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Potential Utilisation of Rice Husk Ash as Replacement for Cement in Concrete: Concise Review of the Physico-chemical, Mechanical, Fresh and Durability Properties

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***Abstract*—This paper highlights the potentials for utilizing rice husk ash (RHA) as a partial replacement for cement in concrete and cement-based composites during construction. Over the years, the rising energy inputs and environmental impacts of cement production and utilization have prompted the search for alternative construction materials. Rice husk ash (RHA) is the by-product of rice husk combustion, which possesses pozzolanic characteristics for potential utilization as cementitious materials. Hence, the pozzolanic or cementitious characteristics of RHA along with the physicochemical, mechanical, fresh and durability properties are presented in detail. The studies revealed that RHA could be partially utilized to replace cement in the range of 5–30% by weight. Furthermore, the findings revealed that the addition of RHA to the cement increased the compressive strength of the concrete mix but reduced higher RHA content. However, the optimal compressive strength can be accomplished at the addition of 10% RHA to cement. Other studies reported that the addition of 20% RHA enhanced the tensile and flexural strength of the concrete blend. Based on the analysis, RHA is a suitable pozzolanic or cementitious material for concrete production in the construction industry.**

Keywords—Rice Husk, Ash, Silica, Pozzolan, Chemical Composition

I. INTRODUCTION

Cement is a calcium silicate or aluminate-based binding material that possesses cohesive and adhesive properties when mixed with water (hydrated) [1, 2]. It is the world's leading building material used for producing concrete that is widely used in the construction industry [3, 4]. Historically, cement has contributed significantly towards the structural civilization of the ancient world dating from the Egyptian era down to the Roman realm. Studies reveal that the Egyptians utilized calcined gypsum as cement for construction [5-7], while the Romans and Greeks used lime through the calcination of limestone [8-10], which was used with sand or coarse stones for the formulation of mortar and concrete production. With the increase in the global human population, the demand for basic human needs such as water, energy, food, and shelter has soared significantly over the years. Hence, the demand and costs of building materials such as cement, which is an imperative construction material, have also increased markedly. Furthermore, the energy demand and pollutant emissions from the production of cement have also increased over the years. It is estimated that 1 kg of carbon dioxide (CO2) is generated for 1 kg of cement produced globally [11]. This indicates that 3-4 billion tonnes (Giga tonnes) of CO2 are generated annually from the production of cement worldwide [12, 13]. Based on these estimates, scientists posit that cement production accounts for 8% of all carbon-based emissions annually [11, 12].

Therefore, the combined effects of high demand, energy, and greenhouse emissions from cement have prompted calls for alternative renewable and sustainable materials for building construction [14, 15]. One potential approach is the production and utilization of pozzolanic materials from renewable and sustainable sources such as wastes. Agricultural wastes currently account for significant proportions of the waste profile in various agrarian societies [16-18]. Hence, the collection, conversion, and utilization of such agricultural wastes into sustainable building or construction materials will address the twin challenges of waste management and greenhouse gas emissions [19, 20]. Rice husks (RH) currently account for a large proportion of the various agricultural by-products obtained from processing rice in many countries around the world [21, 22]. However, strategies for the disposal, management, or valorization of RH remain either ineffective or are grossly inefficient. However, various researchers have recently examined its use as pozzolanic materials after ashing [23, 24]. The resulting material from the process of ashing RH is called rice husk ash (RHA) [25, 26]. Various studies have also sought to examine the partial substitution of cement with RHA due to its pozzolanic properties.

