IOP Conference Series: Earth and
Environmental Science

# Strength and heat emissions performance of high strength concrete containing fine metakaolin & palm oil fuel ash as partial cement replacement

To cite this article: M N R Abu Bakar *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1347** 012070

# Strength and heat emissions performance of high strength concrete containing fine metakaolin & palm oil fuel ash as partial cement replacement

**M N R Abu Bakar[1], M H Ismail[1*], N A N Che Rahim[1], M A Majid[1], N Md Noor[1] and A F George[2]**

[1] Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat, 86400, Johor, Malaysia
[2] Kinetic Building Technology Sdn Bhd, No 8-3 (2nd Floor), Jalan USJ 9/5N, UEP Subang Jaya 47620 Subang Jaya, Selangor, Malaysia.
*Corresponding author: mohdhanif@uthm.edu.my

**Abstract.** Cement production significantly contributes to greenhouse gas emissions, specifically carbon dioxide ($CO_2$). In addition to the $CO_2$ emissions from cement production, the increase in palm oil fuel ash (POFA), which is the by-product of the palm oil industry, can also contribute to environmental pollution. This study carried out on POFA and metakaolin (MK) as a partial cement replacement can reduce the problem of greenhouse and environmental effects. Apart from that, it can also increase the level of concrete strength. The slump and compressive strength tests were carried out first on concrete that uses fine metakaolin (FMK) only as a partial cement replacement to obtain an optimum value of FMK. Thus, the optimum FMK content found in this study was 20%. Next, slump tests, compressive strength tests, and heat of hydration tests were carried out on samples containing FMK and POFA content as a partial cement replacement up to 40% of the total cement replacement. The POFA content starts at 5%, followed by 10%, 15%, and 20%. In addition to that, FMK content of 20% and superplasticizer (SP) of 2% were constant for all design mixes. The workability of concrete decreases with the inclusion of FMK and POFA as partial cement replacements and 2% of SP as a constant. However, the strength of concrete containing 20% FMK and 5% POFA as partial cement replacement has given better compressive strength than ordinary Portland cement (OPC) concrete up to 14.07% at 28 days. Additionally, it is found that the exact amount of 20% FMK and 5% POFA enables concrete to be reduced to 5.54% in peak temperature compared to OPC concrete. Furthermore, the formation of C-S-H gel was increasingly generated and able to fill in the gaps in concrete when the POFA content increased, thus making the concrete denser and stronger than the control series.

## 1. Introduction

In Malaysia, concrete is commonly used in the construction of buildings, bridges, and other infrastructure projects. The grade of concrete used in the industry refers to the strength of the material. It is determined by the ratio of the components used in its composition. Furthermore, the compressive strength of concrete is an important factor in determining its overall quality and suitability for various construction applications. In addition, the composite materials of concrete are made up of various materials such as coarse and fine aggregates, cement, and water. High-strength concrete (HSC) has recently become increasingly popular in Malaysia due to its superior strength and durability compared to normal concrete. According to Bahri et al. [1], HSC generally has a compressive strength of 50 MPa or more when measured after 28 days of curing, even though the exact curing time may vary depending on the specific application and requirements. In general, HSC has been chosen as the primary type of concrete used in high-rise buildings, bridges, and other large-scale infrastructure projects due to its high strength and durability. The use of HSC with a low water-binder ratio (w/b) is generally considered more suitable in the construction sector compared to normal concrete [2], as it reduces the amount of water in the mixture and, therefore, increases the OPC content.

Around the world, people have become increasingly aware of the importance of preserving and conserving the environment in recent years. An increasing number of individuals and organizations have taken action to address these issues, including through initiatives to reduce greenhouse gas emissions. On top of that, advances in technology and innovation have been introduced in many sectors, including renewable energy, resource efficiency, and waste management. Besides that, these innovations are helping to reduce the environmental impact of human activity and promote a more sustainable future. As the demand for HSC increases in Malaysia, the demand for the use of cement content is also likely to increase. The cement manufacturing process will release carbon dioxide gas which will cause the greenhouse effect, which will become a serious matter when the demand for cement increases. Cement production will roughly emit one tonne of carbon dioxide (CO2), contributing about 5% of carbon dioxide emissions in the cement industry globally [3]. Other than that, the high cement content in the HSC will produce high temperatures through the hydration process, which can contribute to the internal cracking of the concrete and lead to an increase in local temperature. Besides that, this phenomenon can also cause structural failure in the long term period. The heat generated during hydration is due to the exothermic chemical reactions that occur between the cement and water in the mixture. In order to address the problems, the amount of cement content used in HSC should be reduced by replacing it with another material, such as pozzolanic material.

