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Impact of rice husk ash on geopolymer concrete: A literature review and future directions

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ABSTRACT

In recent years, the pursuit of sustainable materials in concrete production has increased, driven by the essentials of environmental conservation, energy efficiency, and resource optimization in construction. Rice husk ash (RHA), distinguished for its abundant silica content, has emerged as a promising biomass-derived material capable of enhancing both the performance and sustainability of geopolymer concrete (GPC) structures. This study undertakes a comprehensive review of literature published between 2014 and 2024, focusing on the chemical composition and physical properties of RHA, and its influence on the physical, mechanical, durability, and microstructural properties of GPC. The results indicated that the addition of a small amount of RHA enhances the strength and durability of concrete, especially with Metakaolin (MK). For instance, the addition of 15 % RHA increases the compressive strength by 21 %. The addition of 20 % RHA reduced the water absorption of GPC by 14 %. Furthermore, the research supports the extensive utilization of treated RHA to counteract the adverse effects associated with conventional cement concrete, thereby fostering greater sustainability in construction practices.

1. Introduction

In the search for sustainable construction practices, the integration of biomass into concrete formulations has emerged as a critical area of research and development. Rice husk ash (RHA), a byproduct of rice milling processes, has surfaced as an abundant and environmentally friendly resource with huge potential for application in concrete technology [1,2]. RHA is an agricultural waste produced from the grinding of rice, which is frequently underutilized or landfilled, leading to negative environmental effects and higher costs to produce rice [3]. As the rice production rate increases, the RHA amounts increase, and this increase is associated with the increase in populations and their food requirements. Its high silica content and pozzolanic properties render it an attractive candidate for enhancing the mechanical strength, durability, and sustainability of concrete structures [4]. Therefore, the use of RHA as

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a cementitious material in normal concretes has been widely investigated [5–7]. On the other hand, to mitigate the harm of cement on the environment and to enhance the concrete properties, a new product instead of normal concrete has appeared, namely GPC [8]. Davidovits in 1972 discovered that geo-polymerization has a significant effect in enhancing the strength and durability of concrete [9]. GPC can be prepared with aluminosilicate materials without cement and thus can be considered as one of the best sustainable construction materials due to its contribution in reducing cement production [10,11]. The mix of GPC can be prepared from two significant parts, namely binder materials (alkali-activated materials) such as (NaOH and Na_2SiO_3) and raw materials with high silica (SiO_2) and Alumina (Al_2O_3) content, like blast furnace slag, fly ash, RHA, and kaolin [12,13]. Numerous researchers used fly ash as a rich material in silica and alumina oxides essential in geopolymerization process [14]. Others used GGBS [15,16] and Kaolin [17,18]. However, few studies used RHA as a geopolymer source instead of fly ash and GGBS [19,20].

Globally, rice is the second food crop, and the total production of rice between 2020 and 2021 reached up to 503 million tons of [21]. In a recent study by Kordi et al. [22], reported that the annual global rice production reached up to 150 million tons of husk that was generated from 750 million tons of grain. The increased amount of rice already generates higher amounts of rice husk, for each kg of rice, around 0.2–0.25 kg has been generated. Researchers observed that the agriculture waste as biomass has been rich in silica oxide more than 60 %, and has the potential to possess a high pozzolanic reaction [23,24]. The high silica content in these materials led to increased activity of pozzolanic, therefore, it has been extensively utilized in the production of GPC.

Liang [25] and Liu et al. [26] examined the influence of RHA as a biomass on the properties of GPC, such as compressive strength, thermal stability, and water absorption. Hossain et al. [19], conducted a comprehensive review on the effect of waste RHA as a sustainable material on the properties of GPC, especially on the pozzolanic activity and reduction of CO_2 emission. But did not focus on details of mechanical, durability, and microstructure properties of GPC. It also did not address the effect of different chemical compositions and physical properties on the performance of GPC. Also, Das et al. [3], conducted a review paper on the effect of RHA on the properties of alkali-activated materials (AAMs), especially related to the fresh and hardened mechanical properties, but they did not address durability and microstructure properties in detail. Even though RHA comprises non-crystalline silica and that making it is a highly pozzolanic reaction, especially when the rice husk is burning in organized situations. However, lack of studies investigated the chemical composition of RHA and its effect on the performance of GPC. There is no study reviewed the characterization of RHA in terms of chemical composition, physical properties, and microstructure and its effect on the physical, mechanical, durability, and microstructure properties of GPC. In addition to that, the effect of using RHA as an alumino-silicate on the environment and economic aspects has not investigated yet. Therefore, this paper introduced and prepared to close the knowledge gap and addressed these aspects as a comprehensive review of the characterization of RHA and its effect on the physical, mechanical, durability, and microstructure properties of GPC. Besides, identify the benefits desired due to the use of the RHA in GPC on the environmental and economic aspects.

1.1. Significance of study

GPC, characterized by its reliance on alkali-activated materials instead of conventional cement, has emerged as a viable alternative to traditional concrete [27]. Its composition typically includes pozzolanic materials, alkaline activators, aggregates, and water [28]. By substituting industrial byproducts like fly ash and slag with renewable biomasss such as RHA, GPC presents a promising avenue for reducing CO_2 emissions and reliance on non-renewable resources in the construction sector [29]. The incorporation of RHA into GPC mixtures offers numerous advantages, including reduced workability, enhanced mechanical properties, and reduced environmental impact [19]. The pozzolanic reactivity of RHA contributes to the formation of calcium silicate hydrate (C-S-H) gel, which serves as the primary binding phase in geopolymer matrices [30]. Furthermore, the high surface area and reactive nature of RHA facilitate the densification of concrete microstructure, resulting in enhanced strength and durability [31]. This review paper aims to provide a comprehensive analysis of the effect of RHA as a biomass on the performance of GPC. Through a systematic review of existing literature and experimental studies, it seeks to elucidate the influence of RHA content, particle size, curing conditions, and other key factors on the properties and behavior of GPC. By synthesizing and critically evaluating the available evidence, this paper intends to contribute to the body of knowledge surrounding sustainable concrete technologies and inform future research directions in the field.

2. Literature review

GPC has emerged as a promising alternative to traditional Portland cement-based concrete due to its potential to mitigate the environmental impact of construction activities [32]. GPC is characterized by its binder system, which relies on alkali-activated materials such as fly ash, slag, and metakaolin to form a durable and high-strength matrix [33]. Unlike conventional cement production, the manufacturing process of GPC generates lower CO_2 emissions and utilizes industrial byproducts, contributing to sustainability in the construction sector [34]. For instance, Geraldo et al. [35] used water treatment sludge (WTS) as partial replacement of metakaolin (MK). While the RHA was used in the GPC mix to save SiO_2/Al_2O_3 molar ratio constant. They concluded that the use of sodium silicate solution from RHA and non-calcined WTS as MK replacement in GP mortar is technically useful to achieve eco-friendly alternative for RHA and WTS disposal. Nuaklong et al. [36] used RHA from agricultural wastes and recycled aggregates in the production of GPC. Also, they used nano silica to enhance the properties of recycled aggregates and find out their effect on the fire-resistant performance and mechanical properties of GPC. They observed that the addition of RHA with high silica content had a negative influence on the post-fire residual strength of GPC.

RHA is a byproduct of rice milling processes and has garnered significant interest as a supplementary cementitious material in concrete production [37]. RHA possesses pozzolanic properties due to its high silica content, which enables it to react with calcium hydroxide in the presence of water, forming additional cementitious compounds [38]. As a renewable and abundantly available resource, RHA presents an attractive option for enhancing the performance and sustainability of concrete structures [39]. Numerous studies have investigated the influence of RHA on the mechanical properties of GPC. For instance, Nuaklongt al. [36], reported that the addition of RHA into GPC mixtures led to significant increase in strength of GPC to reach up to 38.1 MPa, mainly when increase the ratio of SiO_2/Al_2O_3 up to 4.17. Also, addition of RHA significantly improved the pozzolanic reactivity of GPC through formation of additional C-S-H gels, thus obtaining higher density and durability than that of GPC without RHA. As reported by Kim et al. [40], RHA is one of the highest two silica-rich sources utilized in GPC, namely Nano silica and RHA. However, RHA has better durability in terms of higher resistance against sulfate and acid attacks due to the absence of Ca $(OH)_2$.

The durability of GPC incorporating RHA has been extensively studied in various environmental conditions [41,42]. Research indicates that RHA enhances the resistance of GPC to chemical attack, sulfate attack, chloride ingress, and alkali-silica reaction [43]. The incorporation of RHA mitigates the deleterious effects of external factors on concrete performance, leading to increased service life and reduced maintenance requirements [44]. The addition of RHA to GPC mixtures can influence workability and setting time characteristics [45,46]. While higher RHA contents may result in reduced initial slump and extended setting times, proper mix design and optimization strategies can mitigate these effects. Studies have explored the use of superplasticizers, activator combinations, and curing regimes to achieve desired workability and setting properties in RHA-based GPC [47].

Microscopic analyses have provided insights into the microstructure of GPC incorporating RHA. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) techniques have revealed the formation of geopolymer gel and crystalline phases within the concrete matrix [48]. The presence of RHA particles promotes nucleation and growth of hydration products, leading to improved interfacial bonding and mechanical performance. The literature review highlights the significant impact of RHA as a biomass on the performance of GPC. Through its pozzolanic reactivity, RHA contributes to the enhancement of mechanical properties, durability, and microstructural characteristics of geopolymer matrices.

