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Study on the application of a self-regulating heater for pre-control of concrete curing temperature in winter

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As a concentrated high-temperature exothermic material, a self-regulating heater is embedded in the concrete for heating and maintenance in winter, which can greatly improve the short concrete construction period in a severe-cold area. In order to achieve the expected temperature control, adjust the performance of concrete and optimize the design method of heating and curing, a pre-control method of concrete temperature history with the change of hydration degree is established based on the first law of thermodynamics, using the concept of equivalent age, considering the effect of temperature on the hydration reaction and thermal performance of concrete through the expected mechanical strength design. The method was verified by a temperature control test. The results show that the method can effectively control the heating rate of concrete. When the temperature at the design stable phase is 45°C, the temperature at the concrete phase is relatively stable due to the decrease of hydration reaction, slowly decreasing at a rate of 0.11 °C /h and 0.08 °C /h. The temperature at the actual stable phase is in the range of 39.69-45.63 °C, the variation range is 0.12%. The buried heat source can effectively accelerate the hydration reaction, and the hydration degree under the condition of 45 °C for 3 curing days equals to that at 20 °C for 7 curing days.

Keywords: Curing in winter; Equivalent age; Self-regulating heater; Pre-control

INTRODUCTION

The winter in severe cold areas can last for several months, resulting in a short effective construction period of many concrete projects. If the concrete is frozen and kept frozen below -10 °C with only a small extent of cement hydration, the concrete will lose its strength. Therefore, as an important early step of the construction method in winter, the temperature for heating and curing will affect the early performance of concrete, hence assessment and control countermeasures must be fully understood, so as to avoid the impact on concrete performance. Heating and curing mainly consists of steam curing, moist heat curing, electric heat curing, etc. However, with the development and application of high-rise and large-volume concrete structures, under the influence of site construction conditions and site space conversion, the engineering community began to adopt a new type of concentrated exothermic material - self-regulating heater to provide a heat source in concrete.

This method is flexible, safe, reliable and energy-saving, it can greatly improve the short duration of concrete in severe-cold areas. Self-regulating heater is a band-shaped electric heater with resistivity positive temperature coefficient (PTC) conductive polymer composite as a heating element. Compared with conventional constant-power exothermic materials which may easily cause local overheating, wire burning and other shortcomings [1], the automatical adjustment of the output power with the heated system permits to reach the temperature balance point and keeps the temperature constant without the need of other equipment.

As early as the 1980s, the Soviet engineering staff made a loop using a 1.2 mm-diameter galvanized wire as the heating wire and applied it in concrete heating and curing. In 2010, Ni [1] used an internally installed circulating electrical heating as the method of curing in the Polo Pearl project of St. Petersburg, Russia to achieve concrete heating by laying a resistance wire in the concrete. However, the heating wire is of constant power type and cannot be automatically adjusted, as this may easily lead to local overheating, wire burning and concrete cracks. In 2004, Lu [2] successfully adopted the self-regulating "ribbon heater method" in the construction of a 9 m reinforced concrete platform for the No.5 converter project in the winter construction of Bengang Steel Plates Co., Ltd. The method followed the principle of heat conservation, designed the laying plan and calculated the length of heater in the concrete, but did not consider the effect of the water spray heat release of the concrete on the temperature field. In 2013, through field measurements, Cao and Wu [3, 4] laid ribbon heaters along the forms of Hai river extra-large bridge pier and Yalu river bridge main tower for heat insulation and maintenance. In addition, in the construction of two pouring joint

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surfaces, electric tracing was used prior to pouring. These results were mostly combined with specific engineering research, by embedding pre-assumed temperature control points in temperature sensors for temperature control. Man-made blackout will be made in case of exceeding the specified temperature, resulting in outage of the local or the entire loop, and achieving passive intervention of the temperature field. Based on the theory of heat transfer, the influence of temperature on concrete hydration reaction was considered by the maturity of equivalent age, and the hydration degree was used to express the development of concrete thermal performance. According to the pre-set strength, the temperature history was set, the adjustment time and speed of the designed temperature were pre-controlled, and verified by experiment.

BASIC THEORY

Equivalent age

In 1951, Saul [5] pointed out that whatever the temperature history of concrete, as long as the maturity is equal, the strength must be equal, that is, the concept of concrete maturity. He also put forward the “Nurse-Saul” maturity equation that expresses the joint role of different curing conditions, age and temperature in the development of concrete strength, as shown in formula (1).

$$M = \int_0^t (T(t) - T_0)\mathrm{d}t \tag{1}$$

where M is the maturity coefficient, t is the curing age, T is the temperature at age t, T_0 is the initial temperature parameter and is usually -10 °C.

