Civil and Sustainable Urban Engineering

Review
Volume 5(2), 2025, 130–140
https://doi.org/10.53623/csue.v5i2.819

Valorization of Palm Oil Fuel Ash for Sustainable Partial Cement Replacement in Concrete: A Mini Review

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SUBMITTED: 14 September 2025; REVISED: 22 October 2025; ACCEPTED: 2 November 2025

ABSTRACT: Palm Oil Fuel Ash (POFA), a by-product from the combustion of palm oil mill residues, has emerged as a highly promising supplementary cementitious material (SCM) to enhance sustainability in the construction industry. This paper reviews the physical and chemical characteristics, mechanical performance, optimal replacement levels, and the associated economic and environmental implications of incorporating POFA in concrete. Physically, POFA is characterized by its low specific gravity, initially coarse particle size, and porous structure, which can be refined through grinding to achieve finer particles with increased surface area and improved pozzolanic reactivity. Chemically, POFA is rich in silicon dioxide (SiO_2), with appreciable amounts of aluminium trioxide (Al_2O_3) and ferric oxide (Fe_2O_3), meeting the ASTM International C618-12 requirements for Class F pozzolans. These characteristics enable POFA to react with calcium hydroxide produced during Ordinary Portland Cement (OPC) hydration, forming additional calcium silicate hydrate (C-S-H) gel, thereby enhancing strength and durability. Experimental studies have demonstrated that partial replacement of OPC with finely ground POFA, particularly at levels between 10–30%, can improve long-term compressive strength, reduce permeability, and enhance resistance to chloride penetration and sulphate attack. Economically, incorporating POFA reduces dependence on energy-intensive OPC, resulting in lower production costs, while environmentally, it minimizes landfill waste, decreases greenhouse gas emissions, and promotes circular economy practices. In palm oil-producing nations such as Malaysia and Indonesia, utilizing POFA in concrete can simultaneously address the challenges of industrial waste management and cement industry decarbonization, offering a viable pathway towards sustainable construction.

KEYWORDS: Palm oil fuel ash; supplementary cementitious material; concrete performance; sustainability; circular economy

1. Introduction

The growing demand for infrastructure and urban development has driven the global production of cement to unprecedented levels. OPC, the most widely used binder in concrete, is associated with high energy consumption and the release of substantial amounts of CO_2. Cement manufacturing involves the calcination of limestone ($CaCO_3$) at high temperatures (~1450 °C), a process that releases CO_2 from both the decomposition of limestone and the combustion of fossil fuels used to heat kilns [1]. It is estimated that cement production contributes about 7–8% of total anthropogenic CO_2 emissions worldwide, making it one of the largest industrial sources of greenhouse gases [2]. The environmental burden of cement production has prompted significant interest in developing low-carbon alternatives and SCMs to partially replace OPC in concrete mixtures [3].

In parallel, rapid industrial and agricultural activities in equatorial countries particularly Malaysia and Indonesia, have led to the accumulation of vast amounts of agro-industrial by-products. One such by-product is POFA, which is generated in large quantities during the combustion of palm oil industry residues (fibers, empty fruit bunches, and kernels) in boilers to generate electricity [4]. Malaysia alone produces approximately two million tons of POFA annually, a figure expected to grow with the continued expansion of the palm oil sector [5]. The improper disposal of this ash in landfills poses serious environmental concerns, including leachate contamination, air pollution from wind-blown ash particles, and the loss of potentially reusable materials [6]. As the palm oil industry continues to expand, sustainable waste management strategies are urgently required to mitigate these adverse impacts.

In this context, the construction industry is increasingly exploring the utilization of agro-industrial wastes as SCMs to reduce the carbon footprint of concrete while valorizing industrial by-products. POFA is rich in SiO_2, Al_2O_3, and Fe_2O_3, which are key pozzolanic components known to contribute to secondary cementitious reactions when mixed with calcium hydroxide in concrete [7]. The pozzolanic reactivity of finely ground POFA has been shown to improve concrete's mechanical and durability performance while lowering its clinker content and associated CO_2 emissions [8, 9]. Thus, the beneficial reuse of POFA aligns with the principles of the circular economy and sustainable construction, offering both environmental and economic advantages.

