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Identifying fatigue failure in asphalt binder time sweep tests

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HIGHLIGHTS

- The fatigue failure of asphalt binder is identified by both phenomenological and energy-based parameters.
- Phenomenological parameters consist of $S_{0.5}$, maximum $S \times N$ and maximum phase angle.
- Dissipated energy parameters include *DER* and *RDEC* approaches.
- Statistical analysis indicate that maximum $S \times N$, maximum phase angle and *RDEC* approach are effective to define identical fatigue lives.

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ABSTRACT

Identification of fatigue failure of asphalt binder in time sweep test results remains a question crucial to asphalt binder fatigue performance evaluation and prediction. This paper presents a comparison of different analysis approaches for defining the occurrence of fatigue failure during time sweep fatigue tests conducted in both control-displacement and control-stress loading modes. The candidate failure definitions evaluated include the traditional 50% reduction in stiffness parameter ($S_{0.5}$), dissipated energy indicators including the dissipated energy ratio (*DER*) and the ratio of dissipated energy change (*RDEC*), as well as two phenomenological parameters corresponding to the peak in $S \times N$ and peak in phase angle. Both phenomenological parameters and dissipated energy based indicators were found to be effective in defining fatigue failure. Statistical analysis results further indicate that maximum $S \times N$, maximum phase angle and *RDEC* approach provide equivalent fatigue life results, however, peak in $S \times N$ is strongly recommended for detecting fatigue failure of asphalt binder in time sweep tests because it is easy to calculate and well defined.

1. Introduction

Fatigue cracking, resulting from repeated traffic loading, is a primary distress in asphalt pavements. Many factors including climate, loading history, material properties, structural design, and maintenance activities impact the fatigue performance of pavements. For accurate performance assessment and prediction of the complex fatigue cracking phenomenon, characterization of material properties coupled with pavement structural analysis are required. For material characterization, multi-scale modeling approaches are gaining interest in recent years which have the potential to elude underlying mechanisms of distress and constituent material contribution to performance. Asphalt binder characterization is generally used as an input to such multi-scale model frameworks. Fatigue cracks generally initiate and propagate within the binder or mastic phase of asphalt concrete. Therefore, the fatigue resistance of asphalt binder can contribute significantly to the overall fatigue performance of an asphalt pavement.

According to the current Performance-Grading (PG) specification for asphalt binder, developed under the Strategic Highway Research Program (SHRP), the Dynamic Shear Rheometer (DSR) is employed for evaluating the viscoelastic properties of asphalt binder in terms of rutting and fatigue potential [1]. However, verification and calibration efforts for PG specification have clearly demonstrated that the linear viscoelastic SHRP parameter used to evaluate fatigue resistance, ($|G^*| \cdot \sin\delta$ et al.), is not related to mixture or pavement fatigue, especially when modified asphalt binders are used. To improve the PG specification, the Time Sweep (TS) test was introduced during NCHRP 9-10 for improved binder fatigue characterization [2–4]. The TS test was designed to follow the common experimental means of evaluating fatigue damage, which is the material integrity deterioration under repeated loading. The

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Table 1
Summary of tested asphalt binders.

Binders	Modifiers	PG Grade
Neat-NC	None	PG 64-22
Control	None	PG 70-22
CR-TB	5.5% crumb rubber + 1.8% SBS rubber terminal blended	PG 76-28
Terpolymer (TP)	2.2% reactive terpolymer	PG 70-28
SBS-LG	3% linearly grafted SBS polymer	PG 70-28
SBS-BJ	2% linearly grafted SBS polymer	PG 76-28
CR-BJ	5% crumb rubber	PG 76-22
SBS-HD	5% linearly grafted SBS polymer	PG 70-22

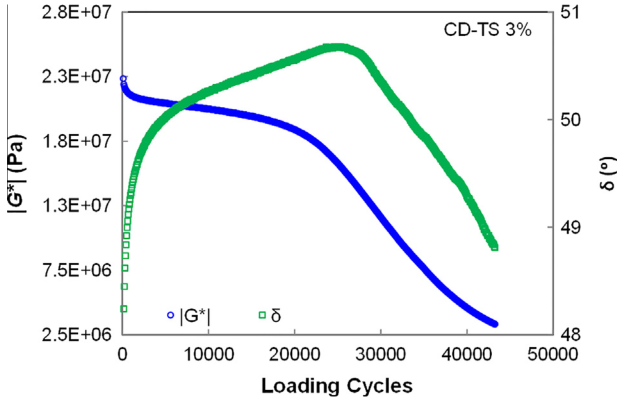

Fig. 1. Typical materials responses during control-displacement time sweep (CD-TS) fatigue test.

