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# Mechanical Properties of High Strength Concrete Containing Fine Metakaolin, Palm Oil Fuel Ash and Coal Bottom Ash

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## Abstract

The increased use of high-strength concrete in the construction industry causes a significant amount of cement production that contributes to major carbon dioxide (CO2) emissions. However, various additives such as fine metakaolin (FMK), palm oil fuel ash (POFA), and coal bottom ash (CBA) can be used to improve concrete performance and reduce carbon footprint. A portion of cement in the concrete was replaced with 20% of FMK and various percentages of POFA (5%, 10%, 15%, and 20%) by weight. While sand was replaced with 10% of CBA. Slump test, water absorption test, compressive strength test, flexural strength test, and split tensile strength tests were performed on concrete samples comprising FMK and POFA as cement replacements and CBA as sand replacements in this research. The partial replacement of FMK and POFA for cement and sand for CBA decreased the workability of the concrete. The small particle size of FMK and POFA serve as fillers, reducing concrete's water absorption. The replacement of POFA by 10% shows the highest compressive strength compared to the control sample. However, water absorption, flexural strength, and split tensile strength improved with the addition of up to 20% POFA. This proves that the incorporation of FMK, POFA, and CBA causes the reaction of alumina oxide, silica oxide, and calcium oxide with calcium hydroxide (C-H) from cement with water during the hydration process of the concrete. In general, the addition of 20% FMK and POFA, with a range of 10% to 20%, together with 10% CBA, enhanced the mechanical properties of high-strength concrete.

## 1. Introduction

The construction industry plays an important role in the development of the economy of a country as it creates more job opportunities and provides essential infrastructures for society. Concrete is a durable and multipurpose material that can be cast into multiple sizes and shapes, making it suitable for various construction projects. High-strength concrete is commonly used in bridges and high-rise buildings due to its greater compressive strength compared to normal concrete. Nevertheless, high-strength concrete requires a huge amount of cement, which needs superplasticizers to maintain workability [1]. Based on the National Oceanic and Atmospheric

Administration [2] in 2023, carbon dioxide ($CO_2$) contributes to the highest radiative forcing among other greenhouse gases, which increases global warming. Global $CO_2$ emissions from burning fossil fuels and making cement totalled 36.1 ± 0.3 $GtCO_2$ in 2022 in comparison, emissions in 2019, 2020, and 2021 were 35.3, 33.4, and 35.5 $GtCO_2$, respectively, indicating increases in 2022 of 2.0%, 7.9%, and 1.5% over those years [3].

The vital component of Malaysia's 12th Malaysian Plan (RMK-12) is to promote green growth and sustainability. To achieve sustainability and resilience, the Malaysian government prioritizes promoting the use of natural resources to move towards a low-carbon nation. The emissions of CO2 during cement production can be minimized by using pozzolanic materials as cement replacements in concrete [4]. One of the most frequently used pozzolanic materials as cement replacement concrete includes metakaolin (MK). MK is a highly reactive aluminosilicate material produced by calcining kaolin clay at a high temperature. Both Chen et al. [5] and Yuan et al. [6] reported that MK's calcination process occurs at temperatures ranging from 500°C to 900°C. It is classified as a pozzolan because alumina oxide (Al2O3) and silica oxide (SiO2) in MK react with calcium hydroxide (C-H) in the presence of water to form calcium silicate hydrate (C-S-H) gel, the same binder formed in the hydration of Portland cement [7], [8]. One of the advantages of MK as a supplementary cementing material is that it can enhance the compressive strength of concrete. Pillay et al. [9] and Chen et al. [5] reported MK as cement replacement by 5 to 10% and 20%, respectively, increasing high-strength concrete's compressive strength. Yuan et al. [6] concluded that about 10% to 25% of MK as cement replacement in concrete developed the compressive strength of concrete. Besides the enhancement of strength, MK also reduces the porosity of concrete. Comparing controlled concrete with water absorption of 4.72% with the addition of 20% MK, the water absorption is reduced to 4.16% [10]. Overall, using MK as a partial cement replacement can help reduce the construction industry's carbon footprint, as it requires less energy to produce cement.

