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Heat of Hydration of Mass Concrete Incorporating Different Binding Materials

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ملخص البحث

الغرض من هذه الدراسة هو دراسة تأثيرات استخدام أنواع الأسمنت المصرية المختلفة وبدائل الاسمنت للتحكم في حرارة الاماهة الناتجة من الخرسانة الكتلية. تم استخدام ثلاثة أنواع مختلفة من الأسمنت، ، وثلاثة نسب مختلفة من الرماد المتطاير. وهذه الأنواع الثلاثة من الأسمنت هي: أسمنت بورتلاند الخبث الحبيبي ، وأسمنت بورتلاند الحجر الجيري، والأسمنت البورتلاندي العادي الممزوج مع الرماد المتطاير (F) في ثلاثة نسب مختلفة (30٪، 40٪، 50٪). الخلطات المحتوية على الأسمنت المخلوط تمت مقارنتها مع المحتوية على الاسمنت البورتلاندي العادي . لكل نوع اسمنت، يتم استخدام اثنين من خليط الخرسانة (نسبة المياة الى الاسمنت 0.5 و 0.6). أظهرت النتائج أن حرارة الاماهة تتناقص مع زيادة استخدام بدائل الاسمنت مع الأسمنت المخلوط. وانخفضت حرارة الاماهة بنسبة 12٪ بالنسبة لأسمنت الخبث و 21٪ للأسمنت الحجر الجيري مقارنتا بأسمنت بورتلاند العادي. كما انخفضت بنسبة 14٪ و 22٪ و 25.5٪ في حالة استخدام 30٪ و 40٪ و 50٪ استبدال الرماد المتطاير على التوالي

Abstract:

The purpose of this study is to examine the influences of using different Egyptian cement types and supplementary cementitious materials (SCMs) to control the hydration heat developed in massive concrete. Three different sorts of cements and three different fly ash ratios were used. For each binder type, two concrete mixes (w/b ratio 0.5 and 0.6) are produced. The results show that the hydration heat decreases with increasing SCM and with using blended cements. Hydration heat was decreased to 88% for slag cement and 79% for limestone cement regarding ordinary portland cement. It was also decreased to 86%, 78%, and 74.5% in case of using 30%, 40%, and 50% fly ash substitution respectively.

Keywords: Hydration heat; Temperature; Blended cement; Pozzolan; Blast Furnace Slag; Limestone

1. INTRODUCTION

Mass concrete is used to build massive structures to withstand external loads. A substantial measure of heat in large size members is produced. Hydration heat is a great problem in mass concrete causing a difference between the inner core and the surface temperatures, which leads to thermal shrinkage cracks. The differential in temperature increases with the increase in volume of massive concrete element.

The hydration heat has a negative effect on concrete durability owing to the volume changes of the elements, resulting in internal microcracks [5]. The heat of hydration and the heat evolution in concrete increase with increasing Tricalcium Silicate (C_3S) and Tricalcium Aluminate (C_3A) contents. On the contrary, pozzolanic reaction such as fly ash is slower than Calcium Silicate (CS) hydration and it produces lower heat than does cement hydration [10]. Concrete containing supplementary cementitious materials (SCMs) shows slow hydration joined by a less increase in temperature.

Mass concrete with fly ash (FA), slag, or lime stone as a fractional substitution for ordinary portland cement (OPC) creates a lower temperature rise and a slower rate of heat increment than OPC mass concrete [4]. The utilization of FA and GGBS diminishes the measure of heat created during the acceleration stage and retard the hydration procedure [14]. FA is more effective in the heat of hydration reduction in concrete than GGBS because the potential heat generation capacity of FA is significantly lower than that of GGBS [8]. Using large amounts of SCMs significantly contributes to the sustainability of concrete in terms of low CO_2 emissions [17], preservation of characteristic assets, and recycling of by-products in addition the improvement of workability and durability of concrete [7]. High volume Fly Ash concrete had better fire resistance than OPC concrete [11]. Incorporation of slag is reported to retard and reduce the hydration development [1]. However, several investigations report enhanced early cement hydration caused by fine pozzolanic materials [16]. Replacement of fine cement particles with slag and coarse particles with a less-reactive SCM can give low hydration and improved microstructure development [15].

