International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:9, No:11, 2015

Response of Pavement under Temperature and Vehicle Coupled Loading

Yang Zhong, Mei-jie Xu

***Abstract*—**To study the dynamic mechanics response of asphalt pavement under the temperature load and vehicle loading, asphalt pavement was regarded as multilayered elastic half-space system, and theory analysis was conducted by regarding dynamic modulus of asphalt mixture as the parameter. Firstly, based on the dynamic modulus test of asphalt mixture, function relationship between the dynamic modulus of representative asphalt mixture and temperature was obtained. In addition, the analytical solution for thermal stress in single layer was derived by using Laplace integral transformation and Hankel integral transformation respectively by using thermal equations of equilibrium. The analytical solution of calculation model of thermal stress in asphalt pavement was derived by transfer matrix of thermal stress in multilayer elastic system. Finally, the variation of thermal stress in pavement structure was analyzed. The result shows that there is obvious difference between the thermal stress based on dynamic modulus and the solution based on static modulus. So the dynamic change of parameter in asphalt mixture should be taken into consideration when theoretical analysis is taken out.

***Keywords*—**Asphalt pavement, dynamic modulus, integral transformation, transfer matrix, thermal stress.

I. Introduction

UNDER the action of vehicle loading and temperature circularly changing, the cracks are easy to produce on asphalt pavement. While cracks get through pavement, damage will be caused by water entering into the base course. In consequence, based on the rules of 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] In view of the cracking of asphalt pavement, scholars have done a lot of research by establishing model of pavement structure and analyzing temperature field. Hill and Brien developed model of estimating fracture, in which thermal stress can be calculated while the temperature fell, but it ignored the temperature gradient along the pavement depth [4]. Christison predicted thermal stress and low temperature fracture susceptibility of asphaltic concrete pavements [5]. Harik et al. took the research on a two-dimensional issue of nonlinear temperature distributions through the thickness of rigid pavements by 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 by using boundary value theory of generalized analytic function and theory of singular integral equation [8]. Zhong and Geng used stiffness matrix method to calculate the solutions of thermal stresses for axisymmetric problem in multilayered elastic half-space system in combined action of vehicle loading and temperature [9]. Geng and Zhong used transfer matrix method to analysis thermal stress of asphalt pavement with the material characteristics changing with temperature [10]. All these researches used different methods to derive the thermal stress of asphalt pavement as multilayered elastic half-space system, in which static modulus was assumed. But some researches indicated that modulus of asphalt would change while the external temperature and frequency of vehicle loading changed [11]-[12].

In this article, stress distribution of asphalt pavement was researched by regarding asphalt pavement as multilayered elastic half-space system and taking dynamic modulus as parameter. First of all, the laws of temperature and vehicle loading changing along with time in one day was analyzed, and based on the test of dynamic modulus of asphalt mixture, dynamic modulus of asphalt mixture with a function of time was get using time-temperature displacement principle. The analytical solution for thermal stress in single layer was derived by using Laplace integral transformation and Hankel integral transformation respectively by using thermal equations of equilibrium. The analytical solution of calculation model of thermal stress in asphalt pavement was derived by transfer matrix of thermal stress in multilayer elastic system. The stresses based on dynamic modulus and static modulus have obvious differences, therefor, dynamic modulus should be considered when theoretical analysis was taken out.

II. Derivation of Transfer Matrix of Multilayered Elastic System

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

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

The constitutive of an axisymmetric system can be expressed as:

Prof. Dr. Yang Zhong is with the Dalian University of Technology, China (e-mail: Zhongy@dlut.edu.cn).

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

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, $e=\frac{\partial u}{\partial r}+\frac{u}{r}+\frac{\partial w}{\partial z}$; E* represents dynamic modulus, a function of temperature and vehicle loading frequency; μ and α represent Poisson ratio and thermal expansion coefficient; λT 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 (1) was applied $\frac{\partial}{\partial r}+\frac{1}{r}$, the second equation was applied partial derivative of z, resulting in:

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

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

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

Laplace transformation (6) and Laplace inverse transformation (7) are utilized on both sides of first foundation in (5), and Hankel transformation are utilized on (5), resulting in (8)-(11):

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

$$f(r,z,s)=\frac{1}{2i\pi}\int_{\sigma-i\infty}^{\sigma+i\infty}\hat{f}(r,z,s)e^{st}ds \tag{7}$$

