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Research Article

Study on Temperature Field Massive Concrete in Early Age Based on Temperature Influence Factor

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In order to solve the problem of insufficient accuracy of early temperature field caused by the change of hydration rate under different temperatures, the theoretical formula of finite element calculation based on temperature influence factor is put forward and then the theory is tested. On this basis of this theory, the early temperature field of a RCC dam is numerically simulated and the variation law of concrete hydration rate under different temperatures is studied. The numerical simulation results are compared with the results without considering the temperature effect and the measured temperature data. The results show that the theoretical results are in agreement with the measured temperature data, and the accuracy and applicability of the theoretical formula are proved.

1. Introduction

Due to great temperature difference, the temperature stresses are caused by heat of hydration of cement which leads to temperature cracks during mass concrete construction processing. Temperature cracks seriously affect the durability of concrete structures and reduce the service life of the project [1–3]. Cement hydration of mass concrete produces vast quantities of heat. However, concrete as a poor conductor of heat leads to its slow heat dissipation and high internal temperature. The heat of hydration generation rate of cement varies with different temperatures, and in the first 2 days, the heat of hydration of cement is 40–80% of the total heat [4, 5]. Therefore, it is more significant to simulate accurately the early-age temperature field of mass concrete considering temperature effect.

Considering the temperature influence on the mass temperature field, Saul [6] and Rastrup [7] firstly proposed the concept of equivalent age. Based on the concept of equivalent age, the domestic and foreign scholars have carried out a lot of research. For example, the Jin et al. [8] calculated equivalent age based on the equivalent quantity of cement and determined the concrete temperature field equation; Zhang et al. [9]. studied the influence of equivalent age on the adiabatic temperature rise of concrete; Schindler [10] studied the temperature effect on hydration heat of concrete based on equivalent age; Schutter [11] studied the heat of hydration from concrete based on the degree of hydration, which is consistent with the concept of equivalent age. Dong and Li [12] considered the chemical reaction rate of cement at different curing temperatures and deduced the hydration-heat released model of cement based on equivalent age. In order to directly reflect the change of hydration rate during the actual age, Zhang et al. [4]. proposed the temperature influence factor to accurately simulate the temperature field of PCCP (Prestressed Concrete Cylinder Pipe) on the high temperature curing stage. On this basis, this study presents a finite element theoretical formula based on the temperature influence factor and studies the early-age temperature field variation law of mass concrete considering the influence of temperature. Furthermore, compared with the measured temperature data, the theoretical formula is verified to be the correction and a basis for accurately simulating the temperature field of mass concrete is provided.

2. Hydration Rate Based on Temperature Influence Factor

2.1. Temperature Influence Factor. Arrhenius proposed the empirical formula for the rate of chemical reactions [13–18]:

$$v = Ae^{-(E_a/RT)}, \tag{1}$$

where A is the pre-exponential factor and E_a is the reaction activation energy; Ordinary Portland cement E_a is 33500/ $(\mathrm{J \cdot mol^{-1}})$, atmospheric constant $R = 8.314$ $(\mathrm{J \cdot mol^{-1}})$; T is temperature (k).

Integral expression of equation (1) is shown as

$$\ln\left(\frac{v_i}{v_r}\right) = \frac{E_a}{R}\left(\frac{1}{T_r} - \frac{1}{T_i}\right). \tag{2}$$

Making temperature influence factor $c_{T_i} = (v_i/v_r)$, c_{T_i} is the temperature influence factor at time i, which is the ratio of the reaction rate corresponding to the temperature at time i to the reaction rate at reference temperature. Formula (3) of temperature influence factor is obtained:

$$c_{T_i} = e^{(E_a/R)((1/T_r)-1/T_i)}, \tag{3}$$

where T_r is the reference temperature and T_i is the concrete temperature at a certain moment i.