In this study, another pozzolanic material, POFA, was utilized as a cement replacement. POFA is a natural pozzolan and a waste product from palm oil mills. Malaysian Palm Oil Board (MPOB) reported the increment of oil palm plantations had reached 5.65 million hectares in 2023 from 4.85 million hectares in 2010 [11]. The high production of palm oil waste from the process of crude palm oil is reused to generate electricity at the oil palm factories and then produce ashes that include POFA for about 3 million tonnes each year [7]. The overproduction of POFA from palm oil industries threatened the environment and human health due to the excessive waste being discarded at landfills [12]. POFA is rich in SiO2, which contributes to the increment of concrete's compressive strength because of its pozzolanic reaction with C-H from cement and water-formed C-S-H that provide a stronger bond between binder and aggregate [13]. According to Kamaruddin et al. [13], concrete with 5% POFA as cement replacement enhanced concrete's compressive strength, while Chalee et al. [14] reported concrete up to 15% POFA replacement still shows a higher compressive strength of concrete compared to cement-based concrete. As for flexural strength, 10% of POFA replacement shows slightly greater flexural strength compared to controlled concrete [15]. However, the replacement of POFA by 10% exhibits slightly greater water absorption compared to cement-based concrete [16]. Hamada et al. [17] discovered that the nano size of POFA decreases concrete water absorption by up to 30% replacement by weight, while Zeyad et al. [18] found that heat treatment on POFA contributed to lessening the porosity in concrete up to 60% replacement. For the most part, using waste products as cement replacements can help reduce the amount of waste going into landfills and reduce the need to produce cement which contributes to CO2 emissions.

CBA is a coal combustion waste product extracted from the furnace's bottom. It contains poisonous elements like arsenic, cadmium, and mercury. If this material is not properly disposed of, it may contaminate groundwater, rivers, and drinking water. India produces 25 million tonnes of coal bottom ash (CBA) annually, more than any other country, followed by the US with 14 million tonnes, Europe with 4 million tonnes, and Malaysia with 1.7 million tonnes [19]. The production of coal bottom ash in these nations adds to global environmental problems. Efforts are being made in many countries to mitigate the environmental impact of CBA. For example, some countries are exploring ways to reuse or recycle CBA, such as in construction materials or cement production. Consequently, it is essential to use CBA in the concrete production process as this would reduce the need for a landfill. A study by Meh et al. [20] discovered that the particle size, fineness modulus, and interlocking features of CBA were proportionate to sand, making CBA a suitable sand replacement in concrete. Using CBA in concrete reduces the amount of sand required in the mix, which can help conserve natural resources. CBA particles enhance the interparticle friction of concrete and hinder the fresh concrete flow due to their angular and rough texture [21]. Overall, using pozzolanic materials in concrete production can be a cost-effective and environmentally friendly way to reduce greenhouse gas emissions in the construction industry.

## 2. Materials and Method

The research was fully conducted at Universiti Tun Hussein Onn Malaysia laboratories such as the Advanced Materials Laboratory, and Geotechnical Engineering Laboratory.

