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Review Article

Influence of palm oil fuel ash as agricultural waste on the environment and strength of geopolymer concrete

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Abstract

The utilization of agricultural waste in concrete has gained important attention owing to its potential to improve sustainability and reduce environmental impact. Palm oil fuel ash (POFA), a by-product of the palm oil industry, is one of the agricultural waste materials that has shown promise as a supplementary cementitious material (SCM) in geopolymer concrete (GPC). This paper presents a comprehensive review of the influence of POFA on the environment and strength properties of GPC. The review highlights the chemical composition and physical properties of POFA, its environmental impact, and the challenges and potential strategies for its sustainable utilization. The main factors affecting the strength enhancement or reduction in GPC containing POFA are discussed, including the optimal replacement level and curing condition. The results reveal that the silica oxide in POFA ranges between 55.7% and 69.02%, depending on the POFA source and treatment conditions. The increase in POFA replacement from 0 to 20% led to an increase in the compressive strength of GPC from 28.1 to 30.1 MPa, while in another case the compressive strength decreased from 24 to 18.5 MPa for the same replacement level. There is no specific optimum replacement level. However, the low replacement levels between 0 and 20, are the best. The review also summarizes experimental studies evaluating the effect of POFA on GPC strength. In general, the review provides valuable insights into the use of POFA in GPC and suggests future research directions to enhance its utilization and sustainability in the construction industry.

1. Introduction

Geopolymer concrete (GPC) is a type of concrete that is produced by reacting aluminosilicate materials like slag and fly ash with alkaline activators, like sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) [1]. Unlike normal cement concrete, which relies on calcium silicate hydrates (CSH) for strength, GPC forms a three-dimensional aluminosilicate polymer network, as shown in Figure 1. This chemical reaction, known as geopolymerization, results in a binder that can provide comparable or even superior mechanical properties to Portland cement-based concrete [2]. Reducing carbon dioxide (CO_2) emissions compared to Portland cement concrete is one of the significant advantages achieved by GPC [3]. The production of Ordinary Portland cement (OPC) required in huge amounts to produce conventional cement concrete, constitutes a major source of CO_2 emissions due to the high-temperature calcination of limestone in kilns [4]. In contrast, GPC can be produced at much lower temperatures, leading to a significant reduction in CO_2

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emissions [5]. Mortar and concrete are used in construction and infrastructure projects, which consume huge amounts of materials and most of these materials are extracted as virgin materials and generate greenhouse gasses in the atmosphere. For instance, cement alone is responsible for the generation of more than 7% of the global CO_2 emissions that mainly contribute in climate change [6]. Additionally, GPC offers several other sustainability benefits. It can utilize industrial by-products and waste materials as precursors, reducing the consumption of natural resources and minimizing the accumulation of waste in open areas [8]. This is associated with the philosophies of the circular economy, where materials are reused or recycled to minimize environmental impact. GPC also exhibits excellent durability and resistance to harsh environments, leading to longer service life and reduced maintenance requirements compared to traditional concrete [9]. Overall, GPC represents a promising alternative to Portland cement concrete, offering improved sustainability, reduced environmental impact, and comparable or superior performance [10]. Incorporating agricultural waste materials, like palm oil fuel ash (POFA), into GPC further enhances its environmental identification by reducing waste generation and supporting the efficient use of resources [11].

The use of agricultural waste like POFA in GPC production is important due to its environmental and economic advantages. Agricultural activities produce large amounts of waste, presenting disposal challenges and environmental risks [12]. Incorporating these wastes into concrete can address these challenges and support sustainable development. Using agricultural waste in GPC production reduces waste disposal costs and turns waste into a valuable construction resource [13]. Moreover, POFA enhances GPC performance by containing pozzolanic materials that react with calcium hydroxide to form additional cementitious compounds [14]. This improves concrete strength, durability, and chemical resistance, while also reducing the risk of thermal cracking. Even though conducting numerous studies about the use of POFA in the GPC. For instance, Liu et al. [15] used POFA instead of fly ash in different replacement levels in the production of lightweight GPC. They used Oil palm shell (OPS) as one of the palm oil wastes as aggregate to obtain low lightweight GPC. They used POFA in 0, 10, 20, 40, and 100% as fly ash replacement with two alkaline solutions to binder ratios of 0.35 and 0.55. They found that the maximum compressive strength of GPC was 30 MPa achieved due to the use of 20% POFA as a fly ash replacement.

