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# EARLY AGE THERMAL CRACK CONTROL IN MASS CONCRETE

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**Abstract:** Early age thermal cracking due to temperature differential is one of the major issues related to mass concrete construction. Temperature differential is created due to heat of hydration of cement and heat loss from the surface. If induced tensile stresses due to temperature differential exceed tensile strength of concrete, concrete tends to crack. Current practice in the local construction industry is to limit the temperature differential to 20ºC irrespective of the grade of concrete. A Finite Element Model (FEM) was developed using ANSYS to predict early age thermal stress behavior. Appropriate position of thermocouples to measure the temperature differential in mass concrete was also proposed based on a thermal analysis using FEM. Limiting values for the temperature differential were proposed based on analytical methods to minimize the risk of thermal cracking.

**Keywords:** early age; FEM; mass concrete; thermal cracking;

## 1. Introduction

The temperature in concrete increases during the early age due to heat of hydration of cement. Fresh concrete expands freely, without any restraints during heating because, concrete is at semi-liquid state. Since fresh concrete is hardened at an elevated temperature, contraction occurs during cooling under restraint condition [1]. Surface zone is cooling faster relative to core of a concrete element due to low thermal conductivity of concrete and higher rate of hydration process at the core [2] creates a temperature differential between surface and the core. Therefore, surface zone contracts relative to the core causing development of tensile stresses at the surface zone due to internal restraints of the element. If those tensile stresses exceed the tensile strength of concrete, concrete cracks. Therefore, it is important to control thermal stresses by limiting temperature differential in mass concrete to prevent early age thermal cracks due to temperature differential.

At present, the local industry is specifying 20˚C as the limiting value for temperature differential irrespective of the grade of concrete. Using inappropriate value for the maximum allowable temperature deferential affects the construction process of mass concrete elements such as time of removal of formwork and thermal insulation. Therefore, it is important to determine the limiting value for the temperature differential under local conditions. It is also important that monitoring the temperature variation with time during mass concrete construction to ensure that the temperature differential is maintained within the limiting value.

The main aim of this research is to determine a suitable limiting value for the temperature differential in mass concrete and to propose the location where adiabatic condition can be expected in a mass concrete element so that the thermocouple can be located to measure maximum core temperature. Two separate finite element (FE) models were developed using ANSYS to achieve above tasks.

## 2. FEM used to predict early age thermal stresses in mass concrete

The center element of a mass concrete volume was modelled in ANSYS. Two FE models, thermal and structural, were combined to obtain early age thermal stress behavior with time in mass concrete. The maximum tensile stress at each time step was compared with tensile strength of concrete at that time to estimate the probability of cracking.

### 2.1 Finite element model for thermal analysis

Predicting accurate temperature distribution of a concrete volume is complex due to complexity of models for heat generation, specific heat capacity, conductivity and convection. Since the aim of this research is to obtain limiting temperature differential, a parabolic variation of temperature across the depth of a section of the concrete volume was assumed. To verify the FE model, a set of measured temperature data across the depth of a raft foundation (2.5m thick) was assigned to each node of the FE model at different time steps assuming parabolic variation as shown in Figure 1. Output file was generated which is an input for the structural analysis using following parameters [3].

- Element type: SOLID70
- Specific heat capacity – 0.23 kcal/kg.°C (962.96 J/kg.K)
- Conductivity – 55.2 kcal/m.day.°C (2.67 W/m.K)
- Density – 2300 kg/m³

