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Temperature response in concrete under natural environment

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HIGHLIGHTS

- We investigated the temperature variation in natural environment.
- Segmented fitting method was proposed to predict the temperature spectrum.
- A novel method was proposed to solve the concrete's thermal parameter.
- Sheltered condition has a significant effect on concrete's temperature response.
- Deficiencies of temperature spectrum are in terms of the amplitude and extreme value.

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ABSTRACT

Temperature variation in natural environment was conducted in order to predict the action spectrum of temperature under natural environment by substituting the model to the segmented fitting method. A novel method based on the measured data was proposed to solve the concrete thermal parameter. Results showed that the temperature variation of the concrete and natural environment periodically fluctuates, and the theoretical action and response spectra of the temperature agree well with the measured results. The presence or absence of sheltered condition has a significant effect on temperature response in concrete in terms of the amplitude, extreme value and arising time.

1. Introduction

Changes in environmental conditions, such as temperature and humidity, affect structural durability and service life [1–5]. Temperature is one of the most typical environmental factors [6–10]. In the natural environment, reinforced concrete structures chronically suffer from the effects of periodic seasonal alternating temperature and daily temperature variation [11]. Because the thermal conductivity of the concrete is poor, a great temperature gradient may exists creating thermal stress, which results in cracking and reducing the service life of concrete structures [12–14]. Numerous studies were presented to understand the effect of temperature on the performance of concrete, such as compressive strengths, autogenous deformation and relative humidity change, and shrinkage and creep affected by various temperatures [15–18], and several positive results were obtained [19–23]. Meanwhile, the influence of temperature on the reinforcement corrosion, alkali–silica reaction, internal relative humidity, thermal and moisture transfer behavior, carbonation and chloride ingression has also been conducted [2,24–28]. Zivica et al. [29] proposed that ambient temperature is the dominant factor in the process of reinforcement corrosion. In addition, a great many methods were presented to depict the environmental temperature variation, such as the extreme difference dissection method, G-functions, finite difference method, physico–statistical model and simplified approach [30–36].

Almost in all cases, the temperature affecting the performance of concrete structures is the concrete micro–environment temperature rather than the natural environment [37]. However the existing studies are almost all based on the hypothesis that the natural environment's temperature is considered as concrete micro–environment temperature, which is completely unrealistic. Consequently, large errors exist between the theoretical

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calculation and the measured results based on such kind of substitution, but some internal correlations may be established. If the natural environment temperature is assumed as an action or excitation, the corresponding temperature of the concrete micro-environment may be considered as a response [38,39]. Correspondingly, temperature variation of the natural environment and concrete are quantified as action and response spectra. Expectedly, their internal correlations are proposed to represent the change rule of the temperature. Nevertheless, the existing researches rarely mention its accurate correlation because of the randomness and complexity of the temperature variation in natural environment. The defects of fitting precision are difficult to overcome by using traditional methods based on the in situ measured data due to the artificial subjectivity and experience, which are the main reason for the limited application. In addition, the temperature response of the concrete structures relates to the location, which affects the absorbed quantity of radiant heat [40]. Therefore, investigating the temperature change is necessary in concrete under the natural environment with or without the sheltered condition. Although lots of achievements have been made by many scholars worldwide, but drawbacks such as accuracy, initial conditions, boundary conditions and sensitiveness still exist.

The aim of study is to propose a predictive response spectrum of temperature in concrete under natural environment, which quantizes the variation of temperature and determines the thermal parameters for the simulated environmental test. Unless otherwise stated, the mentioned temperature in concrete throughout the text is assumed to be only 1D temperature response.

2. Methodology

2.1. Action spectrum of natural temperature

Ref. [41] showed that the temperature variation in natural environment can be described by a cosine or sine function, as given in Eq. (1).

$$\theta_t = \theta_a + \theta_0 \cos(\omega t - \varphi) \tag{1}$$

where θ_t represents the temperature in natural environment at time t, °C; θ_a and θ_0 are the mean temperature and amplitude of the temperature in natural environment respectively, °C; ω is the angular frequency of earth revolution in rad/s; and φ denotes the phase angle in rad.

Although Eq. (1) can be used to describe the temperature variation of natural environment for an entire day, this single representation form may be unsuitable to represent a year-round temperature change because of earth revolution in different seasons resulting in the difference in the daylight hours.

