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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:

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

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 (kcal kg^{-1} °C^{-1}); T is temperature (°C); t is time and Q is the internal heat source defined as the amount of heat generated per unit time per unit volume of the material. The heat generation within the concrete block comes from the hydration of cementitious materials in the paste. Galerkin-Ritz discretization of the above partial differential equation [Eq. (1)] leads to:

$$[C]\left\{\frac{dT}{dt}\right\} + [K]\{T\} = \{F_n\} \tag{2}$$

where, $[K]$ is the heat conduction/ convention matrix; $[C]$ is the capacitance matrix; and $\{F\}$ is the forcing term due to the internal heat resources and natural boundary conditions, $\{T\}$ is the nodal vector containing the temperature values. Convective thermal boundary conditions applied for solving [Eq. (1)] is modeled by assigning environment temperature as ambient temperature at concrete surface. This boundary condition is mathematically expressed as:

$$K\left(\frac{\partial T}{\partial y}n_y + \frac{\partial T}{\partial z}n_z\right) = h_t(T - T_\infty) \tag{3}$$

where, h_t is heat transfer coefficient; T_∞ is ambient temperature; n_y and n_z are components of the vector normal to the boundary.

Internal heat source (Q) in [Eq. (1)] is the rate of heat generation during cement hydration process, which is proportional to the heat of hydration and the rate of hydration process. In this model adiabatic hydration model is used to simulate hydration of cementitious materials. Accordingly, the entire heat of hydration developed in concrete under adiabatic conditions, is converted to adiabatic temperature, which is used to estimate the extent of hydration [6]. The rate of heat generation is then computed using experimentally measured adiabatic temperature rise in a concrete block, using the equation proposed by Schindler and Folliard [18] and is given as:

$$\frac{dT}{dt} = \frac{Q_H}{\rho c_p} = \frac{dH}{dt}\left(\frac{1}{\rho c_p}\right) \tag{4}$$

where, Q_H is rate of heat generation (kcal h^{-1} m^{-3}), and H is heat of hydration of the concrete (kcal m^{-3}). Eqs. (1)–(3) are to be solved in time domain. The generated temperature-time history will serve as an input to the stress analysis.

The stresses resulting from the high temperature gradients, developed due to the heat of hydration, are evaluated through the stress analysis. At a given time step the temperature history from the preceding time step serves as an input to the stress analysis. During curing no loads are assumed to be present on the concrete block hence elastic, plastic and creep strain components are neglected. However, the shrinkage strain is accounted for in the model by means of thermal coefficient and temperature change. Hence, for the stress analysis, during curing of concrete, the only source of strain is that resulting from thermal strain (ε_{th}). Thermal strain component for each element is computed as $\varepsilon_{th} = \alpha\Delta T$ in which α and ΔT are coefficient of thermal expansion and temperature gradient, respectively. Temperatures are applied at nodes of the elements in a finite element mesh of discretized structures and thereby thermal strains are computed. The total potential energy (Π) over each finite element arising from the total strain (ε_t) is due to energy resulting from thermal strain (ε_{th}), developed in concrete, and is given by:

$$\Pi = \frac{1}{2}\int_V \varepsilon^T \sigma dV - \int_V F.udV + \int_S P.udS \tag{5}$$

where, u is the is the displacement vector, F and P, are body force and surface force vectors, respectively. Minimizing total potential energy over each finite element will lead to following system of equations:

$$[K]\{u\} = \{f\} \tag{6}$$

where, K is the stiffness matrix and f is the force vector. Eq. (6) forms the basis of any finite element software and is solved using Newton-Raphson solution technique. Solution of Eq. (6) gives deflection which are then used to compute the stresses. Evolution of elastic modulus and compressive strength and tensile strength in concrete as a function of time is taken into account during the course of analysis.

3.2. Discretization of concrete block

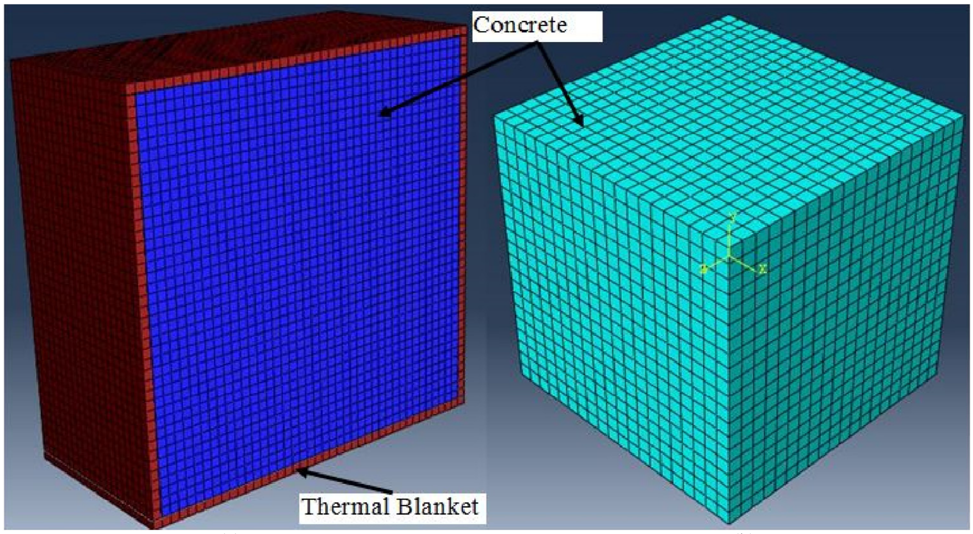
For thermal and structural analysis, concrete block is discretized into elements by utilizing different element types available in ABAQUS. For heat transfer analysis, the concrete block is discretized as a set of 8 noded linear brick elements (DC3D8), with temperature as degree of freedom at each node. Following the thermal analysis, these DC3D8 thermal elements, are transformed to C3D8 elements for undertaking stress analysis. C3D8 elements are 8 noded brick elements with translation in three directions as degree of freedom at each node. The concrete block is meshed using equal side quadrilateral-type mesh to ensure uniformity. The size of each brick element adopted for discretization of concrete block is 25 mm × 25 mm × 25 mm.

