***International Journal Of Engineering Research And Development***
*e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com*
*Volume 20, Issue 7 (July, 2024), PP. 384-392*

# Heat of Hydration of Mass Concrete in Controlling Temperature Performance by Construction Stages

Dr Vinayaga Moorthy [1]; Banoj Mohapatra [2]
*[1] Technical Director- AECOM , Dhubri, Assam, India*
*vinayaga.mariappan@aecom.com*
*[2] Associate Director, AECOM , Dhubri, Assam, India*
*banoj.mohapatra@aecom.com*

***Abstract:***
*Thermal analysis is one of the main components in the design and construction of any mass concrete foundation. In this article, the heat transformation in concrete by hydration process is analysed and cooling method was introduced to perform the thermal analysis of a couring system in mass concrete structures. Several typical models are selected to verify the performance of this method. The proposed method is then applied to a bridge pile foundation concrete called in the pilecap for the Dhubri Phulbari Bridge, which is still under construction in India. The actual climatic conditions and thermal properties of the materials are considered in this analysis. The temperatures determined by numerical simulation are in good agreement with the actual monitored values. The simulation results indicate that the proposed method can accurately simulate the hydration temperature statge, the temperature rise along the water flow, and the effect of directional changes of flow in temperature distributions. Moreover, the maximum temperature for 24 hours was examined shown the development in concrete and compared with foundation with the curing system. Mainly from the extreme temperature in the core of the concrete and fluctuation during the cooling process of concrete. The untimely application of water-cooling systems during hot seasons will induce extreme tensile stresses and increase the risk of cracking.*

***Author keywords**: Foundation; Heat of hydration; Heat-fluid coupling method; Thermal analysis; Cooling pipes.*

Date of Submission: 15-07-2024 Date of Acceptance: 30-07-2024

## I. Introduction:

Controlling temperature-induced cracking in concrete is one of the main concerns in the design and construction of concrete of mass concrete foundation. In compacted concrete (RCC) foundation, the application of continuous casting with different-layer of concrete combined with the large use with less cement content during construction makes mass structures significantly different from conventional concrete structure with respect to the temperature due to hydration process, cooling conditions, and the main factors affecting thermal stress. Particularly, the quick construction process and large size of concrete lifts will induce a high temperature or extreme thermal gradient within the concrete and cause significant thermal stresses during the cooling of the foundation, which are sufficient for cracking (Zhu 1999). Thus, it is necessary to simulate and analyse the temperature and stress fields during construction and then suggest some effective temperature control measures to prevent cracking (Tatro and Schrader 1992; Zhu 2006). Cooling by the flow of water through an embedded cooling pipe has become a common and effective artificial temperature control measure in the construction of concrete foundations, such as in the Larsen and Toubro. A great deal of research has been conducted to simulate the cooling effect of this water flow. Cervera et al. (2000a, b) presented a numerical procedure for the thermal and stress analysis of the evolutionary construction process of RCC foundations. This procedure took into account the ambient temperature, placing temperature, casting schedule, and, in particular, the more applicable features of the behaviour of concrete during the early stages after construction, such as hydration, aging, creep, and foundation age. The U.S. Bureau of Reclamation (USBR 1949) conducted research on the calculation of the final stage of water cooling and presented an analytical solution using a two-dimensional (2D) program, and an approximate solution using a three-dimensional (3D) program with no heat source by using the separation-of variables method. The calculation of the initial stage of water cooling and obtained an analytical solution using a 2D program and an approximate solution using a 3D program with a heat source by using the integral transform method. The polythene pipes had fewer joints, which appeared to be more convenient than steel pipes in construction, and also four methods for computing the effect of cooling by non-metal pipes. In addition, the simplified analysis and proposed methods to compute the equivalent radius and equivalent horizontal spacing of non-metal pipes. Zhu (1991) treated water cooling as negative hydration heat and presented a cooling equivalent algorithm based on the

FEM. The water cooling effect to every element in the FEM analysis, easily obtaining an approximate distribution of the temperature field

