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# Experimental Investigations on Temperature Gradient in Massive Raft Foundation

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**Keywords**
Hydration heat; Blended cement; Blast Furnace Slag; Temperature Gradient.

**Abstract**

Thermal cracks are the major problem as temperature increases in massive concrete structures. It is imperative to investigate the temperature rise and to find effective techniques to control the heat of hydration of massive concrete. In this research, based on a segmental model test of high-rise building raft, the temperature field for the bottom, middle and top surface concrete of the raft caused by the heat of hydration were measured. Blast furnace slag cement (CEM III/A 42.5N) was used due to its lower percentage of C3A and C3S and lower surface area. The tested temperature rise curves indicated that the temperature increases quickly but diminishes gradually. The maximum temperature rises at the middle surface of the concrete reached 56oC, and the maximum temperature difference between the middle and the top surface was 15.80oC. The most extreme temperature difference between the top surface and the surrounding environmental temperature was 26.5oC. So, using slag cement controlled the heat of hydration of concrete leading to environmentally friendly concrete mixes.

## 1. Introduction

Mass concrete is common in heavy civil structures because of the encountered loads and environmental effects. In such members, a substantial amount of heat accumulated due to cement hydration. Hydration heat is a great challenge in mass concrete causing temperature gradients between the inner core and the surface temperature, which leads to thermal cracks. The differential temperature increases with the increase in volume of massive concrete elements [1]. Special considerations and attentions shall be taken in relation to heat of hydration for mass concrete especially for raft slab. Minerals such as limestone, slag, or fly

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ash can be added to concrete to reduce the hydration reactions and, in the case of slag and fly ash, to protect against delayed ettringite formation (DEF) [2]. The hydration reaction of cement is exothermic and the heat that is created can lead to DEF or cracking under specific conditions and especially in mass concrete elements [3]. Usually, cement, mineral additions, water to cement ratio, and chemical admixtures are optimized with reference to workability, setting time, compressive strength and the hydration heat in order to limit the risk of cracking [4, 5].

The hydration heat has a negative impact on concrete durability because of the volume changes of the elements, resulting in internal microcracks [6]. The heat evolution in concrete increases with increasing Tricalcium Silicate (C3S) and Tricalcium Aluminate (C3A) contents. On the contrary, pozzolanic material such as blast furnace slag reacts with calcium hydrates CH and water slower than regular hydration of CH [7]. Mass concrete with slag as a partial substitution for ordinary Portland cement (OPC) creates a lower temperature rise and a slower rate of heat increase than mass concrete with OPC only [8]. The utilization of ground granulated blast furnace slag (GGBS) diminishes the heat created during the acceleration stage and retard the hydration procedure [9]. GGBS, which is amorphous calcium aluminosilicate, has been considered to promote both pozzolanic and hydraulic activity [10]. Reactivity of GGBS is monitored by parameters such as chemical composition, fineness, and particle size distribution [10, 11]. Moreover, the reactivity of GGBS can be increased by the existence of calcium sulfates [10, 12, 13], so commercial GGBS regularly includes some sort of calcium sulfate [14, 15]. However, several investigations report early cement hydration caused by fine pozzolanic materials [16]. Substitution of fine cement particles with slag and coarse particles with less-reactive supplementary cementing materials (SCM) can provide low hydration heat and improved microstructure development [17]. For cement; calorimetry method can give steady estimations and is a suitable techniques to examine the early period of hydration where the heat rate is high. The objectives of the present study is to relate adiabatic heat of hydration to the mix designed to control hydration heat of mass concrete.

## 2. Experimental Work

### 2.1. Materials

Blast furnace slag cement (CEM III/A 42.5N) according to EN 196 with slag content 50% and specific gravity of 2.90 was used. The chemical composition of CEMIII/A is shown in Table 1. Ice water was used. Crushed dolomite with a nominal maximum size of 10 mm and specific gravity of 2.50 was used as coarse aggregate. The fine aggregates used was natural siliceous sand with fineness modulus of 2.34 and specific gravity of 2.64 conforming to ECP 203-2007 [18].The grain size distributions of coarse and fine aggregate are shown in Fig.1. Viscocrete admixture was used as a superplasticizer and powerful water reducer.