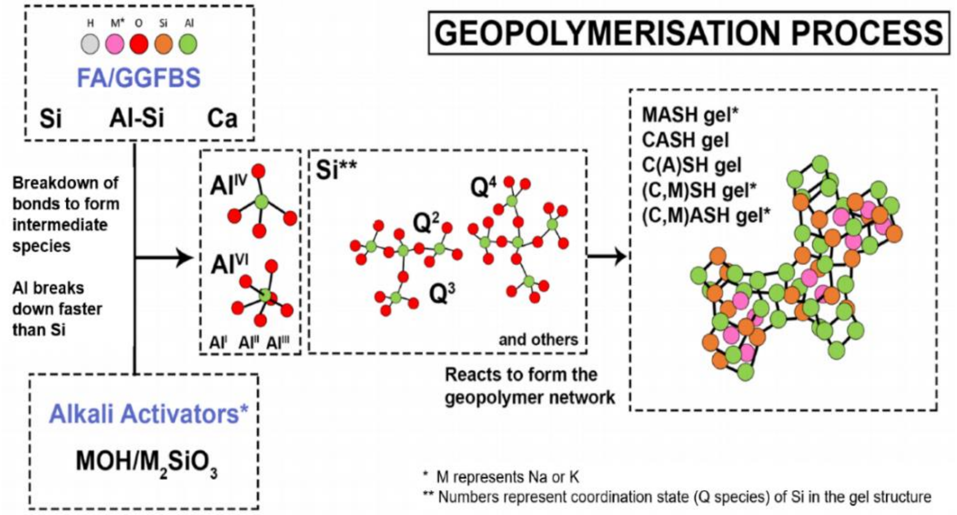

Fig. 1. Geopolymer model with different Si/Al molars [7]

Huseien et al. [16] investigated the effect of different calcium content and curing temperatures on the properties of geopolymer mortars (GPM) comprising agricultural and industrial wastes, such as POFA, GGBS, and fly ash. They detected that the GPM strengths and the reaction products depended significantly on the composition's nature, curing temperatures, and activators. However, there is no study conducted as a review paper discussed the effect of POFA on the environment and strength development. Therefore, this paper reviews the impact of POFA, as agricultural waste, on the strength of GPC and the environment. It highlights the environmental benefits of using agricultural waste in GPC production and emphasizes the significance of POFA in improving the strength of GPC and reducing waste disposal costs. The review aims to provide insights into the effects of POFA on GPC strength, offering valuable information for researchers and academics in sustainable construction.

2. Palm Oil Fuel Ash (POFA) as Agricultural Waste

2.1 Overview of Palm Oil Production and The Generation of POFA

Palm oil is one of the most widely produced and consumed vegetable oils globally, with its production primarily concentrated in tropical regions, particularly Malaysia, Indonesia, Thailand, and Nigeria [17]. As reported by Al-Sabaeei et al. [18], palm oil trees are one of the economic sources in terms of production of huge amounts of oil, palm oil includes crude and kernel oil palm producing 54% of total oil, as shown in Figure 2.

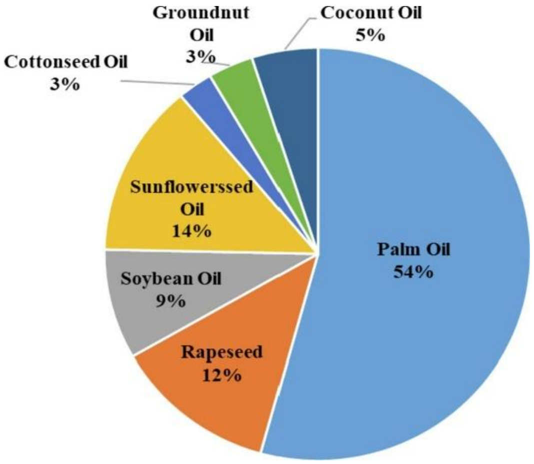

Fig. 2. Capacity per hectare proportion of main corps oil generated in 2018 [18]

