Construction and Building Materials 151 (2017) 767–774

Contents lists available at ScienceDirect

Construction and Building Materials

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

Comparison of the fatigue failure behaviour for asphalt binder using both cyclic and monotonic loading modes

Yang Wang [a], Chao Wang [a,*], Hussain Bahia [b]

[a] Department of Road and Railway Engineering, Beijing University of Technology, Beijing 100124, PR China
[b] Department of Civil and Environmental Engineering, University of Wisconsin, Madison, WI 53706, United States

HIGHLIGHTS

- Fatigue failure of asphalt binders are studied using cyclic and monotonic tests.
- A failure parameter is proposed to characterize the post-peak behaviour for BYET.
- The BYET based failure strain relates well to the LAS based fatigue parameters.
- The DSR-ER test is also effective to distinguish the binder fatigue resistance.

ARTICLE INFO

Article history:
Received 19 April 2017
Received in revised form 14 June 2017
Accepted 22 June 2017

Keywords:
Asphalt binder
Fatigue failure
Cyclic loading
Monotonic loading

ABSTRACT

The objective of this paper is to investigate and compare the fatigue failure characteristics of neat and modified asphalt binders using both cyclic and monotonic loading modes, and further discuss the potential possibility of using the monotonic test for binder fatigue resistance ranking of purchase specification. The cyclic linear amplitude sweep (LAS) test (AASHTO TP 101) has been introduced to quantify the strain at peak stress, and also to predict the strain-controlled binder fatigue life from applying the simplified-viscoelastic continuum damage modeling (S-VECD) approach. Although the LAS is getting acceptance, the mathematical fitting approach is very complicated and require advanced curve fitting and analysis procedure. A simple alternative for characterizing binder failure properties is the use of monotonic loading as described in the binder yield energy test (BYET) and dynamic shear rheometer-elastic recovery (DSR-ER) test (AASHTO TP 123). In this study the BYET based failure strain is found to most efficiently correlate to the LAS based failure strain and predicted fatigue life. However, the multiple-peak phenomenon observed in the BYET stress-strain curves of some of the complex modified binders makes it very difficult to clearly identify the failure parameters. Results collected in this study show that using the DSR-ER test results can be a good addition to the BYET to predict fatigue life of a number of highly modified binders as estimated from the complex LAS mathematical procedure. Therefore, the combined use of the monotonic BYET and DSR-ER tests is recommended as an alternative to the cyclic LAS test for ranking the fatigue resistance of modified asphalt binders in routine practice.

1. Introduction

Fatigue cracking caused by repeated traffic loading is one of the main distress that affects the long-term performance of asphalt pavements. It is well known that both material properties and structure design contribute to the fatigue resistance in the field pavements. From the material level of asphalt mixture, a significant effort has been conducted on the laboratory based fatigue studies of asphalt mixtures using various testing methods (bending beam, direct tension and indirect tension, etc.) [1–5]. In recent years, the multiple-scale modeling approach is introduced to asphalt paving materials for performance evaluation and prediction, which requires the specific characterization of smaller material phase like asphalt binder. Also the fatigue cracks are found to normally initiate and propagate from the weakest parts within the asphalt concrete like binder and mastic phases and thus, the fatigue resistance of asphalt binder plays an important role in the fatigue performance of asphalt mixtures and pavements [6,7].

Fatigue characterization of asphalt binders has been actually an important topic of research in the past 2–3 decades. During the

* Corresponding author.
E-mail addresses: wy14030221wy@emails.bjut.edu.cn (Y. Wang), wangchao@bjut.edu.cn (C. Wang), bahia@engr.wisc.edu (H. Bahia).

http://dx.doi.org/10.1016/j.conbuildmat.2017.06.144
0950-0618/

Strategic Highway Research Program (SHRP), a fatigue parameter of $|G^*| \cdot \mathrm{Sin}(\delta)$ was proposed for Superpave specification of asphalt binder, where $|G^*|$ is the dynamic shear modulus and δ represents the phase angle measured from a cyclic oscillation test using a dynamic shear rheometer (DSR) [8]. However, the verification and calibration studies demonstrated that this $|G^*| \cdot \mathrm{Sin}(\delta)$ parameter is not correlated well to the fatigue performance of asphalt mixtures and pavements, especially for modified asphalt binders [9]. This is probably due to a fact that the SHRP study was conducted within the linear viscoelastic (LVE) range of asphalt binder and thus, no damage effect could be quantified. To overcome these limitations, a new fatigue test of time sweep (TS) was developed during the National Cooperative Highway Research Program (NCHRP) project 9–10 for binder fatigue evaluation [9]. The TS procedure applies a repeated cyclic sinusoidal loading on a binder sample at a fixed frequency, temperature and amplitudes, which commonly follows the fatigue definition of the material integrity deterioration under repeated cyclic loading. The loading cycles at failure occurrence that defined as the fatigue life (N_f) could be identified from the TS test either in stress-controlled or strain-controlled loading modes [10–15]. However, the unpredictable time, and usually very long time, required for the TS test is strongly dependent on the selection of loading amplitude at a given temperature and frequency, which makes the TS a *trial and error* process to measure failure occurrence. Therefore, the TS test is still not implemented for specification use due to the uncertain time-consuming issue though it is widely applied for laboratory binder fatigue research studies.