**Table 1:** Chemical Composition of Used Cement

| Compound (%) | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $K_2O$ | $Na_2O$ | Loss on Ignition |
|---|---|---|---|---|---|---|---|---|---|
| (CEM III/A) | 29.58 | 8.93 | 1.51 | 49.46 | 4.57 | 1.46 | 0.62 | 0.48 | 1.12 |

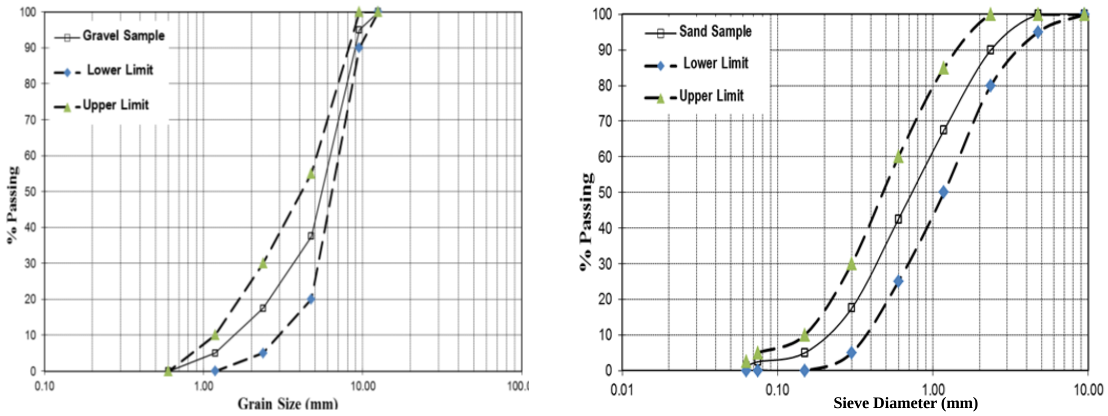


**Fig. 1** Grain size distribution for (a) Coarse aggregate and (b) fine aggregate

## 2.2 Mix Proportioning

Concrete mixtures with 0.40 w/c ratio and S/D ratio of ~ 1.0 as shown in table 2 were designed to investigate the impact of using blended cement (slag cement of grade 42.5N) on the heat production. The concrete in its fresh state requires high fluidity and segregation resistance ability. Therefore, many trial batches are often required to generate the data that enable to identify optimum mix proportions of the specifically used raw materials.

**Table 2:** Details of concrete mix proportions

| Component | W/b (%) | Weight per unit volume (kg/m$^3$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | w | C | SF | S | D | VMA |
| Content | 0.40 | 150 | 370 | 30 | 908 | 959 | 10.50 |

Note: w/b= water-to-binder ratio by weight, w= water, C= CEMIII/A, SF= Silica fume, S= sand, D= dolomite, VMA= viscocrete.

## 2.3. Testing procedure, set-up, and instrumentation

### *2.3.1 Preparation of Model (Raft)*

A mass RC model of 5mx5mx5m was prepared. The reinforcement ratio was 1%, Fig. 2. The model simulates part of the raft foundation of high-rise building. Standard cube samples were casted and tested at the age of 28 days to confirm that concrete grade is c45 (45N/mm$^2$), Fig. 3. Slump flow of the fresh concrete mix was measured to be 69 cm which qualifies as self-compacting concrete as shown in Fig. 4. The mix did not show segregation. The concrete temperature during casting was 22.0$^{\circ}$C, Fig. 5.


Figure 2: Raft reinforcement


Figure 3: Casting cube samples


Figure 4: Slump Flow Test


Figure 5: Measuring Concrete Temperature

*2.3.2 Temperature Acquisition System*

The temperature acquisition system consists of data logger box connected to the thermocouples embed in the mass RC model. The data logger transmits temperature records wirelessly to the processing computer which manipulates the collected records and plots time – temperature curves for each thermocouple. The records are collected every 5 minutes.

*2.3.3 Temperature Development Measurements*

Adiabatic tests were established in field for measuring hydration heat of massive concrete blocks. Concrete was cast into a thermally isolated wooden box. During test period the ambient temperature was recorded by a temperature sensor hung above the surface of the concrete test block. The temperature rise of concrete block was measured by twenty thermocouples. Temperature monitoring points are set at 4 locations. These four locations were selected in different positions of the concrete block after many trials to involve the overall differential temperature happened. Temperature sensors are evenly arranged at each point along the height direction every 1m, Fig. 6. The top sensor is 300mm to the concrete surface, and the bottom sensor is 300mm to the bottom of raft foundation (4700 mm to the concrete surface). The measurements were taken for 20 days directly after casting. The readings are automatically recorded and transmitted to processing unit wirelessly.

