Cross Tension Prestressed Concrete Pavements Temperature Stresses

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ABSTRACT: Temperature fields and stresses of Cross Tension Retard-bonded Prestressed Concrete Pavements (CTRPCP), which are constituted by cross tension retard-bonded prestressed concrete slabs, sand gravel sliding layers, and semi-rigid bases, are studied. First, first, second, and fourth types heat transfer boundary conditions are programmed to analysis the CTRPCP' transient temperature fields, on ABAQUS heat transfer analysis platform. Then, the temperature fields are imported into the mechanical model to implement coupled thermo-mechanic analysis is to obtain temperature stresses of CTRPCP. On this basis, axle force gauge and vernier caliper are installed on test pavement to measure the prestressed reinforcement axial forces and displacement changes of pavement slab end with temperature changes in typical summer cloudless conditions. By comparing with the results of numerical analysis, the rationality and accuracy of the calculation model of coupled thermo-mechanical analysis of concrete pavement are verified.

INTRODUCTION

Cross tension retard-bonded prestressed concrete pavements are constituted of cross tension retard-bonded prestressed tendons that are stretched stage setting in the concrete slab, sandy gravel sliding layer, and base (Guo Chao 2015). Sandy gravel sliding layer can effectively release base constraint on up slab, cross tension retard-bonded prestressed tendon can effectively resist residual temperature stresses (Huang Wei 2000, Lou Yihong 2005). Contact-Thermal-Resistance (CTR) of the sandy gravel sliding layer make the temperature field of the pavement surface to a step type, so that the temperature gradient and temperature stress that caused by the temperature field in the pavement is different from traditional concrete pavement (Tan Zhiming 2001, 2003). At present, some scholars obtained the temporal and spatial distributions of the continuous temperature field of pavement layered system and analyze relationship between maximum temperature gradient and warped stresses of concrete pavements (Mark Belshe 2011, Pejman 2004), and mastered the influence of material thermal property and friction layer on the temperature field of concrete pavements, on the theory of heat transfer (Liao Gongyun 2014).
By analyzing prestressed reinforcement axial force of test road and slab end displacement of pavement in situ, and combining with the coupled thermo-mechanical analysis, accomplishes the calculation of the temperature stresses caused by the step type temperature field of CTRPCP.

![Diagram of CTRPCP](image)

**CTRPCP TEMPERATURE FEATURES**

**Basic Equation of CTRPCP Heat Transfer**

CTRPCP is shown in Figure 1: continuous pavement slab length over 100m, width near 10m, and thickness of 0.2m. A cross section is taken as Figure 1-a show that: the first layer is CTRPCP, the second is sandy gravel sliding layer, and the third is cement stabilized macadam base. Assuming the $i$ layer conductive coefficient of temperature is $a_i$, conductive coefficient of thermal is $\lambda_i$, thickness is $h_i (h_n=\infty)$, the temperature function of $T_i(x,t)$ should meet the heat transfer equation:

$$\frac{\partial T_i}{\partial t} = a_i \left( \frac{\partial^2 T_i}{\partial x^2} \right) \quad i = 1,2,\cdots,n$$

(1)

t: time variable.

The temperature field appears step because of CTR of sandy gravel. The fourth type boundary condition of heat transfer as follows:

$$\begin{cases}
\lambda_1 \frac{\partial T_1}{\partial x} = \frac{1}{R_e} (T_{2B} - T_{2A}) \\
\lambda_1 \frac{\partial T_1}{\partial x} = \lambda_2 \frac{\partial T_2}{\partial x}
\end{cases}$$

(2)

$T_{2A}$=temperatures at the bottom of CTRPCP
$T_{2B}$=temperatures at the top of base.

$$\lambda_1 \frac{\partial T_1}{\partial x} = \frac{T_{2A} - T_{2B}}{L_g/2\lambda_1A_v + L_g/2\lambda_2A_v} + \lambda_f/A_v \frac{T_{2A} - T_{2B}}{L_g} = \frac{T_{2A} - T_{2B}}{R_e}$$

(3)

$$h_i = \frac{1}{L_g} \left[ A_v \left( \frac{\lambda_1 \lambda_2}{\lambda_1 + \lambda_2} + \lambda_f/A_v \right) \right]$$

(4)

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\( R_s = \frac{1}{h_c A} \) \hfill (5)

\( L_g \) = thickness of sandy gravel; 
\( A_c \) = contact area 
\( A_v \) = air area 
\( A \) = bottom area 
\( \lambda \) = thermal conductive coefficient of interstitial fluid in sand gravel 
\( h_c \) = The contact coefficient between the pavement slab and the sandy gravel layer.

