Building a nomogram to predict maximum temperature in mass concrete at an early age

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Abstract. During the construction of massive concrete structures, the main factor that affects the structure is temperature. The resulting temperature is the result of hydration of the cement and some other factors, which leads to the formation of thermal cracks at an early age. So, the prediction of temperature history in massive concrete structures has been a very important problem. In this study, with the help of numerical methods, a temperature nomogram was built to quickly determine the maximum temperature in concrete structures with different parameters such as size, cement content, and the initial temperature of the concrete mixture. The obtained temperature nomogram has been compared with the results of the finite element method and the model experiment gives reliable results. It can be used to predict maximum temperature in mass concrete structures to prevent the formation of thermal cracks.

1 Introduction

At an early age, large concrete structures such as dams, foundations, abutments and piers of bridges, etc., thermal cracks often appear due to cement hydration [1-3]. The rate and amount of heat generated significantly affect the temperature and thermal stress fields in mass concrete structures. The temperature rise and temperature drop between the center and the surface of the concrete will form thermal stress and thermal deformation. When the thermal stress exceeds the stress limit, thermal cracks will form on the surface of mass concrete blocks. Thermal cracks can expand and develop in mass concrete structures. This seriously affects the strength, durability, and waterproofing of the structure [4, 5].

The definition of mass concrete differs from each country is listed as blow:

In the USA, massive concrete is understood as any volume of concrete with dimensions large enough, it is necessary to take measures to prevent the formation of thermal cracks [6]. In Korea and Japan, mass concrete is defined as follows: the size of the mass concrete depends on the type of structure, the composition of the concrete mix, and the construction conditions [7].

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Besides, In Vietnam, the standard TCXDVN 305.2004 “Mass concrete - code of practice of construction and acceptance” shows that, any structure having the smallest dimension larger than 2m shall be considered mass concrete. There are two main issues to control in mass concrete structures: maximum temperature and temperature difference. Previous studies have all shown that, the main factors influencing temperature variation in the mass concrete structure are the size of the structure, the ambient temperature, the initial temperature of the concrete at the time of placement and curing program, the cement type, the cement content in the mix, etc [8].

The temperature of the inner structure will peak a few days after the concrete is placed; this is followed by cooling to a stable temperature [9]. During the rising temperature phase, delayed ettringite formations (DEF) occur if the internal temperature exceeds a critical value. The DEF is expansion and cracking of concrete associated with the delayed formation of the mineral ettringite which is a normal product of early cement hydration.

To evaluate and prevent the appearance of thermal cracks, several criteria are given. Usually, in order to prevent thermal cracking, the maximum temperature and the temperature drop between the center and the surface of the concrete should be considered. The temperature drop should not exceed 20°C. In Japan, the crack index is used to evaluate and control the appearance of thermal cracks in large concrete structures and is presented by Equation (1).

$$I_{cr} = \frac{f_{sp}(\tau)}{f_t(\tau)}, \tag{1}$$

where: I_{cr} is the index of thermal cracking; $f_t(\tau)$ - tensile strength, corresponding to the "age" of concrete τ; $f_{sp}(\tau)$ is the maximum temperature stress caused by the cement hydration process per day τ.

To limit crack, the crack index should not be larger than 1.2 [8, 9]. According to the maximum temperature control criterion in the concrete block indicates that, DEF is a result of high early temperatures (above 70-80°C) in the concrete which prevents the normal formation of ettringite. Amongst the numerous causes for temperature associated concrete cracking, delayed ettringite formation plays a major role [9]. Besides, according to CIRIA C600 (UK) standard, the allowable temperature difference is determined by the formula (2) [10]:

$$\Delta T_{\max} = \frac{3.7\varepsilon}{\alpha}, \tag{2}$$

where: ε - ultimate tensile strength of early age concrete; α is the coefficient of thermal expansion of concrete. For example, after substitution of approximately known values $\alpha = 13.10^{-6}$ and $\varepsilon = 70.10^{-6}$ into expression (2), the allowable temperature difference is obtained $\Delta T_{\max} = 19.9^{\circ}C \approx 20^{\circ}C$.

Nowaday, there are two ways to minimize a thermal crack of mass concrete: One is a construction method such as pre-cooling and pipe-cooling and the other is to control material by adjusting the content of cement or using low hydration material. And all the methods are essential to check the analysis of thermal stress to evaluate thermal crack index for quality and function of structure in terms of design, material, and construction [11-13].