Among other pozzolanic materials is palm oil fuel ash (POFA). According to Zeyad et al. [4], POFA is a waste listed as one of the pozzolanic materials that are increasing every day and also contributing to the increase in waste at the landfill. POFA is generated by turning solid wastes such as palm shells, fibers, and husk from 900ºC to 1000ºC [5]. According to the data collected by the United States Department of Agriculture in 2017, Malaysia was stated as the second-largest producer of palm oil in the world after Indonesia [6], and this matter can cause serious environmental pollution caused by the increasing quantity of POFA at landfills. In order to address this matter rather than becoming more serious, POFA can be used as an additive or partial replacement for cement in concrete due to POFA is listed as one of the pozzolanic materials [7] because it contains a high level of silica. The silica can react with calcium hydroxide ($Ca(OH)_2$) to form calcium silicate hydrate (C-S-H) compounds which this compound are similar to those formed during the hydration process of cement. Studies have shown that with inclusion of POFA as a partial cement replacement in concrete can improve its performance in several ways [8]. At the same time, the inclusion of POFA can make the concrete less workable and indirectly increase the demand for superplasticizers. Indeed, the inclusion of POFA can improve the compressive strength of concrete, making it more durable and resistant to cracking. This is due to the pozzolanic reaction between silica content found in POFA with the $Ca(OH)_2$. However, POFA is generally known to be more effective in enhancing the late strength of concrete in comparison to the early strength. This is due to the slow process of producing C-S-H gel, additional cementitious materials that strengthen the concrete when silica content found in POFA reacts with $Ca(OH)_2$. Based on the study by Thomas et al. [9], the late strength of concrete is contributed by the amount of silicon dioxide (SiO) present if POFA.

Meanwhile, according to Kamaruddin et al. [10], a strong bond between the binder and aggregates can enhance the interlocking effect, thus making the concrete matrix more compact and dense, improving the compressive strength of the concrete itself. This statement has been proven by Mohammadhosseini et al. [8], who found that the compressive strength of OPC-based concrete in seven days is higher than that of concrete containing 20% POFA. Nevertheless, the compressive strength shows the vice versa pattern after 91 days. It is different from the study of Chalee et al. [11]. It appears that using POFA as a partial replacement for cement up to 15% of the weight of cement has improved the compressive strength of concrete. Nonetheless, when the POFA content is increased beyond this value, the compressive strength of concrete starts to decrease. Most studies found that the content of

POFA used as partial cement replacement can provide good compressive strength between 5% to 15% by cement weight. On the other hand, using POFA as partial cement replacement can also reduce the heat which is occurs from the hydration process in the concrete.

Another material listed as pozzolanic material is fine metakaolin (FMK), produced by the calcination process. The reaction between calcination and dihydroxylation of kaolinite clay at temperatures between 500ºC and 900ºC creates alumino-silicate highly reactive natural pozzolan [2]. FMK is chosen as another pozzolanic material besides POFA in this study as it can improve performance in terms of strength and durability at the early ages of concrete. However, same as POFA, the workability of concrete containing FMK will decrease, and the demand for superplasticizers will increase. FMK is able to contribute to increasing the compressive strength of concrete by improving the microstructure of the material. The fine particles of FMK can fill in the gaps between the cement particles, resulting in denser and stronger concrete [2]. It also proved that FMK could improve the pore structure of cement paste in concrete by forming a secondary C-S-H gel. This is the primary binding agent in concrete and is responsible for its strength and durability. Research has shown that replacing cement with FMK at levels ranging from 10% to 20% can lead to maximum improvement in strength, particularly in terms of compressive strength. Nevertheless, replacing FMK with cement content in concrete can result in a decrease in strength. Moreover, Chen et al. [12] have found that 20% of FMK as partial cement replacement in HSC can provide maximum strength in 28 days. From the heat of hydration point of view, using FMK as partial cement replacement gives a vice-versa pattern when compared to POFA. Using FMK in concrete can accelerate the cement hydration process and increase the rate of heat evolution, which can lead to a higher autogenous temperature rise. A comparison has been made by William et al. [13] between control concrete and concrete containing 10% FMK, which depicts that concrete containing FMK gives a higher peak temperature.

Overall, the research outcome summarizes the effectiveness of POFA and FMK in HSC. It also summarizes the optimum levels of these materials to achieve maximum strength and durability and the potential risks and challenges associated with their use.

## 2. Materials and Method

In this study, all the proportions for the design mix series were referred from the study of Zeyad et al. [4], with some minor modifications to achieve the target strength of concrete which is 50 MPa at 28 days by using 550 kg/m$^3$ of cement and 0.27 of water-binder ratio (w/b). Table 1 shows the design mix proportion for every series for 1m$^3$ concrete. The primary materials of this research were OPC, POFA, FMK, fine aggregate, coarse aggregate, water, and superplasticizer. According to ASTM C618-12a, POFA and FMK were classified in class F and N, respectively. POFA undergoes oven-drying with a temperature of 105ºC ± 5ºC for 24 hours to remove all the moisture present in POFA. Next, dried POFA was ground using a grinding machine to refine the particle size of POFA further and followed by the sieved process in which the desired size of POFA in this study was passed through a 75 micrometre sieve.

