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Recycling Agricultural Waste for Green Concrete: The Case of Palm Oil Ash

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ABSTRACT

Aim of the Study: This study explores the potential of palm oil ash (POA), an agricultural by-product rich in amorphous silica and alumina, as a partial cement replacement in concrete. The aim is to assess POA's effectiveness in reducing cement consumption and environmental impact while maintaining adequate mechanical performance and durability.

Methodology: Concrete mixes were prepared using a 1:2:4 ratio, with 30% of cement replaced by POA. The POA was sourced from a palm oil mill, air-dried, sieved, and finely ground before use. Mechanical and durability tests, including compressive strength at 7, 14, and 28 days, a slump test for workability, and water absorption assessment, were conducted to evaluate performance.

Findings: Results indicated that concrete containing POA developed lower early-age compressive strength compared to the control mix (5.4 MPa at 7 days, 10.2 MPa at 14 days). However, at 28 days, POA-based concrete (17.5 MPa) surpassed the conventional mix (15 MPa), confirming its pozzolanic contribution to long-term strength. Workability decreased slightly due to POA's high water absorption, with slump values reducing from 38 mm (control) to 36 mm (POA mix). Water absorption increased progressively during curing, indicating higher porosity, but remained within acceptable limits for structural use.

Conclusion: The study demonstrates that POA can effectively substitute up to 30% of cement in concrete, contributing to sustainable construction practices. Although early-age strength and workability are reduced, extended curing enhances compressive strength and durability. POA utilisation offers a promising pathway for recycling agricultural waste into green building materials.

Keywords: Palm Oil Ash (POA); Sustainable Concrete; Compressive Strength; Workability; Agricultural Waste Recycling; Pozzolanic Activity.

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1. INTRODUCTION

Due to the escalating demand for construction materials to facilitate rapid development, numerous countries are utilising substantial quantities of non-renewable natural resources. As a result, rising demand has resulted in higher raw material acquisition costs and an obstinate shortage of natural resources (Bayagoob et al., 2024). The second most consumed structural product in the world today is concrete, which is only beaten by water, with an output of 25 × 109 tons a year. Cost, durability, formability in any shape, and availability of binder ingredients are some of the characteristics that set concrete apart (Amran, Lee, et al., 2021).

According to earlier research, some agricultural waste materials can be utilised in place of cement for making concrete. Concrete that is more environmentally friendly and sustainable can be made using resources from agricultural waste, such as palm oil (Hamada et al., 2021). The adverse impact of climate change, global warming, and current emphasis on environmental sustainability (Bayagoob et al., 2024) cannot be overemphasised. The quest for environmental cleanliness repeatedly faces obstacles powered by constant contributions to built-up toxic waste and by-products responsible for high greenhouse gas emissions from industrial processes (Amran, Murali, et al., 2021).

Environmental cleanliness pursuits are repeatedly thwarted by ongoing industrial activities, causing toxic waste and by-products associated with increased greenhouse gas emissions. The structure industry has changed as a result of the use of industrial wastes; without these resources, the air would become contaminated, and land and water would suffer greatly (Alnahhal et al., 2021). Muja explained that PFA is attained from residual burning palm oil, as shown in Figure 1. The material contained a high number of amorphous silicon and aluminium oxides. Various studies have been conducted to establish how ground-PFA can be used as a filler in concrete, while simultaneously improving its strength, water permeability, and sulfate resistance (Aisheh, 2023).

POFA is a byproduct created when oil palm fruit bunches and shells are burned to create power. The primary factors influencing POFA's chemical and physical properties POFA are source properties, temperature, and burning time. The characteristics of concrete are adversely affected by the significant amounts of fibres, large solid particles, and unburned shells found in raw POFA. Therefore, before being used as a cement substitute, POFA is often separated and crushed, separated or heated, and ground. POFA was screened using a 300 mm screen in the majority of earlier research on its use as a cement substitute (Al-Shwaiter et al., 2022).

Between 1990 and 2010, the worldwide oil palm tree planting area increased from 6 million hectares to 16 million hectares, owing to the economic benefits of the palm oil business. The two largest manufacturers of oil palm in the world are Indonesia and Malaysia. According to reports, Indonesia had the largest oil palm plantation in 2019 with 2,424,545 hectares (Hamada et al., 2022).

Furthermore, the high energy content and abundant availability of agricultural biomass lead to the existence of palm oil ash in biomass-electricity plants and the excessive handling of agro-waste ashes. Because certain cement plant locations do not have easy access to industrial by-products, recent research has focused on locally accessible agricultural waste ash (Santhosh et al., 2022a).