Research on temperature and thermal stress fields in mass concrete structures is known as scientists Aniskin N.A, Zhu Bofang, Barbara K., Mohammad H. A., etc [14-16]. However, with different construction conditions and different concrete mixes, the problem of thermal cracks still exists and has not been completely resolved by now.

In this study, the numerical method has been performed to create a temperature nomogram that allows to quickly determine the maximum temperature in the mass concrete depending on the cement content and the laying temperature of the concrete. Besides, in order to check the correctness of the temperature nomogram, an experimental study was performed. The results show that the temperature nomogram is reliable enough and can be used in the preliminary assessment of the formation of thermal cracks for large concrete structures.

2 Materials and methods

2.1 Materials

The formation of a temperature field in mass concrete structures is influenced by many factors such as cement content, cement type, the initial temperature of concrete mixes, the size of the concrete block, etc. In this study, to build a temperature nomogram to predicts the maximum temperature in the mass concrete, the following main factors are considered [17, 19, 20]:

X_1 (C) - the unit cement content is from 200 to 400, kg/m^3;

X_2 (t_{pl}) - the placing temperature is from 10 to 30, ^{o}C;

X_3 (A/V) - the ratio of the surface area to the volume of the mass concrete form 1.2 to 3.

Consider the cube of concrete with the size of a×a×a, ratio between surface area and volume of concrete block A/V is determined by Equation (3) [18]:

$$A/V = \frac{6.a.a}{a^3} = \frac{6}{a}\left(m^{-1}\right) \tag{3}$$

For concrete blocks of sizes 2m×2m×2m, 3m×3m×3m, 4m×4m×4m and 5m×5m×5m, the ratios A/V are 3.0, 2.0, 1.5 and 1.2 respectively.

Ambient temperature varies during a day and also varies from day to day. It is thus difficult to input correctly this fluctuation in the model. A constant ambient temperature has been adopted instead for simplicity purpose. As per our hydrology report, the average ambient temperature for August, September and October is about 27.1°C.

The temperature at the center of a mass concrete structure is approximately equal to the adiabatic temperature. The temperature rise process and curve shape may change depending on the composition of the concrete mixture, the initial temperature of the concrete mixture. As proposed by Sukiaky (Japan), the adiabatic curve is defined by the following Equation (4):

$$T(t) = K(1-e^{-\alpha t}), \tag{4}$$

Where: T - amount of adiabatic temperature rise at time (°C); α - the coefficient of temperature rise (reaction rate); K - the final amount of diabatic temperature rise acquired by test (°C); t - time (day); K and α are experience values depending on the expected quantity of cement in 1m^3 concrete, type of cement, and casting temperature . These values can found in the Korean standard and are presented in Table 1 [6].

Table 1. Coefficients for estimating adiabatic temperature.

Type of cement	**Pour temperature, ^{o}C**	**$T(t) = K(1-e^{-\alpha t})$**			
		K(C) = aC+b		**α(C) = gC+h**	
		a	**b**	**g**	**h**
Fly ash cement	10	0.15	-3.0	0.0007	0.141
	20	0.12	8.0	0.0028	-0.143
	30	0.11	11.0	0.003	0.059

Where: C - cement content in 1 m^3 of concrete; a, b, g and h - coefficients determined from experiment.

All the input parameters of the analysis are summarized in Table 2.

Table 2. Input parameters in model.

Property	**Concrete block**	**Subsoil**
Specific heat (kcal/kg.°C)	0.25	0.20
Density (kgf/m^3)	2400	1800
Rate of heat conduction (kcal/.hr.°C)	2.3	1.7
Convection coefficient - with styrofoam 5cm (kcal/m^2.hr.°C)	4.5	
Ambient temperature (°C)	27.1	-
Thermal expansion coefficient	1.0×10^{-5}	1.0×10^{-5}
Poisson ratio	0.18	0.20

2.2 Methods

2.2.1 Using an experimental planning method to create a regression function of the maximum temperature in the mass concrete

Assume that the approximate polynomial function represents the experimental region written by Equation (5) [17].

$$Y_i = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{23}X_2X_3 + b_{13}X_1X_3 + b_{123}X_1X_2X_3 \quad (5)$$

The number of experiments necessary (N) to determine the coefficients of the regression equation is determined by Equation (6):

$$N = 2^k + 1, \quad (6)$$

where: k - number of basic parameters; 1 - experiments in the center; therefore N = 2^3 +1= 9; b_{ij} – coefficients to be determined.