The palm oil industry generates a substantial quantity of effluent waste and biomass residue; which can be considered a significant source of greenhouse gases. Therefore, numerous studies have been conducted to investigate the potential use of waste generated from the palm oil industry in different applications. Palm oil fuel ash (POFA) is one of the by-products generated during the production of palm oil. POFA is obtained from the combustion of palm oil biomass, including empty fruit bunches, palm kernel shells, and palm oil mill effluent, in boiler furnaces to generate electricity and steam for palm oil mills [19], as shown in Figure 3 [20]. POFA is a finely divided, pozzolanic material that contains high amounts of silica (SiO2) and alumina (Al2O3), along with other minor constituents [21]. Its chemical composition and pozzolanic properties make it suitable for use as a supplementary cementitious material (SCM) in concrete and GPC production.

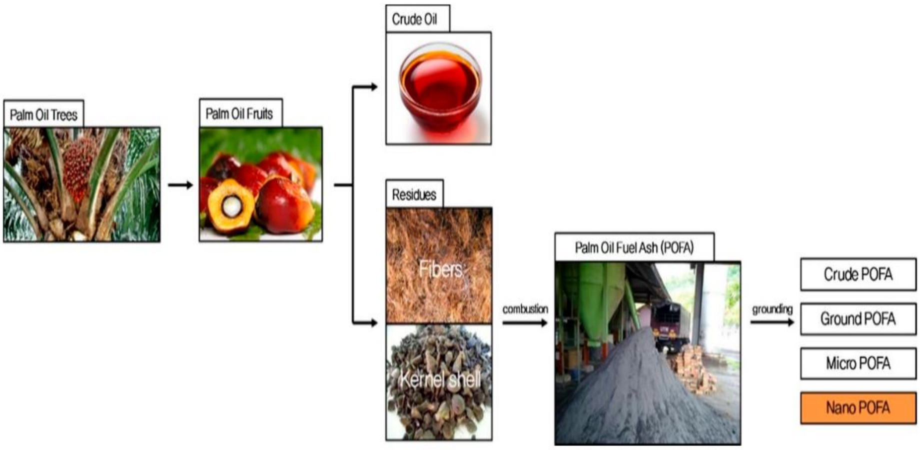

Fig. 3. Production of POFA [20]

2.2 Chemical Composition and Properties of POFA

POFA is a by-product of the combustion of palm oil biomass, mainly generated in palm oil mills. The chemical composition of POFA can vary depending on several factors, including the type of palm oil biomass burned, combustion conditions, post-combustion treatment, and others [22]. As reported by Demirboga and Farhan [23], the chemical composition of POFA has a significant impact on the strength and workability of concrete. The chemical composition of POFA is affected by the source of raw materials, heating temperature, particle fineness, and production process. These factors can affect directly or indirectly on the classification of pozzolanic of POFA, to produce either class C pozzolan [24] or Class F pozzolan [25]. Thanks to the reviewer for the insightful comment. Finer particles of POFA have a larger surface area, which can increase the pozzolanic activity. The chemical composition of POFA is usually classified as Class C Pozzolan due to containing higher amounts of calcium oxide (CaO), more than 10%, or Class F Pozzolan due to having lower calcium oxide content, less than 10%.

Table 1. Chemical composition of POFA

References	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
Salami et al. [29]	66.91	6.44	5.72	5.56	3.13	5.20	0.19	0.33	2.3
Hamada et al. [30]	67.5	4. 2	8.12	3.97	2.72	8.45	0.115	0.535	1.48
Tangchirapat et al. [31]	65.3	2.5	1.9	6.4	3.0	5.7	0.3	0.4	10.0
Kroehong et al. [32]	55.7	0.9	2.0	12.5	5.1	11.9	1.0	2.9	4.7
Bashar et al. [33]	67.72	3.71	4.71	5.57	4.04	7.67	0.16	1.07	6.2
Alsubari et al. [34]	69.02	3.9	4.33	5.01	5.18	6.9	0.18	0.41	1.8
Liu et al. [35]	63.4	5.5	4.2	4.3	3.7	6.3	---	0.9	6.0
Olivia et al. [36]	64.3	4.36	3.41	7.92	4.58	5.57	---	0.04	4.97
Mijarsh et al. [37]	61.33	7.018	5.11	8.20	4.69	6.50	0.123	0.27	2.53
Yusuf et al. [38]	60.42	4.26	3.34	11.0	5.31	5.03	0.18	0.45	2.55

