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The temperature nomogram to predict the maximum temperature in mass concrete

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Abstract. At an early age, the problem of cracking in concrete structures in general and large block structures in particular often appears. Many factors affect the formation of cracks in mass concrete structures. One of the factors considered is thermal cracking. Temperature is the most important factor to consider while constructing mass concrete. The temperature is affected by cement hydration and other factors, which leads to the production of thermal cracks at an early age. Tensile stresses that are greater than the concrete's tensile strength are typically the cause of cracking in mass concrete. These tensile stresses are more frequently caused by constraints against volumetric change, though they can also result from loads placed on the structure. Therefore, the prediction of temperature fields in massive concrete structures has been a significant challenge. This study presents a temperature nomogram by using numerical methods to quickly determine the maximum temperature in concrete structures with various characteristics, such as cement content and the initial temperature of concrete mixtures. The research results are meaningful for construction management agencies to use temperature diagrams to predict the maximum temperature in large concrete structures without the need to model the mass concrete. Besides, a nomogram can be used to predict the maximum temperature in mass concrete structures in order to prevent thermal cracks during construction and thereafter.

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1. Introduction

Mass concrete has different definitions and requirements depending on each country. However, the minimum size is the most important consideration in determining the mass concrete construction properties. According to ACI 116R-90 [1], mass concrete is defined as a concrete block of sufficient size that requires methods to deal with heat generation due to cement hydration and the concomitant volume transformation to prevent cracking. ACI 301-10 defines mass concrete as a concrete structure with a minimum size of 4 feet (1.3 m) [2]. The process of heat transfer from the concrete block's interior to the surrounding environment is influenced by the surface area of the mass. To evaluate that influence, the study [3, 4] considered the ratio of surface area to volume of concrete to affect the temperature field inside the mass concrete [3, 4]. Additionally, it is necessary to take measures to prevent the thermal crack formation at an early age not only for large-sized structures but also for small-sized structures that use a high cement content or high-heat cement. According to TCXDVN 9341:2012: "Mass concrete – Construction and acceptance", conventional reinforced concrete and concrete constructions with the smallest side greater than 2 m can be called mass block concrete [5]. Mass concrete structures include dams, mass block foundations, pile caps, earth retaining walls, tunnel walls, bridge piers, etc. [5].

In Vietnam, during concrete structure construction, cracks often appear on the surface of the structural members at an early age for a variety of reasons. One of them, considered as the main reason, is due to heat generation of the hydration process. The formation of cracks impacts the expectancy, loading capacity, waterproofing ability, as well as aesthetics of the structures. Many domestic and international studies have discussed the process of heat generation and thermal stresses in large pouring blocks in order to propose technical solutions for controlling thermal cracking. However, the process of assessing, calculating, and evaluating the distribution of temperature fields and thermal stress fields determining the formation of thermal cracks in mass concrete blocks has still not been completed. As a result, more researches are required because many materials and technological factors influencing the problem of thermal analysis in mass concrete structures need more consideration, such as component size, concrete mix composition (cement content and type, cement substitutes used), initial concrete mix temperature, ambient temperature, construction progress, curing conditions, etc. [6].

As a result of this research, the development of a nomogram to predict the maximum temperature helps in the prevention of thermal cracks in mass concrete structures with changing material and technological parameters. The above study results are very useful in the design and construction of mass concrete blocks. The study extends to building theory and practice by preventing the formation of thermal cracks in mass concrete structures at an early stage.

In addition, the creation of a nomogram based on the conditions of materials and construction techniques will effectively and quickly support the processes of design and construction in the preliminary determination of the maximum temperature in mass concrete structures.

2. *Materials and Methods*

2.1. Research subjects

Consider a 8 m (length) × 6 m (width) × 3 m (height) cubic concrete block with geometric dimensions of a 3D numerical analysis model placed on a 16 × 12 × 3 m foundation as presented in Fig. 1. The physical properties of concrete and the foundation are presented in Table 1.

