# EARLY-STAGE MOISTURE TRANSFER OF SHALLOW BURIED HEAT-SOURCE CONCRETE IN WINTER BASED ON THERMAL HYDRAULIC COUPLED PROCESS

**LIU LIN[1,2]* , HAIXIA ZHANG[1], KAI GUO[1]**

[1]*School of Civil Engineering，Shenyang Jianzhu University，Shenyang，Liaoning Province, 110000，China*
[2]*School of Resources & Civil Engineering, Northeastern University，Shenyang，Liaoning Province, 110000，China*

***In terms of curing method for buried heat-source concrete in winter, internal temperature field of concrete shows characteristic opposite to temperature field in the traditional concrete curing period during the curing process, with surface temperature higher than internal temperature. Therefore, based on porous structure characteristics of concrete, concrete moisture movement control equation is established according to the mechanism of moist heat transfer. The effects of ambient temperature, heat source temperature and heat source heating time on moisture transfer of buried heat-source concrete columns during the curing period in winter are analyzed by numerical simulation. Studies have shown that before the end of hydration, for the influencing factors, the higher the concrete-casting temperature and ambient temperature is, the lower the relative humidity is. After the end of hydration, the lower the ambient temperature is, the lower the relative humidity is, while the effect of surface exothermic coefficient on humidity is exactly opposite. The effect of heat source heating time on relative humidity is shown after the end of hydration. That is, for a longer heating time, vapor pressure in the pores increases due to the temperature field, and the relative humidity increases. The heat source temperature rises in the hydration stage accelerates hydration, and shortens the time for relative humidity to reach the reduction inflection point.***

***Keywords:*** *heat and moisture coupling; winter construction maintenance; moisture movement*

## 1. Introduction

Winter lasts for several months in severe cold areas. Heating curing, as an important early construction method for concrete in winter, can greatly lengthen the short construction period of concrete in severe cold areas. At present, based on a new type of concentrated exothermic material, Self-regulating Heater, the engineering community proposes to bury the material in concrete to provide a heat source so that internal ambient temperature required for concrete curing is met. Self-regulating heater is a strip-shaped electric heater using resistivity positive temperature coefficient (PTC) conductive polymer composite as heating element, which can automatically regulate the output power as the temperature is changed to reach a temperature equilibrium point, and maintain constant temperature without adding other equipment. As a concentrated exothermic material, the heater can quickly reach the design temperature and maintain constant temperature after being electrified. It can reach 110 ° C for high temperature type, and 65 ° C for low temperature type. The existing research shows that [1-2] self-regulating heater, a concentrated exothermic material, quickly reaches the design temperature and maintains constant temperature after being electrified. Since the beginning of pouring, there is a large temperature difference from the concrete throughout the electrification process, and the previous phenomenon of high internal temperature and low surface temperature of the temperature field is changed. Therefore, based on thermal-humidity coupling relationship, this paper establishes concrete moisture movement control equation by studying the influence factors of moisture transfer in the humidity field. Targeting at the temperature influence factors such as ambient temperature, heat source temperature and heat source heating time, moisture transfer of buried heat-source concrete during the curing period in winter is studied to clarify mass transfer mechanism of the material field and optimize winter construction maintenance method for buried heat-source concrete.

## 2. Mechanism of action of self-regulating heater on early temperature field of concrete

For the concrete with buried concentrated exothermic heat source (self-regulating heater), the main characteristics of the temperature field control equation include: the control equation is an unsteady heat conduction equation, there is a variable power concentrated heat source in the region, cement hydration and heat release are not synchronized owing to temperature difference.

The rate for concrete cement hydration and energy generation of heater

$$E_g = q\,\mathrm{d}x\mathrm{d}y\mathrm{d}z + PL_s\,\mathrm{d}x\mathrm{d}y\mathrm{d}z \quad (1)$$

---

* Autor corespondent/*Corresponding author*,
E-mail: liumumu118@163.com

Where: $q$ is heat energy generated in unit volume concrete cement hydration per unit time, kW/m$^3$; $P$ is heater power, kW/m; $L_s$ is heater length per unit volume, m/m$^3$.

Then the temperature field control equation with concentrated exothermic heat source is

$$\rho c\frac{\mathrm{d}T}{\mathrm{d}t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+q+PL_{\mathrm{s}} \qquad (2)$$

Where: $T$ is transient temperature of concrete, °C; $t$ is time of process, s; $\lambda$ is thermal conductivity of concrete, kJ/(m·h· ℃ ); $\rho$ is concrete density, kg/m$^3$; $c$ is current specific heat of concrete, kJ/ kg·℃.

## 3. Mechanism of action of concentrated esothermic heat source on early humidity field of concrete

The concrete moisture movement control equation is established according to the principle of mass conservation, non-equilibrium thermodynamics theory and Fick's law. The main reasons for the decrease of the humidity in the concrete with the age of pouring include water consumption in cement hydration, the driving of humidity gradient, and the influence of internal temperature gradient on internal moisture form and moisture transfer of concrete.