Generally, POFA contains a significant amount of silica, typically ranging from 40% to 70%, and alumina content ranging from 20% to 30%. Other constituents found in POFA include iron oxide (Fe2O3), calcium oxide (CaO), magnesium oxide (MgO), potassium oxide (K2O), and sodium oxide (Na2O), among others. Table 1 shows the chemical composition of POFA.

The pozzolanic properties of POFA are attributed to its amorphous silica content, which reacts with calcium hydroxide (Ca(OH)2) in the existence of water to produce further calcium silicate hydrate (C-S-H) gel [26]. This reaction enhances the durability and strength of concrete by filling in voids and improving the overall microstructure [27]. In addition to its chemical composition, POFA also possesses certain physical properties that influence its suitability for use in concrete. POFA is typically a fine powder with a specific surface area ranging from 1230 m2/kg to 7670 m2/kg, making it highly reactive when mixed with alkaline activators in concrete [28]. Its particle size distribution, density, and color can also vary depending on the combustion process and post-combustion treatment.

As shown in Table 1, the silica oxide recorded the highest value among other POFA components, it was ranging between 55.7% and 69.02%. The study investigated different content of SiO2 of POFA on the strength of GPC. The chemical composition of POFA differs from one study to another, and this difference depends on the sources, treatment conditions, and other factors. The differences in the chemical composition of POFA mainly affect the strength of concrete and GPC [39]. For instance, Khankhaje et al. [40] reported that POFA is rich in SiO2 content with slight amounts of magnesium and calcium. Therefore, the existence of large amounts of silica content affects the pozzolanic activity essential to produce further calcium-silicate-hydrate (C–S–H) gels, thus increasing the GPC strength. Liu et al. [35] stated that the sum of silica, alumina, and Iron is 73.1%, which means that the POFA produced has a high pozzolanic activity and can be used to enhance the GPC strength. Overall, the chemical composition of POFA is various and depends on numerous factors. The use of POFA especially with high silica and alumina oxide can enhance concrete properties.

2.3 Physical Properties of POFA

The physical properties of POFA have mainly contributed to enhancing GPC properties. The fine particle size of POFA as micro and nanoparticles has affected the strength and durability of GPC. The physical properties of POFA are influenced by several factors such as the burning temperature and source of palm oil waste [28, 41], for instance, the color of POFA is converted from grey into darker, if it includes a high quantity of unburned carbon; and converted into grey after exposing to further burning [42]. For instance, Khalid et al. [43], reported that the POFA exposed to the milling process can produce further fineness of POFA. Awal and Shehu [44] detected that the specific surface area of treated POFA was 4930 cm^2/g and the amount of POFA retained on the 45 mm sieve was 10.5%. Table 2 shows the physical properties of POFA that have been examined by the previous studies.

Table 2. Physical properties of POFA

References	Specific gravity	Specific surface area m^2/g	Median particle size μm
Lim et al. [45]	2.56	7.205	1.10
Shehu and Awal [46]	2.42	---	2.89
Hossain et al. [47]	---	1.230	13.37
Kroehong et al. [48]	2.36	670	15.6
Zeyad et al. [49]	2.59	7.67	2.06
Sumesh et al. [50]	2.1	509	19.4
Hamada et al. [51]	2.52	1962	1.0
Yusuf et al. [52]	2.6	13.4	1.07

As shown in Table 2, the specific gravity of POFA ranges from 2.1 to 2.6 and the particle size of POFA ranges from 1.0 to 19.4 μm. These physical properties are affected by several factors as mentioned above. These properties also affect the properties of GPC, especially the fine particle size POFA has a higher influence than that of a larger one. For instance, Elbasir et al. [53] investigated the effect of different particle sizes of POFA on the strength of alkaline-activated mortars (AAM). They found that the high strength of AAM has been achieved due to the addition of POFA with greater fineness. This result can be attributed to the production of extra N–A–S–H and C–S–H in the AAM which used POFA with higher fineness.

