A Concrete Pouring Temperature Forecast Method for Hydraulic Structures

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Abstract. To address problems with the existing concrete pouring temperature forecast methods, an improved forecast method is presented in this paper. A concrete temperature variation calculation method during pouring is proposed. In this method, the effect of the external environmental temperature on the concrete pouring temperature for various measures is calculated using a finite element model. The relationships between heat conductivity, thermal diffusivity, surface heat transfer coefficient and the concrete temperature rise coefficient are obtained via fitting, and the reliability of these relationship equations are verified.

1. Introduction

Concrete temperature stress control measures include pouring temperature control, water cooling, surface heat insulating and dam body parting [1-5]. Pouring temperature control is one of the most effective hydraulic concrete temperature stress control measures. Concrete pouring temperature should meet design requirements. During the period from concrete production to pouring, its temperature changes continuously. Temperature variation during the process should be accurately calculated to obtain the temperature at the mixer outlet, to ensure it satisfies the temperature control requirement. In the current version of the Hydraulic Structure Concrete Standard of the People’s Republic of China, the definition of pouring temperature is the temperature of the concrete located 10 cm beneath the paving layer surface before it is covered by additional layers of concrete [6]. Although there are studies on concrete pouring temperature, the solution process is complex and the definition of pouring temperature is significantly different from the definition in the standard.

Currently, the achievements and pending issues related to pouring temperature estimation include:

(1) The calculation of the mixer outlet temperature. The mixer outlet temperature is the temperature of concrete when mixing is completed. The mixer outlet temperature is related to concrete raw material temperature and the mixer outlet temperature control. The method for calculating the mixer outlet temperature from the temperature of the raw materials is mature.

(2) The calculation of concrete temperature variation during transport. After production, concrete must be transported to a storehouse surface for pouring. During this process, the concrete temperature is affected by the environmental temperature and changes constantly. The method for calculating the placement temperature from the mixer outlet temperature is mature.

(3) The temperature rise during pouring, including the temperature rise during concrete spreading, the temperature rise during paving and the self-hydration heat induced temperature rise during pouring. The temperature rise during concrete spreading has been studied extensively. The temperature rise
during paving and the hydration heat induced temperature rise during pouring should be investigated further.

Based on the results obtained from a finite element calculation, equations governing the relationships for parameters such as thermal diffusivity, paving layer thickness, external temperature, paving layer pouring duration, heat conductivity, surface heat transfer coefficient and temperature rise during paving layer pouring are derived.

2. The Existing Methods to Calculate the Concrete Temperature Rise During Pouring

The calculation of temperature during the period from concrete production to pouring includes the following items: mixer outlet temperature calculation, temperature variation calculation during transport, temperature variation calculation during spreading and vibration and temperature variation calculation during pouring. Currently, there are some achievements in temperature calculation during pouring:

The concrete pouring temperature $T_p$ is calculated via the following equation [7]:

$$ T_p = T_i + (T_h + R/\beta_n - T_h)(\varphi_1 + \varphi_2) $$

Where $T_p$ is the pour temperature; $T_i$ is the placement temperature; $T_h$ is the air temperature; $R$ is the solar radiation heat; $\beta_n$ is the surface heat transfer coefficient (the value recommended by Zhu Bofang is 80 kJ/m²·d·ºC); $\varphi_1$ is the concrete spreading and vibration influence coefficient; and $\varphi_2$ is the paving layer interval influence coefficient.

The coefficient $\varphi_1$ is calculated via the following formula:

$$ \varphi_1 = kt + \varphi $$

Where $t$ is the duration of concrete spreading and $k$ is an empirical coefficient for spreading, and $\varphi$ is the coefficient for concrete vibration.

The existing methods only consider those projects using manual vibrating concrete, in which, spreading and vibration cannot be separated. Then, only $k$ can be under consideration. According to previous research results, for those projects, when actual measurement data are unavailable, $k=0.003$(1/min), or $k=0.18$(1/h).

3. A New Method to Calculate the Temperature Variation During Concrete Pouring

The temperature variation during concrete pouring is the difference between the pouring temperature and the placement temperature. The following factors influence the temperature during concrete pouring: the environmental temperature, the concrete hydration heat and the old paving layer heat conduction. The pouring process is divided into two phases: the spread vibration phase and the paving layer interval phase. The calculation procedure is as follows:

(1) To calculate the effect of the environmental temperature on the concrete pouring temperature during pouring, assume the newly poured concrete and the old concrete have identical temperatures. A paving layer with arbitrary thickness is calculated via FEM. Additionally, length of the layer is set to a very large value, and the old paving layer heat conduction effect is ignored. The concrete temperature rise at a location 10 cm beneath the paving layer surface during the paving layer interval is calculated.

(2) Next, determine the effect of the old paving layer heat conduction on the concrete pouring temperature.

(3) The temperature variation during pouring is the combined result of the environmental temperature and the old paving layer heat conduction.

