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The Effects of Insulation Thickness on Temperature Field and Evaluating Cracking in the Mass Concrete

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ABSTRACT: This paper is mainly to study the effects of insulation thickness (0 - 3) cm on temperature field and evaluating cracking in the mass concrete by using Finite Element Midas Civil 2011. The finite element method is developed for simulation analysis of the temperature field in the concrete in early age mass concrete. From the results temperature field and evaluating cracking for the mass concrete it is concluded that insulation with adequate thickness at the face of massive concrete should be used to reduce the temperature differentials and control cracking of early-age concrete. Finally, the results are applied to provide some references for the constructions in the mass concrete such as dams, bridges beams, bridge piers, foundations of bridges and buildings.

KEYWORD: Heat of hydration, temperature gradient, crack, mass concrete, mathematical model

1 INSTRUCTIONS

Mass concrete is defined by American Concrete Institute Committee 207 as "any volume of concrete with dimensions large enough to require that measures be taken to cope with the generation of heat from hydration of cement and attendant volume change to minimize cracking"[1]. Mass concrete structures include massive mat foundations, bridges beams, bridge piers, dams, and other concrete structures [2-4].

Temperature differences within the concrete occur when the heat being generated by the concrete is dissipated to the surrounding environment causing the temperature at the surface of the concrete to be lower than the temperature at the inside of the concrete. Simultaneously, the heat generated is a function of the temperature on time. Therefore, the temperature difference between the center and the outside of the concrete blocks will create tensile stress. If the induced tensile stresses are larger than the early age tensile strength of the concrete, cracking will occur [5-7].

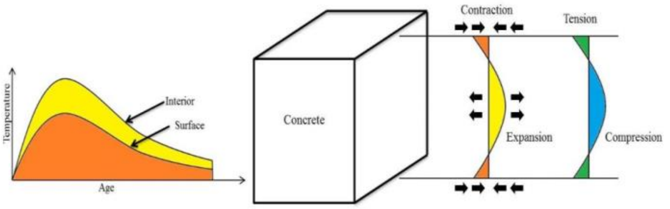

Figure 1. Stress distribution in mass concrete due to temperature differential [8].

The most important factor when analyzing early age thermal stress is the temperature development in the mass concrete [9].

- cement consumption;
- type cement;
- thermal properties of concrete;
- conditions during the placing of concrete (the initial concrete temperature, internal cooling or layered placing of concrete);
- environmental conditions;
- dimensions and geometrical of the mass concrete.

There are several ways to control maximum temperature and control cracking of early-age in the mass concrete, such as reducing the cement content, pre-cooling the concrete mix, using the pipe cooling, the insulation materials etc [10-12].

Surface heat preservation is an important measure for temperature control and cracks prevention. The selection of insulation materials, insulation thickness is particularly important. In this paper to study the effects of insulation thickness on the temperature field and evaluating cracking in the mass concrete [13].

2 MATERIALS AND METHODS

2.1 *Materials*

The mass concrete is designed to be C40 (American ACI standard), self - compacting, flowing 650 mm, using low heat cement, partly cement replaced with fly ash to reduce the quantity cement. The purpose is to reduce the amount of cement used to reduce the amount of hydrothermal heat [14]. The concrete mix design is detailed in Table 1.

Table 1. Mix design of concrete.

W/(C+FA)	C+FA	Materials for 1 m^3 of concrete					
		S (kg)	R (kg)	C (kg)	FA (kg)	W (l)	Additives
42%	385	880	951	289	96	160	1.35%

where: W - Water; C - Cement, FA - fly ash; S - Sand; R - Rock.

Thermal insulators are meant to reduce the rate of heat transfer by conduction, convection, and radiation. The main purpose of surface insulation is not to restrict the temperature rise, but to regulate the rate of temperature drop so as to lower the stress differences due to steep temperature gradients between the concrete surface and the interior [15]. This research paper deals with the study on the thermal behavior of a massive concrete with Insulation (polystyrene). Table 2 the properties of mass concrete, insulation (polystyrene) and the foundation.

Table 2. Material properties in temperature behavior analysis.