2.4 Environmental Impact of POFA Disposal and the Need for Sustainable Utilization

The disposal of POFA into landfills and open areas leads to numerous environmental issues. Inappropriate disposal practices can lead to soil contamination, air pollution, and groundwater pollution [54]. POFA comprises trace elements and fine particles that can cause risks to environment issues and human health if not appropriately managed. Furthermore, the accumulation of POFA in landfills can contribute to the generation of leachate, a liquid that can contain harmful chemicals and pollutants [55]. Leachate has the potential to contaminate surface water and groundwater, posing risks to aquatic ecosystems and human populations. Given these environmental concerns, there is a growing need for sustainable utilization of POFA. By incorporating POFA into concrete production, it is possible to mitigate the environmental impact of its disposal while also providing a value-added application for the waste material. The green use of POFA in GPC production offers several environmental benefits. Firstly, it reduces the need for landfill space, helping to alleviate the pressure on waste disposal facilities. Secondly, it reduces the demand for natural resources, such as limestone and clay, which are used in the production of traditional cement. This contributes to the conservation of natural resources and helps to minimize the environmental impact of cement production [56]. Moreover, the use of POFA in concrete production can help reduce greenhouse gas emissions [42]. The production of Portland cement, the key component of conventional concrete, is a major source of CO_2 emissions [57]. By partially replacing cement with POFA, which requires lower energy inputs for production, the overall carbon footprint of the concrete is reduced.

3. Influence of POFA on the Strength of GPC

3.1 Experimental Studies Evaluating the Effect of POFA on GPC Strength

Numerous experimental studies have been conducted to investigate the influence of POFA on the strength properties of GPC [15, 58, 59]. These studies have demonstrated that the incorporation of POFA can lead to both enhancements and reductions in the strength of GPC, depending on various factors such as the replacement level of POFA, curing conditions, and activator composition. For instance, Isa et al. [60] conducted an experimental study on the influence of POFA and granulated blast furnace slag (GGBS) on the strength of GPC. They observed that the addition of GGBS and POFA in geopolymer mortar (GPM) enhances and increases the 28 days-compressive and flexural strengths up to 28.17 and 4.48 MPa, respectively. The compressive strength increased by 73.3% due to the addition of 40% GGBS as a POFA replacement. Huseien et al. [61] assessed the influence of POFA with fly ash and GGBS on the strength of GPM. They used POFA in different replacement levels to replace fly ash and slag. The bond strength performance of the mortars was assessed in terms of slant shear, flexural, and splitting tensile strengths. They observed that the addition of POFA and fly ash in the GPM led to a significant reduction in the CaO: Al_2O_3 and CaO: SiO_2 ratios, consequently reducing the strength performance and geopolymerization process. The compressive strength of GPC increased by 17% due to the addition of 10% POFA and 20% fly ash with 70% GGBS.

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Table 3. Influence of POFA on the compressive, flexural, and splitting tensile strengths of GPC.

References	Aluminosilicate used	POFA % by weight	Compressive strength MPa	Flexural strength MPa	Splitting tensile strength MPa
Liu et al. [15]	Fly ash	0	28.1	3.55	2.12
		10	28.4	3.70	2.13
		20	30.1	3.74	2.41
		40	16.4	3.11	1.62
		100	10.0	1.95	1.27
Huseien et al. [63]	Slag	30	70	10.2	5.5
		40	70	9.0	4.7
		50	55	7.5	4.7
		60	45	5.5	3.1
		70	31	3.5	2.5
Alnahhal et al. [64]	Fly ash	0	3.8		
		10	5.5		
		20	6.1		
		30	5.9		
Fauzi [65]	Fly ash	0	24		
		5	23		
		10	23		
		15	21.5		
		20	18.5		
Hawa et al. [66]	Metakaolin	0	75		
		5	70		
		10	68		
		15	54		
Chub-Uppakarn et al. [59]	Metakaolin	0	47		
		10	18		
		20	37		
		40	18		
Karim et al. [67]	fly ash and rice husk ash	0	23.1		
		20	12.9		
		30	20.5		
		35	14.9		
		40	5.9		
Liu et al. [68]	Fly ash	0	28.1	3.55	2.12
		10	28.4	3.70	2.13
		20	30.1	3.74	2.41
		40	16.4	3.11	1.62
		100	10	1.95	1.27

