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A new formula to estimate final temperature rise of concrete considering ultimate hydration based on equivalent age

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HIGHLIGHTS

- The real ultimate degree of the concrete is different from the one obtained from the adiabatic temperature rise experiment.
- A formula is proposed to estimate the real final temperature rise with varying placing temperature.
- The result of the algorithm which considers both the equivalent age and the proposed formula is more close to the reality.

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ABSTRACT

When simulating the temperature field of concrete, the conventional adiabatic temperature rise models, which only take the age of concrete into account, can lead to a significant deviation (the maximum relative error nearly 73%) from predicted values to measured values under extreme conditions. To solve this problem, a new prediction formula is presented in this paper for estimating the final temperature rise of concrete, by considering ultimate hydration based on the equivalent age. The formula is developed on the basis of measured data obtained in some real construction cases during the recent years. It essentially reveals the ultimate degree of hydration for concrete with a variation in the placing temperature at the construction site. The degree of hydration at the construction site is not as accurate as measured with an adiabatic calorimeter. Also, the measured data shows that the ultimate degree of hydration of concrete under the non-adiabatic condition is related to its placing temperature. A logarithmic function is proposed to approximate this relationship. The equivalent age is developed to consider the effects of both the age of concrete and its temperature. The comparison shows that the proposed combination of equivalent age and the new formula can reduce the maximum relative error substantially from 73% to 15% than those algorithms which do not consider equivalent age or our proposed formula.

1. Introduction

It is generally accepted that the thermal stress is the main reason [5,9,19] that results in cracking at the early age of the mass concrete structures. Thermal properties of concrete, especially those related to the adiabatic temperature rise model, play a vital role in simulating the temperature field [6,25,22,20]. The parameters of the adiabatic temperature rise model are usually obtained by an adiabatic calorimetry, where the hydration reaction is relatively simplified. However, through using these parameters, the calculated temperature field significantly deviates from the data measured at the construction site. This is due to the fact that the degree of hydration obtained from a lab testing is usually higher [17,14,4] and the conventional models only take the age of concrete into consideration. This phenomenon is less prominent in large concrete dams as the placing temperature is controlled intentionally within a constant range (12–15 °C throughout the year). For other concrete projects, their placing temperature will change along with the air temperature, usually ranging from 5 °C to 40 °C according to measured data. The deviation between the predicted values and measured values is more pronounced when high-grade concrete was employed.

A number of researchers have developed new hydration exothermic models [21,7,16,23,15,11,18,27] which consider both the age and temperature of concrete. The assumption of these models is that the final adiabatic temperature rise is constant no

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matter what the placing temperature is, leading to the large deviation when the placing temperature is comparatively low.

This paper summarizes the final temperature rises of concrete with varying placing temperature based on the measured data obtained from some projects and proposes a prediction formula after analyzing the relationship between the final temperature rise and the placing temperature. The formula is used to estimate final temperature rise of concrete with varying placing temperature, i.e., the ultimate degree of hydration.

This paper combines equivalent age, which takes the age and temperature of concrete into consideration, and the proposed formula, which considers the placing temperature, to simulate the temperature field. By comparing the measured values and the predicted values with different algorithms, it is found that this combination can significantly reduce calculation error. In addition, this formula is computationally efficient.

2. Numerical modelling

2.1. The basic theory for unsteady temperature field

At an arbitrary point in concrete computation domain R, unsteady temperature field T(x,y,z,t) must meet the following control equation of heat conduction:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{\partial \theta}{\partial \tau} \quad (1)$$

where T is the temperature (°C), a is the thermal diffusivity (m^2/h), θ is the concrete adiabatic temperature (°C), t is the time (d), τ is the concrete age (d).

According to the variation principle, the recurrence equation system of temperature field solution can be got, which is expressed as the following function after discretizing the domain R, differencing the time domain on the basis of Eq. (1).

$$\left[[H] + \frac{1}{\Delta t_n}[R]\right]\{T_{n+1}\} - \frac{1}{\Delta t_n}[R]\{T_n\} + \{F_{n+1}\} = 0 \quad (2)$$

where [H] is the heat transfer matrix, [R] is the supplement matrix of heat transfer, $\{T_n\}$ and $\{T_{n+1}\}$ are the temperature matrix of the node, $\{F_{n+1}\}$ is the temperature load matrix of the node, n is the number of the period, Δt is the time step. Based on the Eq. (2), $\{T_{n+1}\}$ can be derived when $\{T_n\}$ is known.