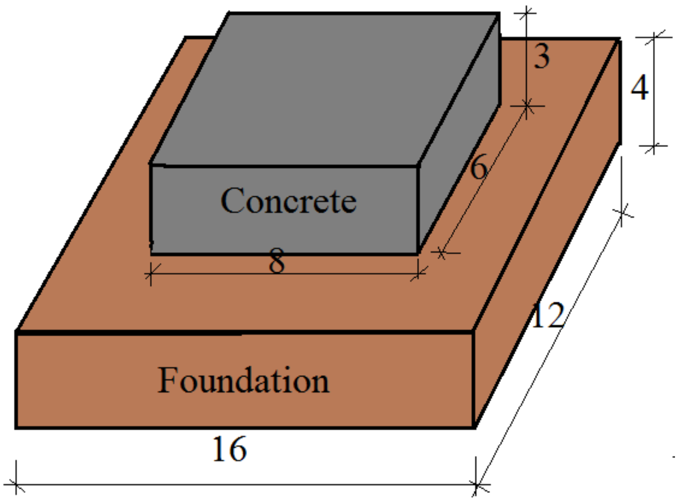

Figure 1. Dimensions of concrete block and foundation, unit: m.

In the process of forming the temperature field in the mass concrete structures, there are many factors influencing temperature distribution in the mass concrete structures, such as material composition, construction technique, and environmental temperature. Material factors should be mentioned, such as the cement content per 1 m^3, the type of cement, and the initial temperature of the concrete mix. Factors in construction technique include division of placing block sizes, construction procedure between placed concrete blocks, the use of cooling pipe systems (if any), and surface insulation. These factors causing major impact on the temperature in mass concrete structures constitute the scope of this study, which takes into account many scenarios of materials and building techniques [7–9].

Mass concrete structures in Vietnam are typically constructed using concrete grades between M150 and M400. When using concrete compressive strength grade varying from M150 to M400 corresponding to the cement content used in the mixture varying from 120 kg/m^3 to 450 kg/m^3. Furthermore, the average ambient temperature in Vietnam normally ranges from 15^{o}C to 30^{o}C, so the initial temperature of the concrete mixture fluctuates within that range. However, under certain conditions, the concrete mixture can be cooled down to 10°C to prevent thermal cracking [5]. Therefore, in the study, two material factors such as cement content and initial temperature of the concrete mixture are considered as follows:

$X_1(C)$ is cement content varies from 120 to 450, kg/m^3;

$X_2(t_{pl})$ is initial temperature of concrete mix from 10 to 30, °C;

Construction technique factors are considered with two construction cases, as follows:

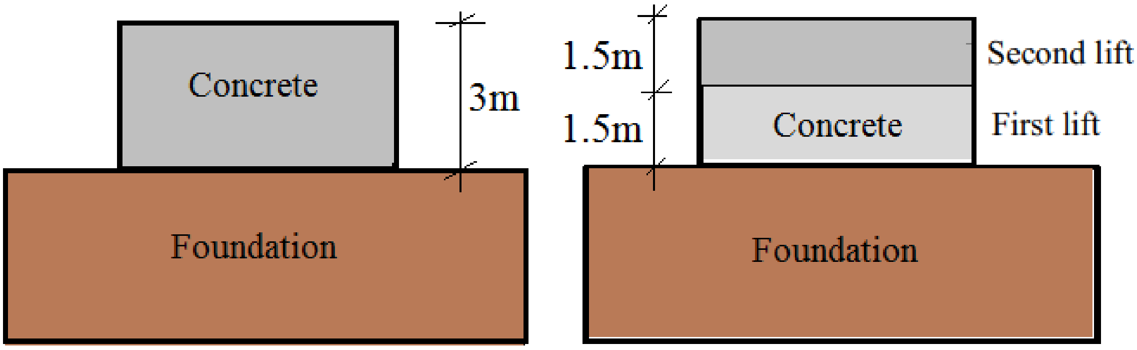

Figure 2. Cases of pouring concrete:
Case 1: Concrete placing without block division;
Case 2: Concrete placing with two 1.5 m thick lifts
and construction schedule of 5 days for each lift.

Table 1. Physical properties of materials used in the analysis.