Meanwhile, FMK comes with a size between 0.5 micrometre to 0.8 micrometre from the factory. The size of fine aggregate used was passed through a 5 mm sieve, while the coarse aggregate was 10 mm. The use of a compliant SP that meets the ASTM C494 standard, which was categorized in Type F, produced concrete with high workability and fluidity. All the materials used in this study, including OPC, POFA, FMK, fine aggregate, and coarse aggregate, have undergone a specific gravity test. The optimization of FMK was carried out with the inclusion of FMK of 10%, 20%, and 30% as partial cement replacement. Then, the optimum value of FMK was used in the next series, including POFA starting with 5%, 10%, 15%, and 20% of POFA as partial cement replacement. Next, the combination concrete mixture between OPC, POFA, and FMK underwent a heat of hydration test to study the heat behaviour of HSC with the inclusion of POFA and FMK. Scanning Electron Microscopy was conducted for ternary concrete series containing OPC, FMK, and POFA to analyze the microstructure.

**Table 1.** Design mix proportion for every series (for 1 m$^3$)

| **Series** | **w/b ratio** | **Water (kg)** | **Cement (kg)** | **FMK (kg)** | **POFA (kg)** | **Fine aggregate (kg)** | **Coarse aggregate (kg)** | **2% SP (kg)** |
|---|---|---|---|---|---|---|---|---|
| Control | 0.27 | 148.5 | 550 | - | - | 742 | 1034 | 11 |
| M10 | 0.27 | 148.5 | 495 | 55 | - | 742 | 1034 | 11 |
| M20 | 0.27 | 148.5 | 440 | 110 | - | 742 | 1034 | 11 |
| M30 | 0.27 | 148.5 | 385 | 165 | - | 742 | 1034 | 11 |
| M20P5 | 0.27 | 148.5 | 412.5 | 110 | 27.5 | 742 | 1034 | 11 |
| M20P10 | 0.27 | 148.5 | 385 | 110 | 55 | 742 | 1034 | 11 |
| M20P15 | 0.27 | 148.5 | 357.5 | 110 | 82.5 | 742 | 1034 | 11 |
| M20P20 | 0.27 | 148.5 | 330 | 110 | 110 | 742 | 1034 | 11 |

### *2.1. Specimen.*

There are three series of mixtures known as optimization of FMK that have been conducted in order to get the optimum value of FMK, namely M10, M20, and M30 (10%, 20%, and 30% of FMK as partial cement replacement) with the inclusion of 2% of SP. Apart from that, the water-binder (w/b) ratio used in this study for all series is constant at 0.27. In addition, the optimization for the optimum value of FMK has undergone a compressive strength test at 7 days and 28 days. Firstly, a slump test was carried out on fresh concrete mix before being put into a 100 mm x 100 mm x 100 mm cube mould. After the concrete mixture placed in each mould was compacted, all the concrete cubes were left for 24 hours to be hardened. After 24 hours, all the cubes mould was removed from the concrete cubes and fully immersed in the water in a tank for the curing process. Samples of 7 and 28 days were subjected to compressive strength only.

Once the optimum value of FMK content was known, it was used in the design mix for ternary concrete containing OPC, FMK, and POFA. The SP content and w/b ratio used in the design mix series for ternary concrete were the same, which are 2% and 0.27, respectively. In this design mix containing POFA, the value of FMK used is a constant due to the optimum value of FMK, which is 20% inclusion of FMK, while the POFA content was started with 5%, followed by 10%, 15%, and 20%. The slump test was carried out on the fresh concrete mix before being placed into 100 mm x 100 mm x 100 mm cube mould and column formwork with a size of 225 mm x 225 mm x 700 mm. After the concrete mixture had been placed in the mould were compacted, it was left for 24 hours to be hardened, and all the cube moulds were removed from the concrete and fully immersed in a tank filled with water for 56 days for the curing process after 24 hours. Concrete cube samples of 7, 28, and 56 days of age were subjected to a compressive strength test. The column specimen was subjected to a heat of hydration test. A Thermocouples sensor was needed in this test to connect the fresh concrete with the data logger.

### *2.2. Testing and Analysis Method*

The slump test was the first test conducted on the fresh concrete for every series to measure the workability of fresh concrete by following BS EN 12350-2. Compressive strength tests were performed on 100 mm x 100 mm x 100 mm concrete cube samples of sufficient age according to BS EN 12390-3 for each design mix. The heat of hydration test was performed to investigate the thermal behaviour of concrete during the hardening process by following the study of Nagaratnam et al. [14]. The thermocouple sensor used in this test is a "K" type known as a probe with a length of 1 meter each. There were three thermocouple sensors used for each column specimen. In addition, fresh concrete was poured into the formwork immediately after the slump test was carried out and the initial temperature started to be recorded. The test was stopped when the concrete temperature reached an approximately constant value. SEM-EDS were performed on the concrete binder, which is taken from the crushed concrete cube at 28 days' age to analyze the microstructure following BS ISO 16700.

