Energy Science & Engineering

SCI where science meets business

REVIEW OPEN ACCESS

A Comprehensive Review of Sustainable Geopolymer Concrete Using Palm Oil Clinker: Environmental and Engineering Aspects

Khamees N. Abdulhaleem[1] | Hussein M. Hamada[2] | Ahmed I. Osman[3,4] | Salim T. Yousif[5] | Ali M. Humada[6] | Ali Majdi[7]

[1]Civil Engineering Department, University of Kirkuk, Kirkuk, Iraq | [2]Department of Architecture, Al-Qalam University College, Kirkuk, Iraq | [3]School of Chemistry and Chemical Engineering, Queen's University Belfast, Belfast, Northern Ireland, UK | [4]School of Engineering, Technology, and Design, Canterbury Christ Church University, Canterbury, UK | [5]Civil Engineering Department, College of Engineering, Nawroz University, Kurdistan, Iraq | [6]College of Information Technology, Imam Ja'afar Al-Sadiq University, Baghdad, Iraq | [7]Department of Building and Construction Techniques, Al Mustaqbal University College, Hilla, Babylon, Iraq

Correspondence: Hussein M. Hamada (enghu76@gmail.com) | Ahmed I. Osman (aosmanahmed01@qub.ac.uk; ahmed.osman@canterbury.ac.uk)

Received: 24 March 2024 | **Revised:** 10 June 2024 | **Accepted:** 3 September 2024

Funding: This study was supported by Queen's University Belfast.

Keywords: aggregate innovation | CO_2 reduction | environmental | geopolymer concrete | palm oil clinker | sustainable construction

ABSTRACT

Amidst the dual challenges of aggregate scarcity and the environmental impact of carbon dioxide (CO_2) emissions from cement production, this study investigates the viability of palm oil clinker (POC) as a sustainable aggregate in geopolymer concrete (GPC). The lack of appropriate alternative coarse and fine aggregates essential in concrete production is one of the critical issues faced by the construction industry. This review evaluates its environmental benefits, chemical and physical attributes, and influence on GPC's microstructure. Previous studies have shown that incorporating POC in GPC significantly reduces density from 2345 to 1821 kg/m^3 while maintaining competitive compressive strength, thus proving its applicability in various structural and nonstructural contexts. Moreover, GPC with POC demonstrates enhanced resistance to aggressive environmental conditions such as water absorption and resistance against acid and sulfate environments. Geopolymer mortar (GPM) exposed to sulfate attack recorded the lowest decrease in strength than GPM containing POC fine aggregates by about 20%. The use of 100% POC aggregates in GPC mix has a 3.2% water absorption, which is lower than the limit for high-performance concrete. The results advocate for the development of POC-aggregate GPC as an environmentally friendly construction material, contributing to the sustainable advancement of the building industry.

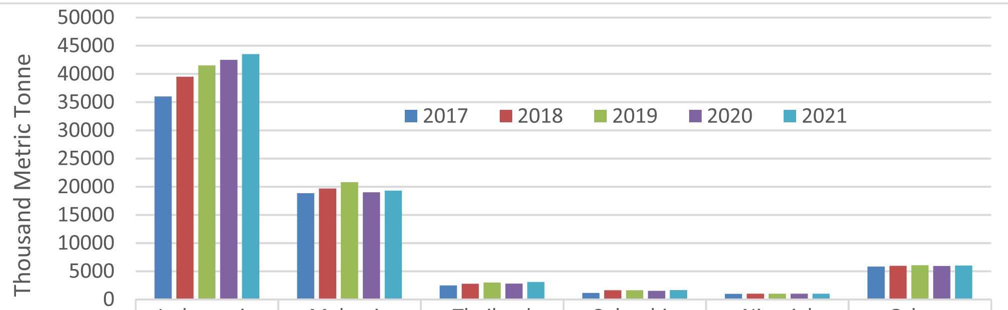
1 | Introduction

The demand for palm oil has surged to satisfy global markets, leading to its widespread cultivation in Southeast Asia's warm, tropical regions, including Malaysia, Indonesia, and Thailand [1, 2]. Malaysia produces 24% of the total global crude palm oil and currently occupies second place in the world in exporting crude palm oil after Indonesia. The revenue of crude palm oil increased by 40% in 2021 compared to 2020, with an average of RM102 billion in revenue; therefore, the palm oil industry can be considered as a backbone economic for Malaysia. This boom has inadvertently produced a substantial amount of biomass by-products, among which palm oil clinker (POC) is notable [3]. POC emerges from the incineration of palm oil waste, such as kernel shells and fruit fibers, during the energy production process in palm oil mills [4]. Without proper management, these by-products can lead to significant environmental and health hazards due to their accumulation [5]. With the expansion of palm oil exports from countries like Indonesia and Malaysia, there is an increasing impetus to utilize these abundant by-products sustainably [6]. Concrete is integral to modern construction, consuming vast quantities of aggregates exceeding 10 billion tons annually [7, 8]. This immense demand, alongside the environmental toll of extracting natural resources, has propelled a search for alternative, eco-friendly aggregates [9, 10]. Utilizing industrial by-products not only conserves natural aggregates for future use but also curtails the environmental degradation associated with traditional extraction methods [11, 12]. Additional benefits of adopting renewable aggregates are saving the virgin raw materials for the next generations and reducing the environmental pollution resulting from the extraction of huge amounts of rocks and sand that require consuming high energy [13].

As the construction sector expands, the need for concrete—and, by extension, cement—escalates. However, cement production is environmentally taxing, contributing to 5%–7% of global CO_2 emissions with an annual production of roughly 2.8 billion tons [14, 15]. This has led to the exploration of geopolymer concrete (GPC), a greener substitute developed in the 1990s using aluminosilicate materials such as fly ash and slag in lieu of cement [16, 17]. Recent research has pivoted toward POC as a viable aggregate for various concrete forms, including lightweight [18–20], semi-lightweight concrete [21], and self-compacting concrete (SCC) [22]. Despite this, its integration into GPC remains relatively unexploited. Recently, Bashar et al. [23] noted a lower elastic modulus in POC-infused GPC compared to standard concrete, attributing this to POC's unique morphology, which enhances binder-aggregate bonds [24].

Similarly, other studies have leveraged POC to curtail greenhouse gas emissions (GHGs), conserve resources, and improve cost-efficiency in construction materials. Ranjetha et al. [25], in an attempt to reduce GHGs and find urgent solutions for the lack of natural resources needed in the production of construction materials and to save cost, energy, and time, used industrial by-products as construction material. They used POC as aggregate and palm oil fuel ash (POFA) as a binder in the production of GPC. Nazari et al. [26] investigated the effect of POC as aggregate alongside rice husk ash and fly ash on the compressive strength of lightweight geopolymers based on artificial neural networks. They examined 144 samples and found that the 28-day compressive strength-to-weight ratio for the samples with a high amount of POC fine aggregate was more than that of GPC samples without POC. Generally, palm oil products can be used in different aspects such as construction materials, water treatment plants, biotechnological and chemical processes, human and animal food industries, fertilizer, cosmetics, and pharmaceuticals. Consequently, it can be decided that the plantation of palm oil enlarged with time to meet the market requirements, especially in tropical countries such as Indonesia, Malaysia, Nigeria, and Thailand, as shown in Figure 1.

Figure 1 shows that the production rate of palm oil in Indonesia recorded the highest rate among other countries, and the production rate increased gradually with time, followed by Malaysia, which occupied the second position after Indonesia. Malaysia somewhat produces about half the amounts of palm oil products that are produced in Indonesia. It is expected that this industry will grow with time in all these countries, and it is necessary to manage the waste produced by palm oil mills. In addition to that, the use of waste materials generated from industrial and agricultural products is growing quickly because they are suitable materials to be used as raw materials in different construction applications. Numerous waste materials with high aluminosilicate have been used as pozzolanic materials, such as fly ash, silica fume, rice husk ash, and ground granulated furnace slag (GGBFS). The use of GPC instead of cement achieved numerous benefits, such as minimizing the negative effect of cement on the environment. CO_2 emissions to the atmosphere were reduced by 44%–64% compared to cement production [27], reducing the high energy required for cement production by up to 15% [28] and reducing the accumulation of waste in landfills and open areas. In addition to that, GPC has higher compressive strength, lower shrinkage, and better resistance against acid attack than cement concretes [29–31]. Nazari et al. [32] studied the pore structure



	Indonesia	Malaysia	Thailand	Colombia	Nigerial	Others
2017	36000	18858	2500	1146	990	5845
2018	39500	19683	2780	1627	1025	5960
2019	41500	20800	3000	1632	1015	6077
2020	42500	19000	2800	1529	1015	5927
2021	43500	19300	3100	1670	1015	6013

Palm oil production globally

FIGURE 1 | Product of palm oil globally per thousand metric Adapted from [4, 33].

and water absorption of lightweight geopolymer concrete (LWGPC) made of POC as aggregate and rice husk ash (RHA) as an aluminosilicate source. They detected that the water absorption of GPC improved significantly due to adding further content of POC aggregates. Darvish et al. [34] studied the performance of POC as a fine aggregate in 100% in the production of geopolymer mortar (GPM); they prepared 16 mixes with different binders and molarity of NaOH. They obtained high compressive strength up to 53 MPa at 28 days due to the use of 50:50 of FA-ground granulated blast furnace slag (GGBS) as binder materials. Also, they have found GPM with higher resistance against magnesium sulfate ($MgSO_4$) and hydrochloric acid (HCl) compared to cement mortar. Kabir et al. [35] used POC and oil palm shell (OPS) as coarse aggregates along with metakaolin (MK), GGBS, and POFA as binder materials in producing GPC. They concluded that the POC aggregate increased the 28-day compressive strength of GPC to 41.5 MPa. The replacement of natural aggregates by POC in GPC can decrease the consumption of energy and environmental pollution instead of dumping these materials into landfills that might cause pollution in soil, air, and water.

While the application of POC as an aggregate has been explored to some extent in traditional concrete forms [18, 21, 22, 36], a synthesis of existing research on its efficacy and impact remains absent. This gap signifies a considerable opportunity for advancing the use of sustainable materials in construction. To date, there is an absence of a synthesized body of work that aggregates knowledge of the utilization of POC in GPC, particularly regarding its implications on the material properties of the concrete. Recognizing the critical need for renewable and sustainable materials to supplant natural aggregates, this study is poised to fill this literature gap. Based on the results obtained from the previous studies, it can be concluded that the inclusion of POC as an aggregate in GPC significantly enhances its environmental sustainability while maintaining adequate mechanical properties. Also, the effect of POC on the mechanical, durability, and microstructure properties of GPC has not been investigated widely, and a lack of a comprehensive to cover the impact of POC on the properties of GPC. Therefore, this gap was addressed in this review paper to be a good base information for the researchers and academics interested in sustainable construction materials, especially sustainable POC as renewable aggregate in the production of sustainable GPC. The current investigation provides a novel, thorough analysis of existing literature concerning the deployment of POC as a complete or partial replacement for aggregates in GPC. The aim is to outline the influence of POC on the overall performance of GPC. This encompasses a rigorous examination of POC's characteristics, its impact on the mechanical, durability, and microstructural properties of GPC, and a review of its applications within the framework of a life cycle assessment. By consolidating and evaluating previous studies, this research contributes to the broader understanding and practical application of POC in GPC to foster sustainable innovation in construction materials.

2 | The Concept of Sustainability in GPC

Currently, the sustainability concept in construction materials is an important and developed by academics and researchers, especially in topics related to the use of industrial and agricultural waste in the construction industry. The adoption of sustainable and renewable new materials comes with saving the natural and virgin raw materials for the next generations, thus creating a clean and green environment for the present and future generations [37]. The use of waste materials that have similar characteristics to natural materials and do not influence the engineering properties of final products is one of the main factors in the use of these materials. Sustainable materials are obtainable and cheaper than natural materials as well as reduce the environmental pollution of eco-friendly materials [38]. The palm oil industry produces huge amounts of waste annually, which is possibly harmful to the environment and causes pollution if left without treatment [39]. Decreasing CO_2 emissions is one of the main aims of the sustainable GPC (SGPC), in addition to reducing the cost, increasing the service life of SGPC, increasing the concrete thermal conductivity, reducing the energy consumption, and increasing the efficiency of waste materials [4, 40]. Figure 2 depicts the process of SGPC made of POC aggregates and their effect on the environment.

From Figure 2, the use of bio-aggregates such as POC in the production of GPC can save virgin materials for future generations and reduce the accumulation of palm oil waste in landfills and open areas that might cause health problems and environmental pollution; in addition, the use of GPC can reduce the CO_2 emissions through using aluminosilicate as binder materials instead of cement in the production of GPC. Recently, Sinoh et al. [41] conducted a study to find out the effect of POC on the environment and the issues related to shifting toward sustainable applications, particularly the application of the circular economy (CE) idea. They evaluated the use of POC as aggregates on the environmental impacts in city zones. They used POC as aggregate along with recycled aggregate and natural aggregates in three different groups to find out the life cycle assessment (LCA) and compare them. They found that the capital of Malaysia, Kuala Lumpur, was the highest potential city for using sustainable aggregates because it had the shortest distances for all materials.

The use of POC as aggregates in the production of GPC has numerous benefits for the environment, especially in reducing CO_2 emissions [25]. For instance, the use of POC aggregate reduces the need for cement, thereby lowering the overall CO_2 emissions associated with concrete production. GPC normally requires lower curing temperatures compared to traditional concrete, which often needs high-temperature curing for cement hydration [42]. This reduction in energy consumption during the curing process further contributes to the reduction of CO_2 emissions associated with concrete production.