For blended cement; calorimetry technique can give consistent estimations and is an appropriate strategy to concentrate the early period of hydration where the heat rate is moderately high. Pozzolanic reactions are known to participate at later stages including lower heat evolution [3, 6]. This low heat evolution makes it hard to be followed by calorimetry method. Differential thermal analysis (DTA) is more reasonable for contemplating hydration at later stages. This strategy has been connected to cement–blast furnace slag systems and cement–fly ash systems [12].

For low w/c ratio, complete cement hydration is unrealistic due to existence of deficient space for the hydration procedure. Conversely, if available water exists in cement, hydration will improved continuously and the available space within the paste will be completely filled. Full cement hydration is all around acknowledged to require a base water/cement proportion of 0.42 [13]. The ambient temperature is very important in determining hydration heat. Cement hydration at higher ambient temperature is quickened at early ages, but slows down later on. This study concentrates on the impact of using blended cement on the hydration heat using two experimental techniques: isothermal calorimetry and adiabatic calorimetry.

The objectives of the present study are to establish heat of hydration isotherms for local Egyptian cement types CEMI and CEMII and Fly ash. Moreover, relating adiabatic heat of hydration to mixes used in heavy water structures and investigating the impact of w/b and environmental temperature on adiabatic heat of hydration.

2. EXPERIMENTAL WORK

2.1. Materials

Three different Egyptian cement types of grade 32.5 were used in all mixes. These cements are ordinary portland cement (CEMI) of Blain surface area of 3650 cm^2/g and Specific gravity of 3.15, Lime stone cement (CEMII-B-L) of Blain surface area of 3050 cm^2/g and Specific gravity of 3.21, and Ground Granulated Blast Furnace Slag Cement (CEMII-A-S) of Blain surface area of 3225 cm^2/g and specific gravity of 3.04. A class F fly ash (FA) was used with three ratios (30%, 40%, and 50%) as a replacement of cement. These percentages are considered moderate and common in mass concrete mixes used for dams construction where high strength is not required. Concrete with w/b=0.5 and 0.6 were used. Locally available natural siliceous sand with a fineness modulus of 2.34 and natural siliceous gravel with a nominal maximum size of 20.00 mm were used in the studied mixes as fine and coarse aggregates, respectively. The specific gravity and unit weight were 2.64 and 1.69 t/m^3 for the fine aggregate and 2.50 and 1.79 t/m^3 for the coarse aggregate. A superplasticizer (SP) admixture was used to enhance the fresh properties of massive concrete mixes.

2.2. Specimens and mix proportions

To illustrate the impact of using different Egyptian cement types and SCM on the heat production, three cements of grade 32.5 (CEMI, CEMII-L-B, and CEMII-S-B) and type F fly ash with three ratios (30%,40%, and 50%) as partial substitution of OPC (CEMI) were prepared. **Table 1** shows the details of the mixes and their components and the test results of fresh properties. Water content was fixed at 100 kg/m^3 for all concrete mixes with w/b=0.5 and 120 kg/m^3 for all concrete mixes with w/b=0.6. The sand to total aggregate ratio (S/A) was fixed at 0.334 for all mixtures. The targeted initial slump of all concrete mixes was zero mm.