## 3. Results and Discussion

### 3.1. Specific Gravity

Table 2 shows the results of the specific gravity for each material. The specific gravity obtained for OPC and POFA were 2.69 and 1.49, respectively. Indirectly, it is clearly seen that the specific gravity of POFA was lower compared to the OPC. In addition, FMK used in this study had a specific gravity of 2.23, meaning that the specific gravity of FMK had the same pattern as POFA, which was lower than the specific gravity of OPC. The lower specific gravity of POFA can be attributed to its composition, as it is a by-product of burning palm oil husks and shells. This process resulted in a material that is lighter in weight and less dense compared to OPC, which is a finely ground powder made from clinker, gypsum, and other minerals. Overall, the specific gravity of OPC was the highest for the binder compared to the other binder materials, such as FMK and POFA. With regards to aggregate, it is found that coarse aggregate, which measures 10 mm in size, has a specific gravity of 2.42, while fine aggregate has a specific gravity of 2.10.

### 3.2. Slump test

Results from a slump test conducted on eight fresh concretes, including the control series, were depicted in Figure 1. Starting with M10, M20, and M30, the workability of fresh concrete decreases as the FMK content increases, as shown in Figure 1. A decrease of 5.49% has occurred FOR M20 in comparison to M10. Moreover, the slump value is decreasing with a percentage of 6.10% for M30 compared to M10. This is due to the high reactivity of FMK, which leads to the rapid consumption of water during the chemical reaction process, making it more challenging to place, compact, and finish.

Moreover, FMK can fill the pores between the binder, fine and coarse aggregate which is very effective in reducing the amount of available space. Meanwhile, the slump pattern for ternary concrete containing OPC, POFA, and FMK is the same as the slump of the optimization of the FMK series, which is a decreased pattern. Other than that, the value of FMK used in the design mix of concrete containing FMK and POFA is constant for every series, which is 20% of the cement weight. This is due to the optimum value of FMK being 20% by cement weight. For the control series, it was found that the slump is at 151 mm.

Nonetheless, the slump pattern for M20P5 to M20P20 decreases as the POFA content increases in the design mix. In addition, the inclusion of POFA as much as 5%, 10%, and 15% caused an increase in slump values of 22.52%, 15.23%, and 7.28%, respectively. The slump value dropped by 0.7% when the POFA content used in the mix was 20%. The pattern of decrease in terms of the workability of concrete with the inclusion of POFA is shown in Figure 1. The best workability is in the M20P5 series and the workability of concrete decreases as the POFA content increases. Compared to the control series, the decrease in workability from series M20P5 to M20P15 is still better. Nevertheless, the pattern of decreasing workability of concrete with the inclusion of POFA in the M20P20 series is lower in comparison with the control series. From the pattern shown, the workability of concrete will decrease as the POFA content increases so that at one level, the workability will be lower than the control series. The same result has also been obtained by Chandrasekhar [15], in which the slump pattern decreases with the increase of POFA content in the concrete. By referring to Hamada et al. [7], workability can be improved because of POFA's lower specific gravity compared to OPC. Thus, this can fill the voids between the aggregate particles and lubricate aggregate particles to move during the slump test.

### 3.3. Compressive Strength Test

Table 3 shows the results of compressive strength tests upon eight series from 7 days until 56 days. However, for the optimization series of FMK, the compressive strength test was only for 7 days and 28 days. Starting with M10, the compressive strength is 65 MPa at 7 days and 73.2 MPa at 28 days. The increase that occurred from 7 days to 28 days was as much as 12.62%. Meanwhile, for M20, the compressive strength showed 67.6 MPa at 7 days and 88.5 MPa at 28 days. The strength increased by 30.92% from 7 days to 28 days.

Nevertheless, the strength shows a drop pattern for M30. In addition to this statement, the strength for both 7 days and 28 days was decreased by 13.69% with a value of 56.1 MPa and 0.68% with a value of 72.7 MPa compared to M10, respectively. Certainly, M20 gives the highest concrete strength at 28 days which is 88.5 MPa, when compared to M10 and M30, with a strength of 73.2 MPa and 72.7 MPa, respectively. Additionally, Dadsetan et al. [16] mentioned that this is due to the high silicon content in FMK, approximately 25%, which can improve the C-S-H gel in concrete, thus improving the strength of concrete. Since M20 is the optimum value that gives the highest strength on binary concrete, then M20 by cement weight was used in ternary concrete containing OPC, POFA, and FMK for every series. For ternary-type concrete, the strongest series in this study is M20P5, which contains 75% of OPC, 20% of FMK, and 5% of POFA. The increase in strength in comparison between M20P5 and control series at 7, 28, and 56 days is as much as 5.05%, 14.07%, and 14.74%, respectively. However, the weakest series in ternary-type concrete happens to be the M20P20, where this series contains 60% of OPC, 20% of FMK, and 20% of POFA, respectively. Based on Akcay & Tasdemir [17], the strength of concrete at early ages is mostly due to the formation of alumina phases that result from the alumina content found in FMK. The finer particle size of FMK compared to cement allows it to fill in the gaps between the cement particles, resulting in a denser and less porous concrete microstructure.

