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Numerical Simulation of Temperature Profile of a Mass Concrete Block using ANSYS

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ABSTRACT

Any volume of concrete with large dimensions and that requires special measures to control the heat that is generated during hydration is termed as the mass concrete. Highly exothermic hydration of cement in concrete causes rise in internal temperature which does not dissipate easily when compared to surface. This gives rise to thermal gradients within the structure and in turn generate thermal stresses depending on the type of restraints. If these thermal stresses outrange the tensile strength of concrete, cracks may develop during early ages, affecting the durability. In this paper, the early age thermal behaviour of a massive concrete block subjected to an assumed constant heat generation is assessed numerically using the popular finite element software package ANSYS. The developed methodology is validated with results available in the literature. A detailed parametric study is also conducted to evaluate the effect of thermal properties like conductivity, specific gravity, rate of heat generation and initial temperature on the temperature distribution of the concrete. The study can be further modified to develop detailed methodology to perform thermal-stress analysis of massive concrete structures.

Keywords: *Mass concrete, Early age, Hydration, Thermal gradient, Thermal stresses, Finite element.*

I. INTRODUCTION

The study of thermal behaviour of mass concrete structures at early ages is important as it governs the performance of the concrete at later ages. The heat generated due to hydration of cement causes temperature rise within the structure compared to the outside temperature, owing to the low conductivity during the early age. The differential volume changes resulting from these temperature gradients induce strains in restrained portions of the concrete. If these strains and stresses outrange the permissible limits, cracks are developed, affecting the durability and structural efficiency of the structure. This is of primary importance in case of massive structures like concrete dams, piers, thick foundations, etc.

Several experimental studies regarding the effect of temperature on the concrete properties are reported in the literature [1], [2]. Apart from costly and time consuming experimental studies numerical simulation procedures using finite elements have proven to be efficient in terms of computation cost and time. Several researchers have developed and implemented finite element procedure for assessing thermal behaviour of mass concrete structures. A coupled thermal-structural analysis of a roller compacted concrete (RCC) dam in Jordan was carried out by Malkawi *et al.* [3]. The study demonstrated that detailed thermal stress analysis should be performed for large RCC dams to provide a basis to minimise and control the occurrence of thermal cracking. Malkawi *et al.* [4] performed a comparative study of temperature distribution in an RCC dam during and after construction using the well known computer package ANSYS and using an in-house programme with COSMOS. The influences of the thermal properties as well as climatic conditions, and the placement schedule of RCC layers on temperature distribution were thoroughly assessed in the analyses. Kuriakose *et al.* [5], [6] developed a finite element programme to investigate the thermal distribution within massive concrete structures. A parametric study was conducted by varying the raft thickness from 0.3 to 3 m and an increase in temperature gradient with raft thickness is reported. Kurian *et al.* [7] conducted transient thermal analysis on a concrete gravity dam to investigate the effect of thermal and concrete properties during its early age using ANSYS. A detailed parametric study of the dam is reported, by varying the parameters thermal conductivity, specific heat, lift height and, initial temperature. Coelho *et al.* [8], conducted thermal analyses on a massive concrete block to investigate the dependence of thermal properties on early age temperature distribution.

The aforementioned studies have proven the importance of thermal stress analysis of early age concrete. In this paper, a finite element procedure is developed for thermal analysis of early age concrete with an assumed uniform heat generation, using the popular finite element programme, ANSYS. A detailed parametric study is also performed to assess the influence of thermal conductivity, specific heat, rate of heat generation and initial temperature on the thermal behaviour of a massive concrete block.

