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# THERMODYNAMIC PROPERTY OF CONCRETE AND TEMPERATURE FIELD ANALYSIS OF THE BASE PLATE OF INTAKE TOWER DURING CONSTRUCTION PERIOD

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## ABSTRACT

This thesis analyzes the mechanism and process of hydration reaction of cement in concrete, the factors that influence the reaction and their corresponding parameters, introduces the thermodynamic parameter of concrete, studies the calculation model of adiabatic temperature rise of concrete and deduces the principle and formula of the cooling of water pipe in concrete. It uncovers the principles of analyzing unstable concrete temperature field, and demonstrates four boundary conditions of concrete. Based on the principle of finite element analysis, a simulation analysis is conducted on the temperature field of concrete base plate of an intake tower during construction period. RT-1 thermometer is used to conduct simultaneous observation on the temperature field. This thesis generates the features and variation patterns of the temperature field of mass concrete during construction period. The comparison between and the analysis of the calculation and actual measurement proves the feasibility of applying the calculation model the thesis proposes in practice.

**Keywords:** Base plate of intake tower; construction period; thermodynamic property; simultaneous observation; temperature field analysis.

## 1. INTRODUCTION

Mass concrete structure has been widely applied in civil and hydraulic engineering. Its temperature field and thermal stress have always been the focus of research. According to the investigation reports by the international commission on large dams (ICOLD) in 1988, among the 243 concrete dams that suffered devastative damage, 30 were temperature-induced. Concrete materials are the mixture of cement, water and aggregates. Its temperature field is influenced by multiple factors, including its own thermodynamic property, the cooling and thermal insulation during construction and hydration reaction, etc. Among them, the hydration reaction between cement and water is the main reason for the generation of temperature. When concrete heats up, its volume increases as it expands, vice versa. If the expansion or contraction of concrete is restrained, stress will be generated in concrete. When the stress outweighs the ultimate tensile strength of concrete, cracks will form in the structure, posing threat to the safety of the entirety. This thesis studies the principles of the temperature field of concrete from the thermodynamic property of concrete materials, hydration reaction, and the cooling effect of water pipes. Finally, it applies the results in the temperature field of base plate of intake tower during construction period, analyzes the variation patterns of temperature field, and compares the results of analysis with those of simultaneous observation to prove the validity of the calculation model.

## 2. THERMODYNAMIC PROPERTIES OF CONCRETE

### 2.1 Hydration reaction

Hitherto, research on hydration reaction of cement has all been based on the silicate-framework assumption proposed by Douigill, et al. in 1968[1]: when cement encounters water, a semi-permeable hydrate shell will form around silicate particles. It separates the waterless surface from the main liquid, thus leading to the induction period. Calcium ion ($Ca^{2+}$) can pass through the shell into the liquid, but silicate ion cannot. Instead, it remains outside the shell, increasing the osmotic pressure. When the osmotic pressure increases, hydrated silicates are forced into the liquid when there is no calcium. At this point, it recombines with $Ca^{2+}$ and forms tubular particles or other shaped particles, which marks the end of the induction period. Cement constituents around the particles further dissolve. Many scholars at home and abroad reached a consistent conclusion on the research of hydration reaction of cement. They think the hydration of cement can be divided into five periods [2-5], namely the initial hydrolysis period, induction period, reaction acceleration period, declining period and stable period, as is shown in Figure 1:

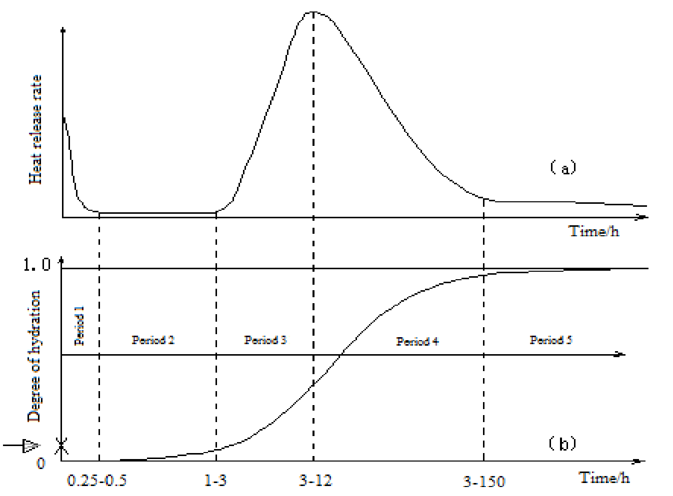


**Figure 1**. The hydration tendency and process of cement

Factors that influence the hydration reaction of cement in concrete abound, and many components in concrete all, to a certain extent, influence the hydration reaction. Ordinary silicate cement clinkers mainly include four kinds, tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetra calcium aluminoferrite. These four clinkers will go through hydration reaction in the presence of water. The speed and intensity order of hydration reaction is: calcium aluminate>tricalcium silicate>calcium ferrite>dicalcium silicate [6].

Mineral additives are intended to improve the property of concrete and reduce the heat emission and when certain fine and active mineral products are added when mixing concrete, such as fly ash, slag, and volcanic ash, etc., the components, the amount, the shape and the size of the particles all have big influence on the hydration reaction of cement and the heat emission [7-12]. Chemical admixtures mainly include water reducing agent and air entraining agent, which can improve the property of concrete. And the influence is mainly on tricalcium aluminate and the hydration of tricalcium aluminate [13-15]. Temperature is another important factor that influences the hydration reaction of cement. As the hydration reaction of cement continuously generates heat, the temperature of concrete rises, which accelerates the speech of hydration reaction, thus increasing the heat emission speed of the hydration reaction.

The thermodynamic property of concrete is not only related to its age, but also its own temperature and temperature history etc. Thus far, two parameters have been often used to describe the hydration reaction of concrete: degree of hydration and maturity.

