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Probabilistic analysis of fatigue life for asphalt mixtures using the viscoelastic continuum damage approach

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HIGHLIGHTS

- New probabilistic method developed to predict HMAs' performance subjected to fatigue.
- The probabilistic approach accounts for uncertainties associated with fatigue tests.
- Fatigue life results of the probabilistic analysis were consistent and reliable.

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ABSTRACT

Fatigue cracking is one of the most serious distress modes affecting the serviceability of asphalt pavement structures. The inherent variability of asphaltic materials exhibited in fatigue test results, especially for specimens acquired from field pavements, makes the task of accurately predicting the material's fatigue characteristics rather difficult. The problem is further exacerbated by the combined impact of a large number of factors, including loading conditions, material heterogeneity, ageing, construction quality and others. For these reasons, notable uncertainty is associated with the predicted fatigue life from laboratory tests based on the use of phenomenological models, which adopt deterministic input parameters despite the varying levels of uncertainty embedded in them. To investigate the effect of inherent uncertainty associated with asphalt mixtures on their fatigue life prediction, a probabilistic analysis approach is evidently needed. In this study, probabilistic analysis was applied to the fatigue life prediction model deduced from the viscoelastic continuum damage theory, based on testing various types of asphalt mixtures. The outcome of the analysis is a newly developed approach with the ability to predict the fatigue performance of asphalt mixtures at more consistent and reliable levels than current practice permits.

1. Introduction

Fatigue damage is a major distress affecting the performance and serviceability of asphalt concrete (AC) pavement structures. It is well-known that fatigue damage characterisation is complex and regularly exhibiting extensive scatter because of variation in experimental factors such as test temperature, specimen dimensions and loading pattern. In addition, microstructure heterogeneity contributes to the uncertainty of the fatigue life results because failure location and pattern vary among AC specimens [6,26,17,29].

Many characterisation approaches are encountered in the literature to predict the fatigue resistance of AC mixtures. The viscoelastic continuum damage (VECD) theory has been used successfully in modelling fatigue response and performance. However, in this deterministic approach, all input parameters are fixed values despite the fact that input parameters for the VECD fatigue life model must reflect the variability in the experimental test results that are used to compute these parameters [13,15]. To investigate the effect of the variability in fatigue model parameters and the uncertainty of fatigue life prediction, a probabilistic analysis approach is appropriate and needed. However, only a limited number of studies on the probabilistic analysis approach of AC mixtures, especially for fatigue resistance evaluation, are available in the literature [6,7,9,14]. In this study, a new probabilistic analysis approach has been developed and used in performance

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prediction of various asphalt mixtures, based on the VECD theory and fatigue life formulation derived from a study by Kutay et al. [11].

The VECD approach was adopted in this study because of its several advantages compared to the other fatigue characterisation approaches (e.g. dissipated energy approach). Many studies have clearly shown the advantages of using the VECD approach in assessing the performance of AC mixtures under fatigue damage [23,28,11,3]. The VECD theory has the ability to unify different temperatures, loading frequencies and loading modes or amplitudes for analysis of asphalt fatigue characteristics [11]. This means that, for an asphalt mixture, only one uniaxial tension-compression (T/C) fatigue test needs to be conducted to predict its performance under fatigue damage at any temperature, frequency, loading mode or amplitude. Furthermore, the method accounts for the initial condition of the specimens before testing. Despite its noted advantages in characterising asphalt damage in fatigue, the VECD analysis has always been performed based simply on the mean values of the fatigue test data and on neglecting any variability in the fatigue life (N_f) input parameters of replicate specimens. Therefore, it is vital to transform the deterministic fatigue characterisation model to a probabilistic model to account for variability in the input parameters, which, if not addressed, can have a major impact on the credibility of the outcomes.

The main objective of this study is to develop a probabilistic framework that incorporates the VECD approach and accounts for variability in the input parameters in order to predict, as accurately as possible, the fatigue life of different AC mixtures. The efficacy of the new framework is demonstrated through a comparative analysis of the response of AC mixtures assessed using cyclic uniaxial tension-compression (T/C) fatigue tests in order to predict their fatigue lives accurately.