Table1: Details of concrete mix proportions and test results

Specimen ID	Cement Type	w/b (%)	Weight per unit volume (kg/m^3)						Test result
			w	C	FA	S	G	SP	UW
Oc-wc5	OPC	50	100	200	0	720.1	1439.7	4	2.23
Lc-wc5	CEMII-L	50	100	200	0	720.1	1439.7	4	2.23
Sc-wc5	CEMII-S	50	100	200	0	720.1	1439.7	4	2.24
Oc-F30-wc5	OPC+30%F	50	100	140	60	714.9	1425.5	3	2.27
Oc-F40-wc5	OPC+40%F	50	100	120	80	712.5	1420.7	3	2.25
Oc-F50-wc5	OPC+50%F	50	100	100	100	710.0	1415.8	3	2.25
Oc-wc6	OPC	60	120	200	0	704.9	1405.7	2	2.29
Lc-wc6	CEMII-L	60	120	200	0	704.9	1405.7	2	2.27
Sc-wc6	CEMII-S	60	120	200	0	704.9	1405.7	2	2.27
Oc-F30-wc6	OPC+30%F	60	120	140	60	698.0	1391.8	0	2.28
Oc-F40-wc6	OPC+40%F	60	120	120	80	696.0	1387.7	0	2.29
Oc-F50-wc6	OPC+50%F	60	120	100	100	693.5	1382.9	0	2.32

Note: w/b = water-to-binder ratio by weight, w = water, FA = fly ash, S = sand, G = gravel, SP = superplastisizer, and UW= unit weight of fresh concrete (kg/m^3).

2.3. Casting, Curing, and Testing

All concrete specimens were mixed using a rotating drum mixer 100 liter in capacity. Oiling of the mixer (disposal of the first mix) was always done before the first intended mix was prepared on the day of casting. The initial slump test is regulated by [2]. Unit weight test was performed with slump test as well. Compressive strength test was accomplished according to the Egyptian Code of Practice test method at 7, 28, 56 and 90 days after casting. All specimens were continuously cured under water until testing time. At any given testing age, three specimens (cubes of 150x150x150mm) were tested in compression using a Universal Testing Machine (UTM). The average compressive strength of each three cubes is reported.

In order to explore the influence of the used blended cements on the rate of heat generation, especially at early age; adiabatic and isothermal hydration tests were done using the following techniques.

2.3.1. Isothermal Calorimeter

An isothermal calorimeter determines the heat of hydration created from samples in constant ambient temperature. The sample preparation requires keeping cement and water in constant room temperature (20^{o}c) before testing. 50 grams of dry cement were added to an admix ampoule. The admix ampoule was transferred into the calorimeter. 25 grams of water were added via a syringe inside the calorimeter. All paste samples were created with w/b proportion of 0.5. Promptly after water expansion, cement and water were blended for 60 seconds utilizing the stirrer of the admix ampoule. Amid the test period the environmental temperature was kept constant at 20^{0}c. Then, measurements of cement hydration were recorded for one day. Measurement was recorded every one minute using one type k nickel/chromium thermocouple connected to data logger. This method was exactly carried out according to *ASTM C186*. Figure 1 shows the device set-up.