2.2. The Equation of Hydration Rate Based on the Temperature Influence Factor. Assuming any point coordinate (x, y, z) in the concrete, the heat conduction equation of the transient temperature field [18] is shown as

$$c\rho\frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{\mathrm{d}Q_{(t)}}{\mathrm{d}t}, \tag{4}$$

where c is the specific heat capacity; ρ is the density; T is the temperature; and t is the actual age.

In the temperature field simulation of mass concrete, the temperature influence factor c_T is introduced to the heat conduction equation (4) considering the temperature effect. The modified formula is shown as

$$c\rho\frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + c_T\frac{\mathrm{d}Q_{(t)}}{\mathrm{d}t}. \tag{5}$$

The heat conduction equation (5) is to consider the temperature effect in transient temperature field, and the innovation is the introduction of temperature influence factorc_T.

Concrete hydration heat is generated and produced, in essence, by the compounds of cement hydration reaction with water hydration heat. Cement hydration heat is not fully released in the hardening process, but gradually released as time [19–22]. The hydration heat of cement changes with time:

$$Q_{(t)} = Q_\infty\left(1 - e^{mt^n}\right), \tag{6}$$

where t is the actual age; Q_∞ is the final hydration heat$t \longrightarrow \infty$; and m and n are the constant coefficients.

The hydration rate equation considering the temperature effect for any element in the finite element model at time t_i is shown as

$$q^T_{(t_i)} = c_{T_i}\frac{dQ_{(t)}}{dt} = e^{(E_a/R)((1/T_r)-1/T_i)}\, t_i^{n-1} e^{mt_i^n} mnQ_\infty. \tag{7}$$

In formula (7), the temperature influence item is $e^{(E_a/R)((1/T_r)-1/T_i)}$, namely, the temperature influence factor c_{T_i}. If $T_r = 20^\circ\mathrm{C}$, when $T_i \geq 20^\circ\mathrm{C}$, $c_{T_i} \geq 1$; when $T_i < 20^\circ\mathrm{C}$, $0 < c_{T_i} < 1$. The age effect term is $t_i^{(n-1)}$; moreover, this item declines with the increase of age and changes in (0, 1).

When the initial time ($t = 1$ d) and pouring temperature is T_0, the initial hydration heat rate value is q_1. If the initial value of the hydration heat rate is known, the temperature T_i at a certain unit time t_i can be obtained by program language programming. Thus, the temperature influence factor c_{T_i} at time t_i can be obtained from the heat conduction equation (3). The temperature field of mass concrete affected by temperature is calculated by the heat conduction equation (5).

3. Verify the Theory

In order to study the temperature field variation law of mass concrete under the influence of different temperature, the concrete finite element model of 1m thickness, 5 m long, and 5 m wide is used to verify the theory. The temperature field of the center point in the model is studied under the different ambient temperatures. Three calculation conditions: the 1st condition is cold environment, 5°C ambient temperature and 10°C pouring temperature; the 2nd condition is high temperature environment, 35°C ambient temperature and 10°C pouring temperature; the 3rd condition is high temperature environment, 40°C ambient temperature and 20°C pouring temperature. Under the different conditions, comparison analysis of temperature field in the center point M considering and not considering the temperature effect is studied. The results are shown in Figure 1.

In Figure 1, we can see that

(1) In the 1st condition, the slope of the point on L_1 curve is obviously smaller than that of curve L_{01} after considering temp-effect. Temperature change rate decreases and the peak temperature is decreased from 20.4°C to 17.2°C. After reaching the peak temperature on the 10th day, the slope difference between the curve L_1 and L_{01} becomes weaker and weaker gradually. The reason is that the temperature influence factor $c_{T_i} < 1$ and the heat of hydration rate are lower than that of without considering. It leads to the decrease of the temperature change rate and the temperature field changes obviously. With the increase of age, the age effect term $t_i^{n-1} e^{mt_i^n}$ is gradually reduced to zero. Thus, the temperature change rate is getting smaller and smaller.