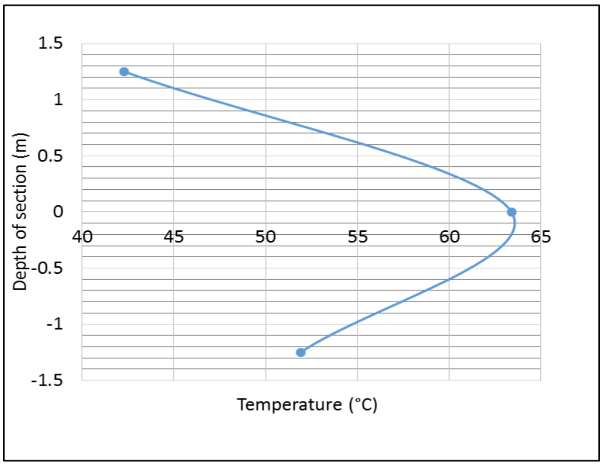


Figure 1: Temperature distribution across the depth of a 3m thick block at 7 days

### 2.2 Finite element model for structural analysis

Behavior of mechanical properties of mass concrete is also complex and critical at early age. Modulus of elasticity and tensile strength are the governing mechanical properties in calculation of stresses and predicting cracking. Coefficient of thermal expansion and Poisson's ratio are the two physical properties required in thermal stress analysis. These properties may depend on material properties of constituent materials and grade of concrete. Since there is no such material model for early age concrete which is suitable for local conditions, material model given in European Standards EN 1992-1-1 [4] was adopted. Temperature distribution was imposed as a thermal load and static analysis was conducted changing material properties with time by using a 'macro' in ANSYS. Output of the structural analysis is the stress distribution due to applied thermal load.

### 2.3 Material model

#### 2.3.1 Modulus of Elasticity and Creep

Since modulus of elasticity depends on age of concrete, material model given in EN 1992-1 [4] was used initially. It was observed that the tensile stresses obtained from FE analysis were higher than what was expected. The material model for modulus of elasticity given in EN 1992-1-1 [4] was compared with test data (see Figure 2). It can be seen that there is a significant difference between the test data and the values given by EN 1992-1-1 [4] material model. Therefore, test data of modulus of elasticity was used in the FE model.

Creep is very important factor for concrete at early age, because significant reduction in thermal stresses occurs due to creep relaxation reducing the probability of cracking at early age. Effect of creep was taken into account in the analysis by introducing effective elastic modulus given by Eq. 1 [5].

$$E_{cm,ef}(t,t_o) = \frac{E_{cm}}{1+\psi(t,t_o)} \qquad (1)$$

Creep coefficient ($\psi(t,t_o)$) was calculated according to EN 1992-1-1-Appendix B [4].

Variation of modulus of elasticity and effective modulus of elasticity with time based on EN 1992-1-1 [4] and test data are given in Figure 2.

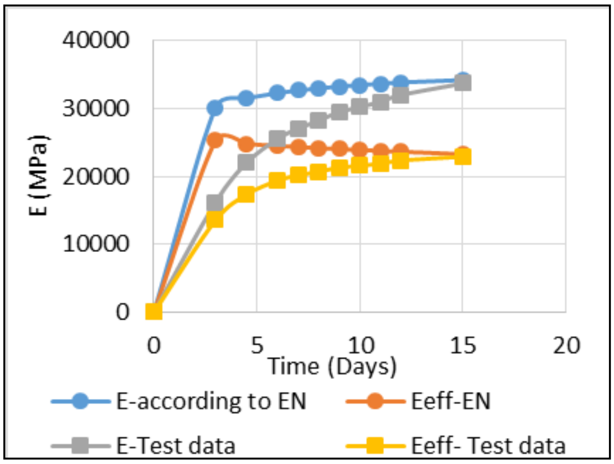


Figure 2: Modulus of Elasticity variation with Time

2.3.2 Tensile strength

Tensile strength of concrete also depends on the concrete grade and age. EN 1992-1-1 [4] material model for tensile strength was used initially but there is a significant difference between test data and material model prediction as shown in Figure 3. Therefore, test data was used to validate the FE model.

