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Rice husk ash in structural concrete: influence on strength, durability and sustainability

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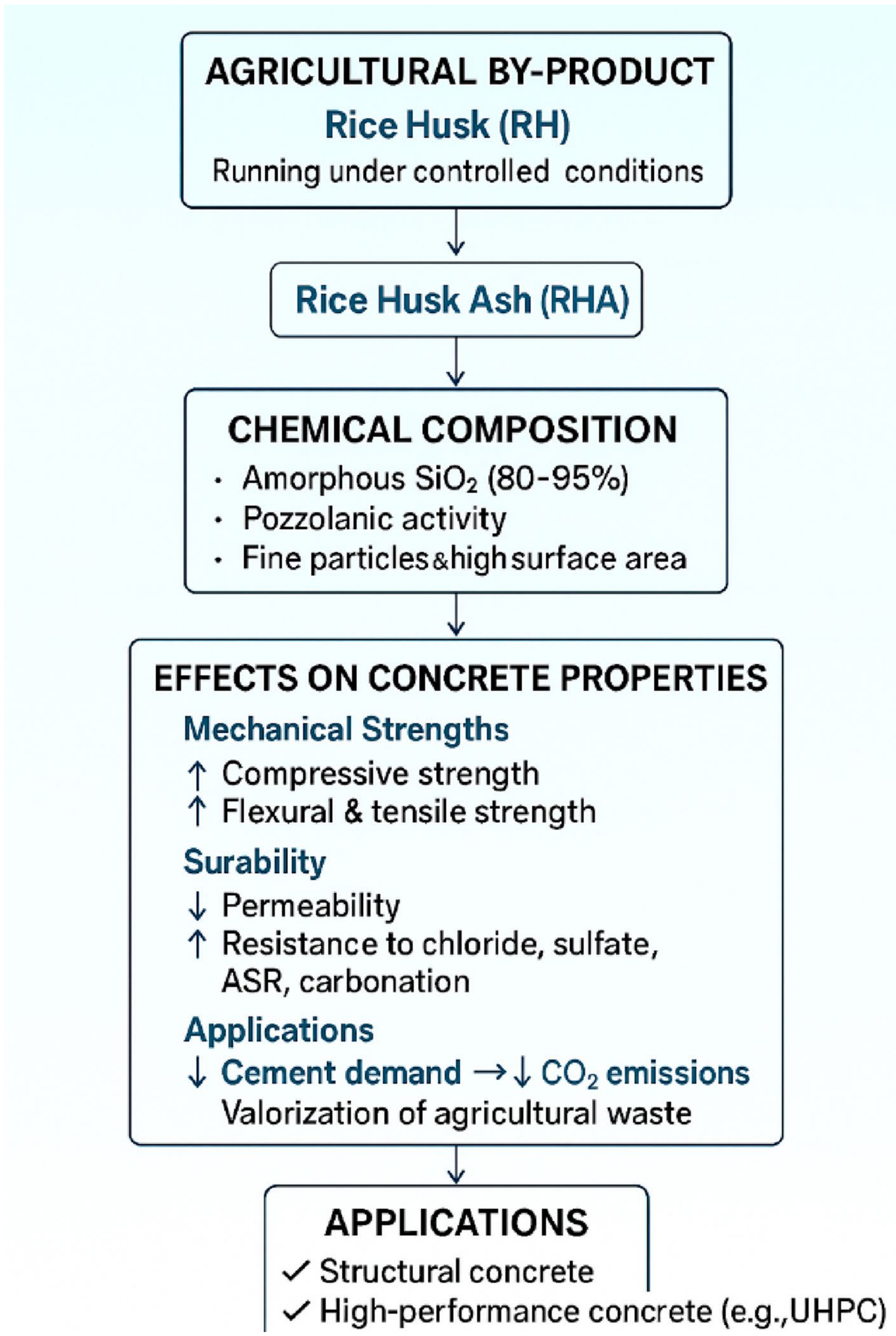
Abstract

In this comprehensive review, the utilisation of rice husk ash (RHA) in concrete is examined. The paper discusses various aspects including the properties and composition of RHA, its incorporation in concrete as a partial replacement for cement and its impact on the fresh and hardened properties of concrete. Furthermore, the review investigates the potential of RHA as a supplementary cementitious material and its influence on cementitious systems. Applications in both structural and non-structural contexts are presented, while also addressing the challenges and limitations associated with the use of RHA. The review concludes by highlighting future perspectives and research opportunities in this area. Overall, this comprehensive review provides valuable insights into the utilisation of RHA in concrete, showcasing its potential for enhancing performance and contributing to sustainability efforts.

Keywords Rice husk ash (RHA), Pozzolanic reaction, Workability, Durability

Graphical abstract



1 Introduction

Rice husk ash (RHA) is a by-product obtained from burning rice husks during the rice milling process. It is an abundant and readily available waste material that can be effectively utilised in concrete production. By repurposing this agricultural waste, the construction industry can reduce waste generation and contribute to sustainable practices. One of the primary advantages of RHA is its pozzolanic activity, which contributes to the formation of cementitious compounds that enhance the strength and durability of concrete [1–3]. This reaction is discussed in more detail in later sections. The pozzolanic activity of RHA contributes to the development of a denser and more compact concrete matrix, leading to improved mechanical properties [4].

The inclusion of RHA in concrete has been found to enhance its compressive strength, flexural strength and split tensile strength [5–7]. The pozzolanic reaction between RHA and calcium hydroxide contributes to the formation of additional cementitious products, resulting in increased strength. Studies have demonstrated that the use of RHA can lead to significant improvements in the mechanical performance of concrete, making it suitable for various structural applications [8–10]. In addition to strength enhancement, RHA also improves the durability of concrete. Concrete containing RHA exhibits improved resistance to chloride ion penetration, sulphate attack, alkali-silica reaction (ASR) and carbonation [11–13]. The pozzolanic reaction between RHA and calcium hydroxide helps to fill the pores and capillary voids in the concrete, reducing its permeability and enhancing its resistance to chemical attacks. This increased durability translates to a longer service life for concrete structures, minimising maintenance and repair costs.

The optimal replacement level of cement with RHA depends on several factors, including the desired concrete properties, project requirements and relevant standards. Generally, replacement levels of RHA range from 10 to 30% by weight of cement [14–16]. However, researchers have investigated higher replacement levels to assess their impact on concrete performance [17–19]. It is important to conduct thorough testing and evaluation to determine the optimum replacement level for specific applications. The use of RHA in concrete offers significant environmental benefits. By replacing a portion of cement with RHA, the overall demand for cement is reduced. Cement production is a major source of carbon dioxide emissions and by decreasing the amount of cement used, the carbon footprint associated with concrete production can be lowered. Additionally, the utilisation of RHA provides an eco-friendly solution to the management of rice husk waste, contributing to sustainable waste management practices [20]. When incorporating RHA in concrete, careful consideration of mix design is crucial. Factors such as the water-to-cementitious materials ratio, superplasticizer dosage and curing methods must be optimised to achieve the desired workability, strength and durability of the concrete. Proper mix design ensures that the RHA is effectively dispersed within the concrete mix and promotes its reactivity.

Extensive research has been conducted to understand and optimise the use of RHA in concrete [21, 22]. Studies have focused on determining the optimal replacement levels, investigating the pozzolanic reaction kinetics, analysing microstructural changes and evaluating the long-term performance and sustainability of RHA-based concrete. Quality control is essential to ensure the suitability and consistency of RHA in concrete production. Testing the pozzolanic activity, chemical composition and physical properties of RHA is necessary to maintain quality and achieve the desired concrete performance. Quality control measures help ensure that the RHA meets the required standards and specifications, guaranteeing the performance and durability of the concrete in real-world applications.

The motivation behind writing this review paper is to consolidate existing knowledge and research findings on the use of RHA in concrete. The aim is to provide a comprehensive and up-to-date overview of the subject, highlighting the benefits, applications and advancements in this field. By synthesizing information from various sources, the paper intends to serve as a valuable resource for researchers, engineers and practitioners in the construction industry. Additionally, the paper aims to promote further research, inform decision-making and encourage the adoption of sustainable and high-performance concrete practices by showcasing the advantages and potential of RHA in concrete production. The limitations of this review paper include its scope and depth, as it may not cover every aspect in great detail. Language and publication bias may also limit the inclusion of relevant research. Additionally, the availability of literature and the evolving research landscape may affect the completeness and currency of the information. Moreover, the generalizability of findings should be considered, as different regions and applications may have varying conditions. Readers should be aware of these limitations and consult additional sources to obtain a more comprehensive understanding of the topic.

2 Properties and composition of rice husk ash (RHA)

2.1 Rice husk: an overview

Rice husk, the outer protective covering of the rice grain, is a valuable agricultural by-product that is abundantly available in rice-producing regions worldwide. It is a lightweight and fibrous material that is usually discarded during the milling process, which can result in waste management challenges (Fig. 1). However, in recent years, researchers and industries have recognised the potential of rice husk and have explored various applications for this versatile material [23–26]. Rice is one of the most widely cultivated and consumed staple crops globally. According to the Food and Agriculture Organization (FAO), global rice production reached approximately 520 million metric tons (milled basis) in recent years. This scale of production results in a substantial amount of rice husk, a by-product obtained during rice milling. Rice husks typically account for about 20% of the weight of harvested rice. This means that from 520 million tons of rice, around 104 million tons of rice husk are generated annually. Upon combustion, these husks yield approximately 18–20% by weight as rice husk ash, translating to an estimated 18–21 million tons of RHA produced worldwide each year.

Fig. 1 The image of rice husk

The composition of rice husk makes it suitable for diverse uses. It primarily consists of cellulose, hemicellulose and lignin, along with silica in the form of microscopic silica bodies called phytoliths [27–29]. The high silica content, estimated to be around 25%, is a notable characteristic of rice husk and contributes to its unique properties and applications [30]. One of the significant advantages of rice husk is its abundance and availability. As rice is a staple crop in many parts of the world, large quantities of rice husk are generated as a by-product of the milling process. This abundance makes it an attractive resource that can be effectively utilised to address waste management concerns and reduce environmental impacts associated with its disposal. Due to its fibrous nature, rice husk exhibits excellent insulating properties [31]. It has low thermal conductivity, making it suitable for thermal insulation applications in the construction industry. Rice husk can be processed into boards or panels that are used for insulation purposes, such as wall insulation, roof insulation and packaging materials. These rice husk-based insulation products offer sustainable alternatives to conventional insulation materials, reducing energy consumption and improving building efficiency. Another valuable application of rice husk is its use as a substrate for the cultivation of mushrooms [32]. The fibrous structure and high lignocellulosic content of rice husk provide an ideal environment for mushroom growth. After proper treatment and sterilization, rice husk can serve as a sustainable and cost-effective medium for cultivating various types of edible and medicinal mushrooms. This not only provides an additional income source for farmers but also promotes sustainable agriculture practices and diversification of agricultural products.

Rice husk also holds potential as a raw material for the production of biofuels and bioenergy [33, 34]. Through various processes such as pyrolysis, gasification, or combustion, rice husk can be converted into biofuels like biochar, biogas, or even electricity. These bioenergy options offer renewable and sustainable alternatives to fossil fuels, contributing to the reduction of greenhouse gas emissions and the mitigation of climate change. Furthermore, the utilisation of rice husk for bioenergy production can help in reducing the dependence on traditional energy sources and promote rural development by providing decentralized energy solutions. Furthermore, the high silica content in rice husk makes it suitable for the production of silica-based products [35, 36]. The combustion or thermal treatment of rice husk produces RHA, which is rich in amorphous silica. RHA finds applications in various industries, including construction, ceramics and the production of silica-based materials like silicon metal, silica gel and sodium silicate. In the construction industry, RHA is used as a supplementary material in cement and concrete production. The pozzolanic properties of RHA improve the strength, durability and workability of concrete, contributing to more sustainable and resilient infrastructure.

2.2 Production of RHA

The production of RHA involves several steps. Firstly, rice husk, the outer protective covering of the rice grain, is collected from rice mills or farms. It undergoes cleaning to remove impurities, followed by drying to reduce moisture content. The dried husk is then subjected to controlled combustion, where the organic components are burned, leaving behind inorganic ash rich in silica. The ash is collected using devices like cyclones or filters, cooled to room temperature and then ground to the desired particle size. Sieving may be performed to obtain a uniform particle size distribution. Finally, the RHA is packaged and stored in a dry environment to maintain its quality.

2.2.1 Collection

Rice husk collection is an important step in the production of RHA. The husk is obtained from rice mills or farms where it is generated as a by-product during the milling process. Rice, being a staple crop in many regions, results in the significant production of rice husk. In rice mills, the husk is separated from the rice grain during the milling operation. It is typically removed using machines called rice hullers or husking machines [37]. These machines effectively separate the outer protective covering, known as the husk, from the edible rice grain. Similarly, in farms where rice is cultivated, the husk is obtained after harvesting the rice crop. The harvested rice stalks are threshed to remove the grains, leaving behind the husk. Both rice mills and farms generate rice husk in large quantities. The volume of husk produced depends on factors such as the scale of rice production, the variety of rice cultivated and the processing methods employed [38]. To manage the collection of rice husk efficiently, it is often stored in designated areas within the rice mills or farms. Proper storage facilities are necessary to prevent the husk from being exposed to moisture, which could lead to mold growth or degradation of its quality. The collection of rice husk provides an opportunity to utilise a by-product that would otherwise contribute to waste management challenges. Instead of being discarded, the husk can be processed into RHA, which has various valuable applications in industries such as construction, agriculture, energy and more. By collecting rice husk in large quantities, its potential as a valuable resource can be maximised, leading to more sustainable and environmentally friendly practices.

2.2.2 Cleaning

The production of high-quality RHA involves a critical cleaning process. Once rice husks are collected from mills or farms, they often carry impurities and foreign materials that need removal. The cleaning process targets these contaminants, ensuring the resulting RHA is free from substances that could compromise its quality or performance in various applications [39]. The cleaning method varies based on available equipment, facilities, and the nature of impurities. Common cleaning techniques include mechanical separation, where devices like screens, sieves, or separators remove larger impurities. This includes stones, twigs, or larger debris mixed with the husks during collection. Another method is air separation, utilizing air currents or blowers to separate lighter impurities from rice husks. The husks pass through an air stream, carrying away lighter materials like dust, chaff, or smaller particles. Magnetic separation involves the use of magnetic separators to eliminate metallic impurities or particles with magnetic properties. Rice husks pass through a magnetic field, attracting and separating any magnetic contaminants. Washing the rice husks with water is also employed to remove surface dirt, dust, or soluble impurities. Husks may be soaked or rinsed, and then the water is drained or filtered to separate the cleaned husks from the washing liquid. Thorough cleaning ensures that the resulting RHA meets required quality standards by eliminating unwanted impurities. This is crucial, as contaminants can affect the reactivity, chemical composition, or physical properties of the RHA and help prevent potential negative impacts on the environment or end-use applications.

2.2.3 Drying

Following the cleaning process, the rice husk undergoes a critical phase called drying, which is indispensable for reducing the moisture content to an appropriate level for subsequent processing [40]. This step holds significance for several reasons. Firstly, it serves as a preventive measure against mould. Rice husk contains organic matter that, when exposed to moisture, becomes conducive to mould and fungal growth. Drying effectively eliminates excess moisture, mitigating the risk of mould proliferation, which not only impacts the quality of the rice husk but also poses health and safety concerns. Secondly, drying contributes to process efficiency. Excessive moisture in the rice husk can disrupt subsequent processing steps. For instance, in cases where combustion is intended, the presence of moisture can hinder optimal combustion efficiency. In grinding or pulverizing the husk, too much moisture can lead to clogging or inefficiencies in the grinding equipment. Drying ensures that the husk is in an optimal condition for efficient processing. Thirdly, drying plays a crucial role in ensuring product quality. The presence of moisture in the rice husk can adversely affect the quality of the final product, such as RHA. Excess moisture can impact the combustion process, resulting in incomplete burning and the formation of undesirable by-products. Drying the husk helps maintain the effectiveness of subsequent processing steps, resulting in high-quality RHA with desirable properties. The drying process is typically conducted at temperatures between 80 °C and 110 °C, depending on the initial moisture content of the rice husk and the drying method used (natural vs. mechanical). It is essential to reduce the moisture content to below 10%, with 5% or less being ideal for efficient combustion and high-quality ash yield. This low moisture content ensures uniform burning and reduces the risk of incomplete combustion or formation of tar.

The drying process can be executed through various methods, including natural drying and mechanical drying [41]. Natural drying involves spreading the cleaned rice husk in a well-ventilated area under the sun or using ambient air to evaporate moisture. Mechanical drying methods, such as hot air dryers or fluidized bed dryers, can expedite the drying process by supplying heated air to remove moisture more rapidly. The duration of the drying process depends on several factors, including the initial moisture content of the rice husk, the chosen drying method, and the desired moisture level for further processing. It is crucial to ensure that the husk undergoes adequate drying to achieve the desired moisture content while considering the energy efficiency of the drying process. Properly drying the rice husk post-cleaning reduces moisture content, minimizing the risk of mould growth, enhancing the efficiency of subsequent processing steps, and ensuring the quality of the final product, such as high-quality rice husk ash.

2.2.4 Combustion

Following the thorough drying of the rice husk, it is now poised for the combustion process, a crucial step in converting its organic constituents into ash, primarily composed of inorganic silica [42, 43]. The combustion methods employed depend on specific needs and the equipment available. One of the simpler and cost-effective approaches is Open Burning. In this method, the dried rice husk is directly burned in an open environment. While widely used in small-scale operations or areas with limited resources, open burning may not match the efficiency or environmental friendliness of other combustion methods. Fluidized Bed Combustion, as illustrated in Fig. 2, introduces the dried rice

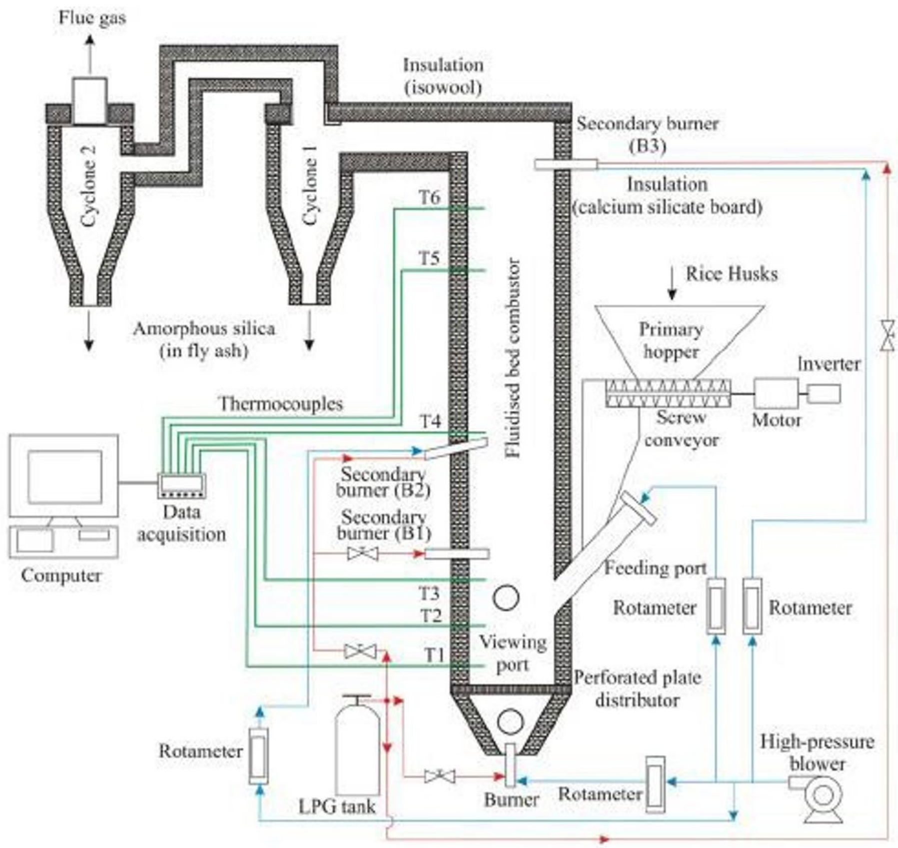


Fig. 2 Overall schematic diagram of the 0.3 inner diameter fluidized bed combustor system [44]

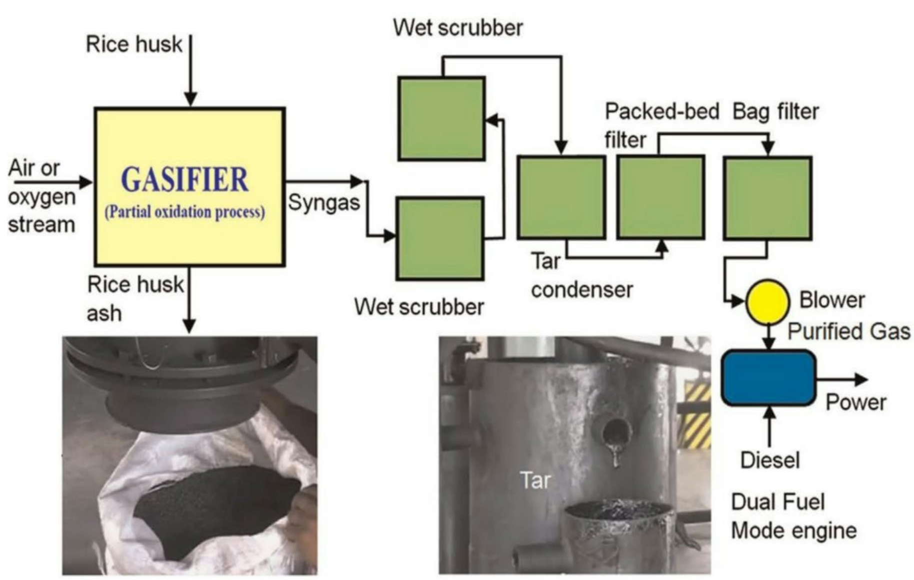


Fig. 3 Obtaining of RHA via a gasifier power system [46]

husk into a bed of inert material, often sand, where combustion takes place. A controlled flow of air or gas passes through the bed, causing the rice husk particles to behave like a fluidized mix. This method not only ensures efficient combustion but also provides better control over crucial parameters such as temperature and residence time.