The presence of any thermal insulating blanket on concrete block, often used to minimize the dissipation of heat and maintain adiabatic conditions during curing of concrete, is also taken into account in the model. The thermal blanket is also discretized using DC3D8 elements for thermal analysis. Thermal blankets are primarily insulating material with very low stiffness and strength properties and hence do not contribute to any mechanical strength in the stress analysis. A discretized concrete block covered with thermal blankets for the analysis is shown in Fig. 1.

At the start of the thermal analysis, concrete and thermal blankets are assumed to be at ambient temperature on the outer surface, which is modeled as the initial boundary condition in ABAQUS. Convective boundary condition is modeled on the surface of thermal blanket using the surface film condition on the surface. The internal heat source in [Eq. (1)] i.e., the rate of heat of hydration is applied as a body heat flux. The heat transfer step available in ABAQUS employs the modified Newton-Raphson solution technique to solve the nonlinear system of equations. Convergence of the solution in thermal analysis occurs when temperature variance at each node, between the equilibrium iterations, is less than 0.5 °C. During the stress analysis the bottom surface of the block is fixed and the temperature history from the thermal analysis is applied for the entire duration of analysis.

3.3. Material properties

For undertaking sequential thermo-mechanical analysis of concrete block during curing, thermal and mechanical properties of concrete are to be provided as an input to the finite element model. Thermal properties comprise of density, specific heat, thermal conductivity and heat transfer coefficients of concrete. These thermal properties remain constant during and after the hydration of cementitious materials and mainly depends on the type of aggregate used in concrete [8]. Mechanical properties include modulus of elasticity and coefficient of thermal expansion. As the structural analysis is essentially a linear elastic analysis it is very essential to define the evolution of modulus of elasticity (E_c) and tensile strength (f_t) as a function of time to calculate the developed stresses correctly. The elastic modulus and tensile strength depends on the compressive strength (f_c) of concrete which increases with time during the early curing stage and is computed using the following equation [17]:



(a) (b)

Fig. 1. Typical discretized concrete block for (a) thermal analysis (b) stress analysis.

$$f_c = 203\exp\left(0.25\left(1-\left(\frac{28}{t-0.4}\right)^{0.5}\right)\right) \tag{7}$$

where, f_c is the compressive strength of concrete in MPa, t is time in days.

The evolution of elastic modulus is related to compressive strength and is given by [17]:

$$E_c = 5.5f_c(t)^{0.45} \tag{8}$$

where, E_c is the elastic modulus of concrete in GPa.The tensile strength of concrete (f_t) is also related to the compressive strength of concrete [17]:

$$f_t = 0.13f_c^{0.8} \tag{9}$$

The tensile strength computed using Eq. (9) is used to check the cracking in the concrete block. Cracking is assumed to occur when the stresses developed in the concrete due to temperature rise and thermal gradients, exceed the tensile strength of concrete. Eqs. (7)–(9) are developed by Maruyama et al. [17] for the ultra-high strength concrete consisting of different mix composition of silica fume and other supplementary cementitious materials.

Table 1
Batch mix proportions and thermal properties of UHPC-1 and UHPC-2.

Component	UHPC-1	UHPC-2
Crushed granite (kg m^{-3})	487	487
Natural sand #9 (kg m^{-3})	512.7	512.7
Silica sand (kg m^{-3})	282	282
Cement type I (kg m^{-3})	480.6	480.6
Silica fume (kg m^{-3})	211.5	297.6
Slag/fly ash (kg m^{-3})	96.1	
Quartz/limestone powder (kg m^{-3})	173	173
Water (kg m^{-3})	144.2	144.2
Superplasticizer (kg m^{-3})	36	36
Steel fiber (kg m^{-3})	120.3	120.3
Compressive strength (MPa)	203	203
Thermal properties for modeling	UHPC-1	UHPC-2
Density (kg m^{-3})	2500	2500
Specific Heat (J kg^{-1} °C^{-1})	960	960
Thermal Conductivity (W m^{-1} °C^{-1})	2.675	2.675
Heat Transfer Coefficient (W m^{-2} °C^{-1})	10	10
Coefficient of Thermal Expansion (°C^{-1})	1×10^{-6}	1×10^{-6}

4. Model validation

The finite element model is validated by comparing temperature rise predicted by the model with corresponding temperature rise measured during curing of ultra-high performance mass concrete block. For this validation, an experiment carried out on ultra-high performance mass concrete block by Soroushian [20] is selected.