Pozzolanic materials are silica or alumina-based materials that within themselves have little or no cementitious value, but when hydrated in cement, they can react with calcium hydroxide [27, 28]. The reaction typically produces a stable and insoluble cementitious compound that improves the strength and rigidity of concrete used in construction [29]. Hence, the use of RHA as a partial replacement for cement could lower the energy and environmental costs of cement production as well as promote sustainable construction. RHA contains 87-97% of either crystalline or amorphous silica along with trace quantities of alkali, alkali earth, and trace elements, depending on the temperature range and burning time [30]. The performance of pozzolanic materials is also determined by the type and quantity of amorphous silica inherent as well as the duration of calcination [31]. Numerous researchers have examined the substitution of RHA with cement in concrete construction, and related research on the area has advanced within the last few years. The studies have shown that RHA has promising pozzolanic properties when mixed with cement. Typically, when RHA is mixed with ordinary Portland cement (OPC), it improves/increases the concrete strength produced against cracking. The mechanism reveals that the improved concrete properties are due to the formation of a C-S-H (calcium silicate hydrate) which thickens the cement region, which becomes remarkably dense and less porous [32]. RHA also lessens the impact of alkali-silica reactivity and drying shrinkage [33].

Therefore, this paper seeks to present an overview of the potentials of utilizing RHA as a renewable and sustainable pozzolanic material for the partial replacement of cement in concrete construction. Furthermore, the physicochemical and mechanical properties of RHA based on various experimental studies in the literature will be highlighted in detail. It is envisioned that the findings of the reviewed literature will provide theoretical knowledge and comprehensive data on the valorisation of rice husks into RHA for utilization as an environmentally friendly, low-cost, and socially acceptable building material.

II. Rice Husk Ash: Overview

Rice husk (RH) is described as the outer cover or external material that encloses the rice grain or seed. The composition of RH includes cellulose-based fibres that are rich in lignin and silica [34], which protect the rice grains during growth and development. When the rice is milled, the husks are generated as a by-product of the process. Typically, the RH can absorb 5-16% kg/m3 of water [35], although it is known to possess a high caloric value of about 16,720 kJ/kg. Due to its high energy potential, RH is typically utilized as fuel for gasification or direct combustion for biofuels and bioenergy production [36]. The combustion or burning of RH generates a by-product termed rice hush ash (RHA), which accounts for almost 25% of the original husk mass. In addition, RHA contains 85-90% silica and 5% alumina in amorphous form, which is suitable for application in construction, ceramics amongst others. The combustion or burning of RH thermally decomposes the hemicellulose, cellulose, and lignin components of RH, thereby yielding porous silica with a high surface area [37]. RHA is a highly porous, lightweight and large surface area material with dimensions of ~50,000 m2/kg. However, the properties of the silica differ under heating temperature and time. The amorphous silica is derived from the burning of RH is kept under control at 500 ºC – 700 ºC for 1 hour. Therefore, the open and uncontrollable combustion of rice husk from 700 ºC – 800 ºC for over an hour produces non-reactive silica minerals such as cristobalite and tridymite. The amorphous silica has a fine particle size with its large surface area abovementioned, which could be ascribed to the microporous arrangement of the ash particles [38].

III. Material Properties of RHA

The section of the paper highlights the chemical, physical, and mechanical properties of RHA. In addition, the new and durable properties of the RHA reported in the literature are also presented in detail.

A. *Chemical Properties*

The chemical action of pozzolanic materials such as RHA occurs within the deepest artificial area of its microspores. The particle size and surface area of RHA are also critical to its pozzolanic properties. Furthermore, geographical location, condition, paddy type, and fertilizer used during cultivation influence the chemical content and chemistry of the ash. Other factors such as soil chemistry, pre-treatment and combustion process are also critical factors that enhance the chemical composition of RHA. Table 1 presents the chemical compositions of RHA and cement from various experimental research works in the literature. According to the ASTM C618 standard, the minimum value standard for SiO2 (silica) in pozzolanic materials is 70% [39-41]. As observed in Table 1, the SiO2 content of RHA ranges from 87.40-95.04%, which is higher than cement. Typically, silica is responsible for the strength of cement, though extremely high values of silica can adversely affect the strength of the cementitious material. On the other hand, the alumina content, which is responsible for swift setting time in cement, is high. According to the study by Edmeades and Hewlett [42], higher values of alumina (Al2O3) in cement result in extensive structural problems, which is typically attributed to its quick hardening characteristics. When compared to RHA (Table 1), the value of alumina is also higher than RHA. This observation indicates that RHA has a moderate hardening time. Furthermore, the value of Al2O3 in RHA is within the accepted limits of the ASTM specification as well as the standards of Nigeria.

