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Thermal stress of asphalt pavement based on dynamic characteristics of asphalt mixtures

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Abstract

This paper presents a rational analytical approach for estimation of thermal stress in asphalt pavements by taking dynamic mechanical characteristics of asphalt mixture layers into consideration. The analytical solution for thermal stress in single layer was derived by utilizing thermal equations of equilibrium and integral transformation. Then the analytical solution of thermal stress for an asphalt pavement structure was derived by transfer matrix method in multilayer elastic system. Functional relationship between the dynamic modulus of representative asphalt mixture and the temperature that was used for the analytical calculation of thermal stress was obtained based on dynamic modulus testing on asphalt mixtures. The proposed approach has been illustrated through a numerical example. Result shows clear difference of calculating results considering dynamic mechanical characteristics of asphalt mixture layers to those with static parameters.

Keywords: Asphalt pavement; Thermal stress; Dynamic modulus; Integral transformation; Transfer matrix

1. Introduction

Thermal cracking of asphalt pavement is a common phenomenon in cold regions. This failure manifests as a series of transverse cracks that extend across the pavement surface in response to the comprehensive action of cold ambient temperatures and vehicle load.

The primary concern regarding this distress is the ingress of moisture to the pavement structure through thermal cracks. The existence of water can increase the stripping rate of asphalt concrete. Also, water infiltration can lead to a progressive depression at the thermal crack by promoting pumping of unbound fines in the underlying material. Additionally, ice lens could form beneath a thermal crack and then progress into an upward lipping or tenting of the crack edges. Finally, thermal cracks can act as stress focal points from which longitudinal cracks may form. In consequence, considering vehicle loading and temperature changing along with time, it is very important to enhance the condition of road operation and design of cracking resistance of asphalt pavement by studying stress response of asphalt pavement [1–3]. Many elaborate studies have been performed on this topic. Hill and Brien developed a model of estimating fracture, in which thermal stress can be calculated while the temperature fall, but it failed to take into account the temperature gradient along the pavement depth [4]. Christison predicted thermal stress and low temperature fracture susceptibility of asphalt pavements [5]. Harik took the research on a two-dimensional issue of non-

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linear temperature distributions through the thickness of rigid pavements using the finite-element method [6]. Zhong and Wang used transfer matrix method to derive the analytic solution of multi-layer elastic half-space system [7]. Wu researched thermal stress of two-dimensional layered pavement structure using boundary value theory of generalized analytic function and theory of singular integral equation [8]. Zhong calculated the theoretical solutions of thermal stress for axisymmetric problem in multilayered elastic half-space system in a combined action of vehicle loading and temperature through stiffness matrix method [9]. Geng analyzed the thermal stress in asphalt pavement by transfer matrix method [10]. In these researches, static modulus of asphalt layers was assumed as material parameter for the derivation. Researchers have indicated that modulus of asphalt mixture would change with temperature and loading frequency [11,12]. In case of slow temperature drop within a narrow range, these above assumptions are reasonable. Under conditions of a sharp drop in temperature or the combined action of vehicle loading and temperature, it would be more rational taking dynamic modulus of asphalt mixture layers into consideration for thermal stress analysis.

In this article, thermal stress in asphalt pavement was researched by taking dynamic mechanical characteristics of asphalt mixture into consideration. Analytical solution for thermal stress in single layer was derived using Laplace integral transformation and Hankel integral transformation based on thermal equations of equilibrium. Then asphalt pavement structure was assumed as a multilayer elastic system and its analytical solution of thermal stress induced by temperature decrease was derived with transfer matrix method. In this system, dynamic modulus of asphalt mixtures was obtained by dynamic modulus test. Case study shows big difference between thermal stresses with dynamic modulus and those with static parameters. The calculating results through this paper might be closer to the true stress solution of asphalt pavement. But further steps are still needed in the further study, i.e. validation of the accuracy of the results through actual measurements of pavement response, consideration of viscoelasticity of asphalt layers for the analysis.

2. Derivation of transfer matrix of multilayered elastic system

When not considering physical strength, the equations of equilibrium in the axisymmetric system are:

$$\left.\begin{array}{c} \frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{zr}}{\partial z} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \\ \frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{zr}}{\partial r} + \frac{\tau_{zr}}{r} = 0 \end{array}\right\} \tag{1}$$

where, σ_r, σ_θ and σ_z are normal stresses in the r, θ and z directions; τ_{zr} is the shear stress.