2.2. The method of pipe cooling temperature field

As Fig. 1 shows, A_i is the element with a cooling pipe. The water flow direction is from section i to section i + 1 and the length between the two sections is ΔL. ΔT_w is the water temperature increment in ΔL range, and the heat absorbed by water in unit time is expressed as:

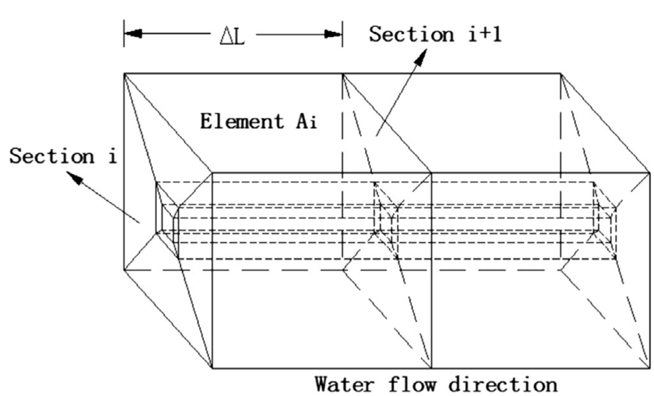

Fig. 1. The element with a cooling pipe.

$$\Delta Q_w = c_w \rho_w q_w \Delta T_w \quad (3)$$

where c_w is the specific heat (J/(kg°C)), ρ_w is the density of water (kg/m^3), q_w is the water flow in unit time (m^3/h).

In ΔL range, the heat released by concrete is:

$$\Delta Q_c = -\lambda \Delta L \int \left(\frac{\partial T}{\partial r}\right)_i ds \quad (4)$$

where λ is the conduction coefficient (J/m·h·°C), ΔL is the length of the element in the water flow direction (m).

According to heat balance, the water temperature increment in the element A_i is:

$$\Delta T_{wi} = -\frac{\lambda \Delta L}{c_w \rho_w q_w} \int \left(\frac{\partial T}{\partial r}\right)_i ds \quad (5)$$

Therefore, the water temperature on section i + 1 is:

$$T_{w,i+1} = T_{w,i} + \Delta T_{w,i} \quad (6)$$

It is necessary to adopt iterative algorithm because $\left(\frac{\partial T}{\partial r}\right)_{i+1}$ is unknown when computing. It is assumed that the water temperature in each section is equal to the intake water temperature. The whole temperature field of concrete is calculated by Eq. (2), and the first approximate water temperature, $T_{w,i}^{(1)}$ is calculated by Eqs. (5) and (6). Then, $T_{w,i}^{(1)}$ is regarded as the initial water temperature to calculate $T_{w,i}^{(2)}$ by repeating the above process. The repeated calculation will not stop until the following convergence criterion is met:

$$max\left|T_{w,i}^{(k+1)} - T_{w,i}^{(k)}\right| \leqslant \in \ (\in \text{ is a designated decimal}) \quad (7)$$

2.3. The equivalent age

The cement hydration reaction is exothermic and normally there is 150–350 J heat released by one gram of ordinary cement. The rate of chemical reaction will accelerate as the temperature of concrete increases. During the reaction, the relationship between temperature and reaction rate satisfies the Arrhenius equation [3]:

$$\frac{d(lnk)}{dT} = \frac{E}{RT^2} \quad (8)$$

where k is chemical reaction rate, E is apparent activation energy (J/mol), R is the universal gas constant (8.314 J/(mol K)).

Bazant established the maturity function [1] to calculate equivalent age compared with reference temperature on the basis of Arrhenius equation. The discrete form of maturity function is described as:

$$t_e = \sum_0^t exp\left(\frac{E_a}{R}\left(\frac{1}{273 + T_r} - \frac{1}{273 + T}\right)\right)\Delta t \quad (9)$$

where t_e is the equivalent age relative to the reference temperature (d), Tr is the reference temperature (20 °C), T is the mean temperature during the time of Δt (°C).

3. The proposed prediction formula

The common forms of adiabatic temperature rise models are exponential, hyperbolic and composite exponential [24,26,12]. As existing research indicates, the calculation results of the latter two forms are more accurate. This paper selects the composite