Table 1: Chemical compositions of RHA and Cement.

References	Code	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI*
Zerbino *et al.,* [43]	RHA	95.04	0.30	0.44	1.25	0.45	0.01	0.09	1.40	0.51
Chao-Lung *et al.,* [44]	RHA	91.00	0.35	0.41	-	0.81	1.21	0.08	3.21	8.50
Madandoust *et al.,* [45]	RHA	90.90	0.83	0.60	0.80	0.56	_	1.55	1.55	-
Rößler *et al.,* [46]	RHA	87.40	0.40	0.30	0.90	0.60	0.40	0.04	0.04	3.39
Dabai *et al.,* [47]	OPC	23.43	4.84	1.52	64.40	1.34	2.79	0.05	0.29	5.68

Table 1 also shows that RHA contains calcium oxide (CaO). Based on Taylor [48], the CaO content also accounts for the strength, particularly at the early stages of concrete construction. As observed in Table, the CaO present in RHA is lower compared to that of cement. Likewise, the magnesia (MgO) content is lower in RHA. However, high MgO content is undesirable because it causes inaccuracies in concrete. The content of iron (III) oxide (Fe2O3) is responsible for the colouration in cement products such as concrete and cement-based composites [49]. For RHA, Fe2O3 content is markedly lower than that of cement, as can be observed in Table 1. Another major alkali oxide linked with cement is potassium oxide (K2O). Typically, K2O is known to damage kilns and simultaneously attack shatterproof concrete when present in high concentrations. It is also known to affect the setting time and promotes alkali-silicate reactions in cement-based composites such as mortar and concrete. Lastly, cement is also known to contain high sulphates, which could be in the form of gypsum added during production. Gypsum is a raw material required to produce cement. It is responsible for managing the setting time of concrete or cement-based composites during construction [50]. In addition, it has been reported that cement products with high sulphate resist acid attack [3], while a low quantity of SO3 in cement can prevent the formation of C3S [48].

B. Physical Properties

i. Bulk Density

Bulk density is a physical property defined as the mass of bulk solid that occupies a specific volume unit. It is quantified by the unit expression g/cm3 or kg/m3 [51]. The bulk density of RHA typically ranges from 90–150 kg/m3, which is smaller compared to the average density of concrete or its derived blends [38]. Sadrmomtazi et al., [52] reported that the density of the blended concrete decreases with the addition of RHA content. RHA has a specific gravity which is typically in the range of 2.11 to 2.27 [53].

ii. Morphology, Colour and Microstructure

RHA is grey to black, like partially combusted carbon. According to Siddique et al., [53], RHA is in the form of amorphous silica particularly at 550–800 °C, whereas it is in the form of crystalline silica when higher temperatures are utilised for the ashing process. Furthermore, RHA is lightweight and known to exhibit high porosity and surface area with particle sizes ranging from 10 – 100 µm [53].

C. Mechanical Properties

i. Compressive strength

This is a mechanical property of concrete and cement-based composite materials. Various studies have demonstrated that the addition of RHA as a fractional substitute for cement advances the compressive strength of concrete. However, the percentage replacement reported in the literature varies between 5% and 30% by the weight of cement. Dabai et al., [47] reported that the compressive strength of the concrete mix increases with curing age but reduces with increasing RHA content. Typically, the optimal compressive strength is accomplished at the addition of 10% RHA to cement. This is corroborated by Chao-Lung et al., [44], whose study reported that the replacement of cement with 10% RHA achieves an adequate compressive strength compared to the control. However, the compressive strength was found to decrease with increasing percentage RHA. Le et al., [54] showed that the addition of 10% RHA in cement increases the strength despite the curing age, which could be due to the high pozzolanic properties (e.g., high silica content). Other studies reported that 20% addition of RHA as partial replacement in cement gives the utmost compressive strength [55, 56]. Ganesan et al., [56] examined RHA-cement blends concerning the review of the most advantageous degree of substitute for strength and permeability properties of concrete. Results made evident that up to 30% replacement of RHA could be the most favourably blend with cement without adversely affecting the strength and permeability properties of concrete. Likewise, de Souza Rodrigues et al., [57] reported that the partial replacement of cement with RHA in concrete exhibited higher compressive strength than the control (i.e., 0% RHA) after 91 days. Nevertheless, the increases reported for the compressive strength of RHA concretes were largely attributed to the effects of the filler and the pozzolanic materials.