(2) In the 2nd condition, when the temperature is between 10 – 20°C, the slope of L_2 curve is smaller than curve L_{02}, the temperature change rate decreases.

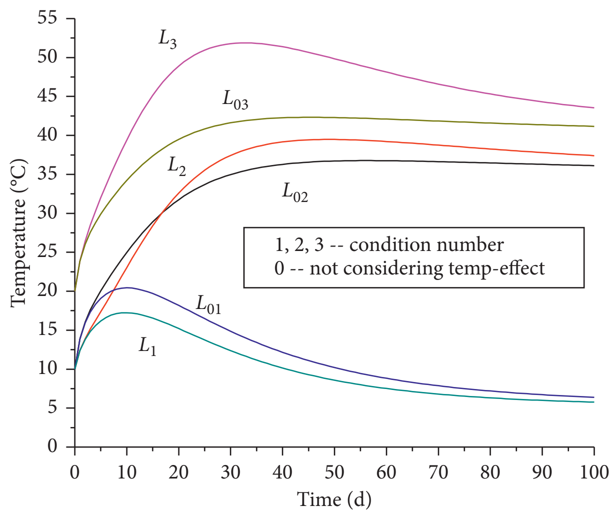

Figure 1: The temperature process curve of point M.

When the temperature is higher than 20°C, the slope of the point on the L_2 curve is obviously larger than that of L_{02} and the peak temperature increases from 36.8°C to 39.5°C. After reaching the peak temperature on the 50th day, the slope difference between the curve L_2 and L_{02} becomes weaker and weaker gradually. The reason is that the temperature influence factor $c_{T_i} > 1$ and the heat of hydration rate is higher than that of without considering temperature influence. It leads to the increase of the temperature change rate and the temperature field changes obviously. With the increase of age, the age effect term $t_i^{n-1} e^{m t_i^n}$ is gradually reduced to zero. Thus, the temperature change rate is getting smaller and smaller.

(3) In the 3rd condition, the slope of curve L_3 is obviously larger than L_{03} in early age. The temperature change rate increases, and the peak temperature increases from 42.3°C to 51.9°C. When after reaching the peak temperature on the 35th day, the slope difference between the curves L_3 and L_{03} becomes weaker and weaker gradually. After considering the temperature effect, the temperature difference between inside and outside increases from 2.3°C to 11.9°C.

(4) The temperature effect is weakened with the increase of age. In order to save the finite element calculation time, the temperature effect is taken into consideration only in early age, which is within two months after pouring concrete. Because after two months, the both temperature changes tend to be consistent. Beyond the time, the temperature effect is not considered. Considering the influence of temperature, the higher the temperature, the faster the hydration rate and the more obvious the change of temperature. It is more unfavorable to the concrete temperature control during the construction period, and vice versa.

The calculation results under the different conditions are shown in Table 1. In Table 1, it can be seen that, in high-temperature areas, the temperature difference has increased by five times after considering the temperature influence factors; however, in cold areas, the temperature difference does not change significantly. For the mass concrete engineering in the high temperature region and the high temperature curing, it is necessary to consider the temperature effect especially in the early temperature field simulation, which can improve the simulation accuracy of the temperature field and better construction temperature control.

4. Engineering Example

4.1. Engineering Overviews. One full section RCC gravity dam is divided into 22 sections. Building surface elevation is 73.0 m, and the crest width is 7 m. The thickness of the roller compacted layer is 30 cm. The interval layer thickness is 2 m, and the interval time is 5–7 days. The typical dam section No. 6 is used for finite element calculation. The length of the dam section is 20 m, and the dam height is 38.5 m. The element type of finite element analysis is solid70. The finite element model has a total of 60102 nodes and 50240 elements, and the finite element model is shown in Figure 2.

4.2. Material Parameters and Hydration Heat Calculation

(1) Material parameters and cement compositions: material parameters and cement components used in the finite element calculation for the RCC dam are shown in Tables 2 and 3, respectively.