## 2.1 Materials Preparation

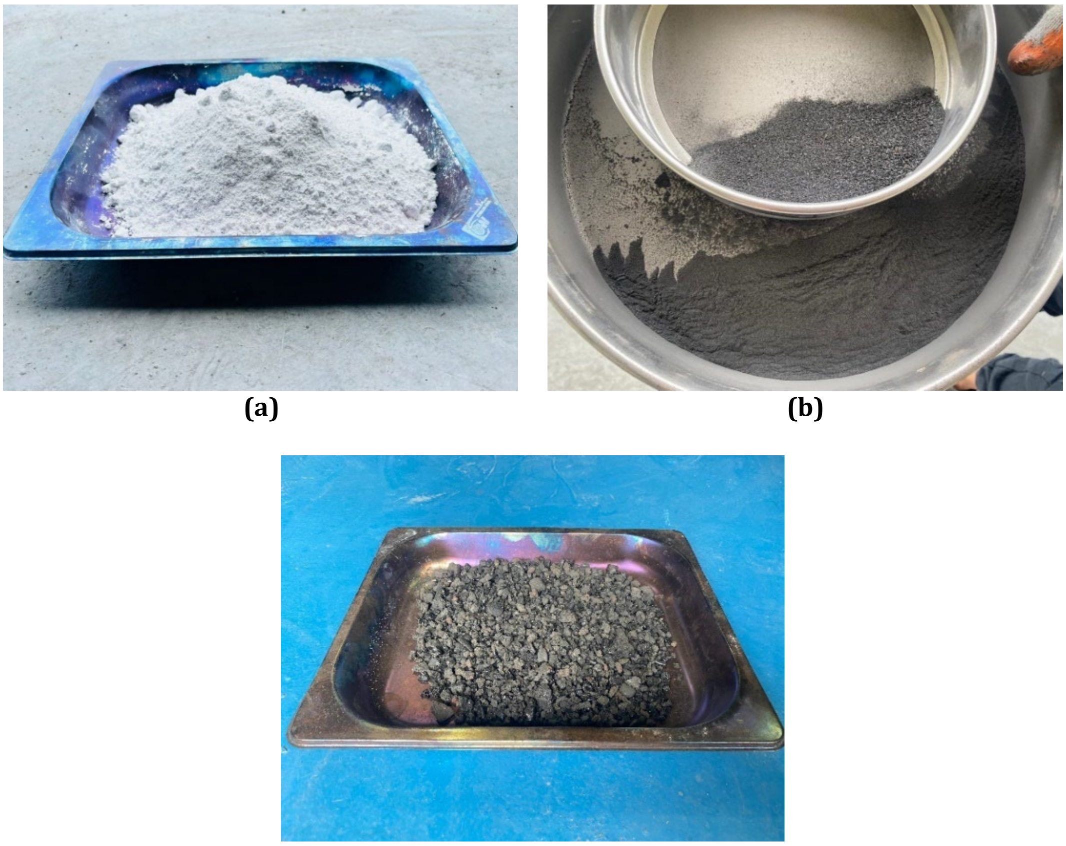
This research used eight raw materials: ordinary Portland cement (OPC), POFA, FMK, sand, CBA, coarse aggregates, water, and superplasticizer. FMK and POFA both were used as partial cement replacements. Kaolin Sdn. Bhd. supplied the FMK shown in Fig. 1(a), while POFA was collected from Ban Dung Palm Oil Mill Sdn. Bhd. oven-dried for 24 hours at 105 ± 5℃ before being ground in LA abrasion machine for 24 hours. After grinding, the POFA then were sieved using a 75 μm sieve pan, such as in Fig. 1(b). The oxide composition of OPC, FMK, and POFA used in the concrete mixing is listed in Table 1. For this research, CBA was used as partial sand replacement and was collected at Tanjung Bin Power Plant, see Fig. 1(c). The size of sand and CBA used for this project was passing through a 5 mm sieve, while the coarse aggregate used was passing a 10 mm sieve and retained at a 5 mm sieve. Table 2 represents the physical properties of FMK, POFA and CBA. The superplasticizer (SP) used was type C and type F, according to ASTM C494.

**Table 1** *Chemical composition of OPC, FMK, and POFA*

| Component | $Na_2O$ | MgO | $Al_2O_3$ | $SiO_2$ | $K_2O$ | CaO | $TiO_2$ | $Fe_2O_3$ |
|---|---|---|---|---|---|---|---|---|
| OPC (%) | 0.19 | 1.98 | 5.05 | 19.3 | 0.43 | 63.8 | 0.22 | 4.44 |
| FMK (%) | 0.09 | 0.04 | 45.2 | 51.6 | 0.15 | 0.25 | 1.54 | 0.79 |
| POFA (%) | 0.07 | 2.45 | 1.63 | 53.1 | 21.4 | 8.72 | 0.16 | 3.32 |

**Table 2** *Physical properties*

| Material | Size | Colour |
|---|---|---|
| FMK | 0.5 to 0.8 μm | White |
| POFA | Sieved passing 75 μm | Black |
| CBA | Sieved passing 5 mm | Dark grey |



**(a)**

**(b)**

**(c)**

**Fig. 1** *Material used in concrete mix (a) fine metakaolin; (b) palm oil fuel ash; (c) coal bottom ash*

## 2.2 Mix Design

The design mix ratio for this research was designed specifically for a concrete design strength of 70MPa at 28 days, utilising 550kg/m3 of cement and a water-binder ratio of 0.27. However, a few changes were made to the pozzolanic material by adding FMK and POFA as partial cement replacement, adding CBA as a partial sand replacement, and different SP dosages. Table 3 shows the material proportion of the five concrete mix series used in this study. The first series was the control mix series without any pozzolanic materials, such as cement and sand replacement. In addition, an optimum value of 20% FMK and 10% CBA replacement was used in this study, respectively. POFA were added in different amounts at 5%, 10%, 15%, and 20% by cement weight. About 2% of SP by cement weight was used to improve the workability of each concrete mix for this project.

