Challenge Journal of Concrete Research Letters

Research Article

Experimental study on the mechanical performance of polypropylene fiber-reinforced concrete incorporating palm oil fuel ash as partial cement replacement

Alaa Omar Tanash [a], Ahmed Mokhtar Albshir Budiea [a,*], Mohd Faizal Md Jaafar [a], Khairunisa Muthusamy [a], Fahrizal Zulkarnain [b]

[a] *Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26300 Kuantan, Pahang, Malaysia*
[b] *Department of Civil Engineering, Universitas Muhammadiyah Sumatera Utara, 20238 Medan, Sumatera Utara, Indonesia*

ABSTRACT

Environmental pollution caused by the disposal of palm oil fuel ash, a type of waste from the palm oil trade, needs to be resolved. At the same time, activities involved in the manufacturing of cement, which is the primary binder in commonly used concrete, have undesirable impacts on the environment. In view of environmental sustainability, the approach of using palm oil fuel ash as a pozzolanic material would contribute towards a cleaner, greener environment. The present study aimed to investigate the fresh and mechanical properties of polypropylene fibre-reinforced concrete mixed with palm oil fuel ash as a cement replacement. Six different mixtures were tested with varying weight percentages of palm oil fuel ash as a cement substitute. Water absorption, workability, compressive strength, and splitting tensile strength were among the tests conducted. Concrete loses some of its workability when palm oil fuel ash is added. The strength of the concrete increases upon incorporating 10% palm oil fuel ash, benefiting from the pozzolanic reaction, which forms a compact internal structure. Notably, at this optimal level, compressive strength improved by approximately 9.5% compared to the control mix after 28 days of curing. This study provides new insights into the underexplored area of incorporating POFA in polypropylene fibre-reinforced concrete (PFRC), where limited prior research exists, thus expanding the understanding of sustainable composite materials. The utilization of palm oil fuel waste for concrete production contributes to the development of environmentally friendly construction materials and supports sustainable building practices.

ARTICLE INFO

Article history:
Received – March 16, 2025
Revision requested – April 14, 2025
Revision received – May 16, 2025
Accepted – May 28, 2025

Keywords:
Palm oil fuel ash
Cement replacement
Fibre-reinforced concrete
Mechanical properties
Water absorption

Citation: Tanash AO, Budiea AMA, Md Jaafar MF, Muthusamy K, Zulkarnain F (2025). Experimental study on the mechanical performance of polypropylene fiber-reinforced concrete incorporating palm oil fuel ash as partial cement replacement. *Challenge Journal of Concrete Research Letters*, 16(3), 115–124.

1. Introduction

Concrete has a high load-bearing capacity and can be used for various construction purposes. The fragile material cannot transfer stresses after fractures. Due to their brittle failure mechanism, fibres make concrete ductile (Hossain et al. 2019). Due to advances in fibre technology and their mechanical strength and endurance, fibres are used in concrete (Liu et al. 2019). Research shows that fibres improve the performance and durability of concrete. Thus, a new composite material has been created by integrating fibres. A cement-based matrix with uniformly and randomly distributed fibres for discontinuous reinforcement forms fibre-reinforced

* *Corresponding author.* Tel.: +60-9-431-5014 ; E-mail address: ahmedbudieea@umpsa.edu.my (A. M. A. Budiea)
ISSN: 2548-0928 / DOI: https://doi.org/10.20528/cjcrl.2025.03.001

concrete (FRC) (Xin et al. 2019). In modern and promising polypropylene fibre-reinforced concrete, fibres in different shapes and geometries are randomly integrated into the cement matrix. The aim is to minimise the susceptibility to fracture and brittleness of cement composites. Due to their low weight, low thermal conductivity, and resistance to acids and alkalis, polypropylene fibres are better than other synthetic fibres (Hesami et al. 2016). FRC is becoming increasingly popular in the construction industry due to increased durability and reduced brittleness, but it also presents challenges in dealing with the environmental impact of cement production. Combining waste materials with FRC is one promising solution to look at.

In 2020, the cement industry produced 4.3 gigatonnes of cement and is expected to increase by 23% by 2050 (EMR, 2025). This growth presents difficulties in meeting the United Nations Sustainable Development Goals in the areas of environment, economics, and society. The main goal of Sustainable Development Goal (SDG) 13 is to tackle and alleviate the consequences of climate change. Meanwhile, cement industry accounts for around 7 to 8% of worldwide carbon emissions (Shah et al. 2022). The use of carbonate minerals harvested from the hills, which involves the removal of green areas, blasting and crushing the rock, and finally calcining it at the factory, causes environmental pollution. By incorporating waste materials from different industries into cement production, the amount of trash being disposed of in landfills can be reduced. This promotes cleanliness (Mohamad et al. 2025). This practice would help to maintain the environment and contribute to the creation of a sustainable and environmentally friendly ecosystem, ultimately leading to improved public health.

