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Application of the logit model for the analysis of asphalt fatigue tests results

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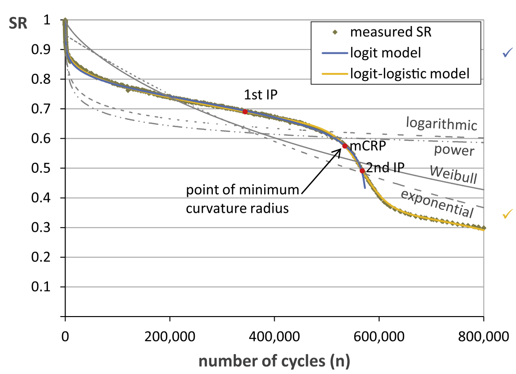
HIGHLIGHTS

- Two models are proposed to reproduce stiffness reduction during asphalt fatigue testing.
- The most suitable model must be selected depending on the level of damage.
- Proposed models significantly improve performance of the models available so far.
- One of the proposed models can reproduce post-failure stiffness reduction.
- One of the models can also reproduce phase angle evolution.

GRAPHICAL ABSTRACT



Stiffness Ratio (SR) Models

✓ Logit model can be used to reproduce SR up to the failure phase (mCRP / 2nd IP).

$$SR = SR_0 - \beta \cdot \ln\left(\frac{p^{\gamma}}{1-p^{\gamma}}\right) = SR_0 - \beta \cdot \text{logit}(p^{\gamma})$$

$$p = \frac{n - N_0}{N_L - N_0}$$ (probability of specimen failure)

✓ Logit-logistic model can reproduce SR beyond failure phase.

$$SR = [SR_0 - \beta \cdot \text{logit}(p^{\gamma})] \cdot \left[a + \frac{1-a}{1 + e^{b\left(\frac{n}{N1}-1\right)}}\right]$$

Logit-logistic model can also reproduce phase angle evolution.

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ABSTRACT

This paper explores the applicability of the logit function to reproduce the evolution of the stiffness of asphalt specimens during fatigue testing. Three logit-based models are formulated, and they are evaluated on the basis of a comprehensive database. Two of the models are proposed after such evaluation, so the most suitable one must be selected depending on the level of damage the specimen has undergone during testing (up to failure, beyond failure phase). One of these two models was also found to reproduce phase angle evolution. The general conclusion is that proposed models significantly improve performance of other models available so far (exponential, power, logarithmic, and Weibull), and provide an almost perfect fit to experimental data regardless of mixture type and testing procedure and conditions.

1. Introduction

Cracking is considered one of the main distress mechanisms of asphalt pavements. Its importance has been known for decades [1], and its prediction is one of the main goals of the great majority of pavement analytical design approaches, including the AASHTOWare Pavement Mechanistic-Empirical Design software [2]. Either it is initiated at the bottom of the asphalt layer

Abbreviations: SR, stiffness ratio; PR, phase angle ratio.

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(bottom-up) or at the surface (top-down), load-related cracking is the result of asphalt fatigue under traffic loads in combination with environmental effects. Different mechanistic-empirical approaches exist for studying this phenomenon. Most of these approaches are based on laboratory fatigue testing, where an asphalt specimen is subjected to repeated loading until a failure criteria is achieved [3].

The rough output of an asphalt fatigue test is the evolution of the overall stiffness of the specimen *vs* number of cycles (n). Stiffness is characterized in terms of the complex modulus in harmonic-loading tests (typically conducted in bending), while it is characterized in terms of the resilient modulus in pulse-loading tests (typically conducted in indirect-tension) [3]. Complex modulus, E^*, is a complex number whose magnitude, termed dynamic modulus, $|E^*|$, is the ratio of peak cyclic stress to peak cyclic strain under harmonic loading, and whose argument, φ, is referred to as phase angle and is the lag between stress and strain. Resilient modulus (Mr) is the ratio of a pulse-loading peak stress to the strain recovered after the load is retired.

The rough output of asphalt fatigue tests is typically processed for different purposes, with determination of number of cycles to failure (N_f) being the most frequent. A number of failure criteria have been proposed. The simplest criterion establishes N_f as the point where specimen modulus ($|E^*|$ or Mr) is reduced to 50% of its initial value, as it is the case of the European and AASHTO standards for asphalt fatigue testing, EN 12697-24 and AASHTO T 321-07, respectively. Other failure criteria have been proposed based on dissipated energy, a function of $|E^*|\cdot\sin(\varphi)$. For strain-controlled fatigue tests, Hopman et al. [4] and Pronk and Hopman [5] defined energy ratios (ER) that change linearly with the number of cycles until a sharp crack appears in the specimen, thus determining N_f as the point where ER *vs* n deviates from a straight line. Shen et al. [6] used the ratio of dissipated energy change (RDEC), which depends on the slope of the dissipated energy *vs* number of cycles, and they defined N_f as the point where a sharp increase of RDEC takes place. A simplified energy ratio according to Rowe and Bouldin [7], $|E^*|\cdot n$, has been incorporated to ASTM D 7460-10 standard, where N_f is defined as the point where such ratio reaches the maximum value. Processing the rough output of asphalt fatigue tests is also required for modeling purposes [8], and in order to extrapolate fatigue life when the failure criterion is not reached during the test. Different functions have been used with this purpose, which are typically fitted to just part of the available data in a process that involves a high degree of subjectivity [9].