Gasification, depicted in Fig. 3, represents a more advanced combustion method. Here, the dried rice husk undergoes partial combustion in a controlled environment with limited oxygen supply. This unique process transforms the husk into a gaseous fuel called producer gas or syngas, which finds applications in various energy-related endeavours. Gasification stands out for its higher energy conversion efficiency compared to traditional combustion methods. In essence, the combustion phase is a transformative process where the dried rice husk undergoes controlled burning, leading to the production of ash with specific compositional attributes. The choice of combustion method is carefully considered based on factors such as scale, available resources, efficiency, and environmental impact.

Regardless of the combustion method used, the organic components of the dried rice husk, including cellulose, hemicellulose and lignin, undergo thermal decomposition during the combustion process. This decomposition releases heat and results in the formation of ash. The ash produced from rice husk combustion is primarily composed of inorganic silica (SiO_2), which accounts for a significant portion of the ash content [45]. The high silica content is a distinctive characteristic of RHA and contributes to its unique properties and applications. The combustion process should be carefully controlled to optimise the conversion of the organic components into ash while minimising emissions and ensuring the efficient utilisation of the energy released. Proper combustion parameters, such as temperature, air/gas flow rates and residence time, need to be considered to achieve desired outcome.

2.2.5 Ash collection

In the course of rice husk combustion, it is crucial to efficiently gather the resulting ash for subsequent processing and utilization. Various methods are employed to separate ash particles from the combustion gases, ensuring a thorough and effective ash collection process [47]. Commonly used techniques encompass cyclones, filters, and electrostatic precipitators. Cyclones are widely adopted for ash collection due to their straightforward design and cost-effectiveness. Operating on the principle of centrifugal force, these separators allow combustion gases and entrained ash particles to enter tangentially. The centrifugal force directs heavier ash particles toward the outer walls, allowing purified gases to exit from the top. Collected ash settles at the bottom of the cyclone and can be discharged for further processing.

Filters, such as bag filters or fabric filters, are frequently employed to capture fine ash particles from combustion gases. These filters, equipped with a porous medium, enable gases to pass through while trapping ash particles. The collected ash can be periodically removed from filters through cleaning or replacing the filter media. Bag filters, in particular, excel in capturing smaller ash particles, ensuring a high level of ash collection efficiency. Electrostatic precipitators (ESPs) utilize electrostatic forces to separate ash particles from combustion gases. As gases pass through an electrode system, an electric charge is imparted to the ash particles. The charged particles are then attracted to oppositely charged plates or collection surfaces, where they accumulate and can be periodically removed. ESPs prove effective in collecting both larger and finer ash particles, making them suitable for larger-scale combustion systems. The choice of ash collection technique depends on factors such as the specific requirements of the combustion system, the size and characteristics of the ash particles, and the desired ash collection efficiency [48]. In some cases, a combination of different techniques may be employed to achieve optimal results.

2.2.6 Cooling

Once the ash has been gathered from the combustion process, it undergoes a crucial cooling step to bring it down to room temperature. This cooling process is indispensable to eliminate any remaining heat present in the collected ash. Its significance lies in ensuring safe handling of the ash and preventing potential reactions or alterations in its properties. The cooling process can be accomplished through various methods, depending on the operational scale and available equipment [49, 50].

One common method is Natural Air Cooling, where the collected ash is allowed to cool naturally by exposure to ambient air. Whether spread out in thin layers or placed in containers with sufficient ventilation, this method facilitates heat dissipation. The gradual natural air circulation brings the ash temperature down to room temperature, making it a simple and cost-effective choice, particularly for smaller-scale operations. Another method is Forced Air Cooling, employing fans or blowers to hasten the cooling of the collected ash. Containers or conveyors hold the ash, and mechanical means circulate air to accelerate the heat transfer process, achieving quicker cooling. This method is often preferred in larger-scale operations where increased production efficiency is sought through swift cooling. Throughout the cooling process, it is crucial to ensure proper ventilation and airflow to prevent heat accumulation and maintain a consistent cooling rate. This precautionary measure helps mitigate potential risks associated with high temperatures, such as fire hazards or undesired reactions.

2.2.7 Grinding

Once the RHA has been cooled to room temperature, it usually undergoes a grinding process to achieve the desired particle size distribution. Grinding is a crucial step in the processing of RHA as it helps improve the reactivity and surface area of the ash, thereby enhancing its potential applications. Grinding can be carried out using various grinding techniques and equipment, depending on the desired particle size and the scale of the operation [51, 52]. Ball Milling is a widely employed technique for grinding various materials, including RHA. In this process, cooled RHA is placed in a rotating container alongside grinding media, typically steel balls. The rotation of the container causes the grinding media to impact and crush the RHA particles, effectively reducing their size. Adjusting the duration of milling and the rotation speed allows control over the particle size distribution. Vibratory Milling involves using a vibratory mill or miller that utilizes vibrations to impart energy to RHA particles. The vibratory motion induces collisions among particles, leading to size reduction. Vibratory mills excel in producing fine and uniform particle sizes. Jet Milling employs high-speed jets of gas or air to impact and grind RHA particles. The rapid collisions between particles and the gas stream result in size reduction. Jet milling is commonly chosen for producing fine powders characterized by a narrow particle size distribution.

The grinding process can be optimised to achieve the desired particle size distribution, which is crucial for specific applications of RHA. Grinding the ash improves its reactivity by increasing the surface area available for chemical reactions [53, 54]. This enhanced reactivity makes RHA suitable for various applications, such as cement and concrete production, as well as in the fields of agriculture, materials science and environmental engineering. The particle size distribution obtained through grinding is influenced by factors such as the duration of grinding, the type and size of grinding media, the rotational speed of the grinding equipment and the initial particle size of the cooled RHA. Careful control of these parameters allows for the production of RHA with specific particle size characteristics that are tailored to the desired applications. The ground RHA should typically achieve a particle diameter between 5 μm and 10 μm, which is suitable for enhancing pozzolanic activity and ensuring proper dispersion within cementitious matrices. This size range ensures a high specific surface area, critical for optimal reactivity with calcium hydroxide in concrete applications.

2.2.8 Sieving

Sieving plays a crucial role in the processing of ground RHA, ensuring a consistent particle size distribution. Once the RHA has undergone grinding, sieving becomes a necessary step to segregate particles based on size, striving for uniformity in material properties. In this process, the ground RHA is placed onto a sieve, a device with a mesh screen of uniform openings. Subsequently, gentle shaking or agitation allows smaller particles to pass through the sieve, while larger ones are retained. Sieves with varying mesh sizes enable the separation of distinct particle size fractions.

Sieving facilitates precise control and selection of specific particle size ranges. Different mesh sizes of sieves divide the ground RHA into fractions with desired particle sizes, ensuring a uniform distribution for consistent RHA performance across diverse applications. Contributing to the uniformity of RHA, sieving eliminates oversized or undersized particles. Consistent particle size distribution is crucial in applications where the predictable behaviour and performance of RHA are paramount. As a quality control measure, sieving ensures that ground RHA adheres to desired particle size specifications, eliminating any coarse or fine particles that could potentially impact the material's properties and performance. Sieving offers the customization of RHA for specific applications requiring precise particle size ranges. Industries and research fields may have distinct particle size requirements tailored to optimize the performance and effectiveness of RHA in their respective applications. Caution must be exercised during sieving to prevent sample contamination and ensure accurate results. Proper cleaning and maintenance of sieves, along with equipment calibration, are essential steps to obtain reliable and consistent particle size distributions. Standard sieving of RHA is performed using sieves with mesh sizes ranging from 45 μm (No. 325 sieve) to 75 μm (No. 200 sieve). This ensures removal of oversized particles and helps achieve a consistent fine powder that enhances the pozzolanic performance of RHA in cementitious systems.

2.2.9 Packaging and storage

After the production and processing of RHA, proper packaging and storage are essential to maintain its quality and prevent degradation. Selection of appropriate packaging materials involves choosing materials that offer protection against moisture and physical damage. Common options include moisture-resistant bags, polypropylene sacks, or airtight containers.

In the packaging process, RHA is carefully placed into the chosen packaging material, ensuring proper sealing to prevent moisture ingress. This packaging is carried out in a clean and controlled environment to minimize contamination. Each package undergoes labelling with relevant information, including the product name, batch number, date of packaging, and any specific storage instructions. Clear labelling facilitates easy identification and tracking of the RHA product.

Storage conditions for packaged RHA involve placing it in a dry and controlled environment to minimize exposure to moisture and humidity. It is essential to keep RHA away from direct sunlight, excessive heat, and sources of moisture, as these can adversely affect its quality and reactivity. Moisture control is addressed due to the tendency of silica-based materials like RHA to absorb moisture. Desiccants or moisture-absorbing packets may be added to the packaging to prevent moisture absorption and maintain the dryness of the RHA during storage.

During handling and transportation of packaged RHA, proper care is taken to avoid any physical damage or puncturing of the packaging material. RHA is stored and transported separately from other materials to prevent contamination. Maintaining an inventory management system is crucial for tracking the quantity, batch numbers, and storage duration of packaged RHA. This ensures efficient stock rotation and helps prevent the use of expired or deteriorated RHA.

Proper packaging and storage of RHA are crucial to maintain its quality and ensure its effectiveness in various applications. By protecting the RHA from moisture absorption and maintaining suitable storage conditions, its chemical composition, physical properties and reactivity can be preserved over an extended period. This allows for consistent and reliable use of RHA in construction, agriculture and other industries that benefit from its unique properties. It is important to note that the production process may vary depending on factors such as the specific equipment used, the desired characteristics of the RHA and the intended applications. Additionally, certain environmental regulations and guidelines need to be followed to ensure safe and sustainable production practices. The production of RHA provides a valuable opportunity to utilise a by-product that would otherwise contribute to waste management challenges. The resulting ash can be utilised in various industries such as construction, agriculture, ceramics and energy,

Table 1 Oxide content of RHA by regions of cultivation [55, 56]

Oxides	Countries of cultivation of rice (%)						Range (%)
	Vietnam	India	USA	Brazil	Malaysia	Russia	
SiO2	86.9	90.7	94.5	92.9	93.1	84.3	85–95
CaO	1.4	0.4	0.25	1.03	0.41	0.5	0.25–1.50
Fe2O3	0.73	0.4	-	0.43	0.21	0.3	0.20–0.75
Al2O3	0.84	0.4	-	0.10	0.21	1.1	0.10–0.90
MgO	0.57	0.5	0.23	0.35	1.59	0.9	0.20–1.60
K2O	2.46	2.2	1.10	0.72	2.31	3.7	0.70-4.00
Na2O	0.2	0.1	0.78	0.02	-	1.0	0-0.8
SO3	-	0.1	1.13	0.1	-	0.1	0.0.15
$SiO_2 + Fe_2O_3 + Al_2O_3$	88.47	91.50	94.50	93.43	93.52	85.70	85.7–94.50
Lossof Ignition	5.14	4.8	-	-	2.36	8.1	-

Table 2 Physical properties of RHA [57–59]

Property	Unit	Values
Dry density	Kg/m^3	2020–2160
Specific surface area	m^2/kg	240-276.5
Pozzolanic activity index	%	81.25–88.90
Average particle size	µm	5.0-7.41
Nitrogen adsorption	Kg/m^2	24.3–28.8
Volume of pores	mL/g	0.073

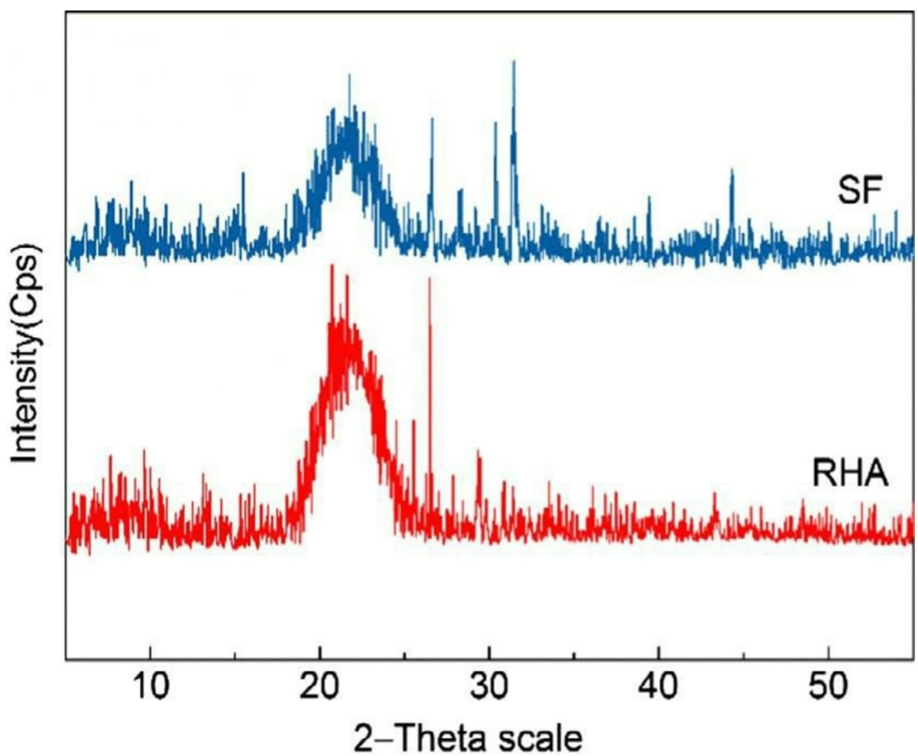


Fig. 4 XRD patterns of RHA and SF [60]

offering sustainable and environmentally friendly alternatives to traditional materials and fuels.

2.3 Chemical and physical properties of RHA

RHA possesses both chemical and physical properties that contribute to its versatility and suitability for various applications. Chemically, RHA is primarily composed of amorphous silica (SiO_2), with a high silica content ranging from 80 to 95%. This silica content gives RHA its pozzolanic activity, enabling it to react with calcium hydroxide in the presence of water and form additional cementitious compounds. RHA also contains residual carbon derived from the organic components of rice husk and may have other mineral compounds present. The oxide content of RHA by regions of cultivation of rice is summarised in Table 1.

Physically, RHA consists of fine particles with a wide particle size distribution, high specific surface area and porous structure. It has a relatively low bulk density, making it lightweight and suitable for use as a filler or additive. RHA exhibits an alkaline pH and its physical properties can be influenced by factors such as particle size, specific gravity, colour, moisture content and porosity. These combined chemical and physical properties make RHA a valuable material with applications in areas such as construction, agriculture, energy and environmental remediation. The physical properties of RHA are summarised in Table 2.

2.3.1 Chemical properties

Silica content: RHA is known for its high silica content, which plays a significant role in its properties and applications. The silica content in RHA typically ranges from 80 to 95% depending on factors such as the combustion process and the composition of the rice husk itself [16]. The XRD analysis shown in Fig. 4 indicates that both SF and RHA contain mainly amorphous silicon dioxide [60]. SiO_2 in RHA exists in the form of amorphous silica, which means it lacks a well-defined crystalline structure. The high silica content in RHA, particularly in amorphous form, underpins its pozzolanic activity. As described in the Introduction, this reactivity plays a central role in the performance of RHA in cementitious applications [61]. The formation of C-S-H gel contributes to the strength and durability of cementitious materials. The presence of amorphous silica in RHA also enhances its reactivity. The fine particle size and large surface area of RHA promote a higher degree of chemical interaction with other components in the system. This increased reactivity allows RHA to participate in various chemical reactions, leading to improved performance and properties in cement-based materials [62].

Carbon content: RHA contains a small amount of residual carbon, which is derived from the organic components present in rice husk. The carbon content in RHA can vary depending on the combustion conditions during the production process. Typically, the carbon content in RHA ranges from 2 to 20% [63]. The presence of carbon in RHA can have several implications for its properties and applications [17]. During the combustion process, the organic components of rice husk undergo thermal decomposition, releasing volatile gases and leaving behind residual carbon. The combustion conditions, such as temperature, oxygen availability and combustion duration, can influence the amount of carbon retained in the RHA. The carbon content in RHA can impact the combustion process itself. Higher carbon content can affect the combustion efficiency and require more controlled conditions to ensure complete combustion. It can influence parameters such as combustion temperature, residence time and oxygen supply. Furthermore, the carbon content in RHA can affect its chemical and physical properties. Carbon particles dispersed within the RHA matrix can contribute to its overall structure, porosity and surface characteristics. The presence of carbon can influence the surface reactivity, adsorption capacity and electrical conductivity of RHA. In certain applications, the carbon content in RHA can be desirable. For example, in the field of adsorption, carbonaceous materials, including RHA, are utilised for their ability to adsorb pollutants and contaminants [64]. The carbon content in RHA can enhance its adsorption capacity, making it effective for water treatment, air purification and remediation of various pollutants. However, in some applications, the carbon content in RHA may be considered undesirable. For instance, in the production of high-purity silica-based materials, such as silicon metal or high-quality silica gel, the carbon content needs to be minimised to achieve the desired purity levels [23, 46].

Mineral composition: In addition to its high silica content, RHA can contain various mineral compounds derived from the original rice husk material. These minerals may include calcium, potassium, sodium, magnesium and iron, among others [65]. The specific composition and concentration of these minerals in RHA can vary depending on factors such as the source of the rice husk and the combustion process employed. The presence of these minerals in RHA can have implications for its properties and potential applications. For example, calcium in RHA can contribute to the pozzolanic reaction and the formation of C-S-H gel, enhancing the strength and durability of cementitious materials. Potassium and sodium may influence the rheological properties of concrete, affecting its workability and setting time [66]. It is important to note that the concentration of these minerals in RHA is generally lower compared to silica. Silica is the predominant mineral component in RHA and is responsible for its pozzolanic activity. However, the presence of other minerals in RHA can still contribute to its overall behaviour and performance in different applications. Understanding the mineral composition of RHA is essential for optimizing its use in specific applications. It allows for a better understanding of the chemical interactions and reactions that occur when RHA is incorporated into cementitious materials. By considering the mineral composition alongside the silica content, researchers and engineers can tailor the properties and performance of RHA-based products to meet specific requirements and achieve desired outcomes.

Pozzolanic activity: RHA is well-known for its pozzolanic activity, a key characteristic that contributes to its effectiveness in cementitious materials. The pozzolanic reaction occurs when RHA is combined with calcium hydroxide (lime) in the presence of water. During this reaction, RHA reacts with calcium hydroxide to form additional cementitious compounds, particularly calcium C-S-H gel. The formation of C-S-H gel is crucial in enhancing the strength and durability of concrete. C-S-H gel is the primary binding phase in cementitious materials, responsible for the development of the material's mechanical properties. By incorporating RHA into concrete mixes, the pozzolanic activity of RHA leads to the formation of more C-S-H gel, resulting in improved compressive strength. Additionally, the pozzolanic activity of RHA contributes to reduced permeability in concrete [55]. The reaction between RHA and calcium hydroxide leads to the formation of additional hydration products, which fills the capillary pores in the concrete matrix. This densification of the microstructure reduces the passage of water and other harmful substances, enhancing the material's durability and resistance to chemical attack. The pozzolanic activity of RHA also contributes to the mitigation of alkali-silica reaction (ASR) in concrete [67, 68]. ASR is a deleterious chemical reaction that occurs between the alkalis present in concrete and reactive forms of silica. By incorporating RHA into concrete, the pozzolanic reaction consumes the available alkalis, minimising the risk of ASR and improving the chemical resistance of the concrete.

Chemical reactivity: RHA is characterised by its high chemical reactivity, primarily attributed to its amorphous silica content and fine particle size [69, 70]. The unique properties of RHA enable it to engage in chemical reactions and form stable compounds when combined with other materials, leading to improved performance in various applications. The amorphous silica in RHA readily reacts with calcium hydroxide (lime) present in the cementitious matrix when exposed to water. This pozzolanic reaction results in the formation of additional cementitious compounds, such as C-S-H gel. The C-S-H gel contributes to the strength, durability and densification of concrete, enhancing its mechanical properties and reducing permeability. In addition to its pozzolanic activity, the fine particle size of RHA provides a larger surface area for chemical interactions

[71]. This increased surface area allows for more extensive contact between RHA and other materials, promoting efficient chemical reactions and the formation of desired compounds. The high reactivity of RHA makes it suitable for various applications. In the construction industry, RHA is used as a supplementary cementitious material in concrete production, where its reactivity enhances the mechanical strength, durability and workability of the concrete. RHA is also utilised in the production of cement-based products, such as bricks, blocks and mortars, where its chemical reactivity contributes to improved performance. Furthermore, the chemical reactivity of RHA extends to other fields as well. It can be used as a filler in polymers and composites, enhancing their mechanical and thermal properties. RHA's reactivity also makes it suitable for applications in wastewater treatment, where it can be employed as an adsorbent to remove heavy metals and other pollutants.

