The Temperature Field in Mass Concrete with Different Placing Temperatures

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Abstract Hydration heat of concrete mix has an important role in the process of temperature increase in mass concrete at an early age. Thermal stress caused by the temperature difference between the core and the surface of mass concrete is the main reason in making thermal cracks if the stress is larger than the tensile strength of concrete. The aim of this study is to investigate the effect of placing temperature on temperature distribution and thermal stresses of mass concrete. A proportion of concrete mix of interest is used for the thermal analysis of a mass concrete sample sized 8×6×3 m. The finite element Midas Civil program is used to conduct the three-dimensional thermal simulation. Four typical scenarios of placing temperature in the range of (15-30)°C of the concrete mix, which is commonly used in actual construction condition, are presented. The analysis results of temperature distribution and thermal stress indicate that the value of 30°C of placing temperature according to the selected proportion of concrete mix may cause thermal crack in the mass concrete. The study gives a useful way for practical construction application to avoid the risk of thermal crack in mass concrete at an early age.

Keywords Maximum Temperature, Temperature Difference, Mass Concrete, Placing Temperature, Thermal Crack

1. Introduction

Mass concrete are normally used for hydraulic structures, bridge, foundation of high-rise buildings, and etc. One of the significant factors affecting the stress-strain state of the concrete mass during construction and operational process is temperature effect due to hydration heat of cement [1-3].

The temperature regime in mass concrete structures is

affected by many factors, such as air temperature, wind speed, water temperature, intensity of solar radiation and shading effect, foundation temperature, and especially amount of hydration heat which is caused by the cement type and its content [4-6].

In addition, the temperature distribution in the mass concrete is also influenced by other factors, such as schedule of placement, aggregate size used in mass concrete, initial temperature of concrete mix, curing condition, etc. As a result, high temperature gradient occurring during the construction may cause significant tensile stresses and lead to thermal cracks [7-9].

The temperature difference between the inner zone and the outer surface of the mass concrete is the reason causing the formation of thermal stress. If the tensile stress is larger than the tensile strength of the mass concrete, thermal cracks form on the surface of the concrete structure, especially at the early age. In order to avoid the formation of thermal cracks, a general condition is that the temperature gradient ΔT should not exceed 20°C [10].

On other aspect, to minimize the temperature difference between the inner zone and the outer surface of mass concrete causing thermal cracks, past researches indicated several curing methods by using different types of insulation material together with its thickness, such as polystyrene [11], sand layers [12]. In addition, cooling pipe system is quite a perfect solution to reduce hydration heat in the core of mass concrete [13].

In the present study, effect of the placing temperatures causing different temperature gradients between inner and outer zones of mass concrete is investigated. The temperature profile versus time and its maximum value together with thermal stresses in mass concrete corresponding to different scenarios of placing temperature are simulated by using the finite element Midas Civil program. From the analysis results, it is proposed an appropriate value of placing temperature to

control the risk of thermal cracks in mass concrete at early and best suit the actual construction conditions.

2. Materials and Methods

2.1. Object of Research

A 3D model of the concrete mass body sized $8 \times 6 \times 3$ m and laid on the foundation sized $16 \times 12 \times 4$ m is modelled. To increase the speed of the simulation, a half of the symmetry model is used to simulate the scenarios of placing temperature as shown in Figure 1. The mesh of the model is divided into 1920 elements and 2509 nodes. It is noted that the element size of the model is carefully selected and fine enough based to get acceptable accuracy results on a parametric study.

Figure 1. 3-D thermal analysis model for concrete mass, unit m

For the definition of contact at the interface of mass

concrete and foundation, a defaulted contact option available in the FE program is used to simulate perfectly conductance between two solid objects through this contact. The temperature difference between the node at center and node at the surface of the concrete mass is affected by the convection coefficient on concrete-air interface. The convection coefficient can be adopted by the proposed empirical equation (1) [14,15]:

$$h_c = \begin{cases} 5.6 + 3.95v, & v \leq 5 \text{ m/s} \\ 7.6v^{0.78}, & v \geq 5 \text{ m/s} \end{cases} \quad (1)$$

where: v - the wind speed, m/s.

