A method of controlling thermal crack for mass concrete structures: modelling and experimental study

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Abstract. The control of the concrete temperature to prevent cracking can be viewed as principal goal in the design and construction of mass concrete. This paper researched on a novel technique for minimizing both the difference and the peak value of the temperature in mass concrete. Following this technique, the mass concrete is divided horizontally into two parts of different concrete mixtures but having the same strength grade. While the upper part is the normal heat concrete, the lower part can be considered as the low heat concrete which generate lower hydration heat than the upper part does. The influences of (i) concrete proportions of the layers; and (ii) thickness of the upper layer on the thermal behavior in mass concrete are two important aspects of the technique. Therefore, these two points represent important objectives of our present research. For this purpose, some numerical simulations with finite element method (FEM) and an in-situ experiment on a mass concrete block were performed. As a result, the simulated temperature field was validated by comparing with the experimental result and the principles of layers’ mixtures and thickness were drawn.

1. Introduction
Mass concrete plays an important role in the modern construction, especially in the construction of large structures such as raft foundations, thick walls and dams [1]. For those structures, huge amounts of concrete are required, contributing to significant heat generation during the cement hydration. The heat of hydration produces temperature rise in the structures and leads to the high thermal gradient between the core of mass concrete and its surfaces due to the difference of their heat dissipation rates [2,3]. A crucial issue of this thermal gradient is thermal cracking that would be formed if the thermal stresses (i.e. tensile stress) in structure exceed the evolving tensile strength of concrete, especially at early ages when the concrete is still developing its full strength [1–5]. Cracks may affect the safety and durability of massive concrete structures, in particular, for concrete underground structures (e.g. foundations, basement walls) for which no amount of cracking is permissible due to the high threat of groundwater.

Furthermore, it is more difficult to reestablish the integrity of the structure if cracks appear in the massive structures. Therefore, the control of the concrete temperature to prevent cracking can be viewed as principal goal in the design and construction of mass concrete [1,6]. Several techniques have been applied for achieving this, mainly focused on the reduction of two fundamental aspects: (i) the maximum temperature; and (ii) the differential temperature in mass concrete [3,5,6]. The amount
of heat generated by cement hydration (point (i)) could be limited by: replacing cement with pozzolans (e.g. fly ash, limestone, silica fume) [6,7]; pre-cooling of mix constituents [7,8]; using aggregates with low thermal expansion; cooling concrete during the mixing processes (i.e. mixing with ice [8]); controlling temperature during transport and placement; selecting suitable formwork for temperature control; scheduling of construction stages (see reviews in [1,6,9]). In order to lower the difference of temperature between the interior and exterior of mass concrete (point (ii)), various methods were used and mainly performed after concrete placement, such as circulating cold water in the pipes (cooling pipe method) [10], and surface insulation. The cooling pipe is one of the most effective ways to lower both the peak and the gradients of temperature. However, this method is not easy to handle, quite expensive and has a lot of risks. For instance, cracks may occur in concrete around the cooling pipes due to the high temperature difference between the water in the pipes and the concrete, or water in pipe may be frozen during winter time due to low ambient temperature and thus cannot flow continuously [11]. In an opposite way, all the surfaces of massive concrete structures are covered by multilayered sheet insulation materials for reducing the temperature gradient [1,5]. This work aims at keeping heat within the massive concrete structure (heating method) and assuring the temperature of its surfaces is not much lower than that of its core. Nevertheless, this method does not help in reducing the peak concrete temperature and may cause cracking from thermal shock if the insulation is removed too early. Therefore, this heating method is normally combined with the pre-cooling (i.e. before the concrete placement) techniques mentioned above to improve the efficiency of hydration heat reduction in mass concrete.

Based on the principle of “heating” method, Park et al. [12] have recently proposed a novel technique for reducing hydration heat in the mass concrete foundation. Following this technique, the mass foundation is divided horizontally into two parts of different concrete mixtures but having the same strength grade. While the upper part is the normal heat concrete, the lower part can be considered as the low heat concrete that generates lower hydration heat than the upper part does. The upper layer can generate higher temperature but dissipate the heat hydration more quickly than the lower layer. Therefore, this technique allows to minimize both the difference and the peak values of the temperature in mass foundation. The advantage of this method is that it does not require the time gap (i.e. the horizontal construction joint) between two layers during concrete placement and thus enhances the integrity of mass concrete. The influences of (i) concrete proportions of the layers; and (ii) thickness of the upper layer on the thermal behavior in mass concrete are two important aspects of the technique. These two points represent important objectives of our present research. For this purpose, some numerical simulations with finite element method (FEM) and an in-situ experiment in a mass concrete block were performed. As a result, the simulated temperature field was validated by comparing with the experimental result and the principles of layers’ mixtures and thickness were drawn.