In addition, the aluminum oxide content found in FMK can also influence the hydration process of concrete. Therefore, this reaction can result in the formation of additional cementitious compounds, leading to the concrete's increased strength. This coincides with a statement by Arslan et al. [18] that MK also can act as a filler that helps to reduce porosity and increase the density of concrete in the early stages, besides accelerating cement hydration at the early age of 3 days. By accelerating the cement hydration process, FMK can promote the formation of $Ca(OH)_2$ in the early stages of concrete hydration. Upon reaction of $Ca(OH)_2$ with FMK and POFA, additional calcium aluminosilicate hydrates (C-A-S-H) are formed. Jaturapitakkul et al. [19] also obtained the same findings where the strength development of their HSC is retarded at an early age. As mentioned by Thomas et al. [9], $SiO_2$ is the main contributor to the late strength of concrete which is the element found in POFA. This is due to the slow process of producing C-S-H, additional cementitious materials that strengthen the concrete when silica content found in POFA reacts with $Ca(OH)_2$.

Nonetheless, the compressive strength of concrete starts to decrease when the POFA content is increased. Most studies have found that the content of POFA used as partial cement replacement can provide good compressive strength between 5% to 15% by cement weight. In addition, the pozzolanic reaction also has its limit where the reaction that occurs is possible to cause a decrease in terms of strength. This has been proven when M20P10, M20P15, and M20P20 have given lower concrete strength when compared to the control series.

### *3.4. Heat of Hydration*

The time-temperature graph, as depicted in Figure 2, shows that the initial temperature for all series is approximately the same during the early period. Nonetheless, with the inclusion of FMK and POFA, affects the heat released during the hydration process. Furthermore, Figure 2 clearly shows that FMK and POFA can be used as partial cement replacements to reduce temperature release. More heat is evolved during the hydration process within 24 hours after casting. The control series recorded the highest peak temperature with a reading of 43.35ºC at the 15th hour after casting. However, starting with M20P5, the peak temperature obtained was 40.95ºC at the 14th hour after casting, and the decrease is about 5.54% compared to the control series. It was followed by the addition of POFA of 10%, 15%, and 20%, where the peak temperature is 40.90ºC, 40.05ºC, and 39.90ºC, respectively, compared with the control series. It can be found that the rate of decrease for M20P10, M20P15, and M20P20 is 5.65%, 7.61%, and 7.96%, respectively, in comparison with the control series. Certainly, the main cause of reduced peak temperature is the decreasing amount of calcium oxide (CaO) found in cement. This is due to the heat released during the reaction between CaO and water (H2O) to produce high $Ca(OH)_2$. Therefore, the inclusion of POFA can reduce the heat released resulting from the cement hydration process in concrete. The same pattern is found in the study of Nagaratnam et al. [14], where the peak temperature also decreases when the content of POFA increases.

### *3.5. SEM*

A binder specimen that contains FMK and POFA as partial cement replacement, together with OPC was taken from the crush concrete samples which already cured up to 28 days. Figure 3 shows SEM images for every series, including control and a ternary binder containing M20P5, M20P10, M20P15, and M20P20. As can be seen in the control series, a few hexagonal platelets of Ca(OH)2 were detected, resulting from the reaction between CaO, which comes from cement content and $H_2O$. In addition, Chen et al. [20] also found the hexagonal platelets of $Ca(OH)_2$ in their test samples. The hexagonal platelets decrease from series M20P5 until M20P20 due to the depletion of $Ca(OH)_2$ content when the POFA content increase. This finding has also been supported by Mujedu et al. [21], who reported that $Ca(OH)_2$ decreases when the content of POFA increases as partial cement replacement.

Furthermore, a small amount of ettringite formed nearly at the fine cracks, just like needles shape, and between the pores in the concrete for the control series. Ettringite is a mineral compound that can form during the curing process of concrete. Ettringite formation is desirable in some cases, but it also causes problems such as expansion and cracking if it occurs excessively or under certain conditions [20].

On the other hand, the C-S-H gel's cloud form is also formed and clearly visible starting in series M20P5 until series M20P20, compared with the control series. The formation of C-S-H gel results from the pozzolanic reaction between both FMK and POFA with $Ca(OH)_2$ is due to the high silica content found in both FMK and POFA. Moreover, the addition of POFA content is able to produce a denser microstructure which is caused by the pozzolanic reaction as well as the ability of micro-filling. The C-S-H gel is clearly visible in the M20P5 series even though it does not fill the pores completely, and because of that, the pores are still visible, making the microstructure less dense. However, more C-S-H gel formed and filling more pores is clearly visible when the POFA content increases, starting from series M20P10 until series M20P20. This indicates that the amount of silica in the mixture significantly affects the formation of C-S-H gel and its ability to fill the pores. According to Mujedu et al. [21], 20% of POFA in a concrete mixture can contribute to the formation of a denser microstructure.