Refining POFA is the key factor that determines concrete strength and durability. Several investigations have examined whether increased POFA fineness and elevated pozzolanic reactivity might lead to improved concrete strength. The researchers assessed POFA as a concrete ingredient by substituting it with ordinary Portland cement (OPC) at varying replacement percentages, commonly at 10-50% of the total overall content of cement (Hasan et al., 2023).

This study aims to determine whether POFA can substitute some amount of cement and produce workable concrete mixes. Twenty concrete formulas were prepared, including the control mix, to determine their strength and durability (Patah et al.). POA has been widely incorporated into concrete to replace cement, to reduce cost, health risks, energy conservation, and environmental impacts. Another benefit of recycling products and waste is that it prevents difficulties in disposing of garbage.

Figure 1. *Production of Palm Oil Ash*

Table 1. *Literature Review*

Year	Author	Objectives	Methods & Materials	Conclusion
2025	(Bakar, Ismail, Rahim, & George)	Investigate the effects of POFA and metakaolin (MK) on lightweight concrete (LWC) with coconut shell aggregate	5% POFA gave the highest compressive (+68.55%), flexural (+39.29%), and tensile (+32.18%) strength; the lowest water absorption (3.75%); slump decreased with POFA content	5% POFA gave the highest compressive (+68.55%), flexural (+39.29%), and tensile (+32.18%) strength; lowest water absorption (3.75%); and a slump decreased with POFA content
2024	(Odeyemi et al., 2021)	Determine optimal POFA–FA–silica fume (SF) blend for early-age strength	60% cement replaced with varying POFA & FA ratios + 2% SF; tested strength & slump	High single replacements (60% POFA or FA) led to low early strength (50% at 7 days); blends improved performance
2025	(Bakar, Ismail, Rahim, Majid, et al.)	Evaluate POFA as a partial cement replacement on compressive strength & sulfate resistance	POFA: 0%, 10%, 20%, 25%; tested compressive strength & sulfate resistance	25% POFA optimised strength and sustainability; 30% POFA improved sulfate resistance but reduced strength
2025	(Patah et al.)	Assess POFA in foamed concrete with varied foam agent dosage	POFA: 0–20%; foam agent/water ratio varied; tests on strength, porosity, absorption, resistivity	10% POFA + 1/60 foam ratio gave highest strength; 20% POFA achieved comparable strength to conventional foamed

				concrete
2024	(Al-Shwaiter et al., 2022)	Study POFA & MK effect on slump, strength, and heat of hydration	POFA & MK varied; superplasticiser constant; tested slump, compressive strength, heat of hydration	20% MK + 5% POFA increased 28-day strength by 14.07% and reduced peak hydration temperature by 5.54%
2021	(Jhatial et al., 2021)	Develop eco-friendly lightweight foamed concrete (LFC) with POFA & eggshell powder (ESP)	LFC with varying POFA & ESP; tested J-ring, strength, elasticity, thermal conductivity, eco-efficiency	POFA + ESP improved mechanical properties, met ACI213R LWC standards, and reduced thermal conductivity
2024	(Hasan et al., 2024)	Evaluate POFA in steel fibre-reinforced concrete (SFRC)	POFA varied up to 20%; tested workability, strength, shrinkage, and heat of hydration	Up to 20% POFA improved compressive strength; reduced workability & drying shrinkage
2022	(Santhosh et al., 2022b)	Review POFA's role in concrete, soil improvement, and wastewater treatment	Literature review	Up to 20% POFA improved the mechanical/durability properties of concrete; enhanced soil engineering properties, and adsorbed heavy metals.
2025	(Chen et al., 2025)	Examine hydration, strength, and carbonation in BFS–POFA cement blends	BFS & POFA varied; tested hydration, strength, carbonation	15% POFA in high-volume slag cement improved long-term strength due to pozzolanic activity