Soroushian [20] developed mix designs and specifications for the production of UHPC using the locally available materials. The use of high heat of hydration for thermal curing of ultra-high performance mass concrete block in the field was also investigated by measuring the temperature rise in a concrete block of size 1.0 m × 1.0 m × 1.0 m. Although, structural members made of UHPC are usually thin and slender, the large size of the block chosen here is for the applicability in large mass concrete structures. The batch mix proportions of UHPC used for casting the block is summarized in Table 1. The concrete block was cast by pouring concrete mix in a 20 mm thick plywood formwork on the two sides and at the bottom of the block. Thermal insulation, in the form of 25 mm thick curing blanket (insulation value R 7.0), was used as insulation on all the four exterior sides of the concrete block. The 7-day compressive strength of the cores extracted from the block was 170 MPa. The blocks were instrumented with type-K thermocouples at bottom, center and top (all central region), as well as at the mid-height on the side, to measure temperature developed during the early stage of curing. The ambient temperature measured during the period of 240 h (10 days) varied from 10 °C to 35 °C. Details of the experiments can be found in Soroushian et al. [20].

This UHPC block, was simulated using the proposed finite element model. The geometry of the UHPC block in the model is similar to the UHPC block in the experiment. The insulating blanket covering the block is explicitly modeled. However, the effect of the formwork is neglected, as the presence of formwork does not significantly affect the temperature distribution within the concrete block. Moreover, according to standard practice, the formwork is usually removed after 24 h of casting of concrete.

The thermal properties of the concrete block, considered for the analysis are summarized in Table 1. These thermal properties of UHPC-1 are taken from Kim et al. [12]. The thermal properties of thermal insulating blanket are; density: 30 kg m^{-3}, specific heat: 2 kcal kg^{-1} °C^{-1}, thermal conductivity: 0.029 kcal m^{-1} h^{-1} °C^{-1}, and heat transfer coefficient: 10 kcal m^{-2} hr^{-1} °C^{-1}. The rate of heat of hydration in UHPC-1 employed in the analysis is based on the measured data and is shown in Fig. 2. A dramatic surge, followed by sudden drop, in rate of heat of hydration during first 15 h after concrete is cast is noticeable in Fig. 2. Heat of hydration culminates at 5100 kcal m^{-3} h^{-1} at the end of 6 h after casting of concrete, known as culmination time and then diminishes to 500 kcal m^{-3} h^{-1} 15 h later. This further decreases linearly to, 80 kcal m^{-3} h^{-1} at the end of 25 h, and then reducing to 50 kcal m^{-3} h^{-1} at the end of 240 h. The initial placement temperature is taken as 35 °C and convective boundary condition is applied on the outer surface of the insulation blanket. The temperatures and gradients developed during curing of UHPC block are predicted for a period 240 h (10 days). The stresses resulting from the temperature rise and the thermal gradients during curing are also evaluated by means of stress analysis.

Due to rapid increase in the rate of heat of hydration in the first 6 h, the dormant period during the hydration of UHPC is very small. The large amount of heat of hydration during the initial period of 6 h leads to significant temperature rise. The temperatures within the block, increases immediately after casting, up to a period of 30 h, as the rate of hydration and heat evolution is maximum during this period. This is followed by gradual decrease in temperature as the rate of heat of hydration decreases. This rapid increase and decrease of temperature is reflected from the temperature progression at different locations in the UHPC block as shown in Fig. 3.

The temperatures predicted by the finite element model are compared with measured temperatures at the top surface (P1), at the center (P2) and at the mid-height on the side (P3) of the UHPC block in Fig. 3. There exists a good agreement between the predicted and measured temperatures progression at various location within the UHPC block during the initial phase (rising temperature). However, in the descending phase (towards the end of 240 h) the predicted temperatures are slightly higher. This can be attributed to constant value of ambient temperature considered in the model. Further, the peak temperature at the end of 29 h, at the center of the UHPC block, as predicted by the model, is 89 °C, which is comparable to the measured temperature of 90 °C. However, at the surface the UHPC block, the predicted and measured temperatures are 86 °C and 89 °C, respectively. This variation in temperature at the surface may be attributed to slight variations heat transfer coefficients and higher heat dissipation at

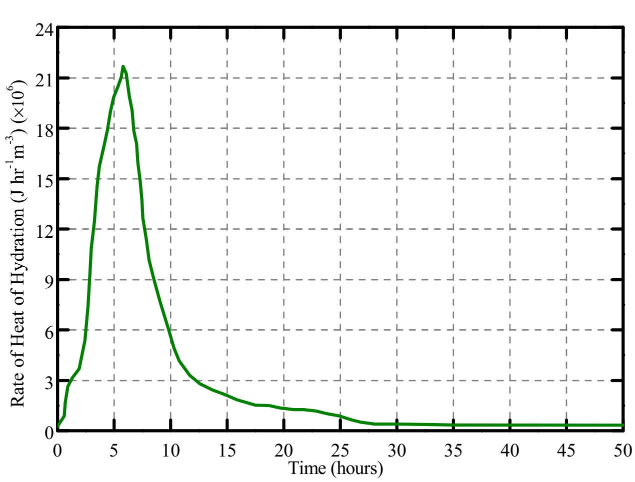


Fig. 2. Rate of heat of hydration in UHPC block.

