# THE EFFECT OF SPLITTING CONCRETE PLACEMENT ON CONTROLLING THERMAL CRACKING IN MASS CONCRETE

**Tran Hong Hai[1]*, Luu Van Thuc[2]**

**Abstract:** *Thermal cracking due to heat of hydration in mass concrete is a common phenomenon. When the internal temperature in a concrete block exceeds the allowable limit, it will generate large thermal stress field which leads to early-age cracks and the loss of structural integrity. Therefore, it is significant to illustrate the thermal cracking process and study how to restrain this phenomenon in mass concrete. The paper presents a method of controlling thermal cracks by splitting concrete placement horizontally into layers at different levels of a structure, based on the finite element analysis. The interval between placing lower and upper concrete layers is also surveyed. Numerical analyses are performed by developing a finite element model of the foundation with and without placing concrete layers. Analytical results demonstrates that not only the position of splitting but also the interval between placing concrete layers has simultaneous effect on forming and controlling thermal cracks. The suitable position of splitting concrete placement and the time limit between placing concrete layers are then determined.*

**Keywords:** *Thermal cracking index; mass concrete placement; stress - temperature field; simulation.*

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## 1. Introduction

Mass concrete construction often constitutes a challenge and requires significant efforts to control temperature rise due to the heat of hydration of the cementitious materials. Excessive temperature increase leads to thermal gradient between the core of mass concrete and its surface and may cause cracking when the thermal stress in concrete exceeds its tensile strength [1,2]. The thermal cracking will destroy the integrity and stability of the mass concrete structure and bring huge damage to it [3]. These thermal cracks lead to a high possibility of developing cracks which penetrate the structural member as well as micro-scale cracks on the surface of concrete member. They can also affect the structural performance, serviceability, cracking probability, and durability of the concrete structures [4]. From this reason, it is significant to illustrate the process of forming the cracks research methods in order to control thermal cracking due to heat of hydration.

There are two problems when heat of hydration in mass concrete is not controlled is that: 1) when a peak temperature in massive concrete elements in excess of 70°C may lead to phenomenon, referred to as a delayed ettringite formation (DEF), a normal product of early cement hydration. Expansive pressures occur in the pores of concrete during ettringite formation, causing cracking in the hardened concrete. Moreover, a temperature rise above 70°C in the fresh concrete mix also causes sulfate to be trapped in hydration products that will be released later, to form ettringite in the meso-pores. DEF can be prevented by limiting the internal concrete temperature to 70°C during its very early-age. This can be achieved either by direct specification, or indirectly by limiting the cement content, specifying the use of low/very low heat cement, arrange suitable casting layers… The ACI specification for structural concrete [9] limits the maximum temperature in concrete to 70°C (158°F) to avoid this thermal cracking [1,7,9]. 2) Excessive temperature differential between the core and the surface would result in cracking at the surface. The ACI committee 207.1 for mass concrete [6] suggests that a thermal gradient in excess of 22 to 25°C can cause cracks in concrete. The temperature generated from the hydration of cement in mass concrete along with the low rate of heat

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dissipation leads to temperature rise in the concrete block. The interior concrete tends to expand, while at a low ambient temperature, the exterior concrete tends to shrink and resist interior concrete to expand, thus causing thermal stress [1,6]. Therefore, methods which control the thermal cracking in mass concrete aim dealing with these two main phenomena.

At present, there are three main methods for controlling construction temperature cracks, including:1) installing a pre-buried cooling water pipe, 2) covering with a thermal insulation material, and 3) adding the new materials (PCM-Phase Change Material) in concrete [10], but there are less studies focusing on controlling thermal cracks by the method of splitting concrete placement horizontally. Seo et al. [11] developed a vertical pipe cooling method and tested it in wall - type mass concrete specimen to validate the method. The experimental result showed that the temperature of concrete specimen with the vertical cooling pipe system was 8-14°C lower than that of the control specimen without the vertical pipe cooling system. Some construction measures [12] have adopted thermal insulation material to cover mass concrete in order to control thermal cracks in mass concrete. Some other studies [13] have investigated the use of phase change material (PCM) to limit the rise in temperature of mass concrete.