On the other hand, both Indonesia and Malaysia more than 85% of world palm oil production (Abdulkadir et al. 2025). Malaysia's palm oil business has grown since the 1970s, extending to rural and suburban regions. Malaysia has 5.9 million hectares of oil palm, 18% of its total land area (MPOC 2021). Malaysian palm oil production is 19.14 million tonnes and is predicted to reach 26.6 million tonnes by 2035 (Gan and Li 2014). Malaysia has 457 oil palm mills that generate biomass waste (Ghulam Kadir et al. 2020). Biomass waste from palm oil farms and mills exceeded 311 million tonnes in 2020 (Terry et al. 2021). Empty bunches, fibres, shells, and liquid effluents are among the waste generated at palm oil mills. Palm oil mills burn palm oil fibres and shells to provide energy for mill operations, producing palm oil fuel ash (POFA). The rise of the palm oil sector will increase palm oil mill byproducts, especially POFA. Disposal of POFA at dumping site pollutes the environment (Patah et al. 2025) and would consume larger space at landfill as it continues to accumulate over the year. The probable harm of POFA disposal to the environment owing to leaching and accidental fire has also been pointed out by Olivia et al. (2024). Thus, using these materials as raw materials in many sectors can help maintain this business and offer a management solution.

Researchers have recently focused on POFA as a viable alternative to cement in the construction industry. Utilising POFA instead of cement in concrete may significantly mitigate the adverse environmental impacts associated with the concrete industry and POFA disposal. The integration of a suitable percentage of ground POFA, which is a pozzolanic ash, as a partial cement replacement, contributes towards an increase in the strength of conventional concrete (Katte et al. 2023; Johan et al. 2023), lightweight concrete (Alnahhal et al. 2021), self-compacting concrete (Mujedu et al. 2020), ultra-high-performance concrete (Abdul Kudus et al. 2023) and paving block (Dasar et al. 2025) via the pozzolanic reaction. The densification of the concrete internal structure, owing to the formation of a larger amount of CSH gel and a reduction in calcium hydroxide, enhances cement-based concrete durability and makes it an attractive waste material to be used in other types of concrete production. So far, the impact of utilising POFA as a cement replacement in polypropylene fibre-reinforced concrete (PFRC) has been explored in a limited scope of research. This study investigates the mechanical performance of PFRC with POFA as a partial cement alternative.

This study addresses that research gap by systematically evaluating the influence of POFA as a partial cement replacement in PFRC across key performance metrics, including compressive strength, splitting tensile strength, workability, and water absorption. The findings aim to advance the development of greener, high-performance cementitious composites and contribute new knowledge to the limited existing literature on POFA-integrated PFRC. While POFA has been extensively studied in self-compacting and lightweight concretes, its role in fibre-reinforced concrete, particularly polypropylene fibre reinforced concrete (PFRC), remains underexplored. This study addresses this gap by investigating the performance of PFRC incorporating varying levels of ground POFA. The research intentions to evaluate the combined effects of POFA's pozzolanic characteristics and fibre reinforcement, offering a novel efforts toward sustainable, durable, and ductile concrete composites suitable for structural applications.

2. Methodology

2.1. Materials

The materials used in producing the PFRC are ordinary Portland cement (OPC), palm oil fuel ash (POFA), aggregate, sand, water, polypropylene fibres, and superplasticizer. Ordinary Portland cement, according to ASTM C150 (2020), was used as the primary binder in the concrete mixture. The POFA, shown in Fig. 1, was gathered from a palm oil mill in West Malaysia. The POFA was then dried in an oven at 110 °C for 24 hours to remove its moisture. It was ground into a fine powder using a grinding machine that meets the ASTM C618 (2019) specifications for particle size (66% of the particles pass through a 45 μm sieve) so that it can be used as a pozzolanic ash. Table 1 tabulates the oxide composition of the POFA used. In this study, polypropylene fibre with a length of 12 mm and a diameter of 0.18 mm, which was purchased from a local supplier, was used. Crushed granite aggregates were obtained from a nearby quarry and utilised as coarse material. River sand was used as fine aggregate. The particle size distribution of the sand is shown in Fig. 2. Tap water was utilised for the preparation and curing of concrete specimens. Superplasticizer was included to sustain a low water-to-cement ratio while preserving the workability of the mixture.

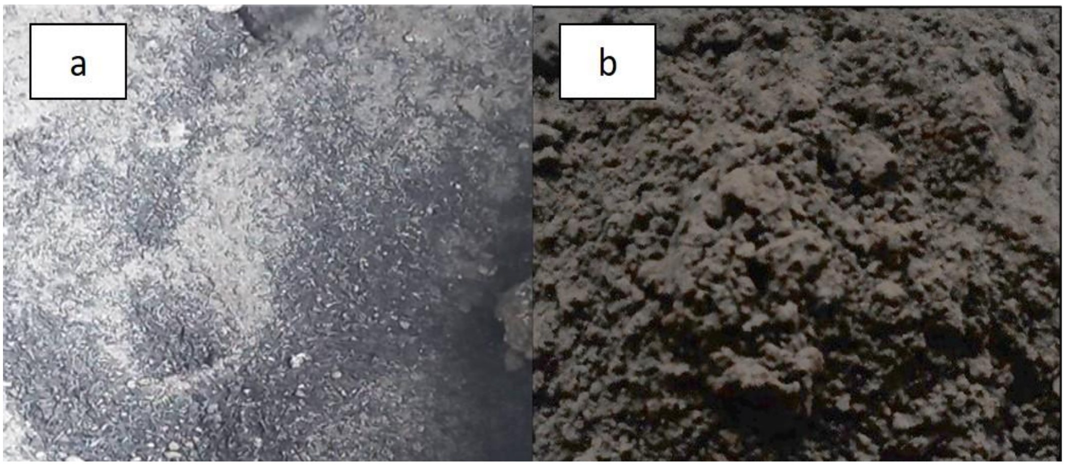

Fig. 1. POFA: (a) As received from the mill; (b) After grinding process.