Kim et al. (2001) developed a 3D FEM program to thermally analyse concrete structures with pipe cooling systems. Line elements were adapted to model pipes, and internal flow theory was applied during the calculation of the temperature variation of the cooling water. Liu (2004) proposed a general analytical model to address heat extraction from mass concrete by employing a rectangular array of cooling pipes. In this study, an analytical solution is derived in terms of the physical parameters for heat diffusion and heat removal. The model can be employed to analyse a temperature the heat is removed using a rectangular pipe frame and can provide guidance in choosing pipe sizes, pipe spacing, aggregates of different heat diffusivity, types of cements, fresh concrete temperature. However, this technique still cannot accurately reflect the velocity and water temperature variation rise along the flow.

The objective of this work is to present an accurate and applicable prediction method for the analysis of the cooling effect exhibited by pipes in mass concrete structures. This work accounts for the following factors: concrete properties, ambient conditions, convection coefficient function, heat source, casting schedule, and, in particular, the actual pipe cooling system. Additionally, it considers the pipe layout (pipe sizes and spacing), the cooling water velocity, the inlet temperature and water-temperature rise along the flow, and the thermal properties of cooling pipes by using a numerical simulation. Thus, the prediction of the thermal fields associated with cooling pipes can be successfully used in practice.

In this study, the heat-fluid is introduced to perform the thermal analysis of pipe cooling systems in mass concrete structures and is applied to an actual RCC foundation. A 3D FEM analysis is conducted using heat-fluid elements in the FEM program Midas FEA. To verify the rationality and applicability of the heat-fluid coupling method, a comparison with several widely used methods is presented. Furthermore, this method is applied to verify and predict the distribution of temperature during the initial stage of the cooling process of the Dhubri Phulbari main span pylon foundation.

## Basic Formulations and Solution Approach of Temperature Field

Based on the energy balance principle, the general partial differential equation governing heat flow in a 3D solid medium is expressed where the concrete temperature; The initial transient temperature can be represented as;

$$T = To\ (x, y, z)$$

## Simulation analysis of finite element procedure

### Project Overview:

This foundation is for Dhubri Phulbari bridge main span foundation project in Hyderabad, India. It has main span length of 425.8m and 28.3m height (Above the ground). The foundation thickness 3500mm and 2500mm of soil base for the analysis. Fig 1 displays plan layout of foundation and temperature measuring point.

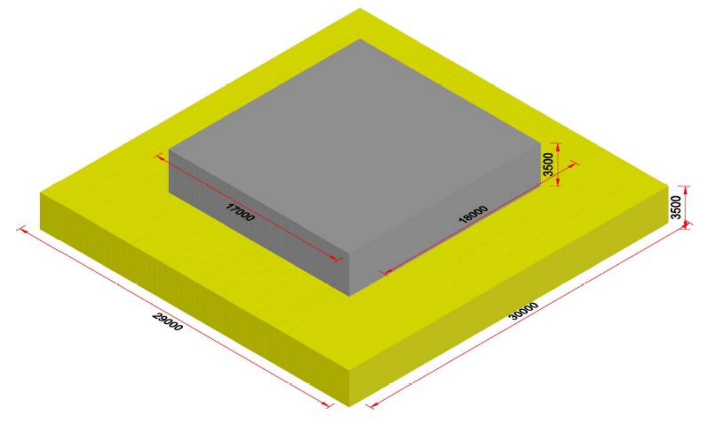
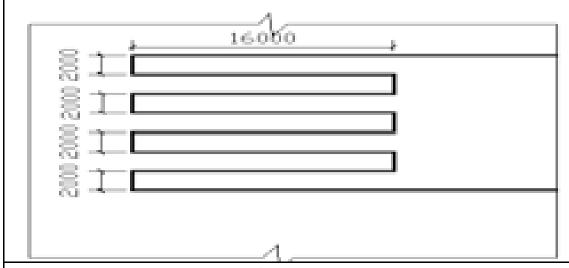
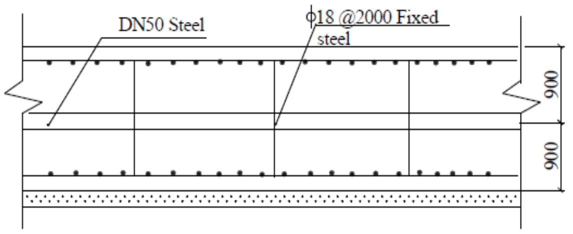