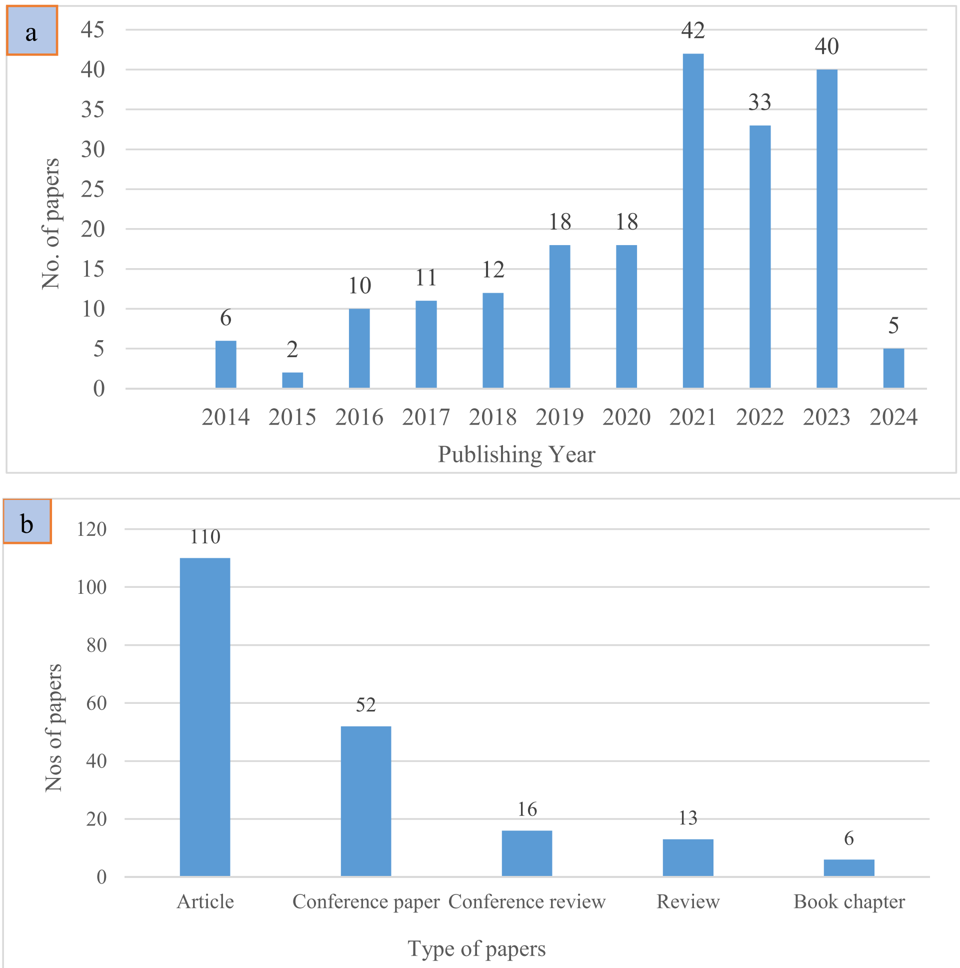

Fig. 1. (a) Number of papers vs publishing year and (b) Number of papers vs type of papers.

3. Methodology

The methodology for this review paper involves a comprehensive literature search to identify relevant studies and scholarly articles relating to the effect of RHA as a rich silica-biomass on the performance of GPC. A systematic approach has been adopted to ensure the inclusion of peer-reviewed journals, conference proceedings, books, and research reports published in reputable databases like Scopus and Google Scholar as specific dates between 2014 and 2024. Keywords and search terms related to "rice husk ash in geopolymer concrete" were adopted to download and collect the relevant papers on this topic. The selection criteria for inclusion in the review paper were determined to ensure the relevance and quality of the literature analyzed. Studies considered for inclusion focus on the use of RHA as a biomaterial in the formulation of GPC. The data collection was conducted in March 2024. Only peer-reviewed articles and academic publications written in English were included, while non-peer-reviewed sources and duplicate studies were excluded from the analysis. In the first stage, 197 papers were collected from the Scopus database and most of them were article papers about 110 and 52 conference papers as shown in Fig. 1b. While most papers were published in 2021 as shown in Fig. 1a. After the screening process, only 130 papers that have associated with the paper content were adopted to write this review paper, while other papers have been neglected.

The selected literature was systematically reviewed and analyzed to extract key findings, methodologies, experimental parameters, and conclusions related to the effect of RHA on the performance of GPC. Data extraction involved categorizing studies based on experimental design, RHA content, particle size distribution, curing conditions, mechanical properties, durability properties, and microstructural analyses. Fig. 2 shows the steps of the data collection method.

4. Characterization of RHA

4.1. Chemical composition of RHA

RHA is an agriculture by-product obtained from the combustion of rice husks, which are the outermost layer of rice grains. RHA is mainly composed of amorphous silica along with various other elements that contribute to its chemical properties [49]. The chemical composition of RHA varies depending on factors such as the source of rice husks, combustion conditions, and post-processing treatments [19]. Examining the chemical composition of RHA is essential for assessing its potential applications, particularly in the development of GPC formulations. Silica oxide (SiO_2) is the primary constituent of RHA, typically accounting for a significant portion of its composition [50]. The amorphous silica content in RHA contributes to its pozzolanic properties, which are crucial for enhancing the strength and durability of GPC matrices [31]. The high silica content in RHA promotes the formation of a stable geopolymer gel during alkali activation, thereby improving the mechanical properties of geopolymers [51]. Sore et al. [52], reported that the RHA comprises 20 % silica, 40 % cellulose, and 30 % lignin. RHA was used as a binder material in the mix with other aluminosilicate sources [53,54] in geopolymerization process, or as a silica source in the activator solution due to its high silica content [55].

Carbon is another component found in RHA, primarily resulting from the organic carbonaceous materials present in rice husks [39, 56]. The carbon content in RHA can influence its reactivity and pozzolanic activity, as well as the properties of geopolymers derived

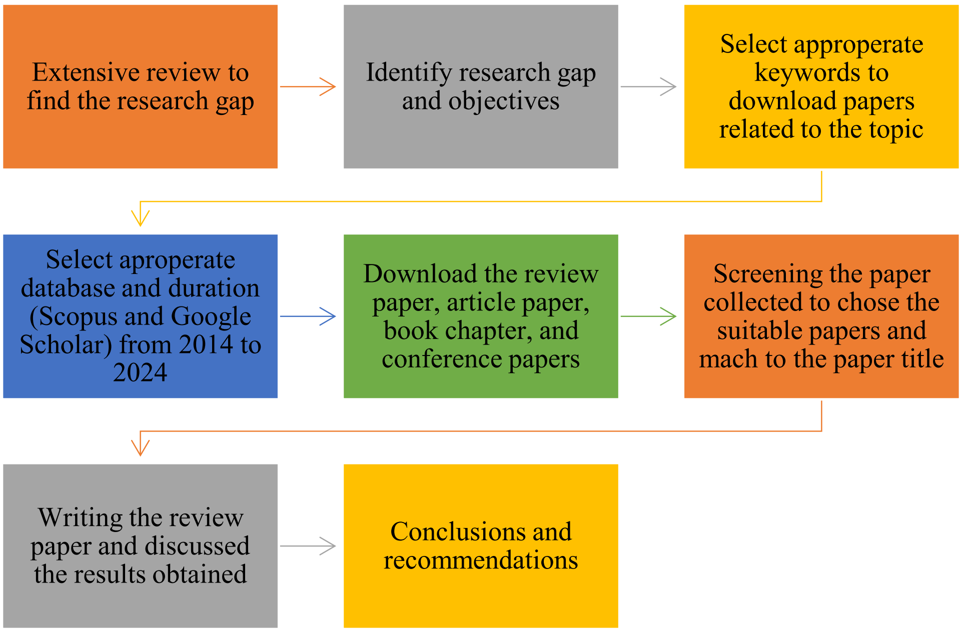

Fig. 2. Methodology for data collection.

from RHA-based binders [57]. RHA contains varying amounts of alkali and alkaline earth metal oxides, including potassium, sodium, calcium, and magnesium [58,59]. These elements may originate from the mineral content of rice husks and the combustion process. Alkali and alkaline earth metal oxides play a role in the alkali activation of RHA, facilitating the dissolution of silica and the formation of geopolymer gels. In addition to the major constituents mentioned above, RHA may contain trace elements such as phosphorus, sulfur, iron, and aluminum. The presence of these trace elements can influence the chemical and physical properties of RHA and its suitability for various applications in construction materials [3]. The chemical composition of RHA is characterized by its high silica content, along with other elements such as carbon, potassium, sodium, calcium, magnesium, and trace elements. Table 1 shows the chemical composition of RHA extracted from the previous studies.

As reported in Table 1, the silica oxide (SiO_2) in RHA, constitutes the highest percentage among other components, up to 96.2 % [20]. The highest proportion of silica oxide has a significant impact on the pozzolanic activity of RHA. On the other hand, RHA has a high LOI and needs further water for mixing, especially if used in large amounts, thus causing lower slump value and need for additives such as superplasticizer to obtain the required workability. The nature and quantity of SiO_2 and other chemical components of RHA are affected by numerous factors, like burning temperature and duration, and the cooling duration, thus these factors mainly affect the chemical composition and physical properties of RHA [68].

4.2. Physical properties of RHA

The physical properties of RHA play a significant role in its suitability as a supplementary cementitious material for GPC formulations. The physical characteristics of RHA are crucial for assessing its potential impact on the performance and properties of GPC [62]. RHA typically exhibits a wide range of particle sizes, ranging from fine powders to coarse particles. The particle size distribution of RHA can vary depending on factors such as the source of rice husks, combustion conditions, and post-processing techniques [19]. Finer particles contribute to the pozzolanic reactivity of RHA by increasing the surface area available for chemical reactions during alkali activation. The surface area of RHA particles directly influences their reactivity and pozzolanic activity in GPC systems. High surface area promotes increased interaction between RHA particles and alkaline activators, leading to enhanced geopolymerization and strength development [69]. Specific surface area measurements provide valuable insights into the physical characteristics and reactivity of RHA in cementitious matrices.

