Effects of construction conditions on built-in temperature gradient of concrete pavement: a numerical study

Lei Quan^{1,a}, Bo Tian^{1,2,b}, Decheng Feng^{1,c} Xinkai Li^{1,d}

¹School of Transportation Science and Engineering, Harbin Institute of Technology, Harbin 150090, China

²Research Institute of Highway Ministry of Transport, Beijing, 100080, China

^acharly08@163.com, ^bb.tian@rioh.cn, ^cfdcgxy@vip.sina.com, ^dlxkhit@126.com

Key words: cement concrete pavement; built-in temperature gradient; construction conditions; numerical simulation

Abstract: The built-in temperature gradient of concrete pavement formed during hardening period caused by various construction conditions will permanently exist in the pavement, which will have significant influence on the service behavior of concrete pavement. However, it's still not involved in the current *Specifications of Cement Concrete Pavement Design for Highway* in China. In this paper, a user subroutine based on the ABAQUS code was developed to simulate the effects of weather condition, paving time, curing method, raw material temperature on built-in temperature gradient. The analyses indicate that these factors always produce obvious positive gradient in the slab and the influences of the first three aspects are obvious and the paving temperature of mixture has limited effect on the increasing of the final set temperature gradient. Furthermore, built-in temperature gradient is proposed as an index to evaluate the influences of various construction factors and optimize construction measures.

1 Introduction

Considering the whole life of cement concrete pavement from paving, early-age concrete experiences the hydration and hardening process including the flow state, plastic state and solid state respectively. During this period, the factors such as hydration heat of cement, the change of surrounding temperature and solar radiate will lead to the sustainable fluctuation of the temperature field of concrete pavement. Before final set, the plastic deformation insures the zero-stress in the slab, but after final set, temperature gradient will cause internal stress and deformation. Therefore, at the time of final set, the slab is still keep flat and zero-stress, but with temperature gradient through the depth. Under this initial status, the slab begins to bear loading and deformation. When the temperature gradient in the slab is zero, the slab curls upward rather than remaining flat. Thus, an effective negative temperature gradient is "built into" the slab, and is referred to as the built-in construction temperature gradient. The magnitude of the built-in temperature gradient is affected by air temperature and weather conditions during set and curing conditions [1]. The deformation caused by this effect is extremely unfavorable for the smoothness of concrete pavement [2,3] and this built-in temperature gradient will also produce significant influence on the service behavior of concrete slab [1,4-8]. However, it's still not involved in the current *Specifications of Cement Concrete Pavement Design for Highway* in China [9].

Based on the studies above, the objectives of this paper are as follows:

- (1) Develop a program which can be used to calculate the temperature field of early-age concrete pavement;
- (2) According to the heat transfer theory and construction conditions of concrete pavement, sort the influence factors and select the represented situations for numerical simulation;
- (3) Analyze the effect regulations of each construction condition on built-in temperature gradient.

2 Numerical methodology

2.1 Governing equation of heat transfer

According to the heat transfer theory, heat will conduct from the high temperature part to the low temperature part. Thus the temperature of the body is a function of its position and time. Here we take a random part Ω_1 , and establish the heat transfer governing equation based on reserve energy principle [10].

$$\frac{d}{dt} \int_{\Omega_1} C_v(x) \rho(x) T(x, t) dV = \int_{\Omega_1} s(x, t) dV - \int_{\Omega_1} \nabla \cdot q(x, t) dV \quad (1)$$

where, C_v is the specific of concrete; ρ is the density of concrete; T is the temperature of concrete; s is hydration heat; q is the heat flow through surface of Ω_1 .

2.2 Concrete pavement model description

Finite element method is chosen to solve this problem. For 2 dimension concrete pavement system, the definite conditions for the solution of heat transfer equation are as follows [11]:

(1) Initial temperature field

(2) Convection

Convection heat transfer is expressed as:

$$q_{conv} = h(T_s - T_a) \quad (2)$$

where h is convective heat transfer coefficient; T_s is the temperature of concrete; T_a is the temperature of air, using the follow equation to fit, $w=2\pi/24$, $t_0=9$.

$$T_a = \frac{T_a^{\max} + T_a^{\min}}{2} + \frac{T_a^{\max} - T_a^{\min}}{2} [0.96 \sin w(t - t_0) + 0.14 \sin 2w(t - t_0)] \quad (3)$$

(3) Irradiation

$$q_{ir} = \varepsilon \sigma (T_s^4 - T_a^4) \quad (4)$$

where, ε is heat emissivity; σ is Stefan-Boltzmann constant.