By leveraging its pozzolanic potential, POFA offers an opportunity to lower the clinker content in concrete, thereby reducing CO_2 emissions and promoting circular resource use in the construction sector [4, 7]. However, research on the standardized processing, performance variability, and long-term durability of POFA-based concrete remains limited, particularly in diverse tropical environments. Furthermore, a comprehensive comparative assessment of POFA and other agroindustrial pozzolans in terms of mechanical properties and sustainability is still lacking. In light of these prospects, this mini review seeks to provide an overview of the physical and chemical characteristics of POFA that influence its performance in cementitious systems, examine its performance as a supplementary cementitious material, and evaluate its sustainability and economic aspects of incorporating POFA as a partial replacement for OPC. By consolidating these aspects, the review aims to highlight the potential of POFA to support sustainable construction practices while addressing the pressing challenge of agro-industrial waste management in Malaysia, Indonesia, and other palm oil-producing regions.

2. Characteristics of POFA

2.1. Physical properties.

POFA is generated as a secondary by-product from the combustion of palm oil mill residues, which include mesocarp fiber, empty fruit bunches, and palm kernel shells, at high temperatures typically ranging from 800 °C to 1000 °C for energy production in palm oil mills [10]. This process leaves behind a substantial amount of ash that would otherwise pose a disposal problem if not reputed. The as received or unground form of POFA is usually light grey to white in appearance, a feature primarily attributed to the relatively higher amount of unburnt carbon particles present in the ash. These residual carbon particles contribute to their low density and uneven texture. However, when POFA undergoes a grinding process, its physical characteristics change noticeably. The color of the ash becomes darker, shifting from light grey to grey or dark grey, as the grinding action reduces the unburnt carbon content and promotes a more uniform surface texture [11, 12]. This color transformation is a visual indicator of the improved homogeneity and reduced organic residue content, which are beneficial for its use as a supplementary cementitious material.

One of the most notable physical characteristics of unground POFA is its lower specific gravity, typically ranging between 1.78 and 1.97, compared to OPC, which has a specific gravity of about 3.14 to 3.25 [13]. This lower density can be explained by the highly porous and irregular structure of the ash particles, which contain numerous internal voids formed during combustion. Such a structure results in reduced packing density and increased water demand when used in cementitious mixtures. Additionally, unground POFA possesses relatively large particle sizes, ranging from 54.3 μm to 183 μm, which are much coarser than OPC particles. Coarse particles tend to have limited surface area, thereby reducing their potential for early hydration and pozzolanic reactions.

Grinding is a crucial step that significantly alters the physical properties of POFA and enhances its reactivity. Through mechanical grinding, the mean particle size of POFA can be reduced drastically to approximately 7.2 μm to 10.1 μm [14, 15]. This size reduction leads to a substantial increase in specific surface area and fineness, which are critical parameters for boosting pozzolanic activity. Finer particles provide more reactive surface sites for chemical reactions with calcium hydroxide released during cement hydration. Microscopic examinations have revealed that ground POFA particles display a more angular shape with denser and smoother surfaces compared to the porous and irregular shape of unground particles [16]. These morphological changes make the ground ash closely resemble the morphology of OPC particles, facilitating better integration and dispersion within cementitious systems. Furthermore, the reduction in porosity and the improvement in particle packing enhance the physical interactions between particles, which contributes to lower void content in the cement matrix. This refinement not only improves the cohesiveness and workability of the fresh mix but also accelerates early hydration reactions, leading to better strength development. Consequently, grinding transforms raw POFA from a low-reactivity by-product into a valuable pozzolanic material suitable for blending with OPC in sustainable construction applications.

