Sustainable Environmental Insight

Research Article
Volume 2(2), 2025, 51–60
https://doi.org/10.53623/sein.v2i2.636

Strength Evaluation of Palm Oil Fuel Ash and Rice Husk Ash as Partial Cement Replacement in Concrete for Sustainable Construction

Muhammad Hakim Abd Razak[1], Najeeha Mohd Apandi[2]*, Mohd Syafiq Syazwan Mustafa[1], Noor Kamalia Abd Hamed[3], Muhammad Rafi Azmi[1]

[1]Department of Civil Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600, Pagoh, Johor, Malaysia
[2]Sustainable Engineering Technology Research Centre (SETechRC), Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Education Hub, 84600, Pagoh, Muar, Johor, Malaysia
[3]Department of Electrical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600, Pagoh, Johor, Malaysia

*Correspondence: najeha@uthm.edu.my

SUBMITTED: 16 March 2025; REVISED: 9 July 2025; ACCEPTED: 12 August 2025

ABSTRACT: The construction industry's dependence on Portland cement considerably increased global carbon emissions, which highlighted the need for environmentally friendly alternatives. This research explored the application of rice husk ash (RHA) and palm oil fuel ash (POFA), two common agricultural byproducts in Malaysia, as partial cement replacements in concrete. The study examined the mechanical performance and durability of several POFA–RHA concrete mix designs with the goal of reducing environmental impact while maintaining structural integrity. A systematic approach was applied for material characterization, which included advanced methods such as Field Emission Scanning Electron Microscopy (FESEM). The workability, compressive strength, and water absorption of concrete samples with varying POFA and RHA proportions were assessed. The findings showed that a mixture containing 25% POFA and 5% RHA achieved notable improvements in strength and durability while reducing water absorption. In contrast, higher replacement levels reduced workability and performance due to increased water demand and particle aggregation. Overall, the combination of 25% POFA and 5% RHA delivered substantial enhancements in strength, durability, and water absorption.

KEYWORDS: Partial cement replacement; palm oil fuel ash; rice husk ash; compressive strength

1. Introduction

A large fraction of the waste produced in Malaysia came from the agriculture sector. Among the most prominent byproducts were POFA and RHA. Malaysia had about 5.07 million hectares of oil palm plantations, producing more than 9 million tons of crude palm oil annually [1]. POFA was produced from the burning of palm oil shells and empty fruit bunches in palm oil mills [2]. Similarly, RHA was generated as a residue during rice processing, where about 1,000 kg of rice grain yielded around 200 kg of husk, and 20% of that was converted into RHA after burning [3]. Disposal of these agricultural wastes posed serious environmental problems, including the need for large landfill areas and high transportation costs.

To address these issues, the utilization of POFA and RHA as supplementary cementitious materials provided an environmentally sustainable solution. Their incorporation into concrete reduced the environmental impact of cement production and improved the mechanical and durability properties of concrete. POFA and RHA possessed pozzolanic properties that enhanced compressive strength by increasing secondary hydration reactions, thereby refining the microstructure of the concrete matrix [2].

Adding POFA and RHA to concrete significantly improved its mechanical properties. Previous studies showed that compressive strength increased when cement was replaced by POFA in the range of 10 to 30%, with the optimum level generally around 20% [4]. The strength improvement was attributed to the pozzolanic reaction between silica in POFA and calcium hydroxide ($Ca(OH)_2$), which formed additional calcium silicate hydrate (C-S-H) that filled voids and strengthened the matrix. The reaction was: $SiO_2 + Ca(OH)_2 \rightarrow$ C-S-H [5]. POFA had relatively slow pozzolanic reactivity, resulting in lower early-age compressive strength, but strength improved with prolonged curing [5].

RHA was also found to enhance compressive strength due to its higher silica content, with optimum replacement levels typically between 10 and 20 % [6]. However, exceeding these levels reduced its integration-enhancing capability, increased water demand, and lowered strength due to particle accumulation and incomplete hydration [6].