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

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

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

$$\frac{d^2\hat{\tilde{e}}}{dz^2}-\xi^2\hat{\tilde{e}}-\alpha\frac{(1+\mu)s}{(1-\mu)\lambda_T}\hat{\tilde{T}}=0 \tag{11}$$

The solutions of (8)-(11) are:

$$\hat{\tilde{\mathrm{u}}}=-\xi(A_1e^{qz}+B_1e^{-qz})+d_1e^{\xi z}-d_2e^{-\xi z}+A_3e^{\xi z}+B_3e^{-\xi z} \tag{12}$$

$$\hat{\tilde{w}}=q(A_1e^{qz}-B_1e^{-qz})-d_1A_2e^{\xi z}-d_2B_2e^{-\xi z}+A_4e^{\xi z}+B_4e^{-\xi z} \tag{13}$$

$$\hat{\tilde{e}}=\frac{s}{\lambda_T}(A_1e^{qz}+B_1e^{-qz})+4(1-2\mu)(A_2e^{\xi z}+B_2e^{-\xi z}) \tag{14}$$

$$\hat{\tilde{\mathrm{T}}}=m(A_1e^{qz}+B_1e^{-qz}) \tag{15}$$

in which,

$$m=\alpha\frac{(1+\mu)\lambda_T}{(1-\mu)s};\ d_1=\frac{2z\xi-1}{\xi};\ d_2=\frac{2z\xi+1}{\xi};$$

$$A_4=\frac{2(3-4\mu)A_2-\xi A_3}{\xi};\ B_4=\frac{\xi B_3-2(3-4\mu)B_2}{\xi}$$

Applying zero order Hankel and one order Hankel on third function and forth function of (2), the solution can be written as:

$$\hat{\tilde{\sigma}}_z=2G\xi^2(A_1e^{qz}+B_1e^{-qz})+d_7A_2e^{\xi z}+d_8B_2e^{-\xi z}-\xi(A_3e^{\xi z}+B_3e^{-\xi z}) \tag{16}$$

$$\hat{\tilde{\tau}}=-2qG\xi(A_1e^{qz}-B_1e^{-qz})-d_5A_2e^{\xi z}-d_6B_2e^{-\xi z}+\xi(A_3e^{\xi z}-B_3e^{-\xi z}) \tag{17}$$

Applying Laplace transformation and zero order Hankel transformation on thermodynamic equation $Q=\lambda_T\frac{\partial T}{\partial z}$, and substituting (15) into the result, we get

$$\hat{\tilde{Q}}=mq\lambda_T(A_1e^{qz}-B_1e^{-qz}) \tag{18}$$

Taking zero of z on both sides of (12), (13), (15)-(18) and a matrix can be get as (19):

$$\begin{Bmatrix} \hat{\tilde{\sigma}}_z(\xi,0,s) \\ \hat{\tilde{\tau}}_{zr}(\xi,0,s) \\ \hat{\tilde{u}}(\xi,0,s) \\ \hat{\tilde{w}}(\xi,0,s) \\ \hat{\tilde{T}}(\xi,0,s) \\ \hat{\tilde{Q}}(\xi,0,s) \end{Bmatrix} = \begin{bmatrix} 2G\xi^2e^{qs} & 2G\xi^2 & d_7 & d_8 & -\xi & -\xi \\ -2Gq\xi & 2Gq\xi & -d_5 & d_6 & \xi & -\xi \\ -\xi & -\xi & d_1 & -d_2 & 1 & 1 \\ q & -q & d_3 & -d_4 & -1 & 1 \\ m & m & 0 & 0 & 0 & 0 \\ mq\lambda_T & -mq\lambda_T & 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} A_1 \\ B_1 \\ A_2 \\ B_2 \\ A_3 \\ B_3 \end{Bmatrix} \tag{19}$$