Table 1. Oxide composition of binders.

Type of bnder	SiO_2	Al_2O_3	Fe_2O_3	K_2O	P_2O_5	MgO	SO_3	CaO
Ordinary portland cement	17.66	3.00	3.64	0.69	–	–	3.16	70.92
POFA	58.4	3.24	7.85	10.2	4.96	3.71	0.90	9.58

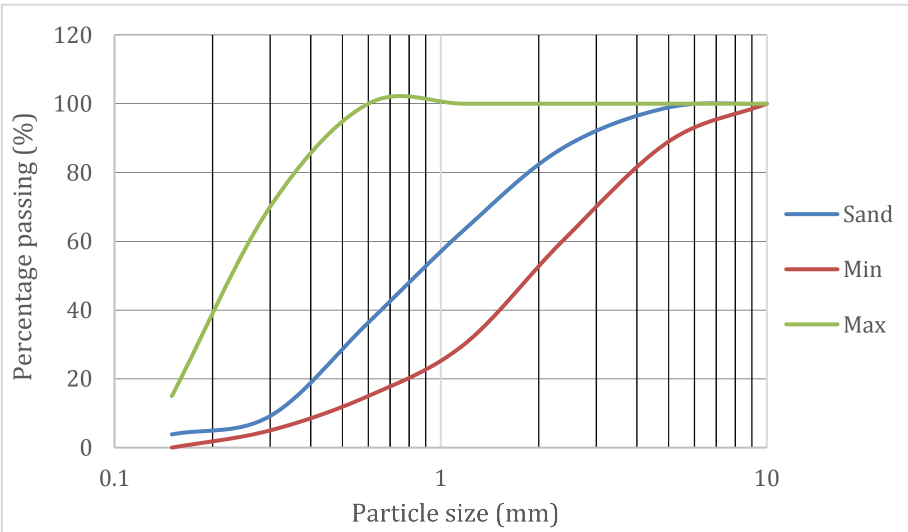

Fig. 2. The particle size distribution of the sand.

2.2. Mix proportion and specimen preparation

In this present study, six different concrete mixes were prepared. A control mixture sample with target strength of 42MPa was prepared with no replacement of OPC with POFA. Five further mixes were prepared, each containing a proportion of POFA as a partial cement replacement comprising 10%, 20%, 30%, 40%, and 50% of the total weight of OPC. An identical water-to-cement ratio was used for all combinations. The mixture proportions are specified in Table 2.

All carefully measured components were mixed in a concrete mixer. Crushed coarse aggregate, sand, POFA, OPC, and polypropylene fibre were mixed in a dry state. The concrete was then fully mixed with the addition of water and superplasticizer before being placed in the prepared moulds. A vibrating table was used to compact the concrete mix. Then, the moulds were covered with wet gunny sacks and left overnight. The next day, the concrete was removed from the moulds, labelled, and then immersed in water for curing purposes.

Table 2. Mix proportion (kg/m³).

Mix designation	Cement	POFA	Coarse aggregate	Fine aggregate	Water	Superplasticizer	Fibre
0%POFA	550	0	825	975	216	5.8	1.5
10%POFA	495	55	825	975	216	5.8	1.5
20%POFA	440	110	825	975	216	5.8	1.5
30%POFA	385	165	825	975	216	5.8	1.5
40%POFA	340	210	825	975	216	5.8	1.5
50%POFA	340	265	825	975	216	5.8	1.5

2.3. Testing

The concrete workability was tested using a slump test following BS EN 12350-2 (2009). The slump test involves filling a metallic slump cone with fresh concrete in three layers, each tamped 25 times with a steel rod. After filling, the cone carefully lifted vertically, and the subsidence of the concrete was measured to evaluate workability.

The compressive strength test was carried out by BS EN 12390-3 (2009). Standard 150 mm × 150 mm × 150 mm cube specimens were cast and cured in water. The test was conducted at 7, 28, and 90 days. Before testing, the cubes were surface-dried, and each sample was placed between the compression platens of a calibrated testing machine and loaded continuously at a rate of 0.5 MPa/s until failure. The average value of three specimens was recorded as the compressive strength for each mix and age.

The splitting tensile strength test followed BS EN 12390-6 (2009). For this, 150 mm diameter × 300 mm cylindrical specimens were used. Each cylinder was placed horizontally between the compression platens of the testing machine. A line load was applied along the length of the cylinder via wooden or steel strips to distribute the load uniformly. The load was applied continuously at a controlled rate until the specimen split along its vertical diameter.

The water absorption test was performed on water-cured concrete cubes following BS 1881-122 (1983). The specimens were oven-dried at 105±5 °C for 24 hours and then cooled in a desiccator to room temperature. The dry weight was recorded. The specimens were then fully immersed in water for 24 hours, surface-dried, and the wet weight was measured. Then the water absorption was calculated following the standard. This procedure helps assess the porosity and permeability characteristics of the concrete.