While previous studies independently examined the effects of POFA and RHA on concrete performance, limited research investigated their combined use in a single mix. Combining these materials had the potential to produce synergistic benefits, as the pozzolanic properties of both ashes could complement each other to improve concrete performance. Therefore, this study investigated the effect of combining POFA and RHA as partial cement replacements on the compressive strength of concrete.

2. Materials and Methods

2.1.Materials.

This study used various materials to produce concrete mixes incorporating POFA and RHA as partial cement replacements. Ordinary Portland Cement (OPC) served as the primary binder, as it was readily available and proven to perform effectively, providing the necessary strength and durability for the mixes. The inclusion of POFA and RHA in concrete contributed to sustainability by reducing cement dependency, as cement production is a major source of carbon dioxide emissions. Substituting part of the cement with industrial byproducts offered significant greenhouse gas mitigation benefits [2]. In addition, characterizing the mechanical properties of concrete using locally sourced raw materials reduced costs while maintaining structural integrity.

POFA was obtained from a local palm oil mill as a byproduct of burning palm oil shells and empty fruit bunches for energy production. The raw POFA was sieved through a 300 μm sieve to remove impurities and unburnt carbon, producing a finer and more reactive material suitable as a supplementary cementitious material [6]. RHA was sourced from a rice milling factory, where rice husks were incinerated under controlled conditions to ensure high silica content. The samples were sieved through a 300 µm sieve to achieve uniform particle size and remove impurities, enhancing pozzolanic activity.

Natural river sand was used as a fine aggregate, sieved to pass through a 5 mm sieve for proper gradation, which ensured density and workability of the concrete mix. Crushed granite, with a maximum size of 20 mm, served as the coarse aggregate, providing the structural framework and contributing to overall strength. Pure, potable water was used for mixing and curing, supporting hydration and maintaining workability in the concrete mixes. The materials used are shown in Figure 1.

Figure 1. (a) Ordinary Portland Cement; (b) Palm oil fuel ash, (c) Rice husk ash, (d) Coarse aggregates, (e) Fine aggregates.

2.2.Method.

The present study investigated the potential of POFA and RHA as partial replacements for cement in concrete. Its objectives included characterizing POFA and RHA using Field Emission Scanning Electron Microscopy (FESEM) and evaluating their influence on the mechanical properties of concrete. FESEM analysis at high magnifications was used to examine surface morphology, particle shape, and texture. The study also assessed how varying percentages of POFA and RHA affected key mechanical properties, such as compressive strength, workability, and water absorption.

By exploring these industrial by-products as supplementary cementitious materials, the research aimed to support sustainable development in construction. OPC was used as the primary binder, making up 70% of the total cementitious material, while the remaining 30% was replaced by different combinations of POFA and RHA in various mix designs. The influence of these ash materials on setting time and workability was evaluated through standard slump and workability tests.

Concrete specimens were tested at different curing stages. The primary assessment was the compressive strength test, conducted at 7 and 28 days of curing. A compressive strength testing machine applied pressure until specimen failure, and the maximum load at failure was recorded to calculate the compressive strength. A process flow chart outlining the sequence of mix preparation, curing, and testing is presented in Figure 2.