Sustainability aims to meet people's requirements because of the many conditions' variations. The use of natural resources from waste by-product materials to prepare construction materials and save virgin raw materials for the next generations can be considered the main goal in achieving sustainability in the construction industry [43]. The use of cleaner and sustainable concrete has numerous advantages, such as reducing the energy and cost required, reducing environmental pollution, and improving the performance of concrete [22, 44]. The transformation and shift of wastes from certain sectors to others could be useful products in different applications. This concept,

FIGURE 2 | Effect of sustainable palm oil clinker (POC) aggregates on the environment.

known as "reusing-recycling-recovering," was applied to the treatment of environmental issues while providing economic and social benefits [45]. In Indonesia, Malaysia, and Thailand, numerous materials display high potential to drive the practice of sustainability in construction materials. The replacement of natural aggregates with palm oil wastes in concrete is one of the sustainability goals [46]. One of the main goals of this study is to assess the influences of alternative sustainable aggregate as POC on the properties of GPC.

In general, the use of POC in the construction industry, particularly in GPC, contributes to sustainability in several ways, focusing on waste reduction and resource conservation. Utilizing POC in GPC transforms this waste material into a valuable construction resource, reducing the volume of waste that needs to be managed or disposed of in landfills. By diverting POC from landfills, the construction industry helps reduce the environmental impact associated with waste disposal, such as soil contamination, methane emissions, and land use, to support the principles of a circular economy. Using POC as an aggregate in GPC reduces the demand for natural aggregates such as sand and gravel [47].

3 | Palm Oil Clinker in GPC

Recently, Bashar et al. [23] used a POC with granite as a coarse aggregate and mining sand as a fine aggregate in the production of GPC. The fly ash was used as the main precursor and activated by 14 M sodium hydroxide (NaOH) and liquid sodium silicate (Na_2SiO_3). The weight proportion of liquid Na_2SiO_3 and 14 M NaOH solution was 1:2.5. The type and concentration of alkaline activators used in GPC significantly impact the performance of POC as an aggregate. These activators influence the overall properties of the geopolymer matrix, which in turn affects how well POC integrates and contributes to the mechanical and durability characteristics of the concrete [48]. The most commonly used alkaline activators in geopolymerization are sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), though other combinations like potassium hydroxide (KOH) and potassium silicate (K_2SiO_3) are also used [49]. The combination of NaOH and sodium silicate typically results in higher early and long-term strength in GPC. A stronger matrix enhances the mechanical interlocking and bonding with POC, contributing to higher overall concrete strength. Higher concentrations of alkaline activators improve the durability of the geopolymer matrix by making it more resistant to chemical attacks (e.g., sulfate, acid), thus improving the durability of GPC.

POC is one of the by-products generated from the palm oil industry during the extraction of palm oil products [50]. It has various properties depending on its source, type, conditions of products, quantity, and others. Huge amounts of POC are disposed of in open areas and landfills without suitable treatment, causing environmental issues [51]. POC is produced from oil palm shells during the burning process of mesocarp fiber. Researchers examined the potential use of POC as aggregate in normal concrete, SCC, pervious concrete, and GPC. The use of POC as aggregate reduces the density of concrete and GPC to about 20%, as reported by Darvish et al. [52]. Also, the use of POC aggregates saves the natural aggregates from depletion. Hamada et al. [19, 36] used POC as aggregate to produce sustainable lightweight concrete (LWC). They investigated the mechanical properties of LWC containing POFA. Palm oil waste is burned at palm oil mills to generate the electric power required to extract palm oil, and the POC is one of its by-products. POC was used as coarse and/or fine aggregate according to the particle size to produce sustainable LWC [18]. Sharmin et al. [53] investigated the effect of POC and oil palm shells as aggregates on the engineering properties of LWGPC. They observed that the POC has an acceptable effect on the engineering properties of LWGPC.

Darvish et al. [34] used the POC to replace the fine aggregate 100% in the production of GPM. The specific gravity of POC and natural sand was determined to find out the volume of the natural sand and POC aggregate. They prepared 16 mixtures with different proportions of GGBS-FA with different mass ratios of alkali-activated solution (AAS) to binder and sodium silicate (Na_2SO_3) to sodium hydroxide (NaOH) of 0.5 and 1.5, respectively. They adopted two different curing types, namely ambient curing and oven curing (under a certain temperature); extra water was added to get the flow recommended by the ASTM C109/C109M-16a, which was 110 ± 5 mm [54]. In the following subsections, the chemical composition, physical properties, and microstructure characterization for the POC used in the GPC are addressed in detail. The composition of binder materials in GPC significantly influences the interaction between POC aggregates and the geopolymer matrix. Optimal proportions of aluminosilicate sources and alkaline activators lead to strong, durable, and environmentally friendly concrete [55]. The dissolution of aluminosilicate sources in the presence of alkaline activators leads to the formation of a geopolymer gel [56]. This gel acts as the binder that encapsulates the POC aggregates, contributing to the overall strength and durability of the GPC.

3.1 | Chemical Constitution of POC

The chemical composition of POC aggregates is an important test to determine the components of materials and is suitable for use in different applications. Overall, palm oil products such as POC and POFA have a high silica content, making them good pozzolans. Jagaba et al. [5] proved that the POC powder has a pozzolanic activity and can be used as aggregates in the production of GPC. Table 1 shows the chemical composition of POC resulting from the previous studies.

As shown in Table 1, silica oxide (SiO_2) constitutes the highest percentage among other components, ranging between 59.63 and 62.78 [61]. The high proportion of silica assists in enhancing the pozzolanic reaction of the POC when added to the GPC mixtures. Thus, it was considered one of the important factors that positively affect the improvement strength of GPC. At the same time, potassium oxide (K_2O) represents the second-highest percentage in the POC aggregates, ranging between 7.24% and 15.10%. The chemical composition of POC differs from one factory to another, and this variety depends on many factors, such as the source variety, treatment type, materials used in palm oil mills, and temperature applied in palm oil mills. In general, the chemical composition of POC mainly affects the physical, mechanical, strength, and durability of POC aggregates, thus affecting the GPC containing POC. The specific chemical properties of POC that make it suitable as aggregates in GPC include its chemical composition. For instance, the high silica (SiO_2) and alumina (Al_2O_3) content in POC aggregates is essential in the production of geopolymers [34]. These compounds serve as the primary precursors for the geopolymerization reaction, where alkaline activators such as potassium hydroxide (KOH) or sodium hydroxide (NaOH) activate the silica and alumina to form a three-dimensional polymeric network [63]. The presence of silica and alumina in POC ensures adequate reactivity during the geopolymerization process, leading to the development of strong bonds within the concrete matrix [4].

3.2 | Physical Properties of POC

The physical properties of POC aggregates are various and affected by numerous factors. Moisture, air content, water absorption, color, shape, specific gravity, thickness, surface texture, shape, and thickness are some of the physical properties of POC [64]. The physical properties of POC significantly influence the strength and density of GPC. The particle size of POC also has an important role in improving the strength, density, and workability of GPCs. POC aggregates with particle sizes of 4.75–20 mm were used as coarse aggregate, while the particle sizes with lower 4.75 mm were used as fine aggregate in the production of GPC. Kabir et al. [35] used POC as coarse aggregates with two particle sizes of 9–14 and 5–9 mm to establish its influence on the properties of GPC. They concluded that the use of 100% POC with a particle size of 9–14 mm increased the 28-day compressive strength up to 42 MPa. Darvish et al. [34] crushed the large chunks of POC 50–200 mm into small size and sieved by sieve no. 4.75 mm; the passing amount was used as a fine aggregate in the production of GPC.

POC has an irregular shape, making it more suitable to increase the bonding with GPM. The particle shape and irregular texture minimize the shear stress in the GPC mixture. The shape of POC is flaky to irregular and has rough and spiky broken edges [35]. The color of POC varies and ranges between whitish gray

TABLE 1 | Chemical composition of palm oil clinker (POC).

References	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	SO_3	P_2O_5	MgO	LOI
Jumaat et al. [57]	59.63	3.7	4.62	8.16	0.32	11.66	0.73	5.37	5.01	
Kanadasan et al. [58]	59.90	3.89	6.93	6.37		15.10	0.39	3.47	3.30	1.89
Karim et al. [59]	60.29	5.83	4.71	3.27	—	7.79	0.11	3.10	3.76	—
Kanadasan and Abdul Razak [60]	59.90	5.37	6.93	6.37	0.24				3.13	
Karim et al. [61]	62.78	3.41	6.49	6.89	0.39	10.54	0.08	—	3.52	3.67
Ahmmad et al. [62]	60.0	4.0	4.0	8.0	—	12.0	—	—	5.0	—
Darvish et al. [52]	60.29	5.83	4.71	3.28	0.20	7.24	0.31	3.78	4.20	—

and light black and relies on the source of waste material and the heating temperature in the furnace [22]. The low specific gravity of POC makes it suitable to obtain LWC and LWGPC; the specific gravity for POC ranges between 1.7 and 2.2.

Similarly, the bulk density of POC relies on the shape and particle size [65], and its value also relies on the source of the material. The bulk densities for POC as fine aggregate range from 860 to 1080 kg/m^3 [22], and the compacted and loose bulk densities for POC as coarse aggregate range from 800 to 840 kg/m^3 and from 740 to 790 kg/m^3, respectively. The porous nature of POC aggregates makes it have higher water absorption than that of natural aggregates [18]. The water absorption of POC as coarse aggregate ranges between 4.7% and 26.5%, while the water absorption of POC as fine aggregate ranges from 1.8% to 5.4% [66]. Table 2 shows some physical properties of POC obtained from the previous studies.

As shown in Table 2, the specific gravity of POC aggregates ranges between 1.62 and 1.92; therefore, the POC aggregates can be considered lightweight or semi-lightweight aggregates. They have a lower density than natural aggregates; therefore, it is preferred to be utilized in applications that require lightweight concrete. The high water absorption of POC, compared to natural aggregates, mainly contributes to reducing the workability and the need for other additives to enhance the workability, like superplasticizers. Darvish et al. [34] used POC as a fine aggregate in the prepared GPC mix. They prepared the particle size in the lab using sieve analysis to obtain a particle size of less than 4.75 mm. POC produced has a porous nature as compared to the natural aggregate. The sieve analysis was performed according to the specifications of ASTM C136/C136M-14 [71]. Recently, Bashar et al. [23] used POC as an aggregate in the production of GPC. They collected different sizes of POC chunks from the nearby palm oil mill and ground them into small particle sizes between 5 and 14 mm using a crushing machine, as shown in Figure 3. They detected that the average bulk dry density and loss on ignition (LOI) of POC are 780 kg/m^3 and 1.02%, respectively.

Malkawi et al. [72] used POC as coarse and fine aggregates in the production of GPC. They concluded that the POC aggregates have suitable properties, making them improve the sustainability in the production of GPC and high-strength concrete (HSC). The use of a geopolymer binder increases the strength and workability of POC aggregate concrete and decreases water absorption. Therefore, the use of POC aggregates with suitable physical properties has a significant effect on the concrete performance, especially related to the particle size and specific surface area.

In conclusion, the physical properties of POC aggregates, including particle size, shape, and porosity, play significant

TABLE 2 | Physical properties of fine and coarse palm oil clinker (POC) aggregates.

References	Specific gravity	Bulk density (kg/m^3)	Fineness modulus	Particle size (mm)	Moisture content	Aggregate impact value	Water absorption for 24 h (%)
Kabir et al. [35]	1.76	801		9–14			6.08
Hamada et al. [19]	1.78	732	6.23	4.75–10	0.38	31.57	5.7
Malkawi et al. [67]	1.62	823		5–14		18.04	4.43
Abutaha et al. [68]	1.81	732			0.28	56.44	4.35
Darvish et al. [34]	1.92		3.52	4.75			3.3 ± 1
Hamada et al. [18]	1.78	823	6.23	4.75–10	0.38	31.57	5.7
Aslam et al. [69]	1.69	860				36.3	7.0
Mohammed et al. [70]	1.82	781.08	6.75			25.36	4.35
Bashar et al. [23]	1.70	780		5 – 14			3.30
Kanadasan and Razak [58]	1.73			5 – 14	1 ± 0.5	56.44	3 ± 2

FIGURE 3 | A large chunk of palm oil clinker (POC) and fine aggregates [24]. Reprinted with permission from Elsevier (2022).

roles in determining the mechanical and durability properties of GPC [73]. For instance, the particle size distribution of POC aggregates influences the packing density and workability of GPC [52]. Likewise, the small particle size of POC can fill the voids between larger particles, leading to a denser and more homogenous concrete structure that ensures better packing, thus increasing compressive strength and other mechanical properties. The shape of POC aggregates affects the interlocking of particles within the concrete matrix. Irregularly shaped particles tend to interlock more effectively than rounded particles, resulting in improved mechanical strength by enhancing load transfer between particles [74]. The porosity of POC aggregates directly influences the porosity and permeability of the GPC [34]. Higher porosity in aggregates can result in increased water absorption and reduced mechanical strength due to the presence of voids within the concrete [75]. Therefore, POC aggregates with lower porosity are preferred as they contribute to denser and more impermeable concrete, resulting in enhanced mechanical strength and durability.

4 | Properties of GPC Containing POC

4.1 | Density of POC-Based GPC

The density of GPC is one of the important tests that determine the weight of the concrete structure, and it usually produces lightweight concrete or semi-lightweight concrete. Kabir et al. [35] used POC and OPS as aggregates in different replacement levels. They found that the drying density ranged between 1955 and 2172 kg/m^3. While the highest density of GPC was recorded with a mix containing 100% POC as coarse aggregate, the reason behind this density is that the specific gravity of POC is higher than that of OPS. The specific gravity of POC and OPS aggregates used in this study was 1.8 and 1.35, respectively. Malkawi et al. [67] investigated the effect of POC as a fine and coarse aggregate at different replacement levels of 0%, 25%, 50%, 75%, and 100% on the density of GPC. They observed that the increased amount of POC leads to a decrease in the density of GPC samples. The reduction in the density of GPC from 2345 to 1821 kg/m^3 by incorporating POC aggregates can be attributed to several mechanisms. First, POC aggregates have a lower density compared to traditional aggregates such as sand and gravel. Therefore, the use of POC instead of conventional aggregates leads to reduced overall density of the GPC [34]. Second, the porous structure of POC aggregates has a porous structure making it of lower density. The porous nature of POC aggregates is due to the existence of voids inside the clinker particles. The use of POC aggregates reduces the density of GPC produced, thus saving more cost in the design and construction of buildings and infrastructure. Table 3 shows the density of GPC due to the use of POC as aggregate at different replacement levels.