II. MATHEMATICAL MODEL

The transient thermal conduction in homogenous and isotropic materials is governed by following differential equation based on Fourier's Law [6]

$$k\nabla^2 T + \dot{q} = \rho c \frac{\partial T}{\partial t} \qquad (1)$$

where, k is the conductivity, ρc is the volumetric heat, T is the temperature, $\dot{q}$ is the rate of internal hydration heat generated and t is the time. The thermal conductivity (k) indicates the rate of heat transfer due to temperature gradient and for normal concrete it ranges between 1.2 and 3.5 W/mK. The specific heat (c) is the amount of energy absorbed and used to raise the concrete temperature by a unit. For ordinary concrete the specific heat (c) typically ranges between 850 and 1170 J/kg K.

Thermal analysis of concrete requires information regarding the heat of hydration. The chemical reactions involved in hydration are exothermic and the heat liberated can be determined numerically or experimentally. This heat of hydration varies with type of cement used and various other conditions [6]. In this paper, the heat generation is assumed to be constant. The dependence of heat generation on thermal properties and vice-versa necessitates a highly non-linear procedure to be implemented in the finite element model [5]. However, simplified linear analysis procedure is utilised in the present study, neglecting the interdependence of the temperature and thermal parameters. In the present finite element formulation, 8-noded plane heat conduction element PLANE55 is utilised.

III. RESULTS AND DISCUSSION

3.1 Validation

A one-dimensional transient thermal problem described in Incropera [9] is considered for validating the developed finite element model. The problem constitute a plane wall of thickness *L*, initially having a linear, steady-state temperature distribution with boundaries maintained at T_1 = 0 ^{0}C and T_2 = 100 ^{0}C, and has a uniform volumetric heat generation of 2×10^7 W/ m^3, as shown in figure 1. The thermal properties of the material of the plane wall are k = 10 W/mK, $\rho c = 2 \times 10^6$ J/kgK.

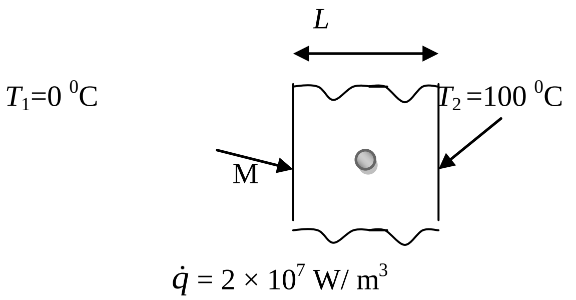


Fig. 1 Schematic representation of plane wall

Temperature simulation was carried out under the assumption that the heat transfer occurs only along the thickness of the wall, resulting in a one-dimensional heat transfer problem. The wall is discretised using eight number of PLANE55 along its thickness. The temperature history at midpoint (M) of the slab (figure 1) with a time step of 5 s is presented in figure 2, which is compared with those results found in the literature [9] and observed to be in excellent agreement.

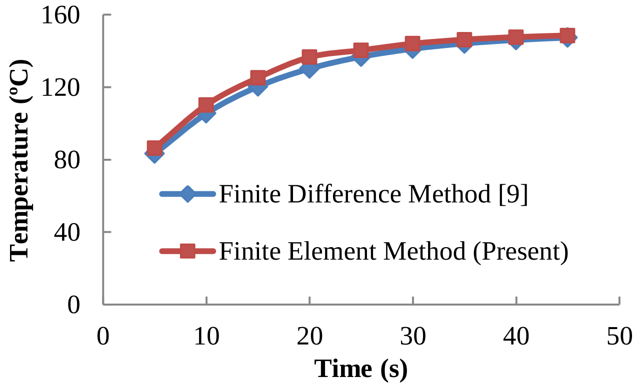


Fig. 2 Temperature distribution at midpoint (M) of the plane wall

3.2 Thermal analysis of a mass concrete block.

The developed numerical model was utilized to study the early age thermal behaviour of hypothetical 1 m × 1 m concrete block with infinite length in the transverse direction. As the third dimension is infinite, the heat transfer problem reduces to a two-dimensional one. The block was discretised into elements of 0.05 m mesh size as shown in figure 3 and was analysed in ANSYS with a time step of 1 day. The properties of the concrete block are shown in the Table 1. A constant average heat generation of 235 W/m^3 was assumed for the block and the temperature distribution within the block for 3, 7, 14 and 28 days are presented in figure 4. It can be seen from figure. 4 that, as time elapses, there is considerable thermal gradient within the mass concrete when compared to the outer surfaces.