3. Results and Discussion

3.1. Workability

Fig. 3 depicts the impact of including POFA as cement replacement in polypropylene fibre-reinforced concrete (PFRC) on slump values. The alterations in the slump pattern correspond to an increase in POFA quantity. The results indicated a substantial association between the rise in POFA content and a marked reduction in the workability of the PFRC. The slump values for samples with proportions of 0%, 10%, 20%, 30%, 40%, and 50% were 160 mm, 150 mm, 145 mm, 130 mm, 120 mm, and 100 mm, respectively. Substitution of 50% of the cement content with POFA, resulted in a 62.5% reduction compared to the reference samples. The workability of PFRC is affected using POFA, which possesses distinct features compared to OPC. The reduction in workability with the incorporation of POFA may be attributed to its higher carbon content, which absorbs more superplasticizer than alternative particles (Johari et al. 2012; Jimma et al. 2015). In addition, Islam et al. (2016a) indicated a continuous trend when cement was partially replaced with POFA, with the maximum substitution limit set at 10% POFA. The study's findings suggested that increasing the POFA content to 25% led to a reduction in slump levels. Comparable behaviour has also been seen with the incorporation of POFA of several types of concrete (Islam et al. 2016b; Khankhaje et al. 2016). However, there are researcher who observed increment in concrete workability upon blending ground POFA and highlighted the coarser size of POFA in comparison to OPC is one of the contributing factor.

3.2. Compressive strength

The compressive strength of the PFRC is affected by the POFA concentration, as depicted in Fig. 4. The compressive strength values of all PFRC mixtures vary in the different phases of curing. After 7 days they range from 23 MPa to 46.39 MPa, after 28 days from 31.55 MPa to 50.79 MPa and after 90 days from 34.8 MPa to 62.5 MPa. The compressive strength was enhanced when 10% POFA was employed as a cement substitute compared to the control mix. The increase in compressive strength at 10% POFA concentration can be attributed to the creation of a more robust CSH gel resulting from hydration and pozzolanic reactions. A beneficial impact of 10% POFA as pozzolanic ash on the mechanical strength of construction materials has been noted in high-strength lightweight aggregate concrete (Muthusamy et al. 2019). Nonetheless, the strength decreased as the POFA level exceeded 20%. The reduction in strength of cement-based composites containing a higher proportion of pozzolanic ash is attributable to the lowered cement content, which results in a reduced formation of CSH gel and a lesser amount of calcium hydroxide necessary for the pozzolanic reaction. The total quantity of CSH gel generated from both hydration and pozzolanic reactions is lower than that of the mixture containing a lower amount of POFA (Muthusamy et al. 2016). The strength of PFRC diminishes by 35.9% when 50% POFA is utilised as a cement alternative. Previous studies by Hamada et al. (2020) and Mujedu et al. (2020) have discovered a similar tendency in the investigation of the compressive strength of concrete with the incorporation of high levels of POFA.

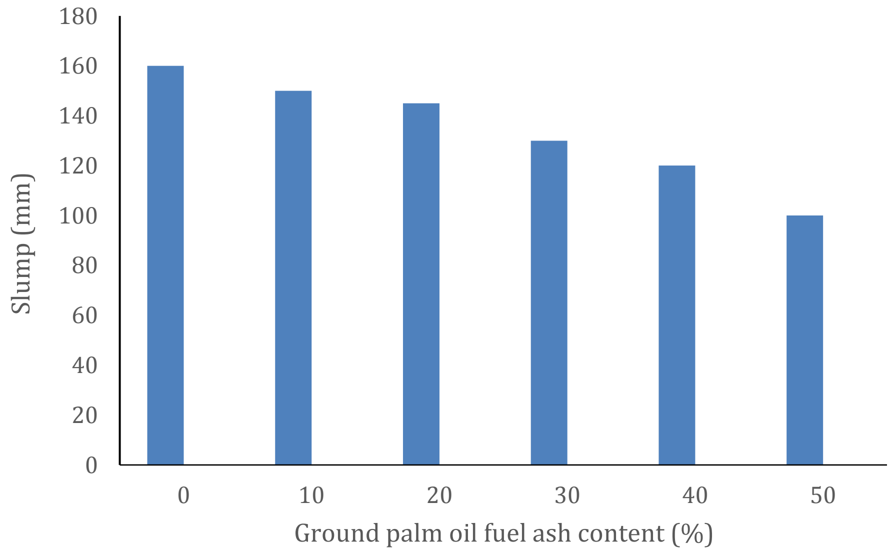

Fig. 3. Workability of PFRC containing diverse content of ground POFA.

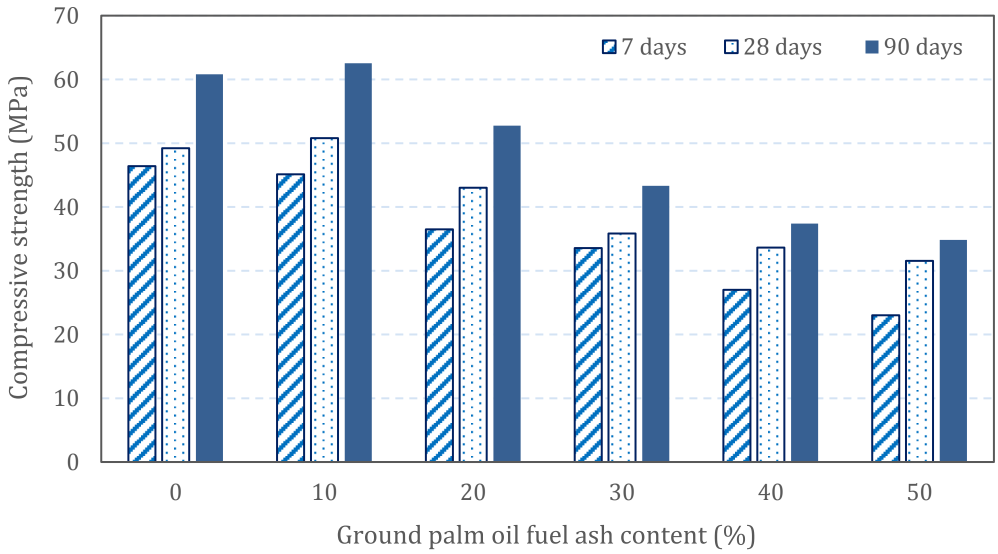

Fig. 4. Compressive strength result of concrete mixes.