Degree of hydration refers to the degree of hydration reaction of cement in concrete. When cement is mixed with water, a series of physical and chemical reactions will happen, emitting heat. The degree of hydration reaction of cement at a certain time is closely related to heat emission from hydration at that time. Based on Kjellsen's research, the degree of hydration of hardened cement paste at the time t can be acquired [16]:

$$\alpha(t) = \frac{W_n(t)}{W_{n,\infty}} \tag{1}$$

In the formula, $W_n(t)$ refers to the chemically combined water content of hardened cement paste at the hydration time t; $W_{n,\infty}$ refers to the chemically combined water content of completely hardened cement paste.

The definition of maturity was first put forward by Saul [17], who thought that when the raw materials and composition of a certain concrete are known, its maturity is mainly determined by temperature and time. Hence, the function of maturity M is defined as:

$$M = \sum (T - T_0)\Delta t \tag{2}$$

In the function, $M$ refers to the maturity; $t$ the concrete age; $T$ the temperature of the concrete; $T_0$ the reference temperature.

Afterwards, Rastrup proposed another way of describing maturity, namely equivalent age. Later, Freiesleben Hansen and Pedersen [18] established the function of equivalent age based on the Arrhenius function:

$$t_e = \int_0^t \exp[\frac{E}{R}(\frac{1}{273+T_r} - \frac{1}{273+T})]dt \tag{3}$$

In the function,

$$\begin{cases} E = 33500 & T \geq 20 \\ E = 33500 + 1470(20 - T) & T < 20 \end{cases}.$$

$E_a$ refers to the activation energy of concrete ($kJ/mol$), $T_r$ the reference temperature of concrete ($^0C$), normally $20\,^0C$, $T$ the average temperature of concrete within the time period $\Delta t$ ($^0C$), $t_e$ the equivalent age or Maturity(d) of concrete in reference to the referecnec temperature.

### 2.2 Calculation of adiabatic temperature rise of concrete

Hitherto, the calculation of hydration heat of cement relies on the age of the concrete. The following three formulas can be adopted [19-21]:

$$Q(\tau) = Q_0(1 - e^{-m\tau}) \tag{4}$$

In the formula: $Q(\tau)$——cumulative hydration heat at the age of $\tau$, $kJ/kg$;

$Q_0$——the ultimate hydration heat when $\tau \to \infty$, $kJ/kg$;

$\tau$——the age, d;

$m$——the constant, which changes according to the type of cement and the grouting temperature.

Hyperbola formula:

$$Q(\tau) = \frac{Q_0 \tau}{n + \tau} \tag{5}$$

$n$ is the constant, which is the age when half of hydration heat is emitted.

Composite exponential function:

$$Q(\tau) = Q_0[1-\exp(-a\tau^b)] \tag{6}$$

$a, b$ are both constants, and $Q_0$ is the ultimate hydration heat.

Adiabatic temperature rise refers to the temperature rise of concrete during the hydration reaction of cement when all boundaries of the concrete are in adiabatic state. For a certain concrete, if the hydration reaction of cement goes on thoroughly, the maximum adiabatic temperature rise is certain, too, which is not influenced by factors like temperature. The adiabatic temperature rise of concrete can normally be estimated based on the heat emission of hydration reaction of cement, its formula being:

$$\theta(t) = \frac{Q(t)(W+kF)}{c\rho} \tag{7}$$

In the formula: $W$ ——cement per unit volume of concrete, $kg/m^3$;

$c$ ——specific heat of the concrete material, $kJ/(kg \cdot {}^0C)$;

$\rho$ ——density of the concrete material, $kg/m^3$;

$F$ ——additive content in the concrete, $kg/m^3$;

$Q(t)$ ——the heat emission of hydration reaction of a unit mass of cement, $kJ/kg$;

$k$ ——the influence coefficient of additives. If additives contain fly ash, its value is 0.25.

The above formulas may induce many inaccuracies. Definitions of degree of hydration and maturity proposed by Guo Lei, Chen Shoukai and Guo Lixia, et al.[22] are adopted to propose a calculation model for adiabatic temperature rise based on the degree of hydration, mainly including the following three:

(1) Exponential hyperbola function

$$\theta = \theta(\alpha(t_e)) = \theta\left(\frac{t_e^m}{n+t_e^m}\right) \tag{8}$$

(2) Composite exponential function one

$$\theta = \theta(\alpha(t_e)) = \theta_u e^{-m \cdot t_e^{-n}} \tag{9}$$

(3) Composite exponential function two

$$\theta = \theta(\alpha(t_e)) = \theta_u(1-e^{-m \cdot t_e^{-n}}) \tag{10}$$

In the formulas: $t_e$ refers to the equivalent age or maturity of the concrete in reference to the reference temperature; $m$ is the time of hydration, which is determined by the experiment data; $n$ is the gradient of the hydration degree curve, which is also determined by the experiment data; $\theta_u$ is the adiabatic temperature rise when cement is completely hydrated. $\theta(\alpha(t_e))$ is the adiabatic temperature rise of concrete based on the degree of hydration, ${}^0C$; $\alpha(t_e)$ is the degree of hydration.

Based on the analysis of the calculation and experiment results of the three adiabatic temperature rise models, the exponential hyperbola formula is more accurate, and this thesis adopts this calculation model.

### 2.3 Thermodynamic parameters of concrete

Thermodynamic parameters of concrete mainly include temperature conductivity $a$, heat emission coefficient of the surface $\beta$, heat conductivity $\lambda$ and specific heat $c$. The choice of thermodynamic parameters directly influences the accuracy of the research of temperature field of concrete.

(1) Temperature conductivity $a$ ($m^2/h$): the temperature conductivity of concrete is closely related to its heat conductivity. $a=\lambda/c\rho$, $\rho$ is the density. It can be known that the bigger the specific heat of concrete is, the bigger the density. The smaller the temperature conductivity is, the weaker the heat conducting property. The temperature conductivity of ordinary concrete is between 0.003~0.006 $m^2/h$, and is mainly determined by the components of rude aggregates. Concretes with different kinds of rude aggregates have different temperature conductivity. The internal temperature conductivity of mass concrete is low, and heat is difficult to be emitted.