The hydration and self-desiccation of concrete cement in early age will cause decreased moisture content. The evaporable water variable amount caused by hydration and self-desiccation of cement in the infinitesimal parallelepiped within time $\Delta t$ is:

$$Q_{\mathrm{h}}=\frac{\partial\omega_{\mathrm{h}}}{\partial t}\mathrm{d}x\mathrm{d}y\mathrm{d}z\Delta t \qquad (3)$$

It can be known from Sorit effect that temperature gradient causes moisture transfer, then evaporable water variable amount caused by temperature gradient in the infinitesimal parallelepiped within time $\Delta t$ is:

$$Q_{\mathrm{T}}=\frac{\partial\omega_{\mathrm{T}}}{\partial t}\mathrm{d}x\mathrm{d}y\mathrm{d}z\Delta t \qquad (4)$$

Therefore, the gross change of evaporable water in the infinitesimal parallelepiped within time $\Delta t$ is:

$$Q_{\omega}=\frac{\partial\omega}{\partial t}\mathrm{d}x\mathrm{d}y\mathrm{d}z\Delta t \qquad (5)$$

Therefore, before the demoulding, according to mass conservation of the infinitesimal parallelepiped:

$$Q_{\omega}=Q_{\mathrm{x}}+Q_{\mathrm{y}}+Q_{\mathrm{z}}+Q_{\mathrm{h}}+Q_{\mathrm{T}} \qquad (6)$$

Then, the moisture movement equation of the unsteady humidity field of concrete can be obtained:

$$\frac{\partial\omega}{\partial t}=\frac{\partial}{\partial x}\left(D\frac{\partial\omega}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial\omega}{\partial y}\right)+\frac{\partial}{\partial z}\left(D\frac{\partial\omega}{\partial z}\right)+\frac{\partial\omega_{\mathrm{T}}}{\partial t}-\frac{\partial\omega_{\mathrm{h}}}{\partial t} \qquad (7)$$

According to the adsorption principle, water content variation and relative humidity variation of the concrete pores are linearly correlated at any time [3], and then moisture movement equation of the buried heat-source concrete humidity field is established with considerations to the effects of self-desiccation, temperature gradient and humidity gradient.

$$\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left(D\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(D\frac{\partial H}{\partial z}\right)+\frac{\partial H_T}{\partial t}-\frac{\partial H_{\mathrm{h}}}{\partial t} \qquad (8)$$

The temperature gradient-induced humidity diffusion formula is

$$H_T=k\Delta T \qquad (9)$$

Where: $k$ is dampness-heat coefficient, which is the change in relative humidity caused by 1°C temperature change under a constant water content and hydration degree [4].

Therefore, the temperature gradient-induced humidity diffusion formula is:

$$\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left(D\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(D\frac{\partial H}{\partial z}\right)+k\frac{\partial T}{\partial t}-\frac{\partial H_{\mathrm{h}}}{\partial t} \qquad (10)$$

## 4. Identification and calibration of moisture movement parameters of buried heat-source concrete

The determination of moisture movement parameters is the key to study the internal humidity characteristics of buried heat-source concrete, which means great significance for studying temperature field variation and engineering volume stability of concrete. Moisture characteristic curve, humidity diffusion coefficient, Sorit coefficient, hydration-consumed moisture characterize the nature and characteristics of moisture movement in early age concrete, which is the premise of numerical simulation modeling application and quantitative analysis of moisture movement of buried heat-source concrete in early age.

### *4.1 Cement hydration reaction*

For the self-desiccation humidity reduction prediction model and parameters proposed by Jun Zhang, Yuan Gao [5] as shown in formula (11),

$$H_s=\begin{cases}0 & \alpha\geq\alpha_{\mathrm{c}}\\ \left(1-H_{\mathrm{s,u}}\right)\left(\dfrac{\alpha-\alpha_{\mathrm{c}}}{\alpha_{\mathrm{u}}-\alpha_{\mathrm{c}}}\right)^{\beta_{\mathrm{H}}} & \alpha<\alpha_{\mathrm{c}}\end{cases} \qquad (11)$$

Where: $H_s$ is the internal relative humidity decrease value of concrete caused by cement hydration, %; $\alpha$ is the degree of hydration; $H_{s,u}$ is the lowest relative humidity value of concrete when cement hydration reaches the final hydration degree $\alpha_u$; $\alpha_c$ is critical degree of hydration, according to the two-stage characteristic of humidity reduction, there are inflection points of humidity saturation period and humidity reduction period; $\beta_H$ is a curve shape parameter.

### *4.2 Humidity diffusion coefficient*

The humidity diffusion coefficient *D* reflects the water diffusion capacity of the concrete structure, which is affected by factors such as temperature, humidity and water-cement ratio[6-8]. Bažant et al. have experimentally proved that when the relative humidity is greater than 90%, $D/D_{sat}$ ($D_{sat}$ saturated water diffusion coefficient) is close to 1; when the relative humidity is greater than 70% and less than 90%, $D/D_{sat}$ decreases rapidly; when the humidity is less than 70%, $D/D_{sat}$ is basically maintained as a constant, and the humidity diffusion coefficient is expressed by the following formula (12).

$$\frac{D}{D_{\mathrm{sat}}}=\alpha_0+\frac{1-\alpha_0}{1+\left(\dfrac{1-H}{1-H_{\mathrm{c}}}\right)^n} \qquad (12)$$

Where: *D* is the water diffusion coefficient when the relative humidity is *H*; $D_{sat}$ is saturated water diffusion coefficient; $\alpha_0$, $H_c$, *n* are empirical coefficients, and the literature recommends $\alpha_0=0.05$, $H_c=0.8$, $n=15$ in the absence of test data;

$D_{\mathrm{sat}}=\dfrac{D_{1.0}}{f_{\mathrm{ck}}/f_{\mathrm{ck0}}}$, where $D_{1.0}$ is $3.6\times10^{-6}$m$^2$/h, $f_{ck}$ can be expressed by the average compressive strength, $f_{ck}=f_{cm}-8$Mpa, and $f_{ck0}$ is 10 MPa.