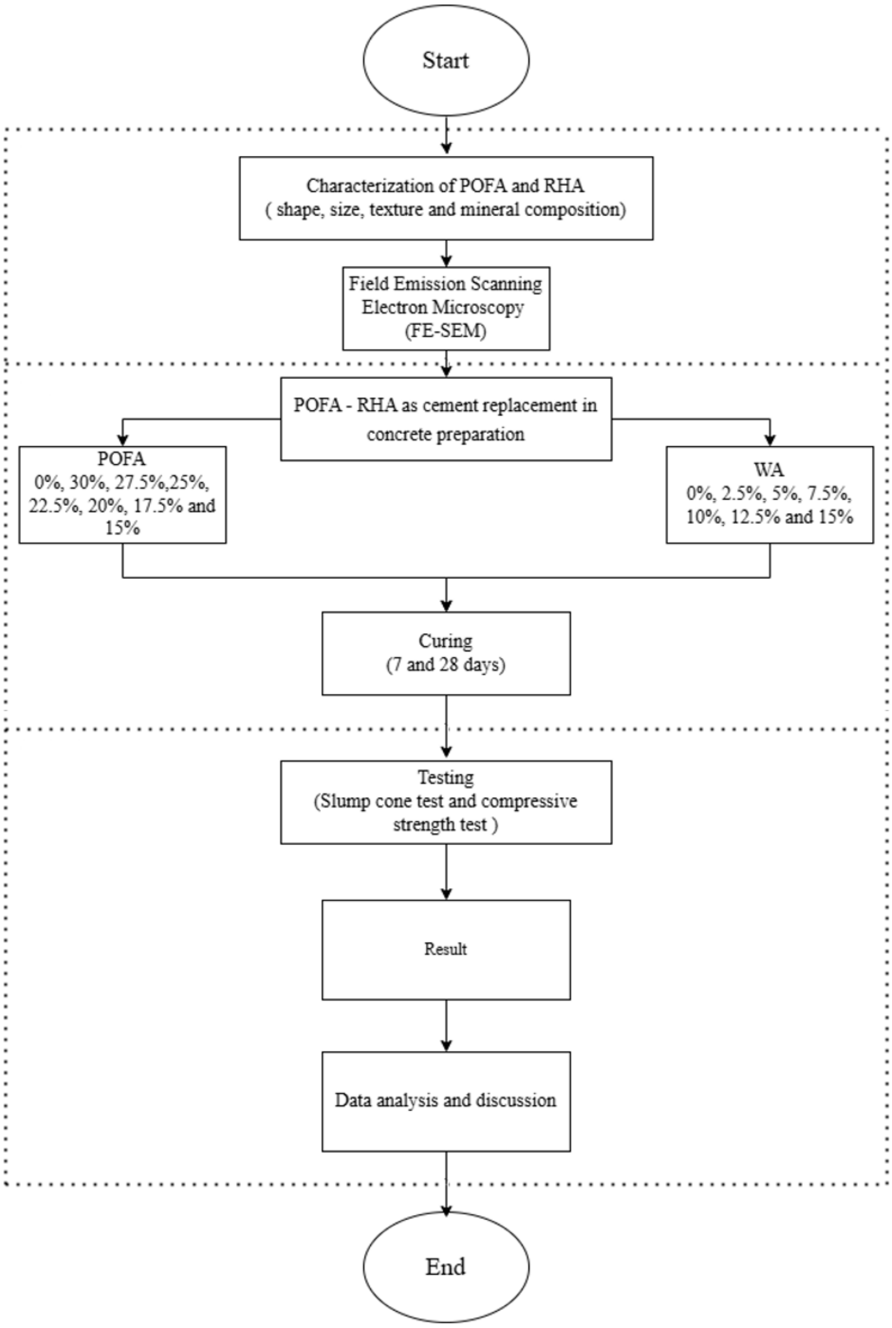

Figure 2. The procedure flow chart for the methodology

2.3. Concrete mix design.

In this study, the British Design of Experiments (DoE) method was employed, aligning with British Standards for designing the concrete mixture. Cube molds measuring 100 mm × 100 mm × 100 mm were used to create the specimens. Table 1 presents the concrete mix design for this study. One control mix (P0R0) was prepared using 100% cement, while the other mixes replaced 30% of the cement with varying proportions of POFA and RHA. POFA content ranged from 15% to 30%, and RHA content ranged from 0% to 15%. The amounts of sand, gravel, and water were kept constant across all mixes to isolate the effects of different POFA and RHA combinations on the concrete properties.

Table 1. Mix designs of POFA and RHA as partial cement replacement in concrete.