2.3.2 Physical properties

Particle size distribution: RHA is characterised by the presence of fine particles that range in size from a few micrometres to sub-millimetre scale. The particle size distribution of RHA can vary depending on factors such as the combustion process and the milling techniques used [72, 73]. The particle size distribution of RHA plays a significant role in its chemical and physical properties. The fine particle size allows for a larger surface area, which promotes better interaction with other materials and enhances chemical reactions. This is particularly important in applications such as cement and concrete, where the pozzolanic reaction between RHA and calcium hydroxide is crucial for improving the strength and durability of the materials. Additionally, the particle size

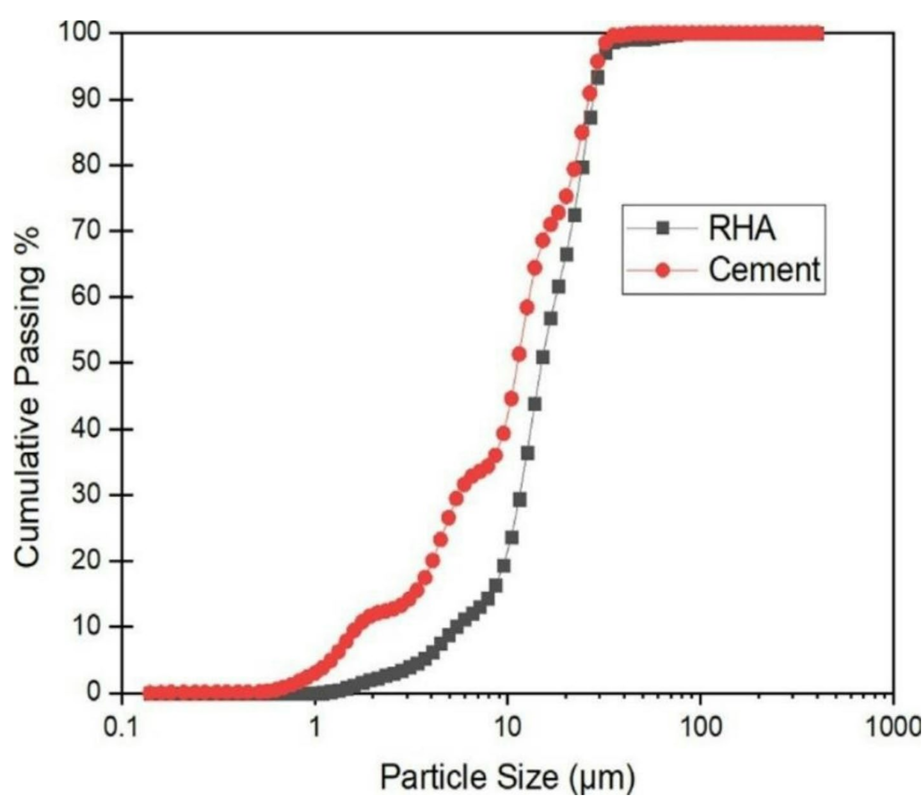


Fig. 5 PSD curve of RHA and cement [75]

distribution affects the flowability and workability of RHA Concrete [74]. Finer particles tend to have better flow characteristics and can be easily incorporated into mixes, while coarser particles may affect the handling and compaction of the material. The particle size distribution can be controlled through grinding and sieving processes, allowing for the customization of RHA according to specific application requirements. It is important to consider the particle size distribution of RHA when selecting it for different applications, as it can influence the overall performance and effectiveness of the material. The PSD of cement and RHA was analysed by a laser particle size analyser (GSL-IOIBI) in a liquid state. RHA and cement were, respectively, dispersed in water and ethanol using a KQ218 ultrasonic treatment machine [75]. The obtained PSD of RHA and cement is presented in Fig. 5.

Specific surface area: RHA exhibits a relatively high specific surface area due to its fine particle size and porous nature. The specific surface area refers to the total surface area of RHA per unit mass and is typically measured in square meters per gram (m^2/g). The fine particle size and porous structure of RHA contribute to its large surface area-to-volume ratio. This increased surface area provides a greater number of active sites for chemical reactions to occur [76, 77]. applications such as cement and concrete, the high specific surface area of RHA enhances its pozzolanic activity, allowing for better interaction with calcium hydroxide and the formation of additional cementitious compounds. The large surface area of RHA also enhances its adsorption capacity. RHA can adsorb various substances, including organic compounds, heavy metals and gases, due to its increased surface area and porous structure. This makes RHA suitable for applications such as water and air purification, where its adsorption properties are utilised to remove contaminants. The specific surface area of RHA can vary depending on factors such as the combustion process, grinding and sieving. These processes can be optimised to control the specific surface area of RHA, allowing for customization based on the intended application requirements.

Bulk density: The bulk density of RHA refers to the mass of RHA per unit volume, typically measured in kilograms per cubic meter (kg/m^3). The bulk density of RHA can vary depending on factors such as the degree of compaction during handling and storage. Generally, RHA has a lower bulk density compared to conventional cement or concrete materials [78]. This is because RHA consists of fine particles with air-filled voids between them, which contributes to its lightweight nature. The lower bulk density of RHA makes it a desirable additive in applications where weight reduction is important, such as lightweight concrete or as a filler in lightweight construction materials. The lightweight property of RHA offers several advantages. It helps to reduce the overall weight of structures, making them more economical and easier to handle during construction. Additionally, the lower bulk density of RHA can improve the workability and flowability of concrete mixes, allowing for easier placement and compaction. It is important to note that the bulk density of RHA can be influenced by factors such as particle size, packing density and moisture content. Therefore, proper handling and storage practices should be employed to maintain the desired bulk density and prevent any adverse effects on the performance of RHA in different applications.

Porosity: RHA possesses a porous structure characterised by numerous interconnecting voids and channels. The porosity of RHA plays a significant role in determining its water absorption capacity, permeability and adsorption characteristics [79]. The porous

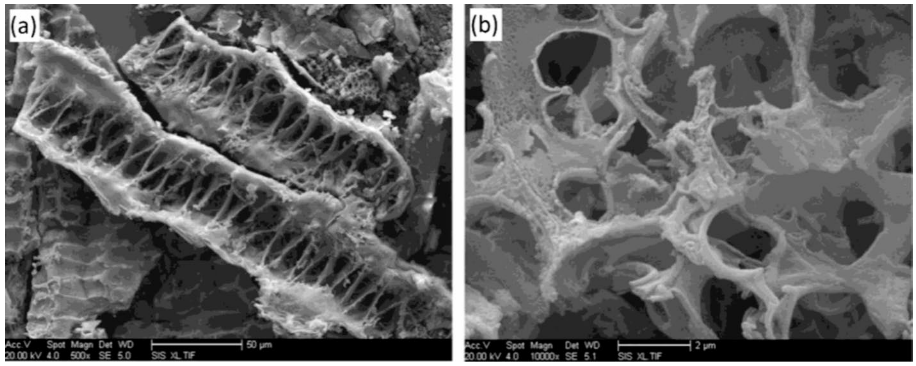


Fig. 6 SEM images of RHA at magnifications of (a) 500x and (b) 10000x [60]

nature of RHA allows it to absorb and retain water, which can be advantageous in certain applications. RHA's porosity enables it to act as a water reservoir, contributing to the moisture retention of concrete mixes and improving the workability and hydration process of cementitious materials [80]. Moreover, the porosity of RHA influences its permeability, or the ability of fluids to flow through its structure. The interconnected voids and channels facilitate the movement of fluids, which can be beneficial in applications where permeability control is desired, such as in filtration or drainage systems. The porosity of RHA also contributes to its adsorption characteristics. The porous structure provides a larger surface area for adsorption, allowing RHA to effectively adsorb and retain various substances, such as organic compounds, heavy metals and pollutants. This makes RHA a potential candidate for environmental remediation applications, including water and air purification [81]. The porosity of RHA can be influenced by factors such as the combustion process, particle size and treatment methods. Proper understanding and control of the porosity of RHA are important to optimise its performance and tailor it to specific applications. The microstructure of RHA is depicted in Fig. 6 through SEM images at two distinct magnifications, namely 500x and 10,000x, revealing its layered and porous nature. Further analysis using Barrett-Joyner-Halenda (BJH) testing, as illustrated in Fig. 6, confirms the presence of nano-sized pores within the range of 3 nm to 10 nm in RHA. This observation explains the high specific surface area (SSA) and water absorption capacity of RHA. The porous structure enables the absorption of water, which can subsequently be released to enhance the compressive strength of RHA.

Moisture content: Proper post-processing and storage of RHA are crucial to maintain a low moisture content. The moisture content of RHA refers to the amount of water present in the ash after processing and is an important parameter that can influence its flowability, handling characteristics and potential reactivity. A low moisture content in RHA is desirable as it enhances the flowability of the ash, making it easier to handle and incorporate into various applications. Excessive moisture can cause the particles to agglomerate or stick together, leading to poor dispersibility and reduced effectiveness of RHA in mixes [82]. Moreover, moisture content can impact the reactivity of RHA in certain applications [83]. Moisture acts as a barrier, hindering the contact between RHA particles and other reactive materials, which can affect the desired chemical reactions and performance of the final product. By maintaining a low moisture content, the reactivity of RHA can be optimised, ensuring its effective utilisation in applications such as cementitious materials or adsorbents. Proper storage conditions, including dry environments and sealed containers, help minimise moisture absorption by RHA. It is essential to store RHA in a controlled manner to preserve its low moisture content and maintain its desired properties for long-term use.

Specific gravity: The specific gravity of RHA is generally lower than that of conventional cement or concrete materials [57]. RHA has a lower specific gravity due to its porous and lightweight nature. During the combustion process, the organic components of rice husk burn away, leaving behind primarily inorganic ash particles. These ash particles have a lower density compared to cement or concrete, resulting in a lower specific gravity for RHA. The lower specific gravity of RHA offers several advantages in different applications. Firstly, it contributes to the lightweight properties of RHA, making it suitable as a partial replacement for heavier aggregates in lightweight concrete or as a filler material in various composites. The reduced weight can result in improved handling, transportation and structural performance of the materials. Additionally, the lower specific gravity of RHA can contribute to the thermal insulation properties of materials when used as an additive. The lightweight nature of RHA reduces the overall density of the material, resulting in lower thermal conductivity and enhanced insulation capabilities.

pH value: RHA exhibits an alkaline pH value, typically ranging from 8 to 11 [65]. When RHA is incorporated into concrete as a partial replacement for cement, it contributes to the overall alkalinity of the concrete mix. The alkalinity of concrete is an important factor that influences its durability and the protection of embedded steel reinforcement. The alkaline environment created by the cementitious materials helps to passivate the steel reinforcement, forming a protective oxide layer that inhibits corrosion. Corrosion of steel reinforcement can lead to structural deterioration and reduced service life of concrete structures. By introducing RHA into the concrete mix, the alkalinity of the system is increased. The alkaline pH of RHA provides an additional source of hydroxide ions (OH^-) in the concrete, which helps to maintain the high pH environment necessary for the passivation of steel reinforcement. It is worth noting that the exact pH value of RHA can vary depending on factors such as the combustion process, rice husk source

Table 3 Comparative evaluation of rice husk ash, fly ash, and silica fume as SCMs

Parameter	Rice Husk Ash (RHA)	Fly Ash (FA)	Silica Fume (SF)
Silica Content (%)	80–95 (mostly amorphous)	45–60 (varies by class)	> 90 (amorphous)
Pozzolanic Reactivity	High (depends on fineness and combustion method)	Moderate to high (Class F is more reactive)	Very high
Particle Size (μm)	5–7	1–100	< 1
Compressive Strength Gain	Moderate to high (10–30% replacement)	Moderate (15–35% replacement)	High (5–15% replacement)
Durability Improvement	High (chloride, sulphate, ASR resistance)	High (especially for Class F)	Very high
Workability Impact	Slight reduction (may need admixtures)	Improves workability	Reduces workability
Cost	Low (agricultural waste by-product)	Low to moderate (industrial by-product)	High
Availability	Regional (dependent on rice production)	Widely available globally	Limited; more costly and less abundant
Environmental Benefit	High (reuses waste, reduces CO_2)	High (reduces cement use, waste reuse)	Moderate (industrial by-product, energy-intensive)
Carbon Footprint Reduction	Up to 30% (if used optimally)	15–30% (varies by dosage and type)	10–20%

and post-processing treatments. Therefore, it is important to consider the specific properties of the RHA being used and adjust the concrete mix design accordingly to ensure the desired alkalinity is achieved.

3 Supplementary cementitious material (SCM) potential of RHA

RHA exhibits significant potential as a supplementary cementitious material (SCM) in the construction industry. As a by-product of rice milling, RHA offers an environmentally friendly and sustainable alternative to traditional cement additives. Its high silica content and pozzolanic activity enable RHA to react with calcium hydroxide in cement, forming additional cementitious compounds that enhance the strength, durability and performance of concrete. RHA can be used as a partial replacement for cement, reducing the demand for cement production and lowering carbon emissions. With its abundant availability and beneficial properties, RHA has the potential to contribute to more sustainable and eco-friendly construction practices. Table 3 provides a comparative overview of RHA alongside commonly used supplementary cementitious materials (SCMs) such as Fly Ash (FA) and Silica Fume (SF). It highlights RHA's high silica content and pozzolanic reactivity, which contribute to notable improvements in strength and durability. RHA is particularly advantageous in terms of cost and environmental impact, given its origin as an agricultural by-product. While SF offers superior performance in terms of reactivity and strength gain, its higher cost and limited availability pose challenges. Fly Ash remains a balanced option, though its performance varies by type. Overall, RHA presents a sustainable, cost-effective alternative.

3.1 Pozzolanic activity of RHA

Pozzolanic activity is a key characteristic of RHA that contributes to its effectiveness in enhancing the properties of cementitious materials. The pozzolanic reaction occurs when RHA reacts with calcium hydroxide (lime) in the presence of water, resulting in the formation of additional cementitious compounds. The high silica content of RHA, typically in the range of 80–95%, plays a crucial role in its pozzolanic activity. Silica in RHA exists in the amorphous form, which provides a reactive surface for chemical reactions. When RHA is finely ground and mixed with lime and water, the amorphous silica reacts with calcium hydroxide to form C-S-H gel. This gel fills the pores and interstitial spaces within the cementitious matrix, leading to improved strength, durability and other desirable properties.

The pozzolanic reaction with RHA results in the formation of additional C-S-H gel, which contributes to the densification and refinement of the microstructure of cementitious materials. The gel acts as a binder, binding the particles together and reducing the porosity of the material. This leads to increased compressive strength, reduced permeability and improved resistance to chemical attacks. In addition to the formation of C-S-H gel, the pozzolanic reaction also consumes calcium hydroxide, a by-product of cement hydration. The consumption of calcium hydroxide helps to reduce the alkali content in the system, minimising the risk of alkali-silica reaction (ASR) and enhancing the long-term durability of the cementitious material.

The pozzolanic activity of RHA offers several benefits in construction applications [84–87]. By incorporating RHA as a partial replacement for cement in concrete mixes, it can reduce the demand for cement, which is a significant contributor to carbon dioxide emissions during production. This contributes to the sustainability of construction practices and reduces the environmental impact. Furthermore, the pozzolanic activity of RHA enables the utilisation of supplementary cementitious materials, such as fly ash or slag, in blended cement formulations. These blends optimise the performance of cementitious materials by enhancing workability, reducing heat generation, improving resistance to sulphate attacks and mitigating the potential for drying shrinkage.

The pozzolanic activity of RHA has been a subject of extensive research, aiming to understand and enhance its effectiveness as a supplementary cementitious material. Several studies have investigated the factors influencing the pozzolanic activity of RHA, providing valuable insights into its structural and chemical properties. Nair et al. [88] conducted a structural investigation to explore the pozzolanic activity of RHA. Their study revealed that the amorphous silica content and the surface area of RHA play a crucial role in its reactivity. The amorphous silica in RHA provides a reactive surface for the pozzolanic reaction, while a higher surface area offers more sites for chemical interactions. These findings highlight the importance of RHA characteristics in determining its pozzolanic activity.

Particle size and specific surface area have also been recognised as key factors influencing the pozzolanic activity of RHA. Cordeiro et al. [74] investigated the influence of particle size and specific surface area on the reactivity of residual RHA. They found that finer particles and higher specific surface area correlated with increased pozzolanic activity. This suggests that the fineness of RHA particles promotes better contact and reaction with calcium hydroxide, leading to enhanced pozzolanic properties. Furthermore, the pre-treatment of RHA has been explored as a means to enhance its pozzolanic activity. Feng et al. [89] investigated the effect of hydrochloric acid pre-treatment on RHA. They found that the acid treatment increased the silica content and surface area of RHA, resulting in improved pozzolanic activity. The acid treatment was believed to remove impurities and activate the surface of RHA, enhancing its reactivity.

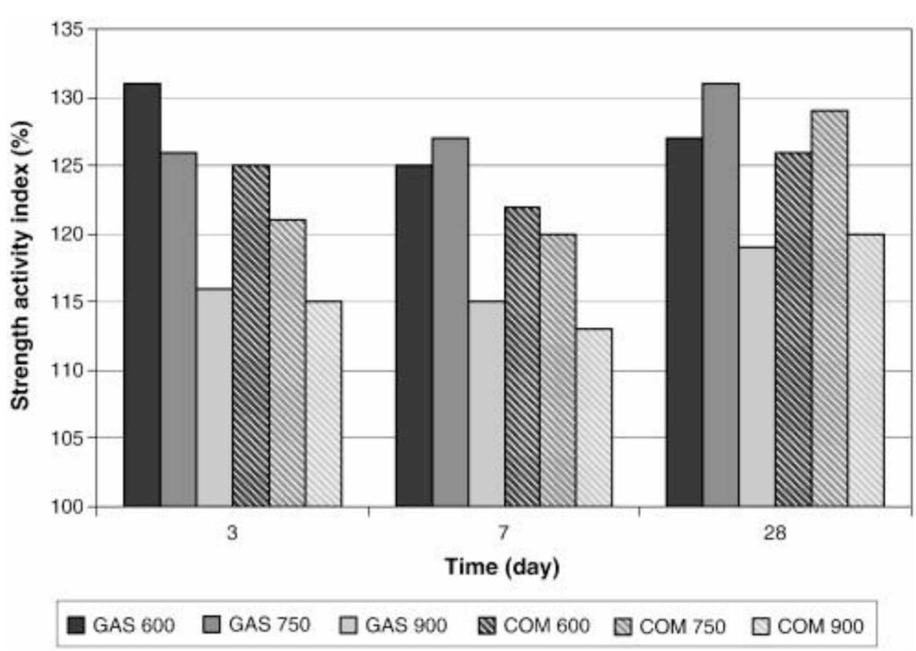


Fig. 7 Strength activity indices of mortars with 10% RHA replacement under fixed flow condition [90]

In a study by Wansom et al. [90], impedance spectroscopy was employed to characterise the pozzolanic activity of RHA. The compressive strengths of mortars with 10% RHA replacement under fixed flow condition, corresponding to the strength activity indices are presented in Fig. 7. The calculations are based on the plain mortar compressive strengths of 21.48, 32.36 and 43.25 MPa at 3, 7 and 28 days, respectively. The results demonstrated that RHA exhibited significant reactivity when mixed with lime and water, leading to the formation of calcium silicate hydrate gel, a key contributor to the strength and durability of cementitious materials. The impedance spectroscopy technique provided valuable insights into the pozzolanic reaction kinetics and confirmed the pozzolanic nature of RHA. Understanding the origin of the pozzolanic effect of rice husks has also been a subject of investigation. Jauberthie et al. [91] explored the factors contributing to the pozzolanic activity of rice husks. They identified the silica content and the presence of amorphous silica in rice husks as the key factors responsible for their pozzolanic behaviour. The amorphous silica in rice husks undergoes a chemical reaction with calcium hydroxide, forming additional cementitious compounds.

These studies collectively demonstrate the importance of various factors in determining the pozzolanic activity of RHA. The amorphous silica content, surface area, particle size, specific surface area and pre-treatment techniques all contribute to the reactivity and performance of RHA as a supplementary cementitious material. By understanding these factors, researchers and engineers can optimise the utilisation of RHA in cementitious materials and enhance the properties of concrete structures. The pozzolanic activity of RHA not only enhances the mechanical properties of cement-based materials, such as increased compressive strength and reduced permeability but also contributes to the sustainability of the construction industry. By incorporating RHA as a partial replacement for cement, the demand for cement production can be reduced, resulting in lower carbon emissions and minimising environmental impact.

3.2 Influence of RHA on cementitious systems

Building on the pozzolanic behavior described earlier, RHA's interaction with calcium hydroxide contributes to the development of additional C-S-H gel. This enhances the density and strength of the cementitious matrix, leading to better durability and mechanical performance [92]. This increased density and strength contribute to improved performance and durability of the cementitious system. The pozzolanic reaction of RHA leads to improved strength development in cementitious systems. The reaction between RHA and calcium hydroxide occurs at an accelerated rate, promoting the early-age and long-term hydration of cementitious materials [93]. As a result, the formation of additional C-S-H gel enhances the compressive strength, flexural strength and tensile strength of the cementitious system. This strength enhancement is beneficial in various applications where high strength is required, such as structural concrete elements. RHA has a significant influence on the workability and rheological properties of cementitious systems. When properly proportioned, RHA acts as a filler material in the concrete mix, reducing the water demand and increasing the viscosity [94–96]. This improved workability allows for easier handling, pumping and placing of the concrete. The increased cohesiveness of the mix helps in achieving better consolidation and reduces the risk of segregation. Consequently, the use of RHA can improve construction efficiency and productivity.