Characteristics	Units	Concrete	Foundation
Specific heat	kcal/kg.°C	0.26	0.21
Density of the material	kg/m^3	2400	2600
The coefficient of thermal conductivity	kcal/m.h.°C	2.49	1.81
The coefficient of convective heat transfer: concrete – air	kcal/m^2.h.°C	12	12
The coefficient of convective heat transfer with wooden formwork	kcal/m^2.h.°C	8	–
Ambient temperature	°C	30	25
Modulus of elasticity	kG/cm²	2.5×10^5	1.0×10^4
The coefficient of linear expansion	1/°C	13.0×10^{-6}	1.0×10^{-5}
Poisson's ratio		0.20	0.30

Convection is the process of transferring heat through the mass motion of a fluid, like air or water, where the heated fluid is moved away from the heat source while transferring heat along with it. Convection is influenced by the type of formwork, setting time, curing procedures, and wind speed. The convection coefficients between the concrete surface – air and the formwork – air, which are 12 kcal/m^2.h.°C and 8 kcal/m^2.h.°C, respectively, are considered in the study based on the local climate condition in Vietnam.

The value of elasticity modulus of the soil can be selected being based on the local conditions. In the study, the value of elasticity modulus of the soil (E = 10000 kg/cm^2) is selected being based on the sandy soil foundation in a local region in the Northern part of Vietnam.

The ambient temperature is a factor varying versus time.The average annual temperature of the air and the foundation is different. According to the depth of soil layers, their temperature gradually decreases. In this study, the average temperature of the air is taken at 30 °C and the ground at 25 °C, suitable for Vietnam's summer climate [5].

The adiabatic temperature equals the temperature at the center of a mass concrete structure. Depending on the content of the concrete mixture and the initial temperature of the concrete mixture, the temperature rise process and the curve form may change. The adiabatic temperature rise curve is defined as mentioned in Equation (1) [10–12]:

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

where T is the amount of adiabatic temperature rise at time (°C); α is the coefficient of temperature rise (reaction rate); K is the final amount of adiabatic temperature rise acquired by test (°C); t is time (day);

K and α are experience values depending on the expected quantity of cement in 1 m^3 concrete, type of cement, and casting temperature. These values can found in the Korean standard and are presented in Table 2 [11].

Table 2. Coefficients for estimating adiabatic temperature.

Type of cement	Placing temperature,(°C)	$T(t) = K(1 - e^{-\alpha t})$			
		$K(C) = aC + b$		$\alpha(C) = gC + h$	
		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 is cement content in 1 m^3 of concrete; a, b, g and h are coefficients determined from experiment.

2.2. Methods

2.2.1. Creating a regression equation for the maximum temperature in mass concrete using an experimental planning technique

Assume that Equation (2) represents the approximate polynomial function reflecting the survey region [13]:

$$Y_i = b_o + b_1 X_1 + b_2 X_2 + b_{12} X_1 X_2 . \quad (2)$$

Equation (3) calculates the number of experiments required (N) to discover the coefficients of the regression equation:

$$N = 2^k + 1, \quad (3)$$

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

2.2.2. The Finite Element Method (FEM) is used to calculate the temperature field in mass concrete

When solving the problem of unstable heat transfer with an internal source, the finite element method is given by the reduced matrix equation as follows [14–16]:

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

With the problem of unstable heat transfer, it is necessary to transient analyze with time steps $\Delta\tau$ as follows:

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

Equation (4) can be rewritten as:

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

where $[K]$ is the matrix of thermal conductivity coefficient; $[C]$ is specific heat matrix; $[Q]$ is matrix of heat generated; $\Delta\tau = \Delta\tau_n - \Delta\tau_{n-1}$ is step of computation time.

The finite element method, which is one of the most powerful and reliable methods, is frequently used in studying temperature distribution of mass concrete. It divides elements, and their features are represented at nodes [17, 18].

Currently, there are many FEM based software solutions for structural problems in general and heat transfer problems in concrete in particular, such as Ansys, Abaqus, Midas Civil, etc. The above software is widely used in universities, research institutes, or companies around the world with high reliability [19–21].

2.2.3. Criteria for evaluating thermal cracking

Each country has adopted different criteria in controlling the formation of thermal cracks based on the characteristics of construction technique as well as local climatic conditions. Each standard represents characteristics that are specific to the climate and construction technique in each of these countries. The temperature difference ΔT between the concrete surface and the core of the mass concrete structure is frequently controlled by placing concrete, as a general rule. Regardless of the construction area or concrete type, the allowable temperature difference is typically around 20 °C [17].