According to the Nurse-Saul equation, the concrete age at different curing temperatures is transformed into an equivalent age under the same maturity, and it can be seen that the equivalent age is essentially the same as the maturity, and the expression is as follows:

$$t_e = \frac{\sum (T - T_0)\Delta t}{T_r - T_0} \tag{2}$$

where T_r is 20°C.

Cement hydration in concrete is an exothermic reaction accelerated by temperature. Thus, Copeland *et al*. [6] pointed out that in chemical reactions, the effect of temperature on the hydration reaction rate follows the Arrhenius function, as shown in formula (3):

$$k(T) = Ae^{\frac{E_a}{RT}} \tag{3}$$

where k(T) is the chemical reaction rate; T is the reaction temperature, using adiabatic temperature. E_a is the activation energy of concrete. R is the gas constant, generally 8.314J/mol·K.

In 1977, Hansen and Pedersen [7] carried out a hydration heat test at different curing temperatures to calculate the activation energy of concrete, as shown in formula (4):

$$E_a = \begin{cases} 33.5 & T_c \geq 20℃ \\ 33.5 + 1.47(20 - T_c) & T_c < 20℃ \end{cases} \tag{4}$$

The equivalent age maturity function based on Arrhenius function was proposed:

$$t_e = \sum_0^t exp\left[\frac{E_a}{R}\left[\frac{1}{273 + T_r} - \frac{1}{273 + T}\right]\right]\Delta t \tag{5}$$

where t_e is the equivalent age. E_a is the activation energy of concrete.

According to formula (5), 1h of concrete curing at 45 °C is equivalent to 2.05 h at 20 °C.

By means of maturity theory, the early compressive strength of concrete at any temperature history can be converted to the compressive strength equivalent at 20 °C using equivalent age conversion formula. Based on this idea, researchers at home and abroad have proposed some compressive strength formulas based on age spray degree, as shown in Table 1.

Table 1. Compressive strength formulas based on equivalent age

Compressive strength	Formula	Ref.
$\frac{f_c(t_e)}{f_{c,u}} = \frac{k_f(t_e - t_0)}{1 + k_f(t_e - t_0)}$	(6)	[8]
$\frac{f_c t_e}{f_{c672}} = exp\left[S \times \left(1 - \sqrt{\frac{672}{t_e - t_0}}\right)\right]$	(7)	[9]

where f_c（t_e） is the concrete compressive strength at an equivalent age of t_e, h, MPa, f_{c672} is the concrete compressive strength at the curing condition of 20 °C for 672 h, MPa, $f_{c,u}$ is the compressive strength when cement reaches the ultimate hydration degree, MPa, S、k_f is the shape coefficient, t_0 is the time when concrete mechanical property starts developing, generally adopting the initial setting time of concrete, h.

If concrete strength is calculated by formula (7), then the compressive strength of C40 concrete at any time t is:

$$f_c t_e = 40 \times exp\left[0.271 \times \left(1 - \sqrt{\frac{672}{t_e - 12}}\right)\right] \quad （8）$$

where S is 0.271 [9], t_0 is 12 h.

Hydration degree

Hydration degree reflects the hydration reaction degree of concrete gelling material at a certain age, since the hydration degree monotonously increases with the hydration reaction of cement [10], so the exothermic heat of hydration was used to express the degree of hydration, see formula (9):

$$\alpha(t) = \frac{Q(t)}{Q_0} \qquad (9)$$

where $\alpha(t)$ is the hydration degree of age t, which monotonously increases with the hydration reaction of cement. $Q(t)$ is the exothermic heat of hydration of age t, kJ. Q_{max} is the exothermic heat under full hydration of cement, kJ.

On the basis of no test, the cumulative hydration heat can be expressed by formula (10):

$$Q(t) = Q_0(1 - e^{-mt}) \qquad (10)$$

where $Q(t)$ is the cumulative hydration heat when age is t, kJ/kg, Q_0 is total cement hydration heat, kJ/kg, it is 330 kJ/kg when is ordinary Portland cement 425, m is heating rate, see Table 2. Then,

$$\alpha(t) = \frac{Q(t)}{Q_0} = (1 - e^{-mt}) \qquad (11)$$

Table 2. Value of heating rate (m)

Pouring temperature (℃)	5	10	15	20	25
m (1/d)	0.295	0.318	0.340	0.362	0.384

Specific heat

The specific heat (C) of concrete refers to the absorbed (or released) heat when the temperature of a unit mass of concrete is increased (or reduced), and can be expressed as follows:

$$c = \frac{Q}{G(t_2 - t_1)} \qquad (12)$$

where Q is the absorbed (or released) heat, kJ, C is specific heat of concrete, $kJ/(kg \cdot °C)$, G is the mass of concrete, kg, $t_2 - t_1$ is the temperature difference before or after the concrete temperature is increased (or reduced), °C.