Property	**Insulation (polystyrene)**	**Concrete**	**Foundation**
Thermal conduction coefficient, W/(m.°C)	0.029	2.30	2.70
Specific heat, kJ/(kg.°C)	1.13	1.05	0.85
Density, kg/m^3	20	2400	2700
Convection coefficient, W/m^2.°C	30.0	12.0	13.5
Modulus of elasticity, N/m^2	3.0×10^9	2.5×10^{10}	2.0×10^{10}
Thermal expansion coefficient, (1/°C)	1.10^{-5}	1.10^{-5}	1.10^{-5}
Poisson's ratio	0.2	0.2	0.2
The amount of hydration heat of concrete, kJ/kg	-	389	-

2.2 *Finite element method of the temperature field*

According to the results of the study [16-17], the model adopted the following equations (1):

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right)+q=\rho c_\rho \frac{\partial T}{\partial \tau}, \qquad (1)$$

where: T is the material temperature (°C);

λ - is the thermal conductivity, that is, $\lambda_x = \lambda_y = \lambda_z$, dependent on temperature by three directions x, y and z, respectively, (W/m ℃);

q - is the rate of internal heat generation (internal energy), per unit volume (W/m^3);

c_ρ - is the heat capacity (J/kg.°C);

ρ - is the density concrete (kg/m^3);

τ - time (day).

To solve equation (1), it is necessary to know the boundary condition, which is defined as follows [18].

$$T = T_p,\ k_x \frac{\partial T}{\partial x} l_x + k_y \frac{\partial T}{\partial y} l_y + k_z \frac{\partial T}{\partial z} l_z + q + h(T_s - T_f) = 0, \qquad (2)$$

where: T_p - the values of the nodal temperatures on the boundaries (°C);

q - surface heat (kcal/m^3);

h – the film coefficient;

T_s - Temperatures at the boundary nodal points (⁰C);

T_f - the ambient temperature (°C);

l_x, l_y, and l_z - the direction cosines of the outward normal to the surface under consideration on x, y and z-axes respectively

According to the results of the study [19-20], the relation between the heat of hydration and the age may be expressed by the following exponent formula (3):

$$Q(\tau) = Q_0(1 - e^{-m\tau}), \qquad (3)$$

where: Q(τ) - is the accumulated heat of hydration per unit mass of cementations materials (J/kg) at age τ;

Q_0 - is the final heat of hydration as $\tau \to \infty$, and m is an experimental constant related to cement and curing temperature.

The analyses of temperature field in the concrete mass belong to transient thermal analysis, and the form of its matrix is expressed as (4):

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

A classical Euler scheme can be implemented. If we assume the following approximation for the first time derivative of the temperature field [21]:

$$\left\{\frac{\partial T}{\partial \tau}\right\} = \frac{1}{\Delta\tau}\left[\{T(\tau_n) - T(\tau_{n-1})\}\right], \qquad (5)$$

Then (4) is written as follows:

$$[K]\{T\} + \frac{[C]}{\Delta\tau}[\{T(\tau_n) - T(\tau_{n-1})\}] = [Q], \qquad (6)$$

where: [K] - is a conductive matrix;

[C] - is a specific heat matrix, considering increased internal energy;

[Q] - is the heat flow rate of the nodes, including heat generation;

$\Delta\tau = \tau_n - \tau_{n-1}$ - time step calculations.

2.3 *Computation of temperature drop allow in the mass concrete*

The equation (7) is given for allowable temperature drop in the mass concrete in the during construction [22]:

$$\left[\Delta T_{б}^{\max}\right]=\left[\Delta T_{б}^{cp}\right]\kappa_{перех};\left[\Delta T_{б}^{cp}\right]=\frac{\varepsilon_{пр}}{\alpha k_{з}k_{р}k_{тр}}, \qquad (7)$$

where: $k_{перех}$ - is a transition coefficient from the average temperature in the unit during the heat evolution period to the maximum one, ($k_{перех}$ = 1.3 – 1.5);

$\varepsilon_{пр}$ - is the limit compliance concrete;

α - Linear thermal expansion coefficient of concrete;

$k_{з}$ - crushing factor (average);

$k_{р}$ - is the relaxation factor (average);

$k_{тр}$ - a factor of crack formation ignorance.