The studies collectively validate that palm oil fuel ash (POFA) is an effective additional cementitious material capable of improving the mechanical and durability properties of concrete when used at optimal replacement levels. Most research indicates that partial substitution of cement with POFA, typically between 5% and 25% can enhance later-age compressive strength, reduce thermal conductivity, and improve resistance to sulfate and chloride ingress, provided proper curing is maintained. However, higher POFA contents often main to reduced early-age power and workability due to their high water engagement and porous structure. Several investigations also highlight the synergistic benefits of combining POFA with other supplementary materials such as metakaolin, fly ash, silica fume, or blast furnace slag, yielding improved strength development and reduced heat of hydration. Additionally, POFA has been successfully incorporated into specialised concretes such as lightweight foamed concrete, steel fibre-reinforced concrete, and hybrid aggregate mixes, further expanding its potential applications in sustainable construction. Akram et al. highlighted that optimising both strength and workability is essential for sustainable concrete. Their findings support the potential of POFA-based mixes to achieve performance and environmental goals (Akram et al., 2025). Muneer et al. demonstrated that agricultural by-products such as sugarcane bagasse ash and silica fumes can significantly improve mortar performance. This supports the present study's aim of utilising POFA to improve concrete strength while promoting sustainable waste recycling (Muneer et al., 2025). Arshad et al. emphasised the value of integrating industrial and natural waste materials to achieve sustainable construction goals. Their conclusions parallel the present study's approach of incorporating POFA as a green alternative in concrete production (Arshad et al., 2025). Akram et al. discussed the role of collaborative frameworks in overcoming resource and sustainability challenges in Pakistan's construction sector. Such insights align with this study's emphasis on leveraging innovative materials like POFA to address industry needs sustainably (Akram et al., 2023).

Building upon this body of knowledge, the present study aims (i) to substitute a significant percentage of cement in conventional concrete with palm oil ash (POA), and (ii) to investigate the resulting mechanical properties of POA-based concrete. This study is significant because it examines the effects of high POA concentrations beyond the commonly tested ranges while integrating sustainability assessment and precise experimental data collection. Furthermore, unlike many previous studies focused solely on cement replacement, this work also considers the substitution of natural aggregates with palm oil clinker (POC) at 50% and 100% levels (Munir et al., 2025), assessing the fresh properties via slump testing. By addressing both binder and aggregate replacement, the study provides a more comprehensive evaluation of agricultural waste utilisation in concrete, offering potential pathways to reduce cement consumption, conserve natural aggregates, lower CO_2 emissions, and promote circular economy practices within Pakistan's construction sector.

2. MATERIAL AND METHODS

The methodology employed in this study involved preparing concrete mixes with a 1:2:4 ratio, with 30% of the cement being substituted by palm oil ash (POA). POA was obtained from a palm oil mill, air-dried, sieved to remove large particles, and ground into fine particles. Typically, Portland cement is used. The testing procedures included compressive strength tests at 7, 14, and 28 days to evaluate strength improvement, workability tests using the slump test, and water absorption tests to determine the weight gain of the cured samples.

Companies that produce palm oil are a source of this waste. A palm oil mill located in Marsa Matrouh, Egypt, provided the POA for this project. For one day, POA was allowed to air dry in an electrical oven set to 110 ± 5°C. A 150 mm sieve was then used to remove any large or unusual particles. After sieving, the POA was ground into extremely tiny particles using a Los Angeles-made grinding machine (Odeyemi et al., 2021).

Figure 2. *Palm oil ash*

Table 2. *Properties of POA*

Sr. #	Properties	Values
1	Water Absorption	-0.1%
2	Specific Gravity	0.9 to 1.0

Aggregate materials are large particulate materials used in construction projects, including sand, gravel, crushed rocks, slag, reclaimed concrete, and geological synthetic aggregates. They are essential components in various construction applications, providing bulk, strength, and durability to composite materials, such as concrete and asphalt.

Figure 3. *(a) OPC, (b) fine aggregate, (c) coarse aggregate*

Table 3. *Properties of Coarse Aggregates*

Sr. #	Properties	Values
1	Water Absorption	0.1%
2	Specific Gravity	2.5

Table 4. *Sieve Analysis*

Sieve Size	Weight retained (kg)	Cumulative weight retained (kg)	Cumulative % retained	Cumulative % Passing
19mm	1.519	1.519	30.380	69.620
12.5mm	2.143	3.662	73.240	26.760
9.3mm	1.301	4.963	99.260	0.740
4.75mm	0.037	5	100	0
Total	**5**		**729.64**	