(4) Solar radiation

$$q_r = \alpha_s q \quad (5)$$

where, α_s is surface heat absorptivity of concrete; q instantaneous solar radiation, using the follow equation to fit:

$$q(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} a_k \cos \frac{k\pi(t-12)}{12} \quad (6)$$

where, $a_0 = \frac{2q_0}{m\pi}$, q_0 is the max solar radiation at noon, $q_0 = 0.131mQ$; $m=12/c$; Q is the total solar radiation; c is the effective solar radiation time.

$$a_k = \begin{cases} \frac{q_0}{\pi} \left[\frac{1}{m+k} \sin(m+k) \frac{\pi}{2m} + \frac{\pi}{2m} \right] & k = m \\ \frac{q_0}{\pi} \left[\frac{1}{m+k} \sin(m+k) \frac{\pi}{2m} + \frac{1}{m-k} \sin(m-k) \frac{\pi}{2m} \right] & k \neq m \end{cases}$$

(5) Conduction

$$q_{cond} = -k \frac{dT}{dx} \quad (7)$$

where, k is thermal conductivities of concrete

(6) Hydration heat

The heat of hydration is expressed as[12,13]:

$$Q_h(t_e) = H_u \cdot C_c \cdot \left(\frac{\tau}{t_e}\right)^\beta \cdot \frac{\beta}{t_e} \cdot \alpha(t_e) \cdot \exp\left(\frac{E}{R} \left[\frac{1}{273+T_r} - \frac{1}{273+T_c}\right]\right) \quad (8)$$

where, $Q_h(t_e)$ is the heat release speed of hydration of concrete at equivalent age t_e ; H_u is the total heat of hydration; C_c is cement content; τ , β , E , R are parameters, T_r is reference temperature; T_c is the temperature of concrete.

2.3 User subroutine development based on ABAQUS code

According to initial and boundary conditions above, develop the user subroutine based ABAQUS code. One issue needs to be noticed is that the equivalent age t_e should be set as global variable.

2.4 Validation of numerical model

(1) Adiabatic temperature rise

Adiabatic temperature rise calculated by the program is quite near to the experimental data in paper [14].

Fig. 1 Adiabatic temperature rise calculated by the program

(2) Temperature field of early-age concrete pavement

As shown in fig.2, compared with the data collected from field experiment [15], the calculated data of different layer of the slab can satisfy the requirements of engineering prediction.

Fig. 2 Comparison between experimental data and calculated data

3 Numerical simulation Schemes

According to the study of Feng[16], the solar radiation absorption ratio and convection coefficient have the most obvious effects on the temperature field of pavement. Actually, during the construction period of concrete pavement, the following factors can exert influences on the definite conditions for the solution of heat transfer equation.

(1) Weather condition

According to the construction requirements select the represented weather condition: listed in table 1.

Reference situation: sunny day; Various situations: cloudy day

Table 1 Parameters of represented weather condition

parameters	spring	summer		autumn	winter
date	2009-4-28	2008-07-22 (sunny)	2008-07-15 (cloudy)	2008-10-19	2008-12-11
total solar radiation (MJ/m^2)	17	21	-	10	5
the effective solar radiation time (h)	14	15	-	12	10
maximum of air temperature ($^{\circ}\text{C}$)	24.5	34.9	24.1	26.1	1.3
minimum of air temperature ($^{\circ}\text{C}$)	12.0	22.3	18.5	7.9	-6.9

(2) Pavement structure and material

Choose the represented pavement structure and material of highway in China for the numerical model in this paper. The parameters are listed in table 2.

Although the pavement structure and thermal physical properties have influences on the temperature field, the values of these parameters are fixed in this paper because the structure and material are always chosen before construction.

Table 2 Parameters of represented pavement structure and material

parameters	cement concrete layer	cement stabilized gravel base	foundation
depth (cm)	26	40	300
thermal conductivity ($\text{J/m/h}^{\circ}\text{C}$)	7896	6000	4600
density (kg/m^3)	2368	2270	1800
specific ($\text{J/kg}^{\circ}\text{C}$)	850	801	983

(3) Curing methods

Different curing materials have obvious difference in solar radiation absorption ratio and convection coefficient according to their color and material characteristics.

Reference situation: exposure curing without any curing materials, the value came from the thesis.

Various situations: the values are determined considering the limited situation (table 3).