The criterion for temperature difference, according to several Russian standard texts, is dependent on the concreting technique and the location of the structure in issue [18]. The difference temperature ΔT in the contact area (concrete and foundation) should not exceed (16–18) °C when pouring concrete with long blocks and (20–27) °C when using for construction according to column cutting, according to Standard SP 357.1325800.2017 [22]. A structural area having a height of 0.2 times the height of a mass concrete structure is known as the contact area. The temperature differential between the core and plate surfaces ΔT should not exceed (20–25) °C for concrete in the free zone (above the contact zone from the substrate surface) [13].

According to Vietnamese standard TCXDVN 9341:2012: “Mass concrete - Code of practice of construction and acceptance”, two factors are controlled to prevent the occurrence of cracks in mass concrete structures. The first, the temperature difference between its center and surface $\left(\Delta T\right)$, should be less than 20 °C. And the second, the temperature gradient $\left(M_T\right),$ should not exceed 50 °C/m [10].

In Table 3, a criterion for the prevention of thermal crack formation in the construction of Chinese gravity dams and arch dams is described, with the allowable temperature difference between the center and surface of the concrete block depending on its size [23]. In particular, the size of the poured block affects the temperature difference in mass concrete. For example, if the length of the pouring block L < 16 m and the height of the pouring block is in the range (0–0.1) L, the temperature difference in mass concrete should not exceed (25–26) °C [23].

Table 3. Permissible temperature gradient T (°C) according to Chinese design standards.

Concrete block height	Length of concrete block L (m)				
	< 16 m	17–20 m	21–30 m	31–40 m	> 40 m
(0–0.1) L	26–25	24–22	22–19	19–16	16–14
(0.1–0.4) L	33–31	31–28	28–26	24–20	20–18

According to the evaluation of thermal crack formation according to CIRIA C600 (UK), the maximum temperature differential between the center and the surface of the concrete block $\left(\Delta T_{\max}\right)$ is defined by Equation (7) [24]:

$$\Delta T_{\max} = \frac{3.7\varepsilon}{\alpha}, \tag{7}$$

where ε is final tensile strength of early concrete; α is coefficient of thermal expansion of concrete.

Substituting the known approximations α = 13.10^{-6} and ε = 70.10^{-6} into expression (7), the value of the maximum allowable difference $\Delta T_{\max}$ = 19.9 °C ≈ 20 °C is adopted. Hence, it is required that the temperature difference between the center and the surface of the concrete block should not exceed 20 °C during construction process.

Criteria for evaluating resistance to thermal cracking are presented in the Russian Standard SP 41.13330.2012 (proposed by GS P.I. Vasiliev) [25]:

$$\sigma(\tau) \le \gamma_{b3}\gamma_{b6}\varepsilon_{\lim}\varphi(\tau) E_b(\tau), \tag{8}$$

where $\sigma(\tau)$ is thermal stress at time τ; γ_{b6} = 1.15 is working conditions for large block concrete structures; γ_{b3} is the coefficient of the mass concrete structure's working condition, taking into consideration the effect of the deformation gradient on the section on the concrete's tensile strength; $\varepsilon_{\lim}$ is ultimate tensile strength of concrete; $\varphi(\tau)$ is the coefficient depending on the age of concrete; $E(\tau)$ is elastic modulus of concrete at age τ.

The crack index is used to evaluate the formation of thermal cracks in concrete structures, and it is determined by Equation (9) [26]:

$$I_{cr} = \frac{f_t(\tau)}{f_{sp}(\tau)}, \tag{9}$$

where I_{cr} is crack index; $f_t(\tau)$ is tensile strength of concrete at age τ; $f_{sp}(\tau)$ is maximum tensile stress induced during cement hydration at a time τ.

The cracking possibility was estimated by the value of the thermal cracking index based on the criteria values presented in Table 4 [26, 27]:

Table 4. Evaluation of cracking according to the Japanese cracking index.

