Determination of the Environmental Temperature and Hydration Heat during Concrete Pouring

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Abstract. In the design process, it is necessary to predict the temperature changes during concrete mixing, transportation and pouring. Prediction of concrete pouring temperature needs to consider the temperature conditions and hydration heat of the concrete in the pouring process. A method for calculating the highest environmental temperature during the paving layer pouring period is proposed, providing a foundation for determining the highest pouring temperature. During concrete pouring, hydration heat affects pouring temperature. Considering that concrete hydration heat is significantly affected by the environment, the equivalent age should be calculated. The effect of concrete hydration heat on concrete pouring temperature is investigated. An equation to calculate the effect of hydration heat on the concrete pouring temperature is proposed. With the measures in this paper, the prediction accuracy of pouring temperature of mass concrete can be improved obviously.

Introduction

The causes of concrete cracks are various, but the temperature crack is the most important factor for the cracking of mass concrete structures in early age [1-2]. Concrete temperature stress control measures include pouring temperature control, water cooling, surface heat insulating and dam body parting [3-6]. Pouring temperature control is one of the most effective hydraulic concrete temperature stress control measures. During the construction of large concrete dams, temperature control measures are generally adopted, and concrete pouring temperature should meet design requirements.

Casting temperature can be calculated by finite element analysis of pavement, and this method has been widely used in construction and design. However, the calculation of boundary conditions by finite element method has not been studied in detail. Among these boundary conditions, the external temperature, solar radiation and hydration heat release of concrete are the necessary conditions for accurate calculation.

Prediction of concrete pouring temperature needs to consider the temperature conditions and hydration heat of the concrete in the pouring process [7-8]. The main factor influencing temperature variation during the period from concrete production to pouring is the difference between the external temperature and the concrete temperature. An accurate calculation of external temperature during the period from concrete production to pouring is critical. Currently, the external temperature is typically based on an average temperature, and it is difficult to accurately determine the highest temperature during pouring. Concrete hydration heat is measured by an adiabatic temperature rise meter. Considering that concrete hydration heat is significantly affected by the environment, the equivalent age should be calculated.

With the measures in this paper, the prediction accuracy of pouring temperature of mass concrete can be improved obviously.
The Existing Calculation Methods

The Existing Methods to Calculate the Concrete Temperature Rise during Pouring

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

$$T_p = T_i + (T_h + R/R_s - T_i)(\varphi_1 + \varphi_2)$$  \hfill (1)

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; $R_s$ is the surface heat transfer coefficient (the value recommended by Zhu Bofang is 80 kJ/m$^2$·d·°C); $\varphi_1$ is the concrete spreading and vibration influence coefficient; and $\varphi_2$ is the paving layer interval influence coefficient.

After spreading, a thin layer of concrete is formed. The temperature coefficient $\varphi_2$ is calculated based on heat conduction theory. The following assumptions apply: the thin layer of concrete is an infinitely large plate with a thickness of $L$, a thermal diffusivity of $\alpha$, a heat conductivity of $\lambda$, and a surface heat transfer coefficient of $\beta$. The bottom of the plate is adiabatic, and the top surface is in contact with air. The plate’s initial temperature is 0°C; the interval between the completion of the paving layer concrete vibration and the time at which the paving layer surface is covered with new concrete is $\Delta \tau$; when vibration is completed, the difference between the concrete temperature and the ambient temperature is $\Delta T$. The problem can be represented as follows\textsuperscript{[9]}:

$$\begin{align*}
\frac{\partial T}{\partial \tau} &= \alpha \frac{\partial^2 T}{\partial x^2} \\
T &= 0 \quad \text{when } \tau = 0 \\
\frac{\partial T}{\partial x} &= 0 \quad \text{when } x = 0 \\
-\lambda \frac{\partial T}{\partial x} &= \beta(T - \Delta T) \quad \text{when } x = L
\end{align*}$$  \hfill (2)

Zhu suggested that the paving layer average temperature during $\Delta \tau$ is $\varphi_2$. Based on different parameters ($L, \lambda/\beta, \alpha$), Eq. (2) can be solved by finite element, difference, analytic or a table lookup method to obtain $\varphi_2$.

