The Effect of Thermo-Mechanical Properties of Concrete on the Temperature Field in Mass Concrete

Duc-Phong Pham
Institute of Techniques for Special Engineering, Le Quy Don Technical University, Hanoi, Vietnam
ducphong357@lqdtu.edu.vn

Trong Chuc Nguyen
Institute of Techniques for Special Engineering, Le Quy Don Technical University, Hanoi, Vietnam
trongchuc.nguyen@lqdtu.edu.vn (corresponding author)

Kim-Dien Vu
College of Industry and Construction, Quang Ninh, Vietnam
kimdienxdtb@gmail.com

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ABSTRACT

The current study explores the effect of three basic thermal properties of concrete on the mass concrete temperature field. It investigates the relationship between thermal conductivity, specific heat capacity, and density with the maximum mass concrete temperature. The results revealed that all three thermal properties have a linear relationship with the maximum mass concrete temperature since the latter decreases while these properties increase.

Keywords-thermo-mechanical properties; temperature field; thermal conductivity; specific heat capacity; density; thermal crack; mass concrete

I. INTRODUCTION

Any large, heavy-volume concrete structure with boundary conditions that are more susceptible to high temperatures as a result of a faster hydration heat rate can be characterized as mass concrete [1]. The latter refers to large in-situ concrete poured constructions such dams, bridge piers, large building foundations, and large concrete installations (minimum 1 m deep) [2, 3]. Concrete's high temperature causes large thermal stresses, cracking, and a reduction in the long-term strength gain. The primary characteristic that sets mass concrete apart from the regular concrete is its thermal behavior [4]. The aforementioned properties are included in the mass concrete definition, as provided by the American Concrete Institute [5]. The hydration reaction generates a great amount of heat, so in the absence of a suitable method to disperse this heat, a big temperature difference between the inner and external surfaces of the mass structure occurs, causing further thermal strains and cracks. Through those cracks, air and water can reach the reinforcing steel leading to corrosion. Thus, thermal cracks create problems with durability [6-8]. The primary factors that can affect mass concrete temperature are: composition and high quality of cement, aggregate content, thermal expansion coefficient, the shape of the structure, the temperature of the materials close to the structure, and the initial temperature of the concrete mixture [9, 10]. Many of the above factors have been the subject of numerous investigations. However, the impact of thermal properties, like thermal conductivity, specific heat capacity, and concrete density on the maximum concrete temperature has not been thoroughly studied. Authors in [11] examined the effect of the specific heat capacity and thermal conductivity coefficient on the roller compacted concrete.

This study investigates the effect of the thermal properties of concrete, such as thermal conductivity, specific heat capacity, and density, on the maximum temperature in mass concrete. This study's results will open a new research direction for the mass concrete temperature field, associated with cement hydration and taking into account that the reinforcement content affects the equivalent thermal properties of reinforced concrete.

II. PROPERTIES AND ANALYSIS

A. *Concrete's Thermal Properties*

1) *Thermal Conductivity*

Thermal conductivity (k, W/(m×K)) refers to the ability of concrete to conduct heat. It is affected by the composition of concrete and humidity. That is, high humidity levels increase thermal conductivity values.

The samples' thermal conductivity was measured by utilizing (1) [5], at a temperature of 40°C, under normal external conditions, namely relative air humidity of 65%, ambient temperature of 20°C, and atmospheric pressure of 1013Pa. The used samples were dried at a temperature ranging from 105°C - 110°C and cooled in an environment with 60% humidity for 24 hours. Therefore, the samples' thermal conductivity can be estimated by:

$$k_0 = k_1 \cdot \left(\frac{h_0}{h_1}\right) \cdot \left(\frac{\Delta T_0}{\Delta T_1}\right) \quad (1)$$

where k_1 is the standard thermal conductivity (W/(m×^{o}C)), h_0 and h_1 denote the thickness of the test sample and standard (mm), ΔT_0 and ΔT_1 are the temperature differences inside the standard and the sample, expressed in ^{o}C.