No	Mixture	Cement (kg/m^3)	POFA (kg/m^3)	RHA (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)
1	P0R0*	2.11	0	0	4.90	8.70	1.37
2	P30R0	1.48	0.63	0	4.90	8.70	1.37
3	P27.5R2.5	1.48	0.58	0.05	4.90	8.70	1.37
4	P25R5	1.48	0.53	0.10	4.90	8.70	1.37
5	P22.5R7.5	1.48	0.47	0.16	4.90	8.70	1.37
6	P20R10	1.48	0.42	0.21	4.90	8.70	1.37
7	P17.5R12.5	1.48	0.37	0.26	4.90	8.70	1.37
8	P15R15	1.48	0.32	0.31	4.90	8.70	1.37

Note: *Control Sample; P0 represents 0% of POFA added, R0 represents 0% of RHA added

3. Results and Discussion

3.1. Properties of POFA.

FESEM analysis revealed that POFA consisted of thin, irregular, and broken particles, appearing grey due to the presence of unburnt carbon, as shown in Figure 3. Its angular, porous, and uneven surfaces enhanced its pozzolanic activity by providing additional reactive sites during hydration, which aligned with the findings reported in [7]. Chemically, POFA was classified as a Class C pozzolan, containing more than 50% silica, alumina, and iron oxide. Its high silica content (51.1%) contributed significantly to the formation of calcium silicate hydrate (C-S-H) gel, which is essential for concrete strength.

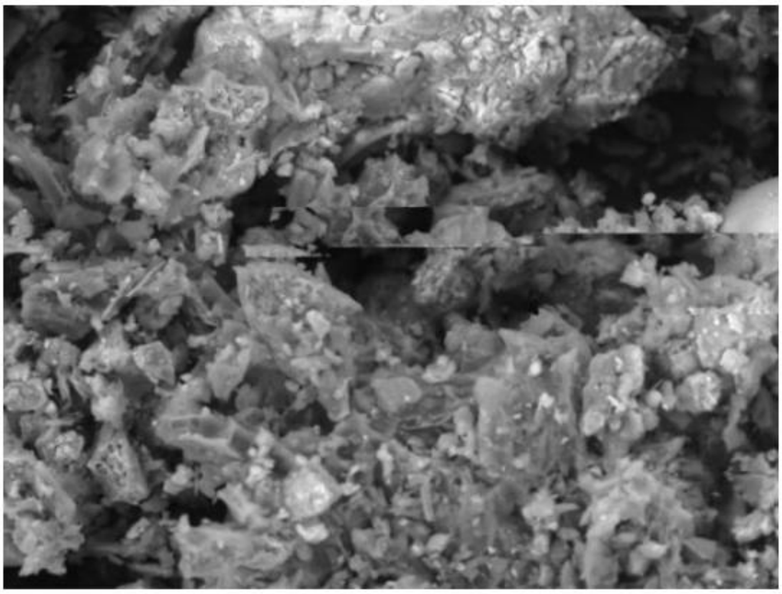

Figure 3. POFA analysis with a FESEM (Mag: 5000X).

3.2. Properties of RHA.

Figure 4 and Table 2 shows that FESEM analysis of RHA revealed irregular, closely graded particles, with a silica content of 73.9%, qualifying it as a Class F pozzolan under ASTM C618. Its fine particle size and high reactivity allowed RHA to fill voids in the concrete matrix, enhancing density and durability, as noted in [8, 9]. Compared to POFA, RHA had a higher iron oxide content (11.5%) and lower calcium oxide, which promoted the formation of calcium silicate hydrate (C-S-H) gel over time and reduced susceptibility to carbonation, as highlighted in [10].