The density and bulk density of RHA influence its flowability, packing density, and handling characteristics in concrete mixtures [70,71]. RHA particles typically exhibit low densities compared to conventional cementitious materials, which can impact the workability and mechanical properties of GPC [72,73]. Determining the density and bulk density of RHA is essential for optimizing its dosage and incorporation into concrete mixes. RHA contains inherent porosity and pore structure, which can affect its water absorption, permeability, and durability in concrete applications [62]. The pore characteristics of RHA particles influence the distribution of pore sizes, pore connectivity, and capillary action within geopolymer matrices [74]. Controlling the porosity and pore structure of RHA-based geopolymers is essential for achieving desirable performance and long-term durability [75]. The physical properties of RHA, including particle size distribution, surface area, density, bulk density, porosity, and pore structure, play critical roles in its performance as a supplementary cementitious material in GPC [76]. For instance, Zhu et al. [67] examined the particle size distribution of RHA and slag, as shown in Fig. 3, and reported that RHA particles are finer than that of slag. The particle size of RHA is about 17.2 μm, while the particle size of slag is about 22.3 μm. These particle sizes play a significant role in enhancing the performance of GPC.

Determining and optimizing these physical characteristics are essential for maximizing the benefits of RHA in terms of strength, durability, and sustainability of concrete structures. Table 2 shows the physical properties of RHA used in the production of GPC by the previous studies.

4.3. Microstructure of RHA

The microstructure of RHA significantly influences its reactivity, pozzolanic activity, and performance as a supplementary

Table 1
Chemical composition of RHA.

References	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SiO_3	K_2O	Na_2O	P_2O_5	LOI
Pham [60]	90.00	0.46	0.43	1.10	0.77	—	4.60	——	2.43	3.90
Chelluri and Hossiney [61]	89.2	1.43	1.27	0.77	0.62	——	1.20	——	——	5.51
Lim et al. [62]	92.80	0.21	0.12	0.51	0.75	0.14	1.35	0.15	—	3.97
Das et al. [20]	96.23	0.281	1.366	0.578	0.269	0.202	0.454	0.054	0.361	——
Liang et al. [63]	93.97	0.37	0.21	1.00	0.47	0.16	2.16	0.08	—	—
Liu et al. [26]	93.01	0.21	0.22	1.43	0.43	——	2.12	0.24	1.32	——
Zhu et al. [64]	93.1	0.3	0.2	1.5	0.6		2.3	0.06		0.8
Pham et al. [46]	86.20	0.46	0.43	1.10	0.77	——	4.60	——	2.43	3.90
Geraldo et al. [35]	89.51	0.13	0.05	—	0.30	—	1.68	——	——	6.95
Jindal et al. [65]	90.0	0.46	0.43	1.1	0.77	—	4.6	—	2.43	3.9
Liang et al. [25]	93.1	0.3	0.2	1.5	0.6		2.3	0.06		0.8
Mahdi et al. [66]	88.84	0.81	0.83	1.68	0.44	0.35	2.06	0.18	—	2.73
Zhu et al. [67]	93.1	0.3	0.2	1.5	0.6		2.3	0.06		0.8

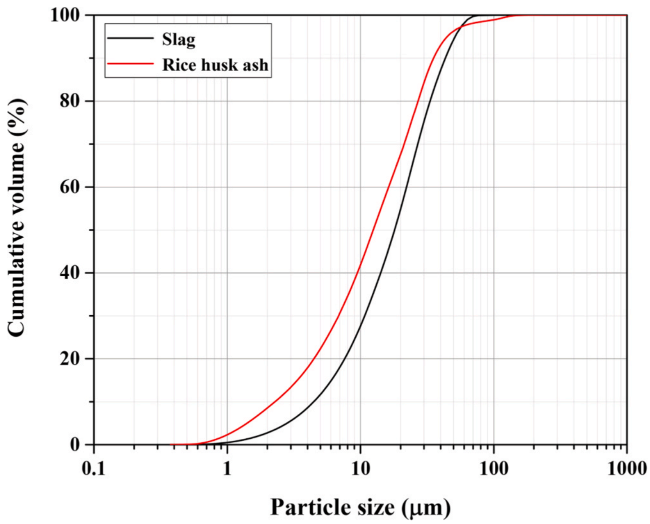

Fig. 3. Particle size distributions of RHA and slag [67].
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Table 2
physical properties of RHA.

References	Specific gravity	Bulk density kg/m^3	Particle size μm	Specific surface area m^2/kg
Pham [60]	2.18	2300	25	1434
Chelluri and Hossiney [61]	2.18	612	33	285
Liang et al. [63]	—	2260	2.43	1234
Liang et al. [25]	—	2300	12.5	757 00
Pham et al. [46]	2.26	—	11.86	910.60
Geraldo et al. [35]	2.14	473	20.4	6500
Mahdi et al. [66]	1.9		29.7	339

cementitious material in GPC production. Investigation of the microstructural characteristics of RHA is crucial for clarifying its mechanisms of interaction within cementitious matrices and optimizing its utilization in sustainable construction materials [57]. RHA particles exhibit diverse morphologies and shapes, ranging from irregularly shaped particles to spherical agglomerates [77]. The morphology and particle shape of RHA are influenced by factors such as the combustion process, temperature, and chemical composition of rice husks [57]. Irregularly shaped particles possess higher surface area and reactivity compared to spherical particles, facilitating enhanced pozzolanic reactions and geopolymerization in concrete matrices [78].

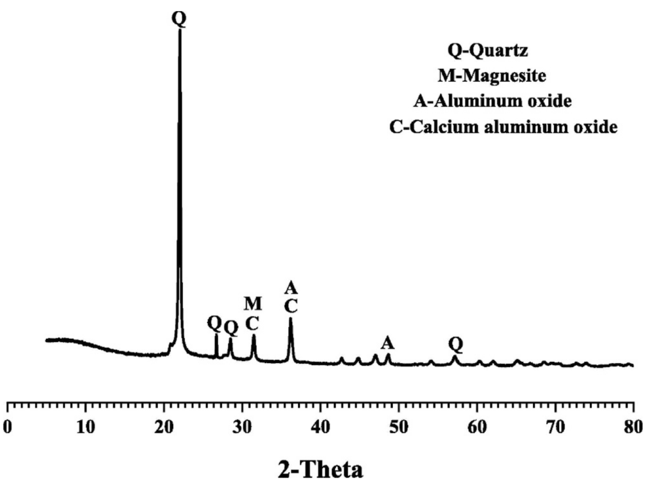

Fig. 4. XRD patterns of RHA [25].
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The microstructure of RHA is characterized by its high content of amorphous silica, which plays a pivotal role in the formation of geopolymer gels and the development of mechanical strength in concrete [75]. Amorphous silica particles in RHA exhibit high surface reactivity and provide nucleation sites for the precipitation of geopolymer phases during alkali activation [19]. The distribution and accessibility of amorphous silica within RHA particles influence the kinetics and extent of geopolymerization reactions in cementitious systems [21]. Liang et al. [25] investigated the effect of RHA on the GPC-based MK. They examined the pozzolanic activity using the XRD test and found that the high silica content of RHA was mostly amorphous with high activity, as shown in Fig. 4.

RHA contains inherent porosity and pore structure, which contribute to its water absorption, permeability, and interfacial bonding with surrounding cementitious phases [79]. The pore characteristics of RHA influence the transport of alkalis, water, and other chemical species within geopolymer matrices, thereby affecting the durability and mechanical properties of GPC [80]. The microstructural interface between RHA particles and alkaline activators plays a critical role in the formation and growth of geopolymer gel networks in concrete matrices [81]. The interfacial interactions between RHA and alkalis influence the dissolution kinetics, gel formation, and microstructural development of geopolymers. Controlling the interface characteristics enhances the homogeneity and strength of GPC while mitigating potential issues such as alkali leaching and efflorescence [82]. As reported by Zhu et al. [67], the RHA has a large amount of angular and irregular shape particles, with loose and layered structures, as shown in Fig. 5.

5. Effect of RHA on the physical properties of GPC

5.1. Effect of RHA on the setting time of GPC

The setting time of GPC is a critical parameter that significantly influences construction workability, and the overall performance of GPC structures [83]. The incorporation of RHA as a rich silica biomass in GPC production can have a notable impact on the setting time characteristics due to its chemical and physical properties [19]. RHA contains amorphous silica, which exhibits high pozzolanic reactivity and contributes to the acceleration of geopolymerization reactions in concrete matrices [84]. For instance, Chelluri and Hossiney [61] recently examined a setting time test on the geopolymer binder according to ASTM C191 [85]. They used a black RHA with and without fly ash and GGBS in the production of GPC mixtures and they observed that the initial and final settings are reducing as the RHA amount increases. This delay in setting time is due to the high content of soluble silica in black RHA which delays the setting time [86]. Liang et al. [87] reported that the addition of RHA and silica fume as supplementary cementitious materials (SCM) in different proportions into GP paste mixtures has a significant effect on the setting time. This effect is due to the further reactions made by RHA and silica fume. The dissolution of SiO_2 in RHA required extra time to complete. Therefore, the high-silica content in RHA and silica fume delayed the setting time of GP paste, as shown in Fig. 6. GPA-control is paste; GPA-R1 is paste with 10 % SCM; GPA-R2 is paste with 20 % SCM; GPA-R3 is paste with 30 % SCM; GPA-R4 is paste with 40 % SCM.

