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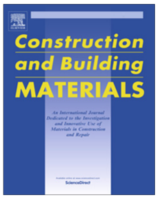

Numerical analysis of shrinkage of steel fiber reinforced high-strength concrete subjected to thermal loading

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HIGHLIGHTS

- Steel fibers reduce significantly the thermal stresses and shrinkage strains.
- Curing temperature increases the rate of the thermal stresses and shrinkage strains.
- Maturity concept can reasonably estimate the temperature effects.
- Two-phase serial model is suitable to predict the thermal stresses and shrinkage strains.
- Non-linear finite element analysis showed good agreement with the experimental results.

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ABSTRACT

In this study, a numerical investigation is conducted to simulate the total shrinkage strain of High-Strength Concrete (HSC) and Steel Fiber Reinforced High-Strength concrete (SFRHSC) by means of the transient thermal-stress analysis. The ANSYS finite element software has been used in order to evaluate the shrinkage by taking into account both the thermal and mechanical properties of the concrete. These properties are calculated using the maturity concept and the two-phase serial model. The experimental work was carried out to assess the influence of the external temperatures, steel fibers (SF) and their volume fraction on the total shrinkage strain of the SFRHSC which has been exposed to isothermal temperature of 20, 35 and 50 °C. Two dosages of 0.5% and 1% for the SF with aspect ratio of 55 have been considered. The main results obtained from the FE analysis show a good agreement with the founded experimental results under different thermal conditions. According to the obtained numerical results, an increase of the dosage of fibers will reduce the total shrinkage strain. Additionally, the curing temperature raises significantly the evolution of the total shrinkage strain.

1. Introduction

Shrinkage is a common phenomenon of HSC which is characterized by a water/cement ratio less than 0.4, incorporating superplasticizers and reactive mineral admixture such as silica fume [1–5]. Volume change of HSC as the total shrinkage is mainly composed of autogenous shrinkage, thermal deformation and drying shrinkage [6–10]. In previous researches it has been shown that the curing temperature increases generally the magnitude of shrinkage strain of HSC [11–18]. High curing temperature, which increases the speed of volume change, might increase the risk of cracking [14]. Thermal deformations resulting from the temperature rise caused by reactions which are proportional to the coefficient of thermal expansion [3,19].

The first detailed study of stresses related with slow seasonal changes of temperature in rigid concrete has been published by Westergaard in 1926 [20]. The second paper considered stresses under various temperatures occurring during shift from a cold night to a hot day and divided them into two components that has been published by Westergaard in 1927 [21].

Shrinkage of concrete is strongly related to the microstructure evolution, which is affected by thermodynamics [22–24]. Therefore, shrinkage could be predicted by using the concept of equivalent age [3,7,22].

In literature, many models are available to predict the shrinkage of HSC [3,25–29]. Each calculation model is strictly applicable to specific conditions and testing procedures. Concrete is being subjected to significant varying temperature induced by the heat

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release due to the hydration of cement, or by changes in ambient conditions if the concrete is to be casted under relatively hot or cold climatic conditions and subsequently cooling due to evaporation [7]. ACI [30] has published a report for the prediction of shrinkage under curing temperature. de Borst and van den Boogaard [31] have studied deformation of concrete modeled by finite element method considering hardening process of concrete, heat production and stiffness evolution.

Wu et al. [32] have studied shrinkage deformation and cracking risk of concrete modeled by transient thermo-structural analysis using the finite element method, taking into account the degree of hydration, thermal properties (such as specific heat, thermal diffusivity), thermal boundary conditions and mechanical properties (such as shrinkage, creep) which occur at early age. Moreover, the thermal–mechanical properties are considered as a function of new maturity concept.

Based on the experimental investigation of Zhang et al. [33] and Liu et al. [34], there are three models for predicting the thermal conductivity and specific heat capacity of concrete; two-phase parallel model, two-phase serial model and two-phase serial-parallel model. The first model is used for concrete containing cement paste and aggregate. The second one is used for concrete containing cement paste, aggregate and steel fibers. The third model is being for concrete containing cement paste, aggregate, steel fibers and other fiber types. The thermal conductivity and specific heat capacity of fiber-reinforced concrete can be calculated via two-phase model which is derived from composite material theory. Liu et al. [34] have founded that the thermal conductivity of steel fiber-reinforced concrete is greater than that of non-fibrous concrete.