(2) Heat emission coefficient of the surface $\beta$ ($kJ/(m \cdot h \cdot {}^0C)$): heat emission coefficient of the surface is closely related to air speed, and the degree of roughness of the concrete surface has great influence on it. The heat emission coefficient of the surface in the air can be calculated through the following two formulas:

Rough surface: $\beta = 23.9 + 14.50 v_a$, smooth surface: $\beta = 21.8 + 13.53 v_a$

In the formulas, $v_a$ is the air speed, $m/s$.

(3) Heat conductivity $\lambda$ ($kJ/(m \cdot h \cdot {}^0C)$): heat conductivity of concrete is a parameter that reflects how easy it is for concrete to conduct heat. Main factors that influence heat conductivity of concrete are the amount of aggregates/the thermodynamic property of aggregates /the temperature and water content of concrete. Experiments show that wet concrete has a bigger heat conductivity than dry concrete. Newly grouted concrete has a bigger water content, thus its heat conductivity can be 1.5~2 times that of dry concrete. Heat conductivity increases as the density and temperature of concrete increase.

(4) Specific heat $c$ ($kJ/(kg \cdot {}^0C)$): the heat absorbed by a unit mass of concrete when temperature rises by 1 ${}^0C$ is called specific heat. Factors that influence the specific heat of concrete abound, mainly including the type, the amount and the size of aggregates.

## 3. THE RESEARCH OF THE COOLING OF WATER PIPE IN CONCRETE

When there is a cooling water pipe in concrete, as concrete hydrates and emits heat, surface heat emission and the heat emission from the pipe wall interact, which is a classic temperature field question. The basic theories of controlling partial differential equation, initial conditions and boundary conditions are the same as aforementioned. But there is a boundary problem of the cooling of water pipe. When iron pipe is used, the boundary of the cooling of water pipe can be seen as a simple temperature-known boundary. But it should be noted that the temperature along the pipe cannot be known beforehand. And when plastic pipe is used, boundary conditions become even more complicated. Pipe wall should be seen as the third kind of cooling boundary for heat exchange[23-25]:

$$-\lambda \frac{\partial T(x,y,z,t)}{\partial n} = \beta(T(x,y,z,t) - T_w(x,y,z,t)) \tag{11}$$

In the equation, $\beta$ is the heat emission coefficient of pipe surface, $kJ/(m \cdot h \cdot {}^0C)$; $\lambda$ is the heat conductivity of pipe, $kJ/(m \cdot h \cdot {}^0C)$; $T_w$ is the water temperature, ${}^0C$.

Based on the governing equation of the finite element method on unstable temperature field, the temperature field at the time $t + \Delta t$ can be acquired through the temperature field at the time $t$.

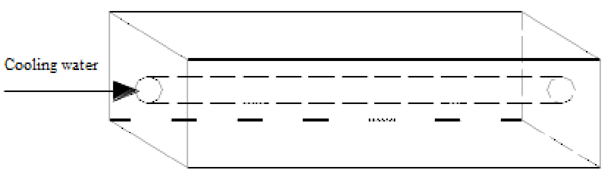


**Figure 2**. Concrete unit that contains cooling water pip

A random section of concrete that contains cooling water pipe is chosen. As is shown in Figure 2, assuming that there is just a small amount of water in the pipe, and that the water temperature changes very little when there is water pumping in the pipe, the calculation equation of water temperature in the pipe can be acquired based on the fourier law of heat conduction and thermal balance:

$$\Delta T_{wi} = \frac{-\lambda}{c_w \rho_w q_w} \iint_{\Gamma^0} \frac{\partial T}{\partial n} ds \tag{12}$$

$$\frac{\partial T}{\partial n} = \frac{\partial T}{\partial x}\cos\alpha + \frac{\partial T}{\partial y}\cos\beta + \frac{\partial T}{\partial z}\cos\gamma \tag{13}$$

In the equation, $\alpha$、$\beta$、$\gamma$ are the angles between axis $x, y, z$ and the normal $n$ of the surface $\Gamma^0$. The initial temperature of the cool water $T_{w0}$ is known. The above equations can be utilized to acquire the temperature along each pipe. It can be observed from the equations that the temperature along the pipe is related to the temperature gradient $\partial T / \partial n$ of the concrete around the pipe. Thus the temperature field of the cooling of water pipe in concrete is a boundary nonlinear problem, which can be solved by iterative method.

## 4. ANALYSIS OF UNSTABLE CONCRETE TEMPERATURE FIELD

### 4.1 Heat conduction equation[26]

Assuming that there is a well-proportioned isotropic solid, an infinitesimal hexahedron $dxdydz$ is extracted, as is shown in Figure 3:

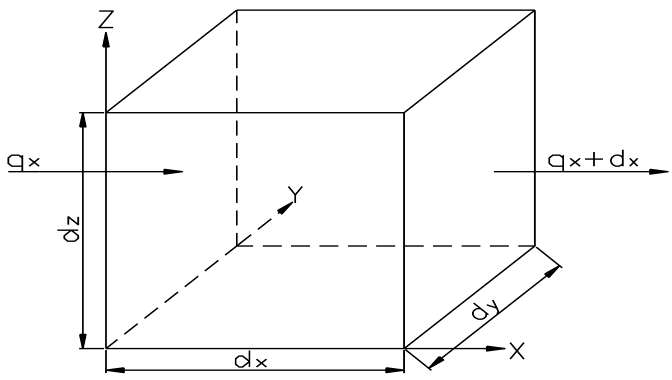


**Figure 3**. A sketch of the hexahedron

The heat that flows from the left side $dydz$ in a time unit is $q_x dydz$, and the heat that flows from the right side is $q_{x+dx} dydz$. The net heat that flows in is $(q_x - q_{x+dx})dydz$. In the heat conduction of solid, the heat flow $q$ (the heat that flows through a unit area in a time unit) is positively proportional to the temperature gradient. But the direction of heat flow is opposite to the direction of the temperature gradient. According to the principle of thermal balance, the sum of net heat that flows in and internal hydration heat should equal the heat absorbed during the temperature rise, namely:

$$c\rho \frac{\partial T}{\partial \tau} d\tau dxdydz = \left[\lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + Q\right] dxdydzd\tau \tag{14}$$

After it is simplified, the heat conduction equation of the well-proportioned isotropic solid is:

$$\frac{\partial T}{\partial \tau} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{Q}{c\rho} \tag{15}$$

In the equation $a = \frac{\lambda}{c\rho}$ ——temperature conductivity, $m^2/h$.