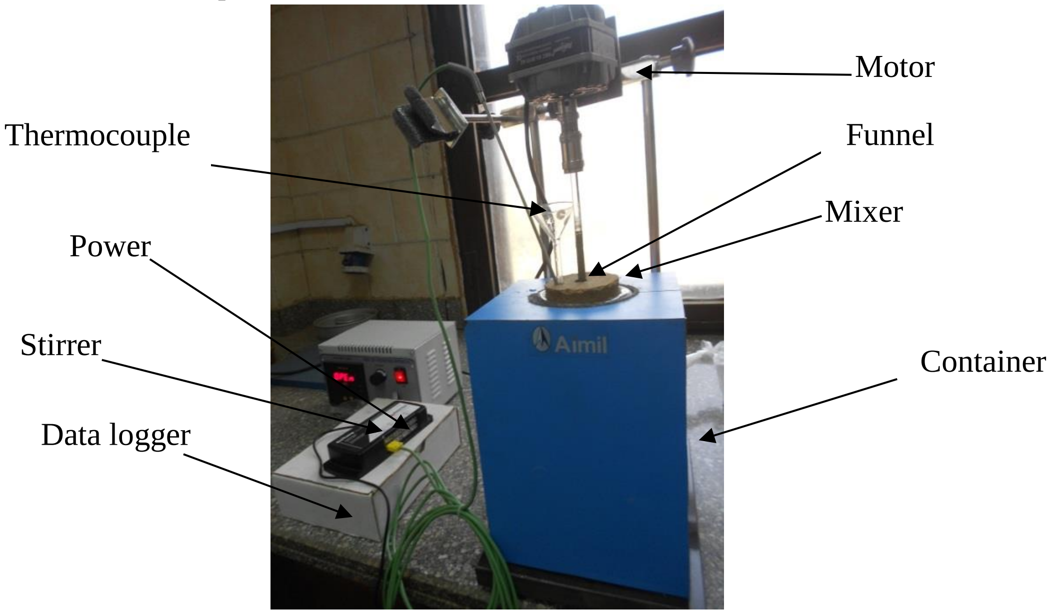

Figure 1: Device Set-up and Connections during the Test

2.3.2. Adiabatic Calorimeter

Adiabatic tests were established in laboratory for measuring hydration heat of massive concrete blocks. The dimensions of every concrete block are 0.6 x 0.6 x 0.6 meters. Concrete was poured into a thermally isolated wooden box. During test period the environmental temperature was recorded and the temperature rise of concrete specimens was measured by five thermocouples of type k nickel/chromium for 7 days directly after casting. The readings were taken every ten minutes using a data logger. Figures 2 and 3 show the test procedure stages including casting concrete in the box, fixing the thermocouples in five different places, and then connecting the thermocouples to the data logger respectively. When the readings became almost constant at the end of measurements period

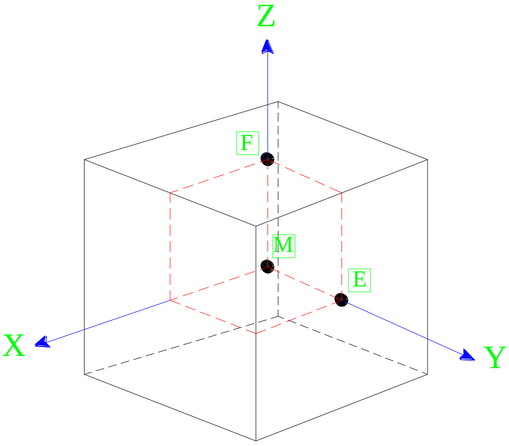

Figure 2: Fixing Thermocouples in Concrete

Where M: centre of mass
F: centre of face (top and bottom)
E: mid-point of edge (right and left)

Figure 3: Connecting Thermocouples Wires to Data Logger

3. TEST RESULTS AND DISCUSSION

3.1 Compressive Strength

As shown in Figure 4, it can be noticed that the compressive strength is affected by the cementitious materials types and proportions especially at early ages. For constant w/b ratio=0.5, compressive strength continued to increase at the ages older than 28 days for the tested mix (Lc-wc5). At ages older than 28 days, the compressive strength for the tested mix (Sc-wc5) was higher than (Oc-wc5) and also, the compressive strength for the tested mix (Oc-wc5) was slightly higher than (Lc-wc5).

In mix-proportioning of traditional concrete, the w/b ratio plays an important role in obtaining the required strength and durability. With mass concrete, the water/binder ratio has to be chosen depending on required strength, lowest gain of heat of hydration, and workability. The average compressive strengths are measured at various curing ages of the investigated concrete mixes. The development of the compressive strength with time is affected by w/b ratio of concrete as shown in Figure 5. All mixes of highest w/b ratio (0.6), showed the lowest compressive strength values at all testing ages, contrary to w/b ratio of (0.5).

The average compressive strength measured at various curing ages of the investigated mass concrete mixes with different fly ash ratios are shown in Figure 6. The compressive strength development with time is affected by fly ash ratio. Mix (Oc-F30-wc5), which has the lowest fly ash ratio, showed the highest compressive strength values at all testing ages. Mix (Oc-F50-wc5), which has the highest fly ash ratio, experienced the lowest compressive strength values at all testing ages. Generally replacing ordinary cement with fly ash reduces the early age compressive strength, but at older ages enhances the strength. From results, after 56 days the increase of compressive strength for (Oc-wc5) mix was nearly zeroed. However, for mixes containing fly ash compressive strength still increase by 18%, 63%, and 43% for (Oc-F30-wc5), (Oc-F40-wc5), and (Oc-F50-wc5) respectively.