Fineness modulus of Coarse aggregate = 729.64/100 = 7.30

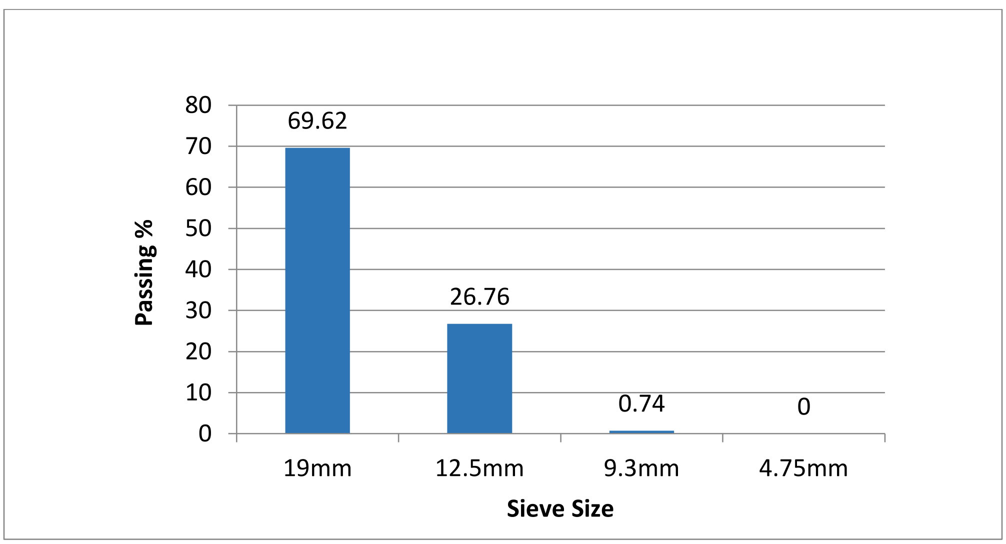


Figure 4. *Sieve Analysis % Passing of Coarse Aggregate*

Sand is used as a filler in concrete to provide construction with more strength and stability. The strength of the concrete mix is affected by the size, shape, and grading of the sand particles [29]. Well-graded sand produces better particle packing, which enhances aggregate particle interlocking and results in a denser concrete matrix. The sample mixtures created for the experiments included sea and sand as fine collections (Hamada et al., 2022).

Table 5. *Properties of sand*

Sr	**Properties**	**River sand**	**Sea sand**
1	Specific gravity (SSD condition)	2.36	2.49
2	Bulk density (kg/m^3)	1462	1543
3	Moisture (%)	3.40	4.50
4	Water absorption (%)	1.92	1.94

Table 6. *Sieve Analysis of Fine Aggregate*

Sieve Size	**Weight retained (grams)**	**Cumulative weight retained (grams)**	**Cumulative % retained**	**Cumulative % Passing**
4.75mm	3	0.3	0.3	99.7
2.36mm	4	0.4	0.7	99.3
1.18mm	82	8.2	8.9	91.1
0.6mm	318	31.8	40.7	59.3
0.425mm	499	49.9	90.6	9.4
0.15mm	68	6.8	97.4	2.6
Total	**1000**		**238.6**	

Fineness modulus of Fine aggregate = 238.6/100 = 2.384

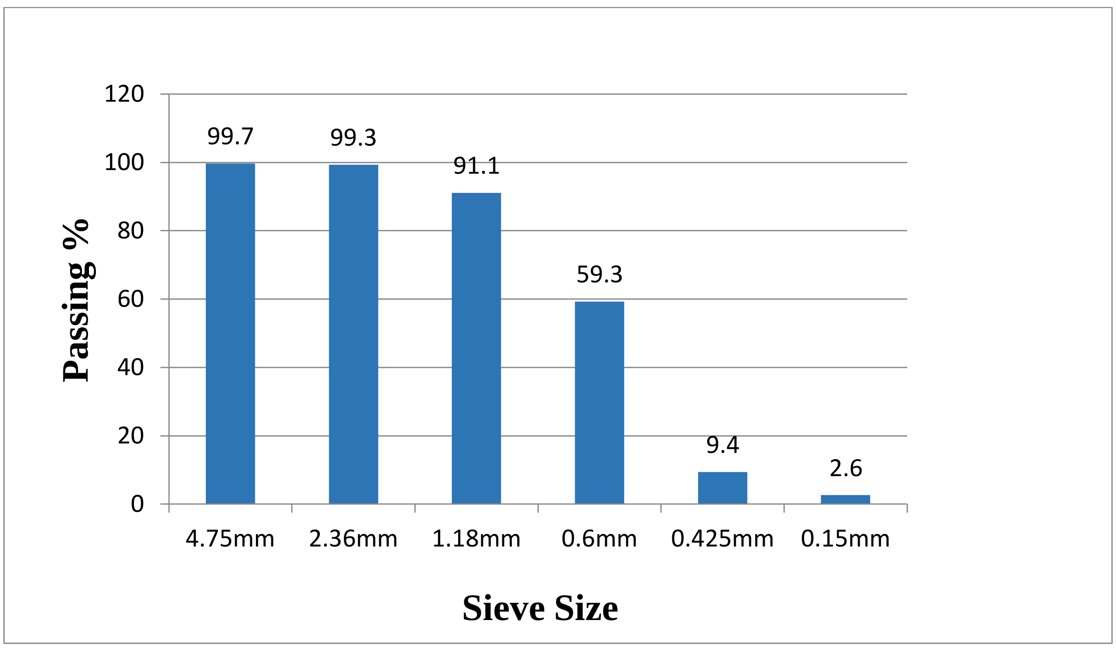


Figure 5. *Sieve Analysis % Passing of Fine Aggregate*

The water spent on the concrete mix was ensured to be free from harmful chemicals and organic materials. Water is used to mix the above materials to make concrete.