Another study stated that the fine particles and high surface area of RHA promote rapid dissolution and polymerization of alkali silicate solutions, leading to accelerated setting times in GPC mixes [19]. The presence of RHA can facilitate the early development of mechanical strength and reduce the overall setting time of GPC formulations [32]. Zhu et al. [86] examined the setting time of geopolymer paste containing RHA and metakaolin (MK) and found a relationship between the setting time of GPC and RHA content. They found that an increase in the RHA amount leads to a delay in the setting time of GPC [86]. This delay might be due to the slow dissolution of SiO_2. The interaction between RHA particles and alkaline activators influences the kinetics and extent of geopolymerization reactions, thereby affecting the setting time characteristics of GPC [47]. Proper dosage and particle size distribution of RHA are crucial for optimizing the setting time and workability of GPC mixes. The effect of RHA on the setting time of GPC can be

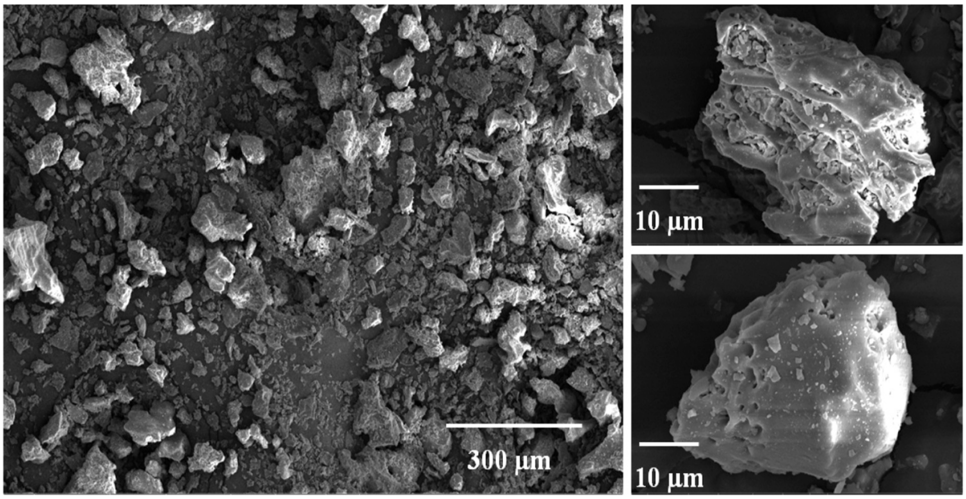

Fig. 5. SEM image of RHA [67].
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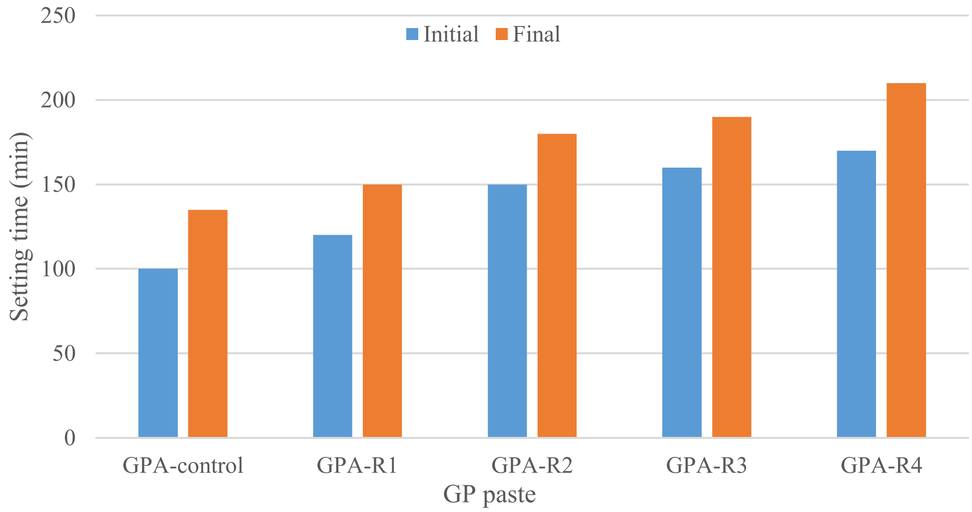

Fig. 6. The initial and final setting times of the GP paste [87].
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controlled and optimized through adjustments in mix proportions, curing conditions, and supplementary additives [88]. The use of RHA as a partial replacement for conventional cementitious materials allows for flexibility in tailoring the setting time properties of GPC to meet specific project requirements and performance criteria. The optimization of setting time characteristics in RHA-based GPC production aligns with sustainable construction practices and promotes the adoption of eco-friendly building materials [47]. Billong et al. [89] examined the setting time and consistency properties of the RHA/MK blend. They observed that the setting time of GPC is delayed as RHA increases. For instance, the initial setting times were 125, 150, 140, and 280 min, while the final setting time was 225. 223, 225, and 450 min, for the GPC mix containing 0, 12.5, 25, and 50 % RHA, respectively. In conclusion, the addition of high silica-RHA into GPC mixtures has a significant effect on decreasing the setting time of cement paste.

Table 3
Effect of RHA on the workability of GPC.

References	Binders used	Alkali-activated	Replacement % of RHA	Workability mm	
				Slump	Flow
Pham et al. [46]	Corn cob ash, fly ash, and RHA	NaOH and Na_2SiO_3	0	125	
			3	112	
			6	100	
			9	95	
			12	85	
Nuaklong et al. [36]	Fly ash, nano-silica, and RHA	NaOH and Na_2SiO_3	0		789
			1.2		721
			2.4		715
			3.6		703
Mahdi et al. [66]	Fly ash and RHA	NaOH and Na_2SiO_3	0	194	
			10	157	
			20	103	
			30	34	
Patel and Shah [92]	GGBS and RHA	NaOH and Na_2SiO_3	0		710
			5		690
			15		680
			25		655
Das et al. [20]	GGBS, fly ash, and RHA	NaOH and Na_2SiO_3	0	40	
			1	30	
			3	20	
			5	18	
			7	16	
			10	12	
Mahdi et al. [93]	Fly ash and RHA	NaOH and Na_2SiO_3	0	210	
			5	200	
Ardiantoro et al. [94]	Fly ash and RHA	NaOH and Na_2SiO_3	0	74.1	
			5	67.7	
			7.5	65.0	
			10	61.3	
			15	55.0	

5.2. Effect of RHA on the workability of GPC

The workability of GPC is a crucial property that directly influences construction practices, ease of placement, and the overall quality of concrete structures. The incorporation of RHA as a rich silica biomass in GPC production can have a significant impact on workability due to its physical and chemical characteristics [20]. RHA particles exhibit a wide range of sizes and shapes, which can influence the rheological properties and workability of GPC mixes [90]. Fine particles with high surface area promote better particle packing and lubrication, resulting in improved flowability and workability of concrete mixes. The particle size distribution of RHA affects the water demand, viscosity, and segregation resistance of GPC, thereby influencing its workability characteristics.

The addition of RHA modifies the rheological properties and flow behavior of GPC mixes by affecting the dispersion, hydration kinetics, and interparticle interactions [82]. RHA particles act as nucleation sites for geopolymerization reactions and contribute to the formation of a stable gel network, which influences the viscosity and plasticity of GPC pastes. Proper selection of RHA dosage and particle size distribution is essential for achieving the desired flowability and workability without compromising the mechanical properties of GPC. Recently, Chelluri and Hossiney [61] conducted the flow test on the GPC containing RHA, fly ash, and GGBS, according to ASTCM C230 [91]. They found that the flow test of binders at mono-level, was 134 mm for the RHA, 165 mm for fly ash, and 220 mm for GGBS. While the flow test increased up to about 240 for the binary-level RHA-GGBS. This performance might be due to quite smoother surface texture of black RHA as compared to fly ash and GGBS.

RHA interacts with alkaline activators in GPC mixes, influencing the rate and extent of geopolymerization reactions and the overall workability of concrete. Patel and Shah [92] reported that the addition of RHA into GPC mixtures leads to a decrease in the flowability of geopolymer binder, and this decrease is due to the high specific surface area and finer nature of RHA. The presence of RHA in GPC mixes can impact segregation and bleeding tendencies due to variations in particle size distribution, density, and settling characteristics. Proper mixing procedures and admixture selection are essential for minimizing the risk of segregation and achieving uniform distribution of RHA particles throughout the concrete matrix. The optimization of workability parameters helps prevent issues such as bleeding, segregation, and surface defects, ensuring the quality and durability of GPC structures. The effect of RHA on the workability of GPC is multifaceted, influenced by factors such as particle size distribution, rheology, interaction with alkaline activators, and segregation behavior. Table 3 shows the effect of RHA on the workability of GPC.

As shown in Table 3, the use of RHA has a negative impact on the workability of GPC. The workability of GPC or mortar should be not excessively stiff or too fluid, otherwise, production proficiency will be significantly influenced [95]. The workability of GPC is typically affected by the mix design, materials characteristics, water-to-binder ratio, alkali amount, alkali type and concentration, and precursor particle size. Moreover, the high specific surface area of RHA tends to reduce the workability because of tending to develop. Therefore, the researchers added different superplasticizers to obtain suitable workability.

5.3. Effect of RHA on the air content of GPC

The air content of concrete is a critical parameter that influences its durability, workability, and resistance to freeze-thaw cycles [96]. Incorporating RHA as a rich silica biomass in GPC formulations can impact the air content due to its physical and chemical properties [46]. As reported by Pham et al. [46], the addition of ultra-fine fly ash in geopolymer paste leads to reduce the air content up to 7.14 % compared to geopolymer mix made of RHA. The increase of air content in geopolymer mix made of RHA and Corn cob ash might be due to its irregular shape and large particle size.