2.2.2 The finite element method (FEM) to determine the temperature field in mass concrete

There are many commercialized finite elements software that can carry out heat hydration analysis such as ANSYS, ABAQUS, LUCAS, MIDAS. Among all these software, Midas has been used in several projects in Viet Nam over the past years and has proved to be a reliable tool for this specific kind of task. In this study, Midas Gen 2019 software was used to determine the temperature fields in large concrete structures.

A normal heat hydration computational analysis can be described as below step:

Step 1: *Defines material properties as follows:* modulus of elasticity, specific heat, coefficient of heat conductivity, etc.

Step 2: *Definition of material properties changes over time such as* creep & shrinkage, modulus of elasticity, etc.

Step 3: *Create a structural model* (create elements, define boundary conditions, input loads, etc).

Step 4: *Heat Hydration Analysis control* (define integration factor & initial temperature. input wether to consider creep & shrinkage and calculation method, etc).

Step 5: *Heat hydration load* (enter ambient temperature & convection coefficient functions, use them to define convection boundary conditions, etc).

Step 6: *Prescribe temperature* (assign constant temperature conditions to the parts which do not undergo any temperature changes with time, etc).

Step 7: *Heat source function, assign heat source* (enter heat source and assign them to the corresponding elements, etc).

Step 8: *Construction stage* (define elements, boundary conditions and load conditions corresponding to each construction stage. Set initial temperature of elements being activated, etc).

Step 9: *Perform analysis* (perform heat transfer analysis and thermal stress analysis)

Step 10: *Analyze the results* (analyze temperature distribution and variation of thermal stress with time, etc).

3 Results and Discussions

3.1 Establish a mathematical model to predict the maximum temperature in mass concrete

Using the finite element method, the maximum temperature values in the mass concrete block of the experimental plan matrix have been determined and presented in Table 3.

Table 3. Experiment planning matrix.

No	x_1	x_2	x_3	Values of the factors			T_{max}
				x_1, kg/m^3	x_2,°C	x_3, A/V	
1	-1	-1	-1	200	10	1.2	33.52
2	1	-1	-1	400	10	1.2	63.40
3	-1	1	-1	200	30	1.2	61.28
4	1	1	-1	400	30	1.2	84.10
5	-1	-1	1	200	10	3.0	31.02
6	1	-1	1	400	10	3.0	60.94
7	-1	1	1	200	30	3.0	59.72
8	1	1	1	400	30	3.0	82.93
9*	0	0	0	300	20	2.1	57.32

The mathematical model for determining the maximum temperature in mass concrete is obtained and can be seen by Equation (7):

$$T_{\max} = 59.24 + 13.60x_1 + 12.77x_2 - 0.84x_3 - 1.72x_1x_2 - 0.27x_2x_3 + 0.05x_1x_3 + 0.04x_1x_2x_3 \quad (7)$$

From the obtained maximum temperature regression function, we can see that all factors influence the maximum temperature value in the mass concrete structure. Examples of most notably, the cement content and the initial temperature significantly affect the maximum temperature in the concrete block. In addition, the size of the concrete block does not significantly affect the maximum temperature in the concrete block compared to the other two factors. This is explained as follows: in this study, the dimensions of the concrete blocks selected are consistent with the ACI 207 definition of mass concrete. The ratio of surface area to concrete block volume (x_3) that changes the maximum temperature value in the mass concrete is about 2°C.

To simplify the maximum temperature in the concrete block can be written by Equation (8) as follows:

$$T_{\max} = 59.24 + 13.60x_1 + 12.77x_2 \quad (8)$$

Based on nomogram building theory, the nomogram to predict the maximum temperature in the concrete block depends on the cement content and the initial temperature of the concrete mixture that has been built and is shown in Figure 1. The nomogram obtained above allows to quickly determine the maximum temperature in the concrete block.