As shown in Table 3, the addition of 50% POC aggregates into the GPC mixture reduced the density of GPC from 2318 to 1618.2 kg/m^3 [32]. Darvish et al. [34] concluded that the use of POC as a fine aggregate in GPMs decreased the density of the mortar samples by around 17%. These aggregates can be used at high replacement levels in construction structures that require lightweight concretes with high performance.

4.2 | Workability

The workability of GPC can be measured by the slump test directly after mixing the concrete mix. Kabir et al. [35] reported that the slump values for the concrete mixtures were between 32 and 45 mm. The low slump value of POC concrete might be due

TABLE 3 | Effect of palm oil clinker (POC) on the density of geopolymer concrete (GPC).

References	Aluminosilicate sources for GPC	Aggregate type	POC % as aggregates	Density of GPC (kg/m^3)
Nazari et al. [32]	RHA and FA	Fine and coarse aggregates	0	2318.0
			5	2248.0
			10	2178.0
			20	2038.1
			40	1758.2
			50	1618.2
Malkawi et al. [67] and [72]	FA	Fine and coarse aggregates	0	2345
			25	2165
			50	2079
			75	1942
			100	1821
Darvish et al. [52]	FA and GGBS	Fine aggregate	0	2220
			100	1900
Ahmat et al. [47]	FA and eco-processed pozzolan (EPP)	Coarse aggregate	0	2420
			100	2120
Darvish et al. [34]	FA and GGBS	Fine aggregate	0	2076.8
			100	1710.4
Kabir et al. [35]	MK, PPOFA, and GGBS	Coarse aggregate	0	2150
			100	1900

to the porous nature of POC that requires further water, thus a negative effect on the slump value. Darvish et al. [34] conducted the flow test according to the ASTM 1437-15 [76]. They designed the GPC mixtures to achieve a flow within 110% ± 5. They detected that the additional water leads to an increase in the workability of GPC for all concrete mixtures. Bashar et al. [23] indicated that the use of POC aggregate without pre-soaking and without the addition of further water into GPC mixtures might have a negative influence on the reactions of the geopolymerization process and interfacial transition zone (ITZ) of POC paste. This is because of the porous nature of POC aggregate, making it tend to fill these pores with geopolymer paste leading to reduced workability of the mix. Arafa et al. [77] conducted the workability test according to the European Standard EN 206-1:2000 [78]. They concluded that the workability and water permeability coefficient of pervious GPC with POC aggregate is not considerably different from that of natural pervious concrete containing natural aggregate. Table 4 shows the effect of POC on the workability of GPC, as reported by previous studies.

As shown in Table 4, adding POC as aggregates on the GPC mixtures reduced the slump value from 100 mm to 85 mm, as reported by Darvish et al. [52]. Malkawi et al. [67] used POC as fine and coarse aggregate at 0%, 25%, 50%, 75%, and 100% replacement levels in the production of GPC mixtures. They found that the increased amount of POC in the GPC mix has a negative effect on the workability. The workability gradually reduces as the POC aggregate increases, as shown in Figure 4. This slump in value reduction mostly results from the POC aggregates' high absorption compared to the natural aggregates. Instead, the POC aggregates have spiky and rough surface that leads to a decrease in the slump values.

Another study by Malkawi [72] reported that the use of the alkaline solution in GPC assists in increasing the slump value due to the use of POC aggregate. This increase is because POC can absorb the alkaline solution owing to its higher viscosity than that of water. As a result, they detected that as POC aggregate increases, the slump value decreases. This decrease might be because POC aggregate has higher water absorption than natural aggregate. From the study mentioned above, it is recommended to use a superplasticizer or other additives to enhance the workability of GPM and concretes when using POC as aggregates in GPC mixtures.

In general, the high water absorption of POC has a significant impact on the workability of GPC [52]. The high water absorption capacity of POC may absorb a significant amount of the mixing water in the concrete mix [79]. This can lead to an increase in the overall water demand of the GPC mix, potentially affecting its workability and consistency. The absorption of mixing water by POC aggregates can result in a decrease in the slump of the concrete mix [80]. This can potentially cause segregation, where heavier aggregates settle at the bottom of the formwork, resulting in an uneven distribution of materials and compromised structural integrity. To mitigate the negative impacts of the high-water absorption characteristic of POC on the workability of GPC, several steps should be conducted, such as pre-wetting POC aggregates before incorporating them into the concrete mix, which can help reduce their water absorption capacity.

4.3 | Hardened POC-Based GPC

The hardened properties of GPC, such as compressive, flexural, and splitting tensile strengths, can be improved by optimizing the mix design of GPC containing POC. A well-graded aggregate mix that includes a suitable proportion of fine and coarse POC aggregates helps achieve dense packing and reduces voids, which enhances mechanical properties and durability. Using suitable alkali activators and the ratio of these activators can significantly affect the setting time, workability, and strength development. Optimize the concentration of the alkali activators [81, 82].

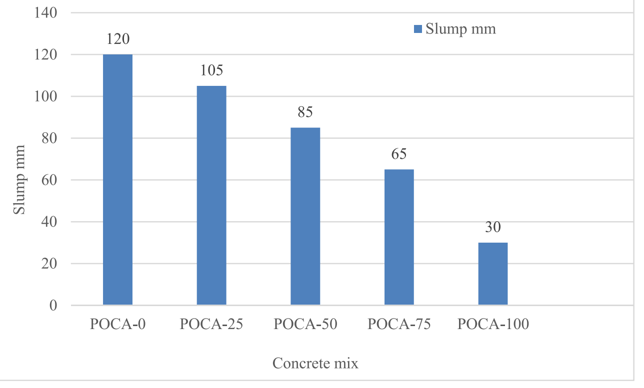


FIGURE 4 | Slump value of geopolymer concrete (GPC) containing palm oil clinker (POC) aggregates [67]. Reprinted with permission from Taylor & Francis (2020).

TABLE 4 | Effect of palm oil clinker (POC) on the workability of geopolymer concrete (GPC).

References	Aluminosilicate sources for GPC	Aggregate type	POC % as aggregates	Workability of GPC (mm)
Darvish et al. [52]	FA and GGBS	Fine aggregate	0	100
			100	85
Darvish et al. [34]	FA and GGBS	Fine aggregate	0	110
			100	114
Malkawi [72]	FA	Fine and coarse aggregates	0	120
			25	105
			50	85
			75	65
			100	30

Maintain an optimal water-to-binder ratio to ensure sufficient workability without compromising strength. Pre-soaking POC aggregates can provide internal curing, reducing autogenous shrinkage and enhancing the mechanical properties [83].

4.3.1 | Compressive Strength

Compressive strength is one of the important tests that determine the performance of GPC. Kabir et al. [35] investigated the effect of partial and full replacement levels of POC in different particle sizes with OPS and natural coarse aggregate on the compressive strength of GPC. They observed that the compressive strength of 0% POC and 100% OPS recorded the lowest strength at all curing ages. The low strength is attributed to the weaker bond between the binder materials and the smooth convex and concave surfaces of OPS particles. In contrast, the highest compressive strength is 41.5 MPa, obtained from a concrete mix made of 100% POC as coarse aggregates. The high strength can be attributed to the better connection between the binders and aggregates. Table 5 shows the effect of POC aggregate on the compressive strength of GPC.

As shown in Table 5, the use of POC as fine aggregate reduced the compressive strength of GPC, as reported by Darvish et al. [52], while the compressive strength of GPC increased as the POC increased, as reported by Kabir et al. [35] and Ahmat et al. [47]. Jagaba et al. [5] reported that the high strength of GPC made of POC can be developed up to 60 MPa for a density of 1995 kg/m^3. Darvish et al. [52] investigated the effect of using different particle sizes of POC as fine aggregates of 0.15–4.75, 0.15–2.36, 0.15–1.18, and 0.15–0.60 mm to form four categories of gradings G-7, G8, G-9, and G-10, respectively, in addition to the natural fine aggregate (G-6) on the compressive strength of GPM. They used 100% POC as a fine aggregate instead of natural sand. They found that the compressive strength of GPM decreases due to the use of the POC aggregates in different particle sizes instead of natural sand for the mixtures of G-7, G-8, G-9, and G-10, as shown in Figure 5. While the G-6 is the control mix made of 100% natural aggregate and 0% POC.

The compressive strength of GPC samples made of POC fine aggregate is lower than that of the control sample without POC aggregates; because of that, the compressive strength of POC aggregate has a lower strength than that of natural aggregates and the weak connection between cement matrix and aggregate surface. In this regard, Malkawi et al. [67] used POC as fine and coarse aggregates instead of natural aggregates to find out the performance of GPC. They observed that the compressive strength of GPC decreases as POC aggregates increase. In addition to that, the reduction in GPC made of POC aggregate can be attributed to numerous factors, such as the higher viscosity of geopolymer binders, air voids spread on the POC surface, and the weak ITZ between the geopolymer binder and the POC aggregates. From the results obtained, it is recommended to use POC as a coarse aggregate in the production of GPC to obtain higher compressive strengths than that of natural aggregate.

In conclusion, the effect of POC in GPC while maintaining competitive compressive strength can be attributed to several factors: first, the high SiO_2 and Al_2O_3 content, which are essential precursors for the formation of geopolymers [84]; second, the pozzolanic reaction of GPC due to incorporation of POC aggregates; third, proper particle packing is crucial for achieving competitive compressive strength in concrete mixes [22]; and fourth, selecting an appropriate mix design to achieve a better compressive strength of GPC depends on the POC aggregates content, the type, and concentration of alkaline activators, curing conditions, and any additional additives or admixtures.

4.3.2 | Flexural Strength

The flexural strength of GPC is one of the significant properties used to evaluate the performance of GPC. The flexural strength of GPM reduced as POC aggregates increased, as reported by Darvish et al. [52]. The lower flexural strength might be due to the lower elastic modulus and stiffness of POC aggregate as compared to natural aggregates [85]. Instead, the GPM created a somewhat higher flexural strength compared to cement mortars. Also, they concluded that the flexural strength is higher with larger particle sizes of POC aggregate that reach up to

TABLE 5 | Effect of palm oil clinker (POC) aggregate on the compressive strength of geopolymer concrete (GPC).

References	Aluminosilicate sources for GPC	Aggregate type	POC % as aggregates	Compressive strength of GPC (MPa)
Darvish et al. [52]	FA and GGBS	Fine aggregate	0	66
			100	56
Darvish et al. [34]	FA and GGBS	Fine aggregate	0	50
			100	52
Malkawi [72]	FA	Fine and coarse aggregates	0	64.51
			25	58.94
			50	51.40
			75	46.44
			100	32.72
Kabir et al. [35]	MK, GGBS, and POFA	Coarse aggregate	0	34.50
			100	39.00
Ahmat et al. [47]	FA and EPP	Coarse aggregate	0	29
			100	35

9.49 MPa, which agrees with the fact that the particle size and water–cement ratio have an important effect on the concrete strength [86]. Table 6 shows the effect of POC on the flexural strength of GPC, as reported by previous studies.

As presented in Table 6, the flexural strength of GPC reduces as the POC aggregate increases, as reported by Darvish et al. [52]. Other studies used POC as coarse aggregate in replacing natural coarse aggregate and found that the flexural strength increases as the POC amount increases, as reported by Ahmat et al. [47]. Therefore, it is recommended to use POC as coarse aggregate in the production of GPC mixtures to ensure high-performance GPC.

4.3.3 | Tensile Strength

The splitting tensile strength of GPC has been affected by the addition of POC aggregates, especially with high replacement levels. The splitting tensile strength decreases as the POC aggregates increase, as reported by Malkawi et al. [67]. They found that the influence of POC aggregate on the compressive strength has a similar influence on the tensile strength. Another study by Ahmat et al. [47] found that the splitting tensile strength of GPC made of 100% natural aggregate had the highest splitting tensile strength of 2.6 MPa, while the GPC mix made of 100% POC aggregate has about 92.31% of GPC mix made of 100% natural aggregate. However, Kabir et al. [35] reported that the addition of POC as coarse aggregate leads to an increase in the splitting tensile strength of GPC. Table 7 shows the effect of POC on the splitting tensile strength of GPC, as reported by previous studies.

As shown in Table 7, numerous researchers investigated the effect of POC on the splitting tensile strength of GPC. However, most of them reported that the POC hurts the splitting tensile strength. Therefore, it is recommended to use different fiber types to enhance the splitting tensile strength of GPC when using POC as aggregates.