The particle size distribution and surface characteristics of RHA particles influence the air entrainment process in GPC mixes. Fine particles with high surface area enhance the dispersion of air-entraining agents and promote the formation of stable air voids throughout the concrete matrix. The incorporation of RHA can improve the effectiveness of air-entraining admixtures by providing nucleation sites and enhancing the distribution of air bubbles in GPC. RHA interacts with alkaline activators in GPC mixes, affecting the rheological properties and stability of air voids [81]. The chemical composition and surface properties of RHA influence the adsorption and distribution of air-entraining agents, as well as the kinetics of geopolymerization reactions [97]. Proper dosage and dispersion of RHA are essential for maintaining the desired air content while ensuring the mechanical strength and durability of GPC. The air content of GPC can be controlled and optimized through adjustments in mix proportions, admixture dosages, and mixing techniques. The addition of RHA allows for flexibility in tailoring the air content of GPC to meet specific project requirements and environmental conditions.

5.4. Effect of RHA on the density of GPC

The density of concrete is a fundamental property that affects its structural integrity, durability, and overall performance in construction applications. The incorporation of RHA as a rich silica biomass in GPC formulations can influence the density due to its physical and chemical characteristics. RHA particles contribute to the overall density of GPC through their particle packing behavior and interaction with other constituents in the mix [76]. The fine particles and high surface area of RHA enhance particle packing efficiency and reduce void spaces within the concrete matrix. Properly graded RHA aggregates can optimize the void structure and increase the bulk density of GPC, resulting in higher overall density. The presence of RHA in GPC mixes affects the porosity and pore structure of the hardened concrete matrix [60]. The incorporation of RHA can lead to a reduction in pore size distribution and interconnectivity, resulting in lower overall porosity and higher density. The fine particles of RHA act as fillers and nucleation sites for geopolymerization reactions, promoting the formation of dense and compact microstructures in GPC.

RHA interacts with alkaline activators in GPC mixes, influencing the hydration kinetics and microstructural development of the hardened concrete [57]. The chemical composition and surface properties of RHA affect the dissolution of silica species and the formation of geopolymer gel networks, which contribute to the density and strength of GPC [20]. Proper optimization of RHA dosage and alkali activator concentration is essential for achieving the desired density and mechanical properties of GPC. High-density GPC formulations offer advantages such as improved resistance to environmental factors, enhanced load-bearing capacity, and reduced permeability [98]. The effect of RHA on the density of GPC is influenced by factors such as particle packing, porosity, alkaline activation, and engineering applications [62]. Table 4 shows the influence of RHA on the densities of GPC, as investigated by the previous studies.

As shown in Table 4, the influence of RHA as rich silica biomass on the densities of GPC are clear. In some results obtained from the previous researchers, the density of GPC increases as RHA amount increase, while other studies showed that the densities of GPC decrease as the RHA amounts increases. This variation in densities might be due to the different sources and treatment process. Also, other SCMs with RHA in the alumina silicate materials contributes either increase or decrease density. The density of GPC has a main associated with the strength and durability of GPC.

6. Effect of RHA on the mechanical properties of GPC

6.1. Effect of RHA on the compressive strength of GPC

The compressive strength of GPC is a critical mechanical property that governs its structural performance and durability in various construction applications. The incorporation of RHA as a rich silica biomass in the production of GPC can have a significant impact on compressive strength due to its pozzolanic reactivity and physical properties [100]. RHA contains amorphous silica, which exhibits high pozzolanic reactivity when activated with alkaline solutions [101]. The fine particles and high surface area of RHA enhance the properties of geopolymer gel networks through polymerization reactions, leading to enhanced bond strength and compressive resistance in GPC [62]. The addition of RHA facilitates the development of dense and homogeneous microstructures, resulting in improved compressive strength properties. The interaction between RHA and alkaline activators influences the kinetics and extent of geopolymerization reactions in concrete mixes [73]. The chemical composition and surface properties of RHA affect the dissolution of silica species and the formation of stable geopolymer phases, which contribute to the mechanical properties of GPC [102]. Proper optimization of RHA dosage, activator concentration, and curing conditions is essential for achieving the desired compressive strength and durability of GPC.

The particle size distribution and packing characteristics of RHA particles influence the microstructural development and mechanical properties of GPC [103]. The incorporation of RHA allows for the optimization of GPC mixes to achieve superior compressive strength properties compared to conventional concrete. RHA-based GPC formulations offer advantages such as increased early-age strength, enhanced resistance to environmental factors, and reduced carbon footprint. The effect of RHA on the compressive strength of GPC is influenced by factors such as pozzolanic reactivity, alkaline activation, particle packing, and microstructural development. Table 5 shows the effect of RHA on the compressive strength of GPC.

Table 4
Effect of RHA on the densities of GPC.

References	Waste used	Alkali-activated	Replacement %	Densities kg/m^3
Zhu et al. [64]	RHA and fly ash		0	2065
			10	2035
			20	2010
			30	1094
			40	1088
			50	1082
Liang et al. [25]	RHA, MK, and OPC	NaOH and Na_2SiO_3	0	1720
			10	1730
			20	1735
			30	1737
			40	2020
Pham et al. [46]	Corn ash, fly ash, and RHA	NaOH and Na_2SiO_3	0	2430
			3	2364
			6	2307
			9	2254
			12	2394
Pham [60]	Basalt fiber, and RHA	NaOH and Na_2SiO_3	100	1900
			90	1930
			80	1950
			70	1970
Liang et al. [99]	MK and RHA	NaOH and Na_2SiO_3	0	1745
			10	1755
			20	1775
			30	1780
			40	1758
			50	1765

Table 5
Effect of RHA on the compressive strength of GPC.

References	Waste used	Alkali-activated	Replacement %	Compressive strength MPa
Zhu et al. [64]	RHA and fly ash		0	69.5
			10	67.5
			20	63.4
			30	47.6
			40	41.6
			50	38.7
Liang et al. [25]	RHA and MK	NaOH and Na_2SiO_3	0	36
			10	47
			20	50
			30	57
			40	51
Pham et al. [46]	Corn ash, fly ash, and RHA	NaOH and Na_2SiO_3	0	60
			3	55
			6	48
			9	43
			12	37
Nuaklong et al. [36]	Fly ash, nano-silica, and RHA	NaOH and Na_2SiO_3	0	33.9
			1.2	38.1
			2.4	37.2
			3.6	36.0
Mahdi et al. [66]	Fly ash and RHA	NaOH and Na_2SiO_3	0	42.75
			10	42.19
			20	34.19
			30	24.08
Zhu et al. [67]	Slag and RHA	NaOH and Na_2SiO_3	0	70
			10	85
			20	75
			30	63
			40	54
			50	49
Liu et al. [48]	MK and RHA	NaOH and Na_2SiO_3	0	45
			5	50
			10	55
			15	57
			20	55
Liang et al. [99]	MK and RHA	NaOH and Na_2SiO_3	0	46.5
			10	50.9
			20	56.6
			30	54.0
			40	53.9
			50	52.4

As shown in Table 5, in most cases the compressive strength of GPC increases as the small amount of RHA added to the mixtures. While, in some cases the compressive strength decreased even though when added small amount of RHA. This difference in results might be due to the change in the source, particle size, and specific surface area of RHA, and others. The addition of Metakaolin or slag with RHA has a positive effect on the development of the compressive strength of GPC [99], while the addition of fly ash with RHA as binder materials in GPC has a negative impact on the compressive strength of GPC [46]. It is important to note that the RHA with high silica content significantly contributed by enhancing the compressive strength through the production of further C-S-H gels essential for hydration products.

6.2. *Effect of RHA on the flexural strength of GPC*

The flexural strength of concrete is a critical mechanical property that reflects its ability to withstand bending loads and resist cracking under applied stresses. Incorporating RHA as a rich silica biomass in GPC can influence flexural strength due to its pozzolanic reactivity and physical properties [100]. RHA contributes to the enhancement of flexural strength in GPC by promoting the formation of durable and cohesive matrix structures. The high pozzolanic reactivity of RHA facilitates the formation of strong chemical bonds between particles and enhances interfacial adhesion within the concrete matrix [104]. RHA particles contribute to the microstructural development of GPC, influencing the distribution of phases and the arrangement of aggregates within the matrix [105]. Properly graded RHA aggregates improve particle packing efficiency and reduce void spaces, resulting in increased flexural strength and crack resistance in GPC formulations. The incorporation of RHA allows for the optimization of GPC mixes to achieve superior flexural strength properties compared to conventional concrete. RHA-based GPC formulations offer advantages such as increased durability, enhanced resistance to environmental factors, and reduced life cycle costs. The utilization of RHA as a sustainable alternative in concrete production supports efforts toward environmental conservation and promotes the adoption of eco-friendly building materials. The effect of RHA on the flexural strength of GPC is influenced by factors such as pozzolanic reactivity, alkaline activation, microstructural development, and particle packing efficiency. Table 6 shows the effect of RHA on the flexural strength of GPC.

As shown in Table 6, in most cases, the flexural strength increases as the RHA amount increases. This increase in flexural strength of GPC might be due to the production further of pozzolanic reactions, resulting from the high content of silica oxide essential for the production of hydration products. Therefore, the addition of RHA into GPC mixtures has a positive effect in enhancing the flexural strength.

6.3. Effect of RHA on the splitting tensile strength of GPC

The splitting tensile strength of concrete is a crucial mechanical property that reflects its ability to resist tensile stresses and cracking under applied loads [107]. Incorporating RHA as a rich silica biomass in GPC can influence splitting tensile strength due to its pozzolanic reactivity and physical properties [108]. RHA contributes to the enhancement of splitting tensile strength in GPC by promoting the formation of a dense and cohesive microstructure. The high pozzolanic reactivity of RHA facilitates the development of strong interfacial bonds between particles, enhancing the resistance to crack propagation and tensile failure [49]. The addition of RHA improves the tensile performance of GPC mixes, making them more suitable for applications requiring enhanced durability and structural integrity. The effect of RHA on the splitting tensile strength of GPC is influenced by factors such as pozzolanic reactivity, alkaline activation, microstructural development, and particle packing efficiency [109]. Table 7 shows the effect of RHA on the splitting tensile strength of GPC.