Fig 3. Finite element model added into the cooling water pipe upon grid distribution

The following temperature control measures are adopted for the project: One layer of straw mat or gunny bag immersed in water for a long time is first laid on the external surface of concrete; then two layers of dry straw mat are laid for heat insulation; the covering materials are increased or reduced according to the temperature gap; the cooling water pipe is set up in the concrete. Fig 4A is layout of cooling water pipe.

The following temperature control measures are adopted for the project: totally seven layers were considered, each layer is 500mm. totally eight construction stages were considered with cumulative time of one hour for each pouring. The cooling water pipe is set up in the concrete shows in layout (Fig 4A) of cooling water pipe.

| | |
|---|---|
|  |  |
| Fig .4A. Plan layout of cooling water pipe | Fig. 4B .Vertical layout schematic of cooling water pipe |

**Construction Methodology**

Foundation concrete will be casted in single pour. It will be casted in layer by layer. Each layer thickness will be 0.5 m and time taken to complete every single layer will be 1 hour. Time required to complete one single footing will be around 8 hours.

| Description | Thickness of foundation casted at each stage | Total thickness casted | Cumulative time taken |
|---|---|---|---|
| Stage 1 | 500 mm | 500 mm | 1 hour |
| Stage 2 | 500 mm | 1000 mm | 2 hours |
| Stage 3 | 500 mm | 1500 mm | 3 hours |
| Stage 4 | 500 mm | 2000 mm | 4 hours |
| Stage 5 | 500 mm | 2500 mm | 5 hours |
| Stage 6 | 500 mm | 3000 mm | 6 hours |
| Stage 7 | 500 mm | 3500 mm | 7 hours |
| Stage 8 | - | 3500 mm | 8 hours |

**Analytical procedure of finite element procedure:**

The article adopts structural analysis finite element software MIDAS/Civil to implement value simulation analysis to the large-volume concrete temperature field and temperature stress. It can be divided into the following three procedures:

**Model establishment and necessary parameter confirmation.**

This process mainly includes the material features related to time such as creep, dry shrinkage and elastic modulus and setup of boundary.

**Analysis of temperature stress process.**

This process mainly includes the setup of temperature, distribution of heat source and setup of construction simulation time. It mainly includes the temperature change graph and temperature stress change graph.

**Procedure model establishment**

The mass concrete and natural foundation is selected and adopted as the calculation object for modelling; the concrete thickness is 1.8m and 2.7m; the length is 38m and width is 46m; the soil thickness is 3m, length is 42m and width is 54m. Axis Z is along the thickness direction, axis X is along the length direction and axis Y is along the width direction.

Table: material property for concrete

| | |
|---|---|
| Density | 25 kN/m3 |
| Grade of Concrete, Fck | 40 MPa |
| Elastic modulus, Ec | 35000 MPa |
| Allowable tension stress | 3.0 MPa |
| Allowable compression stress | 14 MPa |

Table: material property for concrete

| | |
|---|---|
| Density | 78.5 kN/m3 |
| Fy | 500 MPa |
| Es | 200000 MPa |

The grid is distributed according to the concrete shape; the Mass concrete foundation (thickness of 3.5m) length and width direction includes 17m and 18m respectively; the mass concrete foundation (partial part with a thickness of 0.5m) length and width direction includes 8 units and 9 units respectively.