This paper presents a method of controlling thermal cracks by splitting concrete placement horizontally into layers at different levels of a structure, based on the finite element analysis. The interval between the placements of lower and upper concrete layers is also surveyed. Numerical analyses are performed by developing a finite element model of the foundation with and without placing concrete layers. The temperature distribution is calculated by flow analysis of Midas/Civil finite element software. Verification of the results of the thermal analysis of Midas finite element software was performed by experimental studies [1,3,10,11]. Based on the numerical results, the effect of the position of splitting and the interval between placing concrete layers on forming and controlling thermal cracks are estimated and evaluated. The suitable position of splitting concrete placement and the time limit between placing concrete layers are then determined. Some numerical examples provided demonstrate the applicability of the proposed method.

## 2. Finite element simulation

### *2.1 The crack index*

Relationship between thermal stress and temperature in mass concrete is derived as in Equation (1) [8]. In order to control thermal cracking, because the values of *E* and *β* is difficult to change because they are function of aggregates available on site, it seems to be easier to reduce the amount of temperature drop *ΔT*.

$$\{\sigma\} = [R] \cdot E \cdot \beta \cdot \{\Delta T\} \tag{1}$$

where {*σ*} is thermal stresses; [*R*] is restraint ($0 < R < 1$); E is modulus of elasticity; {Δ*T*} is temperature drop; and *β* is coefficient of thermal expansion.

The evaluation of cracking in mass concrete can be made by using the thermal crack index. Thermal crack index is defined as a ratio of splitting tensile strength and tensile stress due to heat of cement hydration, shown as in Equation (2). The thermal crack index will be reviewed at the point where thermal stress is evaluated [2].

$$I_{\mathrm{cr}} = \frac{f_t(t_e)}{\sigma_t(t_e)} \tag{2}$$

where $f_t(t_e)$ is the splitting tensile strength of concrete at day $t_e$; and $\sigma_t(t_e)$ is the maximum thermal stress generated by the heat of hydration at $t_e$. Therefore, when the crack index $I_{cr} \le 1$, a concrete structure starts to crack.

### *2.2 The numerical model*

The analytical model includes a mat foundation often constructed in practice with the dimensions of 14400 × 9600 × 4800 mm, as shown in Fig. 1. For the thermal analysis, a subsoil supporting the mat foundation has the dimensions of 24000 × 19200 × 3000 mm.

Due to the symmetry of the structure, only one quarter of the entire structure is modeled and analyzed as shown in Fig. 2 with all the properties explained in Table 1. That helps observe the temperature and stress field in the center of foundation mass conveniently and reduce the analysis time.

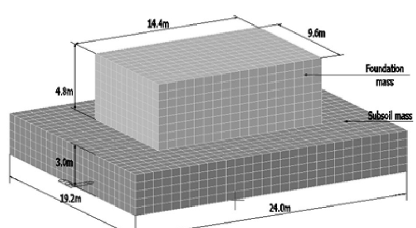



***Figure. 1.*** *Foundation analytical model*

***Table 1.*** *Material and thermal properties used to analyze*

| No | Property | Unit | Lower layer | Upper layer | Subsoil |
|---|---|---|---|---|---|
| 1 | Specific heat | kcal/kg°C | 0.25 | 0.25 | 0.2 |
| 2 | Weight density | kgf/m$^3$ | 2400 | 2400 | 1800 |
| 3 | Rate of heat conduction | kcal/m.h.°C | 2.3 | 2.3 | 1.7 |
| 4 | Convection coefficient, surface exposed to atmosphere | kcal/m$^2$.h.°C | 12 | 12 | 12 |
| 5 | Convection coefficient, steel form | kcal/m$^2$.h.°C | 12 | 12 | - |
| 6 | Ambient temperature | °C | 20 | 20 | - |
| 7 | Casting temperature | °C | 20 | 19 | - |
| 8 | 91-day compressive strength | kG/m$^2$ | 270 | 270 | - |
| 9 | Compressive strength gain coefficient | | a = 13.9; b = 0.86 | | - |
| 10 | 91-day modulus of elasticity | kG/cm$^2$ | $2.7734\times10^5$ | $2.7734\times10^5$ | $1.0\times10^4$ |
| 11 | Thermal expansion coefficient | | $1.0\times10^{-5}$ | $1.0\times10^{-5}$ | $1.0\times10^{-5}$ |
| 12 | Poisson's ratio | | 0.18 | 0.18 | 0.2 |
| 13 | Cement property | | Low heat of hydration cement | | - |
| 14 | Unit cement content | kg/m$^3$ | 320 | 320 | - |
| 15 | Heat source function coefficient | | K = 33.97; a = 0.605 | | - |