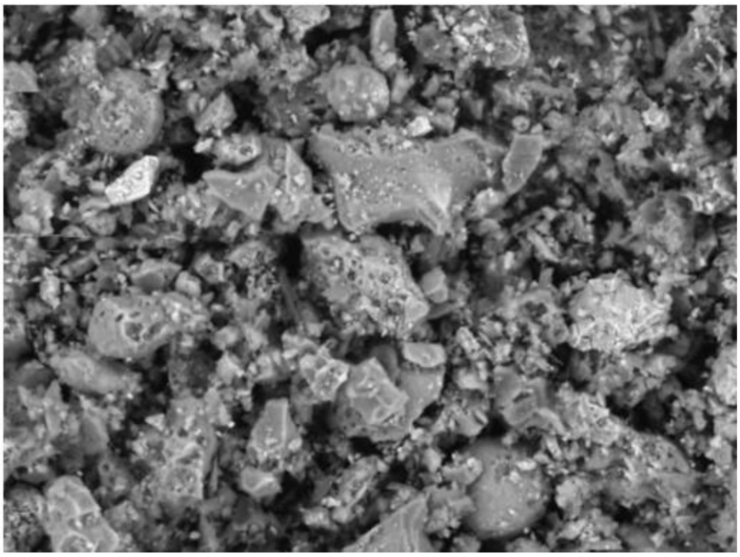

Figure 4. RHA analysis with a FESEM (Mag: 5000X).

Table 2. Percentage of POFA and RHA's chemical composition.

Chemical composition	POFA (%)	RHA (%)
Silicon dioxide (SiO_2)	51.1	73.9
Aluminum oxide (Al_2O_3)	1.39	0.99
Iron Oxide (Fe_2O_3)	4.56	11.50
Calcium Oxide (CaO)	4.86	5.56
Magnesium oxide (MgO)	1.88	1.53
Sodium oxide (Na_2O)	0.0	0.0
Potassium oxide (K_2O)	8.23	5.56
Sulphur trioxide (SO_3)	1.34	0.90

3.3. Slump test.

The slump test results indicated that the workability of concrete mixtures was influenced by the inclusion of POFA and RHA. Table 3 shows that the control mix (0% POFA and RHA) had a slump height of 44 mm, reflecting good workability. Replacing 30% of the binder with POFA reduced the slump to 23 mm, indicating poor workability. This reduction was attributed to POFA's porous nature, high specific surface area, and angular particles, which increased water demand and reduced fluidity. As the RHA content increased from 2.5% to 15%, slump height further decreased, with the combined use of POFA and RHA causing denser particle packing and greater water absorption. These findings were consistent with previous studies [9,11]. The reduced workability could impair compaction and, consequently, compressive strength. Despite the pozzolanic activity of POFA and RHA, higher replacement levels required adjustments to the mix design. The use of superplasticizers, as suggested in [12], was considered beneficial for maintaining workability while preserving strength. The study outcomes confirmed that increasing the proportion of POFA and RHA reduced flowability due to their higher surface area and water demand. Understanding this behaviour is important for designing mix proportions that maintain adequate workability while benefiting from pozzolanic reactions.

Table 3. Result of slump test of POFA and RHA mix designs.

Samples	Slump height (mm)
Control concrete	44
POFA30 – RHA0	23
POFA27.5 – RHA2.5	23
POFA25 – RHA5	22
POFA22.5 – RHA7.5	22
POFA20 – RHA10	20
POFA17.5 – RHA12.5	19
POFA15 – RHA15	18

3.4. Water absorption test.

The The water absorption results for 7 and 28 days (Figure 5) showed the effects of POFA and RHA as partial cement replacements. The control mix recorded an average absorption of 4.44%, indicating a denser microstructure and low permeability. The POFA-only mix (POFA30-RHA0) exhibited the highest absorption, 5.65% at 7 days and 5.22% at 28 days, due to the porous nature of POFA. Absorption decreased slightly over time, reflecting POFA's pozzolanic activity in enhancing the microstructure. The incorporation of RHA significantly reduced water absorption, particularly at 5–10% replacement levels (e.g., POFA25-RHA5 and POFA20-RHA10), with values as low as 2.22% at 28 days. RHA's fine particles acted as fillers, refining the microstructure and promoting C-S-H formation, which improved water resistance. Higher RHA levels (e.g., POFA15-RHA15) increased water absorption from 2.33% at 7 days to 3.67% at 28 days, likely due to poor particle dispersion and increased porosity. Overall, 5–10% RHA achieved the most favourable results, reducing water absorption and increasing concrete density, which correlated with higher compressive strength, as reported in [13] and [14]. These findings aligned with the study's aim of evaluating the durability of POFA–RHA concrete. The reduction in water absorption in optimised mixtures suggested improved pore refinement, contributing to greater durability and resistance to water ingress—critical for long-term performance. Excessive POFA or RHA increased water absorption and reduced strength due to lower cement paste density.