### 2. Modelling study to determine parameters for experimental study

According to the ACI 207.1R-05 standard [5], mass concrete is defined as “any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking”. In addition to making a similar definition, the Vietnamese standard TCXDVN 305:2004 [13] also states that in the tropical climate conditions in Vietnam, concrete structures with the smallest edge or height greater than 2 m could be considered as mass concrete. Therefore, a 2.5x2.5x2.5 m concrete block was used for the experimental study in this research. Before performing in-situ experiments, some initial studies to determine the concrete mixtures as well as the thickness of the layers for the experimental concrete block were firstly conducted. For this work, a 2.5x2.5x2.5 m finite element model of the concrete block was built and analyzed in the Midas/Civil software [14]. This mass concrete block is assumed to be located on the ground base as a massive foundation. Two modelling analyses were conducted. While the first analysis considered a concrete block which used only one concrete mixture in its whole
volume (section 2.2), the second one focused on the concrete block that was built from two concrete layers with different concrete mixes (section 2.3).

2.1. Analytical model geometry and input parameters

Figure 1 shows the model geometry of the massive concrete block considered in the present work. Because of the symmetrical characteristic of both the model and its boundary conditions, in order to reduce the calculation work, a quarter of the concrete block with the corresponding boundary conditions (see figure 2) was analyzed. The values of input parameters used for the model are presented in table 1. At initial research, the ambient temperature was set at 27°C as the average temperature in April in Vietnam (i.e. the time of in-situ experiment). The concrete placing and the ground base temperatures were assumed to be 30°C and 20°C, respectively.

![Figure 1. The model geometry of the massive concrete block.](image1)

![Figure 2. Boundary conditions for the model of a quarter of the block.](image2)

**Table 1.** Input parameters used for the analytical model.

| Parameters                        | Unit          | Foundation | Ground base |
|-----------------------------------|---------------|------------|-------------|
| Specific heat                     | kcal/kg°C     | 0.25       | 0.2         |
| Weight density                    | kg/m³         | 2400       | 1800        |
| Rate of heat conduction           | kcal/m.h.°C   | 2.3        | 1.7         |
| Convection coefficient, concrete surface | kcal/m².h.°C | 12         | 12          |
| Convection coefficient, steel formwork | kcal/m².h.°C | 12         | -           |
| Ambient temperature               | °C            | 27         | -           |
| Ground base temperature           | °C            | -          | 20          |
| Placing temperature               | °C            | 30         | -           |
| 28-day compressive strength       | kG/m²         | 400        | -           |
| Intensities coefficient           |               | a=13.9     | -           |
|                                   |               | b=0.86     | -           |
| Modulus of elasticity             | kG/cm²        | 2.7734 x10⁵ | 1.0 x10⁴   |
| Thermal expansion coefficient     |               | 1.0x10⁻⁵   | 1.0x10⁻⁵    |
| Poisson's ratio                   |               | 0.18       | 0.2         |

2.2. 1st Analysis: analytical model had one concrete mixture

The first analysis was performed on the concrete foundation having only one concrete mixture. The purposes of this analysis were to (i) examine the temperature field of the foundation in case it has one concrete mixture and (ii) investigate on the effect of fly ash on the temperature field. To do so, three analysis cases with three different concrete mixtures were performed. All the three cases used the same amount of sand, aggregates, water and binder (i.e. cement and/or fly ash). In the first case, no fly ash was used, while the amount of fly ash was 10% and 20% of the total binder in the second and third
cases respectively. The cement used in all mixes was PCB40 type Portland cement, satisfying the standard TCVN 2682:2009 [15]. The details of each mixture proportion for 1m$^3$ of concrete are summarized in table 2. The target compressive strength of all the three ready-mixed concrete batches was 400 kG/cm$^2$.