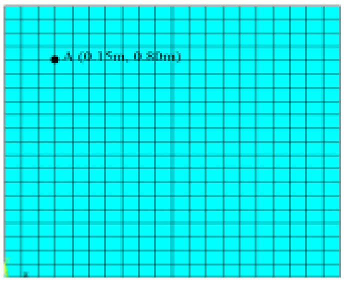
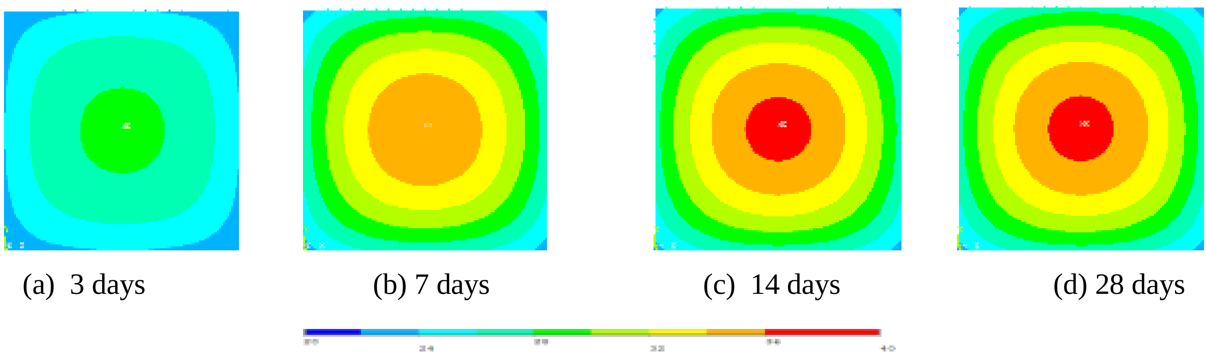


Fig. 3 Numerical model of the concrete block

Table 1 Properties of the concrete block

Properties	Value
Specific heat capacity (*c*) [J/kg K]	880
Convection film coefficient (*h*) [W/m^{2}K]	10
Initial temperature of block [^{0}C]	15
Bulk temperature [^{0}C]	20
Thermal conductivity (*k*) [W/m K]	1.7



(a) 3 days (b) 7 days (c) 14 days (d) 28 days

Fig. 4 Temperature distribution (°C) within the concrete block

3.3 Parametric study

In order to investigate the effect of thermal properties on the thermal profile of the concrete block, a detailed parametric study was conducted. The temperature history at a point A within the concrete block (depicted in figure 3) is monitored.A study on the effect of thermal conductivity on the temperature profile was performed by varying *k* from 1.7 to 2.6 W/mK. The temperature history at A for different values of *k* is depicted in figure 5. It is found that the lower the thermal conductivity of the concrete, the higher the maximum temperature reached. This can be explained by the fact that, with a low thermal conductivity, the greater will be the difficulty of dissipating heat internally generated in the block.

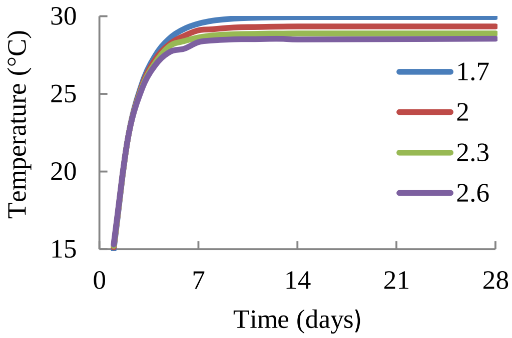


Fig. 5 Variation of temperature history of the block with *k*

A study on the influence of specific heat capacity on the temperature of the block was also performed and the results are presented in figure 6. It is observed that for a lower value of specific heat, higher temperatures are obtained, i.e., less amount of heat is required in order for a temperature rise to occur. Moreover, after 7 days of hydration, constant temperatures are observed for all values of specific heat capacity.