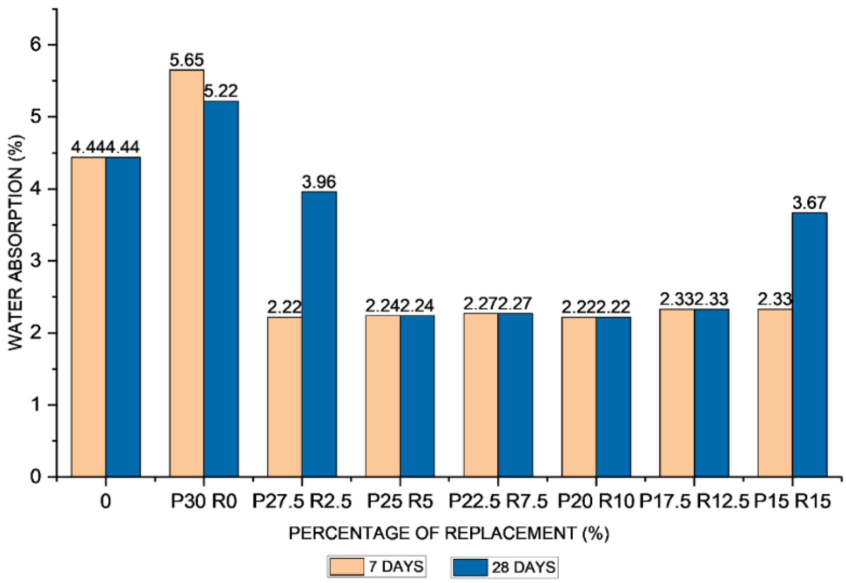

Figure 5. Water absorption against percentage of replacement material.

3.5. Compressive strength test.

Figure 6 presents the compressive strength results at 7 and 28 days. The control mix (0% POFA and RHA) achieved the highest strengths, 11.81 MPa at 7 days and 29.66 MPa at 28 days, due to complete hydration and strong bonding from 100% cement. Replacing 30% of cement with POFA (POFA30–RHA0) resulted in a strength loss of 5.12 MPa at 7 days and 25.18 MPa at 28 days. This reduction can be attributed to POFA's coarse texture and slower reactivity; however, strength gain over time reflected its pozzolanic activity. The addition of 5% RHA (POFA25–RHA5) improved the microstructure through void filling, leading to strengths of 7.28 MPa at 7 days and 25.50 MPa at 28 days. A further increase to 7.5% RHA (POFA22.5–RHA7.5) produced similar results with a slight reduction. Higher RHA contents—10% (POFA20–RHA10) and 12.5% (POFA17.5–RHA12.5)—lowered 28-day strengths to 20.25 MPa and 18.33 MPa, likely due to particle agglomeration. The mix with 15% RHA (POFA15–RHA15) recorded the lowest strengths, 3.15 MPa at 7 days and 12.41 MPa at 28 days, caused by incomplete hydration and weak bonding. The optimized blend, POFA25–RHA5, achieved 28-day strength comparable to the control mix (25.50 MPa), supporting previous findings that partial replacements of POFA and RHA within 5–10% enhance strength. Excessive replacement, in contrast, reduced strength due to incomplete hydration and particle agglomeration. Since compressive strength is a critical performance indicator, these results demonstrate that the optimized mix (25% POFA and 5% RHA) offers substantial cement reduction while maintaining high structural performance, fulfilling the study's objective.