Table 2. Details of the mix proportions for 1m$^3$ of concrete used for the 1$^{st}$ analysis.

|        | Sand (kg/m$^3$) | Aggregates (kg/m$^3$) | Water (l/m$^3$) | Binder | Total weight (kg/m$^3$) |
|--------|----------------|------------------------|----------------|--------|------------------------|
|        |                |                        |                | Cement | Fly ash |                  |
|        |                |                        |                | % Binder | % Binder |                |
| Case 1 | 100            | 0                      |                | 880    | 951     | 160               | 90                 | 10                  | 385                 |
| Case 2 | 80             | 20                     |                |        |         |                    |                    |                     |
| Case 3 | 80             | 20                     |                |        |         |                    |                    |                     |

Figure 3 shows the temperature variation at the center and exposed surface of the foundation corresponding to the three cases. It can be seen that at 50h after placing of concrete, the peak temperatures at center of the block were observed in all three cases. Thereby, the peak temperatures were 80.6°C, 71.1°C and 62.3°C for case 1, case 2 and case 3, respectively (see figure 3). The temperatures at center of block in all three cases then declined gradually to approximately 40°C at 200h after concrete placement due to the heat dissipation. According to ACI 207.1R-05 [5], the temperature rise of more than 70°C (case 1 and case 2) could lead to the phenomenon called Delayed Ettringite Formation (DEF) which may induce damage in mass concrete. The temperature difference between center and surface of the foundation were also observed at 50h after concrete casting with the maximum values were 38.5°C (case 1), 31.2°C (case 2) and 24.6°C (case 3). As mentioned in [3,5], a thermal gradient in excess of 25°C (case 1 and case 2) may cause thermal cracks in massive concrete structures. From the observations above, it can be concluded that (i) both the peak temperature at center and the temperature difference between center and surface of the foundation decrease when the amount of fly ash used increases; (ii) if the partial replacement of cement with fly ash is 20% total binder (case 3), the foundation might not be cracked due to thermal problems. In other words, the usage of fly ash as a partial placement of cement is an effective method to control thermal cracks of mass concrete.

2.3. 2$^{nd}$ Analysis: analytical model had two concrete layers with different mixtures

The second analysis was performed on the same concrete block (massive foundation) used in 1$^{st}$ analysis (section 2.2). However, the foundation in this analysis was built from two concrete layers: the upper layer generates the heat of hydration higher than the lower layer does. The main goal of this
work was to study the influence of the thickness and the concrete mixtures of these two layers on the temperature field in mass concrete.

2.3.1. The influence of the layers’ thickness on the temperature field of mass concrete

In order to find out the influence of layers’ thickness on the temperature field of the mass concrete, four research cases with four different upper layer’s thickness were considered. Based on the result of the 1st analysis (section 2.2), in the present work, the concrete mixtures used for the upper and lower layers were respectively the mix proportion of case 1 and case 3 in table 2. At this analysis, the concrete mixtures of the two layers were kept unchanged for all four cases. The details of concrete mixtures and the thickness of the two layers are summarized in table 3.

Table 3. The details of 1m³ concrete mixture and four different thickness of two layers in the block.

| Concrete layer | Layer’s thickness (m) | Sand (kg/m³) | Aggregates (kg/m³) | Water (l/m³) | Cement (% Binder) | Fly ash (% Binder) | Total weight (kg/m³) |
|----------------|-----------------------|--------------|--------------------|--------------|-------------------|-------------------|---------------------|
| Upper layer    | Case 1                | 0.25         | 880                | 951          | 160               | 100               | 0                   | 385              |
|                | Case 2                | 0.5          | 880                | 951          | 160               | 80                | 20                  | 385              |
|                | Case 3                | 0.75         | 880                | 951          | 160               | 80                | 20                  | 385              |
|                | Case 4                | 1.0          | 880                | 951          | 160               | 80                | 20                  | 385              |
| Lower layer    | Case 1                | 2.25         | 880                | 951          | 160               | 80                | 20                  | 385              |
|                | Case 2                | 2.0          | 880                | 951          | 160               | 80                | 20                  | 385              |
|                | Case 3                | 1.75         | 880                | 951          | 160               | 80                | 20                  | 385              |
|                | Case 4                | 1.5          | 880                | 951          | 160               | 80                | 20                  | 385              |

Figure 4 presents the temperature variation at the center and surface of the foundation model corresponding to four cases of upper layer’s thickness.

Figure 4. Temperature variation at the center and surface of the foundation model corresponding to four cases of upper layer’s thickness.
discussed in section 2.2). This means that, for a 2.5x2.5x2.5 m foundation, it is more effective in controlling thermal crack if the block is designed with two layers of different concrete mixtures (case 2 in this section) than with one layer. Although this improvement was not much for the 2.5-m block, the thermal crack control method of using two layers of different mixtures was proved to be more effective. Besides, with the presented controlling technique, the peak temperatures of the block in all research cases were also reduced.