2.2. Chemical Properties.

Chemically, POFA consists mainly of SiO_2, typically in the range of 44–66 %, making it a highly siliceous material suitable for pozzolanic reactions [17]. It also contains Al_2O_3 (1.5–11.5

%) and Fe_2O_3 (1.5–5.5 %), and the combined content of these three oxides (SiO_2 + Al_2O_3 + Fe_2O_3) often exceeds 70 %, which meets the pozzolanic requirement stipulated in ASTM International C618-12 for Class F pozzolans [18]. Other oxides commonly present in smaller amounts include calcium oxide (CaO, 4–9 %), magnesium oxide (MgO, 1–3 %), potassium oxide (K_2O, 4–7 %), and sulphur trioxide (SO_3, <2 %) [19, 20].

The high silica content enables finely ground POFA to react with calcium hydroxide [$Ca(OH)_2$] released during cement hydration, forming additional calcium silicate hydrate (C-S-H) gel, which is responsible for strength development and durability enhancement in cementitious systems [21]. The relatively low calcium content of POFA reduces the risk of undesirable expansive reactions, while the presence of alkalis like K_2O requires consideration in terms of alkali–silica reactivity mitigation [22]. The physical and chemical properties of POFA is summarized in Table 1.

Table 1. Summary of physical and chemical properties of POFA.

Property	Typical Value / Range	Notes / Implications	Reference
Production temperature	800–1000 °C	Generated from burning palm oil residues	[10]
Color (unground vs. ground)	Light grey → dark grey	Darkens with grinding due to carbon reduction	[11, 12]
Specific gravity	1.78–1.97 (vs. OPC 3.14–3.25)	Lower density affects mix proportioning	[13]
Particle size (unground)	54.3–183 µm	Coarse particles limit early reactivity	[14]
Particle size (ground)	7.2–10.1 µm	Finer size increases surface area and reactivity	[15, 16]
Major oxide: SiO_2	44–66 %	Main source of pozzolanic activity	[17]
Major oxide: Al_2O_3	1.5–11.5 %	Contributes to pozzolanic classification	[18]
Major oxide: Fe_2O_3	1.5–5.5 %	Contributes to pozzolanic classification	[18]
Other oxides (CaO, MgO, K_2O, SO_3)	CaO 4–9 %, MgO 1–3 %, K_2O 4–7 %, SO_3 <2 %	Affect setting, durability, and alkali reactivity risk	[19, 20]
Pozzolanic requirement	(SiO_2+Al_2O_3+Fe_2O_3) ≥ 70 %	Meets ASTM International C618 Class F criteria	[18]
Hydration contribution	Forms additional C-S-H gel	Improves strength and durability when blended with OPC	[21, 22]

3. Performance of POFA-Modified Concrete

3.1. Mechanical properties.

POFA-modified concrete exhibits several mechanical property effects depending on replacement level, POFA fineness, processing, and curing age. One key metric often used is the Strength Activity Index (SAI), defined as the ratio of the compressive strength of POFA-blended mixes to the strength of control OPC concrete at particular curing times. In studies summarized in "Palm Oil Fuel Ash-Based Eco-Efficient Concrete: A Critical Review of the Short-Term Properties," SAI values for ground POFA (GPOFA) and unground POFA (UPOFA) at 7 days were around 75% and 97% of the control, respectively, and UPOFA reached ~105% at 28 days [23]. This indicates that although early strength may lag, it frequently catches up or even surpasses control mixes at later ages, especially when POFA particles are finely ground.

Moreover, treated POFA sometimes shows improved early and later compressive strength because heat treatment reduces unburnt carbon, improving pozzolanic reactivity and efficiency [11, 24]. For instance, in self-consolidating high strength concrete with treated POFA, replacements up to 50% by weight were explored. Although early strengths dropped somewhat with increasing POFA, later-age strengths and various durability measures (such as acid attack resistance) were improved relative to untreated POFA or higher unburnt carbon contents [11].

Durability-related mechanical properties are also enhanced when POFA is finely ground. Studies show that POFA mixes have lower permeability, reduced water absorption, and better resistance to chloride penetration and sulphate attack, likely due to densification of the microstructure (fewer pores, refined pore sizes) and reduction of calcium hydroxide, which otherwise might lead to weaker zones [8, 23]. For example, in studies exposing POFA-concrete to chloride solutions, a 10% replacement level achieved more than 80% of compressive and flexural strengths compared to control under both water and chloride exposures, while higher replacements led to more significant reductions [5, 25].