**The initial and boundary conditions**

Environmental temperature: Average daily temperature is 21ºC. Initial concrete temperature: The measured model entry temperature of concrete is 22 ºC—28ºC; in order to reflect the possible maximum temperature, 28 ºC is adopted for the procedure analysis.

Flowing temperature of cooling water: The measured temperature is 19 to 22 ºC, 21ºC is adopted. The concrete surface, surrounding steel model and air contact surface is treated according to boundary conditions; the natural foundation and foundation contact surface is treated according boundary conditions; the contact is good and natural foundation is simulated into a structure with certain specific heat and heat transmission rate. The natural foundation is treated as follows: The side and lower bottom of natural foundation adopt the fixed natural foundation temperature (22ºC); the model is established for the restriction conditions according to the body unit: general support restriction conditions are adopted.

**Thermal parameters of concrete foundation and natural foundation:**

**Table 2.The material and thermal characteristic parameters**

| Description | Unit | Foundation | Subsoil |
|---|---|---|---|
| Specific heat | Kcal / kg / °C | 1046.5 | 837.2 |
| Rate of heat conduction | Kcal / m / hr / °C | 9627.8 | 7116.2 |
| Ambient temperature | °C | 25 | - |
| Casting temperature | °C | 20 | - |
| Thermal expansion coefficient | - | $11.6 \times 10^{-6}$ | - |
| Heat source function coefficients | K (°C), a (no unit) | K=33.97, a=0.605 | - |
| Density | $kg/m^3$ | 2400 | 1800 |
| Poisson's ratio | - | 0.2 | 0.2 |

**Specific heat:**

The specific heat is the amount of heat per unit mass required to raise the temperature by one degree Celsius with specific heat of concrete is 1046.5 kcal / kg /°C and specific heat of subsoil is 837.2 kcal / kg / °C.

$$C = \frac{Q}{m}/dT$$

Where,
Q – Heat added
m - Mass
dT – change in temperature

### Heat conduction

Conduction is heat transfer by means of molecular agitation within a material without any motion of the material as a whole. If one end of a metal rod is at a higher temperature, then energy will be transferred towards the colder end.

| | |
|---|---|
| Rate of heat conduction in concrete | 9627.8 kcal / m / °C |
| Rate of heat conduction in subsoil | 7116.2 kcal / m / °C |

### Convection coefficient

Convection is another form of heat transfer whereby heat is transmitted between a fluid and the surface of a solid through a fluid’s relative molecular motion.

From an engineering perspective, the heat transfer coefficient, c h is defined to represent the heat transfer between a solid and a fluid, where T represents the surface temperature of the solid, and the fluid flowing on the surface retains an average temperature $T\alpha$.

The convective heat transfer, $q = h_c (T_s - T_f)$

Where,

Hc - convection coefficient

Ts - surface temperature

Tf - Fluid temperature

### Heat source

Heat source represents the amount of heat generated by a hydration process in mass concrete. Differentiating the equation for adiabatic temperature rise and multiplying the specific heat and density of concrete obtain the internal heat generation expressed in terms of unit time and volume. Adiabatic conditions are defined as occurring without loss or gain of heat.

$T = K(1 - e^{-\alpha t})$

Where,

T - Adiabatic temperature

K - Maximum adiabatic temperature rise

α - Reactive velocity coefficient

t - Time

### Ambient temperature

The temperature of the surrounding environment, i.e., the temperature of the air surrounding a medium.

### Thermal expansion coefficient

The coefficient of thermal expansion describes how the size of an object changes with a change in temperature. Specifically, it measures the fractional change in size per degree change in temperature at a constant pressure.

## II. Results and Discussion:

In this analysis, the major cause for thermal stresses is due to the temperature differences within the concrete mass resulting in internal constraints. Recapping the overview, Internal Constraints are caused by unequal volume changes. Initially, cooling surface and warm inner parts cause tension at the surface and compression at the inner parts. At a later stage after the rise in temperature due to heat of hydration reaches the peak level, the cooling (contracting) inner parts relative to the surface cause tension in the inner parts and compression at the surface. The magnitude of the stresses is proportional to the temperature differences between the inner parts and surface. It is also anticipated that the two concrete masses of two separate pours of different ages will exhibit different heat transfer characteristics.