**Table 3** *Design mix series*

| Mix series | OPC ($kg/m^3$) | FMK ($kg/m^3$) | POFA ($kg/m^3$) | CBA ($kg/m^3$) | Sand ($kg/m^3$) | Coarse aggregate ($kg/m^3$) | Water ($kg/m^3$) | SP ($kg/m^3$) |
|---|---|---|---|---|---|---|---|---|
| Control | 550 | - | - | - | 742 | 1034 | 148.5 | 11 |
| 20M5P10C | 412.5 | 110 | 27.5 | 74.2 | 667.8 | 1034 | 148.5 | 11 |
| 20M10P10C | 385 | 110 | 55 | 74.2 | 667.8 | 1034 | 148.5 | 11 |
| 20M15P10C | 357.5 | 110 | 82.5 | 74.2 | 667.8 | 1034 | 148.5 | 11 |
| 20M20P10C | 330 | 110 | 110 | 74.2 | 667.8 | 1034 | 148.5 | 11 |

## 2.3 Samples

The concrete mix with partial cement and sand replacement was conducted based on the weight of cement, and sand was replaced with the weight of the pozzolanic materials as a replacement. Several concrete mixings were performed for the control mix series and four mix series with partial cement and sand replacement for this project. Fresh concrete was mixed, and slump tested before pouring into a cube mould of 100 mm x 100 mm x 100 mm dimensions for compressive strength and water absorption tests, a prism mould of 100 mm x 100 mm x 500 mm for flexural strength tests, and a cylindrical mould of 100 mm diameter by 200mm tall for split tensile strength tests.

The concrete in all the mould was then compacted and removed after 24 hours. All the concrete samples were then undergone the curing process by getting fully immersed in the water tank. The samples for 7 and 28 days of curing were acquired for compressive strength and water absorption test, while samples for flexural strength and split tensile strength test were tested after 28 days of curing ages.

## 2.4 Testing Method

Two types of concrete tests were conducted for this study: fresh concrete and hardened concrete testing. Slump tests were performed on fresh concrete to determine the workability of the concrete according to BS EN 12350-2. As for hardened concrete, the test carried out includes a compressive strength test, flexural strength test, tensile strength test, and water absorption test. The 7 and 28 days of concrete cube samples were subjected to compressive strength tests to determine the ability of the concrete to withstand load under compression by referring BS EN 12390-3. A flexural strength test to investigate the ability of concrete to restrain bending failure was performed on 28 days of concrete prism age as specified in BS EN 12390-5. The split tensile strength test for 28 days of the concrete cylinder was performed according to BS EN 12390-6 to find out the tensile strength of the concrete. The concrete cube of 7 and 28 days for water absorption test to estimate the water quantity that can be absorbed by concrete was conducted as subjected in BS 1881-122.

## 3. Results and Discussions

## 3.1 Slump Test

The slump test was performed immediately after the concrete mix-up accordingly. Table 4 shows the result of the slump test on five different concrete mix series with the same water-binder ratio. It was found that the slump value for control mix concrete was 170 mm. The results also indicate that the incorporation of FMK, POFA, and CBA decreased the slump value of the concrete despite using 2% SP for each mix series to improve the workability of the concrete. The 20M5P10C shows an insignificant difference compared to the control series which indicates the constant cement replacement of FMK by 20% does not crucially affect the slump value. Chen et al. [8] reported that the inclusion of MK also minimizes the deformation of the concrete slump, however, the slump deterioration was insignificant. Based on the bar chart plotted in Fig. 2, the workability of concrete of 20M5P10C, 20M10P10C, 20M15P10C, and 20M20P10C were reduced by 4.1%, 11.8%, 42.9%, and 85.3%, respectively, in comparison with the control concrete mix. This shows the workability deteriorates with a further increment of POFA at 5%, 10%, 15%, and 20% as cement replacement. Increasing the POFA content in concrete results in a greater surface area that requires additional water [22] which can lead to a stiffer and less workable concrete mixture. The replacement of 20% FMK, 20% POFA, and 10% CBA reduced the workability of concrete significantly in comparison with the control mix series. The reduction of concrete workability also may be influenced by the usage of CBA as a partial sand replacement due to its irregular shape and porous particles [21]. Thus, the addition of FMK and POFA as cement replacement and CBA as sand replacement resulted in a crucial impact towards the workability of concrete.