$$\begin{Bmatrix} \hat{\sigma}_z(\xi,z,s) \\ \hat{\tau}_{zr}(\xi,z,s) \\ \hat{u}(\xi,z,s) \\ \hat{w}(\xi,z,s) \\ \hat{T}(\xi,z,s) \\ \hat{Q}(\xi,z,s) \end{Bmatrix} = \begin{bmatrix} 2G\xi^2 e^{qz} & 2G\xi^2 e^{-qz} & d_7 e^{\xi z} & d_8 e^{-\xi z} & -\xi e^{\xi z} & -\xi e^{-\xi z} \\ -2Gq\xi e^{qz} & 2Gq\xi e^{-qz} & -d_5 e^{\xi z} & d_6 e^{-\xi z} & \xi e^{\xi z} & -\xi e^{-\xi z} \\ -\xi e^{qz} & -\xi e^{-qz} & d_1 e^{\xi z} & -d_2 e^{-\xi z} & e^{\xi z} & e^{-\xi z} \\ q e^{qz} & -q e^{-qz} & d_3 e^{\xi z} & -d_4 e^{-\xi z} & e^{\xi z} & e^{-\xi z} \\ m e^{qz} & m e^{-qz} & 0 & 0 & 0 & 0 \\ mq\lambda_T e^{qz} & -mq\lambda_T e^{-qz} & 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} A_1 \\ B_1 \\ A_2 \\ B_2 \\ A_3 \\ B_3 \end{Bmatrix} \tag{20}$$

$$\begin{Bmatrix} \hat{\sigma}_z(\xi,z,s) \\ \hat{\tau}_{zr}(\xi,z,s) \\ \hat{u}(\xi,z,s) \\ \hat{w}(\xi,z,s) \\ \hat{T}(\xi,z,s) \\ \hat{Q}(\xi,z,s) \end{Bmatrix} = \begin{bmatrix} \Phi_{11} & \Phi_{12} & \Phi_{13} & \Phi_{14} & \Phi_{15} & \Phi_{16} \\ \Phi_{21} & \Phi_{22} & \Phi_{23} & \Phi_{24} & \Phi_{25} & \Phi_{26} \\ \Phi_{31} & \Phi_{32} & \Phi_{33} & \Phi_{34} & \Phi_{35} & \Phi_{36} \\ \Phi_{41} & \Phi_{42} & \Phi_{43} & \Phi_{44} & \Phi_{45} & \Phi_{46} \\ \Phi_{51} & \Phi_{52} & \Phi_{53} & \Phi_{54} & \Phi_{55} & \Phi_{56} \\ \Phi_{61} & \Phi_{62} & \Phi_{63} & \Phi_{64} & \Phi_{65} & \Phi_{66} \end{bmatrix} \begin{Bmatrix} \hat{\sigma}_z(\xi,0,s) \\ \hat{\tau}_{zr}(\xi,0,s) \\ \hat{u}(\xi,0,s) \\ \hat{w}(\xi,0,s) \\ \hat{T}(\xi,0,s) \\ \hat{Q}(\xi,0,s) \end{Bmatrix} \tag{21}$$

III. Testing Analysis of Dynamic Modulus of Asphalt Mixture

Regarding the structure of asphalt pavement as three layers, the modulus of base course and soil base course are with 1200MPa and 60MPa respectively. The modulus of asphalt pavement changing with temperature that is the function of time seen in (22) is considered.

$$\mathrm{T} = \psi \sin\left(\frac{2\pi}{24}t + \frac{\pi}{3}\right) + 25 \tag{22}$$

Through dynamic modulus test of asphalt mixture and time-temperature displacement principle, dynamic modulus of asphalt mixture with a function of time was as:

$$\log|E^*| = \delta + \frac{Max - \delta}{1 + e^{\beta + \gamma \log f_r}} \tag{23}$$

in which, t is time; fr is conversion frequency, $\log f_r = \log f + \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} + \frac{1}{T_r}\right)$; Max represents maximum modulus of asphalt mixture; Tr is reference temperature of 20℃; δ, β and γ are all fitting parameters.

TABLE I
Parameters of Pavement Structure

structure layer	top layer	middle layer	bottom layer	base course	soil base course
Ψ/℃	20	15	10	-	-
α	2.16×10-5	2.16×10-5	2.16×10-5	1.5×10-5	5×10-4
μ	0.35	0.35	0.35	0.3	0.4
h/mm	40	60	80	200	1000

IV. Results Analysis

Considering the pavement structure in this article, the thermal stress in different layers where the modulus are different and change with time and frequency is calculated, and is compared with static analysis. The temperature in different layers is in Fig. 1 and the results can be seen in Figs. 2-4.