$c$ ——specific heat, $kJ/(kg \cdot {}^0C)$

$\rho$ ——unit weight, $kg/m^3$

$\tau$ ——time, $h$

Due to the hydration heat effect, the speed of temperature rise of concrete in adiabatic state is:

$$\frac{\partial \theta}{\partial \tau} = \frac{Q}{c\rho} = \frac{\overline{W}q}{c\rho} \tag{16}$$

In the equation $\theta$ ——adiabatic temperature rise of the concrete, $^0C$

$\overline{W}$ ——the amount of cement, $kg/m^3$

$q$ ——hydration heat emitted by a unit mass of cement in a time unit, $kJ/(kg \cdot h)$

According to equation (16), heat conduction equation can be rewritten:

$$\frac{\partial T}{\partial \tau} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{\partial \theta}{\partial \tau} \tag{17}$$

### 4.2 Initial condition and boundary conditions

The initial condition is the distribution pattern of the internal temperature field at the initial moment. Boundary conditions include the interaction pattern between the surrounding media and the surface of concrete, and the geometric shapes of the object. Initial condition and boundary conditions are together called boundary value conditions.

Normally the temperature at the initial moment can be regarded as evenly distributed, or $T = T(x, y, z, 0) = T_0$ . When calculating the temperature of grouting blocks of concrete, the initial temperature is the grouting temperature.

Boundary conditions can be given by the following four ways:

(1) The first kind of boundary condition: the surface temperature of concrete is the known function of time, namely:

$$T(\tau) = f(\tau) \tag{18}$$

When concrete encounters water, surface temperature equals known water temperature, which belongs to this kind of boundary condition.

(2) The second kind of boundary condition: the surface heat flow of concrete is the known function of time, namely

$$-\lambda\left(\frac{\partial T}{\partial n}\right) = f(\tau) \tag{19}$$

In the equation $n$ ——the direction of the normal of the surface.

If the surface is adiabatic, $\left(\frac{\partial T}{\partial n}\right) = 0$ .

(3) The third kind of boundary condition: when concrete encounters air, the surface heat flow is positively proportional to the difference between the surface temperature of the concrete $T$ and the air temperature $T_a$ , namely:

$$-\lambda\left(\frac{\partial T}{\partial n}\right) = \beta(T - T_a) \tag{20}$$

In the equation $\beta$ ——heat emission coefficient, $W/(m^2 \cdot {}^0C)$.

When heat emission coefficient $\beta$ verges to infinity, $T = T_a$ , namely it transforms to the first kind of boundary condition. When the heat emission coefficient $\beta = 0$ , and $\left(\frac{\partial T}{\partial n}\right) = 0$ , it turns to adiabatic condition.

(4) The fourth kind of boundary condition: when two different solids contact each other, if the contact is good, the temperature and heat flow in the contact face are both continuous, namely

$$\left.\begin{aligned} & T_1 = T_2 \\ & \lambda_1\left(\frac{\partial T_1}{\partial n}\right) = \lambda_1\left(\frac{\partial T_1}{\partial n}\right) \end{aligned}\right\} \tag{21}$$

If the contact between two solids is not good, the temperature is not continuous. The definition of thermal contact resistance should be introduced, namely

$$\left.\begin{aligned} & \lambda_1\left(\frac{\partial T_1}{\partial n}\right) = \frac{1}{R_c}(T_2 - T_1) \\ & \lambda_1\left(\frac{\partial T_1}{\partial n}\right) = \lambda_2\left(\frac{\partial T_2}{\partial n}\right) \end{aligned}\right\} \tag{22}$$

In the equation $R_c$ ——thermal contact resistance that is induced due to poor contact, $m^2 \cdot h \cdot {}^0C/kJ$ ; it is determined by experiment.

### 4.3 The principle of finite element solution to unstable temperature field

According to heat conduction equation and variation principle, finite element solution to three dimensional unstable temperature field problem can adopt the following functional $I^e(T)$:

$$I^e(T) = \iiint_{\Delta R} \left\{ \frac{1}{2}\alpha\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right] + \left(\frac{\partial T}{\partial \tau} - \frac{\partial \theta}{\partial \tau}\right)T \right\} dxdydz + \iint_{\Delta C} \overline{\beta}\left(\frac{1}{2}T^2 - T_a T\right) ds \tag{23}$$

In the equation, $\Delta R$ —subdomain unit $e$ contains; $a = \frac{\lambda}{c\rho}$ —temperature conductivity , $\lambda$ —heat conductivity; $T$ —temperature; $\tau$ —concrete age; $\theta$ —adiabatic temperature rise; $\Delta C$ —the area of the surface $C$ , which will only appear in boundary element; $\overline{\beta} = \frac{\beta}{c\rho}$ , $\beta$ — heat emission coefficient ; $c$ —specific heat; $\rho$ —unit weight; $T_a$ —air temperature.