**Table 4** *Slump test result*

| Mix series | Slump (mm) |
|---|---|
| Control | 170 |
| 20M5P10C | 163 |
| 20M10P10C | 150 |
| 20M15P10C | 97 |
| 20M20P10C | 25 |

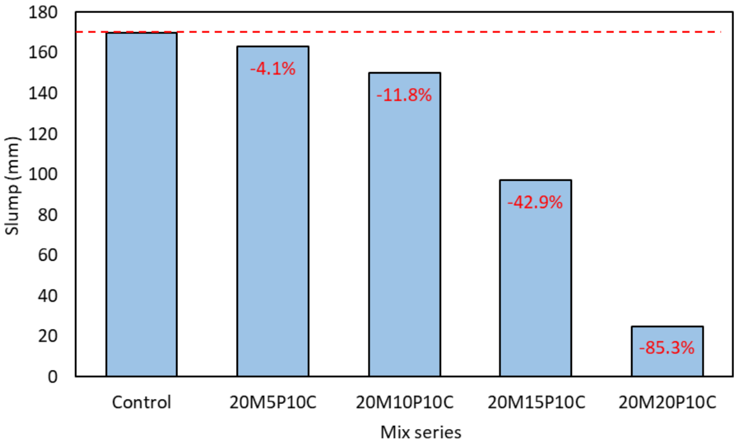


**Fig. 2** *Concrete slump test results*

## 3.2 Water Absorption

Based on Fig. 3, the water absorption of the control mix series has the highest percentages of absorption of 4.06% and 3.89% for both 7 and 28 days of curing age, respectively. The inclusion of 20% FMK, 10% CBA with 5%, 10%, 15%, and 20% POFA shows the reduction of water absorption in concrete for 7 and 28 days of curing age. The concrete relative water absorption depicted in Fig. 4 shows that the water absorption was reduced by 31%, 34%, 46%, and 78% for 20M5P10C, 20M10P10C, 20M15P10C, and 20M20P10C for 7 days, respectively, in comparison with control concrete sample. The water absorption continues to drop by 39%, 44%, 53%, and 85% with a further curing period of 28 days for 20M5P10C, 20M10P10C, 20M15P10C, and 20M20P10C compared to control concrete, respectively. The addition of FMK, POFA and CBA shows the low relative water absorption of concrete indicating the concretes were less porous than the control concrete.

The significant reduction in water absorption of concrete containing pozzolanic materials happened due to the high proportion of cement replacement, which causes a reduction in the gap between particles since both FMK and POFA were only 0.5 to 0.8 μm and 75 μm in size, respectively. The inclusion of 20% FMK and 20% POFA as cement replacement with 10% CBA as sand replacement shows the lowest water absorption due to the ability of FMK and POFA to act as fillers in the concrete mix. According to Muduli et al. [10], the metakaolin closed the concrete capillary and blocked the water from entering the concrete due to the insoluble hydration during the pozzolanic reaction. Mujedu et al. [23] outlined that the incorporation of POFA in concrete resulted in the concrete being denser because of the micro-filling capability and pozzolanic activity. The incorporation of 10% CBA did not negatively impact the concrete water absorption despite previous studies reporting that it has porous particles and greater water absorption than river sand [20].