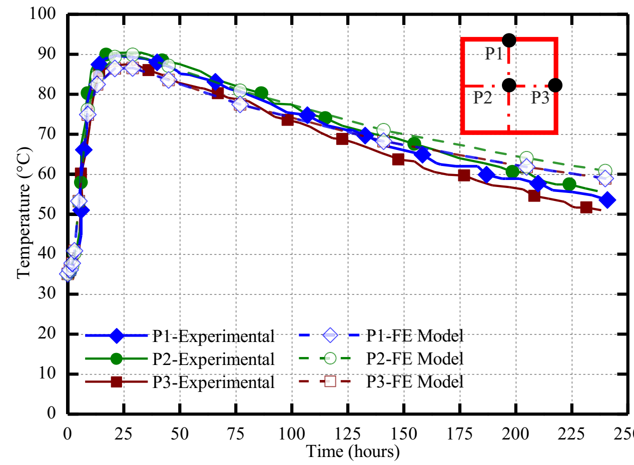


Fig. 3. Comparison of predicted and measured temperatures during curing of UHPC-1 block.

the surface in the model. From the above comparison, it can be inferred that developed FE model is capable of predicting progression of temperature developed during curing of an UHPC block.

The progression of stresses at the center and at the surface of the concrete block, are plotted in Fig. 4, where, S1 and S3 denote the maximum and minimum principal stress. As is apparent from the figure, compressive stresses are developed at the center whereas, tensile stresses occur at the surface. This is because the central portion of concrete tries to expand due to the higher temperatures, whereas the concrete at the surface, which is at relatively low temperature, tries to restrain the expansion. The stress at the surface (S1) is equal to the concrete tensile strength from the early stage until 20 h after casting indicating possibility of surface cracks. Maximum stress of 4 MPa occurs at the surface in 75 h and remains close to 4 MPa for up to about 100 h after the casing of block after which the stresses start to decrease.

5. Parametric studies

The validated finite element model is applied to quantify the effect of different parameters on progression of temperature rise and stresses in ultra-high performance mass concrete during curing. A review of literature indicated that batch mix proportions, size of the block, presence of thermal insulating blanket, and

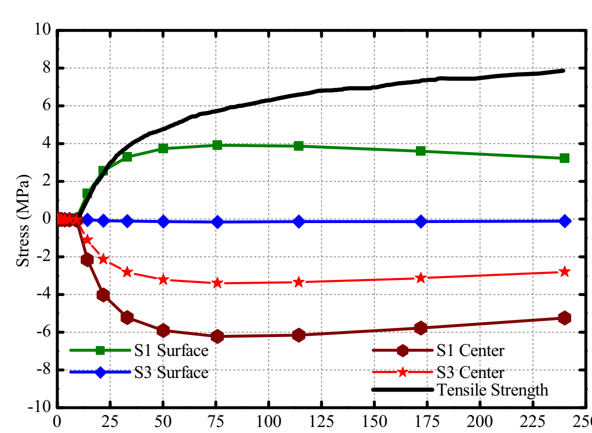


Fig. 4. Progression of stress during curing of UHPC block as predicted by FE model.

presence of reinforcement mesh are the main factors that influence temperature rise in concrete during curing and these parameters were selected for parametric study. The analysis was carried out on a typical UHPC block of size 1 m × 1 m × 1 m. The batch mix proportions and thermal properties of UHPC block used in the study are summarized in Table 1. In the thermal analysis, convective boundary conditions are modeled on the surface of the concrete block, in the absence of a thermal blanket. The thermal analysis is carried out for 240 h i.e. 10 days after casting of concrete. The temperature progression is evaluated at the top surface (T1), at the center (T2) and at the mid-height on the side (T3) of the block. For the stress analysis, the base of the block is fixed and the temperature history from thermal analysis is applied on the nodes of each element. The stresses are evaluated at the center and at the top surface of the concrete block. The resulting temperatures and thermal stresses from the analysis are utilized to draw inferences on the effect of various parameters, on curing of ultra-high performance mass concrete.