2) Specific Heat Capacity

Specific heat capacity (C, J/(kg×^{o}C)) refers to the concrete's ability to absorb energy in the form of heat. It constitutes the amount of heat that must be added to one unit of mass concrete in order to accordingly cause one unit increase in temperature. The typical value for C in regular concrete ranges from 0.8 to 1.20 kJ/(kg×K). The specific heat capacity is calculated by (2) [5]:

$$C = \frac{\beta^2}{\rho_{dry} \cdot k_d} \quad (2)$$

where β is the thermal effusivity (J/(s$^{0.5}$ ×m^2×K)), k_d is the thermal conductivity (W/(m×K)) when concrete is dry, and ρ_{dry} is the dry density (kg/m^3).

3) Density of Concrete

Density of concrete refers to the relationship between a mass of concrete and its volume. It is impacted by the amount of water and the present particles, the aggregates utilized, and the number of voids. The density of concrete samples is calculated by utilizing (3) in a natural moisture condition, with an error of up to 1 kg/m^3 [5]:

$$\rho_C = \frac{m}{V} \cdot 1000 \quad (3)$$

where m is the sample weight (g) and V is the sample volume (cm^3).

B. Methods

This study developed a computer code deploying the Finite Element Method (FEM) [8, 12] to analyze the temperature field. In order to do that, some additional thermal parameters were employed.

Thermal Conduction (TC) is the diffusion of thermal energy (heat) within one material or between materials being in contact to each other. A way to examine TC, is to calculate the heat flux q (W/m^2), which is described by the Fourier's law (4) [13-15]:

$$q = -k \cdot \frac{dT}{dx} \quad (4)$$

where k is the thermal conductivity (W/(m×^{o}C)), T is the temperature (^{o}C), and x is the thickness of the sample (m).

The convection boundary condition refers to the existence of either convection heating or cooling at the surface [16, 17]:

$$q = \beta \cdot (T_s - T_b) \quad (5)$$

where q is the heat flux (W/m^2), β is the heat convective transfer coefficient (W/(m^2×^{o}C)), T_s is the solid surface temperature, and T_b is the temperature of the surrounding fluid.

Heat transfer problems are the subject of transient thermal analysis, with the analysis of the temperature field in mass concrete being one of them. The matrix form of the transient thermal conduction can be written as [18-21]:

$$[K]\{T\} + [C]\left\{\frac{\partial T}{\partial t}\right\} = [Q] \quad (6)$$

where [K] is the conductive matrix, including the thermal conductivity, heat convective transfer coefficient, emissivity and shape factor, [C] is the specific heat matrix, [T] represents the temperature vectors at the nodes, [$\partial T/\partial t$] is the temperature derivative with time, and [Q] is the heat flow rate of the nodes (heat generation).

The parameters [K], [C], [T], [$\partial T/\partial t$], and [Q] will be created automatically in Midas Civil [22] using the model geometry parameter, material performance parameter, and boundary conditions imposed on the model.

For the study, a 2D model with 1m x 1m concrete blocks without reinforcement and a 0.1m grid were used. Concrete properties were defined as:

- k - thermal conductivity : 1.5 - 3.5 (W/(m×K)).
- C - specific heat: 0.8 - 1.20 (J/(kg×K).
- ρ - density: 2000-3000 (kg/m^3).
- The concrete mix consists of 125 kg of Portland cement and 75 kg pozzolan per cubic meter.
- The total heat generated corresponds to 309kJ/kg of the cementitious material.
- The ambient temperature, concrete bottom slab temperature, and the concrete mix temperature when placed are assumed to be 25^{o}C.