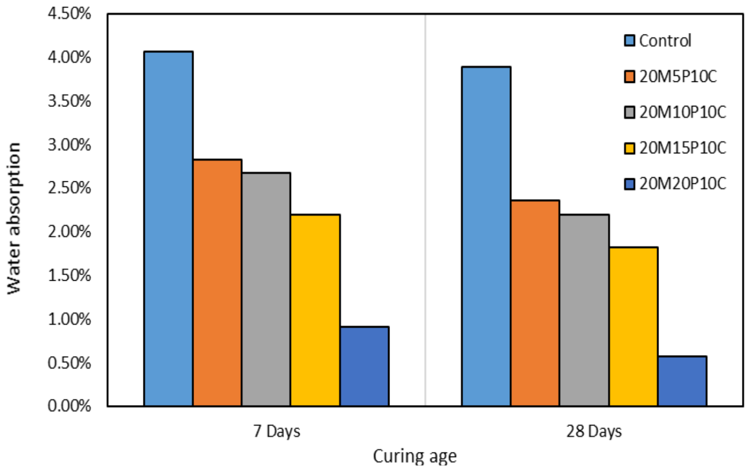


**Fig. 3** *Concrete water absorption*

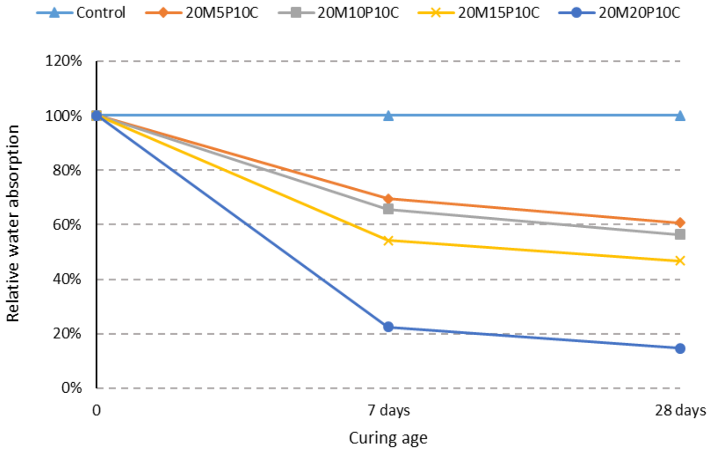


**Fig. 4** *Concrete relative water absorption*

## 3.3 Compressive Strength

Table 5 shows the compressive strength of the concrete series with FMK and POFA as cement replacement with CBA as fine aggregate replacement. The control mix series has a 7-day compressive strength of 57.4 N/mm2 and a 28-day of 72.5 N/mm2. The concrete series of 20M5P10C containing 20% FMK and 5% POFA with 10% CBA shows a compressive strength of 60.5 N/mm2 at 7 days which is higher than the control series. This illustrates that the addition of FMK enhances the compressive strength during the early stages of hydration due to the filler effect [24]. The replacement of 20% FMK also falls within the optimal range of 10% to 25% MK replacement, increasing concrete compressive strength [5], [6]. The Al2O3 and SiO2 in MK react with C-H and water to form calcium silicate hydrate (C-S-H) gel which enhances the strength of concrete [11]. Fig. 5 illustrates the 20M10P10C series has achieved 108% relative compressive strength at both 7 and 28 days of concrete age which is the highest compared to all the concrete series. The substitution of 20% FMK, 10% POFA, and 10% CBA enhanced the compressive strength of the 20M10P10C series. The increment replacement of POFA by up to 10% increases the compressive strength of concrete. The formation of calcium silicate hydrate (C-S-H) due to the reaction of silica oxide in POFA with C-H improves the strength at a later age [25]. However, the POFA increment of more than 10% deteriorates the concrete's compressive strength for 7 and 28 days. The 20M20P10C series has the lowest relative compressive strength by 98% and 95% for 7 and 28 days, respectively in comparison with the control mix series. The decrease in compressive strength particularly at the early stage of hydration can be attributed to the high POFA replacement as binder which leads to limited cement hydration reaction [26]. Nonetheless, the difference in the compressive strength of the 20M20P10C series with the control series is insignificant by only 2% and 5% for 7 and 28 days of concrete age, respectively. The addition of 10% CBA improves the concrete compressive strength for 20M5P10C, 20M10P10C, and 20M15P10C for 7 days of concrete age, and only improves the 20M10P10C series at 28 days of concrete age. CBA is known to have a porous texture, higher than 10% replacement resulted in reducing the concrete compressive strength [27].

**Table 5** *Concrete compressive strength*

| Mix series | Compressive Strength (N/mm²) | |
|---|---|---|
| | 7 days | 28 days |
| Control | 57.4 | 72.5 |
| 20M5P10C | 60.5 | 68.8 |
| 20M10P10C | 62.1 | 78.0 |
| 20M15P10C | 57.3 | 71.2 |
| 20M20P10C | 56.3 | 69.1 |