TS procedure consists of applying repeated sinusoidal loading at fixed frequency and amplitude in either controlled stress or controlled displacement mode. However, a unified means to clearly define fatigue failure in TS tests is missing but crucial to fatigue performance evaluation and prediction.

A significant amount of research has been devoted to defining fatigue failure in asphalt material tests. The simplest fatigue failure definition used in asphalt material tests is 50% loss in stiffness or pseudo stiffness [5–10]. However, this stiffness reduction approach to defining fatigue failure has been challenged because it is arbitrary, without any theoretical or phenomenological justification. Dissipated energy concepts have been used as the basis for alternative, more fundamental, definitions of fatigue failure, including the Dissipated Energy Ratio (*DER*) [11–20] and ratio of Dissipated Energy Change (*RDEC*) [21–25]. Another popular approach for defining the fatigue failure of asphalt materials is to use phenomenological parameters which correspond to marked changes in damage evolution. The peak in phase angle has been applied for defining fatigue failure of asphalt concrete and fine aggregate mortar [26–28]. The peak in $S \times N$, where S is the stiffness ratio and N is the number of loading cycles, was derived from the dissipated energy concept and unified as a simple phenomenological indicator of fatigue failure [29]. The maximum $S \times N$ is employed in ASTM bending fatigue specification [30] and recently extended to binder fatigue failure analysis [31,32]. The aforementioned phenomenological failure parameters have been shown to correlate well with the onset of macro-cracking when applied to asphalt mixtures and also demonstrated promise for identifying fatigue failure in asphalt binders [33].

The objective of this study is to compare the fatigue life of asphalt binders determined from different failure definition approaches applied to TS test results. Such results could provide insightful information towards identifying a unified material-dependent fatigue failure definition for asphalt materials for multiple length scales and under different testing modes.

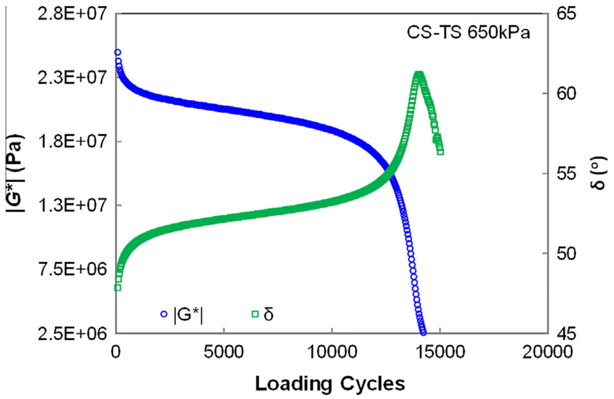

Fig. 2. Typical materials responses during control-stress time sweep (CS-TS) fatigue test.

Table 2
Time sweep fatigue test plan.

Material Name	Material ID	Aging Level	Control Mode	Loading Level	Temperature (°C)
Neat-NC	M1	STA	CD	2%	18
			CD	3%	18
			CD	4%	18
			CS	500 kPa	18
	M2	LTA1	CD	2%	18
			CD	2.5%	18
			CD	3%	18
	M3	LTA2	CD	2%	18
			CD	2.5%	18
			CD	3%	18
			CD	4%	18
	M4	LTA3	CD	1%	18
			CD	2%	18
Control	M5	OB	CD	3%	19
			CS	450 kPa	19
	M6	RTFO	CD	3%	19
			CD	5%	19
			CD	7%	19
			CS	650 kPa	19
			CD	7%	21.2
CR-TB	M7	OB	CD	3%	19
			CD	5%	19
			CD	7%	19
	M8	RTFO	CD	5%	19
			CD	7%	19
			CD	7%	12.1
TP	M9	OB	CD	5%	19
			CD	7%	19
	M10	RTFO	CD	5%	19
			CD	7%	19
			CD	7%	10.8
SBS-LG	M11	OB	CD	5%	19
			CD	7%	19
	M12	RTFO	CD	5%	19
			CD	7%	19
			CD	7%	12.0
SBS-BJ	M13	RTFO	CS	120 kPa	25
CR-BJ	M14	RTFO	CS	120 kPa	25
SBS-HD	M15	RTFO	CS	200 kPa	25

2. Materials and testing

2.1. Materials

Eight asphalt binders were tested in this study. These binders are referred to as Neat-NC, Control, CR-TB, Terpolymer (hereinafter