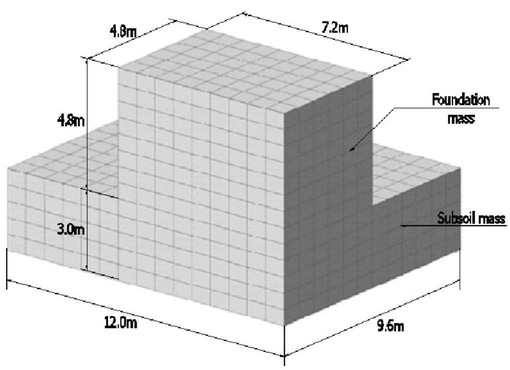



***Figure. 2.*** *Heat of hydration model used for analysis (1/4 symmetry model)*

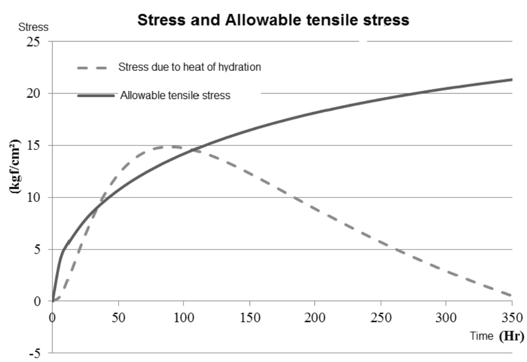
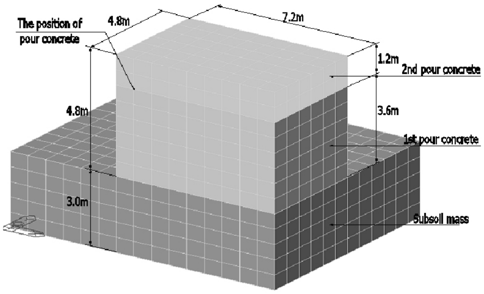



***Figure. 3.*** *Stress and allowable tensile stress on the perimeter of mat foundation in the Case No. 1*

### *2.3 Numerical results and discussions*

Four different cases will be studied. The Case No. 1 is planned to pour the entire fresh concrete of mat foundation continuously. For the case 2, 3 and 4, the concrete placement of mat foundation is split into two layers with the upper layer thickness of 1.2m, 2.4m and 3.6m respectively, as shown in details in Fig. 4, Fig. 8 and Fig. 12. The time interval between concrete layers is surveyed within the limit from 48h to 168h after placing the lower one. The temperature data is collected and analyzed at the time points of 48h, 72h, 96h, 120h, 144h and 168h.

There are two criteria to consider effects of controlling thermal cracks by splitting concrete placement horizontally into layers, including: 1) the maximum temperature generated from the hydration process of cement is analyzed at the center of mat foundation. This index must be lower than 70°C; and 2) thermal crack index is surveyed on the perimeter of mat foundation where could find out the maximum tensile stress. This index is used to assess cracks due to heat of hydration (see Fig. 3). When the crack index $I_{cr}\leq1$, concrete structure starts to crack. Therefore, the aim of controlling thermal cracking is to determine the suitable position of splitting concrete placement and the time limit between placing concrete layers in order to ensure the index $I_{cr} > 1$.