In addition, Grace [9] and Wong [10] found that when the temperature rises from 20 ° C to 40°C, Dsat increases by about 6 ~ 8 times, which indirectly confirms that D is affected by temperature. Moreover, by the concept of equivalent age, Lingli Gong [11] proposed the humidity diffusion coefficient of early age concrete under temperature-moisture coupling based on the influence of temperature on hydration degree.

$$D(H)=D_{sat}(\alpha_0+\frac{1-\alpha_0}{1+\left(\dfrac{100-H}{100-H_c}\right)^n})\cdot f(t_e) \qquad (13)$$

$f(t_e)$ is equivalent age influence function

### *4.3 Sorit coefficient*

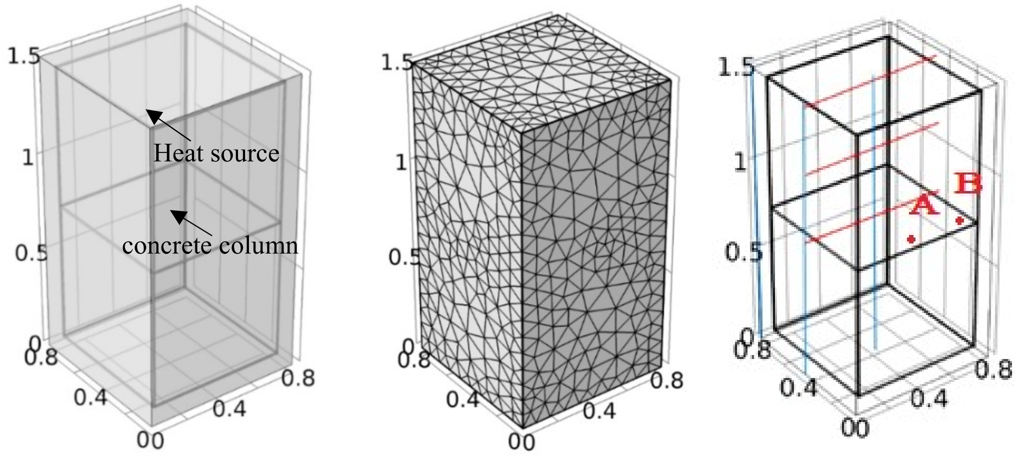
Many literatures believe that the change in internal relative humidity caused by temperature change at room temperature is negligible. However, considering the big temperature change in the heating and cooling stages of concrete curing in winter, this paper will consider the change. The literature proposes a temperature-humidity coefficient *k.*

$$k=0.0135h(1-h)/(1.25-h) \qquad (14)$$

## 5. Study on characteristics of humidity field of early age concrete

### *5.1Heat-moisture coupled concrete numerical model considering equivalent age*

In this paper, according to the unsteady temperature field control equation of early-age concrete with heat source exotherm, the same three-dimensional numerical model of concrete column is established using multi-physics coupling numerical analysis software COMSOLmultiphysics (hereinafter referred to as "COMSOL") based on the test results of heater-buried test column [12]. Figure 1 is a schematic diagram of the three-dimensional numerical model of the concrete column, with length × width × height of 0.8 m × 0.8 m × 1.5 m. Figure 1 (c) is a schematic diagram of



(a)Numerical model profile (b) automatic meshing of the concrete prism (c)Schematic diagram of model survey line

Fig. 1 - Numricalmodel of concrete column

**Table 1**

Equivalent exothermic coefficients of concrete column surface

| Surface position | Equivalent exothermic coefficient/kJ/(m$^2$·h·K) | Calculation time/h | |
|---|---|---|---|
| | | 0-72 | 72-200 |
| Concrete column outer surface | $\beta_{t1}$ | 8.3 | |
| Contact surface between concrete and heater | $\beta_{t2}$ | 418.6 | 418.6 |

**Table 2**

Parameters of concrete column models

| Parameter name | Unit | Parameter value |
|---|---|---|
| Concrete density $\rho$ | kg/m3 | 2500 |
| Concrete thermal conductivity $\lambda$ | kJ/(m·h·K) | 7.185 |
| Specific heat capacity $c$ | kJ/(kg·K) | 0.97 |

**Table 3**

Parameters of humidity field models

| Parameter name | Unit | Parameter value |
|---|---|---|
| $a$ | / | 0.05 |
| Relative humidity $h_c$ when the humidity diffusion coefficient is half of the maximum value $h_c$ | / | 0.8 |
| Fitting coefficient $n$ of relative humidity equation $n$ | / | 15 |
| Concrete diffusion activation energy $E_{ad}$ | kJ/mol | 35 |
| Ideal gas constant $R$ | J/(mol·K) | 8.314 |
| Reference temperature $T_r$ | K | 293 |
| Humidity diffusion coefficient $D$ | m$^2$/h | (13) |
| Age-considered influence function $f(t_e)$ | / | $f(t_e)=\exp[\frac{E_{ad}}{R}(\frac{1}{273+T_r}-\frac{1}{273+T})]$ |