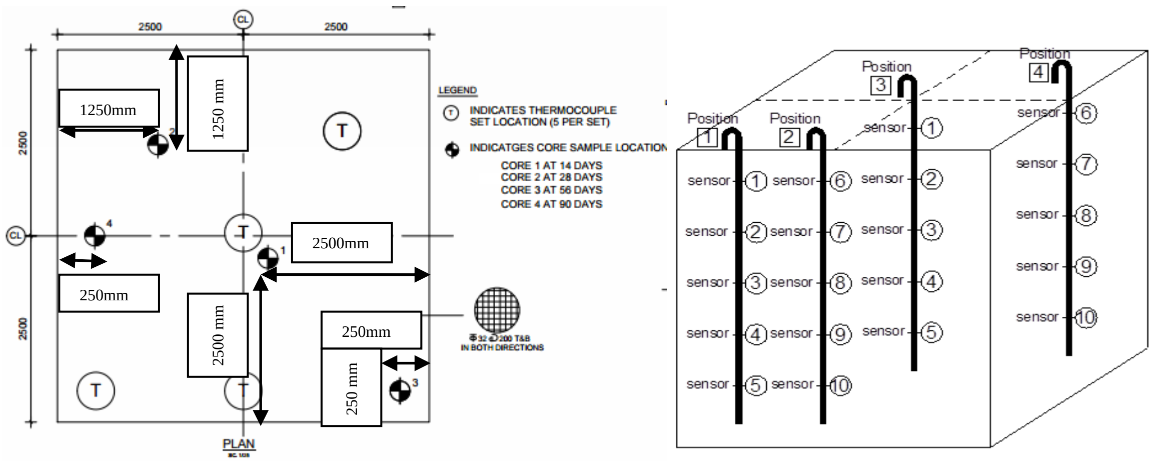


Figure 6: Locations and numbers of thermocouple sensors

## *2.3.4. Curing Method and Core Sample Test*

Within 12 hours of the completion of concrete casting, the concrete is covered with plastic film and quilt. Plastic film is used to seal the water inside the concrete for hydration and quilt is to control the temperature gradient from the core to the surface which is crucial to the quality of mass concrete. Quilt also insulates the concrete surface and surrounding air which will prevent temperature cracks on the concrete surface, Fig. 7. According to the temperature monitoring situation, the covering insulation layer can be adjusted timely to control the temperature difference of the mass concrete. When the difference of the highest temperature inside the concrete and the lowest ambient temperature is less than 20°C, the temperature monitoring can stop, and the insulation maintenance can be removed. Then watering is the major curing method, the principle of watering is to keep the concrete surface moisture for more than 14 days.

Four locations were selected to extract samples vertically, Fig.8. All samples were tested for cube compressive strength and modulus of elasticity. Average compressive strength of 28days is 641.1 Kg/cm$^2$, and modulus of elasticity is 3.52x10^$^6$ Kg/cm$^2$. Central sample from each core had petrographic testing performed in accordance with ASTM C 856-11. The texture of the sample was very fine too coarse-grained, showing porphyritic texture. For mineral composition, the sample was very fine too coarse-grained and composed of quartz, feldspars and rock fragments cemented by very fine-grained matrix of cement material.


Figure 7: Curing method of plastic film and quilt

Figure 8: core sample

# 4. Results and Discussions

## 4.1 Temperature Rise at Different Locations

As mentioned before, there are four positions for measuring the hydration heat within the concrete block (raft). The maximum temperature difference between those positions (1, 2, 3, and 4) was 13℃,14℃,16℃,14℃, and 10℃ at depth 1, 2, 3, 4, and 5 respectively as shown in Fig.9 which may not lead to concrete cracks.