3 RESULTS

3.1 *Calculation model*

In this study, a 3-dimensional finite element model for mass concrete body sized 10×8×3 m, which lays on the foundation sized 20×12×4 m, is used. A half of the symmetry model is used to increase the speed of the simulation, as can be seen in Figure 2. The model was divided into 1800 elements and 2352 nodes.

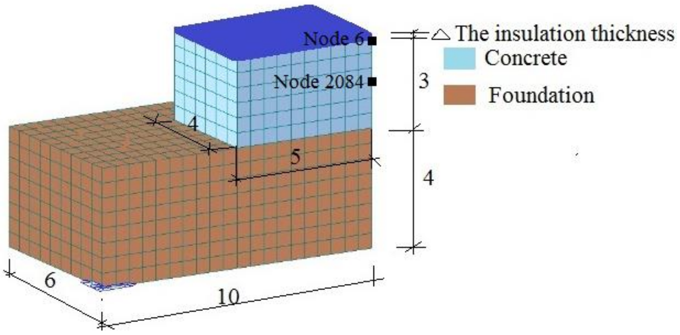

Figure 2. 3-D Finite element model.

The ambient temperature significantly effects on the maximum temperature at the center of the concrete block during the hardening process. This a mass concrete is built in the summer in northern Vietnam with air temperatures are assumed constant 25^{0}C, soil temperature is assumed constant 20^{o}C and temperature of concrete placed 23^{o}C.

3.2 *Analysis results*

The breakdown of the concrete block and the foundation of the array on the final elements of the three - dimensional model is shown in Figure 2. With the help of the computer program Midas civil 2011, the maximum temperature in the mass concrete with insulation thickness differences (0 - 3) cm as shown in Figures 3 - 6.

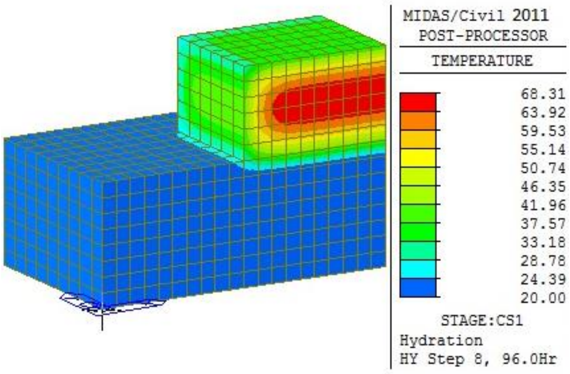

Figure 3. Temperature field in the mass concrete without insulation at 96 hours.

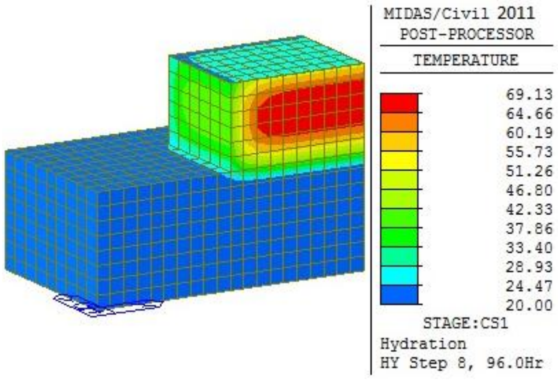

Figure 4. Temperature field in the mass concrete with insulation 1 cm thick layer at 96 hours.

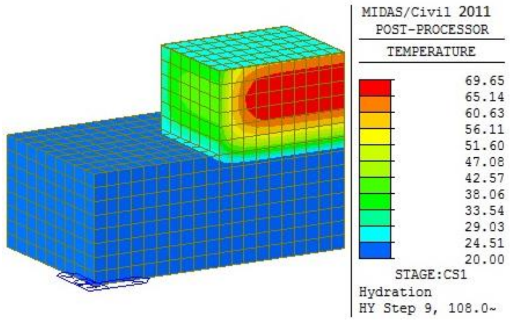

Figure 5. Temperature field in the mass concrete with insulation 2 cm thick layer at 108 hours.