In general, POC aggregates can influence the flexural and tensile strengths of GPC in various ways, which has important implications for its use in structural applications. POC aggregates generally have a rough surface texture and irregular shape [4], which can improve the bond between the aggregates and the geopolymer matrix. This enhanced interfacial bonding

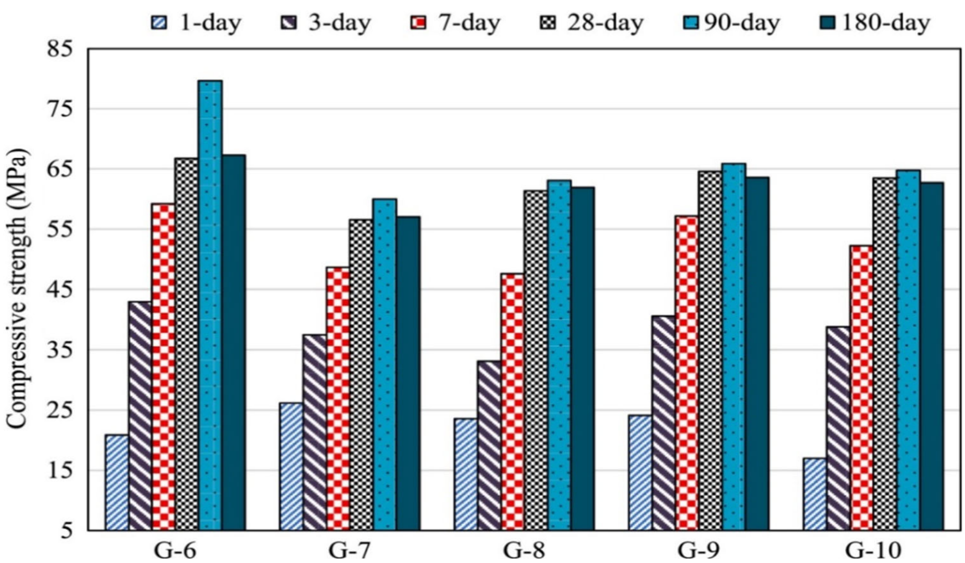


FIGURE 5 | Effect of palm oil clinker (POC) aggregate content on the compressive strength of geopolymer mortar (GPM) [52]. Reprinted with permission from Elsevier (2021).

TABLE 6 | Effect of palm oil clinker (POC) aggregate on the flexural strength of geopolymer concrete (GPC).

References	Aluminosilicate sources for GPC	Aggregate type	POC % as aggregates	Flexural strength of GPC (MPa)
Darvish et al. [52]	FA and GGBS	Fine aggregate	0100	10.99.5
Malkawi [72]	FA	Fine and coarse aggregates	0	6.31
			25	6.02
			50	5.56
			75	5.10
			100	4.78
Kabir et al. [35]	MK, GGBS, and POFA	Coarse aggregate	0	5.48
			100	5.50
Ahmat et al. [47]	FA and EPP	Coarse aggregate	0	3.3
			100	3.6

contributes to better load transfer and can increase the flexural strength of GPC. The internal curing effect of POC aggregates, due to their porous nature, helps maintain moisture levels within the concrete, reducing shrinkage cracks and enhancing the overall flexural performance of GPC. Properly graded POC aggregates can provide a more uniform distribution within the concrete matrix, which can lead to improved flexural strength by reducing stress concentrations and potential crack initiation sites. The strong bond between POC aggregates and the geopolymer matrix enhances the tensile strength of GPC.

4.3.4 | Modulus of Elasticity

Modulus of elasticity (MOE) or elastic modulus is one of the important mechanical properties of GPC. Jagaba et al. [5] reported that the elastic modulus of GPC can be improved by the addition of POC aggregate with particle size less than 2 mm with regular shape, making it increase connection with binder. Ahmat et al. [47] stated that the MOE value is influenced by numerous factors such as microstructure, geopolymeric reaction, aggregate size, and others [35, 87]. They found that the highest MOE value was achieved from the mixture comprising 100% natural aggregate of 16 GPa, which is higher than that of POC aggregate by 33.33%. The decrease in the MOE of POC aggregate is due to the low density and specific gravity of POC aggregate as compared to the natural aggregate. Table 8 shows the effect of POC on the MOE of GPC as reported by the previous studies.

As presented in Table 8, Kabir et al. [35] found that the highest MOE of GPC was 16.10 GPa from a mix containing 100% natural aggregate; the second highest value of 14.5 GPa was produced by a mix containing 100% POC aggregate with a particle size of 9–14 mm. The reduction of MOE for POC aggregate is due to the lower stiffness of POC as compared to natural aggregate. Bashar et al. [23] investigated the performance of GPC containing POC aggregate under compression test. They observed that the failure pattern of granite-based geopolymer concrete (G-GPC) and palm oil clinker-based geopolymer concrete (P-GPC) under compression load is different, as illustrated in Figure 7. P-GPC cylinder showed lower failure in two to three segments, while G-GPC failed by multi-cracks around the cylinder surface.

5 | Durability of POC-Based GPC

5.1 | Water Absorption

The water absorption of GPC-containing POC aggregates is an important property that can affect the durability and performance of the material. Water absorption is typically associated with the porosity of concrete and its ability to absorb and retain water. The properties of the aggregates used influence the water absorption of GPC. POC aggregates have specific characteristics, such as particle size distribution and porosity, which can impact the overall porosity of the concrete. The pozzolanic reaction between the aluminosilicate precursor materials, such as fly ash, GGBS, or metakaolin, and alkali activators in GPC results in the formation of a dense, gel-like structure. This reaction contributes to the reduction of porosity and, consequently, water absorption. The mix design of GPC, including the type and concentration of alkali activators, plays a significant role in determining its water absorption characteristics. Optimizing the mix proportions can lead to a more compact and less porous structure. Proper curing is crucial for the development of the geopolymer structure and the reduction of porosity. Adequate curing regimes, such as steam curing or high-temperature curing, can enhance the material's resistance to water absorption.

TABLE 7 | Effect of palm oil clinker (POC) on the tensile strength of geopolymer concrete (GPC).

References	Aluminosilicate sources for GPC	Aggregate type	POC % as aggregates	Splitting tensile strength of GPC (MPa)
Malkawi et al. [67]	FA	Fine and coarse aggregates	0	4.55
			25	4.31
			50	3.94
			75	3.62
			100	2.91
Kabir et al. [35]	MK, GGBS, and POFA	Coarse aggregate	0	2.31
			100	2.85
Ahmat et al. [47]	FA and EPP	Coarse aggregate	0	2.6
			100	2.4

TABLE 8 | Effect of palm oil clinker (POC) on the modulus of elasticity (MOE) of geopolymer concrete (GPC).

References	Aluminosilicate sources for GPC	Aggregate type	POC % as aggregates	MOE of GPC (GPa)
Kabir et al. [35]	MK, GGBS, and POFA	Coarse aggregate	0	16.10
			100	14.30
Ahmat et al. [47]	FA and EPP	Coarse aggregate	0	10
			100	12

The water absorption test is important to evaluate the durability of GPC and cement concrete [88], and it directs the pore levels of the samples; higher porosity and absorption could be obtained with a higher pore level. Nazari et al. [32] studied the water absorption of GPC made of POC, and they found higher water absorption in POC-GPC than in other samples; this high absorption was due to the high volume of pores in the POC surface. Malkawi et al. [67] reported that the water absorption of GPC remarkably increased due to an increase in the POC aggregate content. This increase in water absorption can be attributed to the low compaction, high porosity, and porous nature of POC aggregates. However, the absorption values obtained were satisfactory and can be used in concrete production. The use of 100% POC aggregates in GPC mix has a 3.2% water absorption, and this value is still much lower than the 10% limit for high-performance concrete as determined by Neville [89]. Table 9 shows the effect of POC on the GPC as reported by the previous studies.

As shown in Table 9, the increase in POC amount leads to an increase in the water absorption of GPC, and this increase in water absorption can be attributed to the porous nature of POC that absorbs high water. Darvish et al. [52] reported that the sorptivity and water absorption rates increased due to the use of the POC aggregate instead of natural aggregates in large particle size and then decreased as the particle size of POC decreased. The water absorption of geopolymer samples was about 1%–2% lower than the recorded value of the cement mortar samples. This lower value might be due to the denser composition of GPM samples than that of natural cement mortar samples.

Ongoing research in the field of GPC aims to optimize mix designs and curing procedures to achieve desired properties, including low water absorption. The interaction between POC aggregates and the geopolymer matrix should be further studied to identify the most suitable combinations for reducing water absorption. To sum up, controlling water absorption in GPC containing POC involves a combination of optimizing mix designs, considering curing conditions, and understanding the specific properties of POC aggregates. Reducing water absorption contributes to the durability and long-term performance of GPC in various construction applications.

5.2 | Resistance to Sulfate and Acid Attacks

Sulfate and acid environments have negatively influenced the durability of GPC. Therefore, numerous studies have been conducted to investigate the effect of these aggressive environments on the durability of GPC. For instance, Darvish et al. [34] reported that the residual compressive strength of GPM containing POC aggregate was reduced for all mixtures, especially after 56 days of immersion of the GPM samples in aggressive environments. The control GPM had the lowest decrease in strength than that GPM containing POC fine aggregates by about 20%. The existence of C-S-H gels in the cement mortar reacts with the sulfate to produce new ettringites, while brucite and gypsum, along with the ettringite, are the products of the GPM with the $MgSO_4$ solution [90]. The physical appearance of the samples was noted after 28 days of exposure to hydrochloric acid (HCl) to display the variations that occurred for the samples during exposure to acid attacks, as shown in Figure 6.

Another study by Kabir et al. [35] detected that the visual appearance of GPC samples exposed to the sulfate attacks immersed in $MgSO_4$ for different periods presented no significant effect on the samples. They observed that the compressive strength of GPC samples has a lower reduction rate in strength as compared with the reference sample that is made of granite aggregate. The low reduction in strength loss might be due to the tendency for aluminosilicate gels in GPC to come into contact with sulfate solution to produce a geopolymeric matrix with a low effect on the strength of GPC. In summary, the nature of GPC and their composition has a significant effect in mitigating the negative impact of sulfate and acid environments on the performance of GPC.

In general, the benefits desired due to the use of POC as aggregates in enhancing GPC against aggressive environmental conditions like sulfate and acid attacks are that POC aggregates have shown a high degree of chemical inertness, mainly against acidic and sulfate environments [4]. This inherent resistance to chemical degradation makes POC the best choice for enhancing the durability of GPC in aggressive environments. Unlike traditional cement-based concrete, which contains calcium compounds susceptible to

TABLE 9 | Effect of palm oil clinker (POC) aggregate on the water absorption of geopolymer concrete (GPC).

References	Aluminosilicate sources for GPC	Aggregate type	POC % as aggregates	Water absorption of GPC (%)
Darvish et al. [52]	FA and GGBS	Fine aggregate	0	9.0
			100	9.9
Kabir et al. [35]	MK, GGBS, and POFA	Coarse aggregate	0	0.203
			100	0.182
Malkawi [72]	FA	Fine and coarse aggregates	0	0.6
			25	0.8
			50	1.4
			75	1.75
			100	3.2
Nazari et al. [32]	RHA and FA	Fine and coarse aggregates	0	0.72
			5	0.81
			10	0.81
			20	0.82
			40	0.82
			50	0.83

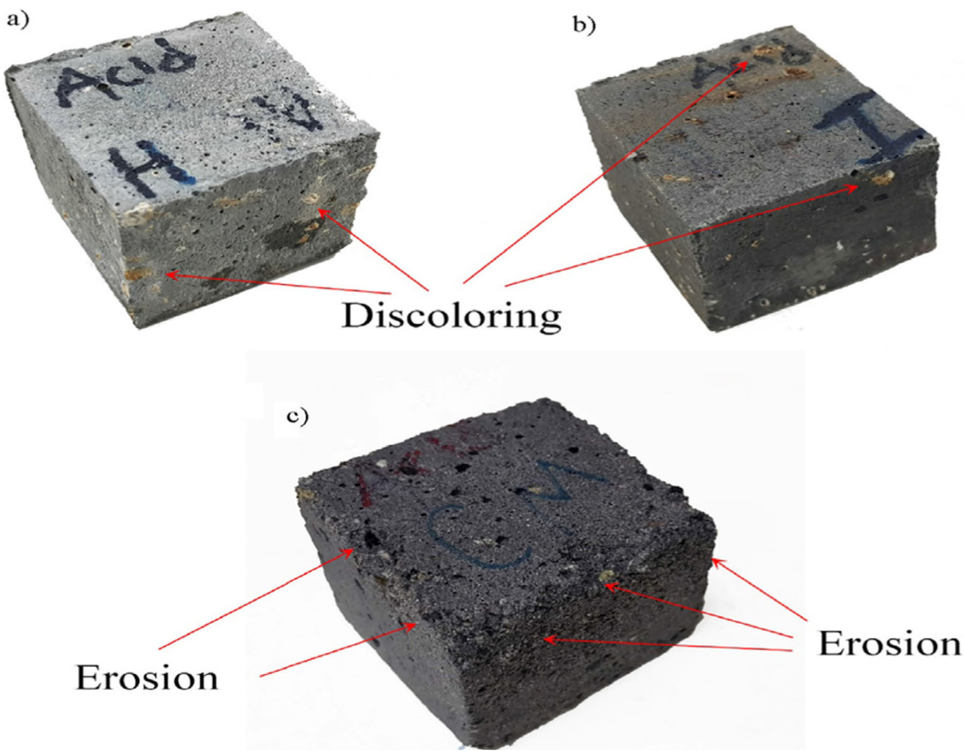


FIGURE 6 | Physical appearance of samples exposed to HCl: (a) FA-MS-based geopolymer mortar (GPM), (b) FA-GGBS-POC-based GPM, and (c) cement-MS mortar [34]. Reprinted with permission from Elsevier (2020).

