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Experimental Evaluation of Heat of Hydration in Concrete Incorporating Supplementary Cementitious Materials

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Abstract

This research aims to study the impact of supplementary cementitious materials on the heat of hydration of concrete. The experimental tests were performed for concrete with three size variations and seven variations of supplementary cementitious materials (SCMs) to investigate its impact on the heat of hydration. The SCMs used in this research mainly come from industrial waste materials. Fly ash (FA), ground bottom ash (GBA), and silica fume (SF) were the waste materials used in this research. Tests were carried out for seven days for each variation to observe the effect of volume changes and the addition of SCMs on the change in concrete temperature. The experimental results indicated a direct correlation between concrete volume and maximum temperature, with notable variations in temperature distribution across the concrete mass. Typically, the highest temperature was observed at the core of the concrete. Fly ash (FA) and bottom ash (BA) demonstrated an inverse relationship between their content as supplementary cementitious materials (SCMs) and the maximum temperature achieved. Increasing the proportion of FA and BA in the concrete mixture resulted in a reduction of the hydration temperature. Additionally, silica fume (SF) was found to accelerate the hydration rate, though its efficacy in lowering the heat of hydration was significant only when its content exceeded 5%.

Keywords

Supplementary cementitious materials (SCMs) , heat of hydration, fly ash, ground bottom ash, silica fume, mass concrete

INTRODUCTION

Concrete remains a prevalent choice in construction, favored by designers for both simple and large-scale projects. For massive structures such as raft foundations, dams, and bridge piers, several critical considerations must be addressed to ensure the stability and durability of the concrete. These considerations include the mix design, temperature control methods, and execution techniques, as massive structures are susceptible to issues such as large volume requirements which leads to cracking and durability concerns. Preventative measures must focus on factors that can trigger such problems, particularly the thermal behavior of mass concrete, which is influenced by its volume and the temperature rise from cement hydration [1].

Concrete with a large volume takes a longer time to release heat from the inside due to its low thermal conductivity. Therefore, during the heat release process, the surface of the concrete will release heat more easily than the inside of the concrete. As a result, during the heat release process, there is a continuous temperature difference between the inside and outside of the concrete [2]. At high temperatures, the inside of the concrete tends to expand while at low ambient temperatures, the outside of the concrete tends to shrink and restrain the inside of the concrete from expanding, increasing the risk of tensile stresses and strains. If the thermal stresses occur in concrete exceed the tensile strength of the concrete, it can lead to thermal cracking [3].

The peak temperature of mass concrete structures occurs 15-17 hours after casting. Generally, after 40 hours, the ambient temperature will begin to affect the temperature changes in the concrete [4]. The tendency for temperature increases at the early age of concrete after casting is closely related to the hydration process. Hydration is a chemical process that occurs between cement and water that will become an adhesive medium that solidifies and then forms a hard mass. This process is complex and involves several chemical and physical reactions to produce hydrated cement paste, which is a solid and durable material [5]. The duration is calculated until the hydration process is complete at a certain temperature. The rate of hydration and heat change increases with the fineness of the cement. Due to the exothermic characteristics of the cement hydration reaction, some massive structures will behave differently at the construction site depending on the overall quantity of heat generated.

Cement material composition, quantity, and water-cement ratio affect the amount of heat emitted during hydration. The maximum temperature ratio (thermal shock) that can trigger the formation of contraction that allows cracking is limited to 40°C/hour and the temperature ratio between the core and the surface of the concrete is expected to be no more than 20°C [6].

The high temperature increases in concrete need to be minimized to prevent these risks. Options include selecting cement types with low heat of hydration such as Type II Portland Cement and Type IV Cement or considering the use of supplementary cementitious materials to reduce the temperature increase due to hydration in concrete [7]. These supplementary cementitious materials can be separated into organic and inorganic additives based on their origin and can also be categorized as natural pozzolan or industrial by-products based on their properties. For many years, natural pozzolanic materials have been widely used in construction such as lime powder (LP) and volcanic rock ash. There are also industrial by-products that are most used in cement and concrete production including silica fume (SF), coal fly ash (CFA), and coal bottom ash (CBA) [8]

Fly ash is part of the residual waste of burning coal in steam power plant boilers in the form of amorphous fine particles and is Pozzolanic in nature which can react with lime at room temperature with water media to form binding compounds. The use of fly ash in concrete construction, especially mass concrete, can reduce thermal stress by reducing the heat of hydration in the mass concrete structure [9]. Fly ash was identified to improve the initial cement hydration. However, it delays hydration during the dormant phase and acceleration period. Then, it accelerates hydration after the acceleration period [10]. Furthermore, the higher the w/c ratio, the more pronounced the effect of slowing down the temperature increase. Concretes with binder levels up to 250 kg/m³ showed a retarding of the temperature rise as the fly ash content increased [11].