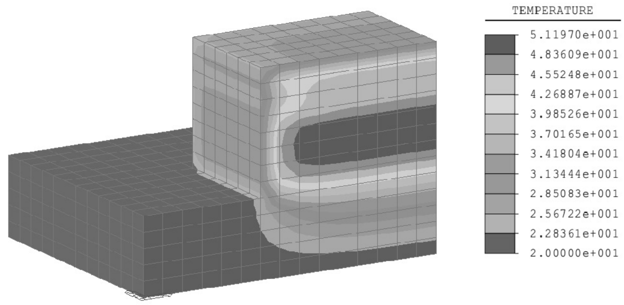




***Figure 4.*** *Numerical model in the Case No.2* ***Figure 5.*** *The maximum temperature field in the Case No.2*

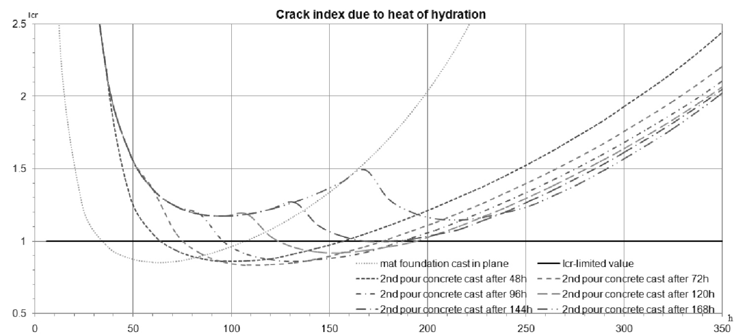



***Figure 6.*** *The thermal crack index in the Case No.2*

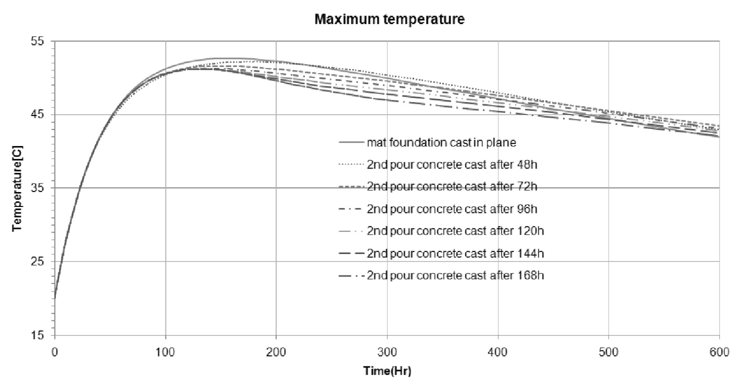



***Figure 7.*** *Temperature curves of interior points at the foundation center in the Case No.2*

*2.3.1 Results of Case No. 1 and No. 2*

With the dimensions and material properties defined, as shown in Fig. 6, analytical results demonstrate that if cast in place continuously, the mat foundation will be cracked at 35h after casting. In the Case No. 2 of two-phase concrete placement (Fig. 1) with the upper layers intended to be poured after 168h (7 days) since the completion of the lower, the value of crack index reaches over than 1 (Fig. 6). That means thermal cracks would not occurr. However, if the top layer of the foundation is poured before 168h, thermal cracks would occur. Therefore, both the position of splitting concrete foundation and the interval between the placement times will affect simultaneously the formation of thermal cracks.

Regarding to the trend in temperature of the case of pouring the 2nd layer after 168h, it can be seen that the crack index changes its direction when the latter is poured. The heat of cement hydration generated from the second placement adds more heat to the center of the lower layer, which results in the temperature increase in this area. That might be concerned as the reason why the temperature difference between the center and surfaces of the foundation rises up. As a result, the tensile stress on the perimeter might increase. The crack index tends to go up to the limited value of $I_{cr}$ and bottom at its lowest value $I_{cr}$ min = 1.15 at 220h (Fig. 6). After 220h, this line tends to go up because the upper layers starts to 2nd pour start to the heat loss, leading to decrease the temperature difference and $I_{cr}$. The trends in temperature of other cases could be explained the same.

The maximum temperature reaches up to 52.6°C at 156h in the center (Fig. 5) when the mat foundation is placed fresh concrete continuously (Fig. 7). For the Case No. 2, the maximum temperature is lower than the first one and tends to decrease corresponding to the increase of the interval between two concrete placements. It can be explained that before pouring concrete at the second time, a part of heat of hydration escapes from the lower layer. The more the time interval between two placements increase, the more the heat escapes. That causes the decrease of maximum temperature occurred in the foundation.

*2.3.2 Results of Case No.1 and No.3*

Analytical results demonstrate that if cast in place continuously, the mat foundation will be cracked at 35h after casting (Fig. 10). In the Case No.3 in which the foundation is divided to pour fresh concrete twice with the construction joint shown in Fig. 8, if the second placement is started after 96h (4 days) since the completion of the first, thermal cracks will not appear (Fig. 10). However, if the time interval is less than 96h, the cracks will appear. Therefore, when the construction joint is located at the middle of the mat foundation, in order to control thermal cracking, the second concrete layer must be placed at least 96h after the first placement.

The maximum temperature peaks 52.6°C at 156h in the center when the mat foundation is placed fresh concrete continuously (Fig. 11). For the Case No.2, the maximum temperature is lower than the first one and tends to decrease corresponding to the increase of the interval between two concrete placements. In comparison with 51.19°C of the Case No.2, the maximum temperature of the Case No.3 is lower with 49.37°C while the upper layer is placed concrete after 168h in the both cases.

