Limiting Values for Temperature Differentials to Control Early Age Thermal Cracking of 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 and to propose limiting value for the temperature differential for different grades of concrete. An analytical method was also considered to obtain the limiting values for temperature differentials for different grades of concrete.

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 (Harrison, 1992). 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 (Lawrence, 2009) 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.

2 PROBLEM STATEMENT

At present, the local industry is using 20℃ 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 realistic limiting values for the temperature differential for different grades of concrete with local materials.

3 METHODOLOGY

- A FEM was developed using ANSYS software package to analyze the thermal stresses in mass concrete under given temperature distribution.
- A set of test results was used to verify the FEM.
- An analytical method proposed by Bam forth, 2007 was also considered to propose limiting value for the temperature differential for different grades of concrete.

4 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.

4.1 *Finite element thermal model*

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 2.5m thick raft foundation was used. Measured temperature data was assigned to each node of the FE model at different time steps assuming parabolic variation of temperature distribution as shown in Figure 1. Output file was generated

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which is an input for the structural analysis using following parameters (Kim, 2010).

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

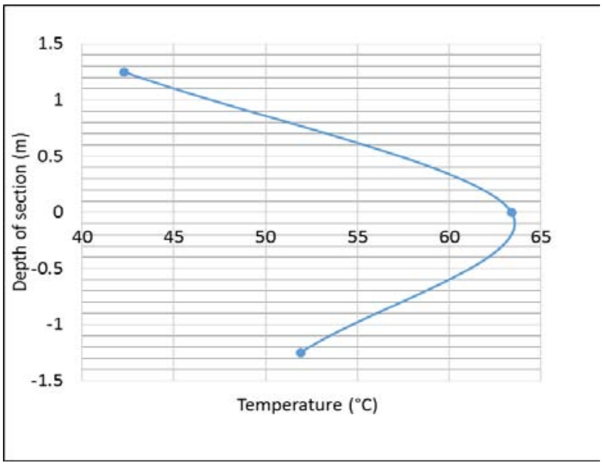

Fig. 1 Temperature distribution across the depth of the block at 7 days

4.2 *Finite element structural model*

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 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.

4.3 *Material model*

4.3.1 *Modulus of elasticity and creep*

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

Creep is very important for concrete at early age, because significant reduction in thermal stresses occurs due to creep relaxation. Therefore, probability of cracking at early age reduces. Effect of creep was taken into account by introducing effective elastic modulus given by Eq. 1 (Nesset et al., 2007).

$$E_{cm,eff}(t,t_0) = E_{cm}/(1+\psi(t,t_0)) \qquad (1)$$

Where E_{cm} is the elastic modulus, $E_{cm,eff}(t,t_0)$ is the effective elastic modulus and $\psi(t,t_0)$ is the creep coefficient.

Creep coefficient was calculated according to EN 1992-1-1-Appendix B. Variation of modulus of elasticity and effective modulus of elasticity with time based on EN 1992-1-1 and test data are given in Figure 2.

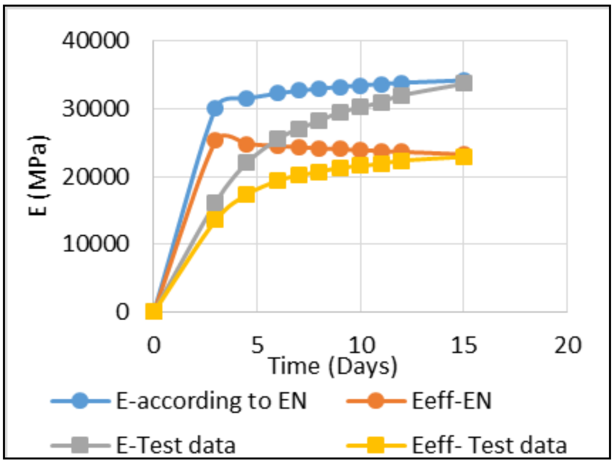

Fig. 2 Modulus of Elasticity variation with Time

4.3.2 *Tensile strength*

Tensile strength of concrete also depends on the grade and age. EN 1992-1-1 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.

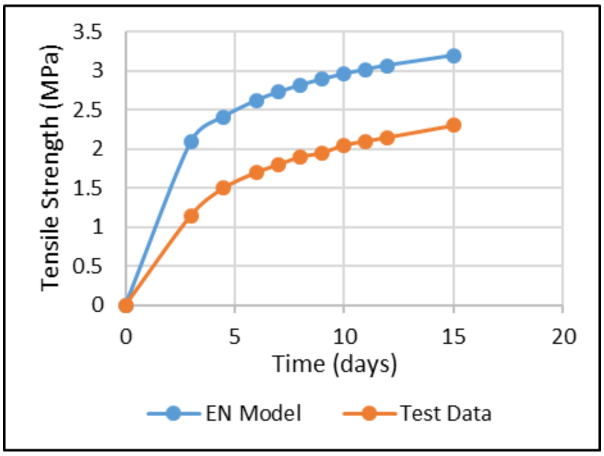

Fig. 3 Tensile Strength variation with Time

4.3.3 *Coefficient of thermal expansion and Poisson's ratio*

A constant value for coefficient of thermal expansion, 10x10-6K^{-1} given in EN 1992-1-1 was used in the analysis.