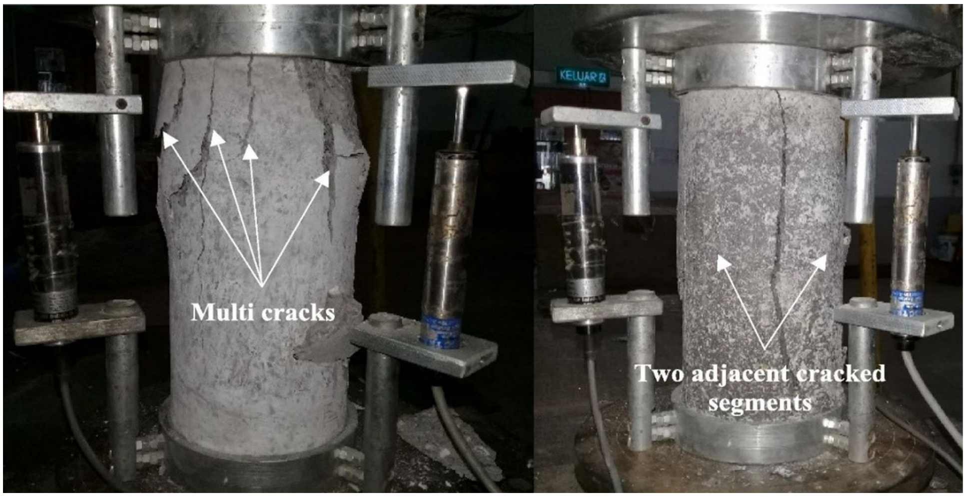


FIGURE 7 | Cracks failure for granite-based geopolymer concrete (G-GPC) and palm oil clinker-based geopolymer concrete (P-GPC) under compression [23]. Reprinted with permission from Elsevier (2022).

sulfate attack, POC aggregates have lower calcium content. This reduces the risk of sulfate attack, as there are fewer reactive calcium ions available to form expansive sulfate compounds, such as ettringite and gypsum, which can lead to concrete deterioration.

5.3 | Shrinkage and Creep

The shrinkage and creep behavior of GPC-containing POC aggregates are important factors to consider in assessing the material's long-term performance and durability. Shrinkage refers to the reduction in the volume of concrete over time due to factors such as drying, autogenous shrinkage, and chemical shrinkage [91]. Excessive shrinkage can lead to cracking, which can compromise the integrity of the structure. Shrinkage in GPC is influenced by factors such as the type of activator used, curing conditions, and the characteristics of the aggregates [92]. Controlling mix proportions, using shrinkage-reducing admixtures, and optimizing curing methods can help mitigate shrinkage in GPC [93]. Additionally, the use of suitable aggregates, such as POC, can impact the overall shrinkage behavior [68, 94].

Creep is the deformation that occurs over time under sustained load [95]. It is a time-dependent phenomenon associated with the gradual flow or deformation of the concrete. Excessive creep can lead to increased deflections and long-term deformations in structures, affecting their serviceability and performance. Careful consideration of mix proportions, curing regimes, and aggregate characteristics can influence the creep behavior of GPC [96]. The type and concentration of alkali activators, as well as the curing temperature, play a role in mitigating creep.

The use of POC aggregates in GPC can influence both shrinkage and creep behaviors [23]. The unique properties of POC, such as its particle size distribution and pozzolanic reactivity, can impact the overall microstructure of the concrete and, consequently, its shrinkage and creep characteristics. POC's contribution to the concrete's overall porosity and pore structure may influence moisture movement and, subsequently, shrinkage. The drying shrinkage of GPC made of different particle sizes of POC aggregates was investigated by Darvish et al. [52], as illustrated in Figure 8. Most of the shrinkage happened in the first 90 days and then increased regularly. The GPM samples using POC aggregates are more influenced by the shrinkage than that of cement mortars. The high shrinkage values in the GPM can be attributed to the existence of GGBS in GPM that produce further C–S–H gels, thus resulting in higher shrinkage in geopolymer samples [97].

Overall, the addition of POC into GPC can affect its shrinkage and creep behavior. POC aggregates with POFA can contribute to a reduction in drying shrinkage in GPC compared to traditional cement concrete [25]. The porous nature of POC allows it to absorb water during the mixing process and release it slowly over time, reducing the rate and extent of drying shrinkage. POC aggregates can act as internal curing agents. By retaining water within their porous structure, they provide a sustained supply of moisture to the geopolymer matrix, mitigating the shrinkage associated with water loss from the concrete.

6 | Microstructure Properties of GPC Made of POC

Scanning electron microscopy (SEM) can provide detailed images of the microstructure of GPC containing POC aggregates [35, 52]. SEM analysis allows for a closer examination of the

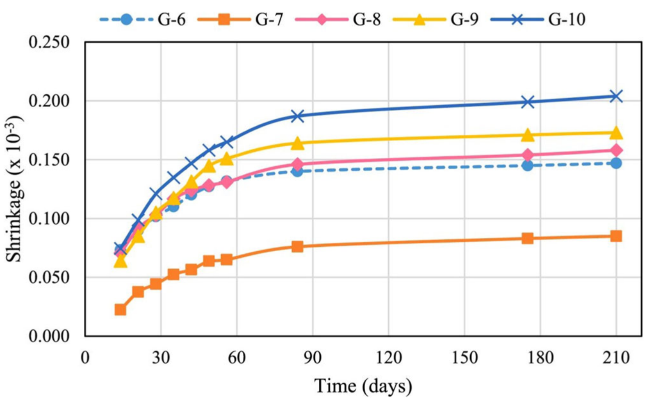


FIGURE 8 | Drying shrinkage of geopolymer mortar (GPM) [52]. Reprinted with permission from Elsevier (2021).

cementitious matrix and the interaction between various components. SEM images can reveal the structure of the geopolymer matrix, showcasing the arrangement of aluminosilicate gel and other reaction products [98]. The microstructure of the matrix will show the binding phases responsible for the strength and durability of the concrete. SEM allows for the examination of the distribution and arrangement of POC aggregates within the geopolymer matrix. It can provide insights into the bonding between the aggregates and the geopolymer binder. SEM images can help in analyzing the porosity and pore structure of the GPC. The presence of pores and their distribution can impact the concrete's permeability and, consequently, its durability. Identification of specific reaction products, such as aluminosilicate gel and other hydration products, can be observed in SEM images. This helps in understanding the geopolymerization process and the development of the concrete's microstructure.

Examination of the ITZ between the geopolymer matrix and POC aggregates is crucial. A well-bonded ITZ is essential for the overall strength and performance of the concrete. SEM can be used to identify and analyze cracks within the GPC. Understanding the nature and extent of cracks is important for assessing the material's structural integrity and potential areas of improvement in the mix design. SEM coupled with energy-dispersive X-ray spectroscopy (EDS) can provide information on the mineralogical composition of the concrete [99]. This helps in identifying the presence of specific elements and minerals contributing to the overall material properties. SEM images reveal the texture and surface morphology of the GPC. This includes the roughness of the surface and any unique features that may influence the material's mechanical and physical properties. The SEM analysis of GPC containing POC aggregates is valuable for researchers and engineers seeking to optimize the mix design, understand the material's microstructure, and ensure its overall performance and durability in various applications.

The addition of POC into GPC can adjust its microstructure in several ways, particularly affecting binder–aggregate interactions and pore distribution. POC aggregates contain reactive components such as silica and alumina, which can participate in the geopolymerization reaction. As the alkaline activator solution penetrates the porous structure of POC aggregates, it reacts with these components to form additional geopolymer gel [35]. This enhances the bond between the aggregates and the geopolymer matrix, resulting in improved binder–aggregate interactions compared to traditional concrete mixes. Furthermore, the ITZ between aggregates and the surrounding geopolymer matrix plays a crucial role in determining the mechanical properties of concrete [100]. Incorporating POC aggregates may lead to the formation of a more homogeneous and well-bonded ITZ, which can contribute to enhanced load transfer and improved overall performance of the concrete.

Nazari et al. [32] investigated the microstructure of GPC made of POC via SEM/EDS test. They found that the SEM images show that the increase of NaOH concentration leads to an increase in the quantity of polymer between the micro-silica particles, thus increasing the density and strength of GPC. Kabir et al. [35] used POC and OPS as coarse aggregates with ternary binders of POFA, GGBS, and MK in producing GPC. They detected that the POC aggregate has a positive effect in improving the compressive strength because of its porous surface, making it able to bond with binder [35]. SEM images show a GPC with microcracks for a denser and more compact matrix. POC is different from OPS, and it has smooth convex and concave surfaces. Malkawi et al. [67] investigated the effect of POC as fine aggregates on the performance of GPC. They found that the POC aggregate has a significant effect on the structure of GPC as shown in Figure 9. They reported that the concrete strength should be increased during the first curing days. The existence of enough alkaline solutions is required for fast geopolymerization reactions. Therefore, increase of POC aggregate amount results in an increase in solution absorption. Thus, the geopolymerization will be stopped and hindered at an earlier age. This was confirmed by the existence of higher quantities of unreacted fly ash particles.

Recently, Ahmat et al. [47] investigated the potential use of POC as a coarse aggregate and EPP as a partial replacement of FA in the production of GPC. They observed that the use of EPP and POC aggregate increases SiO_2 content in the GPC mix, and this increase has a negative impact on the geopolymerization process. Darvish et al. [52] investigated the effect of different particle sizes of POC aggregate on the microstructure of GPC using SEM test. They found that the different particle sizes of POC aggregate have an important effect on the microstructure of GPC, especially GPC mix containing POC aggregate with a particle size of 0.15–4.75 mm. These particle sizes result in a denser structure and higher compaction of the POC-based GPC.

7 | Applications of GPC Containing POC Aggregates

GPC incorporating POC aggregates can offer several advantages and find applications in various construction scenarios [101–103]. POC is a by-product of the palm oil industry and is often considered waste. However, it can be effectively utilized in GPC, which is an environmentally friendly alternative to traditional Portland cement-based concrete [104, 105]. For instance, POC can be used in Roads and Pavements, and GPC containing POC aggregates can be used in the construction of roads and pavements, providing a sustainable and durable alternative to conventional concrete [22, 106]. While in building construction, GPC can be used in the construction of various types of buildings, offering a sustainable and energy-efficient option for structural elements such as walls, floors, and foundations [107]. In addition, the GPC is known for its high compressive strength and resistance to chemicals. It can be employed in industrial settings, particularly for flooring where resistance to chemical exposure is crucial. The GPC can be used in the construction of marine structures such as docks, piers, and harbor infrastructure due to its resistance to harsh environmental conditions, including saltwater exposure. The GPC aligns with the principles of sustainable construction, especially when incorporated POC aggregates, and contributes to reducing the environmental impact associated with traditional concrete production. It was used for repairing and retrofitting existing structures, enhancing their durability and extending their service life. The optimum thermal properties of GPC containing POC make it used in construction buildings that require high thermal insulation and high resistance against fire and high temperature.

In general, POC can provide several improvements in thermal conductivity and resistance to high temperatures when incorporated into GPC [108]. POC aggregates typically have lower thermal conductivity compared to traditional aggregates such as sand and gravel [4]. This lower thermal conductivity helps reduce heat transfer through the concrete, leading to improved thermal insulation properties. GPC-containing POC aggregates can exhibit enhanced resistance to high temperatures and fire. The lower thermal conductivity of POC aggregates helps reduce the rate of heat transfer through the concrete, delaying the

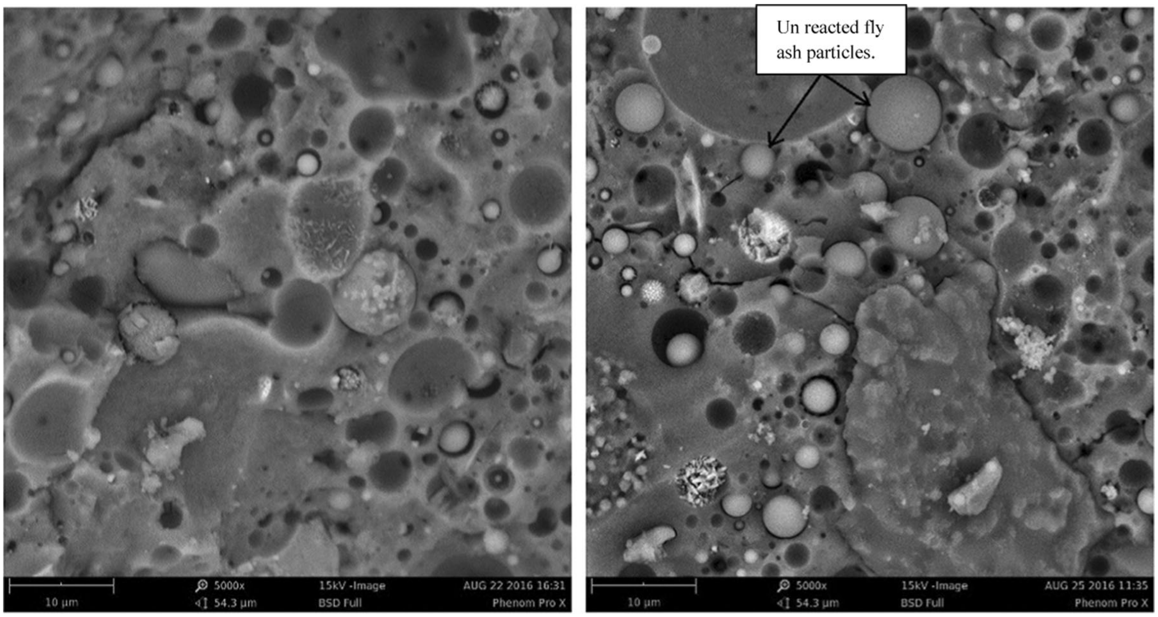


FIGURE 9 | Scanning electron microscopy (SEM) images of (a) control geopolymer concrete (GPC) and (b) GPC with 100% palm oil clinker (POC) aggregate [67]. Reprinted with permission from Elsevier (2021).

onset of structural failure and maintaining the integrity of the concrete during exposure to fire.

Recently, Ranjetha et al. [25] adopted new techniques in the production of new construction units in an attempt to reduce greenhouse gases and enhance the environment and sustainable construction industry, and they adopted new construction materials instead of traditional ones in the construction of new houses. They used POC as aggregate in GPC with POFA as a binder material to produce two single-story houses, specifically geopolymer concrete house (GPCH) and low-cost model house (LCMH), that were constructed using eco-friendly materials at the University of Malaya campus as shown in Figure 10.