The differential in the sign of integration is acquired through equation (2-52):

$$\frac{\partial I^e}{\partial T_i} = \iiint\limits_{\Delta R} \left\{ \alpha \left[ \frac{\partial T}{\partial x} \frac{\partial}{\partial T_i} \left( \frac{\partial T}{\partial x} \right) + \frac{\partial T}{\partial y} \frac{\partial}{\partial T_i} \left( \frac{\partial T}{\partial y} \right) + \frac{\partial T}{\partial z} \frac{\partial}{\partial T_i} \left( \frac{\partial T}{\partial z} \right) \right] + \left( \frac{\partial T}{\partial \tau} - \frac{\partial \theta}{\partial \tau} \right) \frac{\partial T}{\partial T_i} \right\} dxdydz$$

$$+ \iint\limits_{\Delta C} \bar{\beta} \left( T \frac{\partial T}{\partial T_i} - T_a \frac{\partial T}{\partial T_i} \right) ds \tag{24}$$

According to the condition for functional to realize extremum,

$$\sum \frac{\partial I^e}{\partial T_i} = 0 \tag{25}$$

In every joint, there is a function determined by equation (24). The temperature of all joints can be acquired by simultaneously solving this equation set.

## 5. TEMPERATURE FIELD ANALYSIS OF BASE PLATE OF INTAKE TOWER DURING CONSTRUCTION PERIOD

### 5.1 Simultaneous observation

The base plate of intake tower is 25m long, 10.6m wide, 2.5m thick. The calculation of grouting at different layers and blocks is simplified as grouting at different layers. There are five layers, each 0.5m thick. The total time of grouting is 60 hours. At the end of the grouting, the top is blanked with straw, and the four sides are conserved with lined polyester plywood. The curing lasts 15 days from the start of the construction to the end.

During the grouting of base plate, Φ25 pipes are distributed in U-shape. Water is pumped to cool the pipe, and the curing lasts 15 days. The temperature of water pumped into the pipe is $15\,^{0}C$. The external diameter of the cooling pipe is 25mm, and the internal diameter 22mm. The equivalent length of the cooling pipe is 268m. It is distributed as is shown in Figure 4:

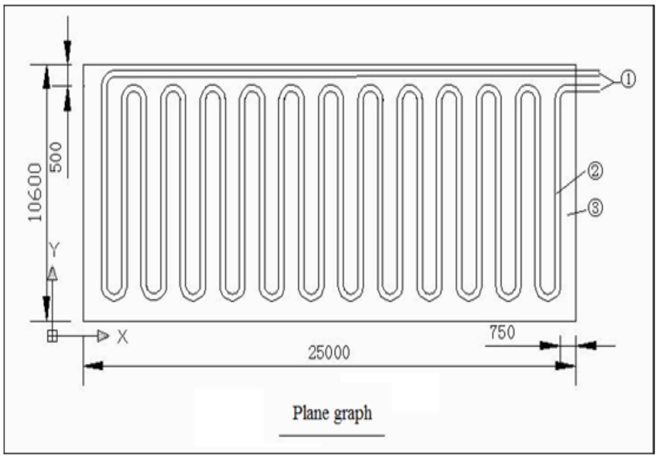


**Figure 4**. The layout of the cooling pipe

In this observation, 7 RT-1 thermometers are distributed in the base plate of intake tower. The specific position where each thermometer is installed is shown in Table 1 and Figure 5.

**Table 1**. The position of thermometers in the base plate of intake tower

| Name of instrument | Model of instrument | Number of measuring points | number of stake/m | Axle distance | Elevation /m | Note |
|---|---|---|---|---|---|---|
| thermometer | RT-1 | T1-1 | 0+012.5 | 5.25 | 87.75 | base plate |
| | | T1-2 | 0+012.5 | 3.94 | 87.75 | base plate |
| | | T1-3 | 0+012.5 | 2.63 | 87.75 | base plate |
| | | T1-4 | 0+012.5 | 1.31 | 87.75 | base plate |
| | | T2-1 | 0+024.95 | 0.01 | 87.75 | base plate |
| | | T2-2 | 0+024.45 | 0.01 | 87.75 | base plate |
| | | T2-3 | 0+022.95 | 0.01 | 87.75 | base plate |

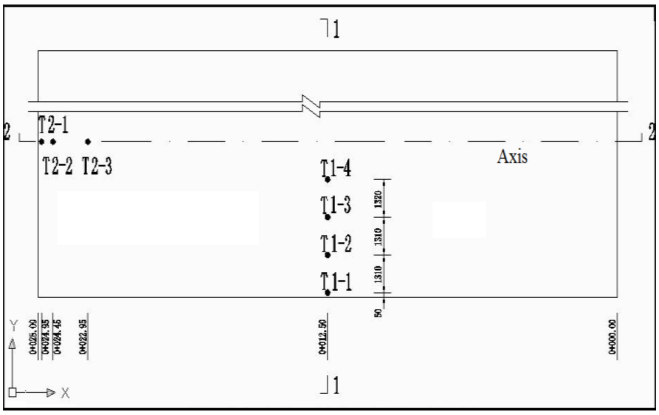


**Figure 5**. The layout of thermometers in the base plate of intake tower

Detailed observation plans are made in accordance with standards. When construction starts, observation is conducted every two hours. After the plate is removed from

### 5.2 Simulation analysis of temperature field

(1) The choice of calculation parameters

the concrete, observation is conducted every six hours. After seven consecutive days of observation, each day with two times of observation. The complete and continuous observation materials are acquired. The extremum of each experimented point is shown in Table 2:

**Table 2**. The eigenvalues observed by the thermometer ( ${}^0C$ )

| Number of measuring points | Maximum | Minimum | Monthly average | Monthly variation | Note |
|---|---|---|---|---|---|
| T1-1 | 19.6 | 9.3 | 14.4 | 10.3 | |
| T1-2 | 37.7 | 12.0 | 24.9 | 25.7 | |
| T1-3 | 37.5 | 12.9 | 25.2 | 24.6 | |
| T1-4 | 37.6 | 13.0 | 25.3 | 24.6 | |
| T2-1 | 23.3 | 9.3 | 16.3 | 14.0 | |
| T2-2 | 33.6 | 18.0 | 25.8 | 15.6 | |
| T2-3 | 34.3 | 20.1 | 27.2 | 14.2 | |