**Table 2.** Specific gravity for materials

| Materials | Specific gravity |
|---|---|
| OPC | 2.69 |
| FMK | 2.23 |
| POFA | 1.49 |
| Coarse aggregate | 2.42 |
| Fine aggregate | 2.10 |

**Table 3.** Compressive strength for every series

| Series | 7d (MPa) | 28d (MPa) | 56d (MPa) |
|---|---|---|---|
| Control | 57.4 | 72.5 | 74.6 |
| M10 | 65.0 | 73.2 | - |
| M20 | 67.6 | 88.5 | - |
| M30 | 56.1 | 72.7 | - |
| M20P5 | 60.3 | 82.7 | 85.6 |
| M20P10 | 50.2 | 67.2 | 71.4 |
| M20P15 | 48.7 | 66.0 | 67.3 |
| M20P20 | 42.6 | 62.1 | 64.9 |

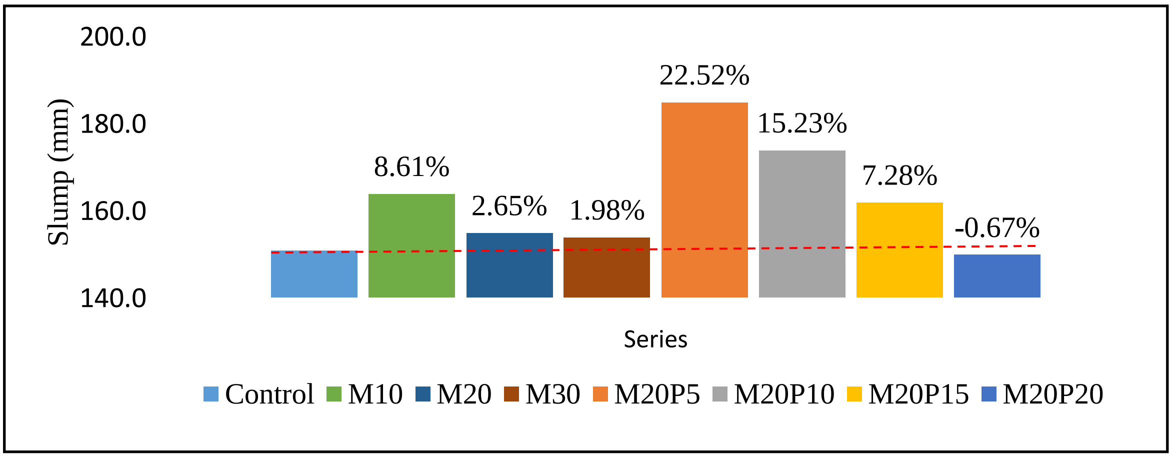

**Figure 1.** Concrete slump results for every series

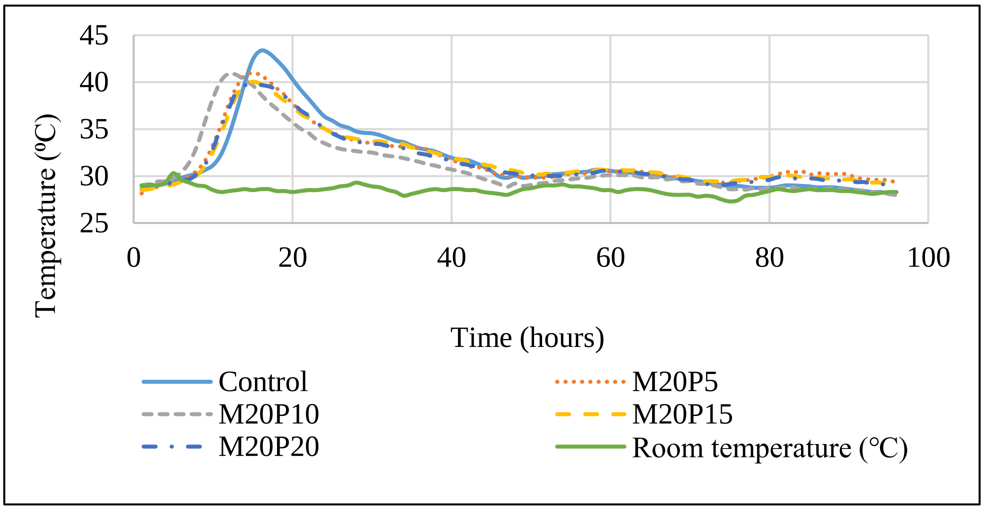

**Figure 2.** Time-temperature graph results for every series

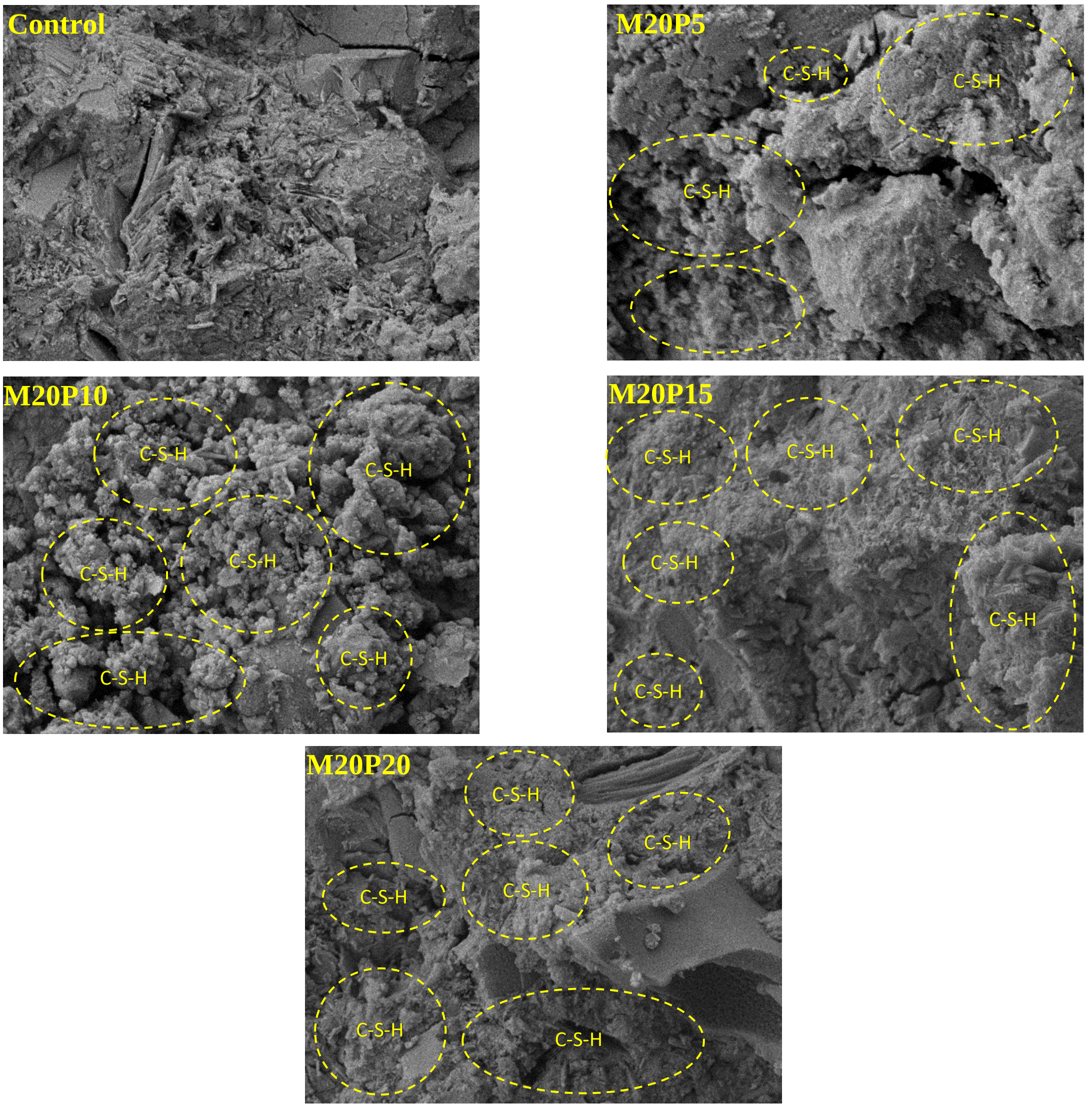

**Figure 3.** Microstructure images for ternary concrete series

## 4. Conclusions

As for optimizing the FMK design mix series, the compressive strength result obtained at 7 days shows that the M20 series achieved optimum compressive strength compared to M10 and M30. Compressive strength at 28 days also gave the optimum results compared to others, making M20 the optimum value of FMK to be used in the design mix series for ternary concrete containing OPC, FMK and POFA. As for the design mix series for ternary concrete, using 20% FMK and 5% POFA (M20P5) has given the highest compressive strength value compared to other series. Moreover, the compressive strength of HSC decreased as the POFA content increased, especially beyond 5% of POFA. The results proved that 20% of FMK content and 5% of POFA (25% as partial cement replacement) by cement weight is the optimum amount of partial cement replacement to obtain the highest strength value of the high-strength concrete.

On the other hand, the temperature drop starts with the M20P5 series for the heat of hydration. The results obtained from this test found that the drop in temperature resulted from cement hydration in concrete when the POFA content was increased. Indirectly, the M20P5 series gives two optimum results, which are compressive strength and heat of hydration simultaneously. The findings of the microstructure for ternary concrete containing FMK and POFA show that the formation of C-S-H gel in concrete increases when the POFA content increases. This is due to the pozzolanic reaction between $Ca(OH)_2$, alumina, and silica found in FMK and POFA. Moreover, all the C-S-H gel formed by the pozzolanic reaction filled the gaps between the particles in the concrete; therefore, the microstructure of concrete becomes denser and improves its strength over time.

## Acknowledgements

This research was supported by the Ministry of Higher Education (MOHE) through Fundamental Research Grant Scheme (FRGS/1/2021/STG05/UTHM/03/2). The authors also would like to thank the Universiti Tun Hussein Onn Malaysia staff in the laboratory of the Faculty of Civil Engineering and Built Environment, where the research was conducted, and would like to thank Ban Dung Palm Oil Mill Sdn. Bhd., for providing POFA in this research.