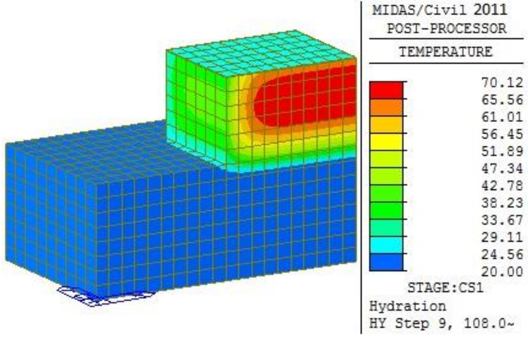

Figure 6. Temperature field in the mass concrete with insulation 3 cm thick layer at 108 hours.

When increasing the insulation thickness, then the maximum temperature in the mass concrete increases. In case 1 (without insulation layer) - maximum temperature is 69.65^{o}C; in case 2 with insulation 1 cm thick layer - maximum temperature is 69.13^{o}C; in case 3 with insulation 2 cm thick layer - maximum temperature is 69.65^{o}C; in case 4 with insulation 3 cm thick layer - maximum temperature is 70.12^{o}C. However, the increase in value maximum temperature is not significant.

Table 3. The maximum temperature, maximum temperature drop and its occurrence time at different thicknesses.

Case	Insulation thickness (cm)			
	0	1	2	3
Maximum temperature (°C)	68.31	69.13	69.65	70.12
Maximum temperature drop (°C)	26.31	16.65	9.54	6.23
Maximum temperature occurrence time (hours)	96	96	108	108

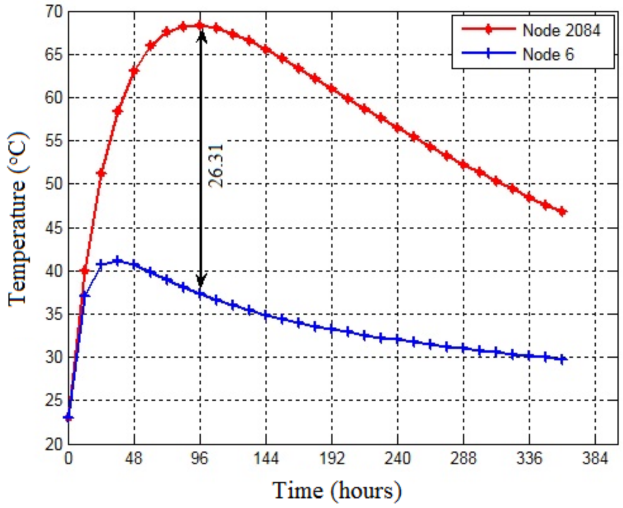

Figure 7. Temperature variation process of two typical points (node 2084 and node 6) without the insulation layer.

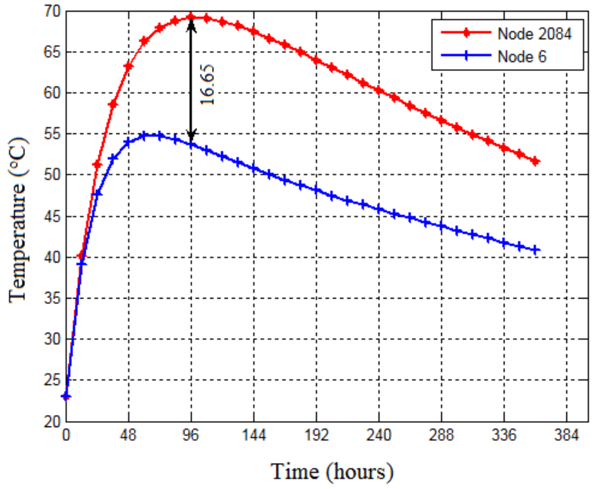

Figure 8. Temperature variation process of two typical points (node 2084 and node 6) with insulation 1 cm thick layer.

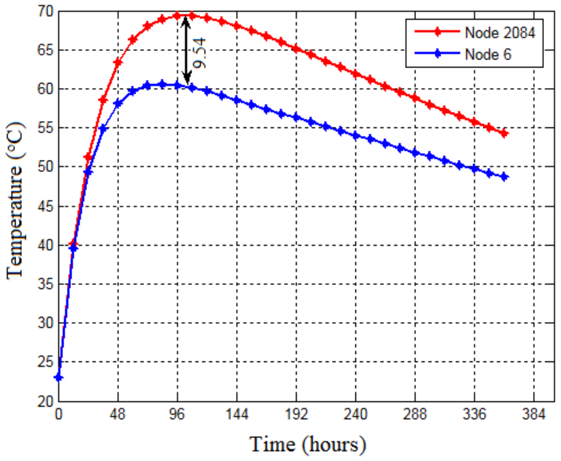

Figure 9. Temperature variation process of two typical points (node 2084 and node 6) with insulation 2 cm thick layer.