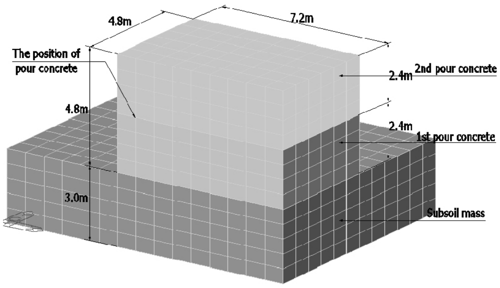



**Figure 8.** *Analytical model in the Case No.3*

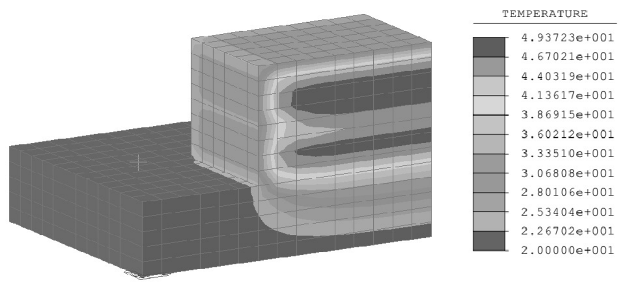



**Figure 9.** *The maximum temperature field in the Case No.3*

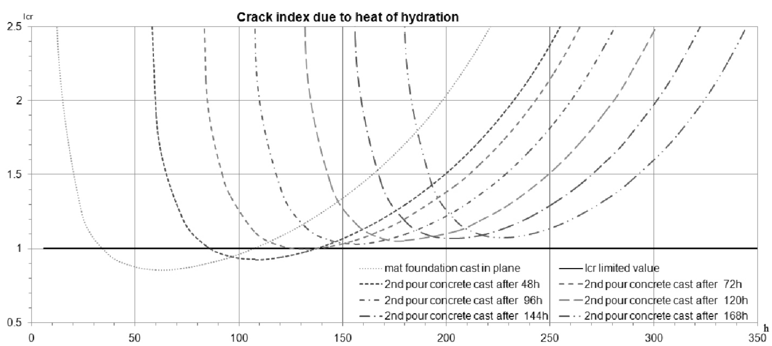



**Figure 10.** *The thermal crack index in the Case No.3*

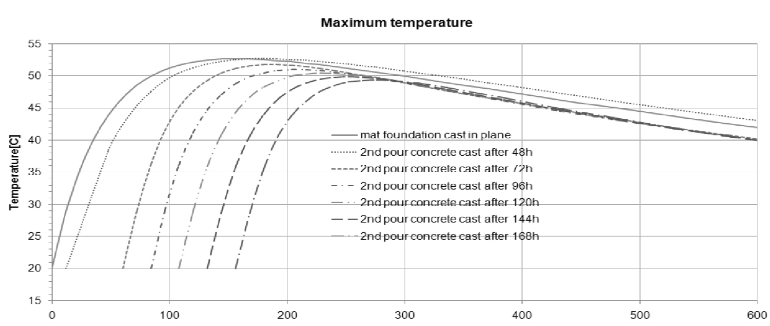



**Figure 11.** *Temperature curves of interior points at the foundation center in the Case No.3*

*2.3.3 Results of Case No.1 and No.4*

Analytical results demonstrate that if constructed by the method of continuous concrete placement, the mat foundation will be cracked at 35h after the placement. On the another hand, when there are two placements with the position of splitting at 3.6m below the top surface of mat foundation, thermal cracks occurs in all cases of setting up the time of the second concrete placement. It is impossible to control thermal cracking in this case. The statement can be explained that the second layer with the thickness of 3.6m generates a significant heat and exposes directly to the atmosphere, causing the increase of temperature difference.