3.3. Splitting tensile strength

Fig. 5 depicts the splitting tensile strength test results at diverse curing ages. The splitting tensile strength of all mixes increases as curing age become longer. The splitting tensile strength values of all PFRC mixtures vary across different curing phases.

After 7 days, they range from 2.29 MPa to 3.2 MPa, after 28 days from 2.38 MPa to 3.55 MPa, and after 90 days from 3.43 MPa to 4.03 MPa. The PFRC containing 10% POFA demonstrated superior tensile strengths among all mixes. The results demonstrated a 6.2% and 9.2% enhancement in tensile strength following the replacement of 10% of the cement with POFA at 28 and 90 days, respectively. The most significant reduction of 35% and 7% was observed in the PFRC mix containing 50% POFA at 28 and 90 days, respectively. The noted reduction in strength with a cement substitution above 20% by POFA can be ascribed to the lowered generation of hydration products, linked to the decreased cement content.

Interfacial transition zone (ITZ) qualities, which affect concrete tensile strength, may explain the observed phenomenon (Islam et al. 2016). Similar behaviour has been seen in other types of concrete by previous researchers, Muthusamy et al. (2016) and Hamada et al. (2022).

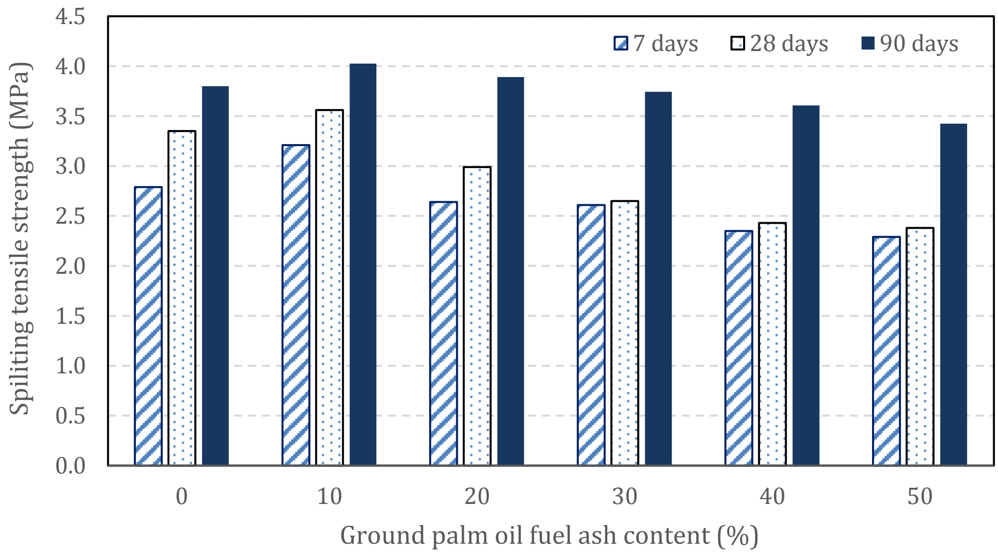

Fig. 5. Splitting tensile strength result of concrete mixes.

3.4. Water absorption

Fig. 6 depicts the outcomes of the water absorption test results. 10% replacement levels demonstrated reduced water absorption values relative to the control concrete. Application of up to 10% POFA results in a slight reduction in water absorption relative to the control samples. The PFRC with sustained 10% ground POFA exhibits a slightly reduced water absorption capacity relative to the PFRC without POFA. However, beyond this threshold, the utilization of POFA resulted in a significant rise in the water absorption of the PFRC specimens. The 50% increase in ground POFA content blended led to a substantial enhancement in water absorption, with an increase of up to 50% relative to the control samples. Overuse of POFA causes significant elimination of a high amount of cement, resulting in lower hydration process, forming less calcium hydroxide, which in turn disturbed the pozzolanic reaction. Nonetheless, all concrete mixes exhibit water absorption of less than 2%, indicating it can be classified as good quality concrete. According to Neville and Brooks (2010), concrete with water absorption not exceeding 10% can be classed as a good quality type.