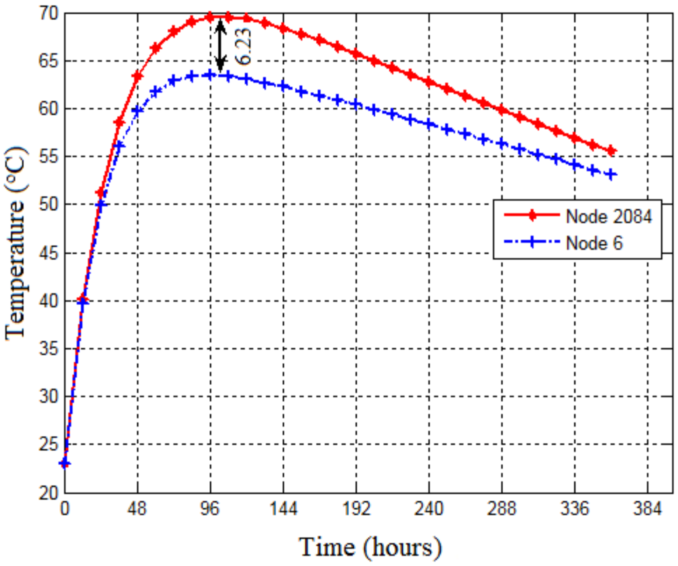

Figure 10. Temperature variation process of two typical points (node 2084 and node 6) with insulation 3 cm thick layer.

Figures 7 - 10 shows that the performance of the concrete improves as the insulation thickness increases. Because when increasing the insulation thickness (0 - 3) cm, then reduce the temperature differentials.

Temperature drop allows in the mass concrete: The thermal expansion coefficient for the concrete mix – M300 was assumed to be $\varepsilon_{пр}$ = 0.9×10^{-4} [22]. This value of 1×10^{-5} is used in the present analysis. For our calculations we take $\alpha = 1\times10^{-5}$. The relaxation coefficient $k_3=f(H/l, E_{con}/E_{bas})$. In the analysis, values of H/l = 0.3; E_{con}/E_{bas} = 1.25 are taken. And, the value k_3 = 0.60 was also indicated in graph 15.6 [22]. The relaxation coefficient $k_p = f(\tau_o, \tau_k, \Delta\tau)$ can be adopted from graph 15.5 [22], and is equal to 0.90. Then, the value of ΔT_6^{max} maximum is calculated as follow:

$$\left[\Delta T_6^{cp}\right] = \frac{0.9\times100000}{1\times10000\times0.6\times0.9} = 16.67^o C$$

$$\left[\Delta T_6^{\max}\right] = 16.67\times1.3 = 21.67^o C \tag{8}$$

Comparing the maximum temperature difference between the center and the outside of the mass concrete with maximum temperature difference allows, we indicate that: in case 1 without insulation layer - maximum temperature difference is 26.31°C is higher than maximum temperature difference allowable temperature (21.67°C). This may lead to the development of cracks. Other cases will not cracks because of maximum temperature difference (16.65°C, 9.54°C, 6.23°C) lower than maximum temperature difference allowable temperature (21.67°C).

4 CONCLUSION

Based on the results of the study lead to the following conclusions:

1. When increasing the insulation thickness layer, then the maximum temperature in the mass concrete increases.
2. The thickness of the insulation layer affects inversely on the maximum temperature difference between the center and the outside of the mass concrete. In the case without the insulation layer, the maximum temperature difference is 26.31°C. When increasing the insulation thickness (0 - 3) cm, then the maximum temperature difference decreases.
3. In case 1 without insulation layer – the maximum temperature difference is 26.31°C is higher than the maximum temperature difference allowable temperature (21.67°C). This may lead to the development of cracks. Other cases will not cracks because of maximum temperature difference (16.65°C, 9.54°C, 6.23°C) lower than maximum temperature difference allowable temperature (21.67°C). This effective technique should be used to prevent cracking of early-age in the mass concrete.

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