Criteria	Cracking index (Icr)
To prevent cracks	$I_{cr} \ge 1.5$
To limit cracks	$1.2 \le I_{cr} \le 1.5$
To limit harmful cracks	$0.7 \le I_{cr} \le 1.2$

3. Results and Discussion

3.1. Developed mathematical model to predict the maximum temperature of a concrete block

In previous studies, Caltrans (State of California Department of Transportation) proposed a nomogram to predict temperature in the mass concrete considering the four most significant factors affecting temperature, such as cement content, element size, the initial temperature of the placing concrete, and the surrounding air temperature. However, the assuption of cement type used as that of type 2 may limit the actual application in other countries, such as Vietnam. Besides, construction technique showing the schedule of placing concrete blocks has not been mentioned [28].

For the present study, the maximum temperature in the concrete block is determined by using the finite element method; it is presented in Table 5 for two construction cases (one lift and two lifts) as a example of considering the construction conditions.

Table 5. Matrix of numerical experimental plans with consideration of technology and materials factors.

#	x_1	x_2	Value		Case 1	Case 2
			x_1, kg/m³	x_2,°C	T_{max}	T_{max}
1	– 1	– 1	120	10	27.91	26.00
2	1	– 1	450	10	66.51	58.33
3	– 1	1	120	30	49.11	45.33
4	1	1	450	30	87.50	75.78
5*	0	0	285	20	57.99	50.96

The mathematical model to determine the maximum temperature in a mass concrete structure is shown by Equations (10) and (11):

Case 1: without division of concrete pouring

$$T_{max} = 57.76 + 19.25x_1 + 10.55x_2 - 0.05x_1x_2. \quad (10)$$

Case 2: concrete blocks are poured in 2 lifts

$$T_{max} = 51.36 + 15.70x_1 + 9.20x_2 - 0.47x_1x_2. \quad (11)$$

From the maximum temperature regression function obtained with two construction options, we can make the following comments:

1. The maximum temperature of the concrete building is influenced by both the cement concentration (x_1) and the initial temperature of the concrete mix (x_2).

2. When changing the cement content from 120 kg/m^3 to 450 kg/m^3, the maximum temperature in the concrete structure changes the value of 38.5 °C for the construction without division of concrete pouring, 31.4 °C for concrete blocks poured in 2 lifts.

3. When the initial temperature of the concrete mix is changed from 10 °C to 30 °C, the maximum temperature change for both construction techniques is roughly 20 °C. That is, if the initial temperature of the concrete mixture is increased by 1 °C, the maximum temperature of the concrete mixture increases by 1 °C. The above linear rule is perfectly consistent with earlier research.

4. When constructing two lifts, the rest time between lifts is enough for some heat to escape to the outside due to the hydration of cement. Based on Equations (10), (11), it can be seen that the maximum temperature in Case 2 is reduced by 11.3 °C compared to Case 1 having the same input parameters of the material.

From the results obtained in Table 5, the author considered Equations (10) and (11) as the most reasonable construction conditions to assess the risk of forming thermal cracks.

3.2. Establishing a nomogram to predict the maximum temperature in mass concrete construction

From the maximum temperature regression function obtained above, there are now many methods to establish mathematical nomograms to represent the correlation between the unknowns (x_1 and x_2) with the maximum temperature, such as Matlab, Maple, or the theory of establishing nomograms. The basis for building a plane nomogram is based on the Equation (12):

$$f_1 + f_2 = f_3. \quad (12)$$

The value f_1 is built into the grid of coordinates (x, y) with:

$$x = 0; \quad y = m(f_1 - a). \quad (13)$$

The value f_2 is built into the grid of coordinates (x, y) with:

$$x = H; \quad y = n(f_2 - b). \quad (14)$$

The f_3 value is built into the grid of coordinates (x, y) with:

$$x = \frac{mH}{m+n}; \quad y = \frac{mn}{m+n}(f_3 - a - b), \quad (15)$$

where $m,\ n,\ H,\ a,\ b$ are arbitrary parameters.

We obtain a nomogram for each construction method (Case 1 or Case 2) by applying the theory of building a nomogram. We chose the values of $m,\ n,\ H,\ a,\ b$ of the two building options so that the ratio on the nomogram of x_1 (cement content) and the initial temperature of the concrete mix (x_2) are identical proportions because the input material is the same. Fig. 3 shows a nomogram for determining the maximum temperature in a mass concrete structure for various construction materials and technologies.