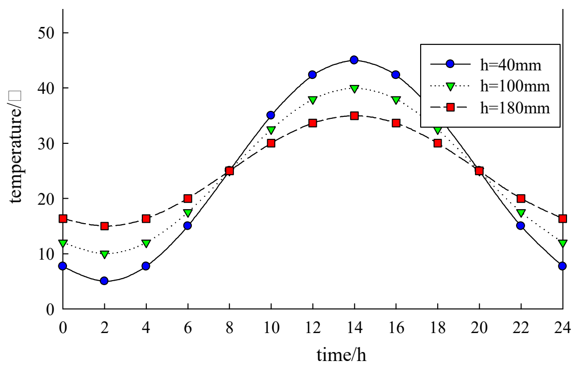

Fig. 1 Pavement temperature-time curve

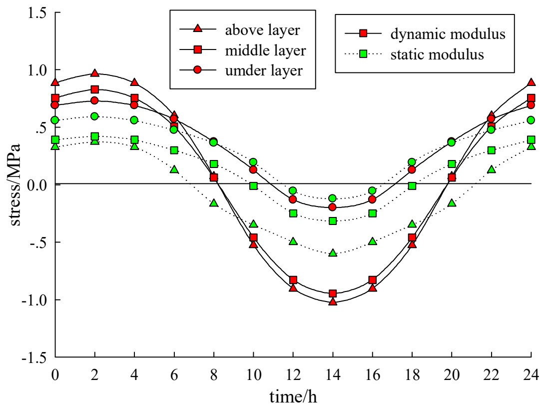

Fig. 2 Thermal stress-time curve of different modulus

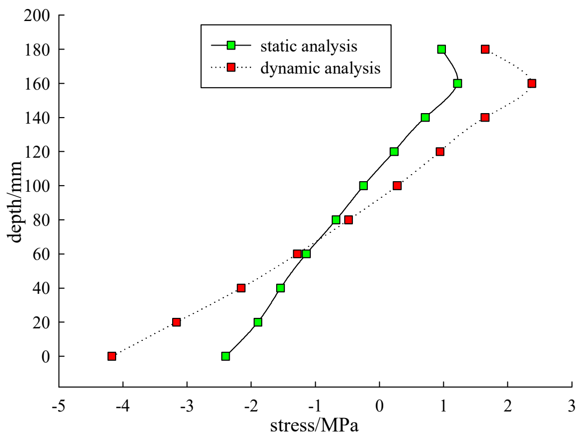

Fig. 3 Thermal stress-depth curve

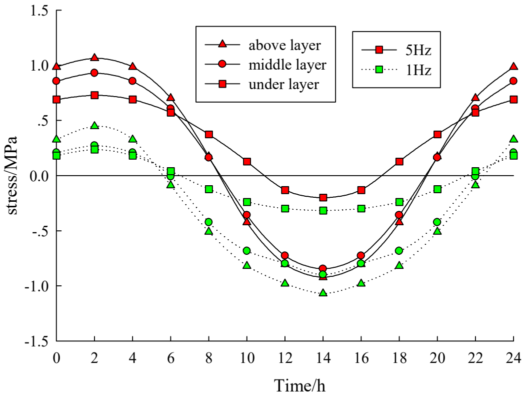

Fig. 4 Thermal stress-time curve of different frequencies

From Figs. 1 and 2, the thermal stress of pavement will decrease while the temperature increases, and the stress of the top layer changes greatest. The thermal stress of top layer at the lowest temperature becomes the biggest tensile stress and at the highest temperature is compressive stress, so the low-temperature cracking and temperature-fatigue cracking appears on the top layer firstly. The thermal stress of middle layer and bottom layer becomes compressive stress when the temperature is enough high, it illustrates rutting phenomenon of asphalt pavement at high temperature. From Figs. 2 and 3, the thermal stress (changing with time and depth) at dynamic analysis is more sensitive than that at static analysis, so dynamic analysis is closer to the actual stress of pavement. As can be seen from Fig. 4, the thermal stress is in line with loading frequency and at 5Hz is more than that at 1Hz, so it is more perfect to consider loading frequency.

V. Conclusions

Considering the modulus of asphalt mixture varying with time, thermal stress problem of asphalt pavement based on dynamic analysis are presented by integral transformations and the transfer matrix method of multilayered elastic half-space axisymmetric system. It indicates that the thermal stress with dynamic analysis is more susceptible to temperature compared with that with static analysis. In order to being closer to the true stress situation of asphalt pavement, it is reasonable to consider dynamic modulus changing with time as the parameter.

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