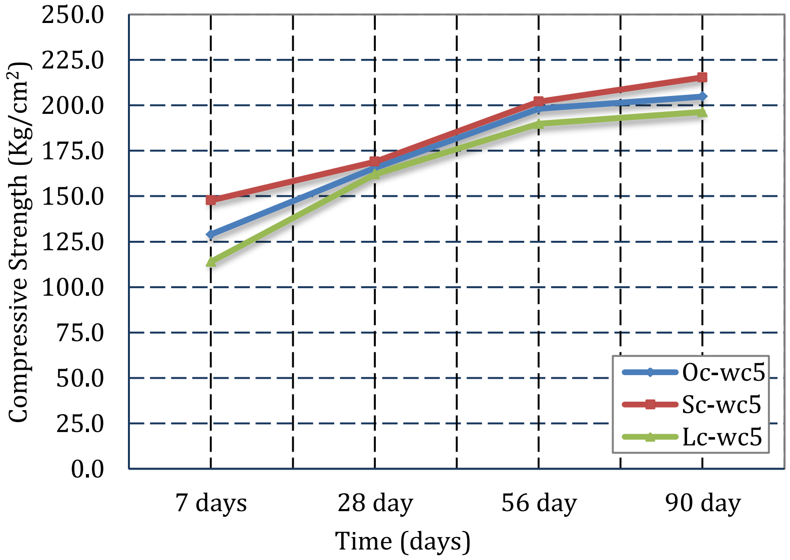

Figure 4: Compressive Strength Development of Different Concrete Mixes

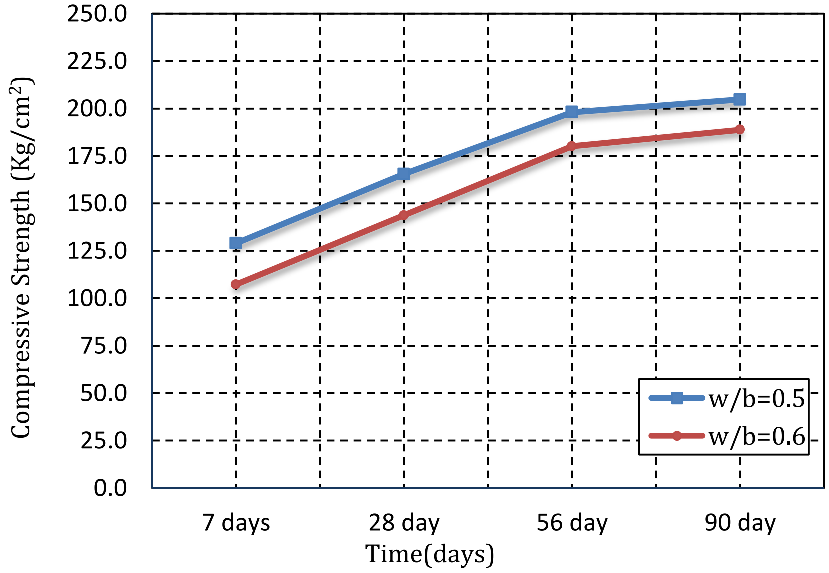

Figure 5: Effect of w/b Ratio on Compressive Strength Development for Oc Mixes

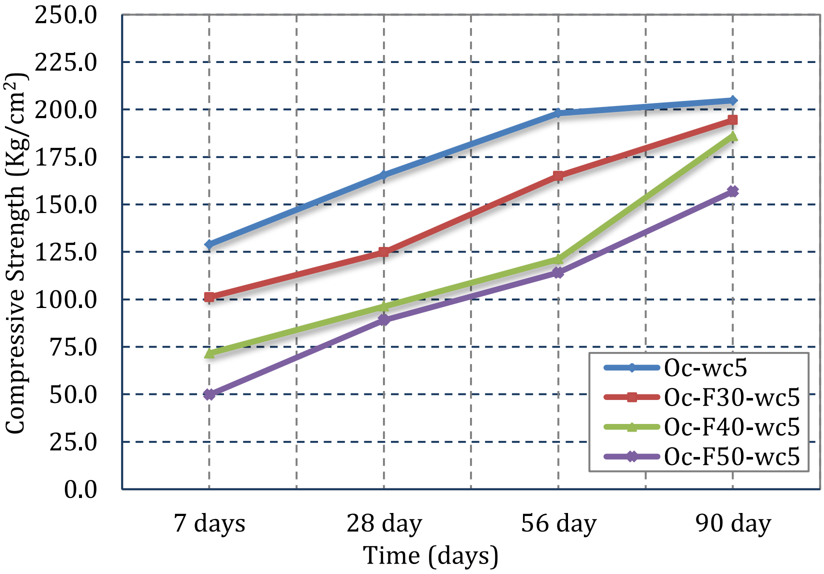

Figure 6: Effect of Fly Ash Content on Compressive Strength Development

3.2 Mortars Heat of Hydration

3.2.1 Effect of Cement Type

The isothermal hydration tests were performed for determining the hydration of cement. Figure 7 shows the rate of temperature rise for mortars made with three different sorts of cement (ordinary, slag, and limestone cement) at constant ambient temperature of 20°C. For constant w/b ratio=0.5, lime cement shows the lowest rate of temperature rise due to its low C_3S and C_3A content and low specific surface area. Since finer cement has a higher specific surface area to contact and react with water and high content of C_3A and C_3S, ordinary cement presents a higher rate of heat evolution during hydration. So, fineness of cement and C_3A and C_3S content has a great impact on heat evolution.

The heat of hydration of slag and lime cements was about 88% and 79% respectively of that of ordinary cement.