As shown in Table 7, in most cases, an increase in the RHA content in GPC mixtures leads to an increase in the splitting tensile strength of GPC. This increase can be attributed to the high silica content in RHA that has a significant impact on the production of further hydration products essential to enhance the GPC samples and increase its resistance against split tensile and cracks. While other studies showed that the incorporation of RHA with fly ash reduced flexural and splitting tensile strengths of GPC [46]. In conclusion, RHA particles have an important effect in enhancing the splitting tensile strength of GPC.

7. Effect of RHA on the durability properties of GPC

7.1. Effect of RHA on the water absorption of GPC

Water absorption is a crucial property that reflects the durability and resistance of GPC to ingress moisture and potentially harmful substances [110]. Incorporating RHA as a rich silica biomass in GPC formulations can influence water absorption due to its physical and chemical characteristics. Fine particle size RHA contributes to the modification of the pore structure and porosity of GPC, thereby influencing water absorption properties [62]. The fine particles and high surface area of RHA promote the formation of a denser microstructure with reduced void spaces, limiting the pathways for water ingress. Properly graded RHA aggregates improve particle packing efficiency and reduce capillary pores, resulting in decreased water absorption and improved resistance to moisture ingress. Proper optimization of RHA dosage and activator concentration is essential for achieving the desired water absorption characteristics while ensuring adequate workability and durability of GPC [65]. Recently, Chelluri and Hossiney [61], examined the effect of black RHA with and without GGBS and fly ash on the water absorption of geopolymer binder at a mono-level, binary level, and ternary level. They observed that the highest water absorption of 22.58 % was detected for G30R70 (30 % GGBS with 70 % RHA). This increase might be due to the increase in RHA content in the geopolymer mortar mix. Similarly, the existence of unreacted crystalline silica in RHA and fly ash fills the spaces and enhances the density of the composite binder [62]. As reported by Jindal et al. [65], the proportion

Table 6
Effect of RHA on the flexural strength of GPC.

References	Waste used	Alkali-activated	Replacement %	Flexural strength MPa
Patel and Shah [92]	Fly ash, GGBS, and RHA	NaOH and Na_2SiO_3	0	1.69
			5	3.46
			15	3.08
			25	2.83
Pham et al. [46]	Corn ash, fly ash, and RHA	NaOH and Na_2SiO_3	0	5.75
			3	5.50
			6	5.23
			9	4.82
			12	4.53
Nuaklong et al. [36]	Fly ash, nano-silica, and RHA	NaOH and Na_2SiO_3	0	3.5
			1.2	3.8
			2.4	3.8
			3.6	3.4
Pham [60]	Basalt fiber, and RHA	NaOH and Na_2SiO_3	100	3.62
			90	4.20
			80	4.78
			70	5.71
Venkatesan and Pazhani [106]	GGBS and RHA	NaOH and Na_2SiO_3	0	6.0
			10	7.0
			20	4.3
			30	1.5

Table 7
Effect of RHA on the splitting tensile strength of GPC.

References	Waste used	Alkali-activated	Replacement %	Splitting tensile strength MPa
Nuaklong et al. [36]	Fly ash, nano-silica, and RHA	NaOH and Na_2SiO_3	0	2.5
			1.2	2.7
			2.4	2.5
			3.6	2.4
Pham et al. [46]	Corn ash, fly ash, and RHA	NaOH and Na_2SiO_3	0	4.55
			3	4.32
			6	4.12
			9	3.75
			12	3.48
Patel and Shah [92]	Fly ash, GGBS, and RHA	NaOH and Na_2SiO_3	0	1.39
			5	2.85
			15	2.75
			25	1.93
Venkatesan and Pazhani [106]	GGBS and RHA	NaOH and Na_2SiO_3	0	6.8
			10	7.0
			20	4.2
			30	1.3

of water absorption of GPC decreases as binder materials (RHA and fly ash) increase. RHA particles have the potential to modify the surface properties of GPC and enhance hydrophobicity, thereby reducing water absorption. Surface treatments or additives containing hydrophobic agents can be incorporated with RHA to create a protective barrier against moisture ingress. Proper selection and application of hydrophobic coatings or admixtures contribute to the reduction of water absorption and improve the long-term durability of GPC in harsh environmental conditions [111]. Table 8 shows the influence of RHA on the water absorption of GPC.

As shown in Table 8, the addition of further RHA into GPC mixtures leads to an increase in the water absorption rate. This increase in water absorption can be attributed to the pore structure and high porosity nature of RHA.

7.2. Effect of RHA on the chloride ion penetration resistance of GPC

Chloride ion penetration resistance is a critical property for concrete structures exposed to marine environments or deicing salts, as chloride ions can cause corrosion of reinforcing steel and deterioration of concrete [112]. Incorporating RHA as a rich silica biomass in GPC can significantly influence chloride ion penetration resistance due to its physical and chemical characteristics. RHA contributes to the reduction of pore structure and porosity in GPC, thereby limiting the ingress of chloride ions. Properly graded RHA aggregates improve particle packing efficiency and reduce capillary pores, resulting in decreased chloride ion penetration and improved durability of GPC in chloride-rich environments. Pham et al. [46] investigated the influence of RHA and other SCM on chloride ion penetration. They observed that the electrical conductivity of the specimens was extra reduced as RHA replaced with corn cob ash.

RHA particles can be utilized to create protective coatings or surface treatments that enhance chloride ion penetration resistance and mitigate corrosion risks [113]. Surface treatments containing RHA-based admixtures or additives form a barrier against chloride ion ingress and promote ion exchange mechanisms that reduce the transport of chlorides within the concrete matrix. The effect of RHA on the chloride ion penetration resistance of GPC is influenced by factors such as pore structure, alkaline activation, surface coatings, and ion exchange mechanisms. Mehta et al. [114] observed that the use of 10 % RHA instead of GGBS at 28 days classified at the “low” (1538 C) penetration category. Similarly, Venkatesan et al. [106] reported that the use of 10 % RHA, 20 % RHA, and 30 % RHA as GGBS replacement results in “low” (1597.5 C), “moderate” (2977.5 C), and “high” (5675.1 C) chloride ion penetration, respectively.

Table 8
Effect of RHA on the water absorption of GPC.

References	Waste used	Alkali-activated	Replacement %	Water absorption %
Zhu et al. [64]	RHA and fly ash	NaOH and Na_2SiO_3	0	0.4
			10	0.52
			20	0.42
			30	1.2
			40	1.78
			50	1.98
Nuaklong et al. [36]	Fly ash, nano-silica, and RHA	NaOH and Na_2SiO_3	0	10.0
			1.2	4.7
			2.4	4.9
			3.6	6.1
Liang et al. [99]	MK and RHA	NaOH and Na_2SiO_3	0	1.75
			10	1.6
			20	1.5
			30	1.55
			40	1.56
			50	1.59

The high replacement levels of RHA led to inadequate aluminosilicate matrix, due to the high silica content in RHA. Mehta and Siddique [114], also proved that the addition of 15 % RHA into the GPC mix resulted in minimum chloride permeability related to the total charge passed. Table 9 shows the different categories of chloride ion penetration according to the total charge passed.

8. Effect of RHA on the thermal conductivity of GPC

Thermal conductivity is a significant property of concrete that influences its ability to transfer heat and regulate temperature variations in structures [115]. Incorporating RHA as a rich silica biomass in GPC can influence thermal conductivity due to its physical and chemical characteristics. RHA possesses inherent insulating properties owing to its low thermal conductivity and high porosity. When incorporated into GPC, RHA acts as an insulating filler that reduces the transfer of heat through the concrete matrix. The fine particles and porous structure of RHA contribute to the formation of thermal barriers within the concrete, limiting heat conduction and improving thermal insulation properties [116]. The addition of RHA to GPC modifies the microstructure and porosity of the concrete matrix, which in turn influences thermal conductivity [117]. The high surface area and fine particle size of RHA promote the formation of a dense and compact microstructure with reduced void spaces, thereby decreasing thermal conductivity. Liang et al. [25] examined the influence of RHA on the thermal conductivity of GPC using different content of RHA. As shown in Fig. 7, the key reduction in weight did at 250 C using TGA test of GPC and cement pastes. They observed that the geopolymer containing RHA displays a higher decrease in mass loss than that of control paste without RHA in this temperature limit.

The incorporation of RHA allows for the optimization of GPC mixes to achieve reduced thermal conductivity compared to conventional concrete [118]. RHA-based GPC formulations offer advantages such as improved energy efficiency, enhanced thermal comfort, and reduced heating and cooling costs. The utilization of RHA as a sustainable alternative in concrete production supports efforts toward environmental conservation and promotes the adoption of eco-friendly building materials in various construction applications.

9. Effect of RHA on the fire resistance of GPC

Fire safety is one of the significant requirements in the design of concrete buildings, therefore, researchers and academics investigated fire safety and what are the factors affecting it [119]. The residual compressive strength, residual mass, and spalling damage are the things that should be examined for the concretes exposed to fire. Nuaklong et al. [36] examined the use of RHA and nano-SiO_2 for enhancing the properties of recycled aggregate GPC made from fly ash. They tested the effect of these materials on the fire resistance of GPC. They observed that the use of RHA is active in increasing the strengths of GPC. However, the addition of SiO_2-rich materials had a negative impact on the residual strength of GPC after exposure to fire. Increasing the fire duration leads to increased fire damage as shown in Fig. 8. The resistance against spalling was determined by the size of the remaining samples after fire damage. It is concluded that the resistance against spalling of the nano silica-added mixtures is very similar to that of the RHA-added mixtures. Nevertheless, some variances were likewise detected due to the ultra-fine particle size of nano silica.