Since the specific heat of water is 5-6 times that of concrete and aggregate, the specific heat has a great effect on the concrete water content. In addition, the more the aggregate content, the smaller is the specific heat of the concrete. Van Breugel *et al.* [11] proposed a formula of concrete considering the temperature, mix ratio and the change of hydration degree, as shown below:

$$c = \frac{\rho_c \alpha c_{cef} + \rho_c(1-\alpha)c_c + \rho_a c_a + \rho_W c_W}{\rho} \qquad (13)$$

$$c_{cef} = 8.4T_d + 339 \qquad (14)$$

where C is the concrete specific heat, $J \cdot kg^{-1} \cdot °C^{-1}$, ρ is the concrete density, $kg \cdot m^{-3}$, W_c、W_a、W_W are the weights of each m^3 of cement, aggregate and water,respectively, $kg \cdot m^{-3}$, C_c、C_a、C_W are the specific heats of cement, aggregate and water, respectively, $J \cdot kg^{-1} \cdot °C^{-1}$, C_{cef} is the assumed specific heat of hydrated cement, $J \cdot kg^{-1} \cdot °C^{-1}$, α is the hydration degree, T_c is the current temperature.

Pre-control of temperature history of concrete with buried heat source based on the first law of heat transfer

For a period of time, the amount of thermal and mechanical energy increase stored in the control vessel must be equal to the difference between the entering and leaving thermal and mechanical energy plus the thermal energy generated in the control vessel. Therefore, for the concrete members with embedded heater as a heat source, we used the first law of thermodynamics considering the convection and radiant heat transfer of concrete surfaces, the chemical energy of concrete (hydration), the changes in thermal energy and its storage items generated by the heater. Therefore, for a concrete me9mber with a designed heater length of L, the formula of the control system is:

$$\Delta\dot{E}_{st} = \dot{E}_{in} + \dot{E}_{out} + \dot{E}_g \qquad (15)$$

where $\Delta\dot{E}_{in}$ is the rate at which the energy is generated by the heater, kJ, $\dot{E}_{out}$ is the rate at which the concrete energy dissipates, kJ, $\dot{E}_g$ is the rate at which the chemical energy of the concrete is generated, kJ, $\Delta\dot{E}_{st}$ is the rate at which the thermal energy storage items change, kJ.

$$\Delta\dot{E}_{in} = PL \qquad (16)$$

where P is the heater power, kW, L is the heater length, m.

$$\dot{E}_{out} = -(q_{conv} + q_{rad}) \qquad (17)$$

$$q_{conv} = \beta_s A(T - T_\infty)$$

$$q_{rad} = \varepsilon\sigma A(T^4 - T_\infty^4)$$

$$\beta_s = \frac{1}{R_s} = \frac{1}{(1/\beta) + \sum(h_i/\lambda_i)}$$

Where q_{conv} is convection heat transfer, kW, q_{rad} is net radiation, kW, β_s is the equivalent surface exothermic coefficient, kJ/ (m^2·h· °C), β is the solid surface exothermic coefficient, kJ/ (m^2·h· °C), λ_i is thermal insulation layer thermal conductivity, kJ/(m·h·°C), h_i is Insulation thickness, m, A is the concrete exothermic area, m^2, T is concrete surface temperature, °C, T_∞ is ambient temperature, °C, σ is Stephen-Boltzmann constant, 5.67×10^{-8}W/(m^2·K^4), ε is emissivity, 0.9.

$$\dot{E}_g = \frac{\mathrm{d}\left[WQ_0(1 - e^{-mt_e})\right]}{\mathrm{d}t} \qquad (18)$$

where W is the amount of cement, kg.

$$\dot{E}_{st} = \rho c V \frac{\mathrm{d}T}{\mathrm{d}t} \qquad (19)$$

Substituting formulas (16) , (17) , (18) and (19) into formula (15), (20) can be obtained:

$$PL-\beta_s A\left(T-T_\infty\right)-\varepsilon\sigma A(T^4-T_{sur}^4)+\frac{\mathrm{d}\left[Q_0(1-e^{-mt_e})\right]}{\mathrm{d}t}=0$$

$$\frac{\mathrm{d}T}{\mathrm{d}t}=\frac{PL-\beta_s A\left(T-T_\infty\right)-\varepsilon\sigma A(T^4-T_{sur}^4)+\frac{\mathrm{d}\left[Q_0(1-e^{-mt_e})\right]}{\mathrm{d}t}}{\rho cV} \tag{20}$$