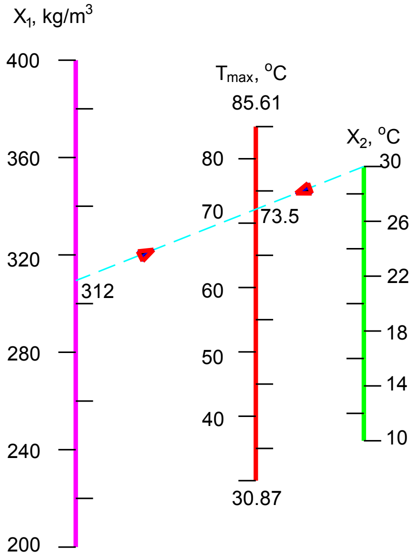

Fig. 1. A nomogram to predict maximum temperature in mass concrete at an early age.

3.2 An experimental study to test the reliability of the temperature nomogram in mass concrete

As shown above, a layer of the subsoil is also included in the model. Without this subsoil, the concrete block shall have soil springs to represent the boundary conditions. The transfer of the concrete heat cannot be accurately represented. Therefore, the soil layer is introduced in the model with its properties of specific heat and thermal conductivity, to closely represent the true behavior.

Table 4. Mix design.

Grade	Slump flow	Admix -ture	Cement	FA	Coarse Aggregate (5-13mm)	River Sand (0-5mm)	Coarse Aggregate (5-20mm)	Water
	mm	kg	kg	kg	kg	kg	kg	kg
C35/45	140±20	5.72	312	128	312	780	728	150

Table 5. Input parameters in model.

Property	**Concrete block**	**Subsoil**
Specific heat (kcal/kg °C)	0.25	0.2
Density (kgf/m^3)	2400	1800
Rate of heat conduction (kcal/hr.°C)	2.3	1.7
Convection coefficient (kcal/m2.hr.°C)	4.5	-
Ambient temperature (°C)	27.1	-
Casting temperature (°C)	30	-
28-days compressive cylinder strength (kgf/cm^2)	350	-
Compressive strength gain coefficients	a=4.0; b=0.85	-
Thermal expansion coefficient	1.0×10^{-5}	1.0×10^{-5}
Poisson ratio	0.18	0.20
Unit cement content (kg/m^3)	312	-
Heat source function coefficients	K=45.32; α =0.995	-

A concrete block of 4.0m×4.0m×4.0m size was analyzed. The formwork used in the experimental model is styrofoam material with 5cm thickness. The composition of the concrete mixture is presented in Table 4. The remaining data necessary for concrete and subsoil to analyze are presented in Table 5.

Due to symmetry, only a quarter of the structure is modeled. Not only it will accelerate the computation but also facilitates the visualization of results in the core of the mass. Figure 2 shows the finite element mesh of 1/4 concrete mass and the subsoil to be numerically analyzed. The result of the numerical analysis is done by Midas GEN software with the maximum temperature after 60 hours of placing the concrete is 78.09°C as shown in Figure 3.

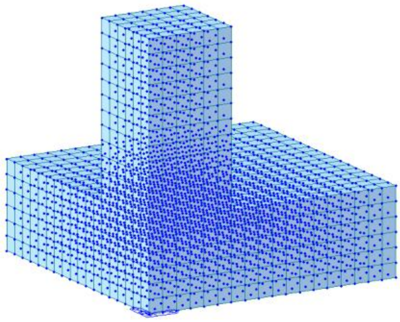

Fig. 2. Finite element mesh for a model experiment.

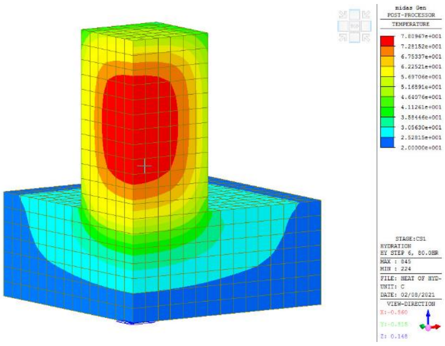

Fig. 3. Distribution of temperature in the concrete block at the time after 60 hours of placing the concrete.

Use the nomogram to determine maximum temperature in concrete block with size of 4m×4m×4m, cement content of 312 kg/m^3 and an initial temperature of 30°C, the maximum temperature in the concrete block is 73.5°C as shown in Figure 1.