Incorporating RHA into cementitious systems contributes to enhanced durability. RHA improves the microstructure of the cementitious matrix by filling the voids and refining the pore structure [97–99]. This results in a denser and more impermeable concrete, reducing the ingress of aggressive substances such as chlorides and sulphates. By minimising the penetration of these harmful ions, RHA helps mitigate corrosion of reinforcing steel and the alkali-aggregate reaction. The improved durability extends the service life of the cementitious system, making it more resistant to deterioration over time. RHA can influence the thermal properties of cementitious systems. The incorporation of RHA can improve insulation properties and reduce thermal conductivity. This is particularly beneficial in applications that require thermal insulation, as the reduced heat transfer through the concrete helps in maintaining desired temperatures. By enhancing the thermal performance, RHA can contribute to energy savings and improved comfort in buildings.

Utilising RHA in cementitious systems offers sustainability and environmental benefits. RHA is an agricultural waste product obtained from the burning of rice husks, making it a renewable and readily available resource. By incorporating RHA as a supplementary cementitious material, the consumption of traditional cement materials can be reduced, resulting in lower carbon dioxide emissions and conservation of natural resources. This promotes sustainable practices and waste management, aligning with efforts to minimise environmental impact. In addition to its technical and environmental advantages, RHA can provide cost benefits in cementitious systems. As a by-product of the rice industry, RHA is often available at a lower cost compared to other supplementary cementitious materials. This cost advantage can contribute to overall project savings without compromising the performance or quality of the cementitious system. It is important to consider various factors when incorporating RHA into cementitious systems, such as the characteristics of RHA (such as fineness and chemical composition), the dosage level, processing methods (such as grinding and blending) and specific application requirements. Proper quality control, mix design optimisation and compatibility testing are necessary to achieve the desired performance and maximise the benefits of incorporating RHA in cementitious systems.

Jamil et al. [1] conducted a comprehensive study on the pozzolanic contribution of RHA in cementitious systems. They investigated the effect of RHA dosage on the compressive strength of concrete and found that an optimal dosage led to improved strength. However, they cautioned that excessive amounts of RHA could negatively impact workability and setting time. Their findings emphasise the importance of carefully controlling the RHA dosage to balance the desired strength enhancement with the practical requirements of concrete production. Robler et al. [80] delved into the mesoporous structure and pozzolanic reactivity of RHA. They investigated the relationship between the presence of mesopores in RHA and its enhanced pozzolanic activity. The study revealed that the mesoporous structure provided a larger surface area for pozzolanic reactions, leading to improved mechanical properties of the cementitious system. This finding highlights the significance of the internal structure of RHA in determining its reactivity and overall performance as a supplementary cementitious material.

Park et al. [100] focused on analysing the effects of RHA on the hydration kinetics of cementitious materials. Their study demonstrated that RHA influenced the early hydration process, affecting the formation and growth of hydration products. The researchers emphasised the importance of understanding and controlling the hydration kinetics when incorporating RHA into cementitious systems. Optimizing the dosage and timing of RHA addition can lead to enhanced early strength development and improved long-term performance. Msinjili et al. [101] investigated the impact of superplasticizers on the rheology and early hydration kinetics of RHA-blended cementitious systems. They found that the addition of superplasticizers improved the workability and early strength development of RHA-based concrete. However, they cautioned against using excessive dosages of superplasticizers, as it could negatively affect the long-term performance and durability of the cementitious matrix. This study highlights the importance of considering the interaction between RHA and chemical admixtures when designing concrete mixes.

Prasittisopin & Trejo [102] focused on the hydration and phase formation of RHA-blended cementitious systems. They observed significant changes in the mineralogical composition and microstructure due to the chemical transformation of RHA during the hydration process. These transformations influenced the mechanical properties and durability of the cementitious matrix. The findings suggest that the pozzolanic reaction of RHA plays a vital role in improving the performance of cement-based materials and understanding the underlying phase formation mechanisms is crucial for optimizing its utilisation. Wang et al. [62] provided a comprehensive review of the action mechanism of RHA and its effects on various performance aspects of cement-based materials. They discussed the role of RHA in enhancing strength, reducing permeability, improving durability and mitigating the environmental impact of cement production. The review highlighted the potential benefits of incorporating RHA in cementitious systems and emphasised the need for further research to fully understand the mechanisms involved and to develop guidelines for the effective and sustainable use of RHA.

3.3 RHA as a sustainable SCM

RHA is widely recognised as a sustainable SCM due to its numerous environmental benefits and positive impact on cementitious systems. One of the key advantages of RHA is its origin as a by-product of the rice milling industry. Instead of being discarded as waste, RHA is repurposed, providing a sustainable solution for waste management. This utilisation of agricultural waste contributes to a circular economy by reducing the environmental burden associated with its disposal.

Incorporating RHA as an SCM in cementitious systems offers significant reductions in the carbon footprint of construction materials. The production of traditional cement, which is primarily composed of clinker, is responsible for a significant amount of greenhouse gas emissions. By partially replacing cement with RHA, the overall carbon dioxide emissions from cement production can be significantly reduced. This substitution helps to mitigate climate change and aligns with global efforts to reduce greenhouse gas emissions. Furthermore, RHA exhibits strong pozzolanic properties, meaning it reacts with calcium hydroxide in the presence of water to form additional cementitious compounds. This pozzolanic reaction leads to the formation of C-S-H gel, which enhances the strength and durability of cementitious systems. The incorporation of RHA improves the microstructure of the cementitious matrix, resulting in a denser and more impermeable material. This, in turn, reduces the permeability of the concrete, limiting the ingress of aggressive substances such as chlorides and sulphates. By improving the durability, RHA extends the service life of concrete structures and reduces the need for frequent repairs and replacements, further contributing to sustainable construction practices.

Moreover, RHA offers enhanced mechanical properties to cementitious systems. The pozzolanic activity of RHA leads to improved strength development, including compressive, flexural and tensile strengths. The additional cementitious compounds formed during the reaction enhance the load-bearing capacity and structural performance of the concrete. This improved strength allows for the construction of more robust and resilient structures, which can withstand various external forces and environmental conditions. In addition to its strength-enhancing properties, RHA also contributes to improved energy efficiency in buildings. By enhancing the thermal insulation properties of cementitious systems, RHA reduces the thermal conductivity of concrete. This means that buildings constructed with RHA-incorporated concrete have better insulation, reducing the energy consumption required for heating and cooling. The improved energy efficiency contributes to sustainable building practices and helps reduce the environmental impact associated with energy consumption. Furthermore, the availability of RHA at a lower cost compared to other supplementary cementitious materials makes it an economically viable option. Its cost-effectiveness allows for cost savings in construction projects without compromising the performance or quality of the cementitious system. This affordability makes RHA an attractive choice for contractors and builders who are seeking sustainable and cost-efficient solutions.

Ahsan & Hossain [103] highlighted the supplemental use of RHA as a cementitious material in the concrete industry. They discussed the sustainable aspects of RHA, including its abundance as an agricultural waste by-product, its potential to replace a portion of cement in concrete and the reduction in carbon emissions associated with cement production. The study emphasised the environmental benefits of utilising RHA as a sustainable SCM, contributing to the reduction of waste generation and carbon footprint in the construction industry. Msinjili et al. [104] focused on the sustainable aspects of RHA as a supplementary cementitious material for improving concrete properties. They discussed the potential of RHA in enhancing workability, reducing water demand, improving strength and increasing the durability of concrete. The study highlighted the sustainable utilisation of RHA as a waste-derived material, contributing to the conservation of natural resources and the reduction of environmental impacts associated with cement production.

Memon et al. [105] investigated the production of eco-friendly concrete by incorporating RHA and polypropylene fibres. The study discussed the synergistic effect of RHA and fibres in improving the mechanical properties, durability and sustainability of concrete. The utilisation of RHA as a SCM in combination with other environmentally friendly materials demonstrated the potential for producing eco-conscious concrete with enhanced performance and reduced environmental impacts. Channa et al. [106] analysed the combined use of sugarcane bagasse ash and RHA as SCM in concrete production. The study explored the sustainable utilisation of agricultural by-products and waste materials to reduce the consumption of traditional cement. The findings highlighted the potential of combining RHA with other supplementary materials to enhance the properties of concrete while reducing the environmental burden of the construction industry. Amin et al. [107] focused on the prediction and optimisation of sustainable concrete utilising RHA as an SCM. The study emphasised the importance of optimizing

Table 4 Quantitative comparison of sustainability metrics for conventional and RHA-Blended concrete

Parameter	OPC Concrete	RHA-Concrete (20% RHA)	Improvement / Reduction (%)	Notes / Source
CO_2 Emissions (kg CO_2/ton concrete)	910	728	↓ 20%	Based on cement CO_2 factor ≈ 0.9 kg CO_2/kg
Embodied Energy (MJ/kg binder)	5.2	4.0	↓ 23%	Assumes RHA energy ≈ 0.5 MJ/kg (waste-derived)
Compressive Strength (28 days, MPa)	40	44	↑ 10%	Average based on literature [e.g., Ganesan et al.]
Water Permeability (m/s × 10^{-12})	9.2	3.1	↓ 66%	Indicates enhanced durability
Chloride Penetration (Coulombs)	3000	1100	↓ 63%	ASTM C1202 Rapid Chloride Test
Lifecycle Cost over 30 yrs (%)	100	88	↓ 12%	Based on reduced repair/maintenance

the mix proportions and properties of RHA-blended concrete to achieve desired performance while minimising environmental impacts. The research highlighted the potential of advanced optimisation techniques for the efficient utilisation of RHA as a sustainable SCM in concrete production. To quantitatively support the sustainability benefits discussed, Table 4 summarizes key indicators comparing conventional concrete and RHA-blended concrete.

3.4 Classification of RHA

Pozzolans are typically classified into two categories according to ASTM C618:

- Class F Pozzolans: These are naturally occurring or derived from the burning of anthracite or bituminous coal. They contain at least 70% of the combined oxides SiO_2 + Al_2O_3 + Fe_2O_3 and exhibit pozzolanic properties with little or no cementing value alone.
- Class C Pozzolans: These are often derived from sub-bituminous or lignite coal and contain at least 50% of the combined oxides. Class C materials may have both pozzolanic and cementitious properties.

Based on its chemical composition, particularly its high combined content of SiO_2, Fe_2O_3 and Al_2O_3 (typically exceeding 85%), Rice Husk Ash (RHA) qualifies as a Class F pozzolan. This classification highlights its effectiveness as a supplementary cementitious material with strong pozzolanic activity, particularly when produced under controlled combustion conditions.

4 Influence of RHA on concrete performance

4.1 Strength development and mechanical properties

The enhancement of compressive strength is one of the primary effects of RHA on concrete. Numerous studies have demonstrated that the incorporation of RHA in concrete mixes leads to increased compressive strength compared to conventional concrete [108–113]. This improvement can be attributed to the pozzolanic reaction between RHA and calcium hydroxide. During this reaction, RHA reacts with calcium hydroxide to form additional cementitious compounds, such as C-S-H gel. The formation of these compounds contributes to a denser microstructure, resulting in improved compressive strength. In addition to compressive strength, RHA also influences the flexural strength

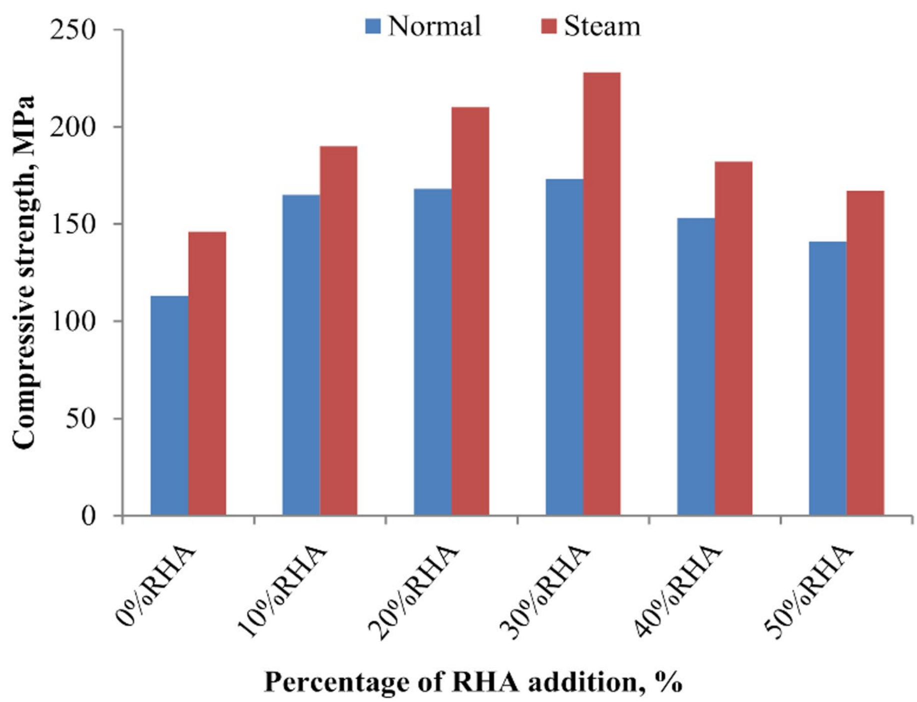


Fig. 8 Concrete compressive strength with different levels of RHA replacement [114]

and toughness of concrete. Furthermore, the inclusion of RHA in concrete leads to reduced porosity and improved density of the concrete matrix. The pozzolanic reaction between RHA and calcium hydroxide helps fill the voids and gaps in the concrete structure, resulting in a more compact and less permeable matrix. The reduction in porosity improves the durability of concrete by limiting the ingress of moisture, chemicals and aggressive substances. This enhanced resistance to penetration and deterioration processes, such as freeze-thaw cycles and chemical attacks, enhances the long-term performance and lifespan of concrete structures.

In the context of Ultra-High Performance Concrete (UHPC), the compressive strength demonstrates a continuous increase up to a 30% replacement level with RHA, as depicted in Fig. 8. Notably, when incorporating 30% RHA into UHPC, a compressive strength of approximately 182 MPa can be attained after 28 days, exhibiting a 51% improvement compared to concrete without RHA (0% RHA). This finding underscores the exceptional reactivity of RHA as a pozzolanic material, which positively impacts the Interfacial Transition Zone (ITZ) and microstructure, ultimately enhancing the strength of the concrete. Nevertheless, it should be noted that surpassing the 30% RHA replacement level leads to a reduction in the compressive strength of UHPC. The concrete compressive strength of various volume of RHA by various scholars worldwide is summarised in Table 5.

In Fig. 9, it is evident that the addition of 10% Silica Fume (SF) or 20% Rice Husk Ash (RHA) in UHPC significantly improved its compressive strength compared to the control sample [117]. Furthermore, the level of compressive strength enhancement observed in the samples with binary blends was comparable. When SF was incorporated, the highest compressive strength of UHPC was achieved with a 10% SF replacement of cement. However, increasing the replacement level, particularly beyond 20%, resulted in a reduction in compressive strength. The utilization of RHA as a partial replacement for cement

Table 5 Concrete compressive strength with different levels of RHA replacement by various scholars worldwide

References	w/b	RHA (%)	Superplasticiser (%)	Compressive strength (MPa)		
				7 Day	28 Day	91 Day
Chopra & Siddique [115]	0.41	0	1	29.0	36.7	-
	0.41	15	1	36.2	48.8	-
	0.41	10	1	32.6	41.2	-
	0.41	20	1	30.4	40.2	-
de Sensale [57]	0.50	20	3.5	37.2	42.9	-
	0.38	0	1.8	32.8	48.5	-
	0.50	40	3.5	28.1	33.5	-
	0.50	30	3.5	35.1	40.9	-
Makul & Sua-iam [116]	0.31	10	2	48.4	54.8	72.6
	0.22	0	2	55.9	65.0	82.8
	0.75	40	2	13.8	19.1	26.4
	0.46	20	2	21.2	28.0	39.6
	1.17	60	2	8.3	10.4	14.8
	2.18	100	2	1.5	2.0	2.6
	1.80	80	2	2.8	4.1	5.7
Memon et al. [105]	0.38	5	3.5	25.2	38.0	-
	0.40	0	3.5	10.5	28.4	-
	0.36	10	3.5	22.5	36.2	-
	0.38	5	4	21.4	37.8	-
	0.40	0	4	6.8	18.3	-
	0.36	10	4	36.8	41.4	-
Ganesan et al. [14]	0.51	0	0	27.2	38.3	-
	0.58	10	1.2	28.0	44.8	-
	0.57	5	1.2	27.6	43.3	-
	0.66	20	1.2	29.7	46.0	-
	0.60	15	1.2	29.3	45.7	-

exhibited a different pattern in compressive strength development. UHPC attained its highest compressive strength when 10% RHA was used at 3 and 7 days, whereas 20% RHA yielded the highest compressive strength at 28 and 91 days. These findings indicate that RHA can be effectively employed to produce UHPC with a replacement level of less than 30%.

The physical and chemical properties of RHA, including its particle size, specific surface area and pozzolanic reactivity, play crucial roles in determining its influence on concrete performance. The particle size distribution of RHA affects the packing density and workability of the concrete mix. Finely ground RHA particles can improve the packing of cementitious materials, resulting in a more densely packed matrix. The high specific surface area of RHA provides more active sites for the pozzolanic reaction, facilitating the formation of additional cementitious compounds. However, it is important to consider the quality and processing of RHA, as factors such as the combustion process and the presence of impurities can affect its reactivity. Proper processing and quality control of RHA are necessary to ensure consistent and reliable performance in concrete applications. By optimizing the physical and chemical properties of RHA, its influence on concrete performance can be effectively harnessed.

The studies by Bie et al. [118] and Madandoust et al. (2011) [119] both highlight the positive effects of incorporating rice husk ash (RHA) on the mechanical properties of concrete. Bie et al. [118] investigated the influence of burning conditions and RHA

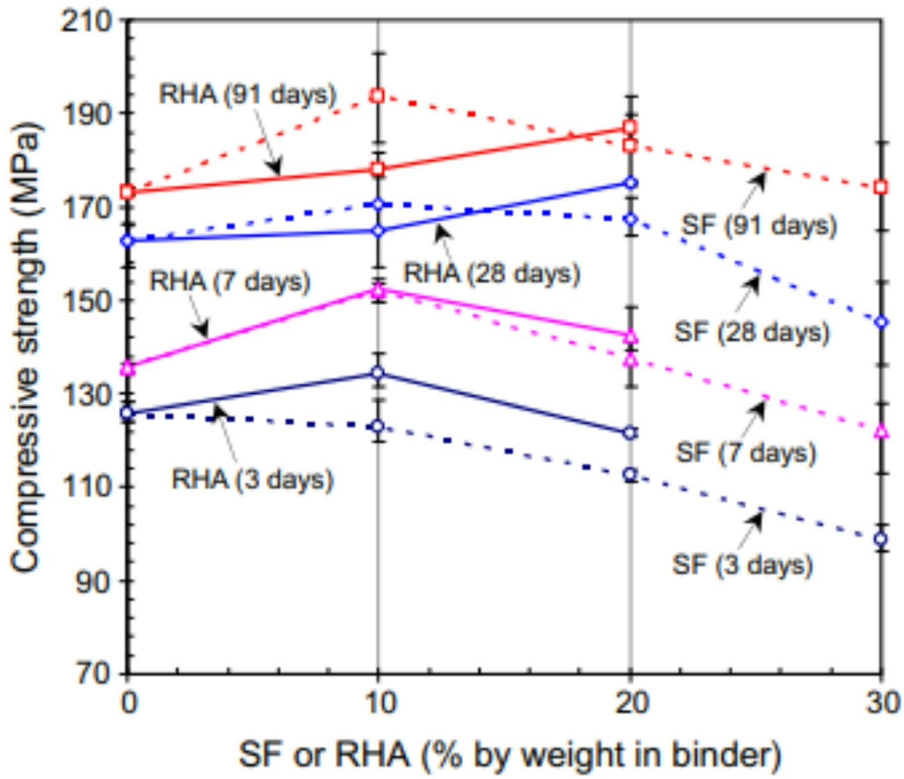


Fig. 9 Compressive strength of UHPC samples vs. % SF (dotted line) or % RHA (solid line), w/b ratio = 0.18 [117]

blending amounts on the mechanical behaviour of cement. Their findings indicated that RHA improved the compressive strength and flexural strength of concrete. This suggests that RHA can be a valuable supplementary material for enhancing the overall strength of concrete structures. Madandoust et al. [119] focused on the mechanical properties assessment of RHA concrete, revealing a positive influence of RHA on the compressive strength and other mechanical properties. These findings further support the potential benefits of incorporating RHA in concrete mixes to improve their mechanical performance. In a similar vein, the study conducted by Madandoust & Ghavidel [120] explored the use of RHA in combination with waste glass powder. They investigated the mechanical properties of concrete containing both RHA and waste glass powder as supplementary materials. The results indicated an improvement in compressive and flexural strength compared to plain concrete. This suggests that the combined use of RHA with other supplementary materials can have synergistic effects, leading to enhanced mechanical properties. The findings of this study provide insights into the potential of utilising multiple supplementary materials in concrete mix design to achieve improved mechanical performance.

Varadharajan et al. [121] emphasised the environmental benefits of incorporating RHA and marble dust in concrete. Their study assessed the mechanical properties of concrete mixes containing RHA and marble dust. The results demonstrated that RHA improved the mechanical properties of concrete, including its compressive strength. Moreover, the study highlighted the environmental advantages of using RHA and marble dust as supplementary materials, indicating their potential for sustainable concrete production. These findings highlight the potential of RHA as a greener alternative to conventional cementitious materials, promoting the use of waste by-products in construction. Liu et al. [122] focused on the mechanical properties and microstructure of recycled aggregate concrete incorporating RHA. The study investigated the effect of RHA addition on the mechanical properties and microstructure of recycled aggregate concrete. The results revealed that the inclusion of RHA enhanced the mechanical properties, such as compressive strength and flexural strength, of recycled aggregate concrete. Furthermore, the microstructure analysis indicated positive changes, suggesting improved interfacial bonding and densification due to the presence of RHA. These findings are significant for the field of sustainable construction, as incorporating RHA can help improve the performance of recycled concrete and promote the use of recycled aggregates.

