphalt mixtures
Fatigue cracking
Crack propagation
Dynamic SCB
CMOD

ABSTRACT

This study established a relationship between static and dynamic fracture properties of asphalt mixtures to predict fatigue performance, and hence quantify crack propagation phenomenon to understand the overall fatigue cracking process. Fracture toughness (K_{IC}) of eight different asphalt mixtures were determined covering two conventional and six modified mixes with varying materials properties using static semi-circular bending (SCB) tests. Further, the study delivered a methodological development of the dynamic SCB test, which potentially advances the current state-of-the-art pertinent to fatigue evaluation of asphalt mixtures. Based on the dynamic SCB test, modified gap-graded mixtures had higher fatigue lives than conventional dense-graded. A correlation between K_{IC} and fatigue life indicated that with increasing K_{IC}, modified mixtures showed higher fatigue lives but conventional mixes showed lower fatigue life. The fatigue cracking mechanism explained by crack mouth opening displacement (CMOD) of asphalt mixtures illustrated that modified mixtures had endured crack propagation phase compared to the conventional mixes. Thus, it was adjudged that CMOD is a promising parameter that explains the fatigue cracking mechanism of conventional and modified asphalt mixtures.

1. Introduction

Fatigue cracking is one of the most challenging problems in flexible asphalt pavements. The intermittent cracking mechanism, wide variations in temperatures and loading conditions, differential loading and unloading time intervals, aging effects, and heterogeneous mix-matrix has made the evaluation, analysis, and prediction of fatigue life of asphalt mixtures much more complex. Thus, a rational fatigue life design of an asphalt mix necessitates an advanced understanding of the materials properties, inclusive of both innate mixture characteristics and extraneous traffic factors, which contribute to the fatigue performance of asphalts.

Although the phenomenological method is conventionally employed to evaluate fatigue cracking based on the stress-strain relationships, there is a growing interest to utilize fracture mechanics approach to analyze fatigue-cracking behavior of asphalt mixtures. Several laboratory test methodologies available in the literature use fracture mechanics to assess the fatigue life of asphalt mixtures. Few of the examples include: single edge notch beam (SENB) test, disc compact tension (DCT) test, and semi-circular bending (SCB) test. Out of the several methods, the advantages such as the direct use of field cores and ease in the testing practices pertinent to the SCB test have led to the wide utilization of this particular technique to assess fatigue and fracture characteristics of the asphalt mixtures [1].

In fracture mechanics, fatigue cracking usually encompasses two phenomena: crack initiation and crack propagation. Although several research studies have employed the static SCB test to

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http://dx.doi.org/10.1016/j.conbuildmat.2017.06.035

evaluate the fracture properties of asphalt mixtures with a view to assessing crack initiation, a constant load deformation/crack mouth opening displacement (CMOD) technique was commonly utilized for the purpose. In particular, the fracture toughness property was a major research interest parameter in numerous research studies [2–15]. On the other hand, a very limited literature [4,16–19] is available about the dynamic SCB test that potentially deals with the crack propagation portion of the overall cracking phenomenon in asphalt mixtures. Very importantly, dynamic loading test helps predict the fatigue life of an asphalt pavement by accounting for the crack propagation phase that is otherwise not well understood through static SCB test.

In this context, it was deemed important to extend the state-of-the-knowledge of fatigue performance of asphalt mixtures from the basic static fracture characteristics to the dynamic fatigue simulation for two major reasons: (a) to investigate whether any correlation exists between the static fracture characteristics and fatigue life, and (b) to quantify the crack propagation mechanism simulated through dynamic testing, and its association with the static fracture properties. Thus, the objective of this study was to establish relationships between the static and dynamic fracture properties of asphalt mixtures in order to predict the fatigue performance, including, quantifying the crack propagation phenomenon that is essential to understand the overall fatigue cracking process in asphalt pavements. The research effort encompassed fracture toughness determination of eight different asphalt mixes, including conventional and modified mixtures with varying materials properties using both static and dynamic SCB tests. One of the significant contributions of this study was to develop a novel methodological approach to perform the dynamic SCB test to assess crack propagation phenomenon of asphalt mixtures. The scope of the effort included:

- Determination of static fracture properties: fracture toughness (K_{IC}) of eight asphalt mixtures accounting for fundamental materials properties
- Comparison and prediction of fracture performance based on K_{IC} using the static SCB test
- Development of the dynamic SCB test methodology to evaluate the crack propagation characteristics of asphalt mixtures
- Investigation of crack propagation behavior using CMOD results of dynamic SCB test
- Establishment of a correlation between K_{IC} of static SCB test and fatigue performance simulated through dynamic SCB test for different asphalt mixtures

2. Materials and experimental program

2.1. Materials

Eight different asphalt mixtures were prepared to evaluate K_{IC} and fatigue life using static and dynamic SCB tests. Two aggregate gradations: dense graded conforming to [20], and gap-graded gradation recommended in [21] from the same aggregate source were used. Further, three asphalt binders, including one viscosity-graded (VG-30) virgin binder, one polymer modified binder (PMB-40), and one crumb rubber modified binder (CRMB-60) was used to blend the corresponding asphalt mixtures. A total of sixteen Superpave gyratory specimens (two per mix type) were prepared using varying asphalt contents (AC), and compaction levels to achieve the desired air voids (AV). The following summarizes the details of the mix composition along with their designations.