The temperature change of the concrete along with time can be obtained by means of numerical integration. When the temperature is basically no longer changed and is relatively stable, $\frac{\mathrm{dT}}{\mathrm{dt}}=0$, the temperature of the concrete can be obtained by the following formula:

$$PL-\beta_s A\left(T-T_\infty\right)-\varepsilon\sigma A(T^4-T_{sur}^4)+\frac{\mathrm{d}\left[Q_0(1-e^{-mt_e})\right]}{\mathrm{d}t}=0 \tag{21}$$

STUDY OF METHOD APPLICATION

Raw materials and mix ratio

Shenyang Dunshi 42.5 ordinary Portland cement was adopted. Coarse aggregate was gravel with a particle size of 5-20 mm and apparent density of 2650 kg/m^3. Fine aggregate was natural sand with an apparent density of 2630 kg/m^3. Water-reducing agent was polycarboxylate high- performance water-reducing agent. Water was tap water. According to compressive strength design, C40 was adopted, the match ratio is shown in Table 3.

Method

Winter temperature is -15°C, casting length×width×height are 0.8×0.8×1.5m concrete columns, temperature of casting concrete is 10°C, the target stability temperature is 45 °C and is expected to reach in 20h, that is, the temperature change is subject to formula (22), formula (23) can be derived from formula (5) and (22). We can see that 20h of temperature rise and 72 hours (3 days) of heating at a stable temperature of 45°C is equivalent to 120h of equivalent age.

$$T=\begin{cases} V_s t+T_m & t<t_s \\ T_h & t_s\le t\le t_s+t_h \\ T_h-V_d t & t>t_h \end{cases} \tag{22}$$

Where V_s is heating rate, 2℃/h, V_d is cooling rate, 0.5℃/h, T_m is concrete pouring temperature, 5℃, T_h is target temperature, 45℃, t_s is target temperature arrival time, 20h, t_h is stable phase time, 52h.

$$t_e=\begin{cases} \sum_0^{\mathrm{t}} exp\left[\frac{E_a}{R}\left[\frac{1}{273+T_r}-\frac{1}{278+2t}\right]\right]\Delta t & t<20\mathrm{h} \\ \sum_0^{\mathrm{t}} exp\left[\frac{E_a}{R}\left[\frac{1}{273+T_r}-\frac{1}{318}\right]\right]\Delta t & 20\mathrm{h}\le t\le 72\mathrm{h} \\ \sum_0^{\mathrm{t}} exp\left[\frac{E_a}{R}\left[\frac{1}{273+T_r}-\frac{1}{318-0.5t}\right]\right]\Delta t & t>72\mathrm{h} \end{cases} \tag{23}$$

According to formula (8), concrete compressive strength $\mathrm{f_c}(120h)=26.85\mathrm{MPa}>0.81\,\mathrm{f_{c672}}$, after the outage of heater power and concrete cooling, cooling rate is less than 0.5˚C /h, then according to formula (20)

$$\frac{\mathrm{d}T}{\mathrm{d}t}=\frac{PL-\beta_s A\left(T-T_\infty\right)-\varepsilon\sigma A(T^4-T_{sur}^4)+\frac{\mathrm{d}\left[Q_0(1-e^{-mt_e})\right]}{\mathrm{d}t}}{\rho cV}<0.5$$

where c is calculated according to formula (13), take the beginning of the cooling phase. The parameters of each component are shown in Table 3, so $\beta_s>10kJ/m^2\cdot\mathrm{h}\cdot{}^\circ\mathrm{C}$. In this case, if there is a protective layer of plastic blanket and quilt, then, $\beta_s=14.15\beta_s>10kJ/m^2\cdot\mathrm{h}\cdot{}^\circ\mathrm{C}$. According to formula (21), L=14 m.

A 15DXW low-temperature limit (self-control temperature of 70˚C) ribbon heater was arranged in the steel skeleton, and the layout is shown in Fig 1. FS-NM15 embedded temperature strain sensor manufactured by Jiangxi Fashion Technology Co., Ltd. was adopted. Temperature measurement error is 0.5˚C, test range: -20 -80˚C, test collecting devices were composed by the TFL-F-10xx series of vibrating wire collector, microcomputer and other devices.