2.3.2. The influence of concrete mixtures on the temperature field of mass concrete
In the previous analysis (section 2.3.1), we demonstrated that the 2.5-m mass concrete block divided horizontally into two layers of different concrete mixtures with the thickness of 0.5m for its upper layer is the most effective way to control the thermal crack. We now considered the influence of different concrete mixtures on the temperature field in the mass concrete block. For this work, based on the case 2 in table 3, we change the amount of fly ash used for concrete mixture of the upper layer. There were three research cases in which the amount of cement and fly ash was different for the upper layer while it was constant for the lower layer (see table 4). For all three cases, the amount of cement of the upper layer was higher than that of the lower layer. This ensured that the upper layer generated higher hydration heat than the lower layer did.

Table 4. Research cases with different concrete mixes of the upper layer.

| Concrete layer | Layer’s thickness (m) | Sand (kg/m³) | Aggregates (kg/m³) | Water (l/m³) | Cement (%) Binder | Fly ash (%) Binder | Total weight (kg/m³) |
|----------------|-----------------------|--------------|--------------------|--------------|-----------------|------------------|---------------------|
| Upper layer    | Case 1                | 880          | 951                | 160          | 100             | 0                | 385                 |
|                | Case 2                | 880          | 951                | 160          | 90              | 10               | 385                 |
|                | Case 3                | 880          | 951                | 160          | 85              | 15               | 385                 |
| Lower layer    | 2.0                   | 880          | 951                | 160          | 80              | 20               | 385                 |

Figure 5 displays the temperature variation in the foundation corresponding to three research cases. Once again, the peak temperatures at center of the block were observed at 50h after concrete placement. In case 1, the peak temperature was 63.6°C, while the peak temperatures were 62.9°C and 62.6°C for case 2 and case 3 respectively. Those values were approximately to each other because the lower layer had the same concrete mixes in all cases. The maximum temperature differences between the core and surface of the block were 24.0°C (case 1), 24.2°C (case 2) and 24.4°C (case 3). The analysis results showed that the temperature difference at the first case was the lowest. It is because the upper layer had no fly ash meaning that the generated hydration heat was the highest when
comparing to other cases, this helps to reduce the temperature difference between the core and surface of the foundation.

From the analysis results above (section 2.3), it is concluded that the experimental block should be divided into two layers whose thickness were 0.5 m and 2.0 m (case 2 in table 3). The mixtures of two layers would be designed as presented in table 3. The concrete mixes of the two layers have the same amount of total binder (cement and fly ash) of 385 kg/m$^3$. Whereby the upper layer has no fly ash (0 %), while the lower layer has fly ash of 77 kg/m$^3$ (20 % of total binder).

### 3. Experimental study

#### 3.1. Preparation of the mass concrete block

One mass concrete block of dimensions 2.5x2.5x2.5 m was built (figure 6) in order to examine the thermal behavior of concrete. The mix proportions and thickness of the two layers in the concrete block were as concluded in the previous section. The cement used was PCB40 type Portland cement and the maximum aggregates size was 20 mm.

Concrete was poured by truck mounted concrete pump. The formwork used was steel formwork. A nylon layer and a 50 mm insulation layer were used to cover the concrete surface and outside of formwork in order to prevent heat to radiate into the ambient environment (i.e. heating method). This curing method is effective to control the temperature difference between the surface and the center of the concrete block as discussed in section 1.

![Figure 6. Experimental concrete block of 2.5x2.5x2.5 m.](image)

![Figure 7. Experimental concrete block with three temperature measuring axes.](image)

#### 3.2. Instrumentation for data collection

Temperature sensors were installed at predetermined positions in the experimental concrete block to record the temperature distribution with respect to time. The layout of the measuring positions is presented in figure 8.
There were 15 measuring positions (TS) located along the corner, edge and center axes of the block (i.e. 5 TS for each axis). At each measuring position, there were two temperature sensors installed in order to ensure the reliability of the collected data. The surface temperature of the block was also recorded. Besides, the temperatures of the ambient environment, placing concrete and ground base were also gathered. All data were recorded at various times.

4. Validation of analytical model

In initial modelling study, the analytical model was simulated with the assumption values of ambient temperature, placing temperature and ground base temperature. In order to validate the model, model analysis was performed again with actual data collected during the experimental period as presented in section 3. The parameters values are shown in table 5.