When the cement content (C = 312 kg/m^3), the initial temperature of the concrete mixture (t_{pl} = 30°C) and the concrete block size 4.0m×4.0m×4.0m (A/V = 1.5), the coded values are obtained $x_1 = 0.12$, $x_2 = 1$ and $x_3 = -0.67$ respectively. Substituting the values x_1, x_2 and x_3 into Equation (7) we obtain the T_{max} value as follows:

$$\begin{aligned}T_{\max} &= 59.24 + 13.60\times0.12 + 12.77\times1 - 0.84\times(-0.67) - 1.72\times0.12\times1 - \\ &-0.27\times1\times(-0.67) + 0.05\times0.12\times(-0.67) + 0.04\times0.12\times1\times(-0.67) = 74.17^{o}C\end{aligned} \tag{9}$$

The temperature error between determined by Equation (7) and the temperature nomogram is (74.17-73.5) /74.17 = 0.9%. That means that an acceptable error is used with the temperature nomogram.

Fig. 4. Setup formwork for mockup with styrofoam 5cm.

Fig. 5. Installation sensor.

To evaluate the accuracy of the proposed nomogram as well as the finite element model, the temperature sensors are arranged in the concrete block and are shown in Figures 4 and 5. The temperature is measured in a concrete block by the temperature sensor. The measurement frequency is every 2 hours for the first 3 days and every 4 hours in the following days.

The results calculated by the finite element method and sensor obtained are presented in Figure 6.

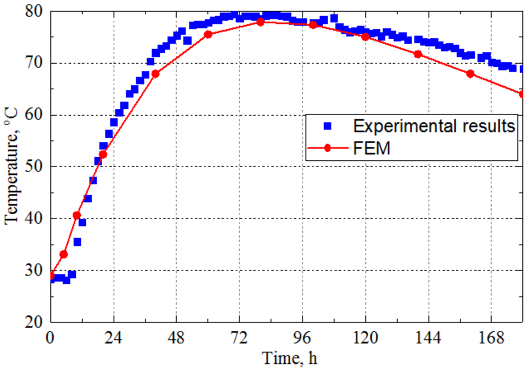

Fig. 6. The results of the comparison between the temperature of calculation by finite element method and experiment.

The development of the temperature at the center of the concrete block over time by the finite element method and the temperature sensor can be seen that the finite element model used is reliable.

Results obtained from the nomogram to determine the maximum temperature in concrete blocks, the finite element method, and the experiment are shown in Figure 7.

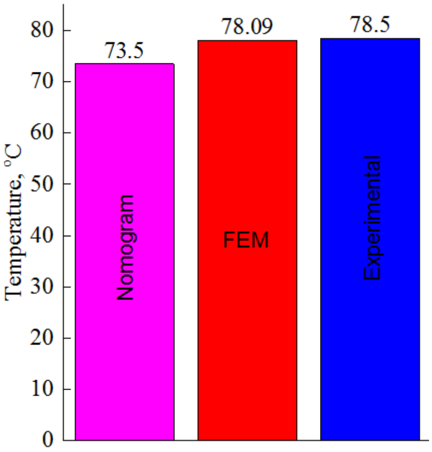

Fig. 7. The results of the comparison between the three methods: the nomogram, finite element method and experiment.

From Figure 7 it can be seen that the temperature error between the results from the nomogram and the finite element method is (73.5-78.09)/78.09 = 5.8%, while the temperature error between the nomogram and experimental results are (73.5-78.5)/78.5=6.3%. Errors between the methods can be explained as follows: The method of determining the temperature from the nomogram has removed the quadratic component of the regression, while a factor such as solar radiation has increased the temperature in mass concrete. Obviously, the temperature error between the three methods is about 5%, which means that the calculation is reliable enough to determine the maximum temperature in the mass concrete.

4 Conclusions

Based on the obtained results, we can draw the following conclusions:

1.The temperature nomogram can quickly predict the maximum temperature in a mass concrete structure with some basic parameters such as the size of the concrete block (A/V), the cement content (C), and the initial temperature of the concrete mixture (t_{pl}).

2.The comparison results between the three methods of determining the maximum temperature from the temperature nomogram, the finite element method, and the experimental method showed that the temperature nomogram is reliable enough. That means, the temperature nomogram can be useful for engineers to use to control and prevent the formation of thermal cracks in a mass concrete structure.

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