Table 3 Concrete mix ratio and thermal performance of material

Component	Cement	Sand	Pebble	Water	Water-reducing agent (polycarboxylate dry powder)
Weight/kg	390	673	1222	165	0.2%
Specific heat	0.456	0.699	0.716	4.18	7

Fig. 1. Layout of temperature measuring points

Results and discussion

(1) The test results are shown in Fig. 2, where T1 was the temperature of the column center, the heating rate was 1.58˚C /h in temperature rise period and the maximum temperature was 45.63˚C, reached after 22.5 h. T2 was the temperature of the same temperature level 5 cm from the surface, more obviously affected by the ambient temperature E than T2. The heating rate was 2˚C /h in temperature rise period and the maximum temperature was 43.38˚C, reached after 17h. T1 and T2 trends were basically the same, the maximum temperature difference was 2˚C, the temperature field of concrete columns was basically uniform and the temperature change was consistent.

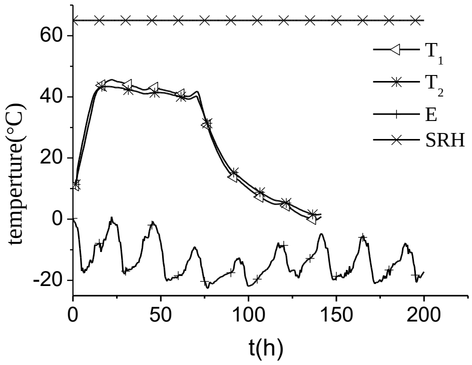

Fig. 2. Test results

(2) The comparison of design temperature history and measurement results is shown in Table 4. T1 and T2 phases have relatively stable temperatures, but are actually slowly declining at 0.11˚C /h and 0.08˚C /h, this is because of the cement hydration reduction in concrete and hydration heat continues to decrease, see Fig. 3. Especially that in the hydration degree under buried heat source after 3 days reaches that of 7 days under 20°C.

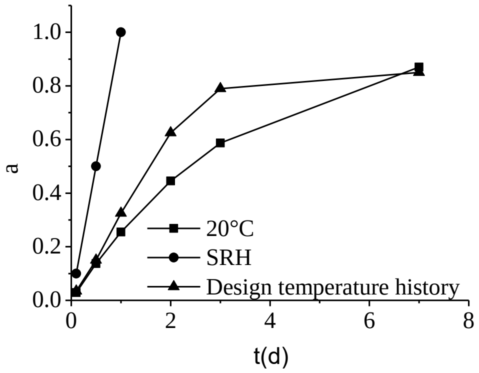

Fig. 3. Design temperature history and hydration degree at 20˚C

(3) When T1 and T2 coincide with the ambient temperature E, that is, when the overall temperature of concrete dropped completely to the ambient temperature on the 7th day, form was removed. Concrete column strength test was conducted using core-drilling method, including the contact area with SRT, the results are shown in Fig. 4. The strength of the concrete is higher than that of the design time, but the strength of the 28d concrete is less than 20℃ and 65℃.

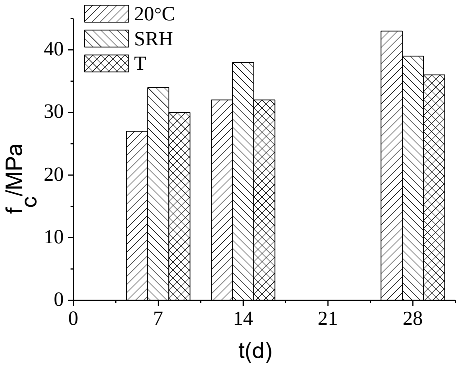

Fig. 4. Concrete strength development

(4) SRH is the temperature of the self-regulating heater, which quickly reaches the rated temperature of 65˚C after connecting power, and keeps the temperature unchanged, see Fig. 2. There is a large temperature difference between SRT, T1 and T2.

Table 4 Comparison of test results

	V_s (˚C /h)	t_s (h)	T_h (˚C)	t_h (h)	V_d (˚C /h)
T	2	20	45	52	0.5
T1	1.58	22.5	45.63-40.25	49.5	0.56
T2	1.96	17	43.38-39.69	55	0.53

CONCLUSIONS

1) Based on the equivalent age hydration degree theory, the pre-control method of the concrete temperature of buried heat source using the first law of thermodynamics is accurate. When the temperature at design stable phase is 45℃, the temperature at the actual stable phase is in the range of 39.69-45.63℃, the variation range is 0.12%.

2) Due to the decrease of the hydration reaction, the temperature at the concrete stable phase is relatively stable, slowly decreasing at a rate of 0.11℃ /h and 0.08℃ /h.

3) The buried heat source can effectively accelerate the hydration reaction and hydration degree, 1h of concrete curing at 45℃ is equivalent to 2.05 h under 20℃, and the hydration degree under the condition of 45℃ for 3 curing days equals to that under 20℃ for 7 curing days.

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