It will analyse the characteristics of thermal stresses in concrete by reviewing the results of heat of hydration analysis for 15Hours reflecting construction stages by graphic and contour results.

1. Max temperature = 36 degree
2. Max tensile stress < Max allowable stress
3. Temperature variation for inner core and outer surface

Temperature distribution at different stages are shown as below:

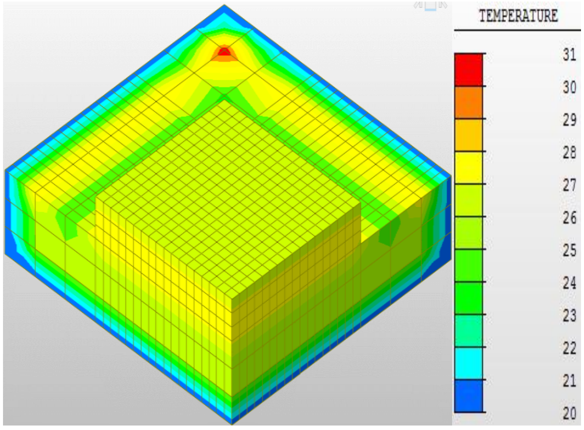


Fig. 5 Temperature distribution at stage 3 (after 3 hours of casting) Unit: Celsius

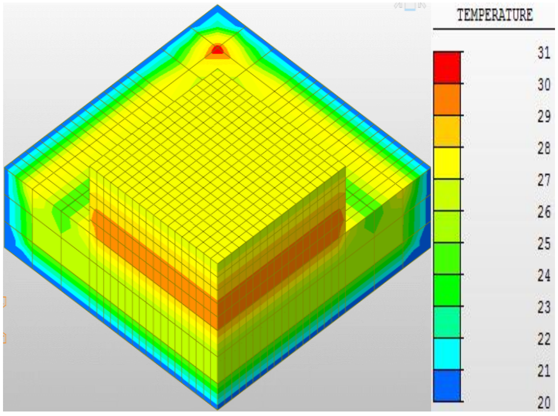


Fig. 6 Temperature distribution at stage 5 (after 5 hours of casting) Unit: Celsius

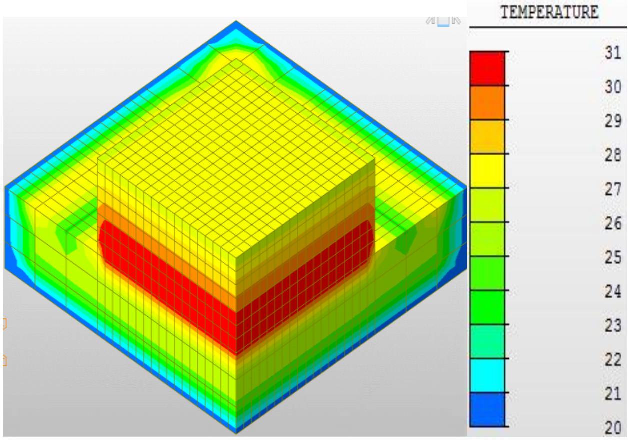


Fig. 7 Temperature distribution at stage 7 (after 7 hours of casting) Unit: Celsius

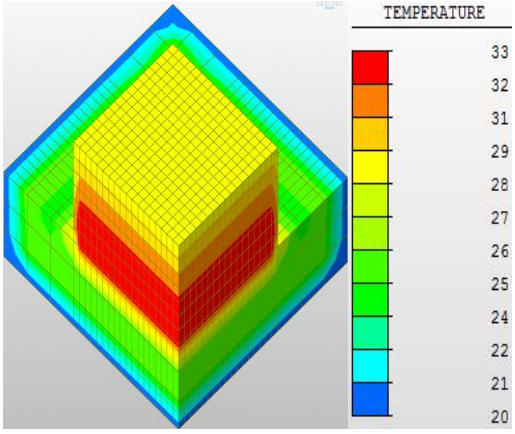


Fig. 8 Temperature distribution at stage 8 (after 10 hours of casting) Unit: Celsius