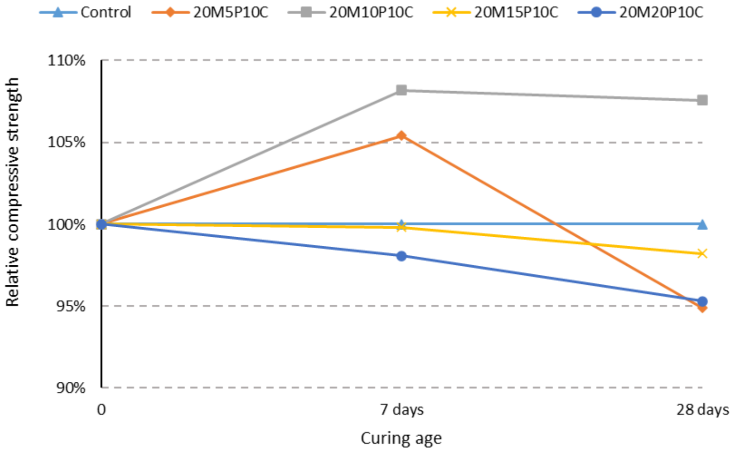


**Fig. 5** *Concrete relative compressive strength*

## 3.4 Flexural Strength

The results of flexural strength of five concrete series for 28 days of curing age are presented in Table 5 and Fig. 6. It was found that, all the mix series with the incorporation of FMK, POFA and CBA surpassed the 28-day concrete flexural strength of control series of concrete. The flexural strength of control concrete is 5.5 N/mm2 for 28 days of curing age. The flexural strength continues to develop with the addition of 5%, 10%, 15%, and 20% POFA. Based on the findings, in comparison with the control series the flexural strength was enhanced by 31%, 36%, 42%, and 49% for 20M5P10C, 20M10P10C, 20M15P10C, and 20M20P10C, respectively. The flexural strength of the concrete mix of 20M20P10C which incorporates 20% POFA and 20% FMK as cement replacements and 10% CBA as sand replacements exhibited that it was the highest compared with all the concrete samples tested including the control series, reaching 8.2 N/mm2.

The bond of binder pastes and aggregates improved with the inclusion of MK, which increases the concrete flexural strength [10]. Pillay et al. [9] also reported that the concrete with MK had higher flexural strength at 28 days and 56 days in comparison with the control concrete. The improvement in concrete strength was also caused by the hydration of silica oxide from POFA with C-H from cement and water. The fine POFA particles reduced the concrete pore by contributing to the filler effect, resulting in denser and greater flexural strength in concrete in contrast with the control concrete sample [15]. Furthermore, the incorporation of CBA provides the addition of C-S-H gel due to its greater calcium oxide content [20] which helps to improve the development of the concrete strength.

## 3.5 Split Tensile Strength

The split tensile strength for 28 days of curing age for all concrete series is shown in Table 6 and Fig. 7. Based on the table, the split tensile strength of the control concrete series is 2.82 N/mm² for 28 days of concrete age. The figure depicted that the addition of 20% FMK and 10% CBA with 5%, 10%, 15%, and 20% of POFA enhanced the split tensile strength of the concrete. Every concrete series that incorporates the replacement materials has surpassed the control concrete series regarding split tensile strength. The percentage rise of concrete split tensile strength at 28 days of concrete age is 33%, 4%, 34%, and 55% for 20M5P10C, 20M10P10C, 20M15P10C, and 20M20P10C, respectively. The concrete's highest split tensile strength, 4.37 N/mm², was obtained when 20% FMK and 20% POFA as partial substitution of cement with 10% CBA as the partial sand replacement was used in the mix.

The utilization of MK decreased the voids in concrete, making it denser and compact, contributing to a stronger bond between bonder paste and aggregates that improved the split tensile strength of concrete [10]. Furthermore, the hydration of silica oxide, which is present in POFA, with calcium hydroxide can be used to account for the increase in concrete strength [15]. Moreover, a study by Haddadian et al. [21] also mentioned that the incorporation of CBA as fine aggregate improves the split tensile strength due to the production of C-S-H gel during the hydration process which provides a greater bond of the concrete mix, which enhances the concrete tensile strength.