One more aspect is the modulus of elasticity and shrinkage behaviour: replacing up to about 30% POFA tends to yield lower modulus than OPC concrete at early ages; however, as age progresses and hydration & pozzolanic reactions occur, the gap narrows [14]. Shrinkage strains tend to be somewhat higher in POFA blends, probably due to increased fines and more paste volume, but these effects may be manageable if mix proportions and curing are optimized [14].

3.2. Optimum replacement levels.

Determining the optimum replacement level of OPC with POFA involves balancing strength performance, workability, cost, and durability. Many studies show that replacement levels between 10% and 30% by mass of cement tend to offer the best trade-offs. For example, in treated POFA in self-consolidating high strength concrete, substitution up to about 30% gave good compressive strength and favourable fresh properties; higher volume (50%) replacements were possible but required adjustments to maintain strength [11, 26].

In comparisons, a study reviewing ~35 previous works found that optima vary by concrete type, but generally replacement in the range 5% to 40% can enhance compressive strength and/or workability depending on the type of concrete, fineness of POFA, and curing regime [7]. For lightweight or cellular concrete applications, lower replacement levels are often better: for example 10% POFA in cellular lightweight concrete mortar produced the maximum strength (for that type of concrete) vs. higher levels leading to strength decline [18].

Higher replacement percentages, above ~30%, commonly lead to reductions in early-age strength, increased water demand, potentially reduced workability, and longer setting times unless mitigated by very fine POFA, chemical activators, or enhanced curing [11, 23, 27]. Thus, where early strength or early time loading is required, lower replacements (≈10-20%) are safer. Where long-term strength, durability, or green credentials are prioritized, higher percentages (≈20-30%) with fine POFA and appropriate processing can be viable. Another factor influencing the selection of optimum replacement is exposure environment: in aggressive environments (chloride, sulphate, acid) moderate replacement with fine POFA (for example ~20%) tends to improve durability compared to OPC alone or OPC with high POFA content, as porosity is lowered and resistance to chemical ingress improves [8, 28]. The mechanical performance of POFA-modified mixes is shown in Table 2.

Table 2. Selected mechanical performance of POFA-modified mixes.

Replacement Level of OPC with POFA	Concrete / Mortar Type & POFA Treatment	Key Mechanical Outcomes	Reference
treated POFA	High-strength mortar with treated POFA (TPOFA), w/b ~0.32	Compressive strengths: ~101.4 MPa (10%); ~88.4 MPa (20%); ~83.6 MPa (30%) at 90 days; strength activity index close to control OPC	[10, 23, 24]
10% POFA	Concrete exposed to chloride solution	Achieved >80% of both compressive and flexural strength compared to control under water or chloride exposure at 28 days; good water absorption	[5, 25]
20–30% POFA	High strength concrete with different fineness (10 µm & 45 µm)	Better resistance to acid, sulphate, and chloride attacks with 20% POFA, particularly when finely ground; durability improved	[8]
~30% POFA	Standard concrete aiming 50 MPa target strength	Modulus of elasticity somewhat lower, shrinkage higher, but compressive strength with time becomes satisfactory; 30% replacement gave viable strength though slightly lower than OPC	[14]
10% POFA	Cellular lightweight mortar / CLC mortar	Optimum compressive strength achieved at ~10% POFA substitution; higher levels reduced strength	[18]

4. Profitability and Environmental Benefits

4.1. Cost–Benefit analysis (CBA).

When considering POFA as a supplementary cementitious material, recent studies show that its integration yields both economic savings and environmental advantages that can outweigh the costs associated with its preparation (mainly grinding and processing). One element of cost savings arises from reduced use of ordinary OPC, which is energy- and carbon-intensive to manufacture. Replacing portions of OPC with POFA lowers cement demand, hence reducing raw material (limestone, clay) extraction and thermal energy consumption during the calcination process. For example, in "Durability of high strength concrete containing palm oil fuel ash of different fineness" [29], a 20% replacement of OPC by very fine POFA (10 µm) has been shown to enhance durability under aggressive environments, which implies potential savings in repair and maintenance over the service life of structures.