Table 7. *Properties of water*

Sr. #	Properties	values
1	Specific gravity	**1.0**

The mixing of palm oil ash (POA) with concrete involves a systematic process to ensure optimal performance and sustainability. Palm oil painting ash, a derivative of burning win oil painting cocoons and filaments, is first collected, settled, and ground into fine grease paint to enhance its reactivity. It is also used as a supplementary cementations material, generally replacing 10% of cement in the concrete blend. During mixing, the POA was combined with cement, summations, and water in precise proportions, resulting in a homogeneous admixture with acceptable plasticity.

Figure 6. *Mixing and casting of concrete blocks*

The curing process is critical for the pozzolanic response of POA, which contributes to long-term strength development. After placement, the concrete is originally covered to help reduce humidity loss and also water-cured for at least 7, 14, and 28 days to maintain hydration and promote the pozzolanic reaction of the ash.

Figure 7. *Curing of Concrete Blocks*

Testing palm oil ash (POA) for use in concrete involves evaluating its physical, chemical, and mechanical properties to ensure that it meets the required standards as a supplementary cementitious material (SCM). Below is a detailed testing procedure and the names of the machines used for each test. To evaluate the strength improvement of concrete containing POA, prepare concrete cubes with POA and test them at 7, 14, and 28 days. To assess the effect of the POA on the workability of fresh concrete, a slump test was conducted. To determine the porosity and water absorption capacity of the POA concrete. The cured concrete samples were immersed in water, and the weight gain was measured.

Figure 8. *Compressive Strength of Concrete Blocks*

Figure 9. *Slump Test of POA-based Concrete Blocks*

3. RESULTS AND DISCUSSION

The compressive strength development of concrete with 30% Palm Oil Ash (POA) replacement was evaluated at 7, 14, and 28 days. The results showed 5.4 MPa at 7 days, 10.2 MPa at 14 days, and 17.5 MPa at 28 days, indicating a progressive strength gain with curing age. Compared to conventional concrete, early-age strength was lower due to the slower pozzolanic reactivity of POA; however, by 28 days, the POA mix exceeded the strength of the control mix (17.5 MPa vs. 15 MPa). This behaviour aligns with previous studies (Hasan, 2023; Akram et al., 2023), where supplementary cementitious materials exhibited delayed but enhanced later-age strength through continued pozzolanic reactions forming additional C–S–H gel.

Workability, assessed via slump testing, decreased with POA addition. At 0% replacement, the slump measured 38 mm, while at 30% replacement, it fell to 36 mm. This reduction is attributed to POA's higher water absorption compared to cement, which increases water demand to achieve equivalent consistency. Similar trends were reported by Hasan et al. (2024), who observed that increased POA content consistently reduced slump due to its porous particle structure.

Water absorption testing revealed that POA mixes gained weight progressively during curing: 7.1 kg (uncured), 7.6 kg at 7 days, 7.8 kg at 14 days, and 8.2 kg at 28 days, indicating higher porosity compared to control mixes. While higher absorption may suggest increased permeability, earlier studies (Akram et al., 2025; Sakri et al., 2025) have shown that the fine POA particles can refine pore structure over longer curing periods, potentially improving long-term durability.

3.1. Compressive Strength

The development of early-age compressive strength in concrete mixes that contain 30% palm oil ash (POA) in place of some of the cement provides information about the pozzolanic activity and initial hydration. After the compressive strength test was completed after 7 days of curing, the compressive strength was 5.4 MPa when tested with a mix that incorporated POA. On 14 day, a compressive strength was achieved at 10.2 MPa was achieved with the ongoing hygroscopic procedure and the start of a pozzolanic reaction. The strength after 28 days reaches 17.5 MPa. Such preliminary results could indicate the delayed reactivity of POA, which is a feature of supplemental cementitious materials; however, in this case, there is an apparent increase in strength with the passage of time. With the additional development of pozzolanic reactions, the ultimate strength improvement that occurs from POA usually occurs at a later stage of curing.