Bottom Ash is ash collected at the bottom of the coal furnace which amounts to almost 25% of the total waste generated by coal-fired power plants [12]. To use bottom ash as a Supplementary Cementitious Material, a smaller particle size is required, and thus bottom ash will be subjected to a grinding process to achieve a fineness like that of cement/fly ash from the same source. The substitution of Portland cement (OPC) with ground bottom ash (GBA) in cement mixes not only reduces the OPC content in concrete but also significantly reduces the heat development in the concrete. The use of GBA helps to reduce the problem of thermal cracking arising from the significant temperature difference between the core and surface of the concrete. The amount of concrete peak temperature rise decreases as the substitution of GBA for OPC increases. Therefore, the use of GBA as a supplementary cementitious material provides a solution to the problem of cracks caused by overheating, which is a common occurrence in highly reinforced concrete, especially in mass concrete structures [13].

Silica fume (SF) is generally finely powdered and highly reactive and produced in electric furnaces during the processing of silicon and ferrosilicon metals with the main component of SF is amorphous silicon oxide. Due to its pozzolanic reaction and microstructure sharpening ability, SF has been used in the production of cementitious materials, especially high-grade and ultra-high-grade concrete, which helps to increase the overall density, strength, and durability of concrete [8], [10]. In terms of hydration in concrete, silica fume can accelerate the cement hydration process when the water-to-cement ratio (w/c) is high. Otherwise, at low w/c ratios, silica fume delays cement hydration, extending the dormant period before finally enhancing the cement hydration process. Generally, the initial stage of cement hydration is accelerated due to the presence of silica fume. Moreover, the higher the w/c ratio, the greater the accelerating effect exerted by silica fume [10]

Therefore, this research aims to investigate the effect of using waste materials as SCM in concrete especially on its effect on the heat of hydration. The experimental teas were performed by varying the type and percentage of supplementary cementitious materials in the concrete mix to see its effect on the heat of hydration generated by observing the temperature increase in concrete. The SCMs utilized in this study include fly ash (FA) and bottom ash (BA) at replacement rates of 15% and 30%, and silica fume (SF) at replacement rates of 5% and 10%. Tests were conducted on concrete cubes of three different sizes: 5x5x5 cm, 15x15x15 cm, and 30x30x30 cm, to evaluate the effect of volume on the temperature rise in concrete over a seven-day observation period.

RESEARCH SIGNIFICANCE

This research is significant in advancing the understanding of the thermal behavior of concrete, particularly in relation to the heat of hydration. By incorporating waste materials such as fly ash, bottom ash, and silica fume as supplementary cementitious materials (SCMs), this study explores innovative ways to manage and reduce the heat generated during concrete hydration. The heat of hydration is a critical factor in the integrity and durability of massive concrete structures, as excessive heat can lead to thermal cracking, compromising structural stability. Through systematic experimentation with varying types and percentages of SCMs, the research aims to identify optimal combinations that minimize the heat of hydration.

METHODOLOGY

In this study, experimental heat of hydration tests was carried out on mortar and concrete cubes with 3 size variations, namely mortar 5 x 5 x 5 cm, concrete cube 15 x 15 x 15 cm, and 30 x 30 x 30 cm, by varying the type and percentage of supplementary cementitious materials by 15% and 30% for fly ash and bottom ash while 5% and 10% for silica fume. Details of these test sample variations are shown in Table 1.

Table 1 Variation of testing samples

Sample Code	Sample Type	Sample Size (cm)
OPC	Mortar	5 x 5 x 5
	Concrete	15 x 15 x 15
	Concrete	30 x 30 x 30
FA15	Mortar	5 x 5 x 5
	Concrete	15 x 15 x 15
	Concrete	30 x 30 x 30
FA30	Mortar	5 x 5 x 5
	Concrete	15 x 15 x 15
	Concrete	30 x 30 x 30
GBA15	Mortar	5 x 5 x 5
	Concrete	15 x 15 x 15
	Concrete	30 x 30 x 30
GBA30	Mortar	5 x 5 x 5
	Concrete	15 x 15 x 15
	Concrete	30 x 30 x 30
SF5	Mortar	5 x 5 x 5
	Concrete	15 x 15 x 15
	Concrete	30 x 30 x 30
SF10	Mortar	5 x 5 x 5
	Concrete	15 x 15 x 15
	Concrete	30 x 30 x 30

Heat of hydration test is carried out by casting concrete/mortar cubes and then embedding thermocouples as temperature sensors into the cubes with the sensor configuration as shown in Figure 1. This aims to see the pattern of heat distribution by observing the increase or decrease in temperature detected by the sensor. The sensor is directly connected to a data logger that will store data according to the specified reading time range. These observations were made for 7 days after casting without curing the specimens.