Another critical factor concerns carbon emissions. Since CO_2 emissions from cement production originate mainly from limestone decomposition and the burning of fossil fuels, reducing OPC content directly reduces both sources of CO_2. Although detailed cradle-to-grave life-cycle assessment (LCA) data for POFA-blended concrete are not exhaustively available, studies such as "Evaluating the impact of reducing POFA's particle fineness on its pozzolanic reactivity and mortar strength" [30] show that grinding to finer particle size improves reactivity, which means that lower POFA replacements or earlier strengths can be achieved, reducing the time to load and thus potentially shortening construction schedules and associated emissions/costs.

On the cost side, processing POFA (drying, grinding, sieving) incurs energy and equipment costs. Transportation from palm oil mills to grinding facility and then to construction sites also adds logistics costs. In "Effect of Utilisation of Nano POFA on Performance of Self-Consolidating High-Performance Concrete (SCHPC)" [31], nano-POFA replacements up to 10% of binder weight showed improved strength (at least in some mixes) but required additional milling or processing, so the marginal cost increase has to be compared with the marginal benefits of improved strength, durability, and possibly longer lifespan.

Waste disposal costs and environmental externalities are also part of the cost-benefit balance. POFA is often landfilled or stockpiled, which results in costs (land use, leachate, dust management) and environmental impact. Reusing POFA in concrete avoids these disposal costs and the associated environmental burdens. For example, in "Durability of high strength concrete containing palm oil fuel ash of different fineness" [29], the authors explicitly mention that using POFA helps reduce environmental problems owing to cutting down on cement production and mitigating solid waste burdens.

Overall, when all these factors are considered reduced cement, lower CO_2 emissions, avoided waste disposal, savings in maintenance and longer service life, the net benefit of using POFA tends to be positive, especially when POFA processing is optimized, when replacement level is moderate (for example ~20%), and when structures face aggressive exposure conditions.

4.2. Sustainability implications.

The adoption of POFA in concrete and related materials aligns with sustainability goals in several ways. First and foremost, it supports circular economic principles: an industrial by-product that would otherwise be a waste becomes a resource. This reduces demand for virgin materials (limestone for cement), reduces waste stockpiling, and reduces environmental issues associated with ash disposal (dust, leachate, land use). In "A critical review of various types of POFA utilization in enhancing concrete and mortar properties" [32], recent evidence is collected that shows POFA can be used in many types of concrete with improved or comparable performance, thereby potentially reducing the construction industry's carbon footprint. The review also highlights that POFA's use in high-performance or ultra-high performance concrete (UHPC) forms, as in "Properties of ultra-high-performance concrete incorporating palm oil fuel Ash as an eco-filler" [33], demonstrates that high strengths can be achieved even with relatively high POFA content (for example 20%), along with reduction in permeability and improved residual strength after elevated temperature exposure. These durability benefits translate into longer service lives and thus lower total environmental burden over the life cycle of structures.

Moreover, using locally available POFA in palm oil producing countries (such as Malaysia, Indonesia) reduces transportation distances compared to importing SCMs or using Portland cement from distant plants. This local sourcing not only lowers transportation costs but also reduces associated CO_2 emissions. There's also the benefit in mitigating the embodied carbon of concrete. Since cement is responsible for major portion of concrete's embodied carbon, reducing OPC content by even 10-20% with POFA can yield measurable decreases in embodied carbon per cubic meter. This is particularly meaningful in policies aiming to reduce greenhouse gas emissions in the building sector, where many countries are setting targets for net zero or carbon neutral building materials [34].

Finally, POFA's inclusion fosters social and environmental justice by reducing negative environmental impacts in palm oil producing regions, where ash disposal can disproportionately affect communities (airborne dust, water pollution). If managed well, POFA reuse can create new business opportunities (processing facilities, supply chains for recycled materials), thereby contributing to local economies.