In this research, a constant value of convection coefficient on the formwork-concrete surface of mass concrete and the average air temperature are assumed to be $12 \text{ kcal/m}^2\text{h}^\circ\text{C}$ and 30°C , respectively. To investigate the effects of placing temperature on the temperature regime in mass concrete, four scenarios of concrete placing temperature, corresponding to 15°C , 20°C , 25°C , and 30°C , are proposed. It is seen that these placing temperatures above spread in a range of placing temperature that is commonly used in actual construction condition. The composition of concrete mix of interest used to describe the development of temperature versus time of the mass concrete are presented in Table 1.

Hydration heat is generated by the products of chemical reactions during hydration of Portland cement with water. Hydration heat is very important factors because it is used as source of heat in concrete mass. The hydration power of concrete mix is shown in Figure 2 [16]. And, the thermal characteristics of concrete used for the analysis are shown in Table 2.

Table 1. Mix proportion of concrete [16]

Material, kg/m ³					
Cement	GGBF Slag	Fly Ash	Water	Aggregate.	
				Fine	Course
202	202	0	202	645	990

Table 2. Important parameters of concrete and foundation

Important parameters	Concrete	Foundation
Thermal conductivity coefficient, k [W/(m. $^\circ\text{C}$)]	2.9	2.1
Specific heat, C [kJ/(kg. $^\circ\text{C}$)]	1.12	0.85
Specific weight, ρ [kg/m ³]	2400	2600
Coefficient of thermal expansion, [1/ $^\circ\text{C}$]	1×10^{-5}	1×10^{-5}
Poisson's ratio	0.2	0.3
Elastic modulus, N/m ²	2.5×10^{10}	1.8×10^{10}

Figure 2. Hydration power of concrete mix

2.2. Finite Element Method to Solve the Thermal Model

The solution of the thermal problem is based on the differential equation of the heat conduction theory [17-20]:

$$k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q_v = \rho c \frac{\partial T}{\partial t}, \quad (2)$$

where: k - thermal conductivity of materials, $W/m^\circ C$;

c - specific heat, $kJ/(kg \cdot ^\circ C)$;

q_v - the rate of thermal energy generated per unit volume, W/m^3 ;

ρ - density, kg/m^3 ;

t - age of concrete at the time, day.

To solve equation (2) it is necessary to apply the boundary condition as given by equation (3) [21, 22].

$$k \left(\frac{\partial T}{\partial x} n_x + \frac{\partial T}{\partial y} n_y + \frac{\partial T}{\partial z} n_z \right) + q_v = 0 \quad (3)$$

where: n - vector normal to the direction of heat transfer.

Finite element method to solve the problem of heat transfer is expressed by the equations as follows [23, 24]:

$$[K]\{T\} + [C]\left\{\frac{\partial T}{\partial t}\right\} = [Q], \quad (4)$$

Time interval for the steps Δt can be described as follows:

$$\left\{\frac{\partial T}{\partial t}\right\} = \frac{1}{\Delta t} [T(t_n) - T(t_{n-1})], \quad (5)$$

Then, the equation (4) can be rewritten as follows:

$$[K]\{T\} + \frac{[C]}{\Delta t} [T(t_n) - T(t_{n-1})] = [Q], \quad (6)$$

where: $[K]$ - the global stiffness matrix at time t_n ;

$[C]$ - capacity matrix;

$[Q]$ - thermal load vector;

$\Delta t = \Delta t_n - \Delta t_{n-1}$ - steps of computation time.

Solving the equation (6) allows to obtain temperature fields in concrete mass at different times. The flow chart of the methodology of finite element analysis for heat transfer problem in mass concrete is given in Figure 3.