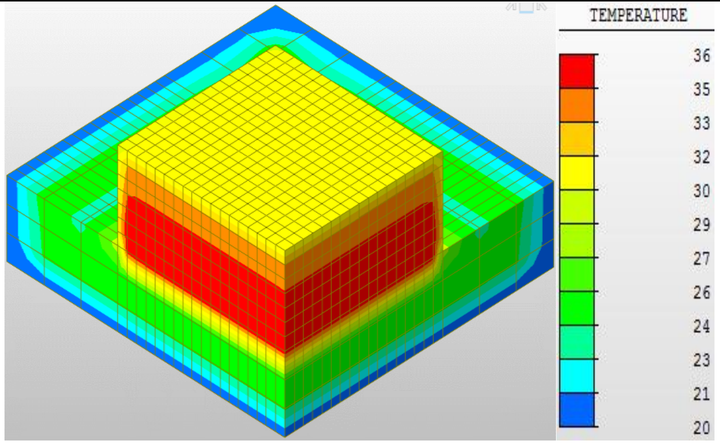


Fig. 9 Temperature distribution at stage 8 (after 15 hours of casting)

**Hydration stress distribution at different stages are shown as below:**

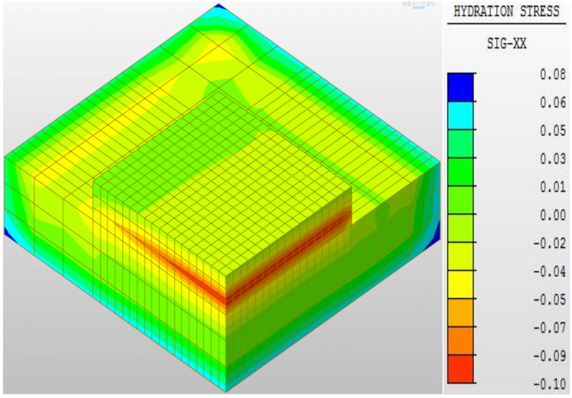


Fig. 10 Hydration stress distribution at stage 3 (after 3 hours of casting)

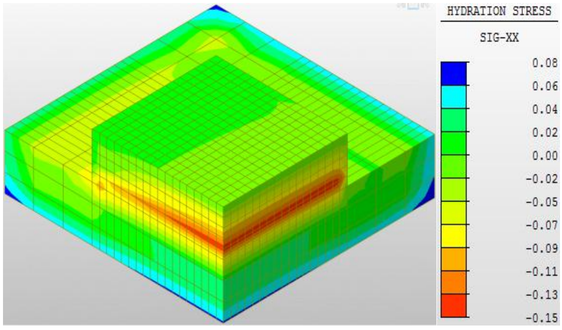


Fig. 11 Hydration stress distribution at stage 5 (after 5 hours of casting)

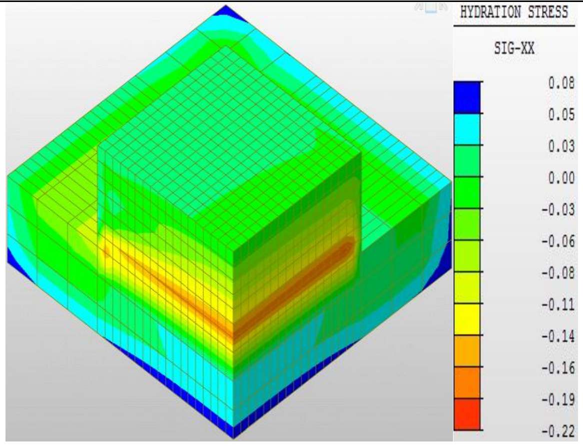


Fig. 12 Hydration stress distribution at stage 7 (after 7 hours of casting)