The variability in the effects of POFA on GPC strength can be attributed to several factors. The pozzolanic reactivity of POFA, which depends on its chemical composition and fineness, plays a crucial role in determining its impact on concrete strength [62]. Additionally, the curing conditions, activator type, and mix proportion can also influence the strength development of GPC containing POFA [14, 60]. For instance, Chub-uppakarn et al. [59] examined the influence of metakaolin (MK) and POFA on the GPM. They partially replace MK with POFA to show the effect of POFA on the strength of GPM. They found that the replace 10% MK by POFA led to an increase in the 28 days-compressive strength by 22.08 %. This increase in strength was attributed to the improvement in the geopolymerization process, thus increasing the compressive strength. Table 3 shows the influence of POFA on the compressive, flexural, and splitting tensile strength of GPCAs shown in Table 3, the use of POFA as a binder material in the production of GPC mostly decreases the strength of GPC. At the same time, some studies proved that the use of POFA as a binder material enhances the strength of GPC, and this enhancement depends on numerous factors like fineness, particle size, materials sources, and chemical composition. Numerous researchers used treated POFA to get better performance when used in the production of GPC. For instance, Mijarsh et al. [37] reported that the use of treated POFA in the GPC mix can increase the compressive strength of GPC at 1, 2, and 7 days up to 42.64, 45.55, and 47.27 MPa. This increase is significantly affected by the treatment methods of POFA. Therefore, the treatment of POFA before incorporation into the GPC mixture is a significant issue to consider. Alnahhal et al. [64] reported that the addition of POFA into fly ash-based geopolymer foamed concrete (GPFC) can increase the compressive strength, as shown in Figure 4.

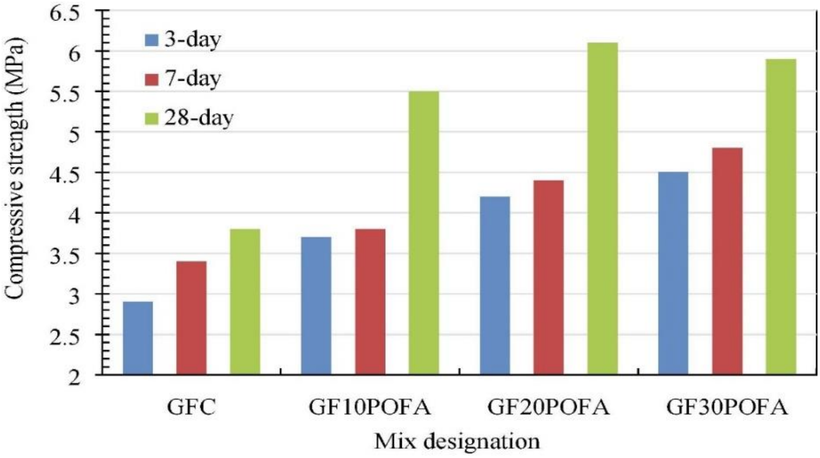

Fig. 4. Improvement of compressive strength for GPFC due to the addition of POFA [64]

3.2 Factors affecting the strength enhancement or reduction.

As mentioned before, the strength of GPC containing POFA can be influenced by various factors, including the chemical composition of POFA, its fineness, the replacement level of cement with POFA, curing conditions, and activator composition. Determining these factors is essential for optimizing the mix design and achieving the desired strength properties. Table 4 shows the important factors effecting the strength enhancement or reduction.

In general, the factors abovementioned in Table 4 interact in complex ways to influence the strength properties of GPC containing POFA. Optimizing these factors through careful mix design and curing practices is essential for maximizing the strength enhancement potential of POFA in GPC. As reported by Elbasir et al. [53], the physical properties of POFA like fineness and particle size also have a significant effect on the strength of GPC.

Table 4. Factors effecting the strength of GPC.