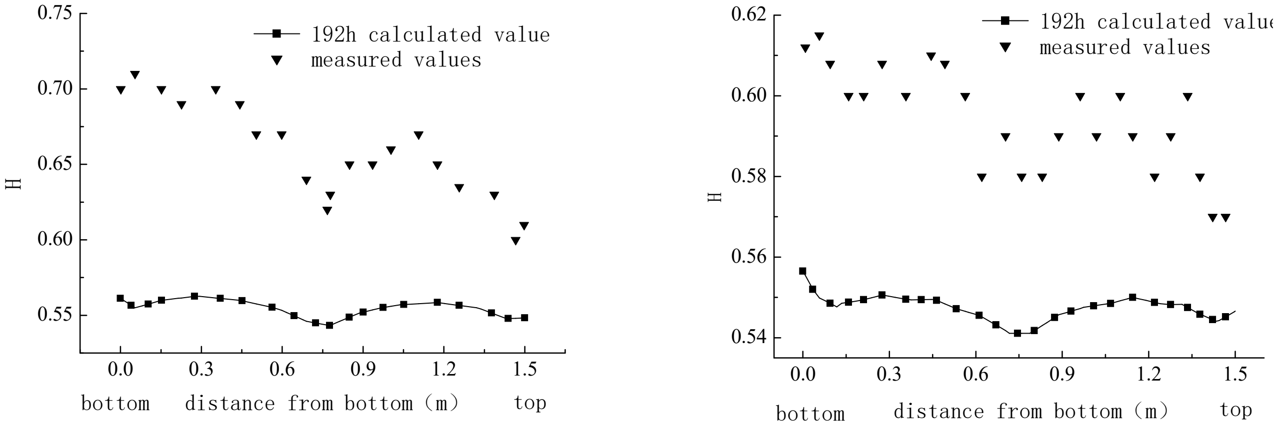
the concrete column model monitoring line. Through the study on relative humidity variation law in the blue survey lines in the figure (the vertical center line of the concrete column, the middle line of the surface, the knuckle center line) and horizontal red survey line in the concrete (as shown in the figure, z=1.475m, z=1.1m, z=0.75m), the distribution variation characteristics and influencing factors of the early age humidity field are identified.

At the initial moment of the calculation, the initial conditions of the model are determined according to the actual conditions of the concrete column temperature field test: the concrete - casting temperature T0 is 288K (15 ° C). In addition, the boundary conditions of the model need to be determined in the model calculation. In the heat transfer analysis, the boundary conditions refer to the heat conduction interaction between the structure surface and the surrounding medium.

There are two kinds of surface contact for the concrete column specimens in this test: the outer surface of the concrete column and the contact surface between the concrete column and the heater. In this experiment, the outer surface of the concrete column is not in direct contact with the air. To simulate the insulation measures taken during the actual winter maintenance process, a layer of insulation is wrapped on the concrete surface. Such boundary conditions can be considered as third type of boundary condition by selecting an appropriate equivalent exothermic coefficient $\beta_t$.

The contact between the concrete column and the heater should be the fourth type of boundary condition for direct contact between the two solids. However, due to the staged heating method in the actual test process, the temperature change law after the heating of the heater is stopped cannot be determined. Therefore, the boundary condition of the part is set as the third type of boundary condition in the numerical model, and the heat exchange mode of the heater and the concrete column is equivalent by controlling heat transfer coefficient. The equivalent exothermic coefficients of the above two boundary conditions in the numerical model are listed in Table 1, and other parameters used in the numerical model are listed in Table 2.

On this basis, based on COMSOL numerical analysis software, "dilute material transfer" module is used to couple the humidity field and temperature field in the early age concrete. The parameters involved in the humidity



(a) Comparison of measured and calculated values on surface centerline

(b)Comparison between measured and calculated values on surface edge

Fig. 2 - Comparison of measured and calculated values on concrete surface.

field are shown in Table 3. Since there is a template and insulation layer around the concrete column, there is no humidity exchange with the external environment, so gamma free flux boundary conditions are applied to each surface of the concrete.

### 5.2 Model Validation

The water content test was carried out on the 7-day-old concrete column after removing template of one side. The comparative numerical results are shown in Figure 2.

It can be seen from Figure 2 that, the lower part of the column surface has more water content than the upper part, and the middle part has more water content than the two sides. The overall reason can be explained as that the upper part has higher temperature than the lower part, the upper part has faster hydration than the lower part, the buried heater temperature in the two sides is higher than that in the middle, with faster hydration and water consumption, and the central humidity of the concrete surface is higher than that of two sides. After power failure of the heater, the concrete cools down, and the upper cooling rate is faster than that of lower part, which accelerates relative humidity reduction of the upper part. Seen from position with significant surface humidity fluctuation, trend of change and magnitude comparison, the numerical simulation of the humidity field has a good fitting effect.

### 5.3 Study on the variation law of humidity field of buried heat-source concrete column

The moisture transport mechanism of the internal humidity field after concrete pouring shows that the change of the humidity field in the concrete is mainly affected by two actions: cement hydration reaction and temperature gradient.