The study by Hesami et al. [9] examined the effects of RHA and fibre in pervious concrete pavement. They investigated the mechanical properties, including compressive strength and permeability, of pervious concrete incorporating RHA and fibre. The results demonstrated improved mechanical properties and permeability compared to plain pervious concrete. This suggests that the addition of RHA and fibre can enhance both the strength and permeability of pervious concrete pavement. These findings have implications for the design and construction of specialized concrete applications, such as pervious pavements, where both strength and permeability are essential. Abolhasani et al. [123] investigated the impact of RHA on calcium aluminate cement (CAC) concrete. The study focused on the mechanical properties and fracture toughness of CAC concrete incorporating RHA. The findings highlighted the enhanced mechanical properties and fracture toughness resulting from RHA addition. This suggests that RHA has the potential to improve the performance of specific types of concrete, such as those containing calcium aluminate cement. The study's results contribute to the understanding of RHA's effects on the mechanical behaviour of specialized concrete mixes. Hu et al. [124] explored the effect of RHA on carbon sequestration, mechanical properties and microstructure evolution. The study investigated the carbon sequestration potential, mechanical properties and microstructure changes of cement-based materials with early-age carbonation treatment and RHA addition. The results revealed that RHA not only improved the mechanical properties but also contributed to carbon sequestration, addressing environmental concerns. The study's findings highlight the multifaceted benefits of incorporating RHA in cement-based materials, including improved mechanical performance and environmental sustainability.

While 28-day compressive strength is commonly used as a benchmark in concrete performance, it is important to note that pozzolanic concretes, including those containing Rice Husk Ash (RHA), often continue to gain strength well beyond 28 days. This extended strength development is due to the ongoing pozzolanic reaction, where amorphous silica in RHA continues to react with calcium hydroxide over time, forming additional calcium silicate hydrate (C-S-H) gel. Studies have reported significant increases in strength between 28 and 91 days, particularly when RHA replaces 10–30% of cement. For instance, research cited in Table 3 shows compressive strengths improving by 20–35% beyond 28 days, depending on the mix design, curing conditions and fineness of RHA. This long-term strength development makes RHA-concrete suitable for applications requiring durability and sustained load-bearing capacity, such as in structural elements, pavements and precast components. Therefore, when evaluating the performance of RHA-based concrete, it's essential to consider longer-term testing (e.g., 56-day or 91-day compressive strength), especially for durability-critical or infrastructure-grade applications.

4.2 Workability and rheological behaviour

The addition of RHA to concrete can have a significant impact on its workability, which refers to how easily the concrete can be handled, placed and finished during construction. When RHA is properly proportioned and mixed with other concrete ingredients, it acts as a filler material that helps reduce the water demand of the mix. This reduction in water content can improve the cohesiveness and plasticity of the concrete, making it easier to work with. The presence of RHA particles enhances the particle packing and lubrication within the mix, allowing for better flow and compaction. As a result, the concrete becomes more manageable during construction activities such as pumping, placing and compacting. It exhibits improved cohesion and is less prone to segregation or excessive bleeding, ensuring a more uniform and consistent concrete placement.

The rheological behaviour of concrete, which refers to its flow and deformation characteristics, plays a crucial role in its performance during mixing, transportation and casting. The addition of RHA can significantly alter the rheological properties of concrete. When RHA particles are properly dispersed within the mix, they contribute to the internal lubrication of the concrete, reducing friction between the particles and facilitating flow. This enhanced flowability and reduced resistance to movement improve the filling of formwork and the overall consolidation of the concrete. The presence of RHA also improves the homogeneity of the mix and reduces the risk of segregation, ensuring a more uniform distribution of materials throughout the concrete. Moreover, the addition of RHA can influence the viscosity of the concrete, affecting its ability to flow and its resistance to deformation. The specific characteristics of RHA, such as its particle size and shape, surface area and chemical composition, can influence the degree of influence on the rheological behaviour of the concrete.

Givi et al. [55] conducted a comprehensive assessment of the effects of rice husk ash (RHA) particle size on the strength, water permeability and workability of binary blended concrete. The study aimed to investigate the influence of different particle sizes of RHA on the performance of concrete. The findings of the study revealed that the addition of RHA to the concrete mix resulted in changes in its workability. Specifically, it was observed that as the particle size of RHA decreased, the workability of the concrete decreased as well. This decrease in workability can be attributed to the increased surface area of the finer particles, which tend to absorb more water and reduce the flowability of the mix. Additionally, the study indicated that the incorporation of RHA led to increased water permeability in the concrete, which can be attributed to the pozzolanic reaction between RHA and the cementitious materials, resulting in the formation of additional pores and channels in the concrete matrix.

Le et al. [125] focused on the effect of macro-mesoporous rice husk ash on the rheological properties of mortar formulated from self-compacting high-performance concrete. The researchers aimed to investigate how the addition of RHA influences the flowability and viscosity of the mortar. The study demonstrated that the incorporation of RHA led to improved flowability and viscosity of the mortar, indicating enhanced rheological behaviour. The presence of macro-mesoporous structures in the RHA was found to contribute to the modification of the rheological properties of the mortar. These structures acted as filler material and improved the flowability of the mortar, allowing for better distribution of the cementitious particles and reducing the risk of segregation. The improved viscosity of the mortar with the addition of RHA can be attributed to the interaction between RHA particles Celik & Canakci [126] investigated the rheological properties of cement-based grout mixed with rice husk ash (RHA). The aim of their study was to evaluate how the addition of RHA affects the flow behaviour and consistency of the grout. The results indicated that the inclusion of RHA had a significant impact on the rheological properties of the grout. Specifically, it was observed that the addition of RHA led to an increase in viscosity and yield stress of the grout. This increase in viscosity can be attributed to the presence of RHA particles, which acted as a filler material and affected the flow behaviour of the grout. The higher yield stress observed in the RHA-containing grout indicated an increase in the resistance to flow, resulting in a more stable and cohesive mix. These findings suggest that the addition of RHA can improve the rheological properties of cement-based grout, making it more suitable for various construction applications.

Jittin & Bahurudeen [127] conducted a study to evaluate the rheological and durability characteristics of binary and ternary cementitious systems incorporating sugarcane bagasse ash and rice husk ash (RHA). The researchers aimed to investigate how the combination of these supplementary cementitious materials influences the flowability and stability of the cementitious mixes. The study findings demonstrated that the inclusion of RHA contributed to improved rheological properties in both binary and ternary cementitious systems. The presence of RHA particles enhanced the flowability of the mixes and increased their stability, reducing the risk of segregation and ensuring uniform distribution of the cementitious materials. The improved rheological behaviour of the cementitious mixes incorporating RHA suggests the potential for its effective utilisation in various construction applications where desired flow characteristics and stability are essential. Medina et al. [128] focused on the design and characterisation of ternary cements containing RHA and fly ash. The aim of their study was to investigate how the inclusion of RHA affects the rheological behaviour of the cementitious systems. The research revealed that the addition of RHA resulted in changes in the rheological properties of the cementitious systems. The yield stress and plastic viscosity of the ternary cements were found to be influenced by the presence of RHA. The incorporation of RHA led to an increase in yield stress, indicating an enhancement in the resistance to flow and affected the plastic viscosity, which is related to the internal friction and deformability of the cementitious systems. These findings suggest that RHA can modify the rheological behaviour of cementitious systems, potentially leading to improved performance in terms of flow, stability and overall workability.

Singh & Singh [129] conducted a study to investigate the influence of RHA on the rheology of conventional concrete. The researchers aimed to examine how the addition of RHA affects the flow behaviour and consistency of the concrete mix. The study findings indicated that the incorporation of RHA resulted in an increase in yield stress and viscosity of the concrete mix. This increase in yield stress suggests a higher resistance to flow, indicating a more stable and cohesive mix. The increased viscosity of the concrete with the addition of RHA can be attributed to the interaction between RHA particles and the water present in the mix, leading to changes in the internal friction and deformability of the concrete. These findings suggest that the presence of RHA can modify the rheological behaviour of conventional concrete, which can have implications for its workability and overall performance in construction applications.

The influence of RHA on the workability and rheological behaviour of concrete is influenced by various factors, including RHA particle size, cementitious system composition and mix proportions. While some studies reported a decrease in workability and others demonstrated improvements in rheological properties, it is evident that RHA can modify the flow characteristics and viscosity of concrete. Understanding these effects is essential for optimizing concrete mixes incorporating RHA and developing guidelines for its effective utilisation in construction applications. Further research is necessary to explore the mechanisms underlying these influences and to establish comprehensive guidelines for incorporating RHA to achieve desired workability and rheological properties of concrete.

4.3 Hydration and microstructure

The presence of RHA in the mix accelerates the hydration process by providing additional reactive silica and alumina. These components act as nucleation sites, promoting the early formation of hydration products. As a result, the concrete exhibits improved early-age strength development and reaches desired strength milestones at a faster rate. This accelerated hydration is beneficial in time-sensitive construction projects where early strength gain is critical. Moreover, the pozzolanic reaction between RHA and calcium hydroxide has an important effect on the composition of the concrete. Calcium hydroxide, a by-product of cement hydration, is considered less desirable for long-term durability. By consuming excess calcium hydroxide, RHA contributes to refining the microstructure of the concrete. The reaction with RHA results in the formation of additional C-S-H gel, which fills the voids and pores within the cementitious matrix. This refinement of the microstructure leads to a denser and more compact concrete, reducing the permeability and improving its resistance to chemical attacks and degradation over time.

The incorporation of RHA also contributes to the refinement of the pore structure in concrete. The additional C-S-H gel formed through the pozzolanic reaction fills the voids and pores within the cementitious matrix. This process reduces the overall porosity of the concrete, improving its density and impermeability. The refined pore structure restricts the ingress of harmful substances, such as chlorides and sulphates, which can cause deterioration and corrosion of the reinforcement. The reduced permeability enhances the long-term durability and service life of the concrete. Additionally, the influence of RHA on concrete hydration is reflected in its impact on strength development. The formation of additional C-S-H gel through the pozzolanic reaction contributes to enhanced bonding between cementitious particles. This improved bonding results in increased compressive, flexural and tensile strengths of the concrete. The inclusion of RHA can lead to a concrete mix with improved mechanical properties, making it suitable for applications that require high strength and structural integrity.

The influence of RHA on the hydration of concrete has been the subject of numerous studies. These investigations have shed light on how the addition of RHA affects the hydration process, including the kinetics of cement hydration and the resulting microstructure. The following discussion expands on the findings from several studies in this field. Van Tuan et al. [130] explored the hydration and microstructure of ultra-high-performance concrete incorporating RHA. The study revealed that the addition of RHA led to changes in the hydration behaviour of the concrete. The researchers observed an acceleration in the early stages of hydration, which can be attributed to the high reactivity of RHA. The incorporation of RHA promoted the formation of additional hydration products, such as C-S-H gel and calcium aluminate hydrate (C-A-H) gel. These additional hydration products contributed to the refinement of the microstructure, resulting in a denser and more compact concrete matrix.

Park et al. [100] conducted an analysis of the effects of RHA on the hydration of cementitious materials. The study demonstrated that the presence of RHA affected the hydration kinetics of cement. The researchers observed a delay in the early hydration period, indicating a slower rate of hydration. This delay can be attributed to the pozzolanic reaction between RHA and the cementitious materials, which consumes a portion of the available water and slows down the hydration process. The incorporation of RHA also led to the formation of additional C-S-H gel, contributing to the densification of the microstructure. Xu et al. [131] investigated the effect of RHA fineness on the porosity and hydration reaction of blended cement paste. The study revealed that the fineness of RHA had a significant impact on the hydration process. The researchers found that finer RHA particles resulted in a higher degree of hydration and a lower porosity compared to coarser particles. The finer RHA particles provided a larger surface area for pozzolanic reactions, leading to the formation of additional hydration products. This finding highlights the importance of RHA particle size in optimizing the hydration process and improving the microstructure of the cement paste.

Liu et al. [132] focused on the effect of RHA on the early hydration behaviour of magnesium phosphate cement. The study demonstrated that the addition of RHA affected the hydration process of the cement. The researchers observed an increase in the setting time and a decrease in the heat release rate, indicating a delay in the hydration reaction. This delay can be attributed to the adsorption of water by RHA particles, which reduces the available water for the hydration process. The incorporation of RHA also influenced the microstructure of the cement, resulting in a denser and more compact structure. Singh & Rai [133] explored the effect of polyvinyl alcohol (PVA) on the hydration of cement with RHA. The study revealed that the presence of PVA influenced the hydration process and the microstructure of the cement. The researchers observed an acceleration in the hydration reaction and the formation of additional hydration products in the presence of PVA. This acceleration can be attributed to the nucleating effect of PVA, which enhances the formation of hydration products. The incorporation of RHA further influenced the hydration behaviour, contributing to the refinement of the microstructure.

The studies reviewed indicate that the addition of RHA significantly influences the hydration process of concrete. The presence of RHA affects the hydration kinetics, leading to either an acceleration or a delay in the hydration reaction, depending on various factors such as RHA reactivity and particle size. The incorporation of RHA also promotes the formation of additional hydration products, contributing to the refinement and densification of the microstructure. These findings highlight the potential of RHA as a supplementary cementitious material in enhancing the hydration characteristics and improving the performance of concrete. It is important to consider several factors when incorporating RHA into concrete mixes. The quality and properties of RHA, such as its fineness, chemical composition and dosage, should be carefully evaluated to optimise its effectiveness. The water-to-cement ratio and curing conditions also play a significant role in achieving the desired hydration characteristics. Proper mix design and optimisation are crucial to ensure the successful integration of RHA and to harness its positive influence on the hydration process of concrete.

4.4 Shrinkage and creep characteristics

The RHA on the shrinkage and creep behaviour of concrete has been a topic of research interest. Shrinkage refers to the decrease in volume of concrete due to moisture loss, while creep refers to the time-dependent deformation of concrete under sustained loading. Studies have shown that incorporating RHA into concrete can help mitigate shrinkage and reduce the potential for cracking [134, 135]. RHA acts as a pozzolanic material, reacting with calcium hydroxide in the presence of water to form additional C-S-H gel. This densifies the microstructure of concrete, reducing pore connectivity and limiting the movement of moisture. As a result, the drying shrinkage of concrete is reduced. Furthermore, the fine particle size and high specific surface area of RHA promote a better packing effect, leading to improved interfacial transition zones and reduced permeability. This can help mitigate the ingress of moisture into the concrete, thereby minimising the potential for shrinkage.

Regarding creep, the addition of RHA has shown potential in reducing the creep deformation of concrete [136, 137]. The formation of additional C-S-H gel due to the pozzolanic reaction with RHA leads to a more compact and denser microstructure. This enhanced microstructure restricts the movement of water and diffusion of ions, thereby decreasing the long-term creep deformation. The specific influence of RHA on shrinkage and creep may vary depending on factors such as RHA content, particle size distribution, curing conditions and mix design. Optimal dosage and particle size distribution need to be carefully determined to achieve the desired reduction in shrinkage and creep.

It is important to note that while RHA can contribute to shrinkage and creep reduction, other factors such as proper mix design, adequate curing and control of environmental conditions also play significant roles. Therefore, a comprehensive approach is required to effectively manage shrinkage and creep in concrete, taking into account the incorporation of RHA along with other strategies. Further research is needed to fully understand the mechanisms and optimise the use of RHA to control shrinkage and creep in different concrete applications. By improving our understanding of RHA's influence on these properties, engineers and researchers can enhance the performance and durability of concrete structures.

4.5 Durability

One significant aspect of concrete durability is its resistance to chloride ion penetration, which is crucial for protecting the reinforcing steel within the structure. When chloride ions infiltrate the concrete, they can initiate and accelerate the corrosion process of the steel reinforcement, leading to structural deterioration and compromised strength. In recent studies, the incorporation of RHA in concrete has demonstrated a positive impact on reducing the ingress of chloride ions [6, 17, 55, 115]. This effect can be attributed to several mechanisms associated with RHA. Firstly, the inclusion of RHA contributes to the densification of the pore structure within the concrete matrix. The fine particles of RHA fill the gaps between cement grains, resulting in a more compact

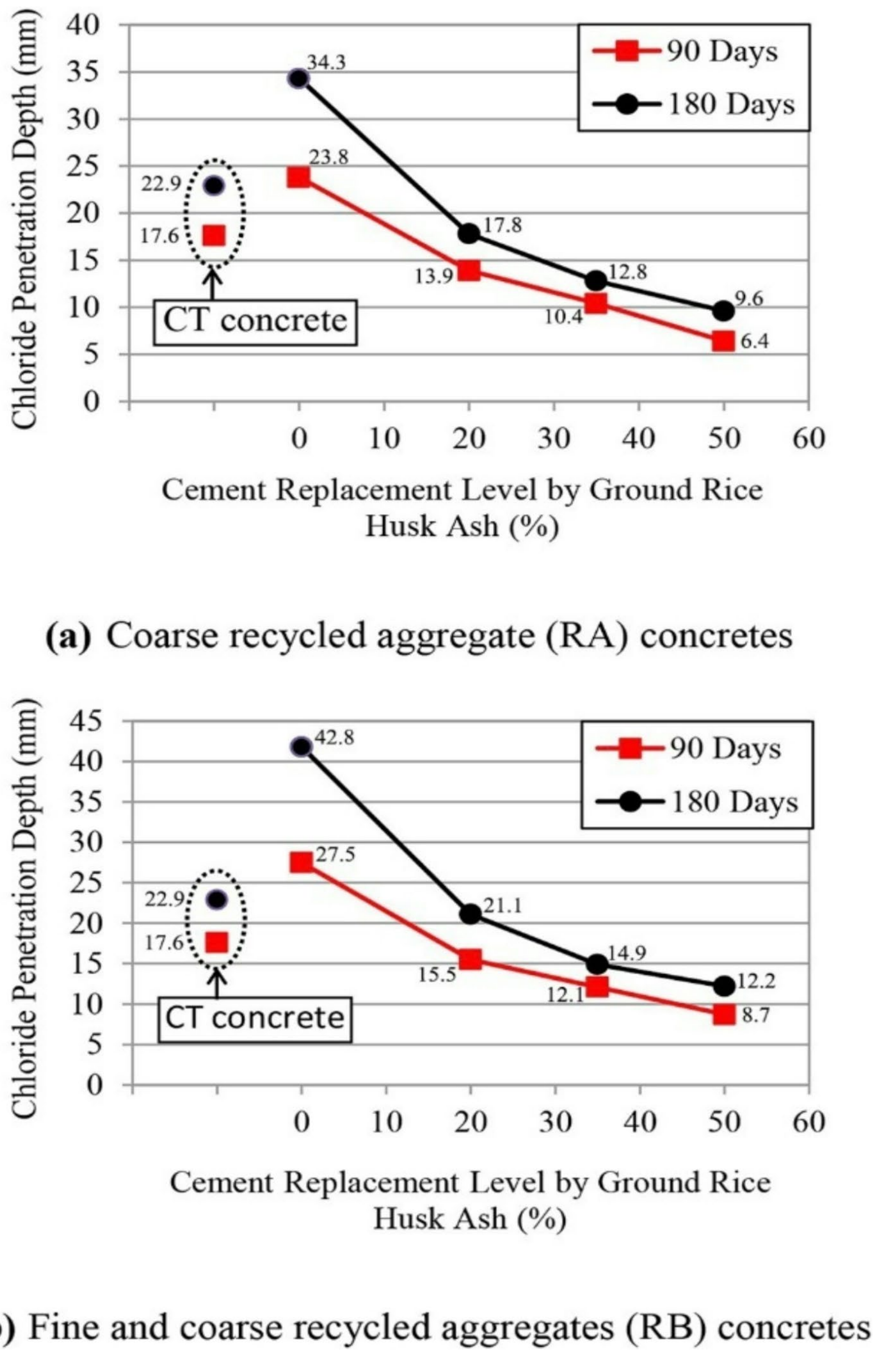


Fig. 10 Relationship between the chloride penetration depth of concrete and the ground rice husk ash replacement level. (a) RA concrete, (b) RB concrete [138]

and less permeable structure. This densification restricts the movement and penetration of chloride ions through the concrete. Secondly, RHA contains pozzolanic materials and reactive silica, which react with the calcium hydroxide present in the cement hydration process. This reaction forms additional C-S-H gel, which further contributes to the densification of the concrete matrix. The increased amount of C-S-H gel enhances the overall impermeability of the concrete, acting as a barrier against chloride ion penetration. By reducing the ingress of chloride ions, the presence of RHA in concrete provides a protective effect on the reinforcing steel. The reduced exposure to chloride ions minimises the risk of corrosion initiation and propagation, extending the service life of the concrete structure. This is particularly beneficial in environments with high chloride content, such as coastal areas or structures in close proximity to de-icing salts.