3.1. Calculating the Effect of Environmental Temperature on the Pouring Temperature during Pouring

During concrete pouring, the external-temperature-induced pouring temperature rise is calculated by iteration. The initial value is calculated using the following equation:
\[ T_{p0} = T_i + \theta(\Delta T) + (T_a - \theta(\Delta T) - T_i)(\phi_1 + \phi_2) \]  

Where \( T_a \) is the environmental temperature in °C; \( \theta(\Delta T) \) is the hydration heat in °C; \( T_i \) is the placement temperature in °C; \( \phi_1 \) is the concrete spreading and vibration influence coefficient; and \( \phi_2 \) is the paving layer interval influence coefficient.

Methods for calculating other parameters in Eq. (3) are elaborated in the following sections.

The pouring temperature is calculated via iteration. The iteration recursion equation is as follows:

\[
\begin{align*}
T_{p1} &= T_i + \theta(\Delta T) + \left[ T_a - \frac{(T_{p0} + T_i)}{2} \right](\phi_1 + \phi_2) \\
T_{p2} &= T_i + \theta(\Delta T) + \left[ T_a - \frac{(T_{p1} + T_i)}{2} \right](\phi_1 + \phi_2) \\
& \vdots \\
T_{pn} &= T_i + \theta(\Delta T) + \left[ T_a - \frac{(T_{pn-1} + T_i)}{2} \right](\phi_1 + \phi_2)
\end{align*}
\]  

After analysis, Eq. (4) has converges rapidly. When \( n \geq 3 \), the pouring temperature can be calculated accurately.

3.2. Calculating the Coefficient

The method for calculating \( \phi_1 \) is similar to Eq. (2). For the mechanized vibration engineering, based on measured results, when actual measurement data are unavailable, \( \phi' = 0.012 \). The calculation method of \( k \) in Eq. (2) is same as \( \phi_2 \), both of which can be fitted by based on the much calculate result of finite element.

3.2.1. Determining the basic format

Based on the finite element analysis, \( k \) and \( \phi_2 \) values for various surface heat transfer coefficients, heat conductivities and thermal diffusivities are calculated. Based on extensive data analysis, \( k \) and \( \phi_2 \) is represented in the following format:

\[
\begin{align*}
k &= \phi_{21}\phi_{22} \\
\phi_2 &= k\Delta T
\end{align*}
\]  

Where \( \phi_{21} \) is the surface heat exchange influence coefficient; and \( \phi_{22} \) is the internal heat conduction influence coefficient.

The surface heat exchange influence coefficient is related to \( \lambda / \beta \). Assume:

\[
\phi_{21} = a(\lambda / \beta)^b
\]  

Where \( a \) and \( b \) are coefficients to be determined.

The internal heat conduction influence coefficient is related to the thermal diffusivity. Considering that the concrete density is similar, we have:

\[
\phi_{22} = (d c / \lambda)^e
\]  

Where \( d \) and \( e \) are coefficients to be determined.
3.2.2. Determining the surface heat exchange influence coefficient $\varphi_{21}$

In this section, the coefficient in Eq. (6) is obtained via finite element calculation and analysis. The calculation conditions are as follows.

The pouring temperature is set to 0°C; and the external temperature is set to 10°C. The concrete pouring model top surface dissipates heat, and the other surfaces are adiabatic. The concrete pouring model height is 0.5 m; the heat conductivity is 164 kJ/m·d·°C; the specific heat is 0.9 kJ/kg·°C. When the surface heat transfer coefficient is $100\text{-}1200$ kJ/m$^2$·d·°C, a unit time, a unit environmental temperature and a pouring-temperature-difference-induced concrete temperature change are calculated.

To facilitate calculation analysis, the coefficient $d$ is set to 182.2, and we have $\varphi_{22}=1$. Based on the calculation result, when the specific heat is 0.9 kJ/kg·°C and the heat conductivity is 164 kJ/m·d·°C, the unit temperature difference induced per unit time concrete temperature rise under varying surface heat transfer coefficients are calculated, and the coefficient $\varphi_{21}$ is obtained.

When the specific heat is 0.9 kJ/kg·°C, the heat conductivity is 164 kJ/m·d·°C, $\varphi_{22}=1$ and $\varphi_{21} = 0.01127 \left( \frac{\lambda}{\beta} \right)^{-0.844}$ . The calculation results and the finite element results are compared via formula fitting, as shown in Fig. 1. The fitting value using Eq. (6) matches the finite element calculation result well.

![Figure 1. Relationship between $\varphi_{21}$ and $\lambda / \beta$](image)

3.2.3. Determining the internal heat conduction influence coefficient, $\varphi_{22}$

In this section, the coefficient in Eq. (7) is obtained via finite element calculation analysis. The calculation conditions are as follows:

The pouring temperature is set to 0°C; the external temperature is set to 10°C. The concrete pouring model top surface dissipates heat, while the other surfaces are adiabatic. The heat conductivity is 164 kJ/m·d·°C, the surface heat transfer coefficient is $600$ kJ/m$^2$·d·°C, and the specific heat is 0.6-1.2 kJ/kg·°C. The unit-temperature-difference-induced concrete temperature rise is calculated, and $\varphi_{22}$ is obtained.