III. RESULTS AND DISCUSSION

A. Thermal Conductivity (k)

Table I shows that when k increases from 1.5 W/(m×^{o}C) to 3.5 W/(m×^{o}C) with 0.5 step, the temperature decreases from 37.28 ^{o}C to 35.23^{o}C, which corresponds to a 5.5% decrease. Figure 1 presents the plot of the results and proves that the relationship between the maximum temperature and the thermal conductivity coefficient is linear. Based on then data analysis, the specific relationship is given by:

$$y_1 = 38.55 - 0.99 \cdot x \text{ with } R^2 = 0.953 \quad (7)$$

where y_1 is the maximum temperature, (°C) and x represent the thermal conductivity.

TABLE I. MAXIMUM TEMPERATURE VALUES IN RELATIONSHIP WITH THERMAL CONDUCTIVITY

k, W/(m×°C)	1.5	2	2.5	3	3.5
T_{max}, **°C**	37.28	36.40	35.92	35.54	35.23

The coefficient of x in (7) is -0.99, which means that when x, namely k, increases by 1, the maximum temperature in the concrete block decreases by approximately 1 °C. Midas Civil produced another plot form of the results, illustrating the thermal spectrum of the concrete sample for the lower (Figure 2) and the higher (Figure 3) value of k.

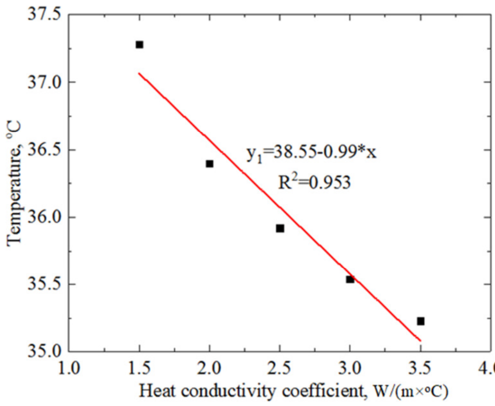

Fig. 1. Maximum temperature and thermal conductivity relationship.

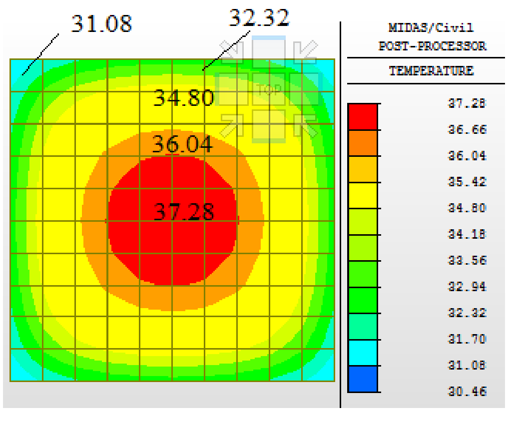

Fig. 2. Thermal spectrum for k = 1.5W/(m×°C).

B. Specific Heat (C)

Table II demonstrates that while C increases from 0.8 kJ/(kg×K) to 1.2 kJ/(kg×K) with 0.1 step, the maximum temperature decreases from 36.49 °C to 35.41 °C, which corresponds to a decrease of 2.9%. Therefore, maximum temperatures are obtained with lower specific heat values, meaning that less heat is needed for a temperature increase to take place

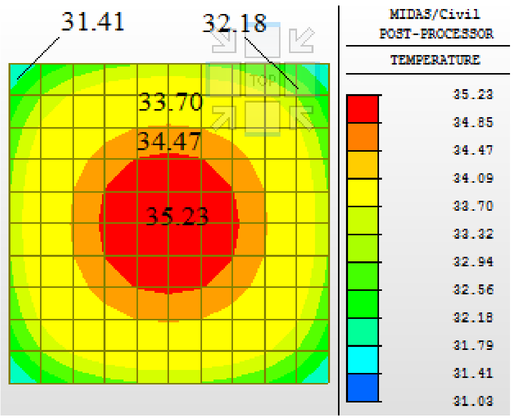

Fig. 3. Thermal spectrum for k = 3.5W/(m×°C).