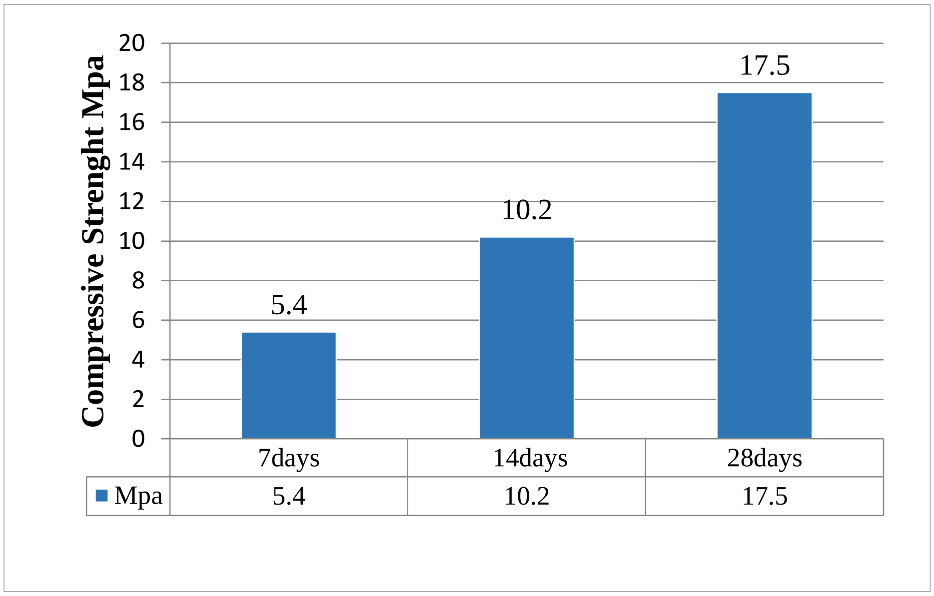


Figure 10. *Compressive Strength of POA-based Concrete Blocks*

3.2. Workability

The figure shows the workability of concrete (slump test) for 0% and 30% POFA replacement. This demonstrated that when the proportion of replacement with POFA increased, the slump height decreased.

As the POFA content increased, the workability of the new POFA concrete decreased, as determined by the slump test. This is because POFA absorbs more water than cement to create a paste with uniform consistency.

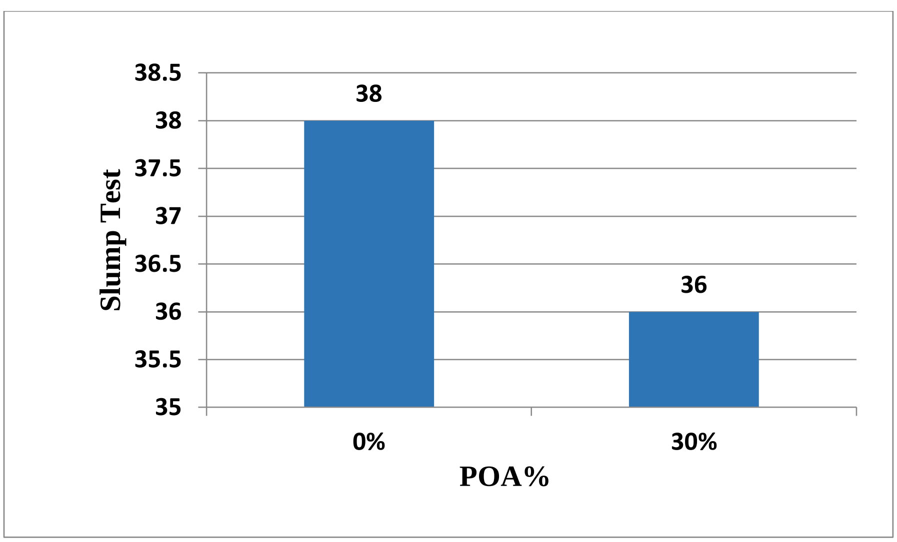


Figure 11. *Slump Test of POA-based concrete blocks*

3.3. Water Absorption

The water absorption characteristics of concrete containing palm oil ash were evaluated by measuring the weight gain of the samples over 28 days. After the compressive strength test was completed after 7 days of curing, the compressive strength was 5.4 MPa when tested with a mix that incorporated POA. On day 14, a compressive strength was achieved at 10.2 MPa was achieved with the ongoing hygroscopic procedure and the start of a pozzolanic reaction. The strength after 28 days reaches 17.5 MPa. Such preliminary results could indicate the delayed reactivity of POA, which is a feature of supplementary cementitious materials; however, in this case, there is an apparent increase in strength with the passage of time. With the additional development of pozzolanic reactions, the ultimate strength improvement that occurs from POA usually occurs at a later stage of curing.