Table 3 Parameters of different curing method

parameters	C1	C2	C3	C4	C5
surface heat absorptivity	0.1	0.1	0.9	0.9	0.24
heat emissivity	0.6	0.6	0.6	0.6	0.6
convective heat transfer coefficient ($\text{J/m}^2/\text{h}^{\circ}\text{C}$)	0	30*3600	0	30*3600	29552

(4) Paving time

The solar radiate and air temperature are fluctuating every year and every day, paving in different time will lead to the different concrete hardening process and final set temperature gradient. The selected represented situations are listed in table 6 according to the investigated distribution regulation of Beijing from June 2008 to June 2009.

Reference situation: paved at 8:00 am in summer;

Various situations: 0:00; 4:00; 12:00; 16:00; 20:00.

(5) Temperature of raw materials

The temperatures of raw materials will various with the saving status, which result in the temperature change of mixture and will have strong influence on the hydration process of cement. This factor is considered by the different placing temperature of concrete mixture.

Reference situation: 20°C; Various situations: 0°C, 10°C, 30°C, 40°C.

4 Results and discussion

(1) Influences of weather condition and paving time

Table 4 shows the weather conditions have a significant influence on the temperature gradient of concrete slab at final set time. The temperature gradients in sunny days are all higher than that in cloudy days. It indicates that the solar radiation is a non-negligible factor leading the temperature rise of concrete. In this table, we can also find that paving the concrete in different time of a day will cause obviously difference in built-in temperature gradient. The values of gradient built in the slab constructed in the daytime are higher as 51.4°C and 11.8°C for sunny and cloudy days, respectively, which have reached 4~9 times of the values in nighttime.

Table 4 Influences of weather condition and different paving time of a day

parameters		different paving time					
		SK1	SK2	SK3	SK4	SK5	SK6
		0:00	4:00	8:00	12:00	16:00	20:00
Sunny	final set time (h)	5.7	5.4	4.8	4.7	5.0	5.4
	$T_{\text{top}}-T_{\text{bottom}} (^{\circ}\text{C})$	3.2	9.0	13.4	12.3	6.5	3.5
	Temperature Gradient ($^{\circ}\text{C}/\text{m}$)	12.4	34.7	51.4	47.4	25.1	13.7
cloudy	final set time (h)	6.0	5.9	5.7	5.6	5.7	5.9
	$T_{\text{top}}-T_{\text{bottom}} (^{\circ}\text{C})$	0.3	1.7	3.1	2.8	1.8	0.6
	Temperature Gradient ($^{\circ}\text{C}/\text{m}$)	1.3	6.7	11.8	10.9	6.7	2.5

The meteorological conditions are always fluctuating in different months of a year, and the effects of paving season on built-in temperature gradient are given in table 5. The result in winter represents that the construction condition can also produce negative gradient in slab. This will lead to the totally opposite service behavior of concrete slab in the future days.

Table 5 Influences of different paving time of a year

group	paving season			
	spring	summer	autumn	winter
final set time (h)	5.9	4.8	5.8	10.7
$T_{\text{top}}-T_{\text{bottom}} (^{\circ}\text{C})$	10.3	13.4	8.2	-3.2
temperature gradient ($^{\circ}\text{C}/\text{m}$)	39.4	51.4	31.5	-12.3

(2) Influences of curing method

Table 6 displayed the influences of various curing conditions. When solar radiation absorption is weak and convection is sufficient, the temperature difference between top and bottom surface of the slab is little, on the contrary, if solar radiation ratio is higher and convection is prevented by the curing material, the built-in gradient will come out quite high, which even exceeding the normal temperature gradient in concrete pavement. This issue needs a high level of concern.

Table 6 Influences of different curing methods

group	curing methods				
	YS1	YS2	YS3	YS4	YS5
final set time (h)	5.4	4.7	3.7	4.2	4.8
$T_{\text{top}}-T_{\text{bottom}} (^{\circ}\text{C})$	8.8	5.0	36.6	21.4	13.4
temperature gradient ($^{\circ}\text{C}/\text{m}$)	33.9	19.3	140.9	82.4	51.4

(3) Influences of raw material temperature

The temperatures of raw materials will various with the surroundings, which result in the temperature change of mixture. As shown in table 7, the effects bring by this phenomenon is not so serious that this factor can be neglect compared with others.