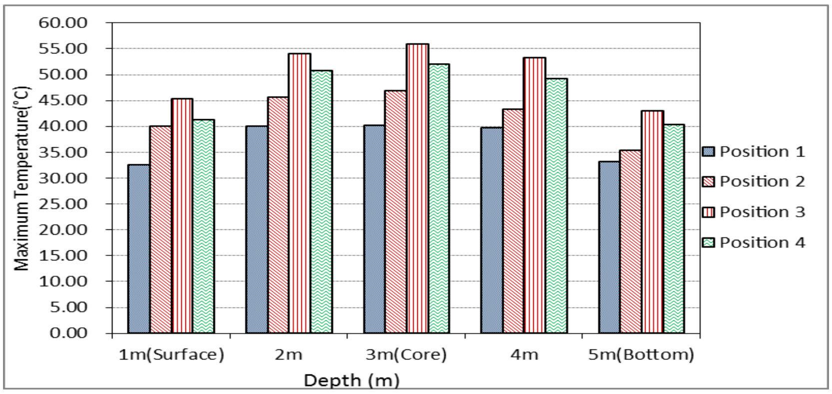


**Figure 9:** The relation between the maximum temperature and the selected depths

## 4.2 Temperature Rise at the Concrete Middle Surface

The Figure 10 showed the temperature rise development at the middle surface of the mass. It can be noticed that position 1 shows the lowest rate of hydration heat and its peak temperature was 40.29˚C achieved after 44.75 hours. This low temperature was due to that the sensor was located at the edge of concrete block. For position 2 the peak temperature was 44.42˚C achieved after 46.88 hours. Position 3 shows the highest rate of heat of hydration as the sensor located at the centre of concrete mass and its peak temperature was 56˚C achieved after 134 hours. The curve disturbance at 340 hours may be caused by the release of quilt. For position 4 the peak temperature was 53.34˚C achieved after 83.33 hours. Slag cement enhances the behaviour of concrete as pertained to hydration heat. The delayed gained in achieving the maximum temperature rise was due to the lower percentage of $C_3A$ and $C_3S$ content and the lower surface area in slag cement.

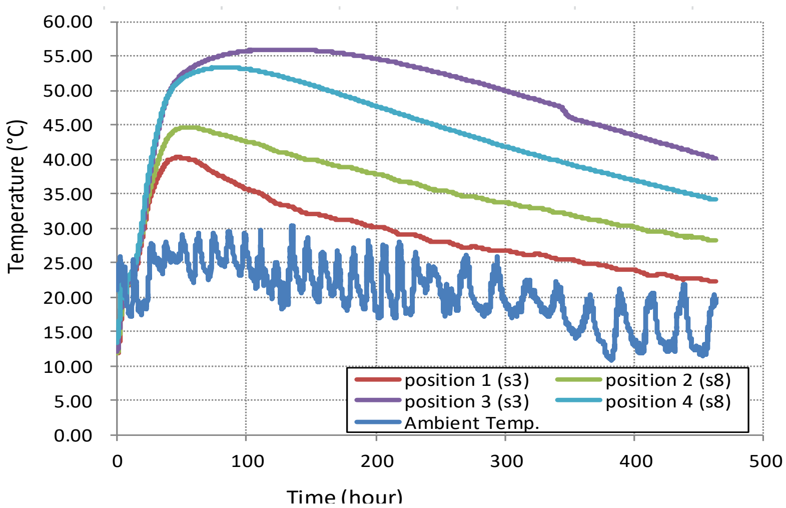


**Figure 10:** Heat of Hydration Development at Midpoint of Each Position

### 4.3 Temperature Rise at the Concrete Top Surface

The Figure 10 showed the hydration heat development at the top surface of the mass**.** It can be concluded that, position 1 shows the lowest rate of hydration heat and its peak temperature was 33.80˚C achieved after 67.80 hours. For position 2 the peak temperature was 40.20˚C achieved after 59 hours. Position 3 shows the highest temperature rise and its peak temperature was 45.66˚C achieved after 111 hours. For position 4 the peak temperature was 43˚C achieved after 83. 33hours. It can be also noticed that the maximum difference between the surrounding temperature and top surface temperature was found 26.50˚C.

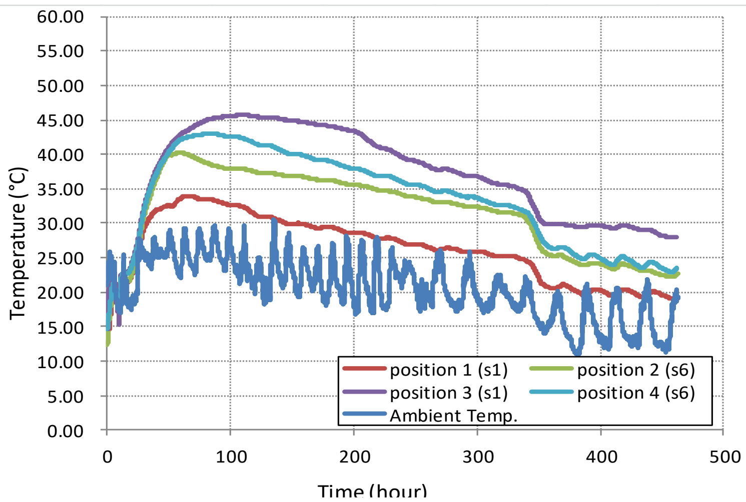


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Figure 11: Heat of hydration development at the top surface of each position