| Parameters                      | Value                                |
|---------------------------------|--------------------------------------|
| Ambient temperature             | actual temperature at various time   |
| Placing temperature of the upper layer | 36.2°C                             |
| Placing temperature of the lower layer | 37.3°C                             |
| Curing temperature              | actual temperature at various time   |
| Ground base temperature         | actual temperature at various time   |
Figure 9 shows the comparatively results of the observed temperature field and the simulated temperature at three measuring points, i.e. TS3 (at the core of the block), TS5, and at the surface of the block, on the center axis of the concrete block (see figure 8 for their locations in the concrete block). It can be seen that the temperature curves provided by modelling and experimental studies at three measuring points had similar shapes and the deviation of simulated temperature values from experiment were little. The experimental peak temperature at the core of the block (TS3) was 73.7°C and the simulated value was 72.3°C. The experimental peak temperature at the measuring point TS5 was 70.2°C while the simulated value was 69.4°C. The experimental peak temperature at the surface of the block was 60.0°C while the simulated value was 59.2°C. The maximum temperature difference observed during experimental period was 18.3°C while the simulated value was 17.3°C. Besides, the comparisons between the experimental and simulated temperatures at other measuring points in the block provided the same conclusions. Those comparisons demonstrated that the simulation results are reliable.

Furthermore, both the observed and simulated values of temperature difference between the core and surface of the block were lower than 25°C meaning that the block might not be cracked due to thermal problems. This is consistent with the reality that there was no crack on the experimental block.

5. Discussion
The modelling and experimental studies performed on the 2.5x2.5x2.5 m block demonstrate the effectiveness of the usage of two layers with different mixtures for mass concrete in controlling thermal crack. The results show that the upper layer should generate more hydration heat than the lower layer does, so that reducing the temperature difference between the core and surface of the block. It is clear that the concrete at the surface loses heat to the ambient environment at a higher rate than the core part of the mass concrete block. This is the reason to cause large temperature difference between the core and surface of block, which is a condition to cause thermal cracks in mass concrete. The adjustment of the used amount of fly ash and the total binder determines the generated heat of hydration in concrete. Furthermore, the thickness of the upper concrete layer also affects the effectiveness of the method. The upper layer with the thickness of 0.5 m is the most proper division for the 2.5 m block.

The validation of the analytical model shows that the analysis results provided by numerical simulation are reliable. Therefore, in order to support those above research conclusions, further
modelling studies were performed similarly on a 5.0x5.0x5.0 m foundation model. Various scenarios of different mixtures and thickness were analyzed. Thereby, four cases of different upper layer’s mixtures at which the amount of fly ash varied from 0% to 30% of total binder and seven cases of different upper layer’s thickness ranging from 0.5 m to 3.5 m were investigated. The conclusions about the influence of layers’ mixtures and thickness were similar to the results discussed in section 2. Besides, for the 5.0 m block, the upper layer’s thickness of 1.0 m provided the lowest temperature difference (23°C) between the core and surface of the block. It is founded that, for both research blocks, the thickness of upper layer to that of lower layer ratio of ¼ was the best division scenario for the purpose of minimizing the temperature difference. This ratio is also similar to the ratio used for the 5.7 m block in the research conducted by Park et al. [12], where the 5.7 m block was divided into two layers whose thickness were 1.2 m and 4.7 m.

6. Conclusion
A novel thermal cracking control of mass concrete was researched. Thereby, the mass concrete is divided horizontally into two layers of different concrete mixtures but having the same strength grade. While the upper part generates higher hydration heat but dissipate heat quickly to environment, the lower part can be considered as the low heat concrete. This method helps to reduce both the temperature difference and peak temperature in mass concrete. With this method, concrete structures can be constructed without the need to provide horizontal construction joint between concrete layers.

This research adopted both analytical modelling and experimental study to investigate the influence of concrete layers’ mixtures and thickness on the thermal behavior in mass concrete. At first, the initial modelling study was performed on a 2.5x2.5x2.5 m concrete foundation to predict the temperature distribution in the foundation. Thereby, two analyses were performed in which the foundation had one concrete layer (1st analysis) and two layers (2nd analysis). In both analyses, various research cases of different layers’ concrete mixtures and thickness were conducted. The simulation results showed that the 2.5 m block should be designed with two concrete layers whose thickness were 0.5 m and 2.0 m and the upper layer should generate higher hydration heat than the lower layer does. This design helps to minimize the temperature difference between the core and surface of the block and reduce the peak temperature at the core. Then, the 2.5 m concrete block was built with temperature sensors installed inside in order to examine the temperature field. The experimental data were then used to validate the analytical model. Later, further modelling study was performed similarly on a 5x5x5 m concrete foundation in order to support the research results confirmed on the 2.5-m block. Overall, it is concluded that (i) the method of horizontally dividing mass concrete blocks into two layers where the upper layer generates higher hydration heat than the lower layer is an effective method to control thermal cracks in mass concrete; and (ii) the ratio of upper layer’s thickness to lower layer’s thickness is highly recommended to be ¼.

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