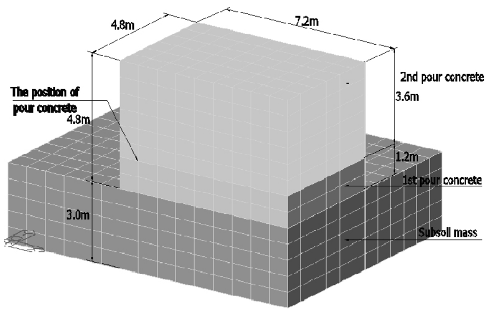



**Figure 12.** *Analytical model in the Case No.4*

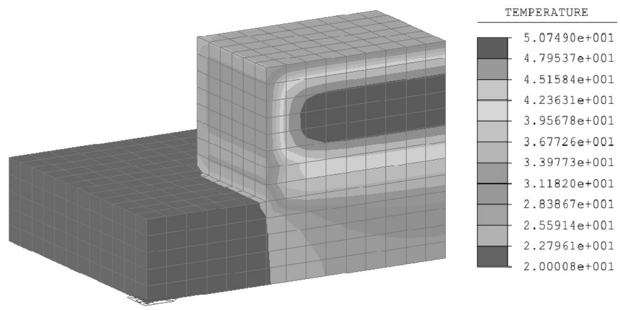



**Figure 13.** *The maximum temperature field in the Case No.4*

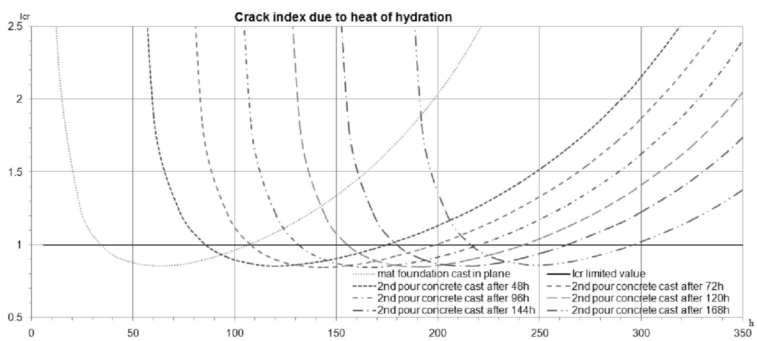



**Figure 14.** *The thermal crack index in the Case No.4*

Comparing the analytical findings of 4 cases, it can be realized that the Case No.2 provides the best optimal crack index and thermal cracks are controlled. At 168h after the concrete placement of the first layer, $I_{cr}$ obtained in the Case No. 2, No. 3, No. 4 are 1.15 (Fig. 6), 1.07 (Fig. 10), and 0.87 (Fig. 14) respectively whereas Icr reaches only 0.85 if the entire mat foundation is placed concrete continuously. Regarding to reduction of the maximum temperature, the position of splitting concrete placement should be located at the foundation middle to achieve the most effective result. At the surveyed time of 168h after the first concrete placement, the temperatures of the Case No. 3, No. 2 and No. 4 peak 49.37$^o$C, 51.19$^o$C and 51.2$^o$C respectively while for the Case No. 1 of continuous concrete placement, the maximum temperature is 52$^o$C. Both the crack index and the maximum temperature must be considered simultaneously in order to establish a suitable plan for controlling thermal cracking in mass concrete.

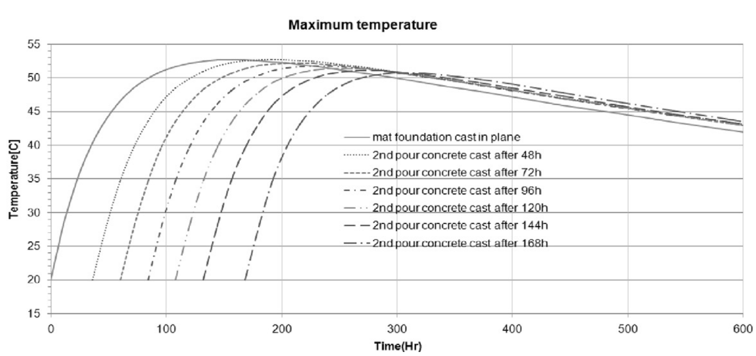



**Figure 15.** *Temperature curves of interior points at the foundation center in the Case No. 4*

## 3. Conclusions

The conclusions can be drawn from the research on controlling thermal cracks in mass concrete foundation structures by splitting concrete placement horizontally as follows:

- In order to illustrate the effectiveness of the method of controlling thermal cracking by splitting concrete placement, the results obtained from the analyzed simulation for this method and the case of continuous concrete placement are compared. The results show that placing concrete in layers could control thermal cracks successfully.

- The research discovers that not only the position of splitting concrete placement but also the interval between placements influence on the formation of thermal cracks simultaneously. Hence, a plan to control thermal cracks in mass concrete should consider those two problems together.

- With the simulation model and material properties as defined, the optimal crack index Icr is obtained when the mat foundation is placed concrete twice with the horizontal construction joint located at 1/3 of the foundation depth. On the another hand, the maximum temperature could get the lowest value if the joint is located at the middle of mat foundation and the upper concrete layer is placed after 168h since the first placement./.

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