In addition, the solution must meet the bounded condition, as follows:

\[ |T_c(x, t)| \leq M \quad (x \to \infty) \] \hfill (6)

M is a finite constant.

**Boundary Conditions of Temperature Field**

**Solar Radiation**

Periodic change of pavement structure temperature field is influenced by solar radiation can be approximately described as the cosine function.

\[ q(t) = \begin{cases} 
0 & 0 \leq t < 12 - \frac{c}{2} \\
q_0 \cos \omega(t - 12) & 12 - \frac{c}{2} \leq t \leq 12 + \frac{c}{2} \\
0 & 12 + \frac{c}{2} < t \leq 24 
\end{cases} \] \hfill (7)

\( q_0 \) = maximum radiation in a day, 
\( q_0 = 0.131 \text{mQ} \)

\( m = 12/c \), 
\( Q \) = total solar radiation in a day ( J/m²),
\( c \) = effective time of sunshine (h),
\( \omega \) = the earth's rotation frequency, \( \omega = 2\pi/24 \), rad.

**1.2.2 Air Temperature**

A linear superposition method of the double sine functions is used to simulate the temperature diurnal variation function.

\[ T_a = \overline{T_a} + T_a \left[ 0.96 \sin \omega(t-t_0) + 0.14 \sin 2\omega(t-t_0) \right] \] \hfill (8)

\( \overline{T_a} \) = daily average temperature, 
\( T_a \) = daily temperature variant amplitude, 
\( t_0 \) = initial time, usually, taking \( t_0 = 9 \text{h} \).
Air Convection

The heat exchange coefficient of the atmosphere to CP surface is mainly influenced by the speed of wind, and there is a linear relationship between them:

$$h_c = 3.7v + 9.4$$  \hspace{1cm} (9)

$h_c$=heat exchange coefficient, W/(m²·℃), $v$=the speed of wind, m/s

Effective Radiation of the Pavement

The effective radiation is calculated by Stefan-Boltzmann's law:

$$q_r = \varepsilon \sigma \left[ (T_1 - T_z)^4 - (T_a - T_z)^4 \right]$$  \hspace{1cm} (10)

$q_r$=effective radiation of the CP surface ,W/(m²·℃); $\varepsilon$=surface emissivity (blackness),$\varepsilon$=0.7; $\sigma$=black body radiation coefficient; $\sigma$=5.6697×10⁻⁸W/(m²·K⁴); $T_1$|$z=0$= surface temperature; $T_a$=atmospheric temperature; $T_z$=absolute zero degree value, $T_z$=−273℃.

TEMPERATURE FIELD NUMERICAL of CTRPCP

Table 1. Thermal physical parameters and size of pavements.

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat J/(kg·℃)</th>
<th>$\rho$ kg·m⁻³</th>
<th>$\lambda$ J/(m·h·℃)</th>
<th>Diam m/mm</th>
<th>$E$ (MPa)</th>
<th>μ</th>
<th>Exp (℃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>973</td>
<td>2500</td>
<td>8388</td>
<td>0.2</td>
<td>3.25×10⁴</td>
<td>0.15</td>
<td>1×10⁻⁵</td>
</tr>
<tr>
<td>Tendon</td>
<td>460</td>
<td>7800</td>
<td>209520</td>
<td>15.2</td>
<td>18×10⁴</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>Sand</td>
<td>920</td>
<td>1800</td>
<td>280</td>
<td>0.01</td>
<td>80</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>base</td>
<td>912</td>
<td>2200</td>
<td>5616</td>
<td>0.4</td>
<td>1200</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>subgrade</td>
<td>1040</td>
<td>1800</td>
<td>5500</td>
<td>0.6</td>
<td>45</td>
<td>0.4</td>
<td>-</td>
</tr>
</tbody>
</table>

On ABAQUS heat transfer platform, the first and second heat transfer boundary conditions subroutines are programmed. Temperature field of pavements is generated by coupled solar radiation, temperature, air convection and effective radiation in typical summer cloudless weather. The thermodynamic parameters and the geometrical dimension of pavement materials are shown in Table 1.