**Table 3**. Heat emission coefficient of steel plate and straw blanket

| | steel plate | straw blanket |
|---|---|---|
| heat emission coefficient $kJ/(m^2 \cdot h \cdot {}^0C)$ | 45 | 10 |

**Table 4**. Parameters of concrete

| Density | The temperature of concrete when put into the plate | heat conductivity | specific heat | temperature conductivity |
|---|---|---|---|---|
| $2447.5\ kg/m^3$ | $15\ {}^0C$ | $9.47\ kJ/(m \cdot h \cdot {}^0C)$ | $0.92\ kJ/(kg \cdot {}^0C)$ | $0.0042\ m^2/h$ |

During the calculation period of the base plate grouting, the calculation of temperature change adopts fitting sine formula:

$$T = 15 - 6 \times \sin(day \times \pi / 28) \tag{26}$$

When considering the cooling of water pipe, the water pipe is seen as a hea **Table 3**t sink. The cooling effect of the water pipe is considered on average[2]. The cooling effect is seen as heat absorption of concrete, which is treated as negative hydration heat, and the adjusted hydration heat equation is adopted:

$$Q(t) = Q_0 \times m/(m-p) \times [1 - \exp(-m \times t)] \tag{27}$$

In the equation, $Q_0 = 81175 kJ/kg$ , $m = 0.34$, $p = 0.132$.

(2) The calculation results of the temperature field of base plate during construction period

During construction period of base plate, 7 characteristic points are chosen as study subjects. For the convenience of comparison, the 7 characteristic points share the same positions with thermometers in the simultaneous observation of base plate in the previous chapter. The calculation results are shown in Figure 6 and Figure 7:

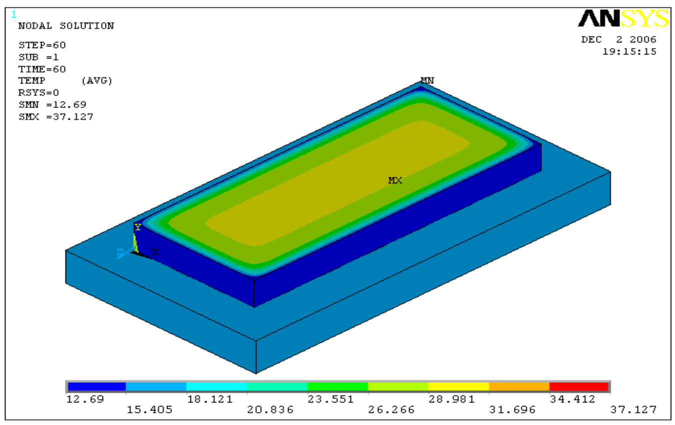


**Figure 6**. The temperature distribution of the base plate at the end of the construction period

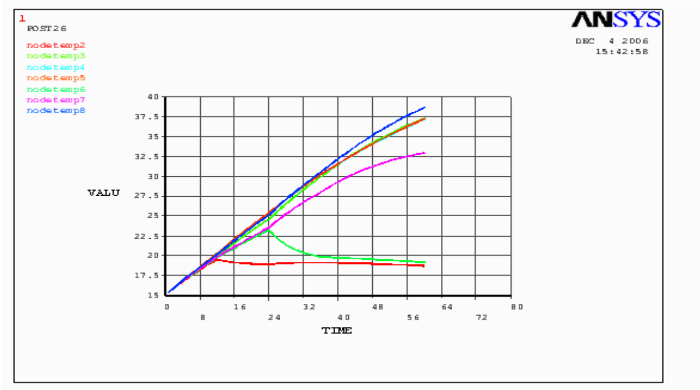


**Figure7**. Temperature variation curve of characteristic points of the base plate during construction period

It can be observed from Figure 6 and Figure 7 that the maximum temperature of concrete during construction period is 37.127 $^{0}C$ , and it appears at the end of the construction of the base plate. During the grouting, except point 2 and point 6, other points of the concrete display an increase in temperature. Hence, after the end of base plate grouting, the internal temperature of concrete can still not reach the maximum. The temperature still continues rising. Since point 2(T1-1) and point 6(T2-1) are close to the surface of concrete, at the initial phase of grouting, temperature rises due to the hydration heat effect. Later, the temperature decreases due to the heat emission effect of the surface of concrete.

### 5.3 The comparison between the calculation results of the temperature field of base plate and the observation results

The calculation curve and the observation curve of points 3(T1-2), 4(T1-3), 5(T1-4), 7(T2-2), 8(T2-3) are shown in Figure 8－12:

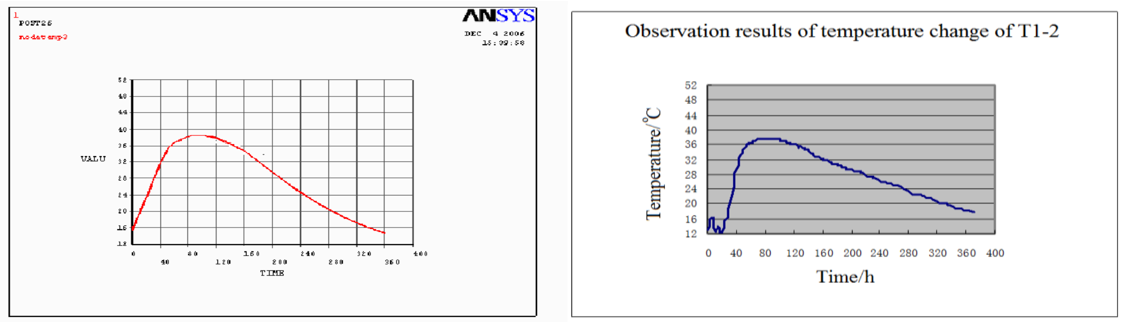


**Figure 8**. Calculation results and observation results of temperature change of points 3(T1-2)

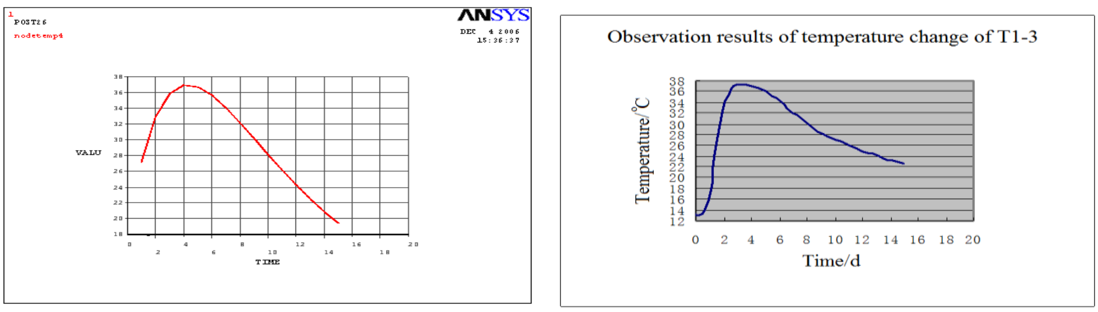


**Figure 9**. Calculation results and observation results of temperature change of points 4(T1-3)

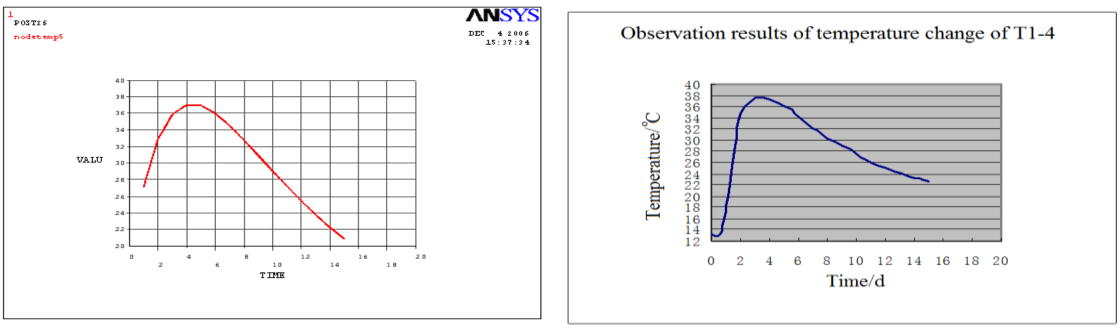


**Figure 10**. Calculation results and observation results of temperature change of points 5(T1-4)

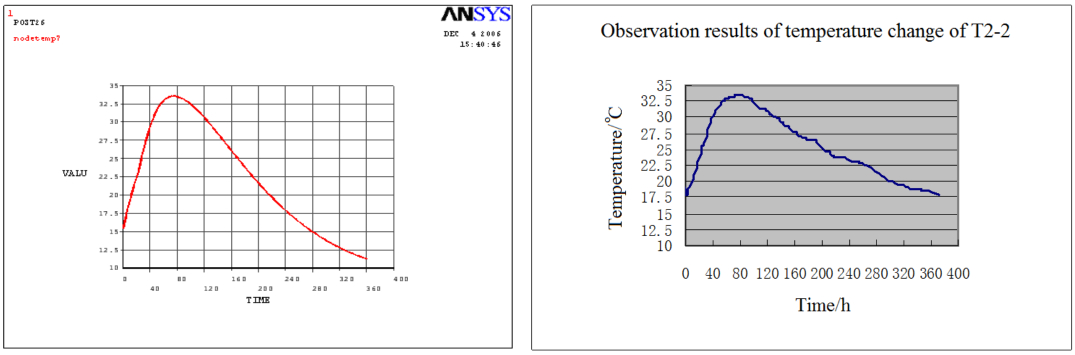


**Figure 11**. Calculation results and observation results of temperature change of points 7(T2-2)

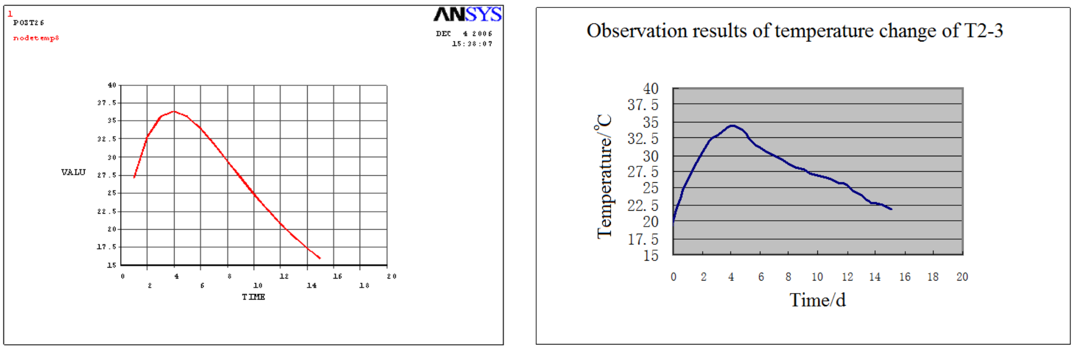


**Figure 12**. Calculation results and observation results of temperature change of points 8(T2-3)

Through comparison between the calculation curve and the observation curve of temperature change of characteristic points, it can be known that:

(1) The increase tendency of the calculation results is basically consistent with that of the observation results.

(2) The maximum calculation result of temperature is basically consistent with the observation result. It appears on the 3rd～4th day of the construction, and later disappears due to hydration heat of cement. The temperature decreases gradually. The maximum temperature during the construction of the base plate and water cooling period is 38.1 $^0C$, not exceeding the designed temperature value of concrete.

(3) During the later period of water cooling, the temperature decrease curve of the calculation result is basically consistent with that of the observation result. Temperature rise induced by hydration heat during construction period is within 20 $^0C$ ～25 $^0C$, the highest being 23.1 $^0C$, which suggests that the temperature controlling scheme of construction at different layers and different blocks and water pipe cooling is reasonable and effective.