The linear amplitude sweep (LAS) test (AASHTO TP 101) is developed as an accelerated fatigue procedure for binder fatigue specification, in which a linearly incremental strain sweep cyclic loading is applied to binder sample for only 5 min [16]. Following the main principles from the simplified-viscoelastic continuum damage (S-VECD) fatigue modeling of asphalt mixture [17–20], the LAS test data could be interpreted to predict the cyclic strain-controlled TS fatigue life of asphalt binder [21,22]. Recently, an energy-based unified failure criterion is proposed for LAS test to improve the predictive accuracy of binder TS fatigue life [23]. This newly developed LAS-based binder fatigue modeling approach is a promising approach to relate binder fatigue property to the fatigue performance of asphalt mixtures and field pavements [24,25]. The only drawback with the LAS is the required curve fitting and complicated mathematical modeling analysis procedure. The interpretation of the results of the analysis could be considered as a challenge for implementation in a specifications practical environment.

Compared with the cyclic fatigue loading mode, the monotonic loading mode is another alternative for an accelerated quantification of the cracking resistance of asphalt materials [26–30]. The newly released AASHTO TP 123 specification provides two procedures, namely the binder yield energy test (BYET) and DSR-based elastic recovery (DSR-ER) test, to characterize the binder properties at intermediate temperature using a monotonic constant shear strain rate loading [31]. The binder performance determined from the monotonic tension or shear tests were indeed previously shown to give good correlation to fatigue or thermal cracking performance of asphalt mixture and filed pavements [32–36]. Additionally, the ER performance with a traditional ductilometer has also been claimed as a promising test to estimate the binder cracking resistance, especially for modified asphalts [37,38]. Although the ductilometer test has many shortcomings, the new binder elastic recovery in the DSR described in AAHTO TP 123 is much easier and perhaps a more technically sound test that can be done in the main equipment in the current PG specification system [39,40].

Both testing procedures and data interpretation of the binder monotonic tests (BYET and DSR-ER) are simpler and easier to use than cyclic LAS test that currently requires a series of mechanical modeling and analysis steps. Therefore, the objective of this paper is to compare the fatigue failure behaviour of asphalt binders using both cyclic and monotonic loading modes, and further to investigate the possibility of using monotonic test as a surrogate fatigue ranking test to the cyclic LAS test in the routine practice for purchase specification of asphalt binders.

2. Materials and testing

2.1. Materials

Three neat asphalt binders with different penetration grades, and six modified asphalt binders, were tested in this study. The modified binders covered two typical styrene–butadiene–styrene (SBS) modified binders, high viscosity (HV) asphalt binder, high modulus asphalt binder (HMAB) and two SBS+HV hybrid modified asphalt binders. The HV binder is usually used for producing open graded friction course (OGFC) mixtures due to its higher viscosity level. The HMAB is a special binder modified with special polymers and is used for production of high modulus asphalt concrete used in extremely high temperature or high traffic areas. These binders were selected because they are frequently applied for the heavy traffic pavement structure or extremely climate conditions in China. The details regarding to the binder modification are given in Table 1, in which the neat binders are labeled with penetration grades whereas the modified binders are referred to the corresponding modifiers.

The neat and modified asphalt binders were subjected to short-term aging according to conventional rolling thin-film oven (RTFO) test to simulate the short-term aging process during the pavement construction. The fatigue performance tests were completed on the RTFO-aged binder samples with an Anton Paar MCR 302 Rheometer. The standard 8-mm parallel plate geometry with 2-mm gap height was utilized for both cyclic and monotonic tests at a single intermediate temperature of 20 °C.

2.2. Linear amplitude sweep (LAS) test

The standard LAS specification (AASHTO TP 101) test consists of two step (16): first, a non-destructive frequency sweep test is run to determine the non-damaged material properties of the tested binder sample. Then, a cyclic loading of oscillatory strain sweep with the strain amplitudes ranging from 0.1% to 30% in 5 min (hereinafter referred to LAS-5) is conducted to quantify the fatigue damage tolerance of asphalt binder. A typical measured stress-strain curve from LAS-5 test is shown in Fig. 1(a).

Recently, Wang et al. proposed a *pseudo strain energy* (PSE) based failure definition for the LAS data analysis and the Eq. (1) presents the calculation method for the parameter of *stored PSE* (W_s^R) during the LAS test. It was previously demonstrated that the W_s^R firstly increased during the LAS test followed by decrease and thus, a maximum W_s^R can be identified which implies that the material is losing the ability to store PSE as the loading input increases, as typically shown in Fig. 1(b). This maximum W_s^R is proposed to define the cohesive failure within asphalt binder in the LAS test (23). The identified failure point is also typically shown on the LAS stress-strain curve in Fig. 1(a).

$$W_s^R = \frac{1}{2} \cdot \tau_p \cdot \gamma_p^R \tag{1}$$

$$\gamma_p^R = |G^*|_{LVE} \cdot \gamma_p \tag{2}$$

$$\gamma_p = \mathrm{CSR} \cdot \mathrm{t} \tag{3}$$

Table 1
Summary of tested asphalt binders.

Asphalt Binder Materials	Binder ID	Modifier Addition
Neat Asphalt Binders	30#	/
	50#	/
	70#	/
SBS Modified Asphalt Binders	SBS-R	4% SBS radial additives
	SBS-L	4% SBS linear additives
High Viscosity Asphalt Binder	HV	4% High viscosity additives
SBS+HV Modified Asphalt Binders	SBS+5% HV	4% SBS radial+5% high viscosity additives
	SBS+8% HV	4% SBS radial+8% high viscosity additives
High Modulus Asphalt Binders	HMAB	0.3% Polyolefin additives