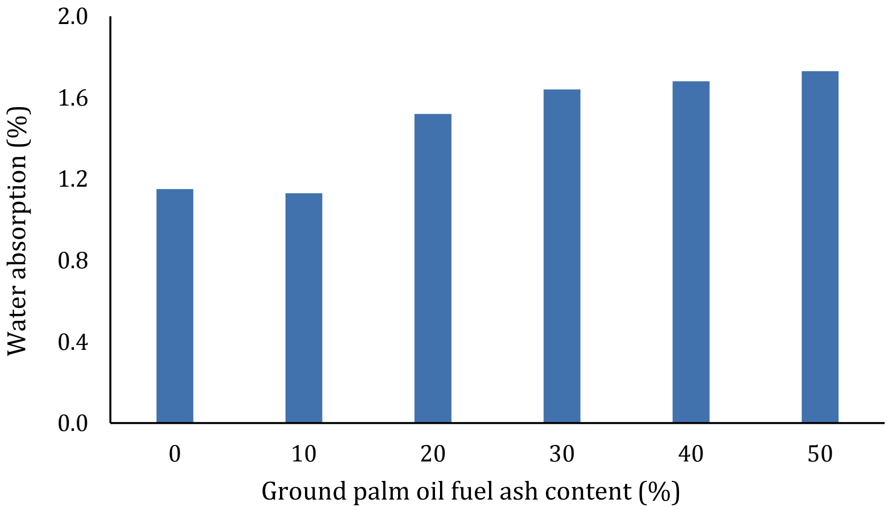

Fig. 6. Water absorption result of concrete mixes.

3.5. Predictive model using ANOVA and response surface methodology

The relationship between the compressive strength of PFRC to the curing age and the different percentage levels of POFA using ANOVA is presented in Table 3. The results showed that the sum of squares (1894.01) and *F*-value (107.58) indicate that the model is significant. The corresponding *p*-value of %POFA and curing age obtained from ANOVA is < 0.0001 (less than 0.05) and it indicates the POFA and curing age significantly affect the compressive strength. The results also show that POFA content may contribute to the overall performance of compressive strength of PFRC when compared to curing age. The sum of squares for %POFA (1368.49) was found to be higher than the curing age (525.52), indicating that POFA content significantly influences the compressive strength of PFRC. The linear regression model using ANOVA yielded that curing age and altered POFA content significantly affected the compressive strength of PFRC as tabulated in Table 4. It also indicates that the relationship between compressive strength and those factors is very strong, where R^2 is 0.9348. The model has explained about 93.48% of the variance in compressive strength is explained by the linear model. The empirical relationship between compressive strength (CS) against curing age (A) and POFA content (B) is expressed by Eq. (1), which is only appropriate within the range of POFA content and curing ages adopted in the present research work.

$$CS\,(\text{MPa}) = 47.88544 + 0.153347 \cdot A - 0.51055 \cdot B \quad (1)$$

Table 3. Interaction on the responses to the compressive strength of PFRC using ANOVA.

Source	Sum of squares	df	Mean square	F-value	p-value	Remark
Model	1894.01	2	947.01	107.58	< 0.0001	significant
A-Age	525.52	1	525.52	59.7	< 0.0001	
B-POFA	1368.49	1	1368.49	155.46	< 0.0001	
Residual	132.04	15	8.8			
Cor. Total	2026.05	17	947.01			

Table 4. ANOVA fit statistic for compressive strength of PFRC towards curing age and %POFA.

Model	Std. deviation	R^2	Adjusted R^2	Predicted R^2
Linear	2.97	0.9348	0.9261	0.9029

The 3D response surface and perturbation plots offer an understanding of the relationship between curing age, %POFA and compressive strength (CS) of polypropylene fibre reinforced concrete (PFRC) as presented in Fig. 7. The 3D surface in Fig. 7(a) shows a positive relationship between concrete compressive strength (CS) and curing age. The compressive strength increases dramatically as the curing time increases from 7 to 90 days. This pattern is consistent with the behaviour of normal concrete where the process of hydration continues and strengthens after prolonged curing. Interestingly, the effect of POFA content on compressive strength looks like a non-linear relationship.

The inclusion of POFA in PFRC has a significant influence at lower POFA content (10% POFA). However, the compressive strength behaves to decrease for higher contents. This indicated an adverse impact on the strength of PFRC from higher percentages of POFA up to 50%. This occurs through the use of only a partial replacement for cement by POFA that either does not bind well or affects positively strength development. Fig. 7(b) demonstrates perturbation plots visualize the individual effects on compressive strength. Line A (Age) shows an upward slope compared to Line B (%POFA), confirming that curing age consistently enhances its compressive strength. The steepness of Line B indicates that POFA content has a strong and direct impact on the compressive strength of the PFRC. The slope is downward for Line B reflecting the influence of lower content of POFA associated with the highest compressive strength. This line of argument is logical as it reflects the behaviour of POFA, which is not always highly reactive when compared to cement itself and could result in strength loss at higher replacement levels.

A summary of the ANOVA to evaluate the significance of the curing age and POFA replacement to splitting tensile strength of PFRC is provided in Table 5. This model was significant with a p-value of 0.0001 and an F-value of 65.96. Moreover, it shows that when the p-value is less than 0.05, meaning that the combination of factors has a statistically significant effect on the splitting tensile strength of the PFRC. Obviously, their combined effect is more pronounced when the sum of squares for curing age is higher than %POFA. The results revealed that different levels percentage of POFA have a smaller effect on the splitting tensile strength of the PFRC compared to curing age. This suggests that as the curing age increases, the splitting tensile strength increases significantly, confirming the positive relationship.