Table 8. *Water Absorption*

Days	Weight
0 Day (without curing)	7.1kg
7 days curing	7.6kg
14 days curing	7.8kg
28 days curing	8.2kg

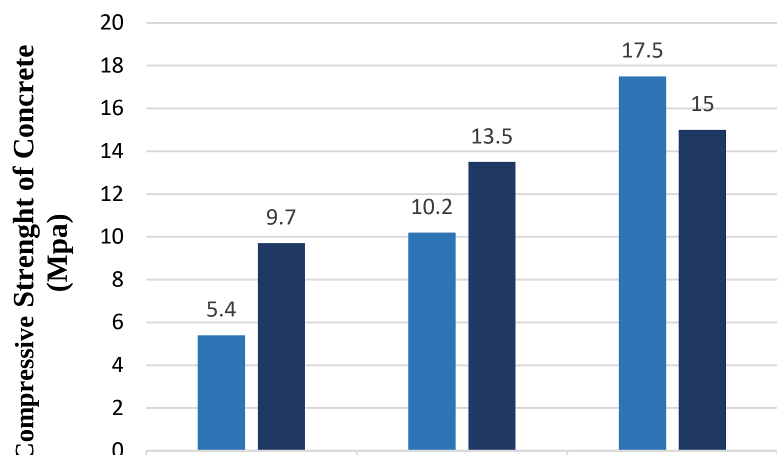
Palm oil ash (POA) is being explored as a possible replacement for cement in concrete to stimulate the design of more environmentally friendly building materials (Bakar, Ismail, Rahim, & George). The reviewed POA physical and durability attributes in the concrete setting investigated its effectiveness in achieving 30% cement replacement. Conventional concrete initially offers a stronger compressive strength than POA concrete, but the study revealed a progressive strengthening effect during the testing. The greater water absorption capacity of the POA had a negative impact on both the manufactured products and workability during construction. Over 28 days, the water absorption tests showed a consistent increase (Golewski, 2023).

In particular, a mix containing POA demonstrated a compressive strength of 16% after 7 days, 31% after 14 days, and 53% after 28 days. With a slump of 38 for 0% POFA and 36 for 10% POFA, the slump test demonstrated a decline in workability as the replacement percentage with POFA increased. According to the water absorption tests, the weight increased by 32% kg after 7 days of curing, 33% after 14 days, and 36% after 28 days. In general, the goal of turning agricultural waste into sustainable building materials is supported by POA. According to published research, POA consistently up to 20% may improve mechanical quality and durability, which could eventually lead to an increase in strength (Patah et al.).

Higher levels of treated palm oil fuel ash (POFA) in self-compacting concrete (SCC) produce different results than the 10% replacement of POA in standard concrete, which shows a strength gain over 28 days (up to 17.5 MPa), decreased workability, and increased water absorption. 60% POFA showed better impermeability and less water/chloride penetration, while SCC with 40% POFA had a much higher strength (85.11 MPa at 180 days) (Assaggaf et al., 2021). The slower initial reactivity of supplementary cementitious materials such as POA in comparison to regular Portland cement is the main cause of the lower initial results when 10% POA is substituted. As pozzolanic reactions advance, POA's full strength potential of POAs emerges over longer curing times (Zeyad et al., 2025).

Compared to traditional concrete, concrete mixes that use palm oil fuel ash (POFA) instead of cement show unique performance traits. Initially, the development of compressive strength with 10% POFA replacement was slower, but as time went on, the strength grew, and the pozzolanic reactions of POFA may have led to improved later-age strength (Hasan et al., 2023). However, the addition of POFA results in a decrease in workability, as determined by the slump test, because a higher POFA content lowers the slump height.

The main reason for this is that POFA requires more water to reach a consistency comparable to that of cement, because it absorbs more water. Over 28 days, the weight gain increased in concrete containing palm oil ash, indicating higher water absorption. These variations are explained by the characteristics of POFA: its higher water absorption capacity decreases the workability of the mix, while its fine particles function as micro-fillers and enhance later-age strength through reactions with calcium hydroxide (Sakri et al., 2025).