5.1. Effect of batch mix proportions

To quantify the effect of batch mix proportions on temperature and stress development in concrete during curing, a concrete block of 1 m × 1 m × 1 m size made with two different types of concrete mixes is analyzed. The two different mixes represent ultra-high performance concrete mixes designated as UHPC-1 and UHPC-2 The batch mix proportions for UHPC-1 are same as the one used for validation problem in previous section whereas, for UHPC-2, the batch mix proportions used in UHPC-1 is modified by replacing fly ash (10% by weight of cementitious materials) with silica fume (10% by weight of cementitious materials). This addition of silica fume accelerates and increases the hydration process of cementitious paste in UHPC. This was observed in the investigations carried out by Souroushian [20]. Moreover, the addition of silica fume also increases cumulative heat released during hydration [9]. This parametric study is to illustrate the effect of addition of silica fume on the temperature distribution in a UHPC block. These mix proportions and their thermal properties are summarized in Table 1. For this study the concrete blocks are not covered with any thermal insulation blanket.

The temperatures developed in concrete block made of two different UHPC mixes, are compared in Fig. 5. There exists a severe thermal gradient within these concrete blocks which would lead to significant differential stresses. The temperature at center of both blocks increases rapidly within the first 20 h of curing and reaches a maximum value of 86 °C and 96 °C in UHPC-1 and UHPC-2 respectively. The corresponding temperature at the surface of UHPC-1 and UHPC-2 blocks reaches a maximum value of 75 °C and 84 °C respectively. This indicates that the thermal gradient is higher in the case of UHPC-2 i.e., concrete containing silica fume as compared to the thermal gradient in the case of UHPC-1 i.e., concrete containing fly ash and silica fume. Moreover, higher silica fume content leads to higher temperature rise within the concrete block due to increased hydration in early stages of curing. This is evident from higher temperature rise predicted in UHPC-2 block. At the end of 10 days temperatures within these concrete blocks is close to 44 °C.

The comparative stresses in two blocks are plotted in Fig. 6 which show that the progression of stresses in both blocks exhibit similar trend. The stresses developed at the surface and at the center of UHPC-2 block, are higher than that developed in UHPC-1 block. Moreover, the stress at the surface of UHPC-1 and UHPC-2 blocks exceeds the tensile strength of UHPC until 35 h and 50 h, respectively, from the beginning of curing. This infers that even though UHPC's has significant advantages in terms of strength and durability, specific attention is to be paid during the early stages of curing to control cracking due to high temperature gradients generated while curing.

5.2. Effect of size of concrete block

To evaluate the effect of size of concrete block on temperature and stresses developed during curing, four different sizes of UHPC block, half meter, one meter, two meter and three meters were analyzed.

The progression of temperature rise during curing, at the center (T1) and at the surface (T3) of these four blocks are compared in Fig. 7. The results show that the temperature within the mass concrete block increases with increase in the size of the block. The peak temperature at the center of half meter, 1 m, 2 m, and 3 m blocks are 80 °C, 86 °C, 93 °C and 97 °C respectively. Even after 10 days (240 h) of casting of concrete, temperature within the half meter, 1 m, 2 m, and 3 m size block are above 41 °C, 44 °C, 57 °C, 77 °C. This indicates that temperature in UHPC blocks do not revert back to the ambient temperature conditions even after 10 days of casting. Moreover, with increase in size of block thermal gradients also increase steeply. Thus, it can be concluded that with the increase in size of UHPC block, the temperature rise within the block increases significantly and takes longer time to revert back to ambient temperature.

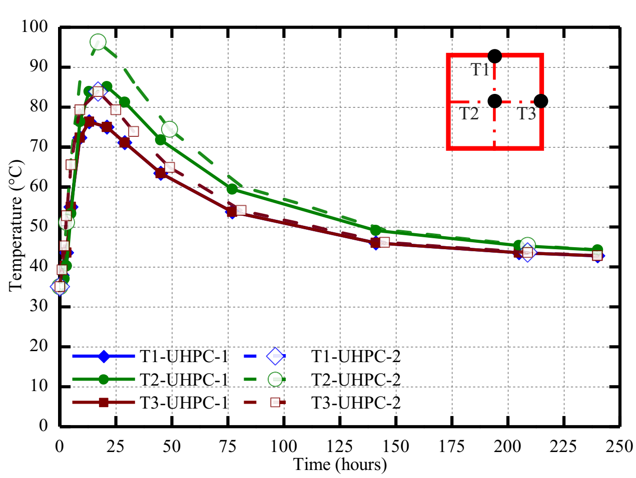


Fig. 5. Effect of batch mix proportions on temperature developed during curing in a concrete block.

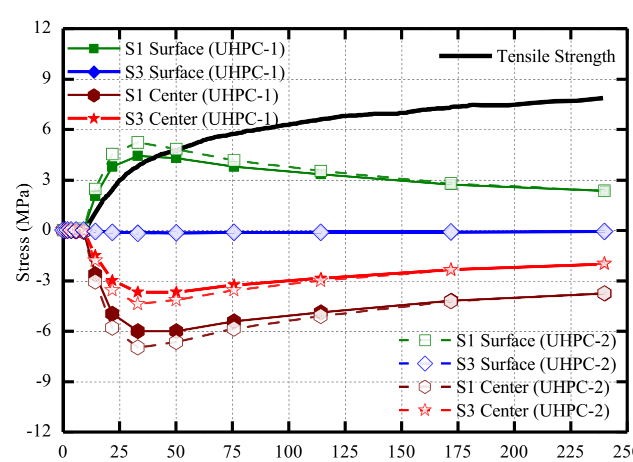


Fig. 6. Effect of concrete strength on stresses developed during curing in a concrete block made with different concrete mixes.