This work investigates the effect of earth revolution on the period of temperature fluctuation T. Segmented fitting method is employed to model the temperature variation in natural environment, i.e., dividing the daily temperature profile into temperature rising and falling curves; therefore, the action spectrum of the natural environment can be written as Eq. (2).

$$\theta_t = \begin{cases} \theta_a + \theta_0 \cos\left(\frac{\pi}{T} t - \frac{T + t_{\min}}{T}\pi\right); & \text{temperature-rise period}: \\ & t \in (t_{\min}, t_{\min} + T) \\ \theta_a + \theta_0 \cos\left(\frac{\pi}{24-T} t - \frac{T + t_{\min}}{24-T}\pi\right). & \text{temperature-fall period}: \\ & t \in (t_{\min} + T, t_{\min} + 24) \end{cases} \tag{2}$$

$t_{\min}$ is the time when the lowest temperature appears, h;π, i.e., Pi, is a number approximately 3.14, which is equal to the distance around a circle divided by its width; and T presents the time duration from the lowest temperature to the highest temperature (i.e., $14 - t_{\min}$), h.

The daily lowest temperature of natural environment appears at sunrise, which can be obtained by the daylight hours $y(D)$, as expressed in Eqs. (3) and (4).

$$t_{\min} = 12 - \frac{y(D)}{2} \tag{3}$$

$$y(D) = A + B\cos(\omega D - \varphi) \tag{4}$$

where $y(D)$ is the daylight hours, h. A and B are the annual average daylight hours and amplitude of daylight hours, h, respectively.

2.2. Response spectrum of temperature in concrete under natural environment with sheltered condition

Assume that the thermal diffusion coefficient of concrete is less affected by temperature, the corresponding unsteady state heat conduction can be determined by the Fourier heat transfer law [42], as given in Eq. (5).

$$\frac{\partial \theta(x,t)}{\partial t} = \alpha \frac{\partial^2 \theta(x,t)}{\partial x^2} \tag{5}$$

where $\theta(x, t)$ is the temperature in concrete at depth x from the surface at time t, °C; t and x are the time and depth from the concrete surface, respectively; α denotes the thermal diffusion coefficient [i.e., $\alpha = \lambda/(\rho c)$], m^2/s; and λ is the thermal conductivity W/(m·K).

Substituting Eq. (5) into Eq. (1), the response spectrum model of the temperature for 1D concrete can be obtained and presented in Eq. (6).

$$\theta(x,t) = \theta_a + \theta_0\, e^{-x\sqrt{\frac{\omega}{2\alpha}}} \cos\left(\omega t - \varphi - x\sqrt{\frac{\omega}{2\alpha}}\right) \tag{6}$$

Compared with Eqs. (1) and (6), the temperature field of semi-infinite solid under the effect of the circular temperature load presents as a continuous unsteady process. It is manifested as a quasi-steady-state harmonic dynamic process when time is sufficient except slight difference in terms of amplitude attenuation and phase lag.

Integrating Eqs. (2) and (6), the response spectrum of the temperature in concrete under natural environment with sheltered condition can be represented by Eq. (7).

$$\theta(x,t) = \begin{cases} \theta_a + \theta_0 e^{-x\sqrt{\frac{\pi}{2\alpha T}}} \cos\left(\frac{\pi}{T} t - \frac{T + t_{\min}}{T}\pi - x\sqrt{\frac{\pi}{2\alpha T}}\right); \\ \text{temperature-rise period}: \quad t \in (t_{\min}, t_{\min} + T) \\ \theta_a + \theta_0 e^{-x\sqrt{\frac{\pi}{2\alpha(24-T)}}} \cos\left(\frac{\pi}{24-T} t - \frac{T + t_{\min}}{24-T}\pi - x\sqrt{\frac{\pi}{2\alpha(24-T)}}\right). \\ \text{temperature-fall period}: \quad t \in (t_{\min} + T, t_{\min} + 24) \end{cases} \tag{7}$$

2.3. Correlation analysis between temperature response of concrete and temperature action of natural environment

2.3.1. With sheltered condition

Heat convection is the main heat transfer manner between the natural environment and concrete structures with sheltered condition, such as shady side and obscured parts of structure. So the solution of heat conducting equation fits the third type boundary condition that is to assume the heat flux through the concrete surface is proportional to the temperature difference between the temperature of the concrete surface and the natural environment [43–45], as written by Eq. (8).

$$q = -\lambda \frac{\partial \theta}{\partial n} = \beta(\theta - \theta_{at}) \tag{8}$$