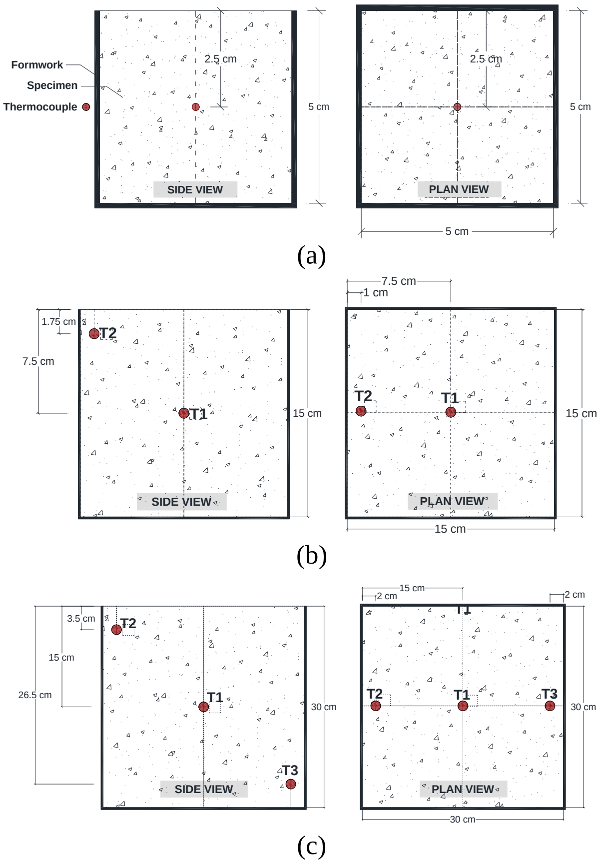


Figure 1 Temperature Sensor Placement Configuration (a) Mortar (b) 15/15 Cube (c) 30/30 Cube

The materials used in this study are not much different from the materials that are used for concrete in general. For fine aggregate, regular sand from Lumajang East Java was used, which is classified as medium sand with a maximum size of 4.75 mm, while for coarse aggregate, crushed stone with a maximum size of 2 cm was used. Cement as a binder used Gresik Ordinary Portland Cement. Fly ash (FA), bottom ash (BA), and silica fume (SF) were used as cement replacement materials. FA and BA were collected from coal combustion waste of PLN Paiton with chemical composition of X-ray Fluorescence (XRF) test results shown in Table 2.

For bottom ash, smaller particle size is needed to ensure the same fineness as cement, so bottom ash needs to go through a grinding process. Grinding using a ball mill tool that smoothes the material with a rotating ball (tube) system, carried out for ± 4 hours to produce grain fineness as shown in Figure 2. For Silica Fume, MasterLife SF was used which is included in the silicon metal alloy type with SiO2 content in the range of 87-98%. Details of the chemical composition of the X-ray Fluorescence (XRF) test results of silica fume are shown in Table 3.

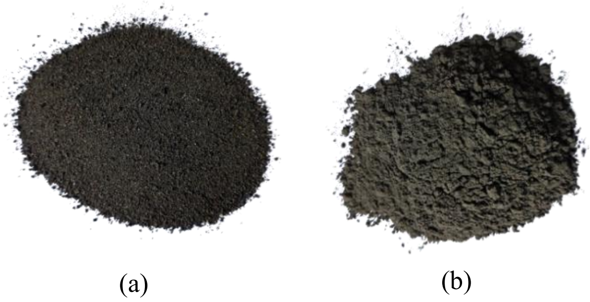


Figure 2 (a) Bottom Ash before grinding. (b) Bottom Ash after grinding

The mortar is composed of cement, sand, and water, while the SCM is used to replace cement partially. The mortar manufacturing process follows the mix methods and proportions as standardized in ASTM C-311. The standard provides instructions on how much water is required to obtain the required consistency as well as the appropriate ratio of sand to cement [14]. The mortar mix proportions for each variation are shown in Table 4.

The composition of concrete is composed of cement, sand, gravel, and water with the casting process following the composition of the mix design calculation with a concrete compressive strength value of 30 MPa.

Table 2 Chemical composition of fly ash and ground bottom ash

SCMs Type	**Components**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**Na_2O**
Fly ash	(%)	37,75	19,11	12,49	13,46	6,25	5,40
Ground Bottom ash		50,63	14,04	13,79	7,46	3,48	3,28
SCMs Type	**Components**	**K_2O**	**TiO_2**	**MnO_2**	**P_2O_5**	**Cr_2O_3**	**SO_3**
Fly ash	(%)	1,92	0,86	0,27	0,38	0,01	0,98
Ground Bottom ash		1,62	0,79	0,77	0,21	0,01	0,43

Table 3 Chemical composition of silica fume XRF results

Components	**Al_2O_3**	**SiO_2**	**P_2O_5**	**SO_3**	**K_2O**	**CaO**
(%)	0,5	93,8	0,96	0,82	1,2	2,14
Components	**Fe_2O_3**	**CuO**	**ZnO**	**As_2O_3**	**Re_2O_7**	**PbO**
(%)	0,28	0,096	0,028	0,009	0,04	0,11

Table 4 Proportion of mortar mix

SCMs Type	Sample Code	Cement (Kg/m^3)	Fine Aggregate (Kg/m^3)	w/c	Variation of SCMs (% of cement)
-	OPC	666,67	1833,33	0,484	0%
Fly Ash	FA15				15%
	FA30				30%
Bottom Ash	GBA15				15%
	GBA30				30%
Silica Fume	SF5				5%
	SF10				10%

Note: the above proportion is for 1 mortar mix of 6 samples.