Another study by Liu et al. [48], reported that the use of RHA with high silica content in MK-based GPC can enhance the fire resistance of GPC samples, as shown in Fig. 9. GPC samples with MK binder after exposure to high temperature suffered from healing cracks, sintering, and spalling considerably due to exposure up to 900 °C. while the addition of RHA enhances the thermal stability of GPC and reduces the cracks as the RHA amount increases.

10. Effect of RHA on the microstructure properties of GPC

10.1. Scanning electron microscopic

Scanning electron microscopy (SEM) is a powerful tool used to investigate the microstructure and morphology of concrete at the nanoscale level [120]. Incorporating RHA as a rich silica biomass in GPC can significantly influence the SEM characteristics due to its physical and chemical properties. The addition of RHA modifies the microstructure of GPC by promoting the formation of a dense and compact matrix with reduced voids and cracks. SEM images demonstrate the interaction between RHA particles and alkaline activators, resulting in the formation of geopolymer gel networks and the enhancement of bond strength within the concrete matrix. Zhu et al. [64] observed that the use of RHA in fly ash based-GPC exhibited microstructure properties and better performance, as shown in Fig. 10. The use of RHA closed the voids spread at the GPC surface. The filling effect of small particles of RHA starts clearly when added

Table 9
Classification of chloride ion penetration of GPC with different RHA amounts [114]. Reprinted with permission from Elsevier (2018).

Mixture mode	Permeability range at 28 days		Permeability range at 90 days	
GPC with RHA0	2269	Moderate	1993	Low
GPC with RHA5	2017	Moderate	1762	Low
GPC with RHA10	1538	Low	1329	Low
GPC with RHA15	1219	Low	1021	Low
GPC with RHA20	1439	Low	1296	Low
GPC with RHA25	1898	Low	1532	Low
GPC with RHA30	2011	Low	1892	Low

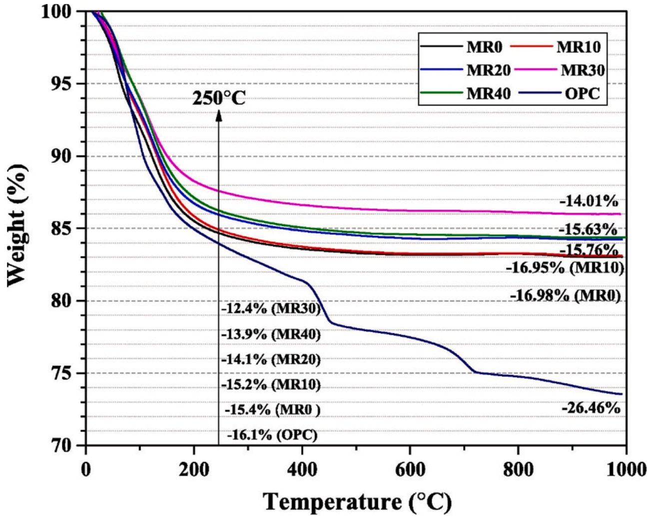

Fig. 7. TG curves of cement and geopolymer pastes before exposure to thermal [25].
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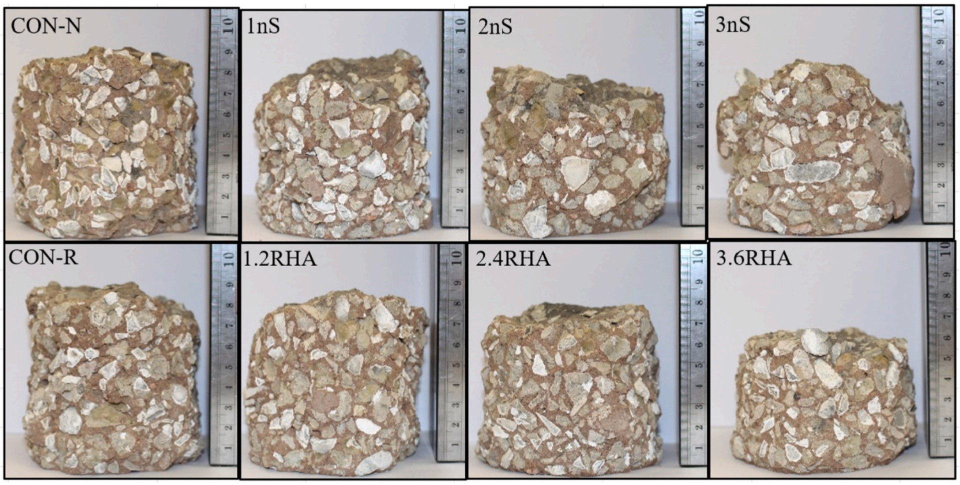

Fig. 8. Images of GPC samples after exposure to fire for 90 min [36].
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to the GPC mixtures. As the RHA content increases, the large amounts of voids start to disappoint. This effect is due to the function of hydration micro-stress and crystallization of the gels.

SEM analysis allows for the characterization of surface features and the assessment of RHA distribution within the GPC matrix, providing valuable information for optimizing concrete mixes and enhancing performance [51,121]. RHA exhibits high pozzolanic reactivity, which is evident in SEM images showing the formation of hydration products and secondary phases within the GPC matrix [62]. The reaction between RHA particles and alkaline activators contributes to the development of C-S-H gel and other hydration products, which fill voids and enhance the mechanical properties of GPC. SEM images reveal the surface morphology and texture of GPC, highlighting the presence of RHA particles and their impact on surface properties. The fine particles and irregular shape of RHA contribute to the roughness and porosity of the concrete surface, which influences properties such as permeability, adhesion, and durability [122].

10.2. X-ray diffraction (XRD)

X-ray diffraction (XRD) analysis is a fundamental technique used to identify and quantify crystalline phases present in concrete materials [123]. Chelluri and Hossiney [61] conducted experimental work on the effect of different binder materials, namely RHA, fly ash, and GGBS on the microstructure properties of geopolymer mortar. They observed that the use of RHA with GGBS in percentages of

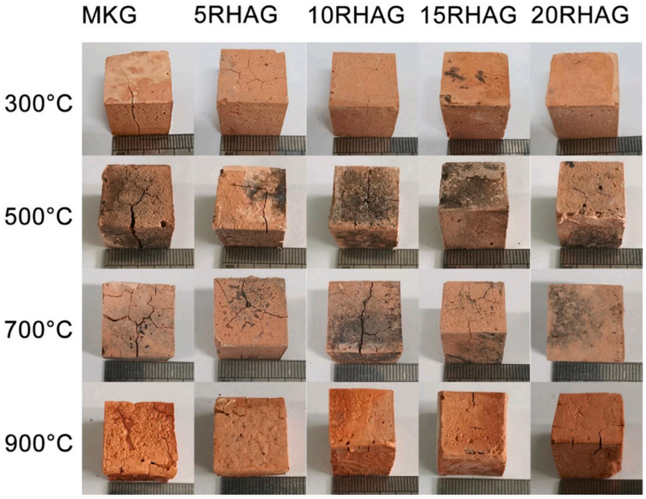

Fig. 9. Appearance of GPC samples after exposure to different temperature [48].
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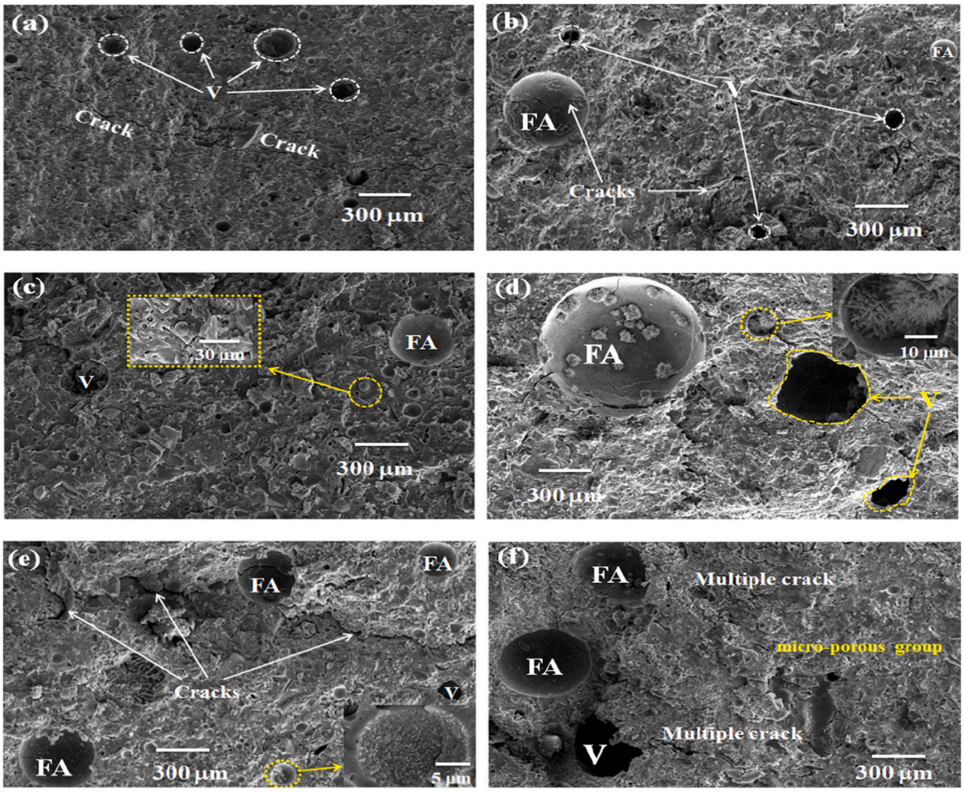

Fig. 10. SEM images of (a) 10 % Fly ash and 0 % RHA, (b) 90 % Fly ash and 10 % RHA, (c) 80 % Fly ash and 20 % RHA, (d) 70 % Fly ash and 30 % RHA, (e) 60 % Fly ash and 40 % RHA and (f) 50 % Fly ash and 50 % RHA samples [64].
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70 %:30 % (70R30G) is the least-performing mix and refers to the existence of omphacite, this mix presented the highest intensity peak which confirms the least geopolymerization degree. Nevertheless, the highest intensity peak was achieved with a mix containing 70 % GGBS and 30 % RHA. Another study by Zhu et al. [64] detected that the increasing of RHA content in GPC mix, leads to improve the peak intensity of calcium silicate phases, thus enhancing the microstructure properties due to create further C-S-H gels and for better hydration reaction. Another study by Liang et al. [25], used different RHA amounts to replace MK in geopolymer and cement pastes.