(2) m and n parameters: Borg analyzed a large number of cement hydration heat test data, using the least squares method to obtain the empirical formula of multiple regression hydration heat [14, 15]:

$$Q(t) = A_t \times P_a + B_t \times P_b + C_t \times P_c + D_t \times P_d. \tag{8}$$

In formula (8), $Q_{(t)}$ is cement hydration heat on the age of t, kJ/kg; P_a, P_b, P_c, and P_d are C_3S, C_2S, C_3A, and C_4AF percent content, respectively; A_t, B_t, C_t, and D_t corresponding to unit mass C_3S, C_2S, C_3A, and C_4AF hydration heat value in t-age, kJ/kg.

The heating quantity of various hydration substances in cement clinker at different ages at 20°C is shown in Table 4 [18–20].

The empirical formula for the hydration heat of mixed cement with admixture [20–24]:

$$Q_P = Q_0 (1 - kp), \tag{9}$$

where Q_p is the hydration heat of the cement mixed with admixture; Q_0 is the hydration heat of the cement without admixture; p is the percentage of the admixture; the maximum value of p is 60%; and k is empirical coefficient 0.55. When the content of admixture is greater than 60%, the empirical coefficient k value is 0.5.

Table 1: The calculation results under different conditions.

Condition number	Ambient temperature (°C)	Pouring temperature (°C)	Peak temperature (°C)		Temperature difference (°C)	
			Without C_T	Considering C_T	Without C_T	Considering C_T
1	5	10	20.4	17.2	15.4	12.3
2	35	10	36.8	39.5	1.8	4.5
3	40	20	42.3	51.9	2.3	11.9

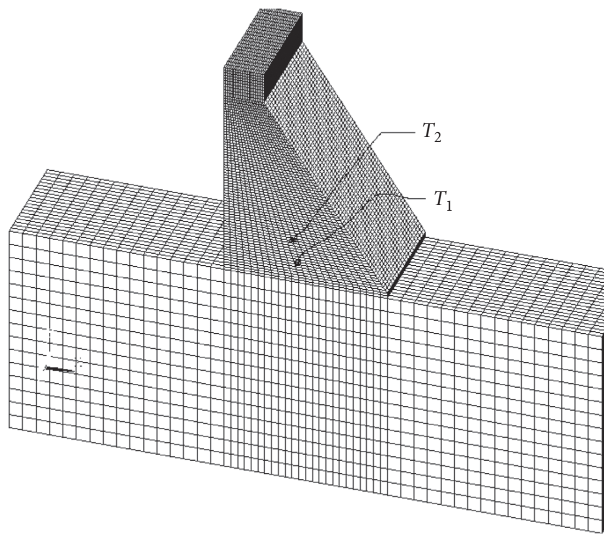

Figure 2: Finite element model.

Table 2: Material parameters.

Material	Density (kg/m^3)	Specific heat capacity (J/kg·K)	Thermal conductivity W/(m·K)	Poisson ratio	Linear expansion coefficient 10^{-6} (m/k)
Normal concrete	2 450	950	1.80	0.166	5.85
RCCII	2 350	950	1.85	0.166	5.85
RCCIII	2 350	950	1.85	0.166	6.75
Bed rock	2 550	780	1.66	0.235	7.10

Table 3: Cement components (%).

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	C_3S	C_2S	C_3A	C_4AF
20.94	5.59	5.24	63.46	2.88	1.8	51.22	21.43	5.77	16.77

Table 4: Heat of hydration substances.