On the other hand, the model accounts for 89.79% of the variance in splitting tensile strength (R^2 is 0.8979), and thus provides a good relationship as tabulated in Table 6. The linear model is significant meaning that the combination of curing age and POFA content effectively explains the variation in splitting tensile strength. There is only 10.21% of other factors not included in the model contribute very little. From the linear equation, the predicted splitting tensile strength (STS) for PFRC at different curing ages (A) and integration of POFA (B) is shown in Eq. (2). However, this equation is applicable only within the range of POFA content and curing ages used in this experimental work.

$$STS\,(\text{MPa}) = 2.94313 + 0.013379 \cdot A - 0.01614 \cdot B \quad (2)$$

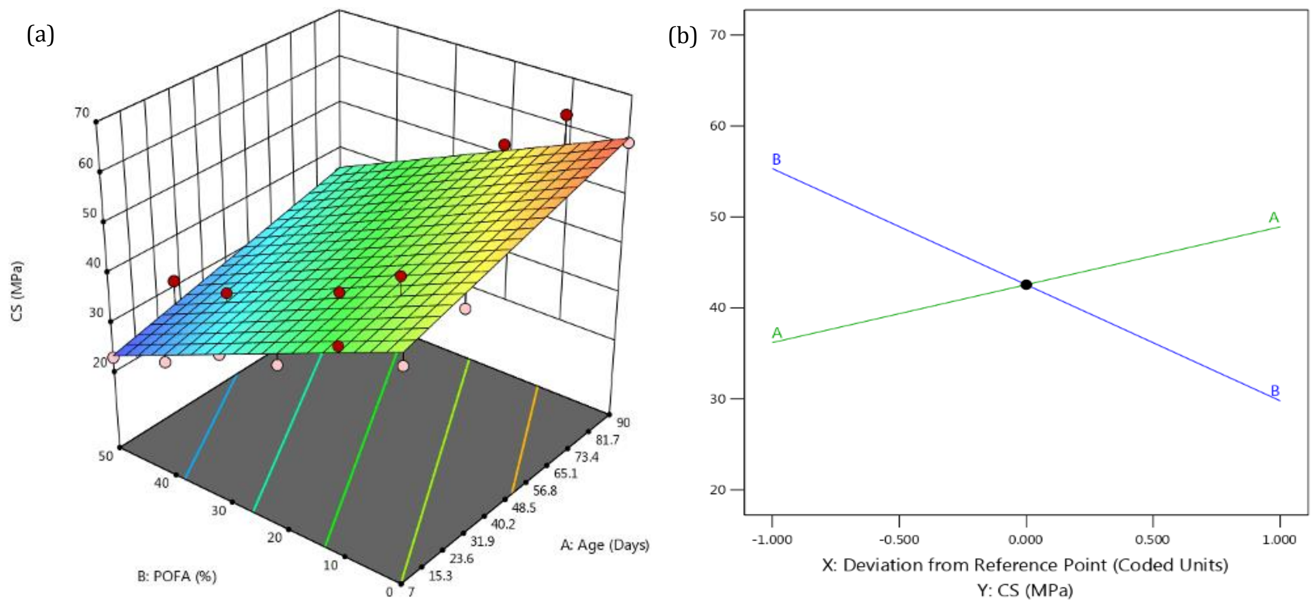

Fig. 7. (a) Effects of curing age and %POFA on the compressive strength of PFRC using 3D response surface; (b) Perturbation plots.

Table 5. Interaction on the responses to the splitting tensile strength of PFRC using ANOVA.

Source	Sum of squares	df	Mean square	*F*-value	*p*-value	Remark
Model	5.37	2	2.68	65.96	< 0.0001	significant
A-Age	4	1	4	98.3	< 0.0001	
B-POFA	1.37	1	1.37	33.63	< 0.0001	
Residual	0.6104	15	0.0407			
Cor. Total	5.98	17				

Table 6. ANOVA fit statistic for splitting tensile strength of PFRC towards curing age and %POFA.

Model	Std. deviation	R^2	Adjusted R^2	Predicted R^2
Linear	0.2017	0.8979	0.8843	0.8325

Fig. 8 depicts the 3D response surface and perturbation plots for splitting tensile strength of PFRC containing various percentages of POFA over the different curing ages. The plot in Fig. 8(a) shows a positive correlation between curing age and splitting tensile strength. It shows that prolonged curing age boosts splitting tensile strength due to the continued hydration process. Meanwhile, PFRC incorporating different levels of POFA content had a less significant effect on splitting tensile strength. However, PFRC containing 10% POFA developed strength compared to control PFRC and modified PFRC incorporating 20%, 30%, 40% and 50% POFA. At lower POFA content, splitting tensile strength tends to be higher as the curing age increases. This indicates that although the curing age improves the overall splitting tensile strength performance, POFA can only replace a certain percentage of cement without affecting the strength performance, particularly when exceeding 20% POFA. The negative effect of POFA content on splitting tensile strength is also supported by the perturbation plot in Fig. 8(b), emphasizing that a higher level of POFA replacement reduces strength. The steepness of Line A representing the curing age shows an upward trend, indicating the splitting tensile strength increases as the curing age increases. The sharp slope of Line B (%POFA) demonstrates a downward trend, a considerable negative effect on the splitting tensile strength. It is evident from the perturbation plot that the percentage of POFA causes a decrease in splitting tensile strength when the replacement percentage exceeds the optimum range. This is because when POFA is used in higher proportions, the lower pozzolanic reactivity of POFA compared to conventional cement contributes to the reduction of splitting tensile strength.