Table 3. Recent studies on economic / environmental outcomes of POFA usage.

Study	Replacement Level / POFA Treatment	Key Environmental / Economic Outcome(s)	Reference
High-strength concrete with 20% very fine POFA (≈10 µm)	20% POFA replacement with fineness 10 µm	Improved resistance to chemical attacks, implying lower maintenance/longer life, plus reduced cement usage, cost & emissions savings	[29]
Nano-POFA in SCHPC	POFA replaced 1-10% in nano form	Highest compressive strength (~73.31 MPa at 28 days for 1%), workability maintained; suggests environmental savings (less cement, better performance) vs cost of nano treatment	[31]
POFA + eco-filler in UHPC	20% micro-POFA + nano-POFA mix	Compressive strength higher than control at 91 days; significantly reduced water permeability; better performance under elevated temperatures, implying improved durability and sustainability	[33]
Polymer concrete with POFA as micro-filler	Ground POFA used as micro-filler	Finer fillers gave superior filling ability and compressive strength; enhances material efficiency and reduces need for virgin filler materials	[34]

5. Conclusion

The integration of POFA as a supplementary cementitious material in concrete presents a viable pathway toward more sustainable and economically advantageous construction practices. The cost–benefit analyses from recent studies indicate that the economic gains arising from reduced OPC consumption, lower energy requirements, and minimized maintenance costs, can surpass the costs of POFA processing, especially when moderate replacement levels (10–30%) are adopted. The incorporation of finely ground or nano-POFA enhances pozzolanic reactivity, thereby compensating for any early-age strength reductions and contributing to long-term durability improvements. These performance gains reduce the frequency of repair and rehabilitation, leading to further lifecycle cost savings. Environmentally, the valorization of POFA mitigates several pressing concerns associated with cement production and agro-industrial waste management. By partially replacing OPC, significant reductions in carbon dioxide emissions can be achieved, directly addressing the high carbon footprint of cement manufacturing. Concurrently, the reuse of POFA diverts substantial quantities of ash from landfills, reducing the environmental risks of leachate formation and airborne particulate pollution. This practice embodies circular economic principles, turning an abundant local waste into a value-added construction material. In palm-oil-producing nations such as Malaysia and Indonesia, the utilization of POFA in construction aligns with national sustainability agendas aimed at decarbonizing the built environment while simultaneously resolving the challenge of managing vast volumes of palm oil by-products. The use of locally sourced POFA also reduces transport-related emissions and costs, amplifying its environmental and economic appeal. Overall, POFA incorporation offers a synergistic solution by enhancing concrete durability, lowering costs, and contributing to greenhouse gas mitigation efforts, thereby representing a promising material strategy for sustainable construction. Adopt a POFA replacement level of 10–30% to balance strength and sustainability. Encourage local sourcing and standardized grinding to ensure consistent quality. Include POFA in national green building standards and promote its use in public infrastructure projects. Future research directions: Examine the long-term durability and microstructure of POFA-infused concretes. Explore nano-POFA applications to enhance early strength and reactivity. Conduct a comprehensive life-cycle assessment and techno-economic analysis to support large-scale implementation. Adopt a POFA replacement level of 10–30% to balance strength and sustainability. Encourage local sourcing and standardized grinding to ensure consistent quality. Include POFA in national green building standards and promote its use in public infrastructure projects. Examine the long-term durability and microstructure of POFA-infused concretes. Explore nano-POFA applications to enhance early strength and reactivity. Conduct a comprehensive life-cycle assessment and techno-economic analysis to support large-scale implementation.

Acknowledgment

The authors express their gratitude to the palm oil mills and construction material laboratories that provided technical information and unpublished data, which greatly assisted this study. We also acknowledge the support from our respective institutions for facilitating access to relevant databases and software used during this review.

Data Availability

No new data was generated or analyzed in this study. All data supporting this article is available from the cited references.

Author Contribution

All authors contributed equally to the conceptualization, literature review, data analysis, and writing of this manuscript. All authors have read and approved the final version of the manuscript.

Competing Interest

The authors declare no known competing financial interests.

Reference

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