TABLE II. MAXIMUM TEMPERATURE VALUES IN RELATIONSHIP WITH SPECIFIC HEAT

C, kJ/(kg×°C)	0.8	0.9	1.0	1.1	1.2
T_{max}, **°C**	36.49	36.19	35.90	35.63	35.41

Figure 4 portrays the temperature decrease when C increases. It also proves that the relationship between the maximum temperature and the specific heat is linear and according the data analysis, it is expressed as:

$$y_2 = 38.64 - 2.72 \cdot x \text{ with } R^2 = 0.997 \quad (8)$$

where y_2 is the maximum temperature (°C) and x is the specific heat.

The coefficient of x in (8) is -2.72, which means that when x, namely C, increases by 1 kJ/(kg×K), the maximum temperature in the concrete block decreases by 2.72 °C.

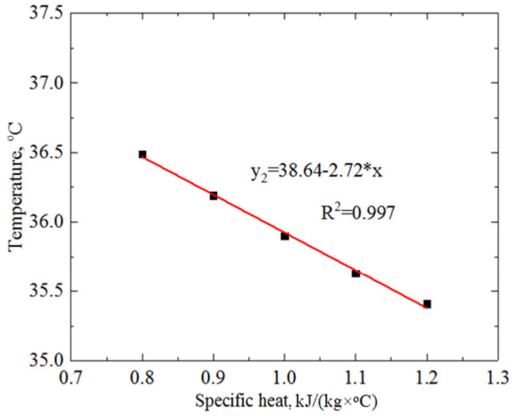

Fig. 4. Maximum temperature and specific heat relationship.

Figures 5 and 6 illustrate the thermal spectrum of the concrete sample, for C = 0.8 kJ/(kg×K) and C=1.2 kJ/(kg×K), respectively, using Midas Civil.

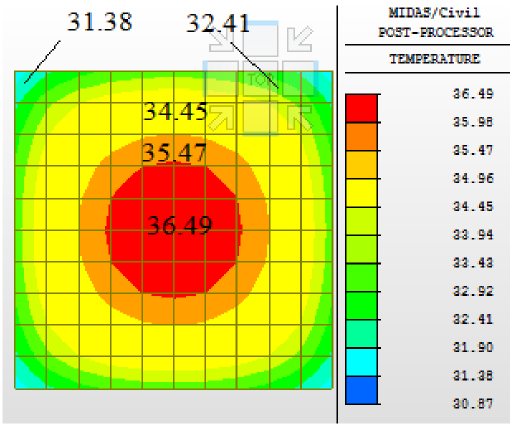

Fig. 5. Thermal spectrum for $C = 0.8$ kJ/(kg×K).

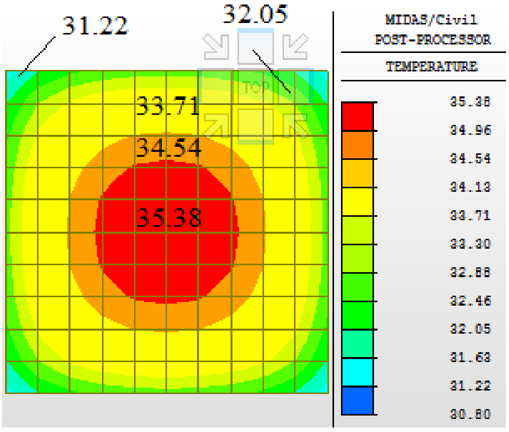

Fig. 6. Thermal spectrum for $C = 1.2$kJ/(kg×K).

C. *Density (ρ)*

Concrete is typically distinguished into two main categories based on its density: normal-weight concrete, which has a density between 2000kg/m^3 and 3000kg/m^3, and lightweight concrete, which has a density between 1350kg/m^3 and 1950kg/m^3. The concrete of normal-weight was the one examined in this investigation. Table III shows that while ρ increases from 2000 kg/m^3 to 3000 kg/m^3, the maximum temperature decreases from 36.42 °C to 35.52 °C, which corresponds to a decrease of 2.4%.

