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Temperature and stress development in ultra-high performance concrete during curing

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HIGHLIGHTS

- Temperature and stresses developed during curing of UHPC members are evaluated.
- High thermal gradients developed during curing of UHPC can lead to cracking.
- Temperature gradients and thermal stresses increase with the size of UHPC blocks.
- Thermal blankets can lower thermal gradient and resulting thermal stresses.

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ABSTRACT

This paper presents the application of finite element based numerical model to trace the progression of temperature rise and consequent stresses during hydration in a mass ultra-high performance concrete (UHPC) blocks. Results from the analysis suggest that severe thermal gradients can develop within UHPC member leading to high thermal stresses, which in turn lead to cracking at the surface of the concrete structure. The main factors that influence temperature rise and stress development in UHPC blocks during curing are batch mix proportions, size of concrete block, mesh reinforcement and presence of any thermal blankets. Provision of thermal blankets or steel wire mesh can lower curing temperature and resulting thermal stress.

1. Introduction

Continuous research and development activity in concrete technology over the last three decades has led to the development of improved types of concrete such as high performance concrete (HPC) and ultra-high performance concrete (UHPC). Concrete with strengths higher than 150 MPa is usually classified as UHPC [22]. UHPC provides superior compressive, tensile and flexural strength, ductility, toughness, as well as excellent durability enhancement [10]. Thus, use of UHPC in various construction applications has increased significantly in the last few years.

UHPC essentially refers to a class of concrete materials with superior material properties achieved by increasing the packing density of cementitious and filler constituents, use of very low water/binder ratios, and effective use of fibers [22]. The low water/binder ratio in concrete leads to significant self-desiccation due to loss of capillary water to the hydration process [15]. Moreover, the high cementitious paste content leads to development of high heat of hydration during curing process. This high heat of hydration, accompanied with low thermal conductivity, leads to generation of high temperatures and associated thermal stresses within mass concrete during curing.

In a typical mass concrete block, thermal gradient generated during curing is directed outwards with higher temperature in the interior and lower or near ambient temperature at the surface of the block. Hence, the interior of concrete block which is at higher temperature tends to expand whereas, the surface of concrete block which is close to ambient temperature tends to shrink and resist the expansion of interior concrete leading to development of thermal stresses. When these stresses exceed the low tensile strength of UHPC at early age of curing, thermal cracks form at the surface. These cracks induced during early stage of curing can jeopardize the performance of concrete. Moreover, UHPC also undergoes significant amount of autogenous shrinkage. The magnitude and rate of this autogenous shrinkage depends on the temperature history of concrete during initial stages of curing [12]. Such adverse effects can be highly prevalent in mass concrete

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structures such as dams, bridge decks, pavements and foundation decks. Hence, it is crucial to take into consideration, development of temperature gradients and stresses during the course of concrete curing in the design of concrete batch mix.

Currently, there is limited understanding on the progression of temperatures and subsequent stresses developed thereof during the early stages of curing of UHPC. To overcome this aspect, a sequential thermo-mechanical finite element model is used to trace the progression of temperatures and thermal stresses during curing of ultra-high performance mass concrete. The model is applied to study the critical factors influencing temperature rise and stress development in mass concrete during curing. Based on the parametric study, solutions are proposed to minimize the adverse effects of differential temperature rise due to high heat of hydration in ultra-high performance mass concrete.

2. Heat of hydration modeling

The development of mechanical properties in concrete is related to the hydration of cementitious particles in the concrete batch mix. Hydration of cementitious materials in concrete is an exothermic reaction releasing large amount of heat known as heat of hydration. This heat of hydration leads to non-uniform temperature rise thereby generating temperature gradients in a mass concrete structure, which affect the development of mechanical properties. The extent of heat of hydration and the subsequent temperature rise depends on several factors such as, amount and type of cementitious content in the batch mix, water to binder ratio, initial placing temperature, curing conditions and boundary conditions [18]. Presence of supplementary cementitious materials significantly affects the hydration kinetics of cement paste. For instance, addition of silica fumes to cement, at low water to binder ratio decelerates the hydration of cement whereas, for higher water to binder ratio silica fume accelerates the hydration process [11,13]. On the contrary, addition of fly ash to the cement has no effect in the initial stages of hydration. However, in later stages it decelerates the hydration process and increases ultimate degree of hydration [18].