They observed that the XRD pattern with a huge amount of silica oxide embedded in RHA is a main reason in enhancing crystalline phases in all geopolymer pastes. Furthermore, the crystalline phases of magnesite, calcium silicate, and aluminum silicate, etc. were also detected.

XRD analysis allows for the quantification of amorphous content in GPC containing RHA. The amorphous silica present in RHA contributes to the formation of geopolymer gel networks, which improve the bond strength and durability of the concrete matrix. XRD patterns provide information about the degree of amorphousness and the crystallinity index, which are crucial for assessing the pozzolanic reactivity and performance of RHA-based GPC formulations. For instance, Zhu et al. [67] investigated the effect of RHA content on the microstructure properties of GPC by XRD test. They observed that there was a different amount of quartz, mullite crystalline phases, and a trace of calcium silicate due to different amounts of RHA. the existence of "N-A-S-H" and "CA-S-H" gels were existence in two spaces of peak between 20∘ to 35∘ 2θ and 36∘–38∘ 2θ, respectively. As shown in Fig. 11, an increase in RHA content in the GPC mix leads to a significant increase in the intensity of quartz at 22∘ 2θ, this increase is associated with the high content of SiO_2 in RHA. This high quantity of SiO_2 can enhance the microstructure of GPC for better performance.

11. Benefits of RHA incorporated GPC on the environment aspect

As one of the United Nations' sustainable development goals (SDGs), the construction industry should reduce the generation of huge amounts of CO_2 by 2025 by using innovative techniques and sustainable materials [124]. Therefore, GPC made of waste materials such as RHA is the best solution and sustainable alternative to decrease the cement production responsible for about 7 % of CO_2 emissions worldwide [125]. The potential use of numerous industrial and agriculture wastes in GPC like RHA, fly ash, and slag, can satisfy the necessity for green and sustainable construction materials. At the same time, the use of RHA in the production of Na_2SiO_3 significantly reduces the production cost and carbon footprints [126]. In general, the utilization of RHA as a rich silica biomass in GPC offers numerous environmental benefits, contributing to sustainable construction practices and resource conservation:

1. RHA is a byproduct of rice milling processes and is abundantly available as agricultural waste. By incorporating RHA into GPC, a significant volume of agricultural waste is diverted from landfills and incineration, reducing environmental pollution and mitigating disposal challenges associated with rice husk disposal [100]. The utilization of RHA promotes the efficient use of natural resources and supports circular economy principles [127].
2. The production of conventional Portland cement is energy-intensive and generates substantial CO_2 emissions, contributing to climate change and global warming. In contrast, the production of GPC utilizing RHA as a SCM requires lower energy consumption and emits fewer greenhouse gases [128]. The use of RHA in GPC formulations helps reduce the carbon footprint of construction activities, supporting efforts to mitigate climate change and promote sustainable development.
3. GPC incorporating RHA reduces the reliance on natural resources such as limestone and clay, which are primary constituents of Portland cement [129]. By replacing a portion of cementitious materials with RHA, the depletion of natural resources is minimized, and ecosystem integrity is preserved. The sustainable use of RHA in GPC formulations reduces the environmental impact associated with resource extraction, land degradation, and habitat destruction.
4. RHA exhibits inherent insulating properties, which contribute to the thermal efficiency and energy performance of GPC structures [130]. GPC formulations incorporating RHA offer improved thermal insulation and energy efficiency compared to conventional concrete, reducing the demand for heating and cooling systems in buildings. The use of RHA in GPC promotes sustainable building practices and enhances occupant comfort while minimizing energy consumption and greenhouse gas emissions.

12. Benefits of RHA incorporated GPC on the economic aspect

The utilization of RHA as a rich silica biomass in GPC offers various economic advantages, contributing to cost savings, resource efficiency, and sustainable construction practices.

1. Incorporating RHA into GPC can lead to significant cost reductions compared to traditional Portland cement-based concrete. RHA, as a byproduct of rice milling processes, is often available at lower costs or even obtained free of charge from rice mills or agricultural facilities. Utilizing RHA as an SCM in GPC reduces the overall material costs associated with concrete production, making it a cost-effective alternative for construction projects.
2. The production of GPC utilizing RHA typically requires lower energy consumption compared to Portland cement-based concrete. The alkaline activation process used in GPC production requires lower temperatures, resulting in reduced energy expenditures during manufacturing. Additionally, the use of RHA as a pozzolanic material reduces the need for energy-intensive processes involved in clinker production, further enhancing energy efficiency, and reducing production costs.
3. GPC incorporating RHA exhibits enhanced durability and longevity compared to conventional concrete. The chemical composition and microstructural properties of RHA contribute to improved resistance against chemical attacks, abrasion, and environmental degradation. As a result, structures built with RHA-based GPC require less frequent maintenance and repair, leading to long-term cost savings and lifecycle benefits for infrastructure projects.
4. Utilizing RHA in GPC formulations can help mitigate environmental compliance costs associated with traditional concrete production. The use of RHA reduces greenhouse gas emissions, energy consumption, and waste generation throughout the construction lifecycle. By adopting sustainable construction practices and utilizing eco-friendly materials such as RHA, construction companies can minimize regulatory compliance costs and enhance their corporate social responsibility initiatives.

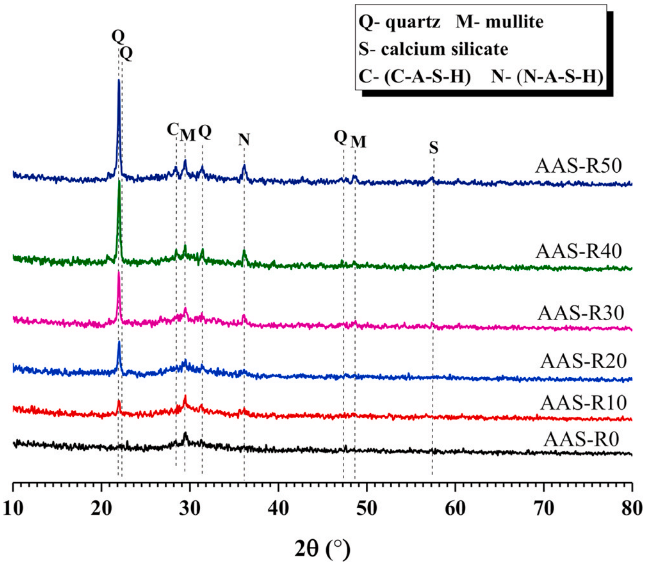

Fig. 11. XRD pattern of GPC comprising RHA in various proportions [67].
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13. Conclusions and recommendations

The study explored the influence of RHA as a rich silica biomass on the properties and performance of GPC. Through a comprehensive analysis of experimental data and observations, several conclusions and recommendations can be drawn:

1. RHA as an agriculture waste produced as a by-product from the milling of rice, contains high silica content and pozzolanic properties making it a suitable binder material for enhancing the properties of sustainable GPC.
2. Incorporating RHA in the GPC mixtures leads to a decrease in the workability of GPC. For instance, the slump value decreased from 194 to 34 mm, due to an increase in RHA and fly ash content from 0 % to 30 %. Also, decrease the slump value from 40 to 12 mm due to increased RHA and GGBS content as an SCM from 0 % to 10 %.
3. The addition of RHA into GPC mixtures enhanced the mechanical properties, including compressive, flexural, and splitting tensile strengths. The addition of 1.2 % of RHA, nano silica, and fly ash increased the compressive strength from 33.9 to 38.1 MPa, flexural strength from 3.5 to 3.8 MPa, and splitting tensile strength from 2.5 to 2.7 MPa.
4. The addition of RHA into the GPC mix has a positive effect on the durability properties of GPC in most cases, even though the RHA particles cause increases in the water absorption rate. However, the chloride ion penetration decreased due to the form of further C-S-H gels contributing to a dense structure.
5. RHA-based GPC formulations demonstrated cost-effective production processes and reduced environmental footprint compared to conventional concrete. The utilization of RHA as an SCM aligns with the principles of circular economy and sustainable development.

Further research should focus on the durability performance of concrete incorporating RHA, particularly in the following aspects: Sulfate and Acid Resistance – Since RHA contains reactive silica, its long-term interaction with sulfates and acidic environments should be thoroughly investigated to assess its impact on degradation mechanisms and overall durability. Chloride Penetration and Corrosion Resistance – The influence of RHA on concrete permeability and porosity needs further study, especially in marine environments where chloride ingress can accelerate reinforcement corrosion. Freeze-Thaw Resistance – Given the potential increase in porosity with higher RHA replacement levels, it is essential to evaluate its effect on freeze-thaw durability in both cold and hot regions to ensure long-term performance. Carbonation Resistance – The impact of RHA on carbonation depth over time should be examined, as increased carbonation could reduce the service life of reinforced concrete structures. These investigations will help optimize the use of RHA in concrete while ensuring its long-term structural integrity in various environmental conditions.

CRediT authorship contribution statement

Beddu Salmia: Investigation, Funding acquisition. **Al-Attar Alyaa:** Writing – review & editing, Funding acquisition, Formal analysis. **Hamada Hussein:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Data curation, Conceptualization. **Askar Mand:** Resources, Validation, Writing – review & editing. **Majdi Ali:** Project administration. **Yousif Salim:** Writing – review & editing, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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