Figure 3 shows variation curve of relative humidity of vertical center of the concrete column at the observation point with time. It can be seen from the figure that, as the curing time progresses, the whole change process of relative humidity of the concrete with time can be divided into three stages: stage with relative humidity at 1, rapid decline stage and slow decline stage.

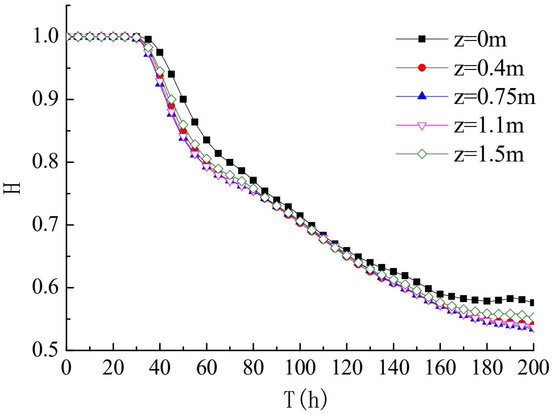
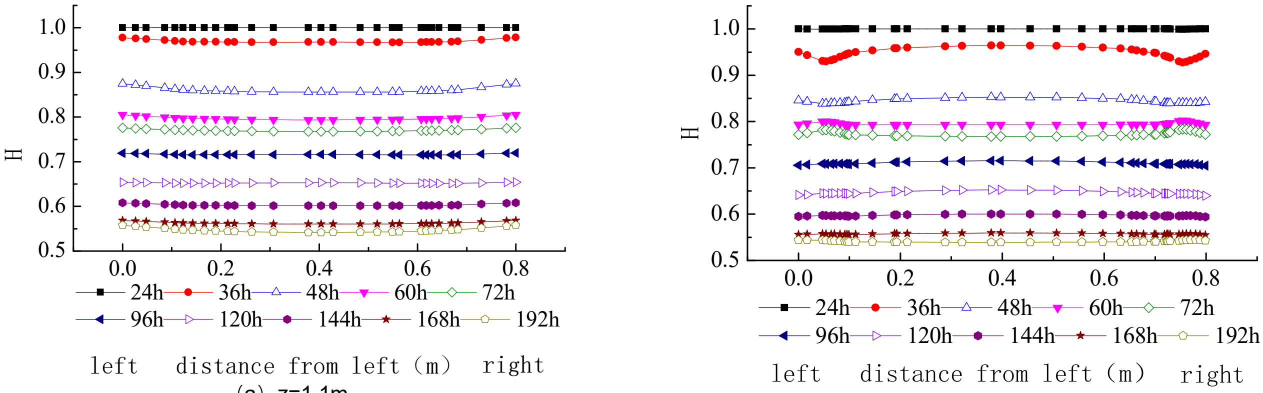


Fig. 3 - Relative humidity changes with time at different positions of concrete column.

Stage with relative humidity at 1: 0 ~ 30 hours after pouring. Although the concrete continuously consumes water due to self-desiccation, the relative humidity inside the concrete column is always maintained at 1.

Rapid decline stage: 30h~60h after pouring. With the hydration reaction progression, the relative humidity curve shows that when t=30h, the internal humidity of the concrete structure begins to decline rapidly. Except for the slightly higher value at the peak, other points have close values. Judging from the curing conditions of the specimens, water consumption during hydration in the concrete hydration stage is the main reason for the relative humidity decline.

Decline stage: 60h after pouring. Hydration is basically completed, temperature drop becomes the main reason for the relative humidity drop, and the humidity drop rate is increasingly slower. Take the bottom z=1.5m as an example. After t=160h, the temperature drops very slowly, so the relative humidity almost does not change.



(a) z=1.1m

(b) z=0.75m

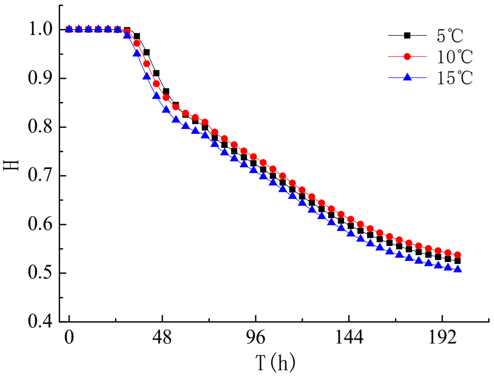
Fig. 4 - Distribution curve of lateral relative humidity distribution of concrete columns with age.

Representative central monitoring points of the transverse section of the concrete column are selected as shown in Figure 1 (c) transverse red survey line. Where, the column at z=0.75m is the section with heater in the middle part; the column at z = 1.1 m is the section without heater. The distribution curve of the relative humidity of each transverse lateral line with age is shown in Fig. 4. It can be seen from the figure that, when the buried heat source is heated, the relative humidity value around the heating zone decreases rapidly. Due to the waterproof effect of the concrete template and the insulation layer on the concrete side wall, the relative humidity of the concrete side wall is relatively high. When t>60h, hydration is basically completed, and hydration-consumed water is reduced. Under the influence of temperature change, the curve shows that relative humidity with higher temperature is higher than that with lower temperature. When t>72h, the heater stops power supply, concrete column rapidly cools down, and the relative humidity of the transverse section of the concrete is continuously and uniformly reduced.