**Table 6** *Concrete flexural strength and split tensile strength for 28 days curing age*

| Mix series | Flexural strength (N/mm$^2$) 28 days | Split tensile strength (N/mm$^2$) 28 days |
|---|---|---|
| Control | 5.5 | 2.82 |
| 20M5P10C | 7.2 | 3.75 |
| 20M10P10C | 7.5 | 2.92 |
| 20M15P10C | 7.8 | 3.78 |
| 20M20P10C | 8.2 | 4.37 |

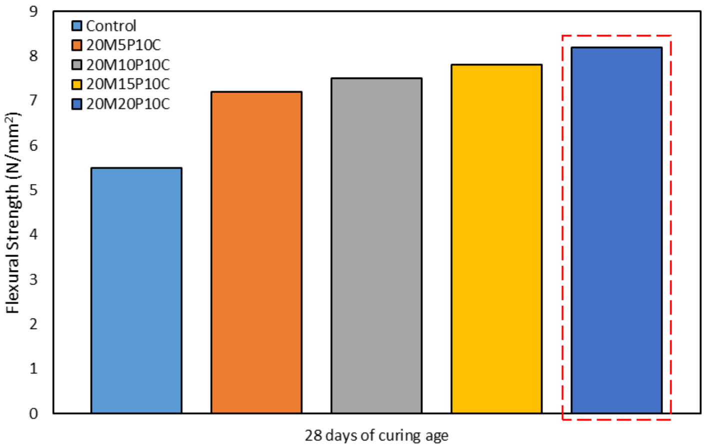


**Fig. 6** *Concrete flexural strength*

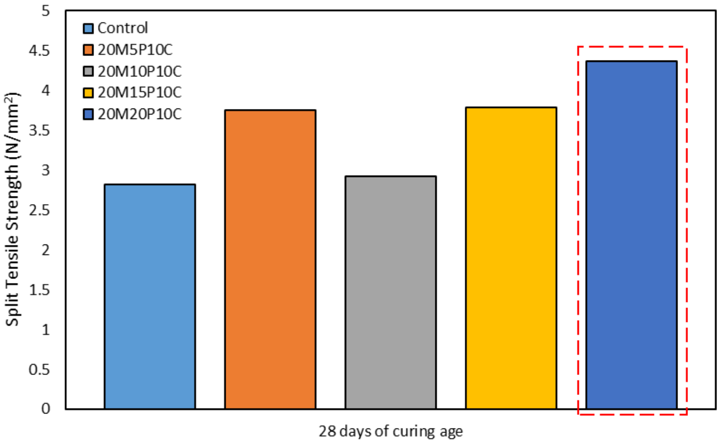


**Fig. 7** *Concrete split tensile strength*

## 4. Conclusion

The research was conducted to study the performance of FMK, POFA as cement replacement and CBA as sand replacement in high-strength concrete in terms of mechanical properties. The evaluation on the concrete performance incorporates several tests such as slump test for workability, compressive strength test, flexural strength test, and split tensile strength test on the concrete sample. Based on the results and discussions, the conclusion of the research can be summarized as the following:

- All concrete mixes that incorporate replacement materials such as FMK, POFA, and CBA exhibit lower workability than the control mix concrete, particularly as the proportion of POFA used as a partial cement replacement increases due to the higher surface area of POFA and the irregular shape and porosity of CBA.
- Notably, the combination of 20% FMK and 10% POFA as cement replacements and 10% CBA as sand replacement (20M10P10C) resulted in the highest compressive strength for both 7 and 28 days of curing age. The alumina and silica oxide in FMK and POFA enhanced the concrete strength and the 10% was the optimal replacement that also improved the compressive strength of the concrete.
- Interestingly, water absorption, flexural strength, and split tensile strength improved when the proportion increased to 20% FMK, up to 20% POFA and 10% CBA. The small particles of FMK and POFA acted as fillers to improve the water absorption, and flexural and split tensile strength of the concrete. Furthermore, the pozzolanic reaction from the high silica and alumina content of POFA and FMK with C-H from cement with the existence of water.

## Acknowledgement

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## Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

## Author Contribution

*The authors confirm their contribution to the paper as follows:* ***designed the study:*** *Nur Anis Natasha Che Rahim, Mohd Hanif Ismail, Muhammad Nur Rasyid Abu Bakar, Masni A. Majid, Nurazuwa Md Noor, Ambros Francis George;* ***performed the experiments:*** *Nur Anis Natasha Che Rahim, Muhammad Nur Rasyid Abu Bakar;* ***analysis and interpretation of results:*** *Nur Anis Natasha Che Rahim, Mohd Hanif Ismail, Muhammad Nur Rasyid Abu Bakar;* ***draft manuscript preparation:*** *Nur Anis Natasha Che Rahim, Muhammad Nur Rasyid Abu Bakar. All authors reviewed the results and approved the final version of the manuscript.*

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