Hydration substances	Heat of hydration (kJ/kg)					
	3 d	7 d	28 d	90 d	360 d	Q_∞
C_3S	242.9	221.8	376.7	435.5	489.8	510.1
C_2S	50.3	41.8	104.6	175.8	226.2	247.0
C_3A	887.7	1557.4	1377.4	1302.2	1168.2	1355
C_4AF	288.8	494.1	494.1	410.4	376.9	427.0

According to different cement mineral compositions and fly ash contents, the heat of hydration value can be calculated in different ages of the project through formulas (8) and (9). And the heat of hydration formula was fitted with the double exponential formula (6) by the hydration heat value of different ages. The fitting results of m and n coefficients are shown in Table 5.

4.3. Temperature Field Simulation. The ambient temperature of the engineering site varies with time according to the cosine curve of $T = 14.8 - 13.3\cos[3.14(t-1.1)/6]$ [24–26]. The mean annual temperature is 14.8°C. Roller-compacted concrete dam is compacted layer by layer, and each layer pouring temperature and time are different. The dam's temperature field is simulated using new heat conduction equation (formula (5)). Because the influence of temperature effect is obvious only in the early age, in order to save the calculation time, the calculation example only takes into account the influence of temperature in 30 days. Point T_1 is chosen to study the temperature field of the RCC dam on the early age. The position of T_1 is at the 82.5 m elevation and shown in Figure 1. The temperature history curve and the monitoring temperature data of position T_1 are shown in Figure 3.

Table 5: Hydration heat of concrete.

Type	Fly ash content (%)	Heat of hydration (kJ/kg) 3 d	7 d	28 d	90 d	360 d	Q_∞	m	n	R^2
Normal concrete	0	234.8	295.3	377.8	404.6	430.0	464.0	0.54	0.3	0.98
RCCII	50	176.1	214.1	273.9	293.3	311.8	336.4	0.57	0.3	0.98
RCCIII	68	155.0	194.9	249.3	267.0	283.8	306.2	0.54	0.3	0.98

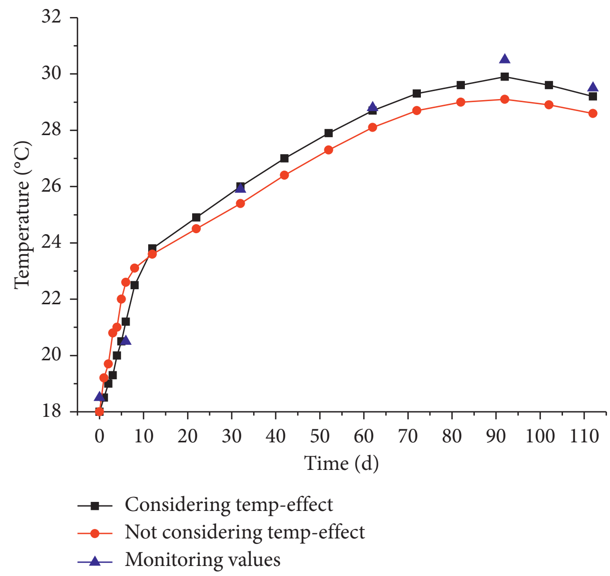

Figure 3: Temperature history curve of position T_1.