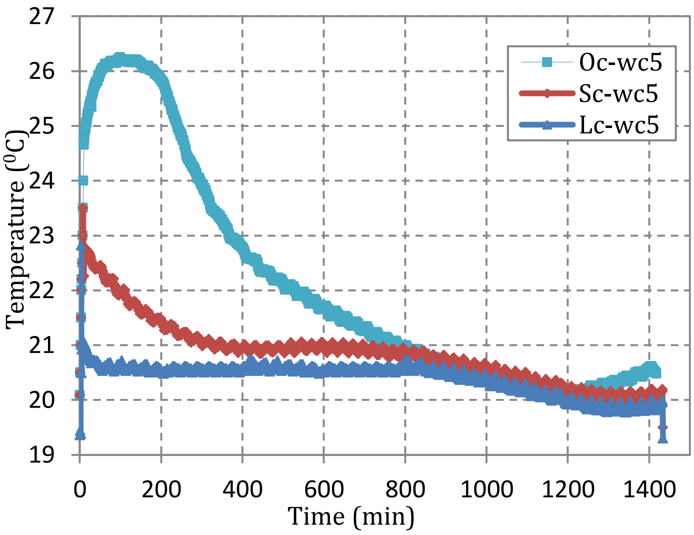

Figure 7: Heat of Hydration Development of Different Cement Mixes at 20^0C

3.3 Concrete Heat of Hydration

3.3.1 Effect of Cement Type

For constant w/b ratio=0.5, the adiabatic hydration tests were performed for concrete mixes having different types of cement, Figure 8. The mix (Lc-wc5) shows the lowest rate of heat of hydration and its peak temperature was 37^0c achieved after 66 hours. Whereas, the mix (Oc-wc5) shows the highest rate of hydration heat and has a similar trend as the mix (Sc-wc5). Their peak temperature of heat of hydration was rabidly achieved after 35 hours. The maximum reached temperature was 40^0c, 38^0c, and 36.50^0c for mixes (Oc-wc5), (Sc-wc5), and (Lc-wc5) respectively. Limestone cement and slag cement enhance the behavior of concrete as pertained to heat of hydration. Moreover, their lowest rate of heat of hydration is due to the low content of C_3S and C_3A. For mix (Lc-wc5), the delay gained in achieving the maximum temperature due to heat of hydration was due to the lower percentage of C_3A and C_3S content and the lower specific surface area in limestone cement.