2. Materials

Various types of AC mixtures were tested in the laboratory in order to assess their fatigue resistance. The first group of AC specimens were taken from AC base layers of a full-scale trial road including six different pavement sections with different materials (aggregate and bitumen grade). The second group of specimens were collected as loose mixtures from the field and then compacted using the Superpave gyratory compactor (SGC) in the laboratory. The third group consists of laboratory specimens that were mixed and compacted using SGC in the laboratory. The following subsections describe the specifications of the specimens according to the corresponding group in detail.

Table 1
Properties of base layer mixtures of the trial sections [27].

Section #	Base layer mixture	Bitumen content by weight (%)
1	Marshall/PRD, 40–50 Pen, Gabbro	3.6
2	Marshall/PRD, 60–70 Pen, Gabbro	3.4
3	Marshall/PRD, 60–70 Pen, Limestone	4.4
4*	Marshall/QCS, 60–70 Pen, Gabbro	3.5
5	Marshall/QCS, Shell Thiopave, Gabbro	3.9
6	Marshall/PRD, PG76-22, Gabbro	3.5

* Mixture of trial section 4 is the control mix.

2.1. Field cores

The first group of the AC mixtures are the ones extracted, cut and prepared from the AC base layers of the six full-scale trial pavement sections investigated in previous studies [20,22,21]. Ten full-depth cores (surface, upper and lower AC base layers) were extracted from each trial section. Each field core had a diameter of 150 mm and a height of approximately 320 mm including the surface layer (≈70 mm), the upper base layer (≈135 mm) and part of the lower base layer (≈115 mm).

After removing the surface AC layer from the field core, the upper and lower base layers (≈250 mm) of the extracted field cores were used in order to prepare specimens on which to perform the uniaxial T/C fatigue tests using the Asphalt Mixture Performance Tester (AMPT). The test specimens were cut to have a diameter of 100 mm and a height of 150 mm (≈75 mm from each base layer) according to AASHTO PP 60-14 [2]. This interface between the two base layers remained within the test specimens. Table 1 and Table 2 show the properties of each base layer mixture cored from the trial sections and their aggregate gradation, respectively.

2.2. Field mixtures

A local contractor in the State of Qatar used two AC mixtures with PMB for the construction of new pavement structures in Qatar in May 2013. The aggregate used in both field AC mixtures was Gabbro, and mixes were designed using the Marshall method following the gradation of a surface layer (SC-Type 1) mix in Qatar Construction Specifications [18]. In the first field AC mixture, the bitumen was modified by Styrene-butadiene-styrene (SBS) polymer for "Extreme" traffic loading condition [1] and graded as PG76-10E. The bitumen in the other AC mixture was also modified by SBS polymer but for "Standard" traffic loading condition and graded as PG76-22S. In both mixtures, the bitumen content by weight was 4.0%. Thus, both field mixtures were identical except for bitumen grade.

During construction, the loose hot mix asphalt of PG76-10E and PG76-22S field mixtures was collected, sent to the laboratory and then compacted using the SGC at around 150 °C to a diameter of 150 mm and a height of 180 mm. The SGC samples were then cored and cut to the standard diameter of 100 mm and a height of 150 mm. The target average air voids value was 7% ± 0.5% in accordance with AASHTO PP 60-14 [2] for preparation of performance testing samples.

Table 2
Aggregate gradation for base layer mixtures of the trial sections [27].

BS sieve size (mm)	Cumulative passing (%)					
	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6
37.5	100.0	100.0	100.0	100.0	100.0	100.0
28.0	99.0	98.0	96.0	98.0	97.9	97.0
20.0	90.0	88.9	93.2	86.1	84.2	90.1
10.0	47.1	51.2	49.3	60.2	60.1	49.8
5.00	34.5	34.8	40.3	42.8	41.8	31.6
2.36	27.9	30.0	28.3	29.0	26.9	26.8
0.30	12.1	13.1	13.0	10.0	11.1	13.9
0.150	8.4	9.2	9.8	7.6	7.9	8.1
0.075	6.3	5.6	6.7	4.6	4.1	5.2