Table 5 Proportion of concrete mix

SCMs Type	Sample Code	Cement (Kg/m^3)	Fine Aggregate (Kg/m^3)	Coarse Aggregate (Kg/m^3)	w/c	Variation of SCMs (% of cement)
-	OPC	253,30	337,26	490,41	0,46	0%
Fly Ash	FA15					15%
	FA30					30%
Bottom Ash	GBA15					15%
	GBA30					30%
Silica Fume	SF5					5%
	SF10					10%

Note: the above proportions are for 1 mix of 1 sample 15/15 cube and 1 sample 30/30 cube.

RESULTS AND DISCUSSIONS

A. TEMPERATURE MONITORING OF MORTAR

Figure 3 shows the mortar that has been molded and embedded with sensors to observe and record the temperature increase or decrease data that occurs using a data logger with a reading time range per 5 minutes for the first 24 hours, and per 30 minutes for the following hours. On the other hand, the ambient temperature was recorded using another data logger device.

Figure 3 Mortar Temperature Measurement

The concrete mix proportions for each variation are shown in Table 5.

The observation results showed that the temperature increase that occurred in the mortar was not so significant. Figure 4 shows the results of temperature monitoring every 30 minutes for 5 days (7200 minutes). The pattern of ups and downs in temperature is not much different from the pattern of ups and downs in ambient temperature. This is due to the small size of the test specimen so that the heat that occurs due to hydration is not so high. A parametric research was conducted to find out how the no-flange concrete segmental box-girder model's volume to surface area ratio affected the way the concrete's temperature developed. The calculation explained by the fact that as the segment's width rises, its volume increases as well, producing more heat as the cement hydrates[15].

This explains why mortar cubes have generally low temperatures in proportion to their low heat of hydration. The maximum temperature recorded in the OPC variation as the control variable was 31.45°C in the first 6-7 hours. For the varied supplementary cementitious materials, SF10 which represents the variation of using 10% silica fume resulted in the highest temperature increase from the other variations with the maximum temperature reaching 31°C at 6-7 hours after casting. While GBA30, the variation using 30% Ground Bottom Ash, showed the lowest temperature increase among the other variations, which was lower than the maximum average daily ambient temperature of 30.4°C with the maximum temperature reaching 30°C which occurred on the third day after casting. This slowing of the heat of hydration was seen in the GBA30, FA30, and SF5 variations.

The slowing down of the heat of hydration can be seen from the accumulated time required to reach the maximum temperature on the 3rd day after casting. This indicates that the rate of hydration decreases, the chemical reaction is slow, and this influences the amount of heat generated. Previous research investigated that the replacement of fly ash for cement reduces the maximum value of the heat flow released and increases the inactive period. As a result, the amount of heat emitted in concrete combinations containing fly ash is reduced. It primarily delays hydration throughout the latent and acceleration phases [16]. In other words, the addition of 30% fly ash and bottom ash respectively as well as 5% silica fume extended the dormant period in the hydration stage of cement in the case of this mortar.

B. TEMPERATURE MONITORING OF CONCRETE

The molding and embedding of the temperature sensors for concrete cubes (15x15x15) cm and concrete cubes (30x30x30) cm are shown in Figure 5.

Figure 5 Concrete Temperature Data Acquisition Scheme

Similar to the mortar, the temperature was observed and recorded using a data logger with readings per 5 minutes for the first 24 hours, and per 30 minutes for the following hours. The configuration for the 15/15 concrete cube used two sensors as shown in Figure 1(b), while the 30/30 concrete cube used three sensors with the configuration shown in Figure 1(c).

The maximum temperature for each variation generally occurred at sensor T1 located in the core of the concrete, which tended to be higher than the temperature recorded at sensor T2. The increase was much more significant than the increase in the mortar described earlier, especially in the first 24 hours after casting. In Figure 6(a), the OPC variation as the control variable shows a maximum temperature of 37.50°C. As for variations outside the control variable, it shows that SF5 is the variation with the highest maximum temperature value compared to other supplementary cementitious material variations at 37.50°C, the same as the OPC variation. The lowest temperature occurred in the GBA30 variation with a value of 33.25°C. This shows that the addition of pozolanic materials, in this case ground bottom ash, helps to reduce the peak heat of hydration normally generated by the rapid reaction of Portland cement. The higher concentration of coal bottom ash showed that the amount of portlandite consumed by the pozzolanic reaction is larger than the amount of portlandite produced by the hydration reactions. Increasing the coal bottom ash content from 10% to 15% showed that it has a slower pozzolanic reactivity that initiates at the latest 14 days after the material has cured in the cement matrix [17]. Thus, in descending order, the cement replacement material variations with the highest to lowest temperature values are OPC = SF5 > FA15 > GBA15 > FA30 > SF10 > GBA30.