When the heat conductivity is 164 kJ/m·d·°C, the surface heat transfer coefficient is $600$ kJ/m$^2$·d·°C. The calculation result shows that $\varphi_{22}$ is unrelated to the pouring interval and is only related to the specific heat.

When the heat conductivity is 164 kJ/m·d·°C, the surface heat transfer coefficient is $600$ kJ/m$^2$·d·°C and $\varphi_{22} = \left( 182.2 \frac{c}{\lambda} \right)^{-0.861}$ . The calculation results are compared with the finite element results using a fit with Eq. (7), as shown in Fig. 2.
3.2.4. Validation of $k$ and $\varphi_2$ application scope

Based on Eqs. (5-7), $\varphi_2$ is determined:

$$
\begin{align*}
  k &= 0.01127 \left( \lambda / \beta \right)^{-0.844} (182.2c / \lambda)^{-0.861} \\
  \varphi_2 &= k \Delta \tau
\end{align*}
$$

Figure 2. Relationship between $\varphi_2$ and specific heat

In this paper, Eq. (8) is validated using different concrete material parameters. Tables 1 and 2 list $\varphi_2$, for various values of specific heat when the surface heat transfer coefficient is 900 kJ/m²·d·°C and the heat conductivity is 164 kJ/m·d·°C. When the surface heat transfer coefficient is 900 kJ/m²·d·°C, it represents the scenario for which heat insulating material is not applied.

Tables 3 and 4 list $\varphi_2$, for various values of specific heat when the surface heat transfer coefficient is 300 kJ/m²·d·°C and the heat conductivity is 164 kJ/m·d·°C. Based on the calculation results, $\varphi_2$ are unrelated to the paving layer pouring interval and can be accurately calculated by fitting Eq. (8). Extensive on-site investigation shows that when the surface heat transfer coefficient is 300 kJ/m²·d·°C, it represents the scenario for which heat insulating material is applied.

Apart from these two typical scenarios (for surface heat dissipation coefficients of 300 kJ/m²·d·°C and 900 kJ/m²·d·°C) this study has also investigated various $\varphi_2$ values when $\lambda / \beta$ is in the range of 0.164 to 1.64. The finite element calculation results are consistent with the fitting result of Eq. (8), indicating that this equation applies to all scenarios.

Table 1. $\varphi_2$ for various values of specific heat (surface heat transfer coefficient: 900 kJ/m²·d·°C)

| specific heat | 3 hours | 4 hours | 5 hours | 6 hours | 7 hours | 8 hours |
|---------------|---------|---------|---------|---------|---------|---------|
| 0.8           | 0.055   | 0.055   | 0.053   | 0.051   | 0.049   | 0.048   |
| 0.9           | 0.049   | 0.049   | 0.048   | 0.047   | 0.045   | 0.044   |
| 1.0           | 0.044   | 0.045   | 0.044   | 0.043   | 0.042   | 0.041   |
| 1.2           | 0.036   | 0.037   | 0.037   | 0.037   | 0.036   | 0.035   |
### Table 2. $\varphi_{22}$ for various values of specific heat (surface heat transfer coefficient: 900 kJ/m²·d·°C)

| specific heat | 3 hours | 4 hours | 5 hours | 6 hours | 7 hours | 8 hours |
|--------------|---------|---------|---------|---------|---------|---------|
| 0.8          | 1.13    | 1.11    | 1.11    | 1.09    | 1.10    | 1.08    |
| 0.9          | 1.01    | 1.01    | 1.01    | 1.00    | 1.01    | 1.00    |
| 1.0          | 0.90    | 0.91    | 0.92    | 0.92    | 0.93    | 0.92    |
| 1.2          | 0.74    | 0.76    | 0.78    | 0.79    | 0.80    | 0.80    |

### Table 3. $\varphi_{22}$ for various values of specific heat (surface heat transfer coefficient: 300 kJ/m²·d·°C)

| specific heat | 3 hours | 4 hours | 5 hours | 6 hours | 7 hours | 8 hours |
|--------------|---------|---------|---------|---------|---------|---------|
| 800          | 0.022   | 0.022   | 0.022   | 0.021   | 0.021   | 0.020   |
| 900          | 0.020   | 0.020   | 0.020   | 0.019   | 0.019   | 0.019   |
| 1000         | 0.017   | 0.018   | 0.018   | 0.018   | 0.017   | 0.017   |
| 1200         | 0.014   | 0.015   | 0.015   | 0.015   | 0.015   | 0.015   |

### Table 4. $\varphi_{22}$ for various values of specific heat (surface heat transfer coefficient: 300 kJ/m²·d·°C)

| specific heat | 3 hours | 4 hours | 5 hours | 6 hours | 7 hours | 8 hours |
|--------------|---------|---------|---------|---------|---------|---------|
| 800          | 1.10    | 1.11    | 1.10    | 1.13    | 1.10    | 1.07    |
| 900          | 0.98    | 0.99    | 0.99    | 1.02    | 1.00    | 0.98    |
| 1000         | 0.87    | 0.89    | 0.90    | 0.93    | 0.92    | 0.90    |
| 1200         | 0.70    | 0.73    | 0.75    | 0.79    | 0.78    | 0.77    |

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