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

4.4 *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.

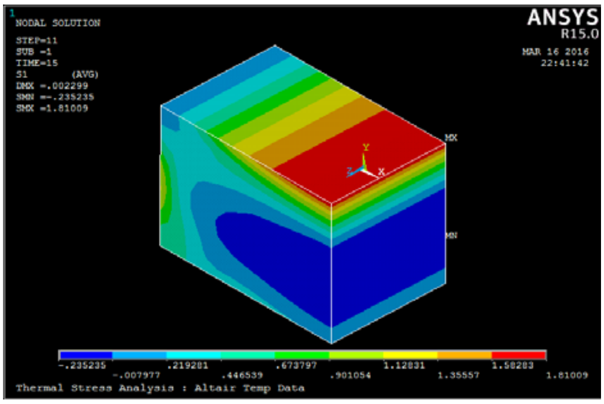

Fig. 4 Thermal Stress distribution of the block at day 15

5 RESULTS AND DISCUSSION

The raft foundation which is 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 a given 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 material model was used. Since it was observed that the test data are quite different with EN 1992-1-1 material model, FE model was analyzed with test data including effective elastic modulus calculated according to EN 1992-1-1. Still higher stresses were obtained with the FE analysis as shown in Figure 5. Therefore stresses of the raft foundation due to internal restraint were calculated using simplified analytical method given by Eq. 2 and Eq.3 (Bamforth, 2007).

$$\varepsilon_r = K_1\ \Delta T \alpha_c R \quad (2)$$

$$\sigma_r = E_t \varepsilon_r \qquad (3)$$

where

ε_r - the restrained strain

ΔT – Temperature differential between centre and the surface

R - the internal restraint factor = 0.42

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

α_c - the coefficient of thermal expansion in concrete = 10 microstrain/°C (Bamforth, 2007)

σ_r – the restrained stress

E_t – the modulus of elasticity at time t

For the temperature data and E_t given in Table 1, calculated stresses based on the Eq. (2) and Eq.(3) are shown in Figure 5. It can be seen that calculated stresses based on Eq (2) and (3) are less than stresses obtained by FEM as well as actual tensile strength of concrete. 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 ε_{ctu} for different grades were calculated based on the recommendations given by Bamforth (2007).

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Table 1 Measured ΔT and E_t for different ages

Age (days)	ΔT (°C)	E_t (MPa)
3	9.6	16200
4.5	16.9	22000
6	19.7	25500
7	21.1	27069
8	20.3	28200
9	19.3	29500
10	17.9	30200
11	16.1	31000
12	15.4	32000
15	9.7	33700

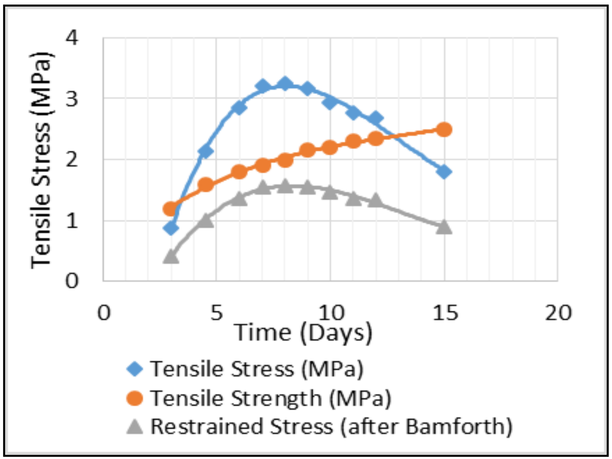

Fig. 5 Tensile Stress obtained by FE analysis, Tensile Strength and Restrained Stress variation with Time

Based on equation (2), maximum temperature differential ΔT_{max} is given by equation (4),

$$\Delta T_{max} = 3.7\, \varepsilon_{ctu}/\alpha_c \qquad (4)$$

Where ε_{ctu} is the tensile strain capacity under sustained loading

Assuming Granite as the aggregate type ε_{ctu} values for different grades of concrete were calculated as follows.

For strength class C30/37, ε_{ctu} = 75 micro strain (Bamforth, 2007)

For other strength classes (20MPa < $f_{ck,\ cube}$ < 60MPa), ε_{ctu} value for class C30/37 was multiplied by the factor 0.63 + ($f_{ck,\ cube}$ /100) as recommended by Bamforth (2007).

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 (ε_{ctu})	75	81	85	92
ΔT_{max}(°C)	28	30	31	34

6 CONCLUSIONS

- FE model developed to predict early age thermal behavior of mass concrete based on the material models given in EN 1992-1-1 gives higher tensile stresses than the actual tensile stresses.
- Further analysis should be conducted using viscoelastic material models considering effects on mechanical properties of concrete due to temperature.
- 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 and mechanical properties of concrete with local aggregates.

ACKNOWLEDGMENTS

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