In a study by Rattanachu et al. [138], Fig. 10 illustrates the relationship between the replacement level of Ground Rice Husk Ash (GRHA) and the depth of chloride penetration in different types of concrete mixtures. The concrete mixtures included RA (100% river sand and 100% Recycled Aggregate (R-CA)) and RB (100% R-CA and 100% Recycled Fine Aggregate (R-FA)) concretes. The incorporation of GRHA in the concrete mixtures demonstrated a positive impact on the resistance of Recycled Aggregate Concrete (RAC) against chloride penetration. For instance, when R-CA replaced crushed limestone in the concrete, the chloride penetration depths into RA20, RA35 and RA50 concretes at 90 days were 13.9 mm, 10.4 mm and 6.4 mm, respectively. These depths increased to 17.8 mm, 12.8 mm and 9.6 mm at 180 days. In comparison, the chloride penetration depths for the control (CT) concrete were 17.6 mm and 22.9 mm at 90 and 180 days, respectively. Similarly, when recycled aggregates completely replaced natural aggregates, the chloride penetration depths into RB20, RB35 and RB50 concretes at 90 days were 15.5 mm, 12.1 mm and 8.7 mm, respectively, increasing to 21.1 mm, 14.9 mm and 12.2 mm at 180 days. These results indicate that the chloride resistance of RAC improved with increasing levels of GRHA replacement.

In addition to its influence on chloride ion penetration and sulphate attack, the incorporation of RHA in concrete has a positive impact on the resistance to alkali-silica reaction (ASR). ASR is a chemical reaction that occurs between the alkalis present in the concrete, typically derived from cement and the reactive silica present in certain aggregates. This reaction can lead to the formation of a gel-like substance, resulting in concrete cracking, expansion and reduced durability. RHA, being a source of reactive silica, plays a beneficial role in mitigating ASR [139]. When RHA is included in the concrete mix, the reactive silica in RHA reacts with the alkalis, consuming them and preventing their participation in the ASR reaction. This consumption of alkalis reduces the availability of alkalis for the ASR reaction to occur and diminishes the potential for damage. By incorporating RHA, the concrete matrix becomes more resistant to ASR-induced cracking and expansion. The presence of RHA helps control the expansion of the concrete by consuming the alkalis responsible for the reaction with reactive silica in the aggregates. This improves the long-term durability of the concrete, especially in environments where the risk of ASR is high. By reducing the occurrence of ASR, the incorporation of RHA in concrete enhances its durability and extends its service life. The consumption of alkalis by the reactive silica in RHA minimises the potential for cracking and expansion, improving the structural integrity and long-term performance of the concrete. This makes RHA a valuable additive for concrete used in environments where the risk of ASR is a concern, such as regions with reactive aggregates or exposure to alkali-rich environments.

The inclusion of RHA in concrete modifies the carbonation process and improves the concrete's resistance to carbon dioxide ingress [140, 141]. RHA contains reactive components, such as amorphous silica and unburned carbon, which interact with calcium hydroxide. During hydration, these components react with calcium hydroxide to form additional calcium carbonate. This reaction between RHA and calcium hydroxide has several beneficial effects on the carbonation resistance of concrete. Firstly, it leads to the densification of the concrete matrix. The formation of calcium carbonate fills the pores and voids, reducing the interconnected porosity and decreasing the diffusion pathways for carbon dioxide. This densification impedes the penetration of carbon dioxide into the concrete and reduces the depth of carbonation. Secondly, the reaction between RHA and calcium hydroxide consumes the calcium hydroxide available in the concrete. As a result, the concentration of free calcium hydroxide decreases, limiting the availability of this alkali compound for carbonation to occur. This reduction in free calcium hydroxide content slows down the carbonation process and enhances the concrete's resistance to carbon dioxide penetration. By enhancing the resistance to carbonation, the incorporation of RHA in concrete helps maintain the alkaline environment necessary to protect the embedded steel reinforcement from corrosion. The densification of the concrete matrix and the reduction in free calcium hydroxide availability contribute to the overall durability and long-term performance of the concrete.

It is important to note that the effectiveness of RHA in improving concrete durability depends on several factors, including the RHA content, particle size, curing conditions and mix design. Optimal dosage and appropriate incorporation techniques should be considered to achieve the desired durability enhancements in concrete. Overall, the utilisation of RHA in concrete offers promising benefits for enhancing the durability of concrete structures. However, it is essential to conduct thorough testing, monitoring and assessment to validate the long-term performance of RHA-incorporated concrete in specific environmental conditions and exposure scenarios. Continuous research and development in this area will further advance our understanding of the influence of RHA on concrete durability and ensure its successful implementation in real-world applications.

5 Applications of RHA

5.1 Structural applications

RHA has gained significant recognition for its applications in various structural elements and systems within the construction industry. One of the primary uses of RHA is as a partial replacement for cement in the production of concrete, offering numerous benefits in structural applications [11, 16, 103, 142]. By incorporating RHA into the concrete mix, the mechanical properties of the material can be significantly improved. RHA acts as a pozzolanic material, reacting with calcium hydroxide in the presence of water to form additional CSH gel. This leads to enhanced strength, increased durability and improved resistance to chemical attacks, such as sulphate and chloride ingress.

In the construction of bridges, RHA has been successfully utilised to enhance the performance and longevity of bridge decks. By replacing a portion of the cement with RHA, the resulting concrete exhibits higher tensile and flexural strengths, improved abrasion resistance and enhanced resistance to cracking. This enables the bridge decks to withstand heavy traffic loads and environmental stresses, ensuring their long-term structural integrity. RHA has also found applications in the production of high-performance concrete (HPC), which is used in various structural elements such as columns, beams and slabs. HPC incorporating RHA exhibits superior mechanical properties, including higher compressive and flexural strengths, improved durability and reduced permeability. This makes it an ideal choice for critical structural components that require exceptional strength, durability and resistance to environmental factors. Additionally, RHA has been employed in the development of lightweight concrete, which is advantageous in applications where weight reduction is a key consideration [143, 144]. Lightweight concrete with RHA offers reduced density while maintaining adequate strength and durability. This makes it suitable for high-rise buildings, precast elements and other structures where the overall weight needs to be minimised without compromising structural performance.

5.2 Non-Structural applications

RHA is not limited to structural applications but also finds diverse uses in various non-structural applications within the construction industry. Its unique properties make it a versatile material for enhancing the performance and sustainability of different construction elements. In the field of pavement engineering, RHA has been successfully employed as a mineral admixture in the production of asphalt concrete [145, 146]. By incorporating RHA into the asphalt mix, the mechanical properties of the pavement can be improved, including increased stiffness, reduced rutting, enhanced resistance to cracking and improved durability. This allows for the construction of durable and long-lasting roads with improved performance under heavy traffic loads. RHA is also widely used in the production of mortar and plaster [147–149]. As a partial replacement for cement in these applications, RHA enhances the workability, setting time and strength development of mortar mixes. It improves the adhesion properties, reduces shrinkage and enhances the overall performance of plaster. This makes RHA an excellent choice for applications such as plastering walls, rendering surfaces and tile fixing.

In soil stabilisation, RHA has been employed as an additive to improve the properties of soil for road construction and geotechnical engineering projects [150–153]. By blending RHA with soil, the stability, strength and load-bearing capacity of the soil can be enhanced. This is particularly beneficial in areas with weak or expansive soils, where the addition of RHA helps mitigate issues such as settlement, erosion and swelling. Moreover, RHA has found applications in the production of lightweight aggregates. By heating RHA at high temperatures, it can be transformed into porous lightweight aggregates with low density. These aggregates are used in lightweight concrete, precast elements and insulation materials, offering excellent thermal insulation properties and reducing the overall weight of structures without compromising their strength.

6 Challenges and limitations of RHA utilisation

Despite the promising benefits of RHA in concrete applications, several limitations and challenges must be acknowledged. One significant concern is the regional variation in RHA composition. The chemical makeup of RHA, particularly its silica content, is highly dependent on the geographical origin and type of rice cultivated. This variation can lead to inconsistencies in pozzolanic reactivity, affecting the performance and reliability of RHA-based concrete across different regions. Another critical factor is the variability in combustion techniques used to produce RHA. The method and conditions of combustion—such as temperature, duration, and oxygen availability—greatly influence the ash's physical and chemical properties. Improper combustion may result in high carbon content or crystalline silica formation, which can impair its effectiveness as a supplementary cementitious material. Additionally, the long-term durability of RHA-modified concrete under diverse climatic conditions remains an area requiring further research.

While laboratory tests show enhanced strength and resistance, real-world performance under freeze-thaw cycles, high humidity, or aggressive chemical exposure has not been comprehensively validated. These environmental factors can impact the longevity and structural integrity of RHA-based concrete, highlighting the need for field studies and performance monitoring over extended periods.

6.1 Quality and consistency of RHA

The quality and consistency of RHA play a pivotal role in its successful utilisation in concrete. RHA is obtained through the burning of rice husks and its properties can exhibit considerable variations depending on various factors, such as the burning conditions, temperature and duration. These inherent variations in RHA can significantly impact its chemical composition, particle size distribution and reactivity, consequently affecting its performance and effectiveness in concrete applications [154].

One of the key challenges is ensuring a reliable and consistent supply of high-quality RHA [155]. Different regions and rice processing industries may produce RHA with diverse characteristics due to variations in rice varieties, husk storage conditions and combustion processes employed. This variability poses difficulties in establishing uniform standards and specifications for RHA usage in concrete. Moreover, the presence of contaminants, such as unburned rice husk particles or impurities introduced during the burning process, can further complicate the quality and consistency of RHA [156, 157]. To address these challenges, it is imperative to implement rigorous quality control measures throughout the RHA production chain. This includes defining standardised protocols for rice husk burning, storage and transportation to minimise variations and ensure consistent quality. Regular testing and analysis of RHA samples should be conducted to evaluate their chemical composition, fineness and pozzolanic activity, providing a clear understanding of their performance potential in concrete mixes. Collaborative efforts between rice millers, researchers and concrete producers can facilitate the development of comprehensive guidelines for RHA quality assessment, thereby promoting consistent sourcing practices and enhancing the reliability of RHA supply.

Furthermore, establishing robust supply chains and fostering partnerships between rice processing industries and the construction sector are essential for maintaining a steady and dependable source of RHA with consistent quality characteristics. These partnerships can facilitate the exchange of knowledge and expertise, enabling rice millers to enhance their RHA production processes and meet the specific requirements of the concrete industry. Additionally, collaboration can contribute to the development of traceability systems and certification schemes, ensuring transparency and accountability in the RHA supply chain. Addressing the challenges associated with the quality and consistency of RHA is crucial for maximizing its benefits in concrete production. By implementing stringent quality control measures, fostering collaboration among stakeholders and establishing industry-wide standards and guidelines, the utilisation of RHA can be optimised. This will not only contribute to sustainable and eco-friendly construction practices but also promote the production of high-performance concrete with improved mechanical properties, durability and long-term performance.

6.2 Potential adverse effects

While RHA offers several advantages in concrete applications, it is important to consider potential adverse effects that may arise from its utilisation. These effects can arise from various factors, including the quality and characteristics of RHA, as well as its interaction with other components of concrete. Understanding and mitigating these potential adverse effects are crucial to ensure the long-term performance and durability of concrete structures.

One of the concerns related to RHA utilisation is its potential impact on the workability of concrete mixes [55]. RHA, when present in high quantities or with specific properties, can significantly affect the rheological behaviour and flowability of fresh concrete. Excessive RHA content or improper particle size distribution may lead to increased viscosity and reduced workability, making it challenging to properly place and compact the concrete. Therefore, careful consideration of RHA dosage and its compatibility with other admixtures and aggregates is necessary to maintain the desired workability of the concrete mix. Another potential adverse effect is the risk of increased drying shrinkage in concrete containing RHA [158]. Due to the high silica content of RHA, it possesses pozzolanic properties that contribute to the formation of additional calcium silicate hydrates during the hydration process. While this can enhance the strength and durability of concrete, it can also lead to increased autogenous and drying shrinkage. The excessive shrinkage may result in cracking and reduced service life of the concrete structure. Therefore, proper mix design considerations, such as incorporating supplementary cementitious materials or using shrinkage-reducing admixtures, should be employed to mitigate the potential adverse effects of drying shrinkage.

Furthermore, the chemical composition of RHA can introduce certain challenges in concrete durability. RHA contains high levels of unburned carbon, which may act as a potential source of organic compounds and promote the development of microorganisms. These organic compounds can lead to microbial-induced corrosion, especially in environments with high moisture and oxygen levels. To prevent such adverse effects, proper curing and moisture control practices should be employed to minimise the availability of nutrients for microbial growth. Moreover, the presence of impurities or contaminants in RHA, such as heavy metals or unburned husk particles, may pose environmental and health concerns [159, 160]. These impurities can leach into the surrounding environment or affect the air quality during RHA handling and processing. Therefore, stringent quality control measures should be implemented to ensure that RHA meets regulatory standards and guidelines for environmental and occupational safety. The understanding the potential adverse effects associated with RHA utilisation in concrete is essential for its responsible and sustainable application. Through proper quality control, mix design considerations and adherence to environmental and safety regulations, the adverse effects can be mitigated, allowing for the realization of the benefits of RHA in enhancing concrete performance while ensuring long-term durability and structural integrity.

6.3 Standardisation and guidelines

Standardisation and guidelines play a crucial role in addressing the challenges associated with the utilisation of RHA in concrete. One key challenge is the quality and consistency of RHA. Establishing standardised procedures for RHA production, including burning conditions and processing methods, can help ensure a consistent quality of RHA. By controlling parameters such as temperature, residence time and air supply during the burning process, variations in the physical and chemical properties of RHA can be minimised. This enables concrete producers to have a reliable and consistent source of RHA, leading to improved quality and performance of RHA-based concrete.

Characterisation of RHA is another important aspect that can be addressed through standardisation. Guidelines can provide clear instructions on the testing methods and parameters to be evaluated, such as particle size distribution, specific surface area, chemical composition and pozzolanic activity. Standardised characterisation methods help in accurately measuring the properties of RHA, allowing concrete producers to select the most suitable RHA for their specific application. Consistent characterisation also facilitates the comparison of different RHA sources and helps determine the optimal dosage in concrete mixes.

Potential adverse effects of RHA on concrete properties need to be addressed as well. Standardised guidelines can define testing procedures to evaluate the impact of RHA on workability, setting time, early-age strength development and long-term durability of concrete. By understanding these effects, concrete producers can assess the risks associated with incorporating RHA and take appropriate measures to mitigate any negative impact. This ensures that the desired performance and durability of RHA-based concrete are achieved. Dosage guidelines for RHA in concrete mixes are essential for optimizing its use. Standardised recommendations can specify the percentage of RHA replacement for cement based on the desired strength, workability and durability requirements. Having clear dosage guidelines allows concrete producers to utilise RHA effectively without compromising the overall properties of the concrete. This promotes consistency and uniformity in RHA utilisation, facilitating its integration into concrete production processes.

Compatibility with other concrete ingredients is another area where guidelines can provide valuable insights. Recommendations can be provided for the selection of suitable materials and proportions to ensure optimal interactions between RHA and cement, aggregates and admixtures. Standardised guidelines assist concrete producers in making informed decisions during mix design, considering the specific characteristics of RHA and its potential influence on the behaviour of other concrete components. This ensures that the RHA-based concrete maintains its desired properties while avoiding any adverse effects on workability, setting and long-term performance. Guidelines can also cover the curing and handling of RHA-based concrete. They can specify the appropriate curing duration, temperature and moisture control to promote optimal hydration and achieve the desired strength and durability of the concrete. Proper handling, storage and disposal practices can be outlined to ensure environmental sustainability and occupational safety throughout the lifecycle of RHA-based concrete structures.

7 Future perspectives and research opportunities

7.1 Potential innovations in RHA utilisation

The utilisation of RHA in concrete has gained significant attention in recent years due to its potential as a sustainable and supplementary cementitious material. Researchers and industry professionals have been exploring various innovative approaches to further enhance the utilisation of RHA in concrete. Here, we discuss some potential innovations in RHA utilisation that show promise for improving concrete performance and sustainability.

1. Nanostructured RHA: Researchers have been exploring the production of nanostructured RHA through various grinding and milling techniques [161–164]. By reducing the particle size of RHA, the surface area is significantly increased, leading to enhanced reactivity and pozzolanic properties. The smaller particle size allows for better distribution and interaction with cementitious materials, resulting in improved strength development, reduced permeability and enhanced durability of concrete structures. The increased surface area of nanostructured RHA facilitates a more efficient pozzolanic reaction, leading to the formation of additional C-S-H gel, which contributes to the densification and strengthening of the concrete matrix.
2. RHA-based Geopolymer Concrete: Geopolymer concrete, an alternative to conventional Portland cement-based concrete, utilises alkali-activated materials. RHA can serve as a suitable precursor for geopolymer binder production [165, 166]. The incorporation of RHA in geopolymer concrete offers several advantages. Firstly, the use of RHA reduces the demand for Portland cement, resulting in lower carbon emissions and a more sustainable construction material. Secondly, RHA-based geopolymer concrete exhibits improved chemical resistance, making it suitable for harsh environments and chemical exposure. Additionally, the presence of RHA contributes to increased fire resistance, making it an attractive option for fire-prone areas. Geopolymer concrete with RHA demonstrates excellent mechanical properties, including high compressive strength and durability, making it a viable alternative to traditional concrete.
3. High-Performance Concrete (HPC) with RHA: The incorporation of RHA in high-performance concrete has garnered significant interest due to its potential to enhance various properties. HPC typically exhibits superior strength, durability and workability compared to conventional concrete [83, 87, 167]. By incorporating RHA in HPC mixes, it is possible to achieve even greater performance. The use of RHA improves workability by acting as a filler and lubricant, allowing for better flow and placement of the concrete. Additionally, RHA contributes to the refinement of the concrete microstructure, resulting in improved strength, reduced permeability and enhanced resistance to chemical attacks. The synergy between RHA and other cementitious materials in HPC leads to the formation of additional hydration products and denser concrete, ultimately improving the overall performance of the material.
4. RHA as a Supplementary Binder: RHA can serve as a supplementary binder in concrete, partially replacing cement content without compromising the mechanical

properties of the material. The incorporation of RHA as a supplementary binder not only reduces the environmental impact associated with cement production but also improves the long-term performance of concrete structures [168–170]. RHA's pozzolanic properties allow for the formation of additional C-S-H gel, enhancing the strength and durability of the concrete matrix. Furthermore, the presence of RHA contributes to the reduction of calcium hydroxide (CH) content, mitigating the risk of alkali-silica reaction (ASR) and improving the concrete's resistance to sulphate attack. By optimizing the RHA content and its interaction with other cementitious materials, the utilisation of RHA as a supplementary binder shows great potential for sustainable concrete production.

5. RHA-based Self-Healing Concrete: Self-healing concrete is an innovative approach aimed at repairing microcracks autonomously and improving the durability of concrete structures [4, 135, 171]. Incorporating RHA in self-healing concrete systems enhances the autogenous healing process. RHA's pozzolanic properties and high silica content contribute to the formation of C-S-H gel, which acts as a healing agent. When cracks occur in the concrete, the presence of RHA facilitates the precipitation of calcium carbonate ($CaCO_3$) in the cracks, sealing them and preventing further propagation. The healing process in RHA-based self-healing concrete is particularly effective in mitigating the ingress of harmful substances and improving the long-term durability of concrete structures, resulting in extended service life and reduced maintenance costs.
6. RHA in Fibre-Reinforced Concrete: Fibre-reinforced concrete (FRC) offers enhanced toughness, crack resistance and ductility. By combining RHA with different types of fibres, such as steel fibres or polymeric fibres, in FRC, the mechanical properties and impact resistance of the concrete can be further improved [172–174]. The synergy between RHA and fibres contributes to the formation of a more ductile and resilient concrete matrix. RHA acts as a filler, enhancing the bond between fibres and the surrounding matrix, effectively bridging microcracks and enhancing crack resistance. The addition of RHA in fibre-reinforced concrete results in a composite material with superior mechanical properties, improved durability and enhanced resistance to cracking and impact loads.
7. RHA in Sustainable Concrete Products: RHA can be utilised in the production of sustainable concrete products, such as lightweight concrete blocks or precast elements. Incorporating RHA in lightweight concrete blocks reduces the overall weight of the blocks, making them easier to handle and transport [175, 176]. Additionally, RHA contributes to improved thermal insulation properties, reducing energy consumption for heating and cooling in buildings. The utilisation of RHA in precast elements offers similar benefits, including reduced weight, enhanced sustainability and improved thermal properties. These RHA-based concrete products provide opportunities for energy-efficient and eco-friendly construction practices, promoting sustainable development in the construction industry.

The utilisation of RHA in concrete opens up numerous possibilities for innovation and improvement. The advancements in nanostructured RHA, geopolymer concrete, high-performance concrete, self-healing concrete, RHA as a supplementary binder, RHA in fibre-reinforced concrete and RHA-based sustainable concrete products demonstrate the potential of RHA to enhance the performance, sustainability and durability of concrete structures. Continued research and development in these areas will further unlock the potential of RHA and promote its widespread utilisation in the construction industry.

7.2 Research gaps and areas for further investigation

While the utilisation of RHA in concrete has shown promising results, there are still several research gaps and areas for further investigation that can contribute to a deeper understanding and improved application of RHA in concrete technology. Some key research gaps and areas for further investigation include:

1. Optimisation of RHA Properties: To optimise the properties of RHA, researchers can explore various methods such as modifying the burning conditions, manipulating the grinding process and controlling the rice husk source. Investigating the effects of different burning temperatures, durations and atmospheres on RHA properties can help determine the optimal conditions for achieving desired characteristics. Additionally, understanding the relationship between RHA particle size distribution, specific surface area and chemical composition can guide the development of tailored RHA products for specific applications. Surface modification techniques such as chemical treatments and thermal treatments can also be investigated to enhance the reactivity and compatibility of RHA with cementitious materials.
2. Long-Term Durability Assessment: Long-term durability assessment of RHA-incorporated concrete can be carried out through accelerated aging tests, field exposure studies and monitoring of existing structures. Researchers can subject RHA-based concrete specimens to prolonged exposure to aggressive environments, including cyclic wet-dry conditions, high temperatures and chemical attacks. By evaluating the evolution of concrete properties over an extended period, such as changes in compressive strength, permeability and microstructure, researchers can gain insights into the long-term durability performance of RHA-based concrete. Additionally, monitoring the performance of real-world structures incorporating RHA will provide valuable data on the behaviour of RHA under actual environmental conditions.
3. Influence of RHA on Fresh Concrete Properties: To understand the influence of RHA on fresh concrete properties, researchers can conduct a comprehensive investigation using various mix design parameters and RHA dosages. Workability tests such as slump, flowability and rheological measurements can be performed to assess the impact of RHA on concrete's ability to flow, compact and maintain its shape. The effects of RHA on setting time, bleeding and air entrainment can also be studied to determine the optimal dosage and its compatibility with different admixtures and cementitious materials. Additionally, advanced techniques such as microscopy and particle tracking can be employed to analyse the dispersion of RHA particles in the fresh concrete matrix and understand their influence on the overall behaviour of the mix.