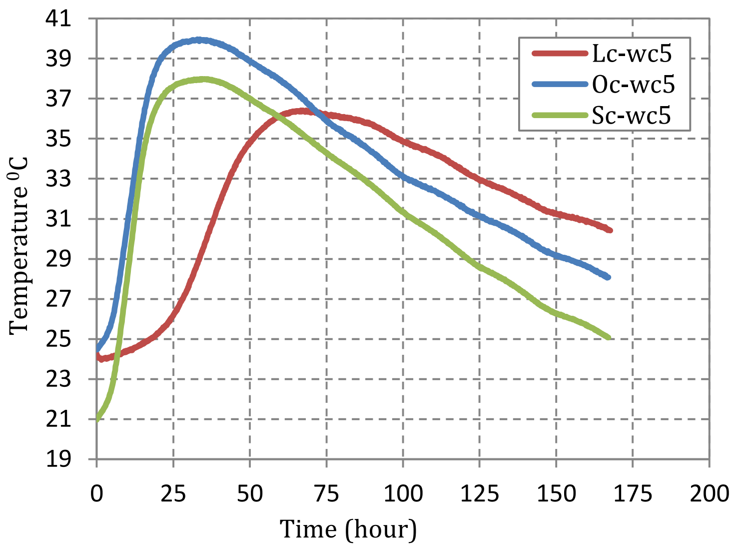

Figure 8: Heat of Hydration Development of Different Concrete Mixes

3.3.2 Effect of Water-to-Binder Ratio (w/b)

The heat of hydration development with time for different w/b ratios for ordinary portland cement was investigated, Figure 9. Cement type CEMI mixes at w/b ratio (0.5), showed higher heat of hydration values than those of w/b ratio of 0.6.

The peak values of heat of hydration were 40^0c at 35 hour and 42^0c at 19 hour for mixes (Oc-wc5) and (Oc-wc6) respectively. The peak values of heat of hydration were 38^0c at 40 hour and 41^0c at 28.50 hour for mixes (Sc-wc5) and (Sc-wc6) respectively. Also, the peak values of heat of hydration were 36.50^0c at 66 hour and 40.25^0c at 28 hour for mixes (Lc-wc5) and (Lc-wc6) respectively. The heat of hydration peak value is primarily attributed to the hydration process of C_3S. Cement hydration responses advance at a speedier rate at early ages with the expansion of w/b proportion.

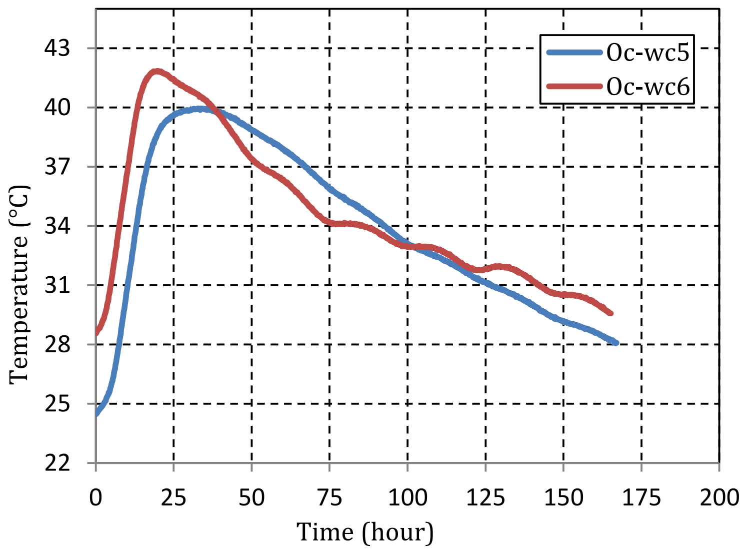

Figure 9: Effect of w/b Ratio on Heat of Hydration for Mixes (Oc-wc5) and (Oc-wc6)