- D4V7: Dense-graded with VG-30 binder, 4% AC, 7% AV
- D5V7: Dense-graded with VG-30 binder, 5% AC, 7% AV
- AR6V7: Gap-graded with CRMB-60 binder, 6% AC, 7% AV
- AR7V7: Gap-graded with CRMB-60 binder, 7% AC, 7% AV
- AR6V9: Gap-graded with CRMB-60 binder, 6% AC, 9% AV
- AR7V9: Gap-graded with CRMB-60 binder, 7% AC, 9% AV
- P7V7: Gap-graded with PMB-40 binder, 7% AC, 7% AV
- P7V9: Gap-graded with PMB-40 binder, 7% AC, 9% AV

Note that the dense-graded mix was prepared with VG-30 designated by "DXVZ". Further, PMB-40 and CRMB-60 asphalt binders were blended with the gap-graded gradation to produce polymer- and rubber-modified asphalt mixtures designated "PXVZ" and "ARXVZ", respectively. Note that X is representative of asphalt content, V is air voids parameter and Z illustrates the air void contents of the asphalt mixtures. For example, AR6V9 indicates that the rubber-modified asphalt mixture was prepared with CRMB-60 binder with 6% asphalt content and 9% air voids.

2.2. Experimental program

In order to prepare the SCB specimens, each of the gyratory plugs (height 120 mm and diameter 150 mm) was cut into two discs with thickness of 50 mm. Then, each cylindrical disc was centrally cut to obtain two SCB specimens. Finally, a notch of 15 mm depth and 1.5 mm width was introduced at the center of the base along the thickness direction of the samples. Air voids were checked before the notch was cut into the SCB specimens, and those samples that did not satisfy the target ± 0.5% air voids were discarded. Thus, a total of eight asphalt mixtures were prepared covering 64 SCB specimens with eight sample replicates per mix type. It is important to note that four samples per mix were used for static SCB test and the rest four for the dynamic SCB test.

3. Evaluation of fracture properties: Static SCB test

K_{IC} of the eight asphalt mixtures was determined using a static SCB test as per AASHTO TP 105 [22]. A total of 32 SCB specimens were tested using a Universal Testing Machine (UTM) at 15 °C with four replicates per mix type. All specimens were conditioned at the desired temperature for four hours prior to testing. It is noteworthy that this test temperature was selected in order to estimate the fatigue performance of asphalt mixtures at intermediate temperature that also validates the utility of static fracture response. Table 1 presents the average K_{IC} of the different mixtures obtained using the static SCB tests.

3.1. ANOVA test

A one-way analysis of variance (ANOVA) test was conducted to statistically investigate the differences in the sample means of K_{IC} magnitudes of the eight asphalt mixtures at 95% confidence interval. Note the experimental matrix was formulated to account for four factors: aggregate gradation, asphalt content, air voids, and asphalt binder type. The overall P-value of the ANOVA test was found to be <0.05 indicating that at least one of the means was not equal in the pooled group mean.

Fig. 1 presents the interval plot of K_{IC} with 95% confidence interval. As observed, the P-mixes showed higher fracture resistance than the D- and AR-mixes with AR-mixes producing the lowest fracture toughness. Although a substantial difference in K_{IC} was noticed between the AR and other mixes, it was not possible to extract additional information from ANOVA results pertaining to the change in the fracture properties accounting for the mixture parameters within and between the mix types. However, it was inferred that the fundamental fracture property, i.e., K_{IC} was statistically different between the mixtures, which set a platform to further study the crack propagation phenomenon on the premise of K_{IC} magnitudes with confidence.

3.2. Dunnett's comparison test

Since the ANOVA test showed a significant difference in K_{IC} between the eight different asphalt mixtures, it was important to identify the pairs of means, which were statistically different from each other. A Dunnett's comparison test was conducted to examine the difference between the pairs of the means with a certain confidence level. The test was conducted on the eight mixtures with pooled means using MINITAB® 17.0. A summary of the differences in the means of the seven pairs of mixtures was presented with a scale of zero-level (Fig. 2). The differences in the pairs were easily