High ambient temperature creates non-linear thermal stresses in the interior of the HSC specimen. This leads to the creation of thermal stresses; which are greater than apparent tensile strength of HSC; and will induce the initiation and the growth of concrete cracking [35]. Due to various types of internally and externally restraints in concrete structures, the volume changes cannot release freely thermal stresses (i.e. tensile stresses) which often arise [3].

The most used methods for mitigating the shrinkage deformation are the addition of steel fibers [36–39] or the use of shrinkage-reducing admixture which reduces the shrinkage by creating an expansion [22]. The use of steel fibers as a strengthening mechanism which by their stiffness helps reducing the stress developed during drying of concrete, and to provide the apparent tensile strength of concrete and reduce the cracking risk [36–41]. In most available studies focusing on the shrinkage deformation and cracking thermal resistance of high-strength concrete reinforced by steel fibers do not simultaneously consider various temperature history, autogenous shrinkage and drying shrinkage under adiabatic conditions.

The main objective of this study is to use the mathematical equation of maturity concept, and the transient thermal properties of concrete, based on the two-phase serial model, into the numerical analysis and to estimate the thermal stress, thermal deformation and total shrinkage of high-strength concrete and steel fiber reinforced high-strength concrete under thermal loading using the ANSYS finite element software.

2. Theoretical analysis

2.1. Maturity concept equations

The hydration of the cement components is a complex phenomenon depending on many factors such as temperature. The degree of hydration $\alpha(t)$ can be expressed as follows [23,32,42,43]:

$$\alpha(t) = \frac{Q(t)}{Q_u} \tag{1}$$

where $Q(t)$ is the cumulative heat of hydration released at time t (J. kg^{-1}) and Q_u is the total ultimate heat of hydration of concrete (J. kg^{-1}).

The relationship between temperature rise and cumulative released heat of hydration is given by [32,44]:

$$Q(t) = c\,\theta(t) \tag{2}$$

where $\theta(t)$ is the adiabatic temperature rise by time t (°C), c is the specific heat capacity (J kg^{-1} °C^{-1}).

Thus, the degree of hydration is expressed as follows:

$$\alpha(t) = \frac{\theta(t)}{\theta_u} \tag{3}$$

where θ_u is the ultimate adiabatic temperature rise (°C).

The maturity concept is used to account for the combined effects of time and temperature on the mechanical properties of concrete. The equivalent age of concrete (t_e) is first computed as follows [45–47]:

$$t_e = \sum_{0}^{i} \exp\left[\frac{E_a(t)}{R}\left(\frac{1}{293} - \frac{1}{273 + T^c}\right)\right]\Delta t \tag{4}$$

where E_a is the apparent activation energy varying from 20,000 to 60,000 (J mol^{-1}), R is the universal gas constant equal to 8.314 (J mol^{-1} K) and T^c is the curing temperature during interval Δt (°C).

Moreover, the apparent activation energy at the micro-level is a function of the cement hydration or, of the cementitious materials type, and will be constant for all mechanical properties [14,48]. The equations of apparent activation energy of HSC with different percentages of silica fume used as a replacement with the exception of concrete with w/b of 0.40 can be expressed as follows [14]:

$$E_a(t) = E_0 e^{-\omega t} \quad t \geq t_s \tag{5}$$

$$E_0 = 44.415 - 124T^c \tag{6}$$

$$\omega = 0.00027T^c \tag{7}$$

where $E_a(t)$ is the apparent activation energy (J.mol^{-1}), E_o is the initial apparent activation energy (J.mol^{-1}), ω is a constant representing the rate of decrease of activation energy with aging, T^c is the curing temperature (°C) and t_s is the age of removal of formwork equal to 1 day.

Based on experimental investigations [32,49], several mathematical models have been proposed for the relationship between degree of hydration and equivalent age. In the current study, the following expression is adopted:

$$\alpha(t_e) = \alpha_u(1 - \exp(-\xi t_e)) \tag{8}$$

where α_u is the ultimate degree of hydration, and ξ is a constant determined by experiments.

Similarly, the formula for the adiabatic temperature rise based on the new maturity concept of the equivalent age can be expressed as follows [32]:

$$\theta(t_e) = \theta_u(1 - \exp(-\xi t_e) \tag{9}$$

2.2. Transient thermal properties of concrete

Specific heat capacity and the thermal diffusivity proportionally decrease with increasing degree of hydration of concrete. For HSC, the following relations may be applied [32]:

$$c(\alpha) = c_0(1.15 - 0.15\alpha) \tag{10}$$