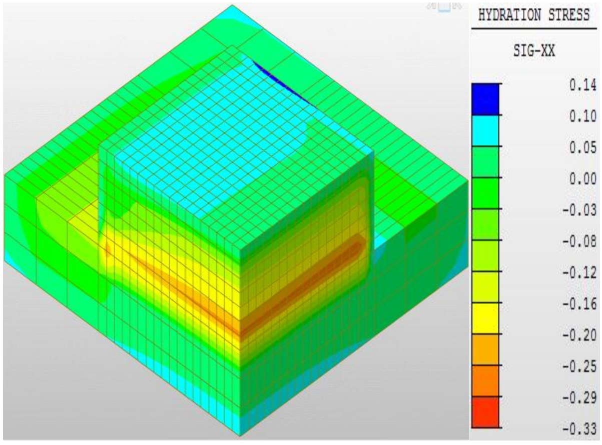


Fig. 13 Hydration stress distribution at stage 8 (after 10 hours of casting)

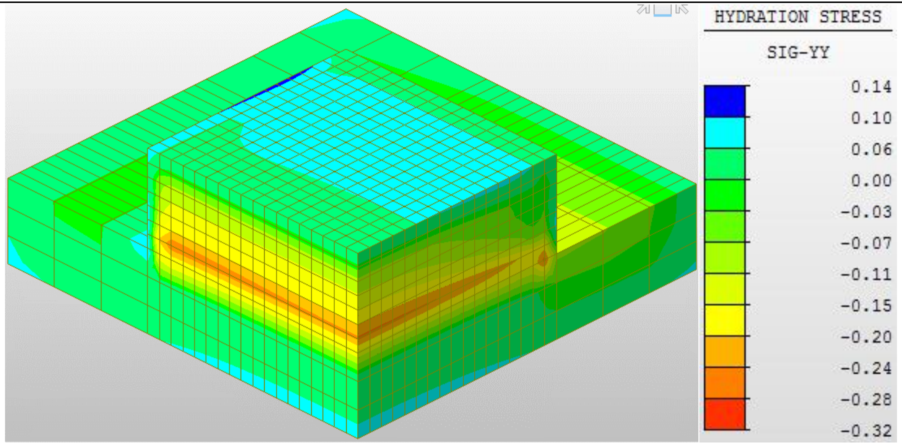


Fig. 14 Hydration stress distribution at stage 8 (after 15 hours of casting)