The experimental validation of GPC with POC has shown promising results, highlighting its potential as a sustainable and high-performance alternative to conventional concrete. Ahmat et al. [47] evaluated the potential use of POC as aggregate and eco-processed pozzolan (EPP) as a partial replacement of fly ash on the performance of GPC. They fixed ratios of sodium silicate to sodium hydroxide and alkaline activator to binder materials. They examined the compressive, flexural, and splitting tensile strengths and modulus of elasticity; in addition, the microstructure properties like XRD and SEM/EDS were also investigated. They observed that the compressive strength increased up to 39 MPa due to the use of 10%–30% of EPP instead of FA. At the same time, the lower specific gravity and stiffness of POC aggregate led to a decrease in the MOE of GPC compared to normal concrete. These attributes make it suitable for a wide range of construction and infrastructure applications.

Jagaba et al. [5] discussed the effect of POC as aggregates on the different geopolymer and traditional concrete structures such as slabs, beams, and columns. Another study by Jagaba et al. [4] stated that the POC aggregate could be used in long-lasting and green structural lightweight concrete by adding fly ash as a binder in GPC to improve the resistance of water absorption [72]. Nazari et al. [32] reported that the use of POC aggregate in the GPC samples decreases the resistance to water permeability at long curing ages. Nevertheless, the application of the POC aggregates leads to improving the resistance for water absorption to be appropriate for LWC applications. Malkawi [72] used POC as fine and coarse aggregates in the production of lightweight GPC with density and compressive strength of 1821 kg/m^3 and 30 MPa, respectively. They observed that the use of a geopolymer binder increases the workability and strength of GPC samples. Other researchers used the POC aggregates in different amounts to produce GPC. They produced beams and investigated the effect of POC aggregates on the ductile behavior of the beams and their failure by presenting normal structural. They depicted that the crack width at service load was between 0.24 and 0.3 mm, and this value was within the limit value according to the BS8110 [109]. In general, GPC containing POC has several potential field applications, particularly in construction and civil engineering, due to its promising properties. GPC with POC can be used in beams, columns, and slabs due to its good compressive strength and durability [4]. Its quick setting time makes it suitable for precast concrete products like panels, blocks, and tiles [110]. It can also be used for non-load-bearing walls, facades, and partitions. The material's high durability and resistance to chemical attack make it ideal for use in road bases and subbases. Due to its high resistance to chloride ion penetration, it can be used in marine structures like seawalls, piers, and docks.

8 | Life Cycle Assessment

A life cycle assessment (LCA) of POC as an aggregate in GPC involves evaluating the environmental impacts associated with the entire life cycle of the material, from raw material extraction to production, use, and end-of-life disposal. Identify the source of POC and assess the environmental impacts of extracting and processing the raw material. There are numerous factors

FIGURE 10 | Low-cost model house (LCMH) made of eco-friendly materials at the University of Malaya campus [25]. Reprinted with permission from Elsevier (2022).

affecting the LCA of POC in GPC, such as land use change, energy consumption, water use, and potential ecosystem impacts. Analyze the transportation of POC from its source to the GPC production site [34]. It is essential to consider the emissions and energy consumption associated with transportation. Assess the environmental impacts of the GPC manufacturing process, including using POC as an aggregate. Evaluate energy consumption, emissions of greenhouse gases and other pollutants, and resource use. Evaluate the environmental performance during the use phase of GPC in construction by evaluating factors such as durability, energy efficiency, and maintenance requirements.

GPC containing POC can be compared to other sustainable aggregate alternatives on two main fronts: mechanical properties and environmental impact [47]. Generally, it shows compressive strengths in the range of 30–50 MPa, depending on the mix design and curing conditions. It typically achieves compressive strengths comparable to conventional concrete but can vary significantly based on the quality of recycled materials. When used, fly ash aggregates in GPC or traditional concrete can result in compressive strengths similar to those of GPC with POC, often in the range of 30–50 MPa. Also, GGBS aggregates often result in high compressive strengths, sometimes exceeding 50 MPa, due to their dense and durable nature. GPC containing POC has excellent durability, including resistance to chemical attacks. At the same time, RCA has lower durability due to the presence of old mortar and microcracks, although it can be improved with proper treatment and mix design. However, fly ash and GGBS have better durability due to the pozzolanic properties of fly ash and GGBS enhancing the geopolymer matrix.

Assessment of the potential for recycling or reusing GPC containing POC throughout the potential disposal options and their environmental impacts, such as landfilling or recycling, comparing the LCA results of GPC with POC to traditional concrete or other alternative materials. Finding out the environmental benefits or drawbacks due to the addition of POC in the GPC is one of the important factors in the LCA of POC. By conducting a thorough LCA, stakeholders can make informed decisions about the sustainability of using POC as an aggregate in GPC and identify opportunities for improvement in the material's environmental performance.

The main findings from the LCA of GPC containing POC are reduced CO_2 emissions as compared to traditional Portland cement-based concrete; GPC containing POC typically exhibits lower CO_2 emissions over its life cycle [25]. Saving energy is due to the fact that the production of GPC involves lower energy consumption compared to the manufacturing of traditional cement-based concrete. The use of POC in GPC can help conserve natural resources by reducing the demand for virgin aggregates and cementitious materials. Additionally, the incorporation of industrial by-products like POC helps divert waste from landfills, further contributing to resource conservation.

Recycling GPC containing POC at the end of its life cycle is a feasible practice that offers several environmental benefits. GPC containing POC generally exhibits high durability and strength, which can remain intact even after the end of its initial life cycle. This makes the concrete suitable for recycling and reuse. The mechanical properties of GPC make it suitable for crushing and reprocessing into recycled aggregate. The POC within the concrete can contribute to maintaining the integrity of the recycled material. Recycled aggregates from GPC containing POC can be used to produce new GPC or traditional concrete, reducing the need for virgin aggregates. By reusing POC and other constituents of GPC, the construction industry can close the material loop, promoting a circular economy and enhancing resource efficiency. Reducing landfill use also lowers waste management costs, providing economic benefits and encouraging sustainable waste management practices. This results in lower overall energy consumption and reduced carbon emissions.

8.1 | Environmental Benefits Due to Use of POC in GPC

The environmental benefits of using POC as aggregates in GPC mixtures are significant, with the primary advantage being the reduction in the use of raw materials, such as aggregates, in GPC production. POC can effectively reduce the weight of GPC structures while enhancing their strength, particularly when used in low replacement levels. Additionally, the utilization of POC helps in reducing waste generated from the palm oil industry, contributing significantly to the recycling of waste materials and promoting a sustainable environment.

Moreover, the use of GPC instead of traditional cement concretes contributes significantly to the reduction of CO_2 emissions, thereby creating a cleaner environment with lower pollution levels. This reduction is attributed to the lower energy consumption required for the calcination of limestone, a process that releases substantial amounts of CO_2 emissions into the atmosphere during the production of normal cement concretes. Furthermore, GPC typically requires lower energy and temperature compared to traditional cement concretes, making it an innovative solution for reducing CO_2 emissions and conserving energy in the construction industry. By using POC as fine and coarse aggregates in GPC production, raw materials are conserved for future generations, as it reduces the need for natural aggregates such as river sand, mining sand, gravel, and crushed stone, thus promoting sustainability in the concrete industry. Additionally, using POC as aggregates in GPC improves the service life of structures, as the durability of GPC containing POC is superior to that of cement concretes, leading to reduced maintenance requirements.

The adoption of POC in GPC is influenced by various environmental regulations that can either support or hinder its use. These regulations encourage sustainable practices and the circular economy, making it easier for industries to utilize waste materials like POC. In some regions, severe regulations on waste classification and handling may pose challenges. Standards that allow for the use of alternative and sustainable materials in construction projects support the adoption of GPC with POC. Green building certifications and sustainable construction codes often encourage the use of eco-friendly materials. The lack of specific standards for GPC may create uncertainty and limit its acceptance in mainstream construction. Regulations aimed at reducing carbon emissions in the construction sector support the use of low-carbon materials like GPC with POC.

8.2 | Economic Benefits Due to the Use of POC in GPC

The use of POC as aggregates in the production of GPC has a significant impact on cost savings. POC, being a by-product of the palm oil industry, is often available in large quantities at little or no cost, unlike river sand and crushed stone. Therefore, using POC as aggregates helps reduce the cost of GPC compared to traditional cement concretes, especially when natural aggregates are scarce and expensive. Additionally, transportation costs are reduced, particularly in areas with palm oil mills, as the need to import natural aggregates from distant locations is minimized. In countries like Malaysia, Indonesia, and Thailand, proximity to palm oil mills not only reduces transportation costs but also helps reduce CO_2 emissions associated with transportation, thus benefiting the economy.

The production process for GPC using POC requires lower energy compared to traditional cement concrete, resulting in lower overall production costs. Furthermore, the elimination of limestone calcination in GPC production further reduces energy requirements and costs. The use of POC in GPC enhances workability and durability properties, potentially leading to lower construction and maintenance costs over the life cycle of a structure. By creating a market for POC in GPC production, the palm oil industry can diversify its revenue streams and reduce waste disposal costs, contributing to its overall economic sustainability.

Scaling up the production of GPC-containing POC for commercial use presents several challenges. Addressing these challenges requires a multifaceted approach involving technological advancements, industry collaboration, regulatory support, and market development. Variability in the quality and properties of POC may affect the performance of GPC. Establish partnerships with palm oil producers to secure a reliable supply of POC. Implement quality control measures to standardize the properties of POC used in GPC production. Developing optimal mix designs that consistently meet performance criteria for various applications can be complex. Conduct extensive research and development to refine mix designs. Use advanced modeling and simulation tools to predict performance and optimize the mix. Explore cost-saving measures such as local sourcing of materials and optimizing production processes. Provide financial incentives or subsidies to offset higher initial costs.

Overall, the use of POC as aggregates in GPC can lead to a reduction in total production costs and provide significant economic benefits, especially for regions with abundant palm oil waste [34, 67]. Using POC as an aggregate can be much cheaper than sourcing traditional aggregates like sand and gravel. In GPC, the primary binder is an alkali-activated aluminosilicate material such as fly ash and slag. The use of POC can reduce the demand for these materials slightly because they act as an aggregate, potentially leading to additional cost savings. Utilizing POC as an aggregate helps mitigate waste disposal costs associated with palm oil production. This can result in significant savings for palm oil mills, which otherwise would incur expenses related to the disposal of clinker waste.

9 | Discussion of the Results

This study provides significant information on the properties of GPC containing POC aggregate such as workability, density, mechanical, and durability properties, in addition to microstructure properties, applications of GPC in the construction industry, and LCA. The incorporation of POC is one of the enhancement solutions for the properties of GPC. This review highlights that POC aggregate mainly contributed to reducing the density of the GPC without compromising its strength. The compressive strength of GPC with POC is found to be comparable to that of traditional concrete, making it a viable alternative for sustainable construction practices [35]. The specific surface area and porous nature of POC also improve the bonding and interlocking within the matrix, resulting in improved compressive strength and overall durability of the concrete.

Additionally, GPC with POC exhibits excellent resistance to chemical attacks, including sulfate and acid attacks, due to the inherent properties of the geopolymer matrix and the stability of POC [34]. This makes it suitable for use in harsh environments and extends the service life of the concrete structures. Finally, the study focuses on the environmental and economic benefits of using POC in GPC. POC is a waste by-product of the palm oil industry, and its utilization in concrete production addresses waste management issues while promoting sustainability. The review emphasizes that using POC as an aggregate in GPC reduces the reliance on natural aggregates, conserving natural resources and reducing the environmental footprint of concrete production. Economically, the integration of POC can lower the material costs, given its abundance and low cost compared to conventional aggregates. This makes GPC with POC not only an environmentally friendly option but also a cost-effective solution for sustainable construction projects.

10 | Summary and Conclusions

In summary, the combination of POC derived from palm oil waste into GPC offers a sustainable solution with several key findings:

1. POC, a by-product of palm oil waste incineration, can be processed into aggregates, providing sustainable use of waste materials and supporting environmental sustainability by conserving natural aggregates and reducing waste accumulation.
2. The fresh properties of GPC, like density and workability, are significantly impacted by POC content, suggesting potential applications for lighter concrete. The density of GPC reduced from 2345 to 1821 kg/m^3 due to an increase in POC aggregate replacement from 0% to 100%. Workability issues with POC aggregates can be mitigated through mix design optimization or the addition of some additives like superplasticizers.
3. The mechanical properties of GPC, such as compressive, flexural, and tensile strength, are influenced by POC content and other factors, including binder composition and aggregate size. The addition of POC as coarse aggregate increased the compressive strength of concrete from

34 to 39 MPa and from 29 to 35 MPa. While in other cases reduced to less than the control sample. Durability aspects, such as water absorption and sulfate resistance, are variably affected by POC, indicating a nuanced impact on GPC's longevity.

4. POC shows promise for use in both structural and nonstructural concrete elements, with potential for broader application with further enhancement of its characteristics.
5. The use of POC as aggregates in GPC has numerous environmental and economic benefits, especially in reducing the cost, energy, and CO_2 emissions. Therefore, it has a significant effect on enhancing sustainability in the construction industry.

Overall, POC presents a viable alternative to natural aggregates, contributing to the construction industry's environmental stewardship and advancing sustainable material technology. It is recommended to investigate the long-term exposure tests under various environmental conditions such as freeze-thaw cycles, marine environments, and chemical exposure to evaluate the durability and service life of GPC with POC. Conduct detailed life cycle assessments to quantify the environmental impact of GPC with POC, including energy consumption, carbon emissions, and resource utilization from cradle to grave, and compare the LCA results of GPC with POC against traditional concrete and other sustainable alternatives to highlight its environmental advantages.

References

1. L. Naidu and R. Moorthy, "A Review of Key Sustainability Issues in Malaysian Palm Oil Industry," *Sustainability* 13 (2021): 10839.

2. R. Uning, M. T. Latif, M. Othman, et al., "A Review of Southeast Asian Oil Palm and its CO_2 Fluxes," *Sustainability* 12 (2020): 5077.