The results of recording the temperature of the 30/30 concrete cube are shown in the graph in Figure 7. Due to the large size of the test specimen, it was possible to install 3 sensors to represent the temperature distribution at certain points in the concrete. The maximum temperature of each variation generally occurred at sensor T1 which was located in the core of the concrete. The heat accumulation recorded at sensor T3 was lower than T1 but higher than the temperature recorded at sensor T2. At sensor T1, the maximum temperature of 55.25°C was obtained from the OPC variation, while the minimum temperature of 47.50°C was obtained from the GBA30 variation. Which in prior study about bottom ash investigated when the amount of coal bottom ash in the cement mixture increases, the hydration process is delayed because the activity of the coal bottom ash is lower in the initial stages. When a mortar or

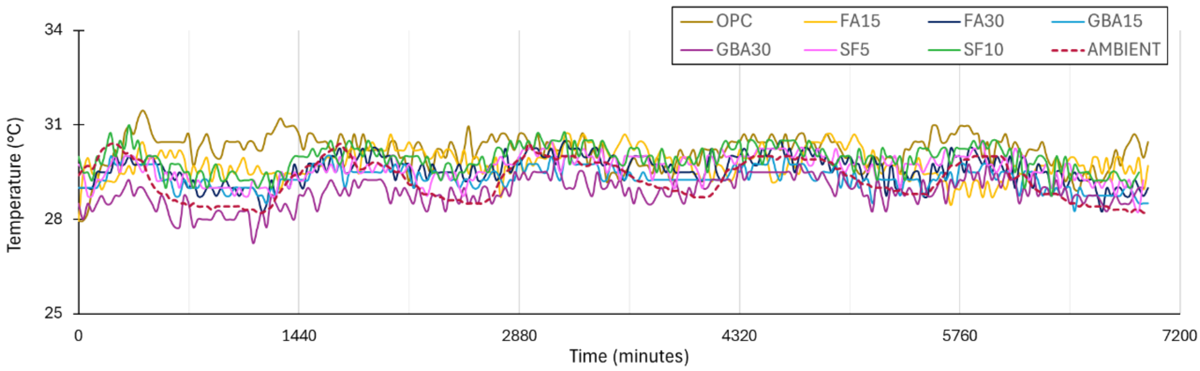
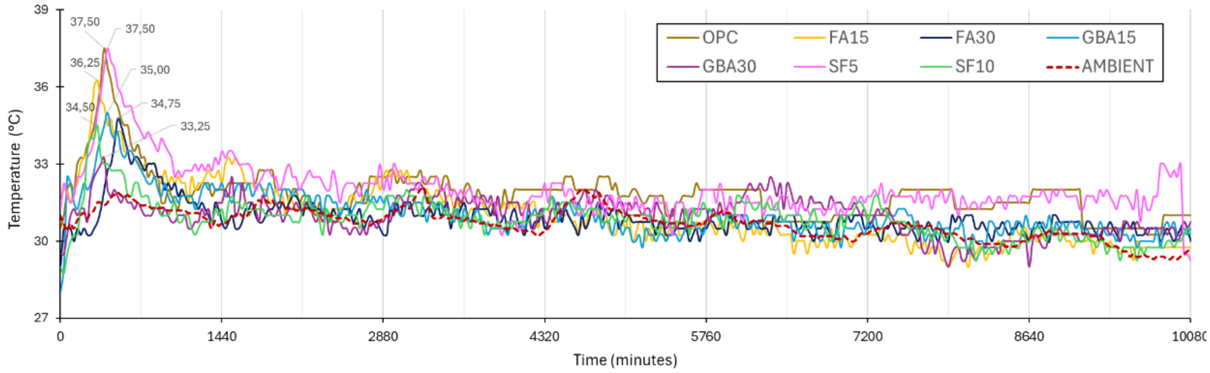
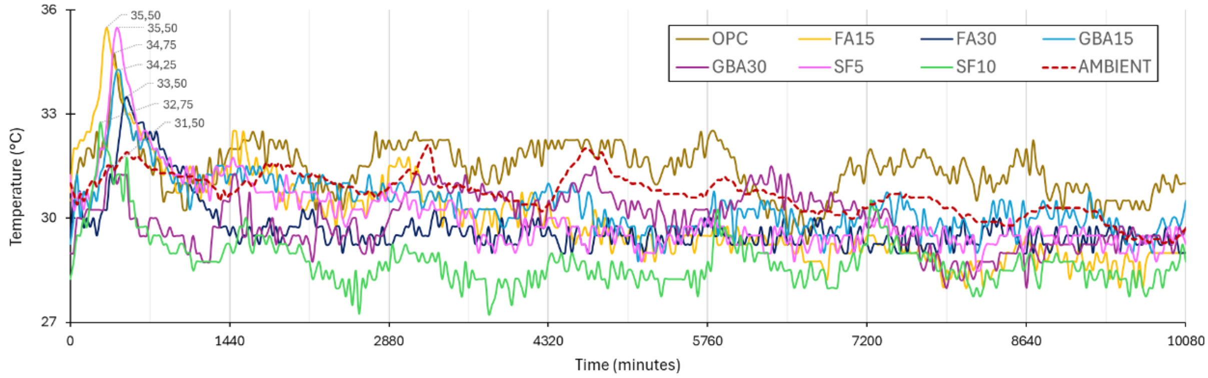


Figure 4 Mortar Temperature Monitoring Result



(a)



(b)

Figure 6 Temperature Monitoring Results of 15/15 Concrete Cube (a) Sensor T1 (b) Sensor T2

concrete contains more than 10% coal bottom ash, the cement hydration process is delayed, delaying the early strength development of the material [18].