No.	Factors	Effect on strength
1	Chemical Composition of POFA	The chemical composition of POFA, particularly its silica oxide (SiO_2) and alumina oxide (Al_2O_3) content, plays a crucial role in determining its pozzolanic reactivity. POFA with higher silica and alumina content is generally more reactive and can contribute to greater strength enhancement in GPC and GPM [14, 61].
2	Fineness of POFA	The fineness of POFA affects its reactivity and its ability to react with the activator solution. Finer particles have a larger surface area, allowing for more effective pozzolanic reactions and potentially leading to higher strength development in GPC [20, 67].
3	Replacement Level of POFA	The compressive strength of GPC significantly affected by the replacement levels of POFA. Further POFA percentage might leads to reduce the compressive strength up to the lowest value, and this reduction is might be due to incomplete pozzolanic reactions [59].
4	Curing Conditions	The curing conditions, including temperature, humidity, and duration, can influence the rate and extent of pozzolanic reactions between POFA and the activator solution. Optimum curing conditions are essential for achieving the desired strength properties in GPC [67, 69].
5	Activator Composition	The composition of the activator solution, including the type and concentration of alkali activators, can affect the pozzolanic reactivity of POFA. Different activator compositions may lead to varying degrees of strength enhancement or reduction in GPC [14, 69].
	Mix Design	The overall mix design, including the proportions of POFA, aggregate, and other ingredients, can impact the strength properties of GPC. A well-balanced mix design is essential for achieving the desired strength and durability [59].

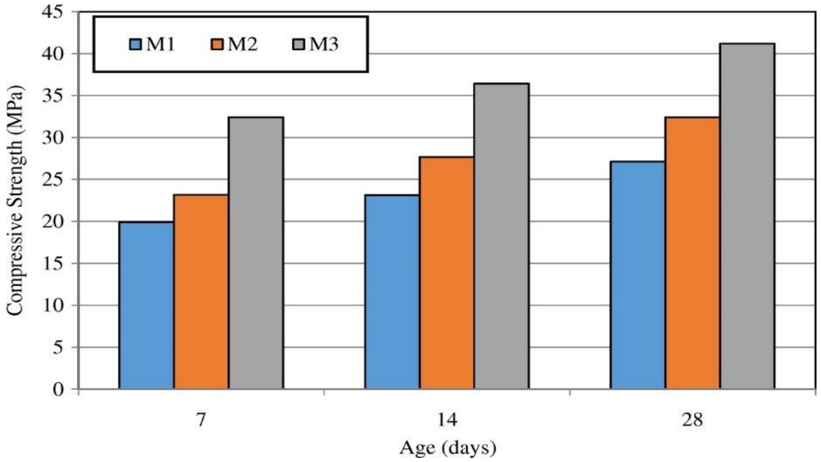

Fig. 5. Compressive strength of POFA based-GPC [53]

For example, the utilization of three distinct particle fineness levels results in varying compressive strengths, as depicted in Figure 5. M1, M2, and M3 represent the specifically treated POFA (t-POFA), fine POFA (f-POFA), and ultrafine POFA (u-POFA), respectively. These three types of POFA have particle sizes of 2.79 µm, 2.04 µm, and 1.1 µm, respectively.

4. Challenges in Addition POFA in GPC

Despite its potential benefits, the addition of POFA in GPC poses several challenges that need to be addressed for successful implementation. These challenges can be summarized in Table 5.

Table 5. Challenges in the use of POFA as a source material in the production of GPC.

No.	Challenges	Results
1	Variability in POFA properties	POFA properties, such as chemical composition and physical properties including, silica oxide content, particle size, fineness, and pozzolanic reactivity, can vary depending on factors such as source, combustion process, and post-treatment [70]. This flexibility can affect the consistency and performance of GPC, thus involving careful characterization and selection of POFA in the production of GPC.
2	Optimum replacement level	Identify the optimum replacement level of POFA in the concrete mix is one of the challenges which effect the performance of GPC. However, the use of high replacement levels of POFA can reduce the environmental issues but reducing strength of GPC. Therefore, finding the best balance of POFA content and strength required is critical.
3	Compatibility with Activators	POFA may show various reactivity with alkali activators compared to other SCMs normally used in GPC, like slag or fly ash. Confirming compatibility between activators and POFA is crucial for getting the desired strength and durability properties.
4	Curing requirements	GPC containing POFA may have specific curing requirements, such as continued curing durations or elevated temperatures, to enhance optimum strength. Meeting these curing requirements can be challenging in practical construction applications and may require special curing facilities.
5	Long-term performance	The long-term performance of GPC containing POFA, including durability and resistance to environmental factors is affected by numerous factors. Confirming the long-term durability of concrete structures incorporating POFA requires careful consideration of factors like maintenance requirements, exposure conditions, and material aging.