3. A. M. Al-Sabaeei, A. Al-Fakih, S. Noura, et al., "Utilization of Palm Oil and its By-Products in Bio-Asphalt and Bio-Concrete Mixtures: A Review," *Construction and Building Materials* 337 (2022): 127552.

4. A. H. Jagaba, S. R. M. Kutty, G. Hayder, et al., "A Systematic Literature Review on Waste-To-Resource Potential of Palm Oil Clinker for Sustainable Engineering and Environmental Applications," *Materials* 14 (2021): 4456.

5. A. H. Jagaba, S. R. M. Kutty, G. H. A. Salih, et al., *Palm Oil Clinker as a Waste By-product: Utilization and Circular Economy Potential* (London: IntechOpen, 2021).

6. A. Rifin, Feryanto, Herawati, and Harianto, "Assessing the Impact of Limiting Indonesian Palm Oil Exports to the European Union," *Journal of Economic Structures* 9 (2020): 26.

7. A. Adesina, "Recent Advances in the Concrete Industry to Reduce Its Carbon Dioxide Emissions," *Environmental Challenges* 1 (2020): 100004.

8. P. N. Ojha, B. Singh, P. Kaura, and A. Singh, "Lightweight Geopolymer Fly Ash Sand: An Alternative to Fine Aggregate for Concrete Production," *Research on Engineering Structures and Materials* 7 (2021): 375–391.

9. J.-F. Rousseau, A. Lauzon, and M. Marschke, "Can Green Concrete Help Address the Sand and Aggregate Crisis? A Scoping Literature Review," *Journal of Environmental Planning and Management*, (2024): 1–19, https://doi.org/10.1080/09640568.2024.2303630.

10. A. Jahami and C. A. Issa, "Exploring the Use of Mixed Waste Materials (Mwm) in Concrete for Sustainable Construction: A Review," *Construction and Building Materials* 398 (2023): 132476.

11. S. Needhidasan, C. Vigneshwar, and B. Ramesh, "Amalgamation of E-Waste Plastics in Concrete With Super Plasticizer for Better Strength," *Materials Today: Proceedings* 22 (2020): 998–1003.

12. A. Kanellopoulos, D. Nicolaides, and M. F. Petrou, "Mechanical and Durability Properties of Concretes Containing Recycled Lime Powder and Recycled Aggregates," *Construction and Building Materials* 53 (2014): 253–259.

13. G. Sua-iam and N. Makul, "Potential Future Direction of the Sustainable Production of Precast Concrete With Recycled Concrete Aggregate: A Critical Review," *Engineered Science* 28 (2024): 1075.

14. M. Alnahhal, U. Alengaram, M. Jumaat, M. Alqedra, K. Mo, and M. Sumesh, "Evaluation of Industrial By-Products as Sustainable Pozzolanic Materials in Recycled Aggregate Concrete," *Sustainability* 9 (2017): 767.

15. E. Benhelal, G. Zahedi, E. Shamsaei, and A. Bahadori, "Global Strategies and Potentials to Curb CO2 Emissions in Cement Industry," *Journal of Cleaner Production* 51 (2013): 142–161.

16. A. Danish, T. Ozbakkaloglu, M. Ali Mosaberpanah, et al., "Sustainability Benefits and Commercialization Challenges and Strategies of Geopolymer Concrete: A Review," *Journal of Building Engineering* 58 (2022): 105005.

17. L. S. Wong, "Durability Performance of Geopolymer Concrete: A Review," *Polymers* 14 (2022): 868.

18. H. M. Hamada, F. M. Yahaya, K. Muthusamy, G. A. Jokhio, and A. M. Humada, "Fresh and Hardened Properties of Palm Oil Clinker Lightweight Aggregate Concrete Incorporating Nano-Palm Oil Fuel Ash," *Construction and Building Materials* 214 (2019): 344–354.

19. H. M. Hamada, A. A. Al-Attar, B. Tayeh, and F. B. M. Yahaya, "Optimizing the Concrete Strength of Lightweight Concrete Containing Nano Palm Oil Fuel Ash and Palm Oil Clinker Using Response Surface Method," *Case Studies in Construction Materials* 16 (2022): e01061.

20. H. M. Hamada, A. A. Al-Attar, B. Tayeh, F. Bin Mat Yahaya, and Y. I. Abu Aisheh, "Optimising Concrete Containing Palm Oil Clinker and Palm Oil Fuel Ash Using Response Surface Method," *Ain Shams Engineering Journal* 14 (2023): 102150.

21. H. M. Hamada, A. A. Alattar, F. M. Yahaya, K. Muthusamy, and B. A. Tayeh, "Mechanical Properties of Semi-Lightweight Concrete Containing Nano-Palm Oil Clinker Powder," *Physics and Chemistry of the Earth, Parts a/b/c* 121 (2021): 102977.

22. H. M. Hamada, G. A. Jokhio, A. A. Al-Attar, et al., "The Use of Palm Oil Clinker as a Sustainable Construction Material: A Review," *Cement and Concrete Composites* 106 (2020): 103447.

23. I. I. Bashar, U. J. Alengaram, and M. Z. Jumaat, "Enunciation of Embryonic Palm Oil Clinker Based Geopolymer Concrete and Its Engineering Properties," *Construction and Building Materials* 318 (2022): 125975.

24. J. Kanadasan, H. A. Razak, and V. Subramaniam, "Properties of High Flowable Mortar Containing High Volume Palm Oil Clinker (POC) Fine for Eco-Friendly Construction," *Journal of Cleaner Production* 170 (2018): 1244–1259.

25. K. Ranjetha, U. J. Alengaram, A. M. Alnahhal, S. Karthick, W. W. Zurina, and K. Rao, "Towards Sustainable Construction Through the Application of Low Carbon Footprint Products," *Materials Today: Proceedings* 52 (2022): 873–881.

26. A. Nazari, "Retracted Article: Artificial Neural Networks Application to Predict the Compressive Damage of Lightweight Geopolymer," *Neural Computing and Applications* 23 (2013): 507–518.

27. B. C. McLellan, R. P. Williams, J. Lay, A. Van Riessen, and G. D. Corder, "Costs and Carbon Emissions for Geopolymer Pastes in Comparison to Ordinary Portland Cement," *Journal of Cleaner Production* 19 (2011): 1080–1090.

28. I. Asadi, M. H. Baghban, M. Hashemi, N. Izadyar, and B. Sajadi, "Phase Change Materials Incorporated into Geopolymer Concrete for Enhancing Energy Efficiency and Sustainability of Buildings: A Review," *Case Studies in Construction Materials* 17 (2022): e01162.

29. R. Kumar, M. Verma, and N. Dev, "Investigation on the Effect of Seawater Condition, Sulphate Attack, Acid Attack, Freeze–Thaw Condition, and Wetting–Drying on the Geopolymer Concrete," *Iranian Journal of Science and Technology, Transactions of Civil Engineering* 46 (2022): 2823–2853.

30. A. Özcan and M. B. Karakoç, "The Resistance of Blast Furnace Slag- and Ferrochrome Slag-Based Geopolymer Concrete Against Acid Attack," *International Journal of Civil Engineering* 17 (2019): 1571–1583.

31. M. A. Asaad, G. F. Huseien, R. P. Memon, S. K. Ghoshal, H. Mohammadhosseini, and R. Alyousef, "Enduring Performance of Alkali-Activated Mortars With Metakaolin as Granulated Blast Furnace Slag Replacement," *Case Studies in Construction Materials* 16 (2022): e00845.

32. A. Nazari, S. Riahi, and A. Bagheri, "Designing Water Resistant Lightweight Geopolymers Produced From Waste Materials," *Materials & Design* 35 (2012): 296–302.

33. M. S. Saad, Wirzal, M. D. H., Putra, Z. A. "Review on Current Approach for Treatment of Palm Oil Mill Effluent: Integrated System," *Journal of Environmental Management* 286 (2021): 112209.

34. P. Darvish, U. Johnson Alengaram, Y. Soon Poh, S. Ibrahim, and S. Yusoff, "Performance Evaluation of Palm Oil Clinker Sand as Replacement for Conventional Sand in Geopolymer Mortar," *Construction and Building Materials* 258 (2020): 120352.

35. S. M. A. Kabir, U. J. Alengaram, M. Z. Jumaat, S. Yusoff, A. Sharmin, and I. I. Bashar, "Performance Evaluation and Some Durability Characteristics of Environmental Friendly Palm Oil Clinker Based Geopolymer Concrete," *Journal of Cleaner Production* 161 (2017): 477–492.

36. H. M. Hamada, A. Al-Attar, J. Shi, F. Yahaya, M. S. Al Jawahery, and S. T. Yousif, "Optimization of Sustainable Concrete Characteristics Incorporating Palm Oil Clinker and Nano-Palm Oil Fuel Ash Using Response Surface Methodology," *Powder Technology* 413 (2023): 118054.

37. S. Nandy, E. Fortunato, and R. Martins, "Green Economy and Waste Management: An Inevitable Plan for Materials Science," *Progress in Natural Science: Materials International* 32 (2022): 1–9.

38. M. Samadi, G. F. Huseien, H. Mohammadhosseini, et al., "Waste Ceramic as Low Cost and Eco-Friendly Materials in the Production of Sustainable Mortars," *Journal of Cleaner Production* 266 (2020): 121825.

39. A. A. Meena R, M. J, R. Banu J, et al., "A Review on the Pollution Assessment of Hazardous Materials and the Resultant Biorefinery Products in Palm Oil Mill Effluent," *Environmental Pollution* 328 (2023): 121525.

40. H. Mohammadhosseini, R. Alyousef, and M. Md. Tahir, "Towards Sustainable Concrete Composites Through Waste Valorisation of Plastic Food Trays as Low-Cost Fibrous Materials," *Sustainability* 13 (2021): 2073.

41. S. S. Sinoh, F. Othman, and C. C. Onn, "Circular Economy Potential of Sustainable Aggregates for the Malaysian Construction Industry," *Sustainable Cities and Society* 89 (2023): 104332.

42. P. Azarsa and R. Gupta, "Comparative Study Involving Effect of Curing Regime on Elastic Modulus of Geopolymer Concrete," *Buildings* 10 (2020): 101.

43. N. Shehata, O. A. Mohamed, E. T. Sayed, M. A. Abdelkareem, and A. G. Olabi, "Geopolymer Concrete as Green Building Materials: Recent Applications, Sustainable Development and Circular Economy Potentials," *Science of the Total Environment* 836 (2022): 155577.

44. M. S. Imbabi, C. Carrigan, and S. McKenna, "Trends and Developments in Green Cement and Concrete Technology," *International Journal of Sustainable Built Environment* 1 (2012): 194–216.

45. V. G. Larsen, N. Tollin, P. A. Sattrup, M. Birkved, and T. Holmboe, "What Are the Challenges in Assessing Circular Economy for the Built Environment? A Literature Review on Integrating LCA, LCC and S-LCA in Life Cycle Sustainability Assessment, LCSA," *Journal of Building Engineering* 50 (2022): 104203.

46. K. H. Mo, U. J. Alengaram, M. Z. Jumaat, S. P. Yap, and S. C. Lee, "Green Concrete Partially Comprised of Farming Waste Residues: A Review," *Journal of Cleaner Production* 117 (2016): 122–138.

47. A. Mahamat Ahmat, U. Johnson Alengaram, M. Fazaulnizam Shamsudin, et al., "Assessment of Sustainable Eco-Processed Pozzolan (EPP) From Palm Oil Industry as a Fly Ash Replacement in Geopolymer Concrete," *Construction and Building Materials* 387 (2023): 131424.

48. W. Gai, F. Dai, B. He, C. Zhou, M. Wei, and Y. Liu, "Influence of GGBFS and Alkali Activators on Macro-Mechanical Performance and Micro-Fracture Mechanisms of Geopolymer Concrete in Split Hopkinson Pressure Bar Tests," *Construction and Building Materials* 434 (2024): 136736.

49. A. Mehmood, M. Irfan-ul-Hassan, and N. Yaseen, "Role of Industrial By-Products and Metakaolin in the Development of Sustainable Geopolymer Blends: Upscaling From Laboratory-Scale to Pilot-Scale," *Journal of Building Engineering* 62 (2022): 105279.

50. H. M. Hamada, A. A. Al-Attar, B. Tayeh, F. Bin Mat Yahaya, and Y. I. Abu Aisheh, "Optimising Concrete Containing Palm Oil Clinker and Palm Oil Fuel Ash Using Response Surface Method," *Ain Shams Engineering Journal* 14 (2023): 102150.

51. N. S. A. Yaro, M. H. Sutanto, N. Z. Habib, et al., "Feasibility Evaluation of Waste Palm Oil Clinker Powder as a Fillers Substitute for Eco-Friendly Hot Mix Asphalt Pavement," *International Journal of Pavement Research and Technology* 17 (2024): 446–459.

52. P. Darvish, U. J. Alengaram, A. M. Alnahhal, Y. S. Poh, and S. Ibrahim, "Enunciation of Size Effect of Sustainable Palm Oil Clinker Sand on the Characteristics of Cement and Geopolymer Mortars," *Journal of Building Engineering* 44 (2021): 103335.

53. A. Sharmin, U. J. Alengaram, S. MohdZaminJumaat, and I. B. AlamgirKabir, "Engineering Properties of Lightweight Geopolymer Concrete With Oil Palm Shell and Palm Oil Clinker," *Revista Técnica de la Facultad de Ingeniería de la Universidad del Zulia* 38 (2015): 34–48.

54. *A. Standard, C109/C109M-16a, "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (using 2-in. Or [50-mm] Cube Specimens)," Committee C-1 on Cement* (West Conshohocken, PA: ASTM International, 2013).

55. J. Fořt, M. Mildner, M. Keppert, and R. Černý, "Waste Solidified Alkalis as Activators of Aluminosilicate Precursors: Functional and Environmental Evaluation," *Journal of Building Engineering* 54 (2022): 104598.