CTRPCP is analyzed by coupled thermal-mechanical analysis as figure 1. Concrete slab is with thickness of 20cm, width of 6m, length of 50m, and base is with thickness of
40cm, retard-bonded prestressed tendons are with diameter of 15.2mm, cross angle of 30 degrees and space of 0.25m, that are set in the middle of the pavements slab. The tendons initial prestresses are 1860×0.75=1395MPa.

A 1/4 structure is analyzed, for temperature field, 8-node first-order thermal conductive hexahedral elements DC3D8 is used, for stresses, 8-node first-order stress hexahedral elements (C3D8) is adopted, tendons use two node linear three-dimensional truss element T3D2 with 3600 elements:

**Numerical Analysis of the CTRPCP Temperature Field**

When the temperature changes from 15℃ to 30℃ in typical summer cloudless weather, temperature of CTRPCP changes from 18 ℃ to 36 ℃, the highest appears at 14:00PM, and the lowest appears at 6:00AM. Temperature change of base and subgrade is not obvious, from 18 ℃ to 21 ℃.

The step type temperature field change curve with time as figure 2. Because of CTR of sandy gravel, the temperature fields of pavement multi-layered system have a step at the contact surface.

Temperature with time as figure 3. With the increasing of depth, the temperature difference gradually decreases. The temperature field in the base almost keeps constant.

**CTRPCP TEMPERATURE STRESS ANALYSIS**

The CTRPCP step temperature fields are imported into the mechanical model to calculate temperature stresses, the temperature stress and the displacement of the CTRPCP are analyzed at 14:00PM in typical summer cloudless weather.

As figure 4, pavement surface compressive stresses reach 6Mpa. As figure 5, pavement compressive stresses are 2.5Mpa in transverse direction; the temperature tensile stress is 1MPa at end of the pavement. As figure 6, and 12, the longitudinal displacement is 7mm at the end of the pavements.

The longitudinal and transverse stresses of the pavement center and bottom surface as figure 7-8. The maximum longitudinal stress is 8Mpa appearing at 12:00, the minimum stress is 0Mpa in a typical summer cloudless weather. The longitudinal stress at the center is almost constant, and it is opposite to the surface.
The CTRPCP test road is in Dashiqiao City Liaoning Province China, as figure 9, and 11. At the center of the tension, axial force meter is buried. The results of axial forces of the tendons, is as figure 10. Axial force of tendons is periodical change with temperature. In a typical summer cloudless weather, the minimum axial force appears at 6:00AM as the
air temperature lowest. The maximum axial force is 3.2KN appearing at 14:00PM. The measured value and numerical value are in agreement with the phase, it fully proves that the numerical analysis results of CTRPCP temperature field and temperature stress are reliable.

ACKNOWLEDGMENTS

This research project was supported by the National Natural Science Foundation of China (No. 51308255, No. E080601), the Colleges and Universities of Liaoning Province Outstanding Young Scholars Growth Plan (No. LJQ2014059), Liaoning Province Research Institute of Environmental Pavements Material.

CONCLUSIONS

By the CTRPCP's transient temperature fields based on ABAQUS heat transfer analysis platform, the rationalities of the numerical analysis are verified by the monitoring data of the CTRPCP tests.

The temperature fields of CTRPCP are affected strongly by air temperature and solar radiation, as a nonlinear periodical variation with time and depth. CTR of sandy can effectively hinder heat transfer between the slab and base. It makes the temperature field in the gravel layer appear a step. This leads to a significant difference of the temperature gradient between CTRPCP and the traditional concrete pavements.

In a typical summer cloudless weather, the temperature stress of CTRPCP, axial force of prestressed tendons and the displacement of the pavement slab are periodical change with transient step temperature field. The maximum temperature stresses appears at 14:00PM. As the spacing of 0.25m, the intersection angle of 30 degrees, the pavement slab can withstand 5 ~ 8MPa longitudinal stresses and 1.5 ~ 4.5MPa transverse stresses under the action of temperature stresses, and 7mm displacement at pavements end.

Sandy gravel sliding layer can effectively decrease base constraint on up slab and release constraint temperature stress of semi-rigid base up to slab, achieve the purpose of reducing the temperature stresses of the pavement. Prestressed tendons can effectively resist slab left temperature stresses. From the view of improving the space of pavement
stress and controlling the development course of pavement cracks, the cross tendons make the slab elements in lateral pressure state, which have significance on anti-crack and anti-fatigue of CTRPCP.

REFERENCES