## 6. CONCLUSIONS

This thesis studies the thermodynamic property of concrete materials. It adopts exponential hyperbola calculation model in regard to the common adiabatic temperature rise model of concrete. It also studies the principle of the cooling of water pipe in concrete, and proposes the calculation method of temperature field of the cooling water pipe. It analyzes the temperature field of base plate of intake tower during construction period, based on simultaneous observation of the temperature field of base plate of a certain intake tower during construction period and the calculation model of hyperbola adiabatic temperature rise. The calculation results are consistent with the results of simultaneous observation. Results all suggest that during the initial phase of construction, temperature rises and the maximum temperature appears on the 3rd～4th day of the construction. Later, the temperature drops due to hydration heat of cement. The calculated maximum temperature rise of the base plate during construction period is 23.1 $^0C$, not exceeding the allowed designed value of temperature rise of concrete.

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## REFERENCES

1 Douigill, J.W. Some effects of thermal volume changes on the properties and behavior of concrete [J].*The Structure of Concrete, Cement and Concrete Associate London*, 1968: 499-513.

2 Miao B., Chaallal O., Perration D., Aitcin P. C. On-site early-age monitoring of high-performance concrete

columns [J]. *ACI Materials Journal*, 1993, 90(5): 415-420.
3 James Andrew Gilliland. Thermal and shrinkage effects in high performance concrete s tructures during construction [D]. The University of Calgary, Calgary, Albert. 2002.9.
4 Anton Karel Schindler. Concrete hydration, temperature development, and setting at early-ages[D]. The University of Texas at Austin, 2002.5.
5 A. Feylessoufi, F. Cohen Tenoudji, V. Morin, et al. Early ages shrinkage mechanisms of ultra-high-performance cement-based materials [J]. *Cement and Concrete Research*, 2001, (31): 1573–1579.
6 Cengiz Duran Atis. Heat evolution of high-volume fly ash concrete [J]. *Cement and Concrete Research*, 2002, (32): 751–756.
7 S.Tsimas, A. Moutsatsou-Tsima. High-calcium fly ash as the fourth constituent in concrete: problems, solutions and perspectives [J]. *Cement & Concrete Composites*, 2005, (27): 231–237.
8 Maria S. Konsta-Gdoutos, Surendra P. Shah. Hydration and properties of novel blended cements based on cement kiln dust and blast furnace slag [J]. *Cement and Concrete Research*, 2003, (33): 1269–1276.
9 M.I. Sanchez de Rojas, M.Frias. The pozzolanic activity of different materials, its influence on the hydration heat in mortars [J]. *Cement and Concrete Research*, 1996, 26(2): 203-213.
10 Cengiz Duran Atis. Heat evolution of high-volume fly ash concrete[J]. *Cement and Concrete Research*, 2002, (32): 751–756.
11 Hossain K,Lachemi M.Strength,durability and micro structural aspects of high performance volcanic ash concrete[J].*Cement Concr Res*, 2007, 37(5): 759-765.
12 Vagelis G. Papadakis. Effect of fly ash on Portland cement systems. Part II. High-calcium fly ash[J]. *Cement and Concrete Research* 30 (2000):1647-1654.
13 Lam L, Wong Y L, Poon C S. Degree of hydration and gel/space ratio of high- volume fly ash/cement system[J]. *Cement and Concrete Research*, 2000, 30(5): 747-756.
14 Li Dongxu, Shen Jinlin, Chen Lin, et al. The influence of fast-setting/early-strength agent on high phosphorous slag content cement [J]. *Cement and Concrete Research*, 2001, 31(1):19-24.
15 Rao G A. Influence of silica fume on long-term strength of mortars containing different aggregate fractions [J]. *Cement and Concrete Research*, 2001, 31(1):7-12.
16 Knut O. Kjellscn, Rachel J. Detwile. Backscattered electron imaging of cement pastes hydrated at different temperatures [J]. *Ceand Concrete Research*, 1990, 20(2): 308-311.
17 A.G.A. Saul. Principles underlying the steam curing of concrete at atmospheric pressure, *Magzine of Concrete Research*, 1951, 2 (6): 127– 140.
18 Freiesleben H P, Pedersen E J. Maturity Computer for Cont rolling Curing and Hardening of Concrete [J]. *Nordisk Betong*, 1977, 1(19): 21-25.
19 Zhu Weiyong, Lou Zongke. Calculation of temperature variation of massive concrete after pouring. *Architecture Technology*, 2013, 44(5): 402-405.
20 Ma Yuexian, Chen Xiaoguang. The application of equivalent heat conduction equation in cooling temperature field calculation of mass concrete water pipe. *Concrete*, 2007, (3): 102-103+106.
21 Zhang Rui, Chang Xiaolin, Xie Lingfei. Study on temperature field of concrete arch dam during construction period. *China Rural Water and Hydropower*, 2005, (6): 39-42.
22 Zhao Shunbo, Guo Lei, Chen Shoukai. Analyses on Thermal Control and Crake Prevention of Concrete Structures. Beijing: China WaterPower Press, 2013.
23 Singh, S.N. Flow and heat transfer studies in a double Pass counter flow Solar Air Heater. *International Journal of Heat and Technology*, 2013, 31(2): 37-42.
24 Zhu Yueming, Zhang Jianbin. Study on application of water cooling pipe measures to RCCDs' thermal control during continuous construction in high-temperature seasons. *Journal of Hydraulic Engineering*, 2002, 33(11): 55-59.
25 Liu Xiaoqing, Li Tongchun, Han Bo. Direct algorithm for simulating cooling effect of water pipes in concrete. *Journal of Hydraulic Engineering*, 2009, 40(7): 892-896.
26 Teggar Mohamed, Mezaache EI Hacene. Heat transfer analysis during heat recovery in cylindrical latent thermal storage unit. *International Journal of Heat and Technology*, 2014, 32(1-2): 191-196.