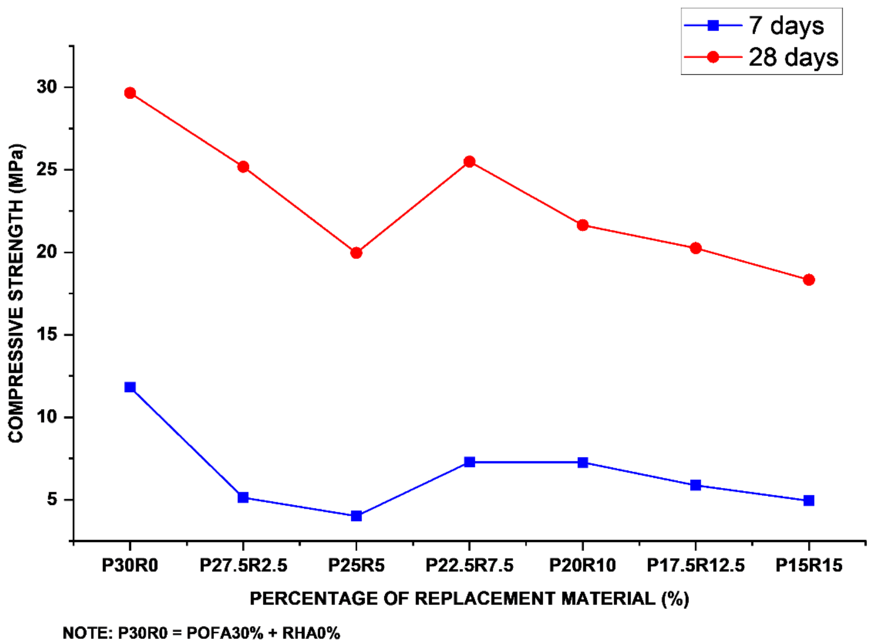

Figure 6. Compressive strength against percentage of replacement material.

4. Conclusions

This study investigated the use of POFA and RHA as partial cement replacements in concrete, targeting a compressive strength of 30 MPa. The control mix (P0R0), made with 100% cement, achieved 29.66 MPa at 28 days. Among the modified mixes, the highest strength was 25.50 MPa, recorded for the mix containing 25% POFA and 5% RHA (P25R5), which also maintained good workability. Although the modified mixes did not meet the target strength, the results demonstrated potential for improvement. The reduction in strength could be attributed to factors such as an unsuitable water-to-binder ratio, non-optimal replacement levels, or insufficient curing. Addressing these factors may enhance performance in future applications. Overall, the findings supported the use of POFA and RHA as sustainable alternatives in concrete production. Their pozzolanic properties contributed to long-term strength development while reducing the environmental impact of cement usage. Proper mix optimization was identified as essential to balance strength, workability, and durability in sustainable construction.

Acknowledgments

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 Vot. (Q962). The authors expressed their gratitude to UTHM for providing the facilities necessary for this research and to all individuals who contributed directly or indirectly to its success.

Author Contribution

Authors should clearly specify the roles and contributions of each individual involved in the research to ensure proper attribution of credit and transparency regarding responsibilities. In this study, the specific contributions were as follows: conceptualization was carried out by Najeeha Mohd Apandi and Muhammad Hakim Abd Razak; methodology was developed by Najeeha Mohd Apandi; data collection was conducted by Muhammad Hakim Abd Razak; data analysis was performed by Muhammad Hakim Abd Razak and Najeeha Mohd Apandi; writing was undertaken by Muhammad Hakim Abd Razak and Muhammad Rafi Azmi; supervision was provided by Najeeha Mohd Apandi, Mohd Syafiq Syazwan Mustafa, and Noor Kamalia Abd Hamed; and funding acquisition was handled by Najeeha Mohd Apandi.

Competing Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

[1] Nagaratnam, B.H.; Rahman, M.E.; Mirasa, A.K.; Mannan, M.A.; Lame, S.O. (2016). Workability and heat of hydration of self-compacting concrete incorporating agro-industrial waste. *Journal of Cleaner Production*, *112*, 882–894. https://doi.org/10.1016/j.jclepro.2015.05.112.

[2] Hamada, H.M.; Jokhio, G.A.; Yahaya, F.M.; Humada, A.M.; Gul, Y. (2018). The present state of the use of palm oil fuel ash (POFA) in concrete. *Construction and Building Materials*, *175*, 26–40. https://doi.org/10.1016/j.conbuildmat.2018.03.227.