## References

[1] Bahri S, Mahmud H B and Shafigh P 2018 Effect of utilizing unground and ground normal and black rice husk ash on the mechanical and durability properties of high-strength concrete, *Sadhana,* **43** pp 1-12

[2] Mindess S 2019 *Developments in the Formulation and Reinforcement of Concrete* (Woodhead Publishing)

[3] Mirza J, Hussin M W and Ismail M A 2019 Chapter 2: Effect of high-volume oil palm biomass waste in mortar, *Recycled Waste Materials in Concrete Constructions: Emerging Research and Opportunities* (Hershey PA, IGI Global) pp 17-28

[4] Zeyad A M, Johari M M, Tayeh B A and Yusuf M O 2016 Efficiency of treated and untreated palm oil fuel ash as a supplementary binder on engineering and fluid transport properties of high-strength concrete, *Constr. Build. Mater.* **125** 1066-1079

[5] Siddique R and Mehta A 2020 Utilization of industrial by-products and natural ashes in mortar and concrete development of sustainable construction materials: *Nonconventional and vernacular construction materials* (Woodhead Publishing) pp 247-303

[6] Zeyad A M, Johari M A M, Tayeh B A and Yusuf M O 2017 Pozzolanic reactivity of ultrafine palm oil fuel ash waste on strength and durability performances of high strength concrete, *J. Clean. Prod.* **144** 511-522

[7] Hamada H M, Alya'a A, Yahaya F M, Muthusamy K, Tayeh B A and Humada A M 2020 Effect of high-volume ultrafine palm oil fuel ash on the engineering and transport properties of concrete, *Case Stud. Constr. Mater.* **12** e00318

[8] Mohammadhosseini H, Tahir M M, Alyousef R and Alabduljabbar H 2020 *Production of sustainable concrete composites comprising waste metalized plastic fibers and palm oil fuel ash*: *New Materials in Civil Engineering* (Butterworth-Heinemann) pp 435-457

[9] Thomas B S, Kumar S and Arel H S 2017 Sustainable concrete containing palm oil fuel ash as supplementary cementitious material: A review, *Renew. Sustain. Ener. Rev.* ***80*** 550-561

[10] Kamarudin S, Goh W I, Mutalib N A N, Jhatial A A, Mohamad N and Rahman A F 2021 Effect of combined supplementary cementitious materials on the fresh and mechanical properties of eco-efficient self-compacting concrete, *Arab. J. Sci. Eng.* **46** 10953-10973

[11] Chalee W, Cheewaket T and Jaturapitakkul C 2021 Enhanced durability of concrete with palm oil fuel ash in a marine environment, *J. Mater. Res. Tech.* **13** 128-137

[12] Chen J, Li Q, Ng P, Li L and Kwan A 2020 Cement Equivalence of metakaolin for workability, cohesiveness, Sstrength and sorptivity of concrete, *Mater.* **13**(7) 1646

[13] Williams A, Markandeya A, Stetsko Y, Riding K and A. Zayed A M 2016 Cracking potential and temperature sensitivity of metakaolin concrete, *Constr. Build. Mater.* **120** 172-180

[14] Nagaratnam B H, Rahman M E, Mirasa A K , Mannan M A and Lame S O 2016 Workability and heat of hydration of self-compacting concrete incorporating agro-industrial waste, *J. Clean. Prod.* **112** 882-894

[15] Chandrasekhar Reddy K 2021 Investigation of mechanical and durable studies on concrete using waste materials as hybird reinforcements: Novel approach to minimize material cost, *Inno. Infra. Sol.* **6** 1-17

[16] Dadsetan S and Bai J 2017 Mechanical and microstructural properties of self-compacting concrete blended with metakaolin, ground granulated blast-furnace slag and fly ash, *Constr. Build. Mater.* **146** 658-667

[17] Akcay B and Tasdemir M A 2018 Performance evaluation of silica fume and metakaolin with identical finenesses in self compacting and fiber reinforced concretes, *Constr. Build. Mater.* **185** 436-444

[18] Arslan F, Benli A and Karatas M 2020 Effect of high temperature on the performance of self-compacting mortars produced with calcined kaolin and metakaolin, *Constr. Build. Mater.* **256** p 119497

[19] Jaturapitakkul C, Tangpagasit J, Songmue S and Kiattikomol K 2011 Filler effect and pozzolanic reaction of ground palm oil fuel ash, *Constr. Build. Mater.* **25**(11*)* 4287-4293

[20] Chen X, Sun Z and Pang J 2021 A research on durability degradation of mineral admixture concrete, *Mater.* **14**(7) p 1752

[21] Mujedu K A , Ab-Kadir M A and Ismail M 2020 A review on self-compacting concrete incorporating palm oil fuel ash as a cement replacement, *Constr. Build. Mater.* **258** p 119541