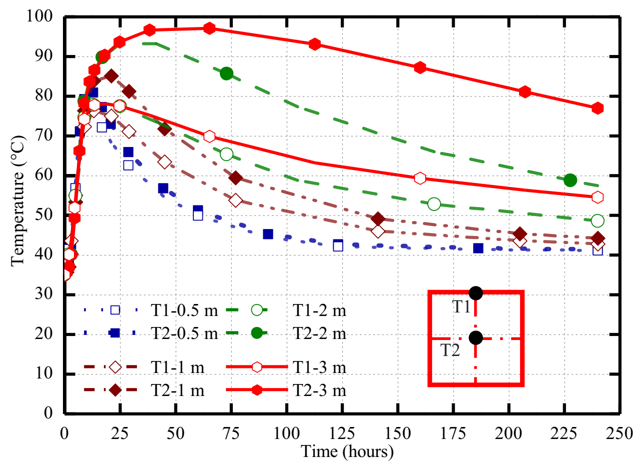


Fig. 7. Effect of size of block on temperature developed during curing of UHPC block.

The stresses developed at the center and at the surface of these four UHPC blocks due to temperature rise during curing are compared in Fig. 8, where evolution of tensile strength of UHPC with time is also plotted. It is apparent from the figure that the tensile stress (S1) at the surface of one-meter, two-meter and three-meter blocks exceeds the tensile strength of UHPC whereas, for half-meter block the tensile stresses are always lower than the tensile strength. These stresses at the surface drops below the tensile strength of concrete after 40 h for one-meter block and after 160 h for two-meter size block. However, for three-meter block the tensile stress at the surface is always higher than the tensile strength of UHPC. These results indicate that significant cracking would occur in three-meter size UHPC block. Thus, with the increase in the size of the concrete structure, possibility of cracking due to tensile stresses resulting from heat of hydration becomes more prevalent.

5.3. Effect of thermal blanket

One of the common strategies adopted in practice to mitigate cracking during curing of mass concrete, is through covering it with thermal insulating blankets. In order to study the effect of thermal insulation blanket on the temperature and stress development, an UHPC block of 1 m × 1 m × 1 m was analyzed under two scenarios; with and without the thermal blanket. The thermal properties of thermal insulating blanket are; density: 30 kg m^{-3}, specific heat: 2 kcal kg^{-1} °C^{-1}, thermal conductivity: 0.029 kcal m^{-1} h^{-1} °C^{-1}, and heat transfer coefficient: 10 kcal m^{-2} h^{-1} °C^{-1}. The temperatures and stresses developed in the UHPC blocks are compared in Figs. 9 and 10 respectively. The temperatures plotted in Fig. 9 are for three different locations i.e., the top surface (T1), at the center (T2) and at the mid-height on the side (T3) of the block.

The temperature rise within the concrete block covered with thermal insulating blanket is higher as compared to the concrete block without thermal insulating blanket. The difference in peak temperature at the surface and the peak temperature at center of the UHPC block with thermal blanket is 2.5 °C whereas, in UHPC block without thermal blanket the peak temperature difference is 10 °C. Hence, the temperature within the UHPC block covered with thermal blanket is nearly uniform indicating lower and less severe thermal gradients. This is due to the fact that the presence of thermal blankets prevents the dissipation of heat to the surrounding environment. The temperature at the end of the 10 days declines to 42 °C in the case of UHPC block without the blanket, whereas in the case of UHPC block with thermal blanket, temperature reduces to 58 °C indicating that the thermal blanket traps the heat and does not allow the temperature to subside. Moreover, this prevention of rapid heat dissipation by blanket helps in developing adiabatic conditions, suitable for hydration of concrete, and mitigates the development of thermal gradient within the block.

The stresses developed from temperature rise during curing in a UHPC block, with and without blanket, are compared in Fig. 10. The progression of stresses in both concrete blocks, follow similar trend. However, in the case of concrete block covered with thermal blanket, the tensile stress at the surface do not exceed the tensile strength of concrete due to lower thermal gradients within the concrete block, therefore, no cracking results in this case. This higher value of stresses in concrete block without thermal blanket is due to higher dissipation of the heat from the surface, thereby reducing the temperature at a higher rate. Whereas, at the core the dissipation of heat is slow leading to higher temperature which give rise to steep thermal gradients within the block.