TABLE III. MAXIMUM TEMPERATURE VALUES IN RELATIONSHIP WITH DENSITY

ρ, kg/m^3	2000	2200	2400	2600	2800
T_{max}, °C	36.42	36.18	35.95	35.73	35.52

Figure 7 exhibits that the relationship between the maximum temperature and the density is linear. According to the data analysis, this relationship can be described by (9):

$$y_3 = 38.57 - 0.001 \cdot x \;\text{ with }\; R^2 = 0.998 \qquad (9)$$

where y_3 is the maximum temperature, (°C) and x are the density ρ of concrete (kg/m^3).

The coefficient of x in (9) is -0.001, which means that when x, namely ρ, increases by 1 kg/m^3, the maximum temperature in the concrete block decreases by 0.001 °C. Figures 8 and 9 display the thermal spectrum of the concrete sample for ρ = 2000 kg/m^3 and ρ = 3000 kg/m^3, respectively, utilizing Midas Civil.

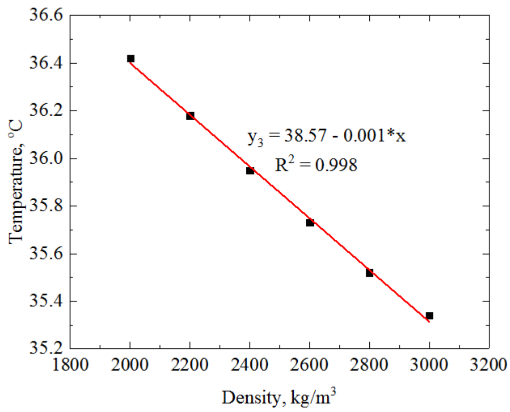

Fig. 7. Maximum temperature and density relationship.

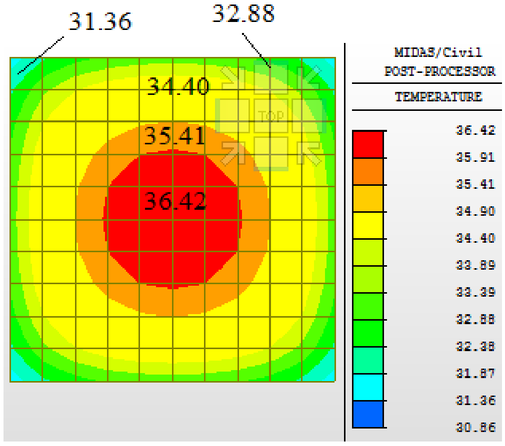

Fig. 8. Thermal spectrum for ρ = 2000 kg/m^3.

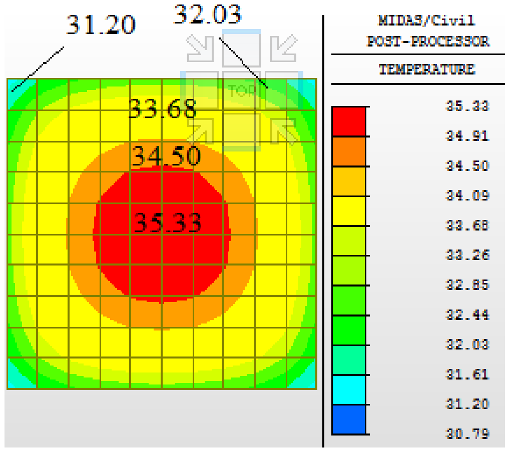

Fig. 9. Thermal spectrum for ρ = 3000kg/m^3.

IV. CONCLUSIONS

This study investigated the influence of thermal conductivity, specific heat capacity, and concrete density, to the maximum temperature of mass concrete. The results reveal that all three properties have a linear relationship with the maximum concrete temperature and as they increase, the temperature decreases. Thus, concrete with greater thermal conductivity, density, and specific heat is preferred for minimizing the maximum temperature core of the mass concrete. It is noticable that the the maximum temperature reduction caused by the three thermal properties is not significant. Specifically thermal conductivity reduces the maximum temperature by 5.5%, while also reducing the specific heat capacity by 2.9%, and density by 2.4%.

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