Mounting instrumentation for monitoring temperature progression during curing of concrete is costly and time consuming as it requires specialized instruments and continuous supervision. Owing to this, various researchers have proposed numerical models for predicting temperatures developed during curing within a mass concrete block made of normal strength (NSC) and high strength concrete (HSC). These includes, simplified equations [14], graphical method of ACI [1] using Schmidt model, micro-scale models [5] and multi-scale models [6,19].

Early attempts in predicting temperature rise due to heat of hydration in high performance concrete (HPC) structure were carried out by Bentz et al. [5] by developing a micro-scale model. This model predicted adiabatic temperature rise within a concrete block containing only cement and silica fume and a minimum water/binder ratio of 0.35. Similar micro-scale model was developed for ultra-high strength concrete (UHSC) by Maruyama et al. [16]. They also investigated the use of hydration model and adiabatic temperature rise, to serve as an input in FE model for predicting temperatures within in a concrete block. Based on the analysis they reported that use of adiabatic temperature rise accurately predicts temperature distribution an ultra-high strength concrete block. Recently, Gu et al. [9] developed a micro-scale model, modeling the hydration of UHPC containing silica fume and fly ash. They observed that addition of silica fume and fly ash accelerates the hydration process in the initial stages and augment the low water/binder ratio. The above mentioned micro-scale models modeling the physio-chemical process of hydration of cement paste predict adiabatic temperature rise within a mass concrete structure. However, these models fail to provide any information on the thermal gradients and resulting stresses that develop within a mass concrete structure. The micro-scale models rely on accurate simulation of hydration of cement, which can get complex for different types of cementitious materials and thus have limited applications.

Numerous macro-scale numerical models [2,4,23] are also proposed for predicting temperatures during curing of mass concrete structure. However, these models do not provide any information on stresses generated due to non-uniform temperature rise. The non-uniform temperature rise during curing leads to differential stresses which when exceed the tensile strength of concrete produces cracking. This was illustrated by Azenha et al. [3] and Tia et al. [21] through a finite element study on a mass concrete block. The above mentioned macro-scale models are validated for concrete structures made of conventional concrete i.e. normal strength and high strength concrete.

As apparent from the above review, a number of models are available for tracing temperature progression during curing in conventional concrete mixes. However, only few models are capable of predicting thermal stresses resulting from heat of hydration during early stages of curing. Although such thermal stresses may not be critical in conventional concrete mixes [7], these stresses can produce cracking in UHPC structures thus affecting development of mechanical properties and overall performance of UHPC. Specifically, thermal induced stresses can be high in the case of large concrete blocks made of UHPC, due to development of high thermal gradients resulting from high heat of hydration. Currently, there is a lack of reliable models for tracing temperature rise and stress progression during early stages of hydration of UHPC. In order to bridge this knowledge gap a thermo-mechanical finite element based numerical model that can predict temperature and stresses during hydration process in UHPC block is developed.

3. Finite element model

To trace the progression of temperature and resulting stresses developed in a mass concrete block during the early stages of curing, a thermal analysis followed by stress analysis is required. This analysis is carried out at various time steps through a finite element model developed in ABAQUS. Appropriate thermal and mechanical properties of UHPC during the early stage of curing are suitably incorporated into the model. The detailed numerical formulation and the element discretization is discussed below.

3.1. Numerical procedure

Computation of temperature rise resulting from high heat of hydration during early stages of curing of concrete and development of associated internal stresses involves two main steps; thermal analysis and stress analysis. These two steps are to be performed through a sequential thermo-mechanical analysis which is governed by different sets of differential equations. The thermo-mechanical analysis can be carried out by discretizing mass concrete block into a set of elements.

The thermal analysis provides a spatial temperature distribution and temperature-time history for the desired duration of curing. These are computed by solving the following heat transfer equation:

$$k\nabla^2 T + Q = \rho c \frac{\partial T}{\partial t} \quad (1)$$

where, k is thermal conductivity (kcal m^{-1} h^{-1} °C^{-1}); ∇ is differential operator; ρ is the density (kg m^{-3}); c is specific heat