With the progression of time, the tensile stress at the surface of UHPC block, without thermal blanket, reduces from a maximum value of 4.4 MPa at the end of 21 h to 2.3 MPa at the end 240 h (10 days) i.e. reduction of 47%. However, in case of UHPC block

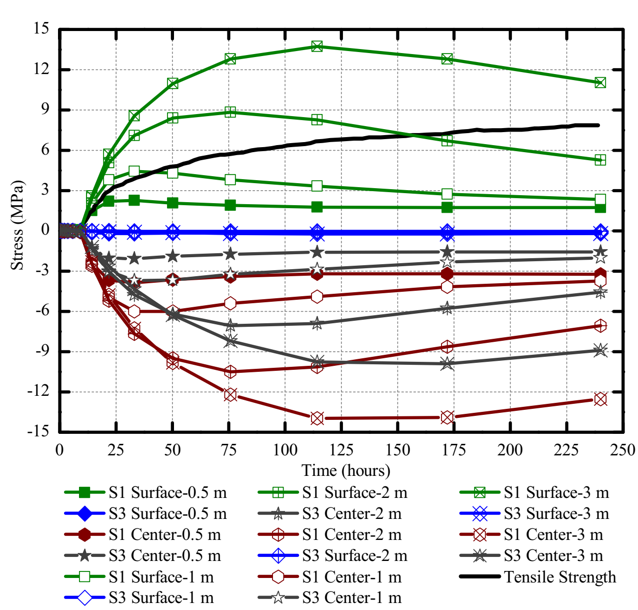


Fig. 8. Effect of size of block on stresses developed during curing of UHPC block.

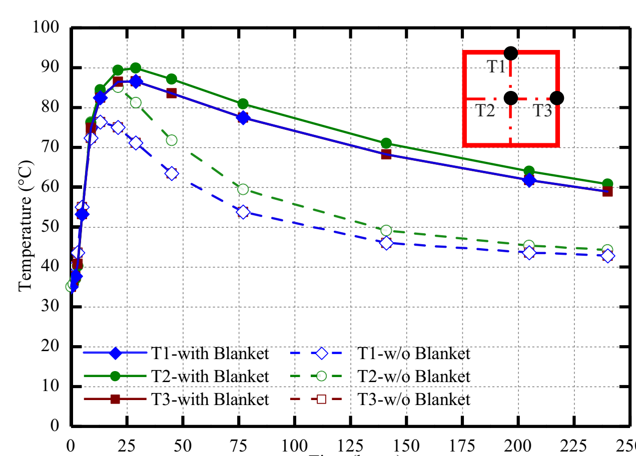


Fig. 9. Effect of thermal blanket on temperature rise during curing of UHPC block.

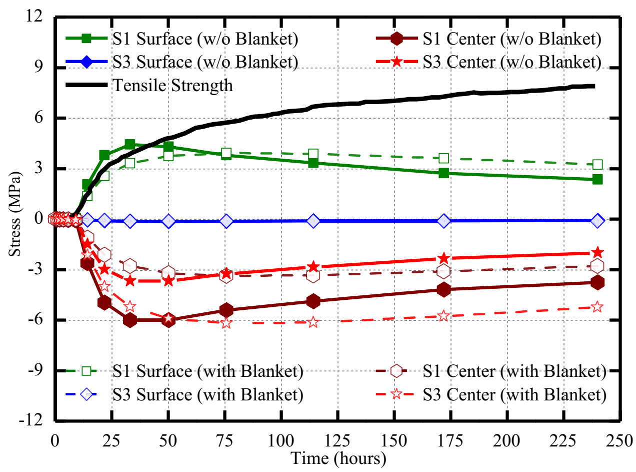


Fig. 10. Effect of thermal blanket on stresses developed during curing of UHPC block.

covered with thermal blanket the tensile stresses reduce from a maximum value of 3.9 MPa at end of 75 h to 3.2 MPa at the end 240 h (10 days) i.e. reduction of 17%. This is due to the fact that temperatures within the concrete block covered with blanket decrease at a much slower rate due to prevention of dissipation of heat. Hence, provision of thermal blanket can prevent dissipation of heat and lead to lower thermal gradients within an UHPC block which in turn can prevent cracking in concrete.

5.4. Effect of reinforcement

In certain scenarios, steel (wire) mesh is provided in concrete structures to minimize cracking during service life. Such wire mesh can minimize adverse effects of heat of hydration during curing. To study the effect of steel wire mesh in minimizing cracking during curing, an UHPC block of 1 m size is analyzed. A wired mesh of 6 mm diameter and of gauge length of 25 mm is assumed to be present in both directions close to the surface of the UHPC block as shown in Fig. 11(a). The properties of steel wire mesh considered in the analysis are; density: 7850 kg m^{-3}, specific heat: 0.108 kcal kg^{-1} °C^{-1}, thermal conductivity: 44.75 kcal $m^{-1}h^{-1}$ °C^{-1}.