Despite the need of data processing, an appropriate analytical expression is not available for the stiffness reduction curve during fatigue testing and neither for the evolution of the phase angle, which makes data processing time-consuming, cumbersome and, frequently, highly subjective. Several functions have been proposed in order to fit the stiffness reduction curve. The exponential model, $a\cdot\exp(b\cdot n)$, is proposed by AASHTO T 321-07. ASTM D 7460-10 recommends a polynomial function to fit $|E^*|\cdot n$ evolution in order to determine its maximum, while it introduces the Weibull function to extrapolate stiffness reduction when the failure criterion has not been achieved. The use of the Weibull function for predicting stiffness reduction during asphalt fatigue testing was proposed by Tsai et al. [10], who simplified the general expression of this model to the following one: $\ln(-\ln(\mathrm{SR})) = a + b\cdot\ln(n)$, where $\mathrm{SR} = |E^*|/|E^*|_{\mathrm{initial}}$. Prowell et al. [9] used this model to extrapolate fatigue life, and they also evaluated the exponential, power, and logarithmic models, the last two models being $a\cdot n\hat{\ }b$ and $a + b\cdot\ln(n)$, respectively. None of these functions provided acceptable results in all cases, although they concluded the Weibull model appeared to give the most reasonable extrapolation of fatigue test results. The lack of an appropriate function is more evident in the case of the phase angle (φ *vs* n), for which no expression has been proposed so far.

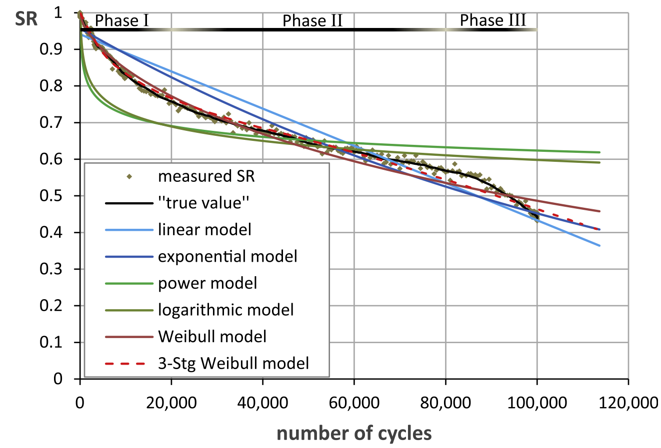

Fig. 1. Example of stiffness ratio evolution during asphalt fatigue testing ($\mathrm{SR} = |E^*|/|E^*|_{\mathrm{initial}}$).

Fig. 1 shows the evolution of stiffness ratio, $|E^*|/|E^*|_{\mathrm{initial}}$, during a typical asphalt fatigue test. Best fits to experimental data (exponential, power, logarithmic, and Weibull models) are also presented in Fig. 1. Three phases can be distinguished in this figure, as reported by Di Benedetto et al. [3]: Phase I, adaptation phase, where a rapid decrease of stiffness takes place (besides asphalt fatigue, heating caused by energy dissipation due to viscoelasticity and probably other reversible phenomena, such as thixotropy, are behind this rapid change); Phase II, quasi-stationary phase, where stiffness changes almost linearly *vs* number of cycles while a network of microcracks is continuously distributed in the material; and finally Phase III, failure phase, where stiffness rate of reduction increases due to coalescence of microcracks to form a sharp crack. This pattern of evolution entails an inflection point, i.e., curvature sign will change during Phase II. This curvature sign change, that has been reported for long time [11], is probably the main reason behind the impossibility of the previous functions (exponential, power, logarithmic, and Weibull) to fit the complete $|E^*|$ *vs* n curve. It can be shown that these four functions result in a curvature that is continuously decreasing in magnitude and always positive. In the best case, they will reproduce half of the complete curve, up to the inflection point, but they never will be able to reproduce the increasing rate of damage accumulation as Phase III approaches. Partial solution to this problem results from piecewise functions, which are defined by multiple sub-functions, each sub-function applying to a certain interval of cycles. This alternative was followed by Tsai et al. [12], who proposed a three-stage Weibull equation with six independent parameters that can be calculated by using a specific software developed by the authors. However, only partial improvement of the goodness of fit is achieved, as reflected in Fig. 1 example.

The Pattern of evolution of measured stiffness ratio in Fig. 1 resembles a sigmoidal function. This shape is actually related to the three phases that take place in fatigue testing, as described above. Consequently, improvement of the goodness of fit could be expected when sigmoidal-type functions are used instead of the constant-curvature-sign functions reported previously. However, this approach has not been evaluated for asphalt fatigue testing.

1.1. Objective

The objective of the research presented herein is to propose and evaluate a sigmoidal-type model that can reproduce the stiffness reduction that takes place during fatigue testing of asphalt