3.6. Economic analysis

In addition to mechanical performance, the economic feasibility of incorporating POFA in polypropylene fibre-reinforced concrete (PFRC) was briefly assessed. Based on local pricing, POFA sourced from palm oil mills is significantly less expensive than ordinary Portland cement (OPC), primarily due to its status as an industrial waste byproduct. According to market estimates (e.g., OPC at USD 100/tonne and POFA at USD 20/tonne), a 10% replacement level results in approximately 8–12% reduction in binder cost per cubic metre of concrete, depending on processing and transport expenses. Furthermore, utilizing POFA contributes to waste reduction and may provide long-term savings through reduced environmental charges and sustainability incentives. This cost-effectiveness, combined with the improved mechanical performance at 10% POFA, highlights the practical potential of this technique in sustainable construction applications.

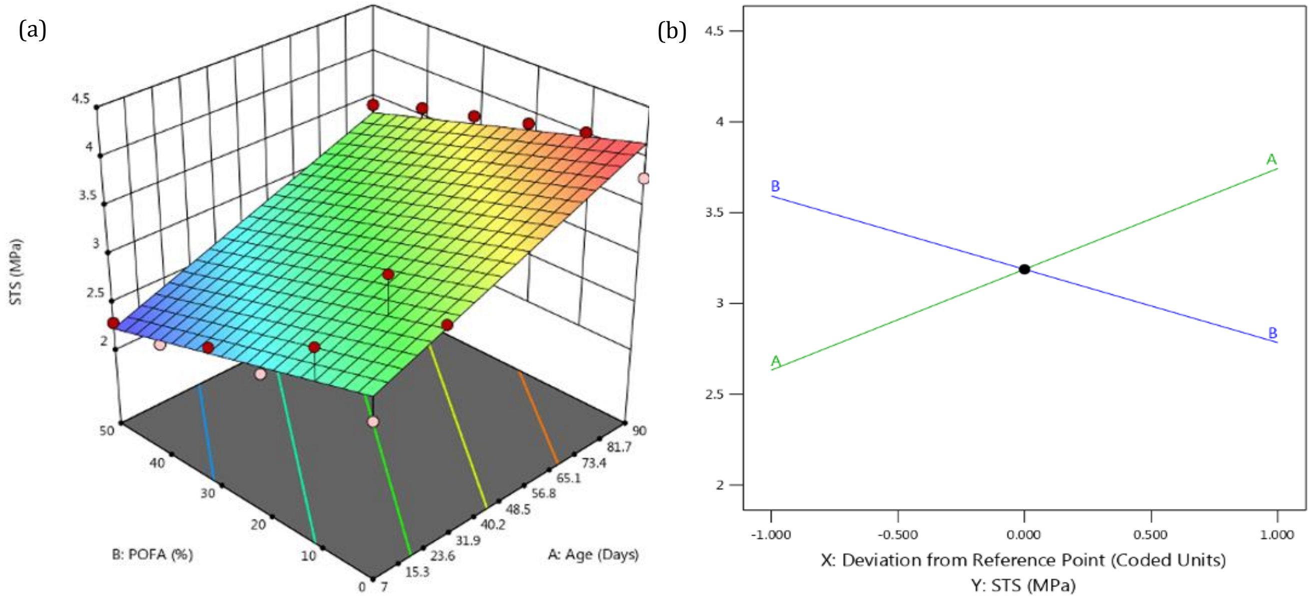

Fig. 8. (a) Effects of curing age and %POFA on the splitting tensile of PFRC using 3D response surface; (b) Perturbation plots.

4. Conclusions

This study explored the impact of incorporating palm oil fuel ash (POFA) as a partial cement replacement on the performance of polypropylene fibre reinforced concrete (PFRC).

The findings highlight that using POFA at a 10% replacement level enhances the mechanical strength. Notably, compressive and splitting tensile strengths improved at this dosage, while water absorption was slightly reduced compared to the control mix. These improvements are attributed to the pozzolanic activity of POFA, which contributes to the formation of additional calcium silicate hydrate (C–S–H) gel. However, beyond the 10% replacement level, the benefits began to diminish. At higher substitution rates, particularly above 20%, the concrete exhibited lower strength and workability. This decline is likely due to the reduced availability of cementitious materials and the limited reactivity of excess POFA. While all mixes remained within the acceptable range for water absorption, the loss in mechanical strength at higher POFA contents suggests a clear performance trade-off. Statistical analysis using ANOVA confirmed that both curing age and POFA content significantly affect strength development. Curing age showed a consistently positive influence, especially on splitting tensile strength, while POFA's effect was more variable, with a peak at 10%. Regression models showed strong predictive accuracy, accounting for over 93% and 89% of the variability in compressive and tensile strengths, respectively. Visual analyses through 3D surface and perturbation plots reinforced these trends, illustrating the optimal performance at low POFA levels and a drop-off as the replacement percentage increased. In summary, POFA can be a viable, sustainable cement substitute in PFRC when used in moderation. A replacement level of around 10% offers the best balance between mechanical strength and sustainability, making it a practical option for improving the environmental footprint of concrete without compromising its structural performance. This places POFA-blended PFRC as a promising material for sustainable construction, particularly in regions with a plentiful palm oil industry byproducts.

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Acknowledgements

The financial support by Universiti Malaysia Pahang Al-Sultan Abdullah, under the International Matching Grant Scheme, was gratefully acknowledged. The contribution from Universitas Muhammadiyah Sumatera Utara was equally acknowledged and appreciated.

Funding

This research was supported by Universiti Malaysia Pahang Al-Sultan Abdullah under grant number UIC231507.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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