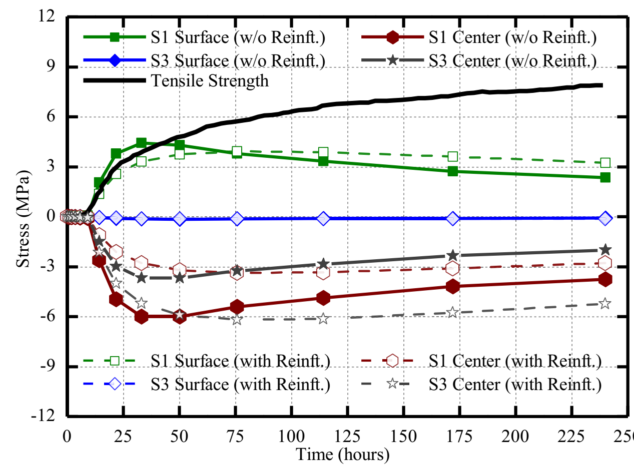


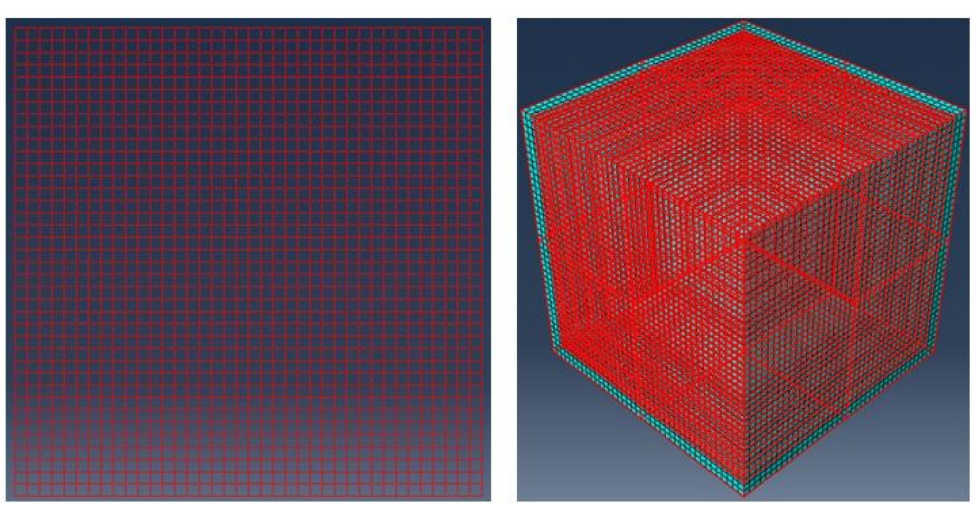
Fig. 12. Effect of reinforcement mesh on stresses developed during curing of an UHPC block.

Steel wire mesh is applied on all 6 sides of the UHPC block at a clear cover of 25 mm, thus forming a cage in the block. For the thermal analysis steel wires are modeled with DC1D2 elements and then converted to T3D2 elements for the stress analysis. The mesh configuration for UHPC block with steel wires is shown in Fig. 11(b).

Results from the analysis indicate that presence of steel wire mesh has no influence on temperature rise within UHPC block, however, stresses at the center and at the surface of concrete block get altered significantly. A comparison of stresses developed in a 1 m size UHPC block with and without reinforcement is shown in Fig. 12. As evident from the figure, tensile stresses (S1) at the surface decreases as the tensile strength increases, when steel wire mesh is provided in UHPC block. Thus, provision of steel wire mesh can reduce stresses developed during early stage of curing in an UHPC block and can mitigate thermal cracking.

6. Research implications

Heat evolved due to hydration of cementitious particles in a batch mix can generate temperature rise in concrete during curing. This temperature rise can lead to significant thermal gradients and



(a) (b)

Fig. 11. Mesh configuration of: (a) steel wire mesh (b) UHPC block reinforced with steel wire mesh.

tensile stresses in mass concrete, which in turn can produce cracking. Ultra high performance concrete has high cementitious content and very low water/cementitious ratio, thereby generating large amount of heat of hydration. This high heat of hydration can lead to significant non-uniform temperature rise, resulting in severe thermal gradients and tensile stresses, causing cracking. Such cracking during curing can affect strength and durability properties of UHPC. Hence, temperature rise within UHPC at early stage of curing must be taken into consideration in the design of UHPC batch mix.

Results from the numerical studies clearly show that temperature rise and resulting tensile stresses increase with increase in the size of an UHPC block and also with increase in the cementitious content in batch mix. However, presence of thermal blanket or mesh reinforcement can reduce tensile stresses and prevent cracking. The finite element model proposed here can be applied for developing optimum strategies for minimizing cracking during curing of ultra-high performance concrete structures.

7. Conclusions

Temperature and stress development due to heat released during hydration of cementitious particles in concrete was modeled through a numerical approach. Further a parametric study was carried out to quantify the effect of critical factors on temperature rise and stress development during curing of an ultra-high performance concrete (UHPC) block. Based on the results generated, the following conclusions can be drawn:

1. The proposed numerical model is capable of predicting temperature and stress development during early age curing of UHPC.
2. Severe temperature gradients develop in ultra-high performance mass concrete structures during curing stage, giving rise to significant tensile stresses at the surface, which in turn lead to cracking of concrete.
3. Temperatures within a mass concrete block increase with increase in the size of the concrete block. This temperature rise can produce large thermal gradients, which in turn can lead to high tensile stresses at the surface and result in thermal cracking in UHPC.
4. Presence of thermal insulating blanket on an UHPC block can reduce thermal gradients within mass concrete, resulting in lower tensile stresses in an UHPC block.
5. Presence of reinforcing mesh can reduce tensile stresses in UHPC batch mix which in turn can minimize thermal cracking during the early curing of UHPC structure.
6. Provision of thermal insulating blanket is an effective strategy to overcome cracking in ultra-high performance mass concrete during early age curing.

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