### 4.4 Heat of Hydration Difference between the Top and Middle Surface

For all positions the difference between the top and middle surface did not exceed 15.80˚C. This is attributed to that the box was sealed from all sides and the maximum readings value was at the middle surface of the concrete block. The hydration heat difference between the surface and the midpoint was found 8.00˚C, 9.00˚C, 15.80˚C, and 13.00˚C for position 1, 2, 3, and 4 respectively as shown in Figures 14, 15, 16, and 17 respectively. This low difference creates no cracks in concrete as a result the mix proportion containing slag cement was suitable for controlling heat of hydration.

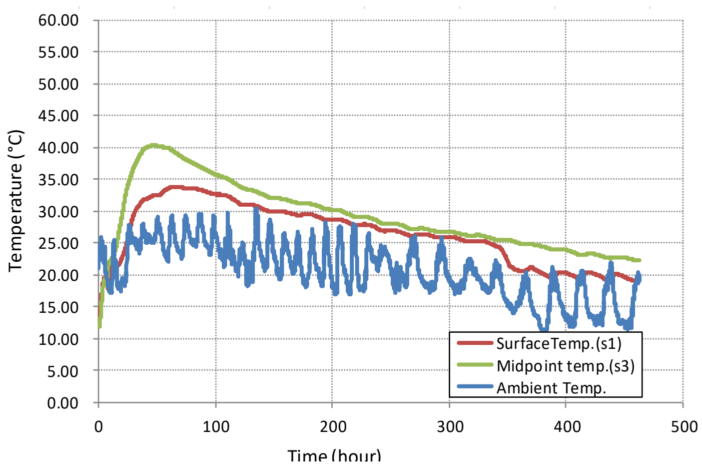


Fig14: Temperature difference between the top and middle surface for position1

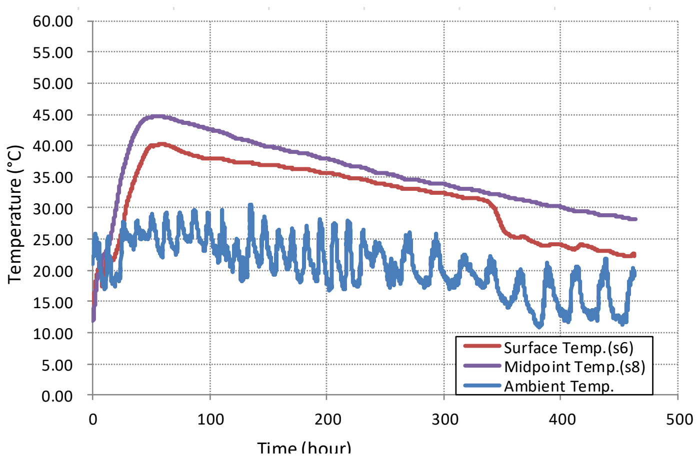


Fig15: Temperature difference between the top and middle surface for position2