3.3.3 Effect of Fly Ash Ratio

Utilizing fly ash as a partial replacement for ordinary Portland cement (OPC) creates a lower temperature rise and a slower rate of temperature increment than OPC. Thus, the impact of fly ash on the heat of hydration was researched, Figure 10. The w/b ratio of 0.5 was kept constant for all mixes. Ordinary Portland cement type was replaced by three different fly ash ratios forming three different mixes. Mix (Oc-F30-wc5), showed the highest heat of hydration values but lower than OPC mixes. Mix (Oc-F50-wc5), experienced the lowest values. The maximum reached temperature was 34.50^{0}c, 31.20^{0}c, and 29.50^{0}c for mixes (Oc-F30-wc5), (Oc-F40-wc5), and (Oc-F50-wc5) respectively. Generally replacement of ordinary cement with fly ash reduces the heat of hydration.

As fly ash replacement for cement increase, the peak of heat of hydration is decreased and the time of occurrence is prolonged due to pozzolanic reaction. This implies heat advancement from Portland cement is slow in fly ash concrete. The reduction in heat of hydration was 32%, 53%, and 61% in case of using 30%, 40%, and 50% fly ash replacement respectively. For w/b=0.5, the peak temperatures for all mixes were at 30 hours, 39 hours, and 41 hours for mixes (Oc-F30-wc5), (Oc-F40-wc5), and (Oc-F50-wc5) respectively.

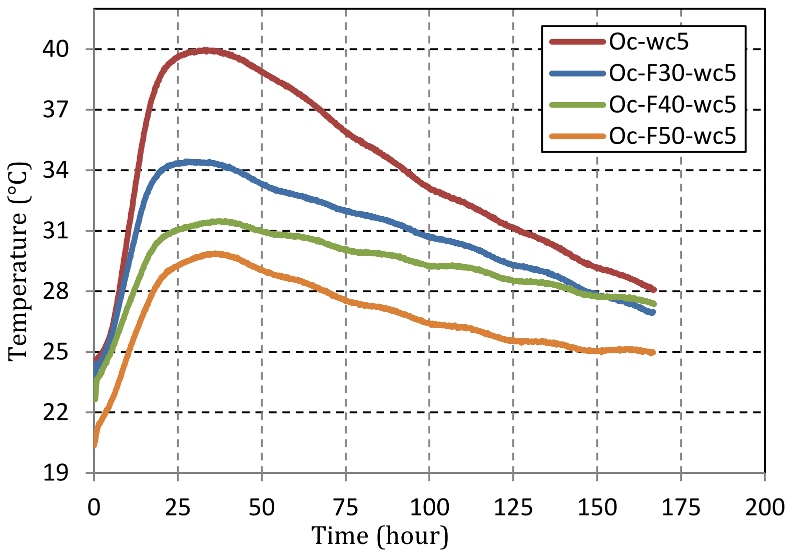

Figure 10: Effect of Different Fly Ash Content on Heat of Hydration Development

4. CONCLUSIONS

From the presented experimental results and the provided discussions for the heat of hydration evolution in mass incorporating different Egyptian cement types and fly ash using two experimental techniques, Adiabatic hydration tests were conducted on cast concrete blocks of dimensions (60x60x60) cm. In addition, isothermal hydration tests were conducted on cement pastes under constant room temperature (T) of 20^0C. The following conclusions may be drawn:

1. The cement type showed a significant impact on the heat of hydration. OPC showed the highest rate of heat of hydration due to the highest content of C_3S, C_3A, compared with CEM II S and CEM II L; and cement fineness.
2. CEM II displays the lowest rate of heat evolution during hydration due to low content of C_3S and C_3A in type II blended cement.
3. The effect of water–binder ratio on hydration is found to be very important as the heat of hydration begins to decrease as the w/b ratio decreases and Cement hydration responses advance at a speedier rate at early ages with the expansion of w/b proportion.
4. When fly ash replacements for cement increase, the peak values of heat hydration are decreased and the time of occurrence is elaborate due to pozzolanic reaction.

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