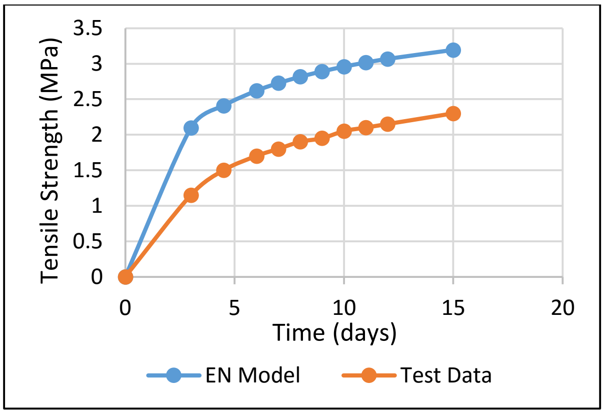


Figure 3: Tensile Strength variation with Time

2.3.3 Coefficient of thermal expansion

A constant value for coefficient of thermal expansion, $10 \times 10^{-6} K^{-1}$ [4], was used in the analysis.

2.3.4 Poisson's ratio

A value of 0.2 as given in EN 1992-1-1 [4] was used as the Poisson's ratio of concrete

**2.4 Boundary conditions**

Since one half of the raft foundation was modelled considering symmetry as shown in Figure 4, plane of symmetry was restrained perpendicular to the plane (in X direction). Base of the block was restrained against upward movement (in Y direction). Top and one vertical face were assumed to be exposed to the environment without restraints. Other two vertical planes were restrained in perpendicular to the plane (in Z direction) assuming no movement compared to other two directions of that plane.

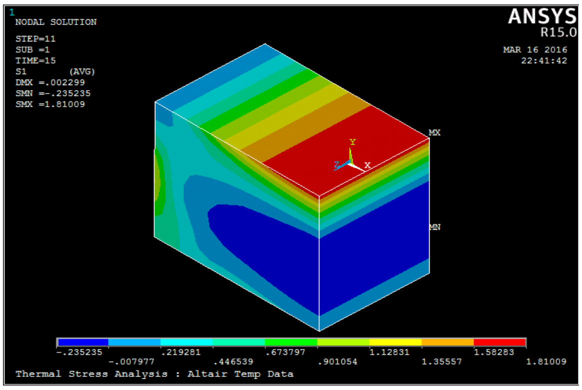


Figure 4: Thermal Stress distribution of the block at day 15

## 3. FEM to find the minimum size of test block to obtain adiabatic temperature rise in a mass concrete block

A concrete mockup was modeled using ANSYS Workbench. Rate of heat generation with time as shown in Figure 5 was used to obtain the rise of temperature. Convection coefficient was used as thermal boundary condition to idealize the heat loss to the

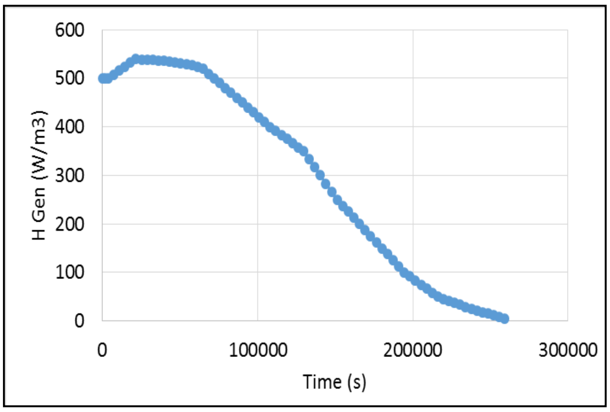


Figure 5: Rate of heat generation with time used to simulate temperature rise

environment [6]. Density, specific heat capacity and conductivity of concrete were used as input parameters as shown in Table 1 which were found in literature [3] and Transient Thermal Analysis was conducted to obtain the temperature distribution.

### 3.1 Procedure

The FE model was analyzed with the same set of heat generation data. Size of mockup, convection coefficient and conductivity were used as variables given in Table 1.