Based on the obtained maximum temperature nomogram, we can quickly determine the maximum temperature in mass concrete structures with different concrete mixes and construction technologies. This helps to preliminarily select such input parameters as cement content, initial temperature of the concrete mix, or special construction methods. According to many current regulations, the maximum temperature in mass concrete members should not exceed 70 °C to ensure the best strength development and no entrigite delay. Based on the above temperature nomogram, it is possible to reverse the cement content, initial temperature, construction conditions with unfavorable case T_{max} = 70 °C. In case of a structure that requires a large amount of cement, the amount of heat generated can be greater than the adverse temperature of 70 °C, thus, it is necessary to take measures to reduce the maximum temperature, such as using a cooling pipe system.

How to use the nomogram. Connecting the cement content (kg/m^3) value in the X_1 axis to the initial temperature value of the concrete mix in the X_2 axis, crossing the maximum temperature axis at 1 point, the maximum temperature value is the value at the cutoff position. When building a concrete block without division of concrete pouring, check the maximum temperature in the mass concrete on the left of the nomogram; when building a concrete block with 2 lifts, check the maximum temperature in the mass concrete on the right of the nomogram.

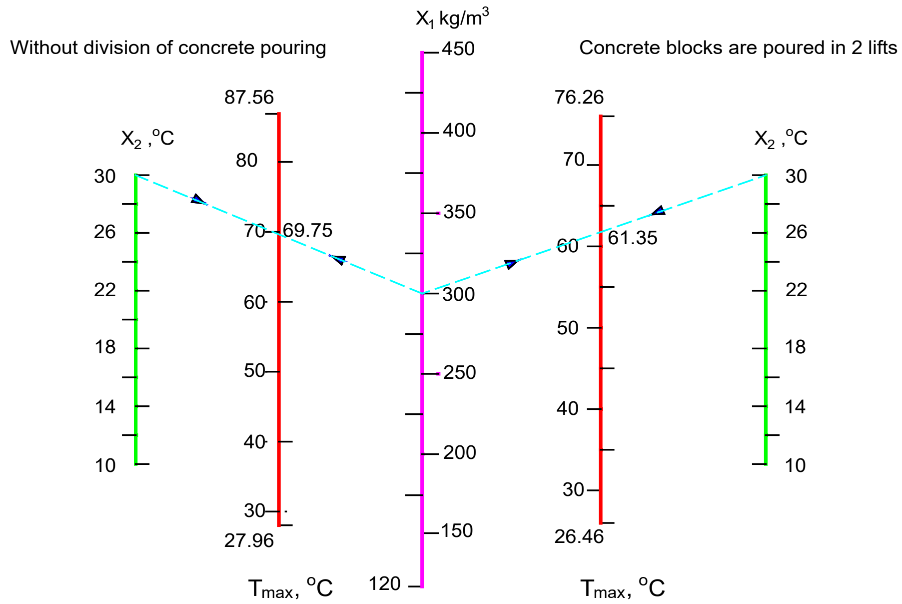

Figure 3. Nomogram for predicting the maximum temperature in concrete structures with different construction materials and technologies.

Example of using the nomogram. Assuming the cement content of 300 kg/m^3, the initial temperature of the concrete mixture is 30 °C, we can completely determine the maximum temperature in the concrete structure without division of concrete pouring as 69.75 °C (on the left of the nomogram) and 61.35 °C (on the right of the nomogram).

3.3. Verifying the correctness of the obtained maximum temperature nomogram

To verify the obtained temperature nomogram, we use the finite element method to model the large concrete structure. The obtained results are compared with the temperature obtained from the temperature nomogram.

Consider a concrete block of sufficiently large dimensions (dimensions greater than 2 m). The cement content is 300 kg/m^3, the initial temperature of the concrete mix is 25 °C. Concrete block is constructed without division of the poured block. Using the left branch temperature nomogram with x_1 = 300 kg/m^3, and x_2 = 25 °C, we get the maximum temperature of 64 °C, as presented in Fig. 4.