56. X. Chen and P. Mondal, "Effects of NaOH Amount on Condensation Mechanism to Form Aluminosilicate, Case Study of Geopolymer Gel Synthesized Via Sol–Gel Method," *Journal of Sol-Gel Science and Technology* 96 (2020): 589–603.

57. M. Z. Jumaat, U. J. Alengaram, R. Ahmmad, S. Bahri, and A. B. M. S. Islam, "Characteristics of Palm Oil Clinker as Replacement for Oil Palm Shell in Lightweight Concrete Subjected to Elevated Temperature," *Construction and Building Materials* 101 (2015): 942–951.

58. J. Kanadasan and H. Abdul Razak, "Engineering and Sustainability Performance of Self-Compacting Palm Oil Mill Incinerated Waste Concrete," *Journal of Cleaner Production* 89 (2015): 78–86.

59. M. R. Karim, H. Hashim, and H. Abdul Razak, "Assessment of Pozzolanic Activity of Palm Oil Clinker Powder," *Construction and Building Materials* 127 (2016): 335–343.

60. J. Kanadasan and H. Abdul Razak, "Utilization of Palm Oil Clinker as Cement Replacement Material," *Materials* 8 (2015): 8817–8838.

61. M. R. Karim, H. Hashim, and H. Abdul Razak, “Thermal Activation Effect on Palm Oil Clinker Properties and Their Influence on Strength Development in Cement Mortar,” *Construction and Building Materials* 125 (2016): 670–678.

62. R. Ahmmad, U. J. Alengaram, M. Z. Jumaat, N. H. R. Sulong, M. O. Yusuf, and M. A. Rehman, “Feasibility Study on the Use of High Volume Palm Oil Clinker Waste in Environmental Friendly Lightweight Concrete,” *Construction and Building Materials* 135 (2017): 94–103.

63. P. Cong and Y. Cheng, “Advances in Geopolymer Materials: A Comprehensive Review,” *Journal of Traffic and Transportation Engineering (English Edition)* 8 (2021): 283–314.

64. J. Kanadasan, A. Fauzi, H. Razak, P. Selliah, V. Subramaniam, and S. Yusoff, “Feasibility Studies of Palm Oil Mill Waste Aggregates for the Construction Industry,” *Materials* 8 (2015): 6508–6530.

65. M. R. Karim, H. Hashim, H. Abdul Razak, and S. Yusoff, “Characterization of Palm Oil Clinker Powder for Utilization in Cement-Based Applications,” *Construction and Building Materials* 135 (2017): 21–29.

66. M. Aslam, P. Shafigh, and M. Z. Jumaat, “Oil-Palm By-Products as Lightweight Aggregate in Concrete Mixture: A Review,” *Journal of Cleaner Production* 126 (2016): 56–73.

67. A. B. Malkawi, M. Habib, J. Aladwan, and Y. Alzubi, “Engineering Properties of Fibre Reinforced Lightweight Geopolymer Concrete Using Palm Oil Biowastes,” *Australian Journal of Civil Engineering* 18 (2020): 82–92.

68. F. Abutaha, H. A. Razak, H. A. Ibrahim, and H. H. Ghayeb, “Adopting Particle-Packing Method to Develop High Strength Palm Oil Clinker Concrete,” *Resources, Conservation and Recycling* 131 (2018): 247–258.

69. M. Aslam, P. Shafigh, M. Z. Jumaat, and M. Lachemi, “Benefits of Using Blended Waste Coarse Lightweight Aggregates in Structural Lightweight Aggregate Concrete,” *Journal of Cleaner Production* 119 (2016): 108–117.

70. B. S. Mohammed, W. Foo, K. Hossain, and M. Abdullahi, “Shear Strength of Palm Oil Clinker Concrete Beams,” *Materials & Design* 46 (2013): 270–276.

71. *ASTM, ASTM C136/C136M-19, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates* (PA: ASTM International West Conshohocken, 2019).

72. A. B. Malkawi, “Engineering Properties of Lightweight Geopolymer Concrete Using Palm Oil Clinker Aggregate,” *International Journal of GEOMATE* 18 (2020): 132–139.

73. W. Li, E. D. Shumuye, T. Shiying, Z. Wang, and K. Zerfu, “Eco-Friendly Fibre Reinforced Geopolymer Concrete: A Critical Review on the Microstructure and Long-Term Durability Properties,” *Case Studies in Construction Materials* 16 (2022): e00894.

74. F. Salari, U. J. Alengaram, A. M. Alnahhal, et al., “Promulgation of Sustainable Palm Oil Clinker Sand in the Development of Structural and Non-Structural Lightweight Foamed Concrete,” *Structural Concrete* 24 (2023): 3952–3968.

75. L. Berredjem, N. Arabi, and L. Molez, “Mechanical and Durability Properties of Concrete Based on Recycled Coarse and Fine Aggregates Produced from Demolished Concrete,” *Construction and Building Materials* 246 (2020): 118421.

76. C. ASTM, Standard Test Method for Flow of Hydraulic Cement Mortar, C1437 (2007).

77. S. Arafa, A. Milad, N. I. M. Yusoff, N. Al-Ansari, and Z. M. Yaseen, “Investigation into the Permeability and Strength of Pervious Geopolymer Concrete Containing Coated Biomass Aggregate Material,” *journal of Materials Research and Technology* 15 (2021): 2075–2087.

78. E. P. Koehler and D. W. Fowler, Summary of Concrete Workability Test Methods, Research Report ICAR-105-1 (2003).

79. H. Guo, Z. Tang, Q. Liu, et al., “Ultra-Stable Anti-Washout Cement Grout Achieved by Super Water Absorbing Villus-Like Nanocomposite Hydrogel,” *Construction and Building Materials* 301 (2021): 124035.

80. M. Sulaiman, M. Ali, M. Al-Amri, et al., “Properties of Concrete Containing Crushed Palm Oil Clinker as Partial Fine Aggregate Replacement.” *IOP Conference Series: Materials Science and Engineering* (IOP Publishing, 2020), 012020.

81. F. A. Shilar, S. V. Ganachari, V. B. Patil, T. M. Y. Khan, S. Javed, and R. U. Baig, “Optimization of Alkaline Activator on the Strength Properties of Geopolymer Concrete,” *Polymers* 14 (2022): 2434.

82. F. A. Shilar, S. V. Ganachari, V. B. Patil, T. M. Y. Khan, and S. Dawood Abdul Khadar, “Molarity Activity Effect on Mechanical and Microstructure Properties of Geopolymer Concrete: A Review,” *Case Studies in Construction Materials* 16 (2022): e01014.

83. L. J. Chai, P. Shafigh, and H. Bin Mahmud, “Production of High-Strength Lightweight Concrete Using Waste Lightweight Oil-Palm-Boiler-Clinker and Limestone Powder, European,” *Journal of Environmental and Civil Engineering* 23 (2019): 325–344.

84. N. I. Azlan, A. H. Ismail, and A. Kusbiantoro, “Strength Development of Geopolymer Concrete Containing Palm Oil Clinker Powder,” *Progress in Engineering Application and Technology* 3 (2022): 351–358.

85. M. N. Huda, M. Z. B. Jumat, and A. S. Islam, “Flexural Performance of Reinforced Oil Palm Shell & Palm Oil Clinker Concrete (PSCC) Beam,” *Construction and Building Materials* 127 (2016): 18–25.

86. V. G. Haach, G. Vasconcelos, and P. B. Lourenço, “Influence of Aggregates Grading and Water/Cement Ratio in Workability and Hardened Properties of Mortars,” *Construction and Building Materials* 25 (2011): 2980–2987.

87. Y. Y. Saloni, T. M. Parveen, Y. Y. Lim, and T. M. Pham, “Effective Utilisation of Ultrafine Slag to Improve Mechanical and Durability Properties of Recycled Aggregates Geopolymer Concrete,” *Cleaner Engineering and Technology* 5 (2021): 100330.

88. G. Lavanya and J. Jegan, “Durability Study on High Calcium Fly Ash Based Geopolymer Concrete,” *Advances in Materials Science and Engineering* 2015 (2015): 1–7.

89. A. M. Neville, *Properties of Concrete* (London: Longman, 1995).

90. P. Sukmak, P. De Silva, S. Horpibulsuk, and P. Chindaprasirt, “Sulfate Resistance of Clay-Portland Cement and Clay High-Calcium Fly Ash Geopolymer,” *Journal of Materials in Civil Engineering* 27 (2015): 04014158.

91. L. Wu, N. Farzadnia, C. Shi, Z. Zhang, and H. Wang, “Autogenous Shrinkage of High Performance Concrete: A Review,” *Construction and Building Materials* 149 (2017): 62–75.

92. B. Zhang, H. Zhu, P. Feng, and P. Zhang, “A Review on Shrinkage-Reducing Methods and Mechanisms of Alkali-Activated/Geopolymer Systems: Effects of Chemical Additives,” *Journal of Building Engineering* 49 (2022): 104056.

93. V. Trincal, S. Multon, V. Benavent, et al., “Shrinkage Mitigation of Metakaolin-Based Geopolymer Activated by Sodium Silicate Solution,” *Cement and Concrete Research* 162 (2022): 106993.

94. M. Aslam, P. Shafigh, and M. Z. Jumaat, “Drying Shrinkage Behaviour of Structural Lightweight Aggregate Concrete Containing Blended Oil Palm Bio-Products,” *Journal of Cleaner Production* 127 (2016): 183–194.

95. L. Su, Y.-F. Wang, S.-Q. Mei, and P.-F. Li, “Experimental Investigation on the Fundamental Behavior of Concrete Creep,” *Construction and Building Materials* 152 (2017): 250–258.

96. Z. Pan, J. G. Sanjayan, and F. Collins, “Effect of Transient Creep on Compressive Strength of Geopolymer Concrete for Elevated Temperature Exposure,” *Cement and Concrete Research* 56 (2014): 182–189.

97. C. Jiang, C. Jin, Y. Wang, S. Yan, and D. Chen, "Effect of Heat Curing Treatment on the Drying Shrinkage Behavior and Microstructure Characteristics of Mortar Incorporating Different Content Ground Granulated Blast-Furnace Slag," *Construction and Building Materials* 186 (2018): 379–387.

98. Z. Q. Tang, F. B. De Souza, R. J. Mulder, W. Kwesisagoe-Crentsil, and W. Duan, "Multistep Nucleation and Growth Mechanism of Aluminosilicate Gel Observed by Cryo-Electron Microscopy," *Cement and Concrete Research* 159 (2022): 106873.

99. P. T. Durdziński, C. F. Dunant, M. B. Haha, and K. L. Scrivener, "A New Quantification Method Based on SEM-EDS to Assess Fly Ash Composition and Study the Reaction of Its Individual Components in Hydrating Cement Paste," *Cement and Concrete Research* 73 (2015): 111–122.

100. H. Alanazi, "Study of the Interfacial Transition Zone Characteristics of Geopolymer and Conventional Concretes," *Gels* 8 (2022): 105.

101. F. A. Shilar, S. V. Ganachari, V. B. Patil, B. E. Bhojaraja, T. M. Yunus Khan, and N. Almakayeel, "A Review of 3D Printing of Geopolymer Composites for Structural and Functional Applications," *Construction and Building Materials* 400 (2023): 132869.

102. F. A. Shilar, S. V. Ganachari, V. B. Patil, N. Almakayeel, and T. M. Yunus Khan, "Development and Optimization of an Eco-Friendly Geopolymer Brick Production Process for Sustainable Masonry Construction," *Case Studies in Construction Materials* 18 (2023): e02133.

103. F. A. Shilar, S. V. Ganachari, V. B. Patil, I. Neelakanta Reddy, and J. Shim, "Preparation and Validation of Sustainable Metakaolin Based Geopolymer Concrete for Structural Application," *Construction and Building Materials* 371 (2023): 130688.

104. F. A. Shilar, S. V. Ganachari, V. B. Patil, and K. S. Nisar, "Evaluation of Structural Performances of Metakaolin Based Geopolymer Concrete," *Journal of Materials Research and Technology* 20 (2022): 3208–3228.

105. F. A. Shilar, S. V. Ganachari, V. B. Patil, S. Javed, T. M. Y. Khan, and R. U. Baig, "Assessment of Destructive and Nondestructive Analysis for GGBS Based Geopolymer Concrete and its Statistical Analysis," *Polymers* 14 (2022): 3132.

106. N. S. A. Yaro, M. B. Napiah, M. H. Sutanto, A. Usman, A. A. Murana, and W. Rafiq, "Effect of Palm Oil Clinker Powder-based Geopolymer on Bitumen and Asphalt Mixture Properties," *Third International Sustainability and Resilience Conference: Climate Change* (IEEE, 2021), 310–315.

107. Y. Agrawal, T. Gupta, R. Sharma, N. L. Panwar, and S. Siddique, "A Comprehensive Review on the Performance of Structural Lightweight Aggregate Concrete for Sustainable Construction," *Construction Materials* 1 (2021): 39–62.

108. G. Kaplan, A. Öz, B. Bayrak, and A. C. Aydın, "The Effect of Geopolymer Slurries With Clinker Aggregates and Marble Waste Powder on Embodied Energy and High-Temperature Resistance in Prepacked Concrete: Anfis-Based Prediction Model," *Journal of Building Engineering* 67 (2023): 105987.

109. B. S. Mohammed, W. Foo, and M. Abdullahi, "Flexural Strength of Palm Oil Clinker Concrete Beams," *Materials & Design* 53 (2014): 325–331.

110. A. V. Isaza, J. M. Arcila, J. Restrepo, M. V. García, and L. W. Peña, *Performance and Applications of Lightweight Geopolymer and Alkali Activated Composites With Incorporation of Ceramic, Polymeric and Lignocellulosic Wastes as Aggregates: A Review* (Heliyon, 2023).