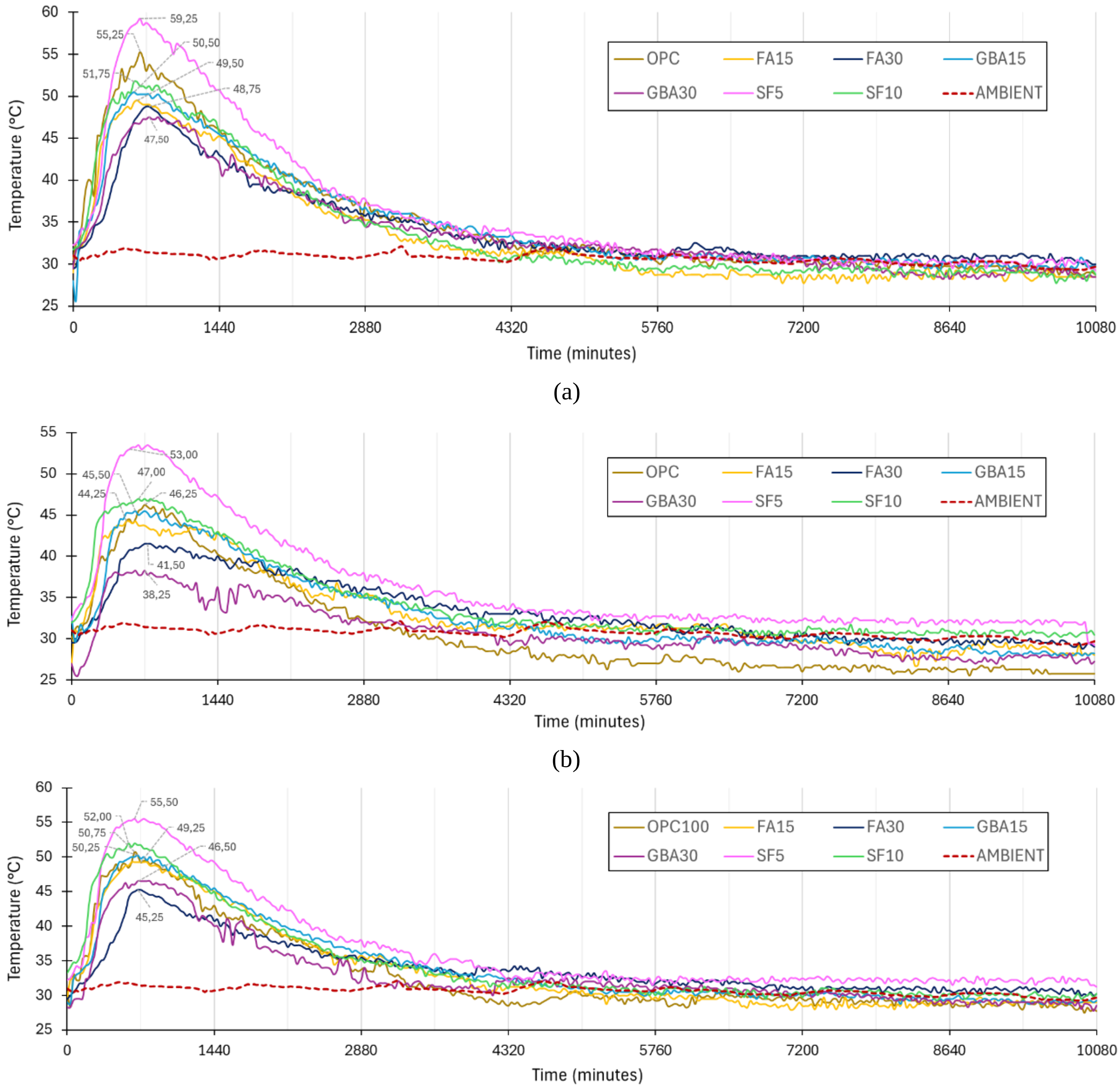
However, it can also be found that for this specimen size, the temperature of the SF5 variation is higher than that of the OPC variation at 59.25°C. The maximum temperature difference between these two variations reaches 4°C. This can be seen in the sensor readings specific to the SF5 variation. Typically, cement "replacement" is reserved for situations in which low heat is necessary. To improve strength and decrease permeability, silica fume is mostly added to base cementitious component in higher performance concrete. The heat of hydration may rise more quickly in the early stages when employed in this manner with a lower water cementitious ratio, which should be considered when the concrete cures [19]. As for other variations, the T2 sensor shows the lowest temperature recording results of all installed sensors.

This is certainly due to the position of the sensor which is closer to ambient temperature so it's easier to release heat compared to other sensor locations. As for sensor T3, it shows results between the recording values of sensors T2 and T1. This could be due to the fact that even though the sensor position is at the edge of the concrete, it is still obstructed by the formwork used so that heat release is not as easy as sensor T2. Thermocouples located at the edge of the specimen do not represent the internal temperature of the concrete as they tend to experience the greatest deviation from the surface plot [20].