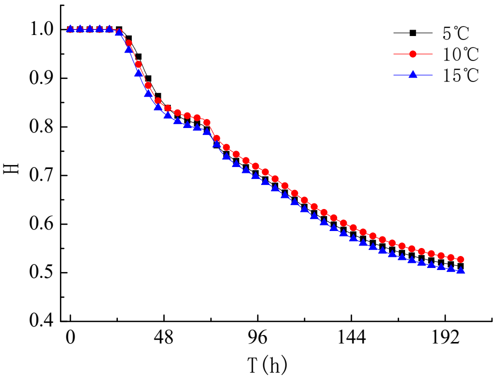
### *5.4 Analysis of humidity field parameters*

(1) Effect of concrete-casting temperature on humidity field

Studies have shown that concrete-casting temperature is an important factor influencing the temperature field of concrete. Therefore, the following studies were conducted on the influence of concrete-casting temperature on the humidity field. When the concrete-casting temperature is 5 °C, 10 °C, 15 °C, the variation in humidity field distribution of the transverse center end of the concrete column is compared as shown in Figure 5. It can be seen from the figure that, when t <30h in initial hydration, the relative humidity is maintained at 1 without change. Owing to cement hydration and self-desiccation effect, when the concrete hydration reaches the critical hydration degree (at about t=30h), there is an inflection point of humidity saturation period and humidity decline period. Afterwards, the relative humidity decreases significantly (30h~48h). When the hydration is basically completed, concrete temperature field is still in a relatively stable stage (48h ~ 72h), during which the heater is still heating, the temperature drops slowly, and the relative humidity slowly decreases. After t=72h, the heater stops heat supply and the concrete enters cooling stage, the vapor pressure in the cooling pores decreases and the relative humidity decreases, especially at angle point of section III. The angle point is adjacent to the heater junction, so the rate of temperature decrease at the time of power failure is more significant than that of other points. It can be seen from Figure 5(b) that, the relative humidity drops significantly after the heater stops power supply. A general survey of Figure 5 reveals that after 72h, the relative humidity decline rate is slower than that in hydration period.



（a）Monitoring stations A

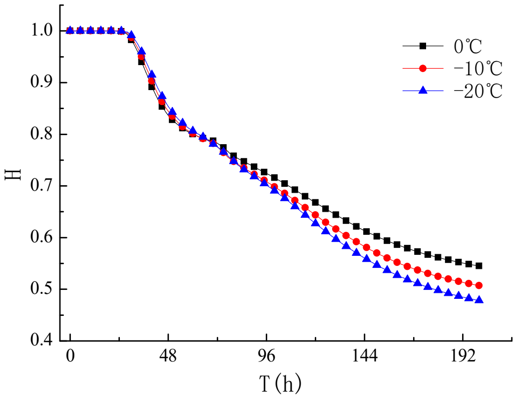


（b）Monitoring stations B.

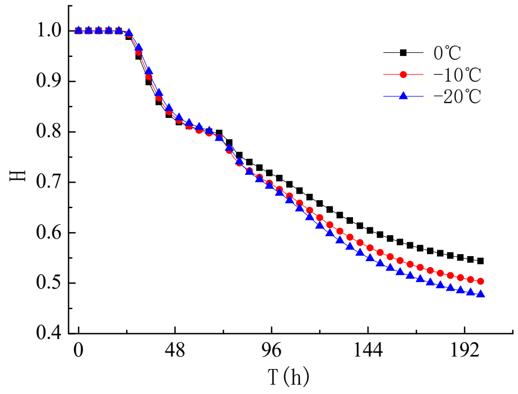
Fig. 5 - Comparison curves of relative humidity of III section varying with entering temperature.

(2) Effect of ambient temperature on humidity field

When the ambient temperature is -20 °C, -10 °C, 0 °C, the distribution variation of humidity field at the transverse center end of the concrete column is compared as shown in Figure 6. It can be seen from the figure that, the relative humidity in the initial stage of hydration is not reduced, and owing to cement hydration and self-desiccation, when the concrete hydration reaches the critical hydration degree (t=30h), there is an inflection point of humidity saturation period and humidity reduction period, and then the relative humidity decreases significantly. When the hydration is basically completed, the concrete temperature field is still in a relatively stable stage (48h ~ 72h). At this stage, the heater is still heating, the temperature drops slowly, and the relative humidity tends to decrease slowly. After t=72h, the heater stops power supply, the concrete enters cooling stage, vapor pressure in the cooling pore decreases and the relative humidity decreases, but the speed is slower compared to that in the hydration period. Nevertheless, it can be clearly seen at this stage that the curve is significantly affected by the ambient temperature, and the relative humidity reduction rate is greater for lower ambient temperature.