The Existing Expression of Environmental Temperature

The environmental temperature includes the ambient temperature and the solar-radiation-induced temperature rise. Zhu suggested that the environmental temperature can be described by the following function:

(1) The daily air temperature variation is represented as a cosine function:

$$T_a(\tau) = T_{\text{av}} + A_s \cos(\pi \tau/12)$$  \hfill (3)

where $T_{\text{av}}$ is the daily average air temperature in °C; $A_s$ is half of the daily air temperature variation in °C; and $\tau$ is the time in h; when $\tau = 0$, the daily air temperature is at its highest.

(2) The solar radiation variation is represented as a cosine function:

$$S(\tau) = 12\pi S_o \cos(\pi \tau/2)$$  \hfill (4)

where $S_o$ is the solar radiation heat in kJ/m$^2$·d·°C; $\pi$ is the time in h; $-P_s/2 \leq \tau \leq P_s/2$, $P_s$ is the total solar radiation; $|\tau| > P_s/2$. 

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where \( S_0 \) is the daily average of the solar radiation heat, considering the effects of clouds, in kJ/m\(^2\)h; \( P_s \) is the duration of sunshine, in h; and \( \tau \) is time, in h; when \( \tau = 0 \), the daily solar radiation is at its highest value.

**Calculating the Daily Average Environmental Temperature during Pouring**

The effects of the pouring period daily average air temperature and the daily average solar radiation on the environmental temperature are calculated using the following equations.

The daily average environmental temperature during pouring is as follows:

\[
T_e = T_{am} + \Delta T_e
\]  

(5)

where \( T_e \) is the environmental temperature or the daily average environmental temperature, in °C, \( T_{am} \) is the daily average air temperature, in °C, and \( \Delta T_e \) is the solar-radiation-heat-induced daily average environmental temperature rise, in °C.

The solar-radiation-heat-induced daily average environmental temperature rise is given by:

\[
\Delta T_e = \frac{k_s S_0}{\beta_a}
\]  

(6)

where \( \Delta T_e \) is the solar-radiation-heat-induced daily average environmental temperature rise, in °C, \( k_s \) is the concrete solar radiation absorption coefficient, which is normally set to 0.65, \( \beta_a \) is the surface heat transfer coefficient (the value recommended by Zhu Bo fang is 80 kJ/m\(^2\)·d·°C), and \( S_0 \) is the solar radiation heat considering cloud effects, in kJ/(m\(^2\)·h).

**Calculating the Average Environmental Temperature during the Pouring Period with the Highest Environmental Temperature**

**Highest Environmental Temperature during Pouring Period**

The average environmental temperature during the pouring period with the highest environmental temperature is given by:

\[
T_e = \overline{T_{am}} + \overline{\Delta T_{am}}
\]  

(7)

where \( T_e \) is the environmental temperature or average environmental temperature during the pouring period with the highest environmental temperature, in °C, \( \overline{T_{am}} \) is the average air temperature for a paving layer with the highest environmental temperature, in °C, and \( \overline{\Delta T_{am}} \) is the solar-radiation-heat-induced average environmental temperature rise for a paving layer with the highest environmental temperature, in °C.

The air temperature variation is represented using Eq. (3). Then:

\[
\overline{T_{am}} = \overline{\int_{\frac{\tau}{2}}^{\frac{\tau}{2}} T_a(\tau) d\tau}
\]  

(8)

Integrating Eq. (8), we obtain:

\[
\overline{T_{am}} = T_{am} + \frac{24A_s}{\pi \Delta \tau} \sin\left(\frac{\pi \Delta \tau}{24}\right)
\]  

(9)

where \( A_s \) is half of the daily air temperature variation, in °C, \( \Delta \tau \) is the thin paving layer interval, in h (hours), and \( T_{am} \) is the daily average air temperature, in °C.