Table 7 Influences of raw material temperature

group	temperature of raw material (°C)				
	0	10	20	30	40
final set time (h)	7.7	6.2	4.8	3.6	2.6
$T_{\text{top}} - T_{\text{bottom}}$ (°C)	15.4	14.8	13.4	11.9	11.3
temperature gradient (°C/m)	59.3	56.9	51.4	45.7	43.6

5 Conclusions

(1) A user subroutine based on the ABAQUS code was developed which can be used to predict the temperature field of early-age concrete pavement. The validity of this program was verified through experimental result from literature and temperature field data collected from a full-scale concrete slab paved in the field.

(2) The effects of weather condition, paving time, curing method, raw material temperature on built-in temperature gradient were analyzed respectively based on the numerical simulation results. They indicate that these factors always produce positive gradient in the slab and the influences of the first three aspects are obvious and the paving temperature of mixture has limited effect on the increasing of the final set temperature gradient.

(3) The study in this paper shows that taking built-in temperature gradient as an index to evaluate the influences of various construction factors and optimize construction measures is effective. These works lay a foundation for the determination for the rational value of built-in temperature gradient based on service performance of concrete pavement.

References

- [1] Rao, S. and Roesler, J.. Characterizing Effective Built-In Curling from Concrete Pavement Field Measurements[J]. Journal of Transportation Engineering. 2005,131(4):320~327
- [2] Hveem, F. N.. Slab warping affects pavement joint performance[C]. American Concrete Institute.1951,47: 797~808
- [3] Hveem, F. N., and Tremper, B.. Some factors influencing shrinkage of concrete pavements[C]. American Concrete Institute, 1957,53: 781~789.
- [4] Zollinger, D. G., and Barenberg, E. J. ~1989!. "Proposed mechanistic based design procedure for jointed concrete pavements." Illinois Cooperative Highway Research Program Project IHR-518, Univ. of Illionis, Urbana, Ill.
- [5] Darter, M., Khazanovich, L., Snyder, M., Rao, S., and Hallin, J. (2001). "Development and calibration of a mechanistic design procedure for jointed plain concrete pavements." Proc., 7th Int. Conf. on Concrete Pavements, Orlando, Fla.
- [6] Beckemeyer, C. A., Khazanovich, L., and Yu, H. T. (2002). "Determining amount of built-in curling in jointed plain concrete pavement: Case study of Pennsylvania I-80." Transp. Res. Rec., 1809, Transportation Research Board, Washington, D.C., 85–92.
- [7] Hiller, J. E., and Roesler, J. R. (2002). "Transverse joint analysis for use in mechanistic–empirical design of rigid pavements." Transp. Res. Rec., 1809, Transportation Research Board, Washington, D.C., 42–51.
- [8] Steven A. Wellsa, Brian M. Phillipsa & Julie M. Vandenbosscheb. Quantifying built-in construction gradients and early-age slab deformation caused by environmental loads in a jointed plain concrete pavement[J]. International Journal of Pavement Engineering. 2006(7): 275-289

- [9] Specifications of Cement Concrete Pavement Design for Highway (JTGD40—2011)[S]. Beijing: People's Communication Press. 2002: Appendix B
- [10] Zhu Bofang. Temperature stress and control method to mass concrete [M]. Beijing: China Electric Power Press. 1999.
- [11] Jin-Hoon Jeong and Dan G. Zollinger. Finite-Element Modeling and Calibration of Temperature Prediction of Hydrating Portland Cement Concrete Pavements[J]. JOURNAL OF MATERIALS IN CIVIL ENGINEERING. 2006: 317~324
- [12] RW.J. Wilde. Computer-based guidelines for concrete pavements volume III—technical appendices[R], Federal Highway Administration Report FHWA-HRT-04-127, McLean, VA, 2005
- [13] ASTM C403/C403M-08. Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance. American Society of Testing and Materials, Pennsylvania. 1999
- [14] Schindler, A.K. and Folliard, K.J. Influence of Supplementary Cementing on the Heat of hydration of Concrete[C]. Advances in Cement and Concrete IX Conference, August 2003
- [15] Quan Lei. STUDY ON TEMPERATURE FIELD AND STRENGTH DEVELOPMENT OF EARLY-AGE CONCRETE SLAB UNDER DIFFERENT CURING METHODS [D], 2011.
- [16] FENG Decheng et al. Impact of Asphalt Pavement Thermophysical Property on Temperature Field and Sensitivity Analysis[J]. Journal of Highway and Transportation Research and Development. 2011, 11(28): 12~19