（a）Monitoring stations A

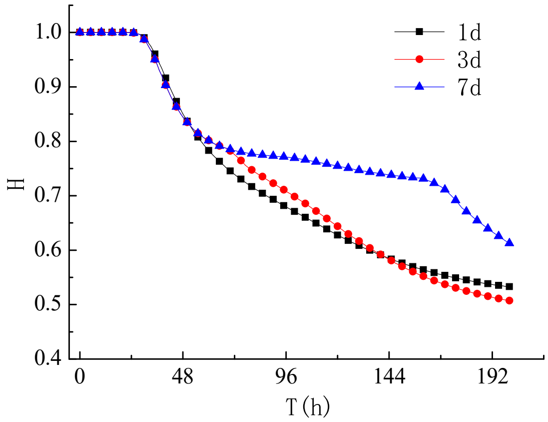


（b）Monitoring stations B

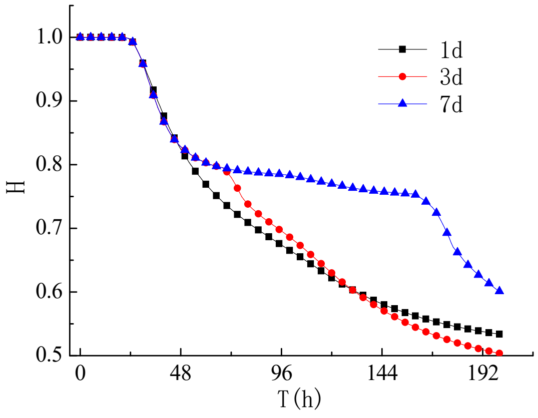
Fig. 6 - Comparison curves of relative humidity of III section varying with ambient temperature.

(3) Effect of heating curing time on humidity field

When the different heating curing time is 1d, 3d, 7d, the transverse central end of the concrete column is shown in Figure 7.It can be seen from the figure that, in the initial stage of cement hydration, before the concrete hydration reaches the critical hydration degree, the heat source heating time does not affect the change of concrete relative humidity. However, when the degree of hydration exceeds the critical degree, the relative humidity begins to decrease, and temperature becomes the main cause of relative humidity change. For lower temperature, the vapor pressure in the pores decreases with lower relative humidity and faster relative humidity reduction. Therefore, it can be seen from the figure that, after the hydration is basically completed (t>48h), the heat source continues heating, temperature reduction rate becomes smaller, and the relative humidity reduction rate also becomes smaller. Therefore, the relative humidity curve after 7d heating is higher than that at other curing time after the hydration is completed. However, affected by temperature reduction, the relative humidity curve of all curing time after power failure is in continuous decline, which is caused by temperature drop-induced smaller vapor pressure



（a）Monitoring stations A



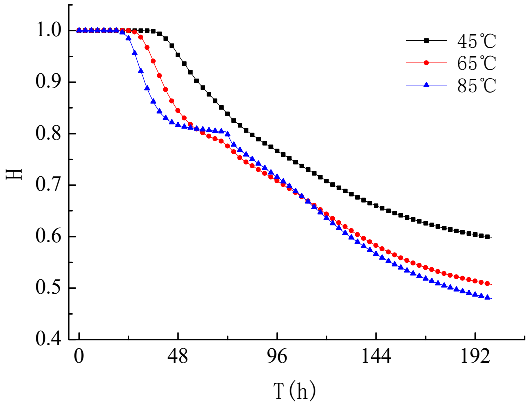
（b）Monitoring stations B.

Fig.7 - Comparison curves of relative humidity of III section varying with heating time.

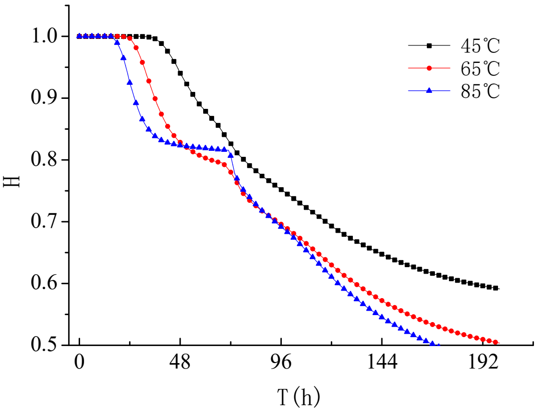
in the pore and decrease of relative humidity. Where, temperature field with 7d heating has obvious temperature changes compared to that under other heating conditions. Hence, relative humidity curve of 7d heating has more significant decline than that of 1d and 3d heating.

(4) Effect of heat source temperature on humidity field

When the heat source temperature is 45 °C, 65 °C, and 85 °C, the relative humidity variation curve of lateral central end of the concrete column at the monitoring point is compared as shown in Figure 8. It can be seen from the figure that, in the initial stage of hydration, regardless of heat source temperature, the relative humidity is maintained at 1 without reduction before the critical hydration degree is reached. Thereafter, for a higher heat source temperature, the hydration speed is faster and the shorter time is required to reach the critical value of hydration (the inflection point of saturated humidity and humidity reduction). From the humidity variation curve under the action of 85 °C heat source, it can be clearly seen that when t=24h, the hydration threshold is reached, the relative humidity begins to decrease, while relative humidity begins to decline when 65°C heat source is at t=30h and 45°C heat source is at t=45h. This is because increased heat source temperature can increase the overall temperature field of the concrete, accelerate hydration, and increase water consumption. In addition, before the hydration is basically completed, for a higher heat source temperature, relative humidity has greater reduction speed. In particular, it can be seen from the figure that, before the heater stops heating, hydration water consumption of the concrete under the action of 85 °C heat source is basically completed, and the curve shows a relatively flat downward trend. After power supply is stopped in the heater (t>72h), the concrete temperature decreases accordingly with vapor pressure in the pores decreased. The relative humidity curves of the concrete under the heat source of 45°C, 65°C and 85°C show slow decrease.