4. Standardisation and Guidelines: Standardisation efforts can involve collaboration between researchers, industry professionals and regulatory bodies to develop standardised procedures and guidelines for incorporating RHA into concrete production. This can include the development of standardised testing methods for RHA characterisation, quality control measures for RHA sourcing and processing and guidelines for concrete mix design incorporating RHA. The establishment of clear specifications for RHA properties, such as its chemical composition, fineness and reactivity, will ensure consistent performance and enable proper utilisation in different concrete applications. Furthermore, guidelines can provide recommendations on RHA dosage, blending methods and compatibility considerations to facilitate its successful integration into existing concrete production practices.
5. Compatibility with Different Cement Types: Investigating the compatibility of RHA with various cement types involves exploring the effects of RHA on hydration kinetics, hydration product formation and mechanical properties of different cementitious systems. Researchers can conduct a systematic study comparing the performance of RHA with different types of cement, including Portland cement, blended cement (e.g., fly ash, slag) and alternative cementitious materials (e.g., geopolymers). By evaluating the influence of RHA on setting time, heat evolution, strength development and microstructural characteristics, researchers can determine the most suitable combinations and optimise the performance of RHA in specific cementitious systems. This research can also explore the potential synergistic effects between RHA and other supplementary cementitious materials to further enhance the overall performance of the concrete.
6. Life Cycle Assessment (LCA) Studies: Life cycle assessment studies can be conducted to evaluate the environmental impact and sustainability of RHA-based concrete throughout its entire life cycle. Researchers can assess the environmental indicators such as carbon footprint, energy consumption, water usage and waste generation associated with RHA production, transportation, concrete manufacturing and end-of-life scenarios. Comparative studies between RHA-incorporated concrete and conventional concrete can provide insights into the potential environmental benefits and identify areas for improvement. Furthermore, life cycle cost analysis can be integrated into the assessment to evaluate the economic feasibility and potential cost savings associated with RHA utilisation in concrete production.
7. Field Performance Evaluation: Field performance evaluation of RHA-based concrete involves monitoring and assessing the behaviour of RHA-incorporated structures in real-world construction projects. Researchers can collaborate with engineers and construction companies to select suitable sites and incorporate RHA-based concrete in various applications such as buildings, bridges, pavements and infrastructure projects. Long-term monitoring of these structures, including periodic inspections, material testing and structural performance evaluation, will provide valuable data on the performance of RHA-based concrete under actual loading, exposure and environmental conditions. This field data can validate laboratory findings, identify any unforeseen challenges and provide feedback for further improvement and optimisation of RHA-based concrete technology.

8. Economic Feasibility and Cost Analysis: Economic feasibility and cost analysis studies can assess the overall cost-effectiveness of utilising RHA in concrete production. Researchers can investigate the availability and cost of RHA in different regions, considering factors such as rice production, husk disposal and processing costs. Cost-benefit analyses can be conducted to compare the expenses associated with RHA procurement, processing, transportation and concrete production against the potential savings in cement consumption, admixture usage and long-term maintenance costs. Additionally, economic feasibility studies can explore potential market opportunities for RHA-based concrete products, considering factors such as sustainability certifications, green building regulations and market demand for environmentally friendly construction materials.

Addressing these research gaps and conducting further investigations in these areas will contribute to a more comprehensive understanding of RHA's potential in concrete technology and facilitate its wider implementation as a sustainable and high-performance construction material.

8 Concluding remarks

In conclusion, the utilisation of rice husk ash (RHA) in concrete holds great promise for improving the performance and sustainability of concrete materials. Through a critical analysis of the available literature, we have explored the influence of RHA on various aspects of concrete, including strength, mechanical properties, workability, rheological behaviour, hydration and microstructure. The research findings demonstrate that RHA can enhance the strength and mechanical properties of concrete when incorporated in appropriate proportions and under optimised burning conditions. It has also been shown to improve the workability and rheological behaviour of concrete, making it suitable for applications that require high flowability and self-compaction. However, further investigations and research are needed to fully explore the potential of RHA in concrete. Research gaps and areas for future investigation have been identified, including optimizing RHA properties, conducting long-term durability assessments, understanding its influence on fresh concrete properties, standardizing procedures and guidelines, evaluating compatibility with different cement types, conducting life cycle assessment studies, assessing field performance and examining the economic feasibility of RHA utilisation. By addressing these research gaps and conducting further studies, we can advance our understanding of RHA and its applications in concrete. This knowledge will contribute to the development of more durable, workable and environmentally friendly concrete materials. Collaboration between researchers, industry professionals and regulatory bodies will be crucial in driving the implementation of RHA-based concrete in real-world construction projects.

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References

1. Jamil M, Kaish ABMA, Raman SN, Zain MFM. Pozzolanic contribution of rice husk Ash in cementitious system. Constr Building Mater. 2013;47:588–93.
2. Das S, Ray S, Sarkar S. Early strength development in concrete using preformed CSH nano crystals. Constr Building Mater. 2020;233:117214.
3. Lim YY, Pham TM. Influence of Portland cement on performance of fine rice husk Ash geopolymer concrete: strength and permeability properties. Constr Building Mater. 2021;300:124321.
4. Ameri F, Shoaei P, Bahrami N, Vaezi M, Ozbakkaloglu T. Optimum rice husk Ash content and bacterial concentration in self-compacting concrete. Constr Building Mater. 2019;222:796–813.
5. Kathirvel P, Saraswathy V, Karthik SP, Sekar ASS. Strength and durability properties of quaternary cement concrete made with fly Ash, rice husk Ash & limestone powder. Arab J Sci Eng. 2013;38:589–98.
6. Praveenkumar TR, Vijayalakshmi MM, Meddah MS. Strengths and durability performances of blended cement concrete with TiO2 nanoparticles & rice husk Ash. Constr Building Mater. 2019;217:343–51.
7. Meddah MS, Praveenkumar TR, Vijayalakshmi MM, Manigandan S, Arunachalam R. Mechanical and microstructural characterization of rice husk Ash & Al2O3 nanoparticles modified cement concrete. Constr Building Mater. 2020;255:119358.
8. Zerbino R, Giaccio G, Isaia GC. Concrete incorporating rice-husk Ash without processing. Constr Building Mater. 2011;25(1):371–8.
9. Hesami S, Ahmadi S, Nematzadeh M. Effects of rice husk Ash and fiber on mechanical properties of pervious concrete pavement. Constr Build Mater. 2014;53:680–91.
10. Nuaklong P, Jongvivatsakul P, Pothisiri T, Sata V, Chindaprasirt P. Influence of rice husk Ash on mechanical properties and fire resistance of recycled aggregate high-calcium fly Ash geopolymer concrete. J Clean Prod. 2020;252:119797.
11. Fapohunda C, Akinbile B, Shittu A. Structure and properties of mortar and concrete with rice husk Ash as partial replacement of ordinary Portland cement–A review. Int J Sustainable Built Environ. 2017;6(2):675–92.
12. Hossain MM, Karim MR, Elahi MMA, Islam MN, Zain MFM. Long-term durability properties of alkali-activated binders containing slag, fly Ash, palm oil fuel Ash & rice husk Ash. Constr Building Mater. 2020;251:119094.
13. Siddika A, Al Mamun MA, Alyousef R, Mohammadhosseini H. State-of-the-art-review on rice husk ash: A supplementary cementitious material in concrete. J King Saud University-Engineering Sci. 2021;33(5):294–307.
14. Ganesan K, Rajagopal K, Thangavel K. Rice husk Ash blended cement: assessment of optimal level of replacement for strength & permeability properties of concrete. Constr Building Mater. 2008;22(8):1675–83.
15. Jaya RP, Bakar BHA, Johari MAM, Ibrahim MHW, Hainin MR, Jayanti DS. Strength & microstructure analysis of concrete containing rice husk Ash under seawater attack by wetting & drying cycles. Adv Cem Res. 2014;26(3):145–54.
16. Zareei SA, Ameri F, Dorostkar F, Ahmadi M. Rice husk Ash as a partial replacement of cement in high strength concrete containing micro silica: evaluating durability and mechanical properties. Case Stud Constr Mater. 2017;7:73–81.
17. Venkatanarayanan HK, Rangaraju PR. Effect of grinding of low-carbon rice husk Ash on the microstructure and performance properties of blended cement concrete. Cem Concr Compos. 2015;55:348–63.
18. Thiedeitz M, Schmidt W, Härder M, Kränkel T. Performance of rice husk Ash as supplementary cementitious material after production in the field & in the lab. Materials. 2020;13(19):4319.
19. Vo DH, Hwang CL, Yehualaw MD, Liao MC. The influence of MgO addition on the performance of alkali-activated materials with slag– rice husk Ash blending. J Building Eng. 2021;33:101605.
20. Hossain SS, Roy PK, Bae CJ. Utilization of waste rice husk Ash for sustainable geopolymer: A review. Constr Build Mater. 2021;310:125218.
21. Kameshwar P, Athira G, Bahurudeen A, Nanthagopalan P. Suitable pretreatment process for rice husk Ash towards dosage optimization and its effect on properties of cementitious mortar. Struct Concrete. 2021;22:E501–13.
22. Iftikhar B, Alih SC, Vafaei M, Elkotb MA, Shutaywi M, Javed MF, Aslam F. Predictive modeling of compressive strength of sustainable rice husk Ash concrete: ensemble learner optimization and comparison. J Clean Prod. 2022;348:131285.
23. Shen Y, Zhao P, Shao Q. Porous silica and carbon derived materials from rice husk pyrolysis Char. Microporous Mesoporous Mater. 2014;188:46–76.

24. Soltani N, Bahrami A, Pech-Canul MI, González LA. Review on the physicochemical treatments of rice husk for production of advanced materials. Chem Eng J. 2015;264:899–935.
25. Athinarayanan J, Periasamy VS, Alhazmi M, Alatiah KA, Alshatwi AA. Synthesis of biogenic silica nanoparticles from rice husks for biomedical applications. Ceram Int. 2015;41(1):275–81.
26. Gebretatios AG, Pillantakath ARKK, Witoon T, Lim JW, Banat F, Cheng CK. Rice husk waste into various template-engineered mesoporous silica materials for different applications: a comprehensive review on recent developments. Chemosphere, 2023;310, 136843.
27. Wang J, Guo H, Ding R, Zhang Y. Investigation of influence of rice husk Ash and corn cob Ash as mineral concrete admixtures on chloride migration using electrochemical technique. Int J Electrochem Sci. 2022;17(221236):2.
28. Shrestha D, Nayaju T, Kandel MR, Pradhananga RR, Park CH, Kim CS. Rice husk-derived mesoporous biogenic silica nanoparticles for gravity chromatography. Heliyon. 2023;9(4): e15142.
29. Bakari R, Kivevele T, Masawa SM, Huang X, Jande YA. Assessment of rice husk biomass from different agro-ecological zones of Tanzania for biofuels feasibility via supercritical water gasification. Biomass Bioenergy. 2023;173:106771.
30. Chen Y, Li H, Liu J, Liu N, Yang J, Zhang Y, Liu Q. Efficient utilization of Silanol group in rice husk to promote the synthesis of Ni-phyllosilicate for CO2 methanation. Int J Hydrog Energy. 2022;47(49):21173–81.
31. Rajamanikandan T, Banumathi S, Karthikeyan B, Palanisamy R, Bajaj M, Zawbaa HM, Kamel S. Investigation of dielectric and mechanical properties of lignocellulosic rice husk fibril for high and medium voltage electrical insulation applications. J Mater Res Technol. 2023;22:865–78.
32. Dávila-Giraldo LR, Zambrano-Forero C, Torres-Arango O, Pérez JFB, Murillo-Arango W. Integral use of rice husks for bioconversion with white-rot fungi. Biomass Convers Biorefinery. 2022; 12(8):1–11.
33. Tauseef M, Ansari AA, Khoja AH, Naqvi SR, Liaquat R, Nimmo W, Daood SS. Thermokinetics synergistic effects on co-pyrolysis of coal and rice husk blends for bioenergy production. Fuel. 2022;318:123685.
34. Tiwari S, Beliya E, Vaswani M, Khawase K, Verma D, Gupta N, Jadhav SK. Rice husk: a potent lignocellulosic biomass for second generation bioethanol production from Klebsiella Oxytoca ATCC 13182. Waste and Biomass Valorization. 2022;1–19.
35. Shams T, Schober G, Heinz D, Seifert S. Rice husk Ash as a silica source for the production of autoclaved aerated concrete–A chance to save energy and primary resources. J Building Eng. 2022;57:104810.
36. Shukla SS, Chava R, Appari S, Bahurudeen A, Kuncharam BVR. Sustainable use of rice husk for the cleaner production of value-added products. J Environ Chem Eng. 2022;10(1):106899.
37. Naik HR, Amin T, Sheraz Mahdi S. Post-harvest management and value addition of food crops. Secondary agriculture: sustainability and livelihood in India. Cham: Springer International Publishing; 2022. pp. 131–46.
38. Ugheoke IB, Mamat O. A critical assessment and new research directions of rice husk silica processing methods and properties. Maejo Int J Sci Technol. 2012;6(3):430.
39. Fernandes IJ, Calheiro D, Sánchez FA, Camacho ALD, Rocha TLADC, Moraes CAM, Sousa VCD. Characterization of silica produced from rice husk ash: comparison of purification and processing methods. Mater Res. 2017;20:512–8.
40. Bazargan A, Gebreegziabher T, Hui CW, McKay G. The effect of alkali treatment on rice husk moisture content and drying kinetics. Biomass Bioenergy. 2014;70:468–75.
41. Contreras LM, Schelle H, Sebrango CR, Pereda I. Methane potential and biodegradability of rice straw, rice husk and rice residues from the drying process. Water Sci Technol. 2012;65(6):1142–9.
42. Chandrasekhar S, Pramada PN, Praveen L. Effect of organic acid treatment on the properties of rice husk silica. J Mater Sci. 2005;40:6535–44.
43. Moraes CA, Fernandes IJ, Calheiro D, Kieling AG, Brehm FA, Rigon MR, Osorio E. Review of the rice production cycle: by-products and the main applications focusing on rice husk combustion and Ash recycling. Waste Manag Res. 2014;32(11):1034–48.
44. Turmanova S, Genieva S, Vlaev L. Obtaining some polymer composites filled with rice husks Ash-A review. Int J Chem. 2012;4(4):1–28.
45. Todkar BS, Deorukhkar OA, Deshmukh SM. Extraction of silica from rice husk. Int J Eng Res Dev. 2016;12(3):69–74.
46. Pode R. Potential applications of rice husk Ash waste from rice husk biomass power plant. Renew Sustain Energy Rev. 2016;53:1468–85.
47. Hossain SS, Mathur L, Roy PK. Rice husk/rice husk Ash as an alternative source of silica in ceramics: A review. J Asian Ceam Soc. 2018;6(4):299–313.
48. De Bhowmick G, Sarmah AK, Sen R. Production and characterization of a value-added Biochar mix using seaweed, rice husk, and pine sawdust: a parametric study. J Clean Prod. 2018;200:641–56.
49. Ji-Lu Z. Bio-oil from fast pyrolysis of rice husk: yields and related properties and improvement of the pyrolysis system. J Anal Appl Pyrol. 2007;80(1):30–5.
50. Siddiqui O, Dincer I. Design and assessment of a new solar-based biomass gasification system for hydrogen, cooling, power, and fresh water production utilizing rice husk biomass. Energy Conv Manag. 2021;236:114001.
51. Cordeiro GC, Toledo Filho RD, de Fairbairn MR, E. Use of ultrafine rice husk Ash with high-carbon content as Pozzolan in high-performance concrete. Mater Struct. 2009;42:983–92.
52. Ramadhansyah PJ, Bakar BA, Azmi MM, Ibrahim MW. Engineering properties of normal concrete grade 40 containing rice husk Ash at different grinding times. Int J Technol. 2011;2(1):10–9.
53. Habeeb GA, Mahmud HB. Study on properties of rice husk Ash and its use as cement replacement material. Mater Res. 2010;13:185–90.
54. Antiohos SK, Papadakis VG, Tsimas S. Rice husk Ash (RHA) effectiveness in cement and concrete as a function of reactive silica and fineness. Cem Concr Res. 2014;61:20–7.
55. Givi AN, Rashid SA, Aziz FNA, Salleh MAM. Assessment of the effects of rice husk Ash particle size on strength, water permeability and workability of binary blended concrete. Constr Build Mater. 2010;24(11):2145–50.
56. Thomas BS. Green concrete partially comprised of rice husk Ash as a supplementary cementitious material–a comprehensive review. Renew Sustain Energy Rev. 2018;82: 3913-23.
57. De Sensale GR. Strength development of concrete with rice-husk Ash. Cem Concr Compos. 2006;28(2):158–60.
58. Zahedi M, Ramezanianpour AA, Ramezanianpour AM. Evaluation of the mechanical properties and durability of cement mortars containing Nanosilica and rice husk Ash under chloride ion penetration. Constr Build Mater. 2015;78:354–61.

59. Gursel AP, Maryman H, Ostertag C. A life-cycle approach to environmental, mechanical, and durability properties of green concrete mixes with rice husk Ash. J Clean Prod. 2016;112:823–36.
60. Huang H, Gao X, Wang H, Ye H. Influence of rice husk Ash on strength and permeability of ultra-high performance concrete. Constr Build Mater. 2017;149:621–8.
61. Zeidabadi ZA, Bakhtiari S, Abbaslou H, Ghanizadeh AR. Synthesis, characterization and evaluation of Biochar from agricultural waste biomass for use in Building materials. Constr Build Mater. 2018;181:301–8.
62. Wang J, Xiao J, Zhang Z, Han K, Hu X, Jiang F. Action mechanism of rice husk Ash and the effect on main performances of cement-based materials: A review. Constr Build Mater. 2021;288:123068.
63. Sandhu RK, Siddique R. Influence of rice husk Ash (RHA) on the properties of self-compacting concrete: A review. Constr Build Mater. 2017;153:751–64.
64. Hongo T, Moriura M, Hatada Y, Abiko H. Simultaneous methylene blue adsorption and pH neutralization of contaminated water by rice husk Ash. ACS Omega. 2021;6(33):21604–12.
65. Tchakouté HK, Rüscher CH, Kong S, Kamseu E, Leonelli C. Geopolymer binders from Metakaolin using sodium waterglass from waste glass and rice husk Ash as alternative activators: A comparative study. Constr Build Mater. 2016;114:276–89.
66. Poulesquen A, Frizon F, Lambertin D. Rheological behavior of alkali-activated Metakaolin during geopolymerization. Cement-based materials for nuclear waste storage; 2013. pp. 225–38.
67. Zerbino R, Giaccio G, Batic OR, Isaia GC. Alkali-silica reaction in mortars and concretes incorporating natural rice husk Ash. Constr Build Mater. 2012;36:796–806.
68. Abbas S, Kazmi SM, Munir MJ. Potential of rice husk Ash for mitigating the alkali-silica reaction in mortar bars incorporating reactive aggregates. Constr Build Mater. 2017;132:61–70.
69. Salas A, Delvasto S, de Gutierrez RM, Lange D. Comparison of two processes for treating rice husk Ash for use in high performance concrete. Cem Concr Res. 2009;39(9):773–8.
70. He J, Jie Y, Zhang J, Yu Y, Zhang G. Synthesis and characterization of red mud and rice husk ash-based geopolymer composites. Cem Concr Compos. 2013;37:108–18.
71. Shelke VR, Bhagade SS, Mandavgane SA. Mesoporous silica from rice husk Ash. Bull Chem Reaction Eng Catal. 2010;5(2):63.
72. Nehdi M, Duquette J, Damatty E, A. Performance of rice husk Ash produced using a new technology as a mineral admixture in concrete. Cem Concr Res. 2003;33(8):1203–10.
73. Hoppe Filho J, Garcez MR, Medeiros MHF, Silva Filho LCP, Isaia GC. Reactivity assessment of residual rice-husk ashes. J Mater Civ Eng. 2017;29(6):04017003.
74. Cordeiro GC, Toledo Filho RD, Tavares LM, Fairbairn EDMR, Hempel S. Influence of particle size and specific surface area on the pozzolanic activity of residual rice husk Ash. Cement Concr Compos. 2011;33(5):529–34.
75. Nasiru S, Jiang L, Yu L, Chu H, Huang Y, Pei C, Gu Y, Jin W, Klu EE, Guo MZ. Properties of cement mortar containing recycled glass and rice husk Ash. Constr Build Mater. 2021;299:123900.
76. 76, Srivastava VC, Mall ID, Mishra IM. Characterization of mesoporous rice husk Ash (RHA) and adsorption kinetics of metal ions from aqueous solution onto RHA. J Hazard Mater. 2006;134(1–3):257–67.
77. Priya AK, Yogeshwaran V, Rajendran S, Hoang TK, Soto-Moscoso M, Ghfar AA, Bathula C. Investigation of mechanism of heavy metals (Cr6+, Pb2+ & Zn2+) adsorption from aqueous medium using rice husk ash: kinetic and thermodynamic approach. Chemosphere. 2022;286:131796.
78. Mayooran S, Ragavan S, Sathiparan N. Comparative study on open air burnt low-and high-carbon rice husk Ash as partial cement replacement in cement block production. J Building Eng. 2017;13:137–45.
79. Mohseni E, Kazemi MJ, Koushkbaghi M, Zehtab B, Behforouz B. Evaluation of mechanical and durability properties of fiber-reinforced lightweight geopolymer composites based on rice husk Ash and nano-alumina. Constr Build Mater. 2019;209:532–40.
80. Robler C, Bui DD, Ludwig HM. Mesoporous structure and pozzolanic reactivity of rice husk Ash in cementitious system. Constr Building Mater. 2013;43:208–16.
81. Okoro HK, Alao SM, Pandey S, Jimoh I, Basheeru KA, Caliphs Z, Ngila JC. Recent potential application of rice husk as an eco-friendly adsorbent for removal of heavy metals. Appl Water Sci. 2022;12(12):259.
82. Mohd Basri MS, Mustapha F, Mazlan N, Ishak MR. Optimization of adhesion strength and microstructure properties by using response surface methodology in enhancing the rice husk ash-based geopolymer composite coating. Polymers. 2020;12(11):2709.
83. Kang SH, Hong SG, Moon J. The use of rice husk Ash as a reactive filler in ultra-high performance concrete. Cem Concr Res. 2019;115:389–400.
84. Hamzeh Y, Ziabari KP, Torkaman J, Ashori A, Jafari M. Study on the effects of white rice husk Ash and fibrous materials additions on some properties of fiber–cement composites. J Environ Manage. 2013;117:263–7.
85. Muthukrishnan S, Gupta S, Kua HW. Application of rice husk Biochar and thermally treated low silica rice husk Ash to improve physical properties of cement mortar. Theoret Appl Fract Mech. 2019;104:102376.
86. Jittin V, Bahurudeen A, Ajinkya SD. Utilisation of rice husk Ash for cleaner production of different construction products. J Clean Prod. 2020;263:121578.
87. Faried AS, Mostafa SA, Tayeh BA, Tawfik TA. The effect of using nano rice husk Ash of different burning degrees on ultra-high-performance concrete properties. Constr Build Mater. 2021;290:123279.
88. Nair DG, Fraaij A, Klaassen AA, Kentgens AP. A structural investigation relating to the pozzolanic activity of rice husk ashes. Cem Concrete Res. 2008;38(6):861–9.
89. Feng Q, Yamamichi H, Shoya M, Sugita S. Study on the pozzolanic properties of rice husk Ash by hydrochloric acid pretreatment. Cem Concrete Res. 2004;34(3):521–6.
90. Wansom S, Janjaturaphan S, Sinthupinyo S. Characterizing pozzolanic activity of rice husk Ash by impedance spectroscopy. Cem Concrete Res. 2010;40(12):1714–22.
91. Jauberthie R, Rendell F, Tamba S, Cisse I. Origin of the pozzolanic effect of rice husks. Constr Building Mater. 2000;14(8):419–23.
92. Königsberger M, Hellmich C, Pichler B. Densification of CSH is mainly driven by available precipitation space, as quantified through an analytical cement hydration model based on NMR data. Cem Concr Res. 2016;88:170–83.
93. Juenger MC, Siddique R. Recent advances in Understanding the role of supplementary cementitious materials in concrete. Cem Concr Res. 2015;78:71–80.