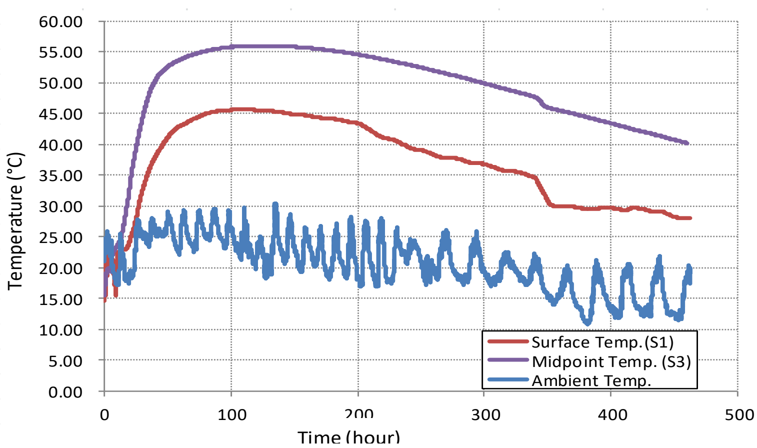


Fig16: Temperature difference between the top and middle surface for position3

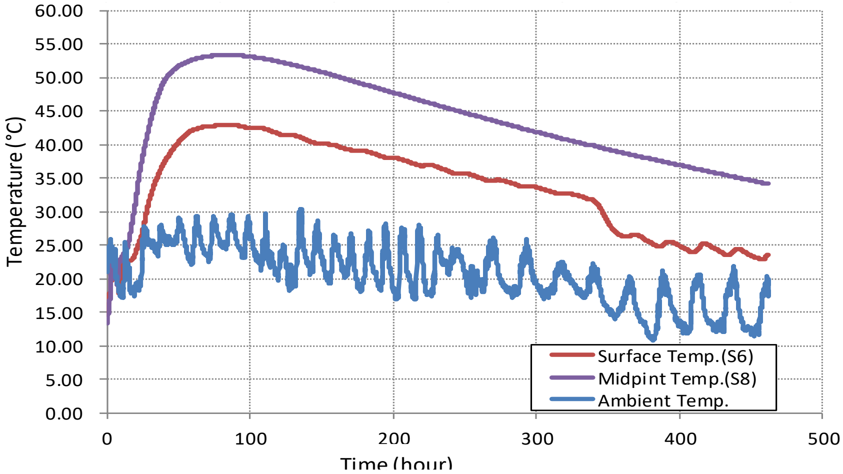


Fig17: Temperature difference between the top and middle surface for position 4

The maximum temperature difference between the top and the middle surface of the raft for all positions was 15.80°C at 355 hours at position 3, Fig 18.

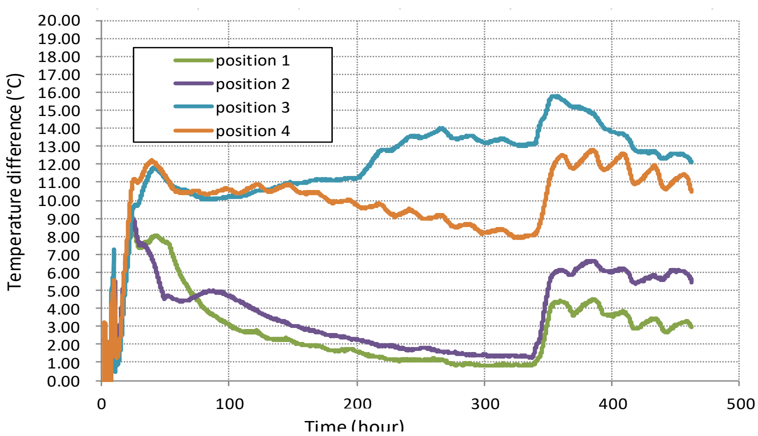


Fig18: Temperature difference between top and middle surface of each position

## 4.5 Temperature Difference between the Top Surface and the Surrounding Air

The maximum temperature difference between the surrounding temperature and the top surface temperature of the raft for all positions was 26.50°C at 126 hours at position 3 as shown in Fig 19.

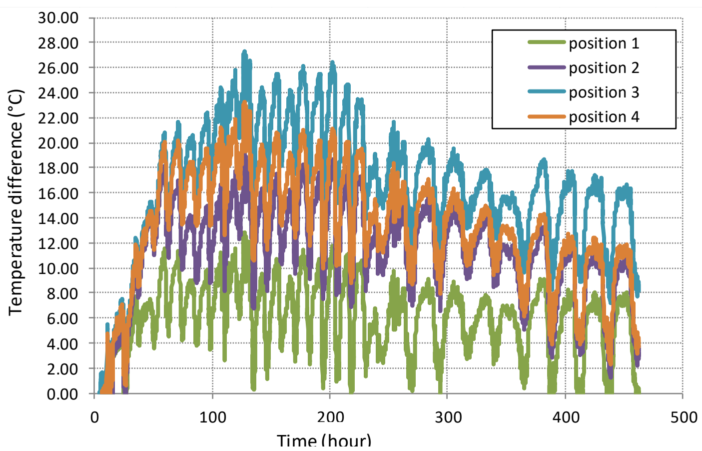


Fig19: Temperature difference between the top surface and the surrounding air.