（a）Monitoring stations A



（b）Monitoring stations B

Fig.8 - Comparison curves of relative humidity of III section varying with heat source temperature.

## 6. Conclusion

In this paper, the basic calculation principles of early concrete humidity field are studied, including the concrete moisture movement equation with concentrated exothermic heat source, and moisture movement parameters of buried heat-source concrete are identified and calibrated. Using COMSOL “dilute material transfer” module, coupling calculation is made on humidity field and temperature field in early age concrete to obtain humidity field characteristics of early age concrete. The effects of ambient temperature, heat source heating time and heat source temperature on the humidity field are studied, with the following conclusions drawn:

(1) The humidity field has much faster change rate than the temperature field. Before the hydration is basically completed, water consumption in hydration is the main reason for the decrease in relative humidity of the concrete. Due to the high temperature effect of the heater, the central relative humidity of the concrete column section with heater is higher than that of the edge, and the edge has higher relative humidity than the angle. For concrete section without heater, as center temperature of the temperature field is higher than that of edge, the relative humidity is lower at the bottom than the middle part and the angle part. In overall, relative humidity of concrete column humidity field is lower in the upper part than the lower part.

(2) When the concrete ratio and curing age are the same, ambient temperature, heat source heating time and heat source temperature are the main reasons affecting humidity field. Before the end of hydration, for a higher ambient temperature, the relative humidity is lower. Temperature change after hydration becomes the main reason for the change of relative humidity. For a lower ambient temperature, the relative humidity is lower.

(3) The length of heat source heating time mainly affects the change of relative humidity after

hydration. For a longer heating time, relative humidity is higher under the effect of the temperature field. The effect of heat source temperature on relative humidity is mainly shown in the fact that high temperature heat source hydration accelerates, so that the starting point for relative humidity decline of the concrete is advanced, and the overall relative humidity is lower than that of low-temperature heat source concrete.

***Acknowledgements***
*This work was supported by National Natural Science Foundation of China (51608334), Liaoning Natural Science Foundation ( 20170540772).*

REFERENCES

[1] X. Zhang, Prevention and control technology of concrete structure cracks, Chemical Industry Press(Beijing), 2006, 6-12.
[2] K.Z. Cao, Comprehensive Measures for Structural Crack Control of Mass Concrete, Building Structure, 2002, **32**(08), 30-39.
[3] M. Wyrzykowski, P. Lura, F. Pesavento, et al. Modeling of internal curing in maturing mortar. Cement and Concrete Research. 2011, **41**(12), 1349-1356.
[4] Z.P. Bažant and L.J. Najjar, Nonlinear water diffusion in nonsaturated concrete, Materials and Structures, 1972, **5**(01), 3-20.
[5] J. Zhang, D. W. Hou, Y. Gao, Calculation of shrinkage stress in early-age concrete pavements. I: calculation of shrinkage strain, Journal of Transportation Engineerin g, 2013, **139**, 961-970.
[6] Z.P. Bažant and W. Thonguthai, Pore pressure and drying of concrete at high temperature, Journal of the Engineering Mechanics Division,1978, **104**, 1059-1079.
[7] Z.P. Bažant and W. Thonguthai, Pore pressure in heated concrete walls: theoretical prediction. Magazaine of Concrete Research,1979, **31**(107), 67-76.
[8] Z.P. Bažant, J. C. Chern, W.Thonguthai, Finite element program for moisture and heat transfer in heated concrete, Nuclear Engineering and Design,1982, **68**, 61-70.
[9] W.R. Grace, Chloride penetration in marine concrete-a computer model for design and service life evaluation, Corrosion, 1991, **47**, 1-19.
[10] S.F. Wong, T.H. Wee, S.L. Lee, Study of water movement in concrete. Magazine of Concrete Research, 2001, **53**(03), 205-220.
[11] G.T. Liu, Dahai Huang, Experimental Study on Thermal Conductivity and Thermal Diffusivity of Moist Concrete (I)——Design Principle of Experimental Device, Journal of China Three Gorges University (Natural Sciences), 2008, (01), 12-1.
[12] L. Liu and W. Zhao, Precise control of concrete temperature history in buried heat source of concrete, Journal of Northeastern University (Natural Science), 2018, **39**(03), 421-425.

***

## MANIFESTĂRI ȘTIINȚIFICE / SCIENTIFIC EVENTS

### 2nd International RILEM Conference - Rheology and processing of construction materials (RheoCon2)
### 9th International RILEM symposium (Self – compacting concrete (SCC9))

**8-11 September, Dresden, Germany**

**Topics RheoCon2**

In addition to concrete and cementitious binders contributions to the RheoCon2 cover grouts, renders, plasters, bitumen, paints, and adhesives. For each of the above construction materials, the following aspects are considered:

- Components' properties and characterization;
- Chemical admixtures and mixture design;
- Laboratory and in-situ rheological testing;
- Constitutive models and flow modelling;
- Mixing, processing and casting processes;
- Additive manufacturing / 3D-printing;
- Process induced properties such as fresh state, mechanical or durability properties.

**Topics SCC9**

- Material design and materials science;
- Rheology and workability;
- Production and placement;
- Mechanical properties and structural design;
- Durability and sustainability;
- Modelling and numerical simulations;
- Case studies.

https://www.rheocon2019.org/Default.asp

***