	1	2	3
POA	5.4	10.2	17.5
Conventional Concrete	9.7	13.5	15

Figure 12. *Comparison of Compressive Strength of Conventional and POA-based Concrete*

The conventional concrete shows greater strength at 7 and 14 days. This is because early strength growth is mostly influenced by cement hydration. The amount of cement available for early hydration is decreased when a sizable fraction (30%) of the cement is replaced. As a supplementary cementations' material (SCM), palm oil ash reacts with calcium hydroxide to produce a pozzolanic reaction that adds strength. This reaction usually starts and develops more slowly than the cement's initial quick hydration. When compared to regular concrete (15 MPa), the POA-containing concrete exhibits a greater strength (17.5 MPa) after 28 days. This suggests that palm oil ash's pozzolanic reaction has grown in importance. As a result of the reaction, more binder material (C-S-H gel) is formed, which refines the pore structure and gradually increases the concrete's density and strength, eventually surpassing the strength of a standard mix. The quality and reactivity of the palm oil ash utilised determine how much strength is gained later (Ramonu et al., 2019).

When palm oil ash (POA) is used to partially substitute cement in the production of concrete, a variety of effects can be induced. From the findings, at first, concrete with POA shows a lower compressive strength than normal concrete, but it improves with time. This indicates that POA is involved in improving the long-term strength of concrete mainly because of its pozzolanic behaviour. However, because POA absorb more water, fresh concrete is less workable (Kearsley, 2022). Additionally, water absorption tests showed that concrete mixes containing POA consistently increased the water uptake over 28 days. Overall, the use of POA in concrete supports the objective of turning agricultural waste into sustainable building materials (Maraveas, 2021).

According to previous research, POA, especially up to 20% replacement, can improve durability and mechanical qualities, which could eventually result in greater strength. Higher amounts of treated palm oil fuel ash in self-compacting concrete have demonstrated improved impermeability and decreased water/chloride penetration, whereas a 10% replacement exhibits strength gain, decreased workability, and increased water absorption (Patah et al., 2025). The full strength potential develops at later curing ages as pozzolanic reactions progress, and the slower initial strength development with 10% POA replacement is explained by its slower initial reactivity compared to regular Portland cement (Uddin et al., 2024).

High concentrations of unburned carbon or impurities in POA may cause durability issues by weakening the concrete's defences against chemical attacks. Because using too much POA can adversely affect workability, setting time, and strength, determining the ideal replacement dosage is also difficult. Furthermore, the broad use of POA in concrete is hampered by the absence of comprehensive long-term research and standardised guidelines. POAs' limited availability of POAs outside palm oil-producing regions and the requirement for grinding and sieving make their use more complicated and expensive.

Overall, the findings confirm that high POA replacement levels (>20%) can produce concrete with acceptable mechanical properties, provided sufficient curing time is allowed. Although workability decreases, later-age compressive strength and durability potential improve, supporting the concept of POA as a sustainable cement substitute in Pakistan's construction sector.

4. CONCLUSION

This study demonstrated that replacing 30% of cement with Palm Oil Ash in concrete results in: 1) Lower early-age compressive strength but significant later-age gains, surpassing the control mix at 28 days, 2) Reduced workability due to the higher water absorption of POA particles, 3) Gradual increase in water absorption during curing, consistent with the porous nature of POA.

The results indicate that POA can be a viable supplementary cementitious material for sustainable concrete production in Pakistan, provided that appropriate mix design adjustments and extended curing are applied. Given the availability of agricultural biomass waste, this approach could reduce cement consumption, lower CO_2 emissions, and add value to agro-industrial by-products.

5. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

There are a number of restrictions on the research on replacing cement with palm oil ash (POA). High concentrations of unburned carbon or other impurities in POA may shorten the concrete's lifespan by making it less resilient to chemical attacks. Because too much POA might affect the concrete's workability, setting time, and strength, it can be difficult to determine the ideal replacement level. Another obstacle to the widespread use of POA in concrete is the absence of comprehensive, long-term research and established standards for its application. Additionally, POA is scarce outside of areas that produce palm oil, and the required grinding and sifting procedures raise the complexity and expense of its use.

According to this research, future studies on using palm oil ash (POA) to recycle agricultural waste for green concrete should concentrate on resolving existing constraints. This involves looking into how impurities like unburned carbon in POA affect the resilience of concrete to chemical attacks and its longevity. Since excessive amounts can adversely affect workability, setting time, and strength, it is imperative to determine the ideal replacement level of cement with POA. To enable the widespread use of POA in concrete, it is also necessary to overcome the dearth of thorough long-term studies and defined criteria. Additionally, studies should look for ways to lessen the difficulty and expense of the required grinding and filtering processes, as well as the restricted availability of POA outside of palm oil-producing countries.

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