The constitutive of an axisymmetric system can be expressed as follows:

$$\left.\begin{array}{c} \sigma_r = \frac{E^*}{1+\mu}\left[\frac{\mu}{1-2\mu} e + \frac{\partial u}{\partial r}\right] - \frac{\alpha E^* T}{1-2\mu} \\ \sigma_\theta = \frac{E^*}{1+\mu}\left[\frac{\mu}{1-2\mu} e + \frac{u}{r}\right] - \frac{\alpha E^* T}{1-2\mu} \\ \sigma_Z = \frac{E^*}{1+\mu}\left[\frac{\mu}{1-2\mu} e + \frac{\partial w}{\partial z}\right] - \frac{\alpha E^* T}{1-2\mu} \\ \tau_{zr} = \frac{E^*}{2(1+\mu)}\left[\frac{\partial u}{\partial z} + \frac{\partial w}{\partial r}\right] \end{array}\right\} \tag{2}$$

in which, E^* represents dynamic modulus, a function of temperature and vehicle loading frequency; μ and α represent poisson ratio and thermal expansion coefficient; u and w represent the radial and vertical displacements; $e = \frac{\partial u}{\partial r} + \frac{u}{r} + \frac{\partial w}{\partial z}$; T is function of temperature.

The heat diffusion equation for the asphalt pavement can be presented as:

$$\lambda_T \nabla^2 T = \frac{\partial T}{\partial t} \tag{3}$$

in which, λ_T is thermal conductivity coefficient; $\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}$.

The first equation in Eq. (1) is applied by $\frac{\partial}{\partial r} + \frac{1}{r}$, and the second one is applied partial derivative of z, resulting in the following equation:

$$\nabla^2 e = \alpha \frac{1+\mu}{1-\mu} \nabla^2 T \tag{4}$$

Then the governing equation of elastic space axisymmetric system can be expressed as:

$$\left.\begin{array}{c} \frac{1}{1-2\mu}\frac{\partial e}{\partial r} + \nabla^2 u - \frac{u}{r^2} = \frac{2\alpha(1+\mu)}{1-2\mu}\frac{\partial T}{\partial r} \\ \frac{1}{1-2\mu}\frac{\partial e}{\partial z} + \nabla^2 w = \frac{2\alpha(1+\mu)}{1-2\mu}\frac{\partial T}{\partial z} \\ \nabla^2 e = \alpha \frac{1+\mu}{1-\mu} \nabla^2 T \\ \lambda_T \nabla^2 T = \frac{\partial T}{\partial t} \end{array}\right\} \tag{5}$$

Laplace transformation Eq. (6) is utilized on both sides of foundation in Eq. (5), and the Laplace inverse transformation is described in Eq. (7). Then Hankel transformation is also utilized on Eq. (5), resulting in Eqs. (8)-(11):

$$\hat{f}(r,z,s) = \int_0^\infty f(r,z,t) e^{-st} dt \tag{6}$$

$$f(r,z,t) = \int_0^\infty \hat{f}(r,z,s) e^{st} ds \tag{7}$$

$$\frac{d^2 \hat{\bar{u}}}{dz^2} - \xi^2 \hat{\bar{u}} - \frac{\xi}{1-2\mu} \hat{\bar{e}} + \frac{2\alpha(1+\mu)\xi}{1-2\mu} \hat{\bar{T}} = 0 \tag{8}$$

$$\frac{d^2 \hat{\bar{w}}}{dz^2} - \xi^2 \hat{\bar{w}} + \frac{1}{1-2\mu} \hat{\bar{e}} - \frac{2\alpha(1+\mu)}{1-2\mu} \frac{\partial \hat{\bar{T}}}{\partial z} = 0 \tag{9}$$

$$\frac{d^2 \hat{\bar{e}}}{dz^2} - \xi^2 \hat{\bar{e}} - \alpha \frac{(1+\mu)s}{(1-\mu)\lambda} \hat{\bar{T}} = 0 \tag{10}$$

$$\frac{d^2 \hat{\bar{T}}}{dz^2} - (\xi^2 + \frac{s}{\lambda}) \hat{\bar{T}} = 0 \tag{11}$$