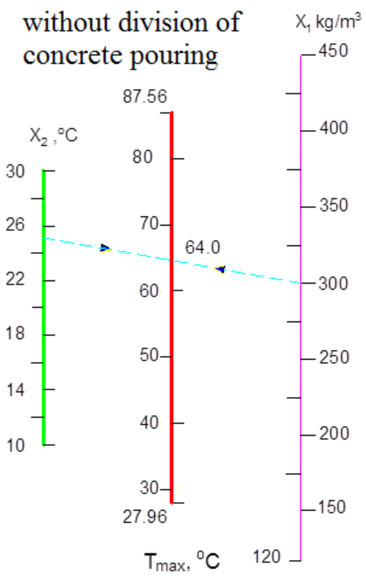

Figure 4. Verification of the maximum temperature in large concrete blocks with x_1 = 300 kg/m3, x_2 = 25 °C when building concrete blocks without division of concrete pouring (left branch of the nomogram).

The maximum temperature in the mass concrete structure from the finite element method is presented in Fig. 5.

Fig. 5 shows that the maximum temperature in the mass concrete structure reached 64.81 °C after 96 hours of pouring. The results from the finite element method model in the above case are consistent with the results obtained from the temperature nomogram and the error of (64.81 – 64) / 64.81 = 1.25 %. This above error is quite small when compared with a maximum prediction error of ± 6.8 °C for a 90 % confidence level between actual application and the established prediction nomogram proposed by Silva and Vít Smilauer [29]. Thus, the maximum temperature result obtained from the nomogram is reliable.

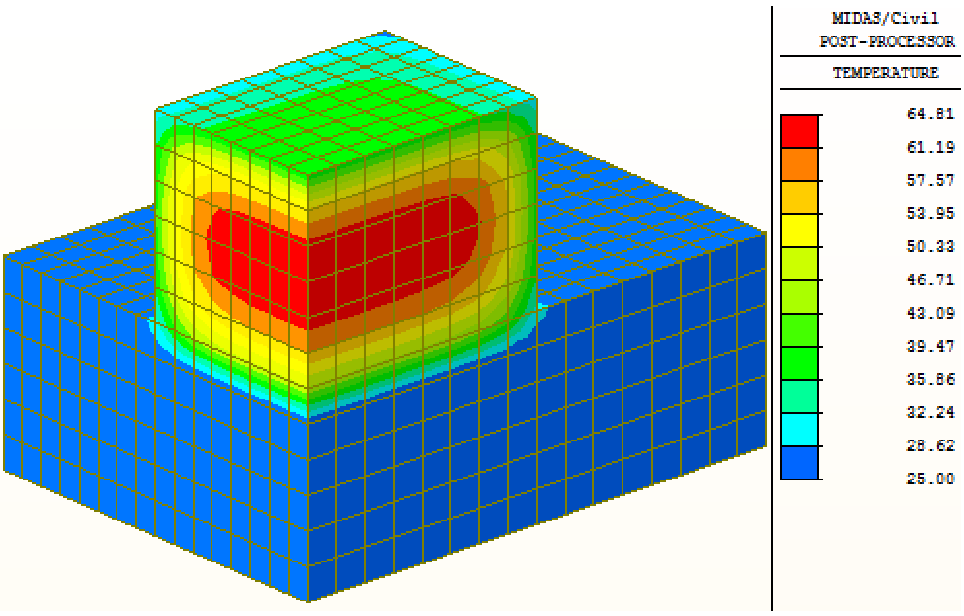

Figure 5. Maximum temperature in mass concrete members at the age of 96 hours after pouring (according to finite element method).

4. Conclusions

Based on the obtained results from the study, the following conclusions can be drawn:

1. The temperature in mass concrete structures is most affected by such factors as concrete mix and construction technique. The nomogram to predict the maximum temperature in the mass concrete structures, based on the mathematical functions of the maximum temperature acquired depending on the material and construction method, is established. The advantage of the maximum temperature nomogram

is that it allows engineers to quickly determine the maximum temperature with variations in cement content, the initial temperature of the concrete mix, and building conditions.

2. Instead of using the finite element method, the obtained math is of great practical value to quickly determe the maximum temperature in mass concrete. Following that, proper construction methods for preventing the formation of thermal cracks in mass concrete structures are proposed.

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