According to the temperature recorded by the 20 sensors, the above Figures illustrated that the temperature is decreased from the middle to the top surface gradually. The maximum temperature is 56˚C. The temperature differences from the middle to the top surface are 15.80˚C and such low temperature differences do not lead to concrete cracks. The following table concluded the temperature difference between the middle and the top surface with the ambient temperature at 1, 3, 7, 14, 20 days.

**Table 4**: Conclusion of the Raft Temperature Measurements at 1, 3, 7, 14, and 20 days

| | **24 Hrs (1 Day)** | **72 Hrs (3 Days)** | **168 Hrs (7 days)** | **336 Hrs (14 Days)** | **480 Hrs (20 Days)** |
|---|---|---|---|---|---|
| **Maximum Core Temperature** | 36.10 | 54.56 | 55.52 | 47.98 | 40.14 |
| **Top Surface Temperature** | 26.88 | 44.22 | 44.37 | 34.91 | 28.07 |
| **Ambient Temperature** | 19.82 | 23.53 | 21.09 | 18.55 | 19.42 |
| **Difference Between Core and Surface** | 9.22 | 10.34 | 11.15 | 13.07 | 12.07 |
| **Difference Between Surface and Ambient Temperature** | 7.06 | 20.69 | 23.28 | 16.36 | 8.65 |

## 6. Conclusions

This paper presented experimental and numerical investigation of temperature rise caused by hydration heat based on a segmental model of high-rise building raft. From the study, the following conclusions may be drawn:

(1) The tested results concluded that the temperature of the concrete increased quickly but diminishes gradually. The maximum temperature rise at the middle surface shows up at time = 134 hrs, with maximum value 56˚C.

(2) The maximum temperature rise at the top surface shows up at time = 111 hrs, with maximum value 45.66˚C.

(3) The maximum temperature difference between the top surface and the core was 15.80°C, which not leads to cracks in concrete.

(4) The maximum temperature difference between concrete surface and surrounding air was 26.5˚C, due to the function of quilt which insulates the ambient cold air and the concrete surface, so there is not any temperature crack on the surface.

(5) The delayed gain in achieving the higher temperature rise due to hydration heat was due to the lower percentage of $C_3A$ and $C_3S$ content and the lower surface area in slag cement.

(6) For mass concrete, temperature gradient is the most important factor to the quality control.

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# التقييم التجريبي لتدرج درجة الحرارة داخل الخرسانة الكتلية لأساسات اللبشة الخرسانية المسلحة

تعتبر الشروخ الناتجة عن الحرارة من المشاكل الرئيسية التي تحدث للخرسانة حيث ترتفع درجة الحرارة في الهياكل الخرسانية الضخمة. لذا كان من الضروري البحث عن أسباب وأماكن ارتفاع درجة الحرارة للخرسانة الكتلية وذلك لإيجاد تقنيات فعالة للتحكم في درجة حرارة الإماهة للخرسانة الكتلية. في هذا البحث، وبناءً على اختبار نموذج موقعي للبشة مبني عالي الارتفاع، تم قياس درجة حرارة سطح الخرسانة السفلي والوسطى والعلوي للبشة الناجمة عن حرارة الإماهة. وللتحكم في ارتفاع درجة الحرارة تم استخدام أسمنت خبث الافران (CEM III / A 42.5N) نظرًا لانخفاض نسبة C3A و C3S للأسمنت ومساحة السطح المنخفضة أوضحت منحنيات ارتفاع درجة الحرارة المختبرة إلى أن درجة الحرارة تزداد بسرعة، ولكنها تنخفض تدريجياً. حيث بلغ أقصى ارتفاع لدرجة الحرارة عند السطح الأوسط للخرسانة (قلب الخرسانة) ٥٦ درجة مئوية، وأقصى فرق لدرجة الحرارة بين السطح الأوسط والسطح العلوي كان ١٥,٨٠ درجة مئوية. وكان أقصى فرق في درجة الحرارة بين السطح العلوي ودرجة حرارة البيئة المحيطة ٢٦,٥ درجة مئوية وهي نسب مقبولة لا ينتج عنها شروخ للخرسانة. لذلك نستنتج أنه باستخدام أسمنت خبث الأفران يمكن أن يتم التحكم في درجة حرارة إماهة الخرسانة مما يؤدي إلى خلطات خرسانية صديقة للبيئة.