Figure 3. The flowchart of the computational temperature fields by FEM

Similarly, the general equilibrium equations of thermal stress depending on space and time, which is calculated in the finite element method [25].

$$[K]\{\Delta \delta\} = \{\Delta Q\}^L + \{\Delta Q\}^C + \{\Delta Q\}^T + \{\Delta Q\}^g, \quad (7)$$

where: $\{\Delta \delta\}$ - displacement increment vector of a time interval Δt ;

$\{\Delta Q\}^L$, $\{\Delta Q\}^C$, $\{\Delta Q\}^T$ and $\{\Delta Q\}^g$ - load increment vectors of external load, creep, temperature and autogenously volume deformation, respectively.

3. Results

The results of the conducted numerical model are shown in Figures 4–7. The adopted temperature distributions in mass concrete with the different cases of placing temperature are described in Figure 4.

(a) - $T_{pl} = 15^{\circ}\text{C}$ (b) - $T_{pl} = 20^{\circ}\text{C}$

(c) - $T_{pl} = 25^{\circ}\text{C}$

(d) - $T_{pl} = 30^{\circ}\text{C}$

Figure 4. Temperature distributions in mass concrete with different cases of placing temperature

Placing temperature has an important effect on the hydration process of concrete mass an early age. The higher placing temperature of the concrete mix, the higher maximum temperature at the core of the concrete block is achieved. The effects of placing temperature on the hardening concrete temperatures are shown in Figure 5. As can be clearly seen, the maximum temperature at the core of the mass concrete is lower when the placing temperature of concrete varies from 30°C to 15°C. The temperature in the core of the concrete block increases fast and gets the peak values at 2-3 days after placement, then the temperature at this location slowly reduces by time. The maximum temperature at the center of the concrete mass, corresponding to the analysis cases T_{pl} of 30°C, 25°C, 20°C, and 15°C are 61.61°C, 57.0°C, 52.51°C, and 48.01°C, respectively.

Figure 5. Temperature development at the centre (node 347) and at the surface (node 7) of the concrete mass

Figure 6. Relation between placing temperature, maximum temperature, and temperature drop in the mass concrete

Figure 6 shows that the maximum temperature and the temperature drop in the concrete block with four cases of placing temperature of concrete mix obtained to the linear lines. So, when increasing 1°C of placing temperature

mixture of concrete, the maximum temperature and temperature difference in the concrete block also approximately increased 1°C.

It is noted that when the placing temperature of the concrete mix exceeds 25°C, the temperature difference between the center and the surface of the concrete block exceeds 20°C. This value is particularly important since many specifications showed that the maximum temperature difference should not exceed the limitation of (15-20)°C to avoid the thermal cracks.

Figure 7. Changes in the thermal stress at node 7 (at the surface of concrete mass)

The surface of the concrete block is the area at which may occur the thermal cracks due to the temperature difference between the center and concrete surface. For more in details, the thermal stress analysis is conducted, the obtained values are presented for the node of interest (node 7) corresponding to different cases of placing temperature as shown in Figure 7.

Figure 7 indicates that the tensile stress on the surface of the concrete block will exceed the allowable tensile stress, corresponding to the case $t_{pl} = 30^\circ\text{C}$. Thus, thermal cracks may form on the surface of the concrete mass in this case. It is recommended to consider the appropriate options to control the exceeded thermal tensile stress, such as reduce the cement content by replacing mineral additives, cooling the mixture before pouring concrete, using cooling pipe and insulation surface.

4. Conclusions

Based on the selected mix proportion of concrete, the analysis results of the study give some conclusions as follow:

1. Based on the selected mix proportion of concrete, the higher placing temperature causes higher maximum temperature in the center of the concrete block.
2. When the placing temperature is higher than 25°C, the maximum temperature difference between the center and the surface of concrete block is higher than the limitation of temperature difference which

commonly varies in the range of 15-20°C to avoid the thermal cracks.

3. The analysis case of $t_{pl} = 30^{\circ}\text{C}$, the high placing temperature causes a tensile stress that exceeds the tensile strength of the concrete and may lead the cracks on the surfaces of the concrete block. It is possible to select one or combined appropriate options to control the thermal stress in the mass concrete block.

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