The solar radiation variation is given by Eq. (4), then:
\[
\Delta T_{\text{max}} = \frac{\int_{\tau_2}^{\tau_1} k_s S(\tau) d\tau}{\Delta \tau \beta_a}
\]

where \(k_s\) is the concrete solar radiation absorption coefficient, which is normally 0.65, and \(\beta_a\) is surface heat transfer coefficient (the value recommended by Zhu is 80 kJ/m\(^2\cdot\text{d} \cdot ^\circ\text{C}\)).

Integrating Eq. (10), we obtain:

\[
\Delta T_{\text{max}} = \frac{3k_s S_0}{10\Delta \tau} \sin\left(\frac{\Delta \tau \tau}{2P_s}\right)
\]

where \(\Delta \tau\) is the thin paving layer interval, in h, \(S_0\) is the solar radiation heat considering cloud effects, in kJ/(m\(^2\)·h), \(P_s\) is the duration of sunshine in h, and \(k_s\) is the concrete solar radiation absorption coefficient, which is normally set to 0.65.

A New Method to Calculate the Hydration Heat Temperature Rise during Pouring

Hydration Heat Temperature Rise Considering Temperature Duration

During concrete pouring, hydration heat affects pouring temperature. Concrete hydration heat is measured by an adiabatic temperature rise meter. Considering that concrete hydration heat is significantly affected by the environment, the equivalent age should be calculated. Actual age is “converted” to an equivalent age of the concrete test block in the adiabatic temperature rise meter for calculation \([8-13]\).

The equivalent time is given by:

\[
\Delta \tau = e^{\left[\frac{4500}{T_i - 273} - \frac{1}{T_f - 273}\right]} \Delta \tau
\]

where \(T_i\) is initial temperature of the adiabatic temperature rise test block, in °C, \(T_f\) is the placement temperature, in °C, \(\Delta \tau\) is the equivalent time, and \(\Delta \tau\) is the thin paving layer interval.

The hydration heat induced temperature rise is \(\theta(\Delta \tau)\). It is recommended that \(\theta(\Delta \tau)\) be calculated directly from test data. When test data are unavailable and the adiabatic temperature rise fitting formula is available, the hydration heat induced temperature rise can be determined from the fitting formula.

When exponential fitting is employed, the hydration heat induced temperature rise is as follows:

\[
\theta(\Delta \tau) = \theta_0(1 - e^{-a \Delta \tau})
\]

where \(\theta_0\) is the eventual adiabatic temperature rise, in °C, and \(a\) and \(b\) are constants determined by the properties of the adiabatic temperature rise curve.

The hydration heat induced temperature rise via hyperbola fitting is as follows:

\[
\theta(\Delta \tau) = \frac{\theta_0 \Delta \tau}{n + \Delta \tau}
\]

where \(\theta_0\) is the final adiabatic temperature rise, in °C, and \(n\) is a constant determined by the properties of the adiabatic temperature rise curve.

When Eqs. (12-14) are employed, the thin paving layer interval unit should be the same to avoid a unit-difference-induced error.
Summary

Pouring temperature control is one of the most effective hydraulic concrete temperature stress control measures. Concrete pouring temperature should meet design requirements. In order to predict the pouring temperature more accurately and consider the environmental temperature and the hydration heat release of concrete accurately, the following work has been done in this paper:

(1) A method to calculate the daily average environmental temperature and the average environmental temperature during the pouring period with the highest environmental temperature is proposed, to calculate the daily average pouring temperature and the highest pouring temperature.

(2) The effect of concrete hydration heat on concrete pouring temperature is investigated. An equation to calculate the effect of hydration heat on the concrete pouring temperature is proposed.

With the measures in this paper, the prediction accuracy of pouring temperature of mass concrete can be improved obviously.

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