[3] Prasara-A, J.; Gheewala, S.H. (2017). Sustainable utilization of rice husk ash from power plants: A review. *Journal of Cleaner Production*, *167*, 1020–1028. https://doi.org/10.1016/j.jclepro.2016.11.042.

[4] Muthusamy, K.; Mirza, J.; Zamri, N.A.; Hussin, M.W.; Majeed, A.P.A.; Kusbiantoro, A.; Budiea, A.M.A. (2019). Properties of high strength palm oil clinker lightweight concrete containing palm oil fuel ash in tropical climate. *Construction and Building Materials*, *199*, 163–177. https://doi.org/10.1016/j.conbuildmat.2018.11.211.

[5] Alsubari, B.; Sha, P.; Zamin, M. (2016). Utilization of high-volume treated palm oil fuel ash to produce sustainable self-compacting concrete. *Journal of Cleaner Production*, *137*, 982–996. https://doi.org/10.1016/j.jclepro.2016.07.133.

[6] Zareei, S.A.; Ameri, F.; Dorostkar, F.; Ahmadi, M. (2017). Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties. *Case Studies in Construction Materials*, *7*, 73–81. https://doi.org/10.1016/j.cscm.2017.05.001.

[7] Hamada, H.M.; Al-Attar, A.; Shi, J.; Yahaya, F.; Al Jawahery, M.S.; Yousif, S.T. (2023). Optimization of sustainable concrete characteristics incorporating palm oil clinker and nano-palm oil fuel ash using response surface methodology. *Powder Technology*, *413*, 118054. https://doi.org/10.1016/j.powtec.2022.118054.

[8] Jamil, M.; Khan, M.N.N.; Karim, M.R.; Kaish, A.B.M.A.; Zain, M.F.M. (2016). Physical and chemical contributions of Rice Husk Ash on the properties of mortar. *Construction and Building Materials*, *128*, 185–198. https://doi.org/10.1016/j.conbuildmat.2016.10.029.

[9] Tambichik, M.A.; Samad, A.A.A.; Mohamad, N.; Ali, A.Z.M.; Mydin, M.A.O.; Bosro, M.Z.M.; Iman, M.A. (2018). Effect of combining Palm Oil Fuel Ash (POFA) and Rice Husk Ash (RHA) as pozzolan to the compressive strength of concrete. *International Journal of Integrated Engineering*, *10*(8). [DOI not located]

[10] Islam, K.; Hossain, Z. (2019). Use of rice husk ash (RHA) as a supplementary cementitious material in producing normal concrete. *MATEC Web of Conferences*, *271*, 07007. https://doi.org/10.1051/matecconf/201927107007.

[11] Saffuan, W.A.; Muthusamy, K.; Salleh, N.M.; Nordin, N. (2017). Properties of concrete containing ground palm oil fuel ash as fine aggregate replacement. *IOP Conference Series: Materials Science and Engineering*, *264*(1), 012008. http://doi.org/10.1088/1757-899X/264/1/012008.

[12] Aisheh, Y.I.A. (2023). Palm oil fuel ash as a sustainable supplementary cementitious material for concrete: A state-of-the-art review. *Case Studies in Construction Materials*, *18*, e01770. https://doi.org/10.1016/j.cscm.2022.e01770.

[13] Nguyen, T.T.; Goodier, C.I.; Austin, S.A. (2020). Factors affecting the slump and strength development of geopolymer concrete. *Construction and Building Materials*, *261*, 119945. https://doi.org/10.1016/j.conbuildmat.2020.119945 .

[14] Ismail, M.H.; Adnan, M.A.; Deraman, R. (2021). Short-Term Effect on Mechanical Strength and Water Absorption of Concrete Containing Palm Oil Fuel Ash Exposed to Chloride Solution. *International Journal of Sustainable Construction Engineering and Technology*, *12*(3), 269–279. http://doi.org/10.30880/ijscet.2021.12.03.026.