Table 6 summarizes the maximum temperature that occurred at each sensor and the temperature difference that occurred (compared to the control variable temperature). For 15/15 concrete, the maximum temperature of all variations occurred on average in the first 6-7 hours after casting. While for 30/30 concrete, the average maximum temperature was reached at 11-12 hours after casting. After the maximum temperature is reached, the temperature will tend to decrease as time increases. However, in order to achieve total heat release until the concrete temperature is equal to ambient temperature, it takes different durations for each concrete size. The 15/15 concrete required 1 day to release heat until the concrete temperature was similar to ambient temperature, while the 30/30 concrete required a longer time of 3 days.

C. EFFECT OF SUPPLEMENTARY CEMENTITIOUS MATERIALS VARIATION ON HEAT OF HYDRATION

The cement hydration process is highly exothermic. In large constructions, the exothermic behavior of cement hydration causes the temperature to increase along with the heat energy in the concrete section. Supplementary Cementitious materials (SCMs) and fillers, which affect the development of heat of hydration, can be added in concrete mix design in addition to cement [21]. In this study, the test results showed different temperature increase responses for each concrete size and each admixture variation used. With the same w/c value of 0.46 and average compressive strength of 30 Mpa for all mixes



(c)

Figure 7 Temperature Monitoring Results of 30/30 Concrete Cube (a) Sensor T1 (b) Sensor T2 (c) Sensor T3

when compared to OPC as the control variable, the decreasing or increasing effect given by the supplementary cementitious material varied depending on the size and type of SCMs used as shown in Table 7.

FA15 concrete and FA30 concrete show an inverse comparison between the proportion of fly ash and the increase in temperature due to the heat of hydration that has been generated. The higher the percentage of cement replacement with fly ash, the temperature increase tends to decrease. In previous research investigated the peak heat rates decrease when FA is added, according to the adiabatic calorimeter results from the binder mixes. The time needed to reach the peak heat rate is slightly accelerated when fly ash replaces 20% and 40% of the Portland cement (CEM1). However, an 80% substitution led to a considerable delay in the hydration activity when compared to the standard CEM I concrete [22].

The contribution of decreasing temperature is more significant when the size of the specimen is enlarged with the same water-cement ratio and compressive strength. Fly ash concrete mixtures with w/c values of 0.4 to 0.5 show a more significant hydration retarding effect than cement water ratios with lower values [10]. This is seen in the cumulative time required for maximum heat to be reached which is about 1-2 hours slower than OPC concrete.

The same correlation was observed in GBA15 concrete and GBA30 concrete variations. These ground bottom ash concrete mix variations show the most significant temperature reduction effect. At a percentage of 30% addition, the percentage of temperature reduction for each test specimen size also decreased and even became the largest percentage reduction of up to 14% of OPC concrete. The results of research on concrete with a mixture of coal bottom ash have a high thermal conductivity value and increase as the bottom ash content rises [23]. This makes it easier for concrete with bottom ash content to release heat than concrete with other binder mixtures. When the proportion of ground bottom ash (GBA) is increased, the overall heat generation decreases, leading to quicker cooling of the concrete and an earlier peak temperature. This shift can relieve thermal cracking issues caused by excessive temperature differences between the core and surface of the concrete. Therefore, substituting cement with GBA offers an effective solution to mitigate cracking due to excessive heat, particularly in high-strength and mass concrete structures [24].

The SF5 concrete shows different results from the other variations. Significantly, the addition of 5% silica fume in the concrete mix actually increases the temperature due to the heat of hydration. The increase even exceeded that of OPC concrete by 7%. In small test specimens (mortar), the effect of this increase is not quite significant. However, in larger test specimens, in which this refers to concrete (30x30x30) cm, the maximum temperature of SF5 concrete reached the highest temperature in all the sensors located. Silica fume is known to be highly reactive not only because of its high SiO_2 concentration but also because of its very fine particle size, which will certainly affect the pozzolanic

Table 6 Summary of maximum temperature of each sensor in each variation

Variation		Sensor	Temperature (°C) Maximum	Temperature (°C) Difference from T1	Time to reach maximum temperature (hour)
OPC (control)	K15/15	T1	37,50	-	6,5
		T2	34,75	2,75	6,5
	K30/30	T1	55,25	-	11
		T2	46,25	9,00	12,5
		T3	50,75	4,50	11
FA15	K15/15	T1	36,25	-	7,5
		T2	35,50	0,75	7,5
	K30/30	T1	49,50	-	11,5
		T2	44,25	5,25	10
		T3	49,25	0,25	11,5
FA30	K15/15	T1	34,75	-	8,5
		T2	33,50	1,75	8,5
	K30/30	T1	48,75	-	12
		T2	41,50	7,25	12
		T3	45,25	3,50	12
GBA15	K15/15	T1	35,00	-	7
		T2	34,25	0,75	7
	K30/30	T1	50,50	-	10
		T2	45,50	5,00	10,5
		T3	50,25	0,25	11,5
GBA30	K15/15	T1	33,25	-	6,5
		T2	31,50	1,75	6,5
	K30/30	T1	47,50	-	13
		T2	38,25	9,25	10,5
		T3	46,50	1,00	11,5
SF5	K15/15	T1	37,50	-	7,5
		T2	35,50	2,00	7,5
	K30/30	T1	59,25	-	11
		T2	53,50	5,75	11
		T3	55,50	3,75	11
SF10	K15/15	T1	34,50	-	5,5
		T2	32,75	1,75	4,5
	K30/30	T1	52,00	-	10
		T2	47,00	5,00	11
		T3	51,75	0,25	10