Table 1: Properties used for the FE model

| Property | Value |
|---|---|
| Density | 2300 kg/m3 |
| Specific Heat Capacity | 900 J/kg.K |
| Conductivity | 2 - 3 W/m.K |
| Convection Coefficient | 0 – 25 W/m$^2$.K |
| Mockup Size | 2x2x2m – 6x6x6m |
| Ambient temperature | 30°C |

Convection was applied for all faces of the mockup and maximum temperature at the core was obtained for each case by analyzing the FE model. Adiabatic temperature rise due to heat of hydration was obtained assigning convection coefficient as zero. Maximum temperature vs Convection coefficient graphs were plotted. Shortest dimension to the center of the mockup that gives the maximum temperature rise close to the adiabatic temperature rise was obtained for every convection coefficient.

## 4. Results and Discussion

### 4.1 Prediction of early age thermal stresses

The raft foundation which was used to validate the FE model was protected against heat loss by insulating and found no cracks at early age. Therefore, the tensile stresses obtained by the FE analysis at any time should be less than tensile strength of concrete at that time. But, higher tensile stresses than the tensile strength of concrete were observed between 3.5 days and 12 days when EN 1992-1-1 [4] material model was used. Since it was observed that the test data are quite different with EN 1992-1-1 [4] material model, FE model was analyzed with test data including effective elastic modulus calculated according to EN 1992-1-1 [4]. Still higher stresses were obtained with the FE analysis as shown in Figure 6. Restrained Stresses of the raft foundation were calculated manually according to Eq. 2 and Eq.3 [7]. Calculated restrained stresses based on the Eq. (2) and Eq.(3) are less than stresses obtained by FEM as well as actual tensile strength of concrete as shown in Figure 6. Since there were no cracks observed in the raft, calculated stresses using equations (2) and (3) can be considered as satisfactory. Therefore, based on equation (2), maximum allowable temperature differentials were calculated for different grades of concrete and given in Table 2. Tensile strain capacity for different grades were calculated based on the recommendations given in reference [7].

$$\varepsilon_r = K_1 \Delta T . \alpha_c R \tag{2}$$

Where; $\Delta T$ =9.6, 16.9, 19.7, 21.1, 20.3, 19.3, 17.9, 16.1, 15.4 and 9.7 in °C at ages 3, 4.5, 6, 7, 8, 9, 10, 11, 12 and 15 days.

$K_1$ = Coefficient for the effect of stress relaxation due to creep = 0.65 (for 35% relaxation)

R = Internal restraint factor = 0.42

$$\sigma_r = E_t \varepsilon_r \tag{3}$$

Where; $E_t$ is the elastic modulus of test data at time t as shown in Figure 2.

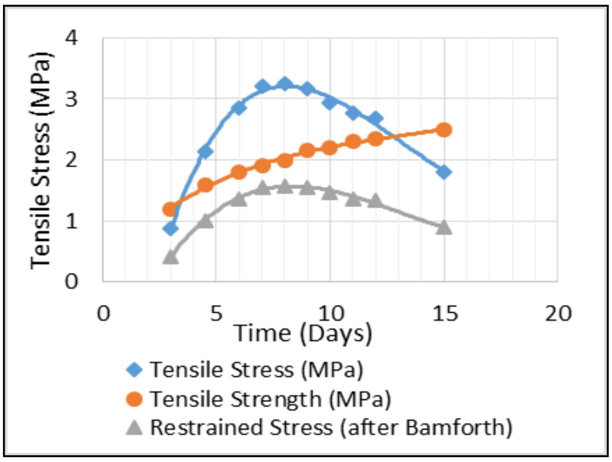


Figure 6: Tensile Stress obtained by FE analysis, Tensile Strength and Restrained Stress variation with Time

Based on equation (2), maximum temperature differential $\Delta T_{max}$ is given by,

$$\Delta T_{max} = \frac{3.7\varepsilon_{ctu}}{\alpha_c} \quad (4)$$

Where; $\varepsilon_{ctu}$ = Tensile strain capacity under sustained loading

Assuming Granite as the aggregate type, $\varepsilon_{ctu}$ values for different grades of concrete were calculated as follows [7].