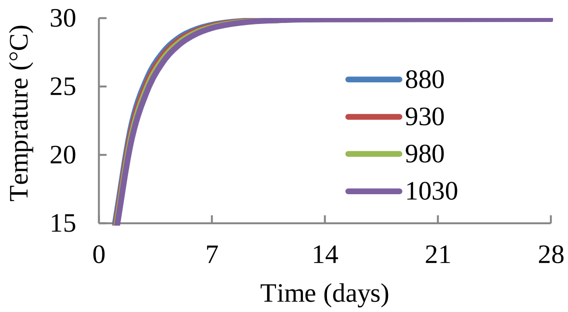


Fig. 6 Variation of temperature history of the block with *c*

The temperature history of the block for different heat generation values is presented in figure 7. It is seen from the figure that temperature of the concrete increases with increase in heat generation.

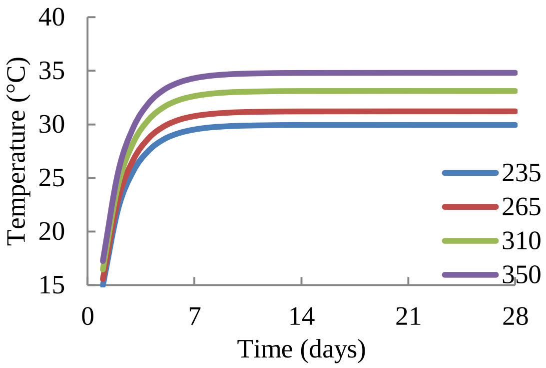


Fig. 7 Variation of temperature history of the block with heat generation

It is observed from figure 8, in which the temperature variation of the block with various initial temperature values is presented, that temperature history up to 3 days corresponding to initial temperature of 30^{0}C is higher than the initial temperature of 10 ^{0}C. Thus it can be concluded that, one can reduce the temperature rise in the structure by precooling the concrete using crushed ice or by introducing cooling pipes.

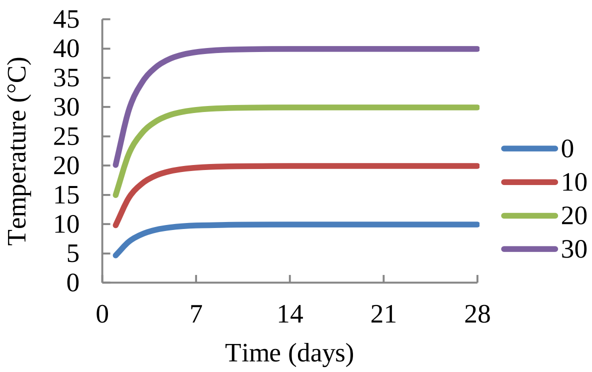


Fig. 8 Variation of temperature history of the block with initial temperature

IV. CONCLUSIONS

In the present study, a numerical model is developed to analyse the early age temperature distribution in a mass concrete block using the finite element software ANSYS. A detailed parametric study was also conducted to investigate the effect of thermal properties of concrete, heat of hydration and initial temperature on the thermal profile of the block during early ages. It is observed that the increase in conductivity and specific heat capacity of concrete decreases the temperature of the concrete during initial days of hydration. Furthermore, increase in heat of hydration as well as initial temperature increases the rate of hydration and temperature of the concrete. The developed model can be further improved incorporating the nonlinearities, which can in turn be utilised for stress analysis of mass concrete structures so as to assess the crack widths and durability.

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