Table 7 Percent decrease or increase in maximum temperature for each variation of Mixture for each test specimen size against the control variable

Variation	Mortar		15/15 Sensor T1		30/30 Sensor T1	
	Tmax (°C)	%*	Tmax (°C)	%*	Tmax (°C)	%*
OPC (control)	*31,45*	-	*37,50*	-	*55,25*	-
FA15	30,95	-2%	36,25	-3%	49,50	-10%
FA30	30,50	-3%	34,75	-7%	48,75	-12%
GBA15	30,00	-5%	35,00	-7%	50,50	-9%
GBA30	30,00	-5%	33,25	-11%	47,50	-14%
SF5	30,50	-3%	37,50	0%	59,25	7%
SF10	31,00	-1%	34,50	-8%	51,75	-6%

*) a minus (-) value means a decrease and a plus (+) value means an increase

activity of silica fume in concrete. The use of 5% silica fume as a cement substitute with w/c 0.4 showed the cumulative heat of hydration after 12 h and 24 h of OPC cement as 117.79 J/g and 176.60 J/g increased to 120.72 J/g and 178.92 J/g, respectively [8]. When the hydration heat of the composite binder is compared under varying fly ash and silica fume ratios, it is evident that the acceleration period is delayed during the early stages of hydration as the fly ash ratio rises. But when the ratio of silica fume rises, the acceleration period gets accelerated. When the ratio of fly ash increases in the late stage of hydration, the peak of the heat flow curve lowers significantly; however, the peaks of the heat flow curve rise to varying degrees when the ratio of silica fume increases [25]. Nevertheless, the SF10 variation showed a decrease in the temperature of the concrete. Although the decrease in temperature was the least of all the variations and the accumulation time of peak temperature in this variation was faster, this shows that the use of silica fume does accelerate the heat of hydration but with a higher content or proportion of addition will help in reducing the temperature due to cement hydration.

The accumulated temperature at sensors T2 and T3 shows that the presence of insulation in the form of mold formwork or Styrofoam also affects the increase in temperature that occurs. The monitoring point of sensor T2 is closer to the concrete surface without insulation (direct contact with ambient temperature) hence the temperature recording result tends to be lower than the other monitoring points. While for sensor T3 monitoring point, the measurement distance is not that far different from sensor T2, but the position of the sensor is on the bottom surface of the concrete which has no direct contact with the ambient due to the mold that blocks it, so the results of temperature recording, although not as high as sensor T1 at the core of the concrete, are much higher than the temperature at sensor T2. The maximum temperature difference that occurs in the concrete core with the concrete surface in terms of the maximum temperature at T1 and T2 is 9°C which is still within the safe limits of the maximum allowable temperature difference of < 20°C [6] so that the possibility of thermal cracking does not occur.

CONCLUSIONS

This research include experimental test to investigate the heat of hydration of concrete with variations in size and variations in supplementary cementitious materials. Based on the tests and analysis that have been carried out, the following conclusions can be drawn.

1. For concrete with w/c 0.46 and an average compressive strength of 30 MPa, the peak temperatures for specimen sizes (5x5x5) cm and (15x15x15) cm occurred at 6-7 hours after casting, while the peak temperature for specimen size (30x30x30) cm occurred at 11-12 hours after casting. The larger the specimen, the higher the peak temperature with the maximum temperature generally occurring at the core of the concrete, while other monitoring points in the concrete tend to vary depending on the treatment given.
2. The use of fly ash (FA) and ground bottom ash (GBA) as supplementary cementitious materials in concrete mixes contributes to reducing the temperature rise due to the heat of hydration of cement. With increasing content of FA and GBA as binders in the concrete mix, the maximum temperature of concrete due to heat of hydration tends to decrease.
3. The use of silica fume (SF) as a supplementary cementitious material contributes to accelerating the hydration rate of concrete but it is necessary to consider the content of its use as a binder in concrete mixes since a higher percentage or proportion of SF addition will have a greater effect on reducing the temperature due to cement hydration. According to the results of this study, the use of SF 10% can be considered.

Following the results of this study, the addition of cementitious replacement materials can be considered as an option for use in construction, especially in relation to mass concrete. These results can also be taken into consideration to predict the maximum heat that can occur in larger test specimens, which are more representative of mass concrete itself. However, this further process needs to also consider whether with the same characteristics and variations, the increase in temperature that occurs can be considered linear or not.

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