For strength class C30/37, $\varepsilon_{ctu}$ = 75 microstrain

For other classes (20MPa < $f_{ck,\ cube}$ < 60MPa), $\varepsilon_{ctu}$ value obtained for class C30/37 was multiplied by 0.63 + ($f_{ck,\ cube}$ /100) as recommended in reference [7].

Table 2: Maximum allowable temperature differentials calculated for different grades of concrete

| Concrete Grade | C30/37 | C35/45 | C40/50 | C50/60 |
|---|---|---|---|---|
| Tensile strain capacity under sustained loading ($\varepsilon_{ctu}$) | 75 | 81 | 85 | 92 |
| $\Delta T_{max}$ (°C) | 28 | 30 | 31 | 34 |

**4.2 Location of maximum (adiabatic) temperature**

Adiabatic temperature was obtained as 66.84°C by assigning convection coefficient as zero for each size of mockup. It can be observed that, when the conductivity of concrete is 2W/mK and mockup size is 5mx5mx5m, the maximum temperature at the core is almost equal to the adiabatic temperature as shown in Figure 7 (difference is 0.02°C). As it can be seen in Figure 8, when the conductivity is 3W/mK, for the same case, the difference between adiabatic temperature and core temperature is 0.15°C. But, when the mockup size is 6mx6mx6m the difference is reduced to 0.02°C.

Therefore, adiabatic condition of a concrete volume can be expected at a point where 2.5m inside from all boundaries with a considerable accuracy.

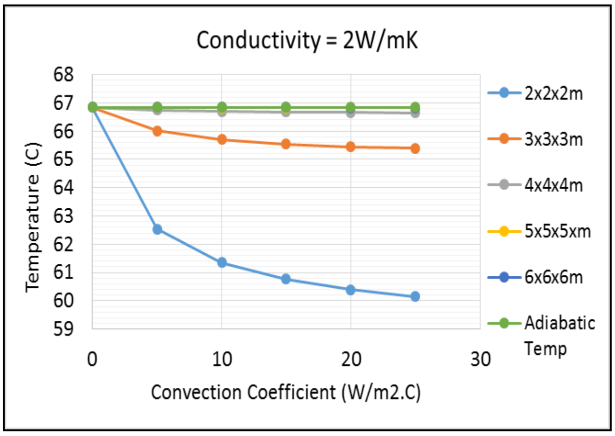


Figure 7: Temperature at the core for Conductivity of 2W/mk

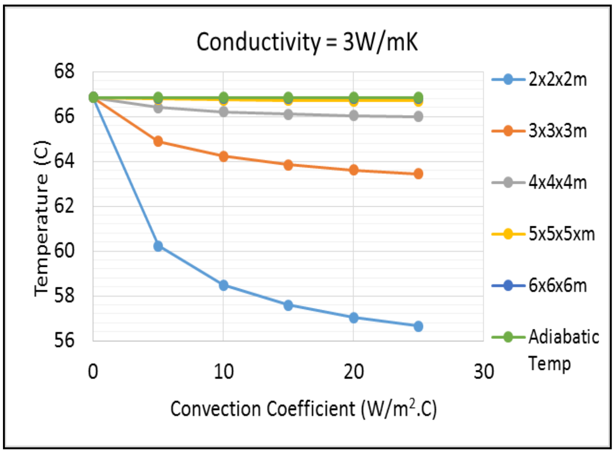


Figure 8: Temperature at the core for Conductivity of 3W/mK .

## 5. Conclusions

- FE model developed to predict early age thermal behavior of mass concrete based on the material models given in EN 1992-1-1 [4] gives higher tensile stresses than the actual tensile stresses.
- Limiting values for temperature differentials for different grades of concrete were proposed assuming thermal properties of granite given in literature. Experimental investigations should be carried out to obtain

appropriate thermal properties of local aggregates.

- Near adiabatic condition of a concrete block can be expected at a point where 2.5 m inside from all exposed boundaries.

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