94. Sargın Ş, Saltan M, Morova N, Serin S, Terzi S. Evaluation of rice husk Ash as filler in hot mix asphalt concrete. Constr Build Mater. 2013;48:390–7.
95. Al-Hdabi A. Laboratory investigation on the properties of asphalt concrete mixture with rice husk Ash as filler. Constr Build Mater. 2016;126:544–51.
96. Rumman R, Bari MS, Manzur T, Kamal MR, Noor MA. A durable concrete mix design approach using combined aggregate gradation bands and rice husk Ash based blended cement. J Building Eng. 2020;30:101303.
97. Patel YJ, Shah N. Enhancement of the properties of ground granulated blast furnace slag based self compacting geopolymer concrete by incorporating rice husk Ash. Constr Build Mater. 2018;171:654–62.
98. Da Costa FBP, Righi DP, Graeff AG, da Silva Filho LCP. Experimental study of some durability properties of ECC with a more environmentally sustainable rice husk Ash and high tenacity polypropylene fibers. Constr Build Mater. 2019;213:505–13.
99. Zhang Z, Yang F, Liu JC, Wang S. Eco-friendly high strength, high ductility engineered cementitious composites (ECC) with substitution of fly Ash by rice husk Ash. Cem Concr Res. 2020;137:106200.
100. Park KB, Kwon SJ, Wang XY. Analysis of the effects of rice husk Ash on the hydration of cementitious materials. Constr Build Mater. 2016;105:196–205.
101. Msinjili NS, Schmidt W, Mota B, Leinitz S, Kühne HC, Rogge A. The effect of superplasticizers on rheology and early hydration kinetics of rice husk ash-blended cementitious systems. Constr Building Mater. 2017;150:511–9.
102. Prasittisopin L, Trejo D. Hydration and phase formation of blended cementitious systems incorporating chemically transformed rice husk Ash. Cement Concr Compos. 2015;59:100–6.
103. Ahsan MB, Hossain Z. Supplemental use of rice husk Ash (RHA) as a cementitious material in concrete industry. Constr Build Mater. 2018;178:1–9.
104. Msinjili NS, Schmidt W, Rogge A, Kühne HC. Rice husk Ash as a sustainable supplementary cementitious material for improved concrete properties. Afr J Sci Technol Innov Dev. 2019;11(4):417–25.
105. Memon SA, Shaikh MA, Akbar H. Utilization of rice husk Ash as viscosity modifying agent in self compacting concrete. Constr Build Mater. 2011;25(2):1044–8.
106. Channa SH, Mangi SA, Bheel N, Soomro FA, Khahro SH. Short-term analysis on the combined use of sugarcane Bagasse Ash and rice husk Ash as supplementary cementitious material in concrete production. Environ Sci Pollut Res. 2022;29(3):3555–64.
107. Amin MN, Khan K, Arab AMA, Farooq F, Eldin SM, Javed MF. Prediction of sustainable concrete utilizing rice husk Ash (RHA) as supplementary cementitious material (SCM): optimization and Hyper-tuning. J Mater Res Technol. 2023,25:1495- 1536.
108. Pereira P, Evangelista L, De Brito JMCL. The effect of superplasticisers on the workability and compressive strength of concrete made with fine recycled concrete aggregates. Constr Build Mater. 2012;28(1):722–9.
109. Padhi RS, Patra RK, Mukharjee BB, Dey T. Influence of incorporation of rice husk Ash and coarse recycled concrete aggregates on properties of concrete. Constr Build Mater. 2018;173:289–97.
110. Safari J, Mirzaei M, Rooholamini H, Hassani A. Effect of rice husk Ash and macro-synthetic fibre on the properties of self-compacting concrete. Constr Build Mater. 2018;175:371–80.
111. Zaid O, Ahmad J, Siddique MS, Aslam F. Effect of incorporation of rice husk Ash instead of cement on the performance of steel fibers reinforced concrete. Front Mater. 2021;8:665625.
112. Haruna SI, Malami SI, Adamu M, Usman AG, Farouk AIB, Ali SIA, Abba SI. Compressive strength of self-compacting concrete modified with rice husk Ash and calcium carbide waste modeling: a feasibility of emerging emotional intelligent model (EANN) versus traditional FFNN. Arab J Sci Eng. 2021;46(11):11207–22.
113. Chiranjeevi K, Vijayalakshmi MM, Praveenkumar TR. Investigation of fly Ash and rice husk Ash-based geopolymer concrete using nano particles. Appl Nanosci. 2023;13(1):839–46.
114. Vigneshwari M, Arunachalam K, Angayarkanni A. Replacement of silica fume with thermally treated rice husk Ash in reactive powder concrete. J Clean Prod. 2018;188:264–77.
115. Chopra D, Siddique R. Strength, permeability and microstructure of self-compacting concrete containing rice husk Ash. Biosyst Eng. 2015;130:72–80.
116. Makul N, Sua-iam G. Effect of granular Urea on the properties of self-consolidating concrete incorporating untreated rice husk ash: flowability, compressive strength and temperature rise. Constr Build Mater. 2018;162:489–502.
117. Nguyen VT, Ye G, van Breugel K, Fraaij ALA, Bui DD. The study of using rice husk Ash to produce ultra high performance concrete. Constr Build Mater. 2011;25(4):2030–5.
118. Bie RS, Song XF, Liu QQ, Ji XY, Chen P. Studies on effects of burning conditions and rice husk Ash (RHA) blending amount on the mechanical behavior of cement. Cem Concr Compos. 2015;55:162–8.
119. Madandoust R, Ranjbar MM, Moghadam HA, Mousavi SY. Mechanical properties and durability assessment of rice husk Ash concrete. Biosyst Eng. 2011;110(2):144–52.
120. Madandoust R, Ghavidel R. Mechanical properties of concrete containing waste glass powder and rice husk Ash. Biosyst Eng. 2013;116(2):113–9.
121. Varadharajan S, Jaiswal A, Verma S. Assessment of mechanical properties and environmental benefits of using rice husk ash and marble dust in concrete. Structures. 2020;28:389–406.
122. Liu C, Zhang W, Liu H, Zhu C, Wu Y, He C, Wang Z. Recycled aggregate concrete with the incorporation of rice husk ash: mechanical properties and microstructure. Constr Build Mater. 2022;351:128934.
123. Abolhasani A, Samali B, Dehestani M, Libre NA. Effect of rice husk ash on mechanical properties, fracture energy, brittleness and aging of calcium aluminate cement concrete. Structures. 2022;36:140–52.
124. Hu L, Yang H, He Z, Chen Z, Hu J, Zhang S. Effect of rice husk ash on carbon sequestration, mechanical property and microstructure evolution of cement-based materials with early-age carbonation treatment. Cem Concr Compos. 2022;133:104672.
125. Le HT, Kraus M, Siewert K, Ludwig HM. Effect of macro-mesoporous rice husk Ash on rheological properties of mortar formulated from self-compacting high-performance concrete. Constr Build Mater. 2015;80:225–35.
126. Celik F, Canakci H. An investigation of rheological properties of cement-based Grout mixed with rice husk Ash (RHA). Constr Build Mater. 2015;91:187–94.
127. Jittin V, Bahurudeen A. Evaluation of rheological and durability characteristics of sugarcane Bagasse Ash and rice husk Ash based binary and ternary cementitious system. Constr Build Mater. 2022;317:125965.

128. Medina C, del Bosque IS, Frías M, de Rojas MS. Design and characterization of ternary cements containing rice husk Ash and fly Ash. Constr Build Mater. 2018;187:65–76.
129. Singh A, Singh B. (2023). Influence of rice usk Ash on Rheology of Conventional Concrete. In International RILEM Conference on Synergizing expertise towards sustainability and robustness of CBMs and concrete structures (pp. 185–196). Cham: Springer Nature Switzerland.
130. Van Tuan N, Ye G, Van Breugel K, Copuroglu O. Hydration and microstructure of ultra-high-performance concrete incorporating rice husk ash. Cem Concr Res. 2011;41(11):1104–11.
131. Xu W, Lo YT, Ouyang D, Memon SA, Xing F, Wang W, Yuan X. Effect of rice husk Ash fineness on porosity and hydration reaction of blended cement paste. Constr Build Mater. 2015;89:90–101.
132. Liu R, Pang B, Zhao X, Yang Y. Effect of rice husk Ash on early hydration behavior of magnesium phosphate cement. Constr Build Mater. 2020;263:120180.
133. Singh NB, Rai S. Effect of Polyvinyl alcohol on the hydration of cement with rice husk Ash. Cem Concr Res. 2001;31(2):239–43.
134. Huang H, Ye G, Fehling E, Middendorf B, Thiemicke J. (2016, March). Use of rice husk ash for mitigating the autogenous shrinkage of cement pastes at low water cement ratio. In Proceedings of the HiPerMat 2016 4th international symposium on ultra-high performance concrete and high performance construction materials, Kassel, Germany (pp. 9–11).
135. Chindasiriphan P, Yokota H, Kawabata Y, Pimpakan P. Combined effect of rice husk Ash and superabsorbent polymer on self-healing capability of mortar. Constr Build Mater. 2022;338:127588.
136. Behnood A, Gharehveran MM, Asl FG, Ameri M. Effects of copper slag and recycled concrete aggregate on the properties of CIR mixes with bitumen emulsion, rice husk Ash, Portland cement and fly Ash. Constr Build Mater. 2015;96:172–80.
137. Mutungi W, Mutuku RN, Nyomboi T. Determination of creep behavior of concrete beams made with rice husk Ash. Open Civil Eng J, 2021;15(1): 339-46.
138. Rattanachu P, Toolkasikorn P, Tangchirapat W, Chindaprasirt P, Jaturapitakkul C. Performance of recycled aggregate concrete with rice husk Ash as cement binder. Cem Concr Compos. 2020;108:103533.
139. Wang Z, Li B, Othman A, Zhang Z. Endogenous alkali silica reaction evaluation of rice husk Ash in mortar. J Building Eng. 2023; 75:106970.
140. Chatveera B, Lertwattanaruk P. Durability of conventional concretes containing black rice husk Ash. J Environ Manage. 2011;92(1):59–66.
141. Thiedeitz M, Ostermaier B, Kränkel T. Rice husk ash as an additive in mortar–Contribution to microstructural, strength and durability performance. Resources, Conservation and Recycling. 2022;184:106389.
142. Sivakrishna A, Adesina A, Awoyera PO, Kumar KR. Green concrete: A review of recent developments. Mater Today: Proc. 2020;27:54–8.
143. Chindaprasirt P, Jaturapitakkul C, Rattanasak U. Influence of fineness of rice husk Ash and additives on the properties of lightweight aggregate. Fuel. 2009;88(1):158–62.
144. Torkaman J, Ashori A, Momtazi AS. Using wood fiber waste, rice husk ash, and limestone powder waste as cement replacement materials for lightweight concrete blocks. Constr Build Mater. 2014;50:432–6.
145. Modarres A, Hosseini Z. Mechanical properties of roller compacted concrete containing rice husk Ash with original and recycled asphalt pavement material. Mater Design. 2014;64:227–36.
146. De Subashi GHMJ, Priyamali MWS. Potential use of waste rice husk Ash for concrete paving blocks: strength, durability, and run-off properties. Int J Pavement Eng. 2022;23(7):2265–77.
147. De Silva GS, Vishvalingam S, Etampawala T. Effect of waste rice husk Ash from rice husk fuelled brick kilns on strength, durability and thermal performances of mortar. Constr Build Mater. 2021;268:121794.
148. Selvaranjan K, Navaratnam S, Gamage JCPH, Thamboo J, Siddique R, Zhang J, Zhang G. Thermal and environmental impact analysis of rice husk ash-based mortar as insulating wall plaster. Constr Build Mater. 2021;283:122744.
149. Srikanth G, Fernando A, Selvaranjan K, Gamage JCPH, Ekanayake L. Development of a plastering mortar using waste Bagasse and rice husk ashes with sound mechanical and thermal properties. Case Stud Constr Mater. 2022;16;e00956.
150. Basha EA, Hashim R, Mahmud HB, Muntohar AS. Stabilization of residual soil with rice husk Ash and cement. Constr Build Mater. 2005;19(6):448–53.
151. Muntohar AS, Widianti A, Hartono E, Diana W. Engineering properties of silty soil stabilized with lime and rice husk Ash and reinforced with waste plastic fiber. J Mater Civ Eng. 2013;25(9):1260–70.
152. Karatai TR, Kaluli JW, Kabubo C, Thiong'o G. Soil stabilization using rice husk Ash and natural lime as an alternative to cutting and filling in road construction. J Constr Eng Manag. 2017;143(5):04016127.
153. Liu Y, Chang CW, Namdar A, She Y, Lin CH, Yuan X, Yang Q. Stabilization of expansive soil using cementing material from rice husk Ash and calcium carbide residue. Constr Build Mater. 2019;221:1–11.
154. Zunino F, Lopez M. A methodology for assessing the chemical and physical potential of industrially sourced rice husk Ash on strength development and early-age hydration of cement paste. Constr Build Mater. 2017;149:869–81.
155. Olutoge FA, Adesina PA. Effects of rice husk Ash prepared from charcoal-powered incinerator on the strength and durability properties of concrete. Constr Build Mater. 2019;196:386–94.
156. Liou TH. Preparation and characterization of nano-structured silica from rice husk. Mater Sci Engineering: A. 2004;364(1–2):313–23.
157. Bernal SA, Rodríguez ED, Mejia de Gutiérrez R, Provis JL, Delvasto S. Activation of metakaolin/slag blends using alkaline solutions based on chemically modified silica fume and rice husk Ash. Waste Biomass Valoriz. 2012;3:99–108.
158. Liu J, Shi C, Ma X, Khayat KH, Zhang J, Wang D. An overview on the effect of internal curing on shrinkage of high performance cement-based materials. Constr Build Mater. 2017;146:702–12.
159. Ferraro RM, Nanni A. Effect of off-white rice husk Ash on strength, porosity, conductivity and corrosion resistance of white concrete. Constr Build Mater. 2012;31:220–5.
160. Wen N, Zhao Y, Yu Z, Liu M. A sludge and modified rice husk ash-based geopolymer: synthesis and characterization analysis. J Clean Prod. 2019;226:805–14.
161. Vijayan R, Kumar GS, Karunakaran G, Surumbarkuzhali N, Prabhu S, Ramesh R. Microwave combustion synthesis of Tin oxide-decorated silica nanostructure using rice husk template for supercapacitor applications. J Mater Sci: Mater Electron. 2020;31:5738–45.

162. Singh R. Synthesis and characterisation of Al-Mg-SiO2 particulate composite prepared by nanostructured silica from rice husk Ash. Mater Today: Proc. 2021;37:3148–53.
163. Carraro PM, Benzaquén TB, Eimer GA. Eco-friendly synthesis of nanostructured mesoporous materials from natural source rice husk silica for environmental applications. Environ Sci Pollut Res. 2021;28(19):23707–19.
164. Araichimani P, Prabu KM, Kumar GS, Karunakaran G, Surendhiran S, Shkir M, Ali HE. Synthesis of Fe3O4-decorated SiO2 nanostructure using rice husk as a source by microwave combustion for the development of a magnetically recoverable adsorbent. Ceram Int. 2022;48(7):10339–45.
165. Pham TM. Enhanced properties of high-silica rice husk ash-based geopolymer paste by incorporating basalt fibers. Constr Build Mater. 2020;245:118422.
166. Buyondo KA, Olupot PW, Kirabira JB, Yusuf AA. Optimization of production parameters for rice husk ash-based geopolymer cement using response surface methodology. Case Stud Constr Mater. 2020;13:e00461.
167. Mosaberpanah MA, Umar SA. Utilizing rice husk Ash as a supplement to cementitious materials on the performance of ultra high performance concrete: A review. Mater Today Sustain. 2020;7:100030.
168. Qureshi LA, Ali B, Ali A. Combined effects of supplementary cementitious materials (silica fume, GGBS, fly ash, and rice husk ash) and steel fiber on the hardened properties of recycled aggregate concrete. Constr Build Mater. 2020;263:120636.
169. Hasan NMS, Sobuz MHR, Khan MMH, Mim NJ, Meraz MM, Datta SD, Rana MJ, Saha A, Akid ASM, Mehedi MT, Houda M. Integration of rice husk Ash as supplementary cementitious material in the production of sustainable High-Strength concrete. Materials. 2022;15(22):8171.
170. Bheel N, Ali MOA, Shafiq N, Almujibah HR, Awoyera P, Benjeddou O, Shittu A, Olalusi OB. March). Utilization of millet husk Ash as a supplementary cementitious material in eco-friendly concrete: RSM modeling and optimization. Structures. 2023;49:826–41.
171. Rajasegar M, Kumaar CM. Hybrid effect of poly vinyl alcohol, expansive minerals, nano-silica and rice husk ash on the self-healing ability of concrete. Mater. Today: Proc. 2021;45:5944–5952.
172. Koushkbaghi M, Kazemi MJ, Mosavi H, Mohseni E. Acid resistance and durability properties of steel fiber-reinforced concrete incorporating rice husk Ash and recycled aggregate. Constr Build Mater. 2019;202:266–75.
173. Althoey F, Zaid O, de-Prado-Gil J, Palencia C, Ali E, Hakeem I, Martínez-García R. Impact of sulfate activation of rice husk Ash on the performance of high strength steel fiber reinforced recycled aggregate concrete. J Building Eng. 2022;54:104610.
174. Meraz MM, Mim NJ, Mehedi MT, Farsangi EN, Arafin SAK, Shrestha RK, Hussain MS. On the utilization of rice husk Ash in high-performance fiber reinforced concrete (HPFRC) to reduce silica fume content. Constr Build Mater. 2023;369:130576.
175. Henry CS, Lynam JG. Embodied energy of rice husk Ash for sustainable cement production. Case Stud Chem Environ Eng. 2020;2:100004.
176. Hu L, He Z, Shao Y, Cai X, Zhang S. Microstructure and properties of sustainable cement-based materials using combustion treated rice husk Ash. Constr Build Mater. 2021;294:123482.

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