Addressing these challenges requires collaboration between industry stakeholders, researchers, and regulatory bodies to determine guidelines, standards, and best practices for the sustainable applications of POFA in GPC. Generally, the use of POFA in the production of GPC in vast quantities depends on finding suitable solutions for the challenges above-mentioned.

5. Future Directions to Use POFA in GPC

There are some potential strategies that should be applied to maximize use of POFA in GPC mixtures, which can be summarized in Table 6.

Table 6. Potential strategies to enhance the use of POFA in GPC.

No.	Strategies	Strategies that should be conduct
1	Optimization of POFA properties	Implement further studies to optimize the properties of POFA, such as its fineness, chemical composition, and pozzolanic reactivity, can enhance its suitability for use in GPC.
2	Blending with other SCMs	Blending POFA with other SCMs, such as fly ash or slag, can enhance the performance of GPC.
3	Use of chemical additives	Incorporating chemical additives, such as silica fume or metakaolin, can enhance the reactivity of POFA and improve its performance in GPC.
4	Optimization of mix design	Conducting detailed mix design studies to optimize the proportions of POFA, activators, and other ingredients in GPC can improve its performance.
5	Development of standardized guidelines	Developing standardized guidelines and best practices for the use of POFA in GPC can facilitate its widespread adoption.
6	Innovative applications	Discovering advanced techniques and applications for additional POFA in GPC, such as high-performance concrete, precast elements, or 3D printing, can expand its potential use and value.
7	Collaboration and knowledge sharing	Encouraging collaboration between researchers, industry stakeholders, and government agencies can promote knowledge sharing and technology transfer related to the use of POFA in GPC.

Adoption of the strategies abovementioned in Table 6, can maximize the use of POFA in GPC, thus enhancing sustainability, reducing environmental impact, and increasing economic value in GPC. Also, the compressive, flexural, and splitting tensile strengths of GPC containing POFA can be improved when obtaining the optimal mix design with suitable additives and curing conditions.

5. Conclusions and Recommendations

This study shows the effect of POFA as agriculture waste and high silica content on the environment and the strength of GPC. The main results can be summarized in the following points:

- The addition of an appropriate replacement level of POFA in GPC can increase compressive, flexural, and splitting tensile strengths. However, this increase is associated with the pozzolanic reactivity of POFA. While the addition of a high volume of POFA decreases the strength of GPC.
- The optimum content and proportion of POFA varies depending on factors like POFA properties, curing conditions, and mix design. While low replacement levels 10% to 20%, have been found to increase strength. The increase in POFA replacement from 0 to 20% led to an increase in the compressive strength of GPC from 28.1 to 30.1 MPa, while in another case the compressive strength decreased from 24 to 18.5 MPa for the same replacement level.
- The properties of POFA, such as its chemical composition, fineness, and pozzolanic reactivity, significantly influence its impact on concrete strength. POFA with higher silica and alumina content and finer particle size tends to exhibit greater strength enhancement in GPC.

- Optimum curing conditions, including temperature, humidity, and duration, are crucial for achieving the desired strength properties in GPC containing POFA. Proper curing can promote the complete hydration of cementitious compounds and enhance the strength development of the concrete.
- Despite the potential benefits of using POFA in GPC, various challenges need to be addressed, such as variability in POFA properties, compatibility with activators, and long-term performance.

In conclusion, the utilization of POFA as agricultural waste in GPC offers a sustainable solution to waste management and contributes to the reduction of environmental impact in the construction industry. By optimizing mix design, addressing challenges, and promoting knowledge sharing, POFA can be effectively utilized to enhance the strength and sustainability of GPC.

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