**Time history graph of hydration stress are shown as below:**

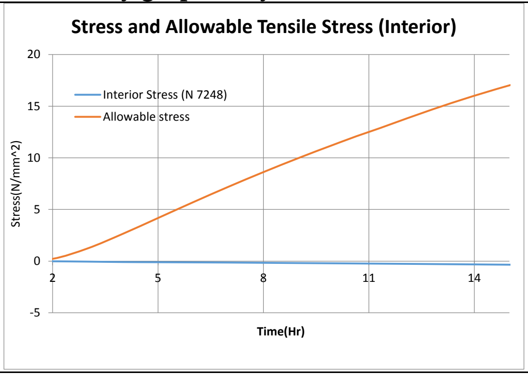


Fig. 15 Time history graph of hydration stress at interior

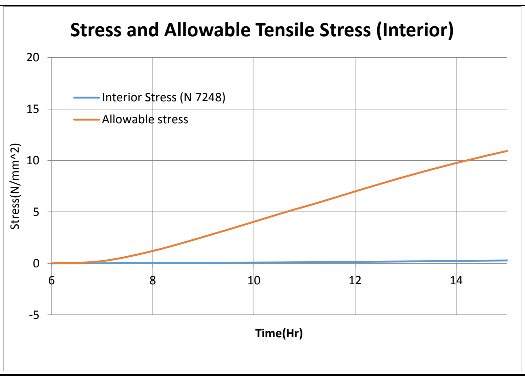


Fig. 16 Time history graph of hydration stress at surface

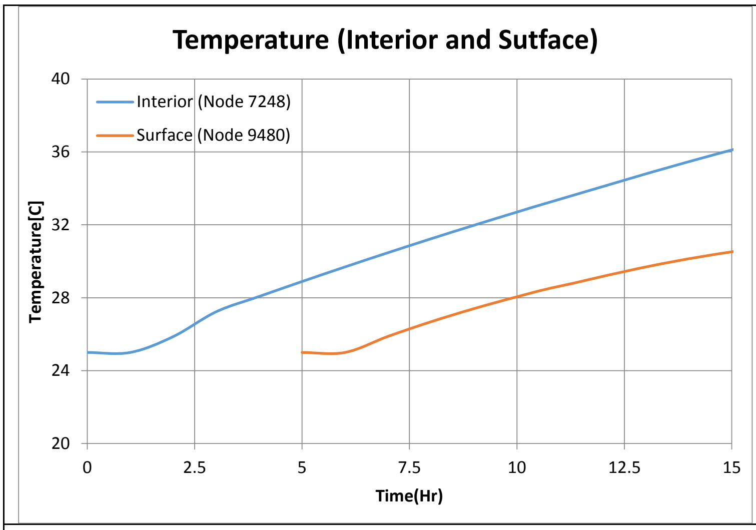


Fig. 17 Time history graph of temperature

## III. Conclusions:

The study aimed at characterizing the hydration phenomenon of early stage concretes is proposed in this work. It emphasizes the role of hydration temperature to describe the evolution of the hardening process. After the analytical formulation of the hydration and heat transfer derivations, a consistent numerical solution based on the Finite element technique for the mass concrete. Then, in order to consider structural applications dealing with the thermal problems, the same constitutive relationships are considered within a general Finite Element (FEM) procedure. Numerical comparisons without cooling pipe system and with cooling pipe system tests performed for rapid hardening cement based concretes establish the soundness and capability of the given application.

1. In a certain concrete structure with considerable mass or where a construction progresses rapidly with a number of construction joints, the rate and amount of heat generation due to hydration are important.
2. Non-uniform thermal expansion and contraction due to heat of hydration and cooling of concrete accompanied by changing constraints create undesirable stresses.
3. The stresses may cause detrimental cracking in the concrete, thereby reducing its strength and durability. Control the temperature and temperature stress is the ultimate point of prevent cracks of mass concrete.
4. So the mass concrete with cooling pipe is reduced the temperature from core surface by 38%, it can realize dual control of temperature and temperature stress; it is feasible as an auxiliary method of temperature control and management wide application in the similar projects.

The simulation analysis of finite element procedure can realise the integration between modern technical measures of actual project.

## Reference:

[1]. Alberto C, Paul H, Kohan, Ricardo D. Q, Mario A. Numerical Modeling Of Hydration Process And Temperature Evolution In Early Age Concrete, Computational Mechanics Vol XXXI, 2012, p. 13-16

[2]. Li JY, Zhou CL, Meng ZP. New concrete techniques of special construction. Beijing: Chemical Industry Press; 2007.

[3]. Wang TM. Control theory and practice of crack in super-long and super-thick large-volume reinforced concrete structure crack. In: Han SF, Geng WS, editors. Control instruction of reinforced concrete structure crack, Beijing: Chemical Industry Press; 2006, p.19-60

[4]. Zhang YP. Study of simulation and temperature crack control in mass concrete of high-rise buildings foundation. Beijing: Hebei University of Engineering; 2007.

[5]. Pan DW, Jin BF, Nie FH. Construction of flat plate raft foundation project of century wealth center. In: Han SF, Geng WS, editors. Control instruction of reinforced concrete structure crack, Beijing: Chemical Industry Press; 2006, p. 267—274

[6]. Fu WQ, Han SF. Prevention and control of concrete project crack. In: Han SF, Geng WS, editors. Control instruction of reinforced concrete structure crack, Beijing: Chemical Industry Press; 2006, p. 213—242