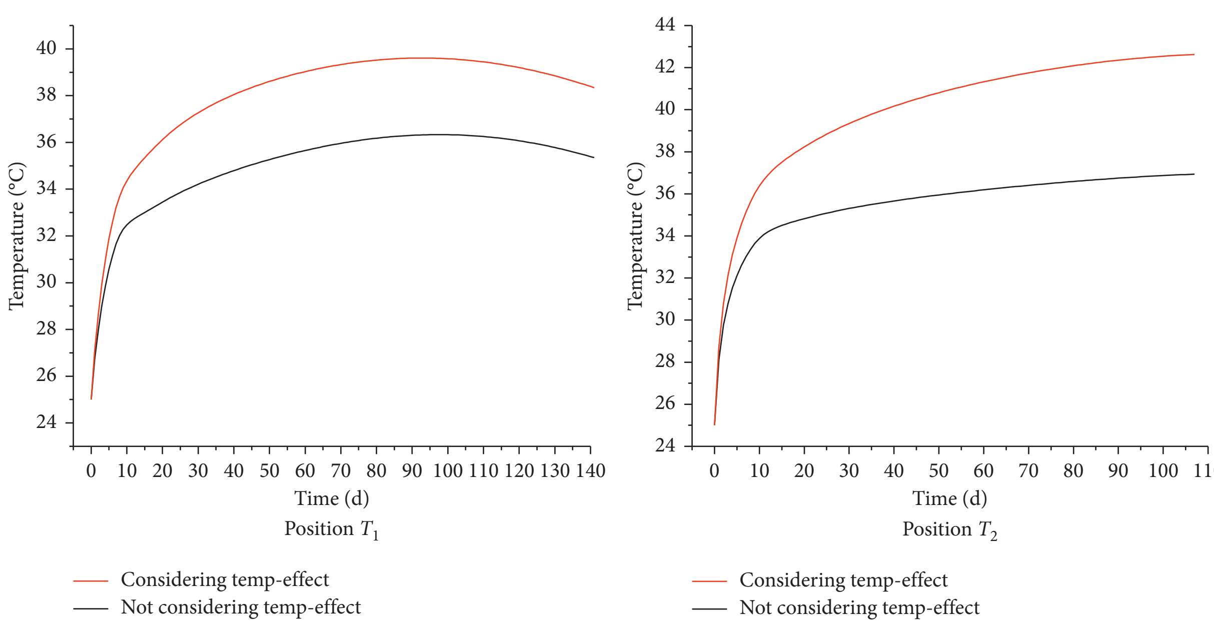

Figure 4: Temperature history curve of position T_1 and position T_2.

In Figure 3, it can be seen that (1) the pouring temperature is 18°C, and the heating rate is slower at the beginning of a few days after considering the influence of temperature. When the temperature is higher than 20°C, the heating rate becomes faster. Maximum temperature increased by 1.2°C. (2) The monitoring data is more consistent with the finite element calculation result considering the temperature effect, which shows that the numerical simulation results are more accurate after considering the temperature effect. (3) The ambient temperature is closer to the reference temperature of 20°C; thus, the temperature range of change is small.

It is assumed that the RCC dam is constructed in a high temperature region with an average temperature of 28°C and the ambient temperature varies with time according to the cosine curve $T = 28 + 10.8\cos[3.14\ (t - 66.8)/6]$. The position of point T_1 and point T_2 is at 82.5 m and 90.5 m elevation, respectively, as shown in Figure 1. The temperature history curves of point T_1 and point T_2 are shown in Figure 4.

In Figure 4, it can be seen that (1) concrete temperature rising speed increases in high-temperature area after considering temp-effect. Point T_1 reached the peak temperature on 100th day. The peak temperature increased from 36.3°C to 39.9°C, and maximum temperature increased by 3.6°C. Point T_2 reached the peak temperature on 110th day. The peak temperature increased from 36.9°C to 43°C, and maximum temperature increased by 6.2°C. (2) When the ambient temperature drops sharply, the larger temperature difference will lead to higher thermal stress and concrete temperature cracks. Therefore, better temperature control is necessary during the summer construction period in high-temperature areas such as pouring temperature control and take concrete cooling measures.

5. Conclusions

The heat conduction equation and the finite element theory formula based on the temperature influence factor are proposed. The theory is verified and the variation law of temperature field is analyzed. The temperature field of the RCC dam is simulated by an engineering example. The finite element simulation results are in agreement with the measured temperature data after considering the temperature effect, which proves that the theory formula is correct.

Temperature has a great influence on the early temperature field. In order to save the finite element calculation time, the temperature effect is considered only in one to two months after the pouring time.

Especially in the high-temperature region, early ages' accurate simulation of mass concrete temperature field, adopting the reasonable temperature control measures, control right into the molding temperature, and break and intermittent layer thickness is important, such as the choice of which can effectively guide the engineering construction rapidly.

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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