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Application of viscoelastic continuum damage approach to predict fatigue performance of Binzhou perpetual pavements

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ABSTRACT

For this study, the Binzhou perpetual pavement test sections constructed in Shandong Province, China, were simulated for long-term fatigue performance using the layered viscoelastic pavement analysis for critical distresses (LVECD) finite element software package. In this framework, asphalt concrete was treated in the context of linear viscoelastic continuum damage theory. A recently developed unified fatigue failure criterion that defined the boundaries of the applicable region of the theory was also incorporated. The mechanistic modeling of the fatigue mechanisms was able to accommodate the complex temperature variations and loading conditions of the field pavements in a rigorous manner. All of the material models were conveniently characterized by dynamic modulus tests and direct tension cyclic fatigue tests in the laboratory using cylindrical specimens. By comparing the obtained damage characteristic curves and failure criteria, it is found that mixtures with small aggregate particle sizes, a dense gradation, and modified asphalt binder tended to exhibit the best fatigue resistance at the material level. The 15-year finite element structural simulation results for all the test sections indicate that fatigue performance has a strong dependence on the thickness of the asphalt pavements. Based on the predicted location and severity of the fatigue damage, it is recommended that Sections 1 and 3 of the Binzhou test sections be employed for perpetual pavement design.

1. Introduction

Over the past several decades, the type of pavement used most widely in China has been the semi-rigid asphalt pavement, which is characterized by a semi-rigid base layer, such as cement-stabilized aggregate and lime-fly ash treated soil, and overlays of asphalt concrete. This type of pavement structure is cost-effective and environmentally friendly as it is able to consume a considerable amount of industry waste

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(Cetin et al., 2010). In addition, the semi-rigid base provides stable support that is necessary for the high traffic volumes (and even overloading) typically seen in China. However, these semi-rigid materials are prone to fatigue cracking under repeated traffic loading. Once cracks initiate in the base, they propagate upward into the flexible asphalt layers, thereby leading to reflective cracking and finally the structural failure of the pavement. Hence, the design life of such pavements is usually limited to 10–15 years.

Inserting a stress-absorbing interlayer between the asphalt concrete and base materials has been one of the major remedies for reflective cracking. Nevertheless, it can only help to delay crack propagation even when high-quality material design and construction are guaranteed for the interlayer, because the base may crack as well. In the end, rehabilitation or even reconstruction is necessary for the whole pavement structure, including all the layers. With consideration of these unavoidable defects associated with the use of semi-rigid materials, another alternative, albeit expensive probably in the short term, is perpetual pavement. Perpetual pavements are typically designed to last 40–50 years without structural failure and only the surface asphalt layer requires rehabilitation or replacement when necessary. Therefore, in the long run, perpetual pavements could be a good choice that provides high cost-effectiveness and sustainability (Amini et al., 2012).

Traditionally, perpetual pavements have been designed by invoking the concept of limiting the critical pavement responses. Generally, the belief is that if the imposed traffic loads produce responses below certain threshold values, then structural damage will not accumulate. The critical pavement responses of interest are the vertical compressive strain at the top of the subgrade and the horizontal tensile strain at the bottom of the asphalt layers for structural rutting and bottom-up fatigue cracking, respectively (Behiry, 2012).

In order to limit rutting to the upper few inches of the pavements, an increase in the structure's thickness or in the stiffness of the materials is required so that the vertical load can be distributed more widely before reaching the subgrade. Experimental evaluation tools for material rutting resistance include the asphalt pavement analyzer, Hamburg wheel-tracking device, and heavy vehicle simulator, to list a few. To simulate the materials' macroscopic behavior and to further understand the underlying deformation mechanisms, readers are encouraged to follow the work by, for example, Cao and Kim (2016), Choi (2013), and Darabi et al. (2012).

On the fatigue side, one way to decrease the probability of bottom-up cracking is to increase the structural thickness as well, thereby reducing the maximum tensile strain at the bottom of the asphalt pavements. The bending beam test has been used conventionally in the laboratory to evaluate the fatigue resistance of asphalt mixtures and to investigate the concept of a fatigue endurance limit, which is the aforementioned threshold level of tensile strain. More advanced explorations regarding the concept of an endurance limit have been conducted by Underwood and Kim (2009) and Bhattacharjee et al. (2009) in the context of viscoelastic continuum damage (VECD) theory.

Despite their wide acceptance, the traditional design principles for perpetual pavements as mentioned above are subject to question. During its service life, a pavement undergoes complex traffic and environmental conditions, and thus, consideration of the effects of temperature, aging, and healing, should be included in both the material and structural design as they all lead to variations in the material properties. Clearly, to approve or disapprove a mix design by testing the material only under certain pre-specified conditions is not a sufficiently persuasive or rigorous approach.

This paper focuses on material characterization and pavement performance evaluation with regard to bottom-up fatigue cracking. A comprehensive analysis system is presented, and its applicability and versatility are demonstrated via simulations of the Binzhou perpetual pavement test sections in Shandong Province, China. The effects of temperature have been incorporated in this framework through the rigorous mechanistic modeling of the asphalt materials. As for other factors, such as aging and healing, continuous efforts are being made in the ongoing research and their effects will be taken into consideration in the future to complete the modeling framework.

2. Overview of Binzhou test sections

Six different asphalt mixes were designed for the Binzhou project. The material designations and descriptions are listed in Table 1. Five different sections were constructed, and the structural layout is illustrated in Fig. 1. As can be observed from Fig. 1, Sections 1–3 are categorized as full-depth asphalt pavements, which reflect the typical design of perpetual pavements in Europe and North America. In this project, Section 1 was designed using 70 $\mu\epsilon$ as the critical value for the tensile strain at the bottom of the pavements, whereas Sections 2 and 3 were designed for 125 $\mu\epsilon$. Section 5 was the semi-rigid asphalt pavement that is used widely in China, as mentioned previously. Section 4 had a design similar to that of Section 5 in which the thickness of the asphalt layers had been increased considerably by inserting a layer of large stone porous mixture (LSPM) right above the semi-rigid base. Note that for all the test sections, the top 30 cm of the subgrade was treated with lime in the field construction in order to increase the soil modulus.

Table 1 – Asphalt concrete materials used in Binzhou test sections.

Designation	Description
SMA	Stone matrix asphalt (PG 76-22, MAC modified)
Superpave-19	19 mm NMAS superpave (PG 76-22, MAC modified)
Superpave-25	25 mm NMAS superpave (PG 64-22)
LSPM	25 mm large stone porous mixture (PG 70-22, MAC modified)
F-1	12.5 mm NMAS superpave fatigue layer (PG 64-22)
F-2	12.5 mm NMAS superpave fatigue layer (PG 76-22, SBS modified)

Note: MAC means multigrade asphalt cement; SBS means styrene-butadiene-styrene.