ii. Flexural and Splitting Tensile Strengths

The flexural and splitting tensile strengths are mechanical properties of cement-based materials. The tensile strength is defined as the amount of load a material can sustain devoid of fracture when stretched.

Day et al., [58] stated that the flexural and splitting tensile strength properties are considered the most important and indispensable mechanical properties of materials after compressive strength. Vigneshwari et al., [59] demonstrated that the partial replacement of RHA up to 20% in cement concrete increases the flexural and splitting tensile strength. Other studies in the literature have demonstrated that the integration of RHA into cement advances the flexural strength of the mortar or cement-based composites [60-62]. The findings also stated that the enhancement is due to pozzolanic reaction and the stuffing aptitude of the RHA fine particles. It is important to state that the percentage rise depends on the curing days, which are relatively consistent at 20% inclusion of RHA between 7 and 120 days.

Conversely, Gravitt [63] reported that the flexural strength starts to decrease when there is an increase in mortar RHA concentration. Mohseni et al., [64] observed that the replacement of RHA up to 30% in cement lowers the flexural strength after 28 days of curing. Nevertheless, the flexural strength was improved overall after long curing days. Furthermore, the addition of 3% nano-sized Al2O3 also enhanced the flexural strength of 10% RHA concrete after 28- and 90-days curing [65]. Concretes containing up to 1% nano-Al2O3 and around 10% partial replacement of RHA stumble upon an increase in flexural strength with curing days of 28 and 90. However, the addition of 0.3% polypropylene fibre to the concrete enhanced the strength properties [64]. Overall, the literature reviewed showed that the prospective utilization of RHA (up to 20%) as supplementary cementitious material advanced the tensile and flexural strength of concrete blends.

D. Fresh and Durability Properties

i. Setting or |Hardening Time

This is considered a fresh property. It is defined as the time required for cement paste to solidify into a definite uniformity. Various researchers have demonstrated that the partial replacement of cement with RHA increases the hardening or setting time [56, 66]. This observation is attributed to the rate of reactivity of the specific surface area or the particles sizes of the RHA. The authors observed that the cement-RHA with finer particles exhibit signs of pre-eminence in setting actions. Likewise, El-Dakroury and Gasser [67] investigated the initial and final setting time of cement and cement-RHA blends. The findings showed that the addition of 30% RHA to cement enhanced the hydraulic stability of the cement-RHA blend. Likewise, the incorporation of RHA improved the overall economic, environmental, and energy-saving potential of the concrete. The impact of RHA on the concrete is ascribed to reactions that occur during the setting process. Typically, the pozzolanic reaction transforms the CH thereby increasing the quantity of the C-S-H present in the cement surrounding substance containing RHA [68, 69]. However, over time various authors have differed on the impact of RHA addition on the setting time. For example, Ganesan et al., [56] reported that the increase in RHA content first increases and then decreases the initial and final setting times. Rostovsky et al., [70] reported that the setting time decreases with increasing RHA content. According to Van et al., [71] the opposing results could be due to variation in particle sizes and pozzolanic reactivity of diverse RHA samples.

ii. Workability

The workability property determines the actions needed to influence freshly mixed concrete with minimal loss of homogeneity. The partial replacement of cement with RHA decreases the workability of freshly mixed concrete [65]. According to Le et al., [54], this observation is attributed to the porosity of the RHA particles. Even so, the workability can be enhanced using a good superplasticizer. In general, superplasticizers are chemical compounds that facilitate the production of concrete with roughly 30% or less water content. Universally, the addition of any fine mineral blend in concrete gives a lift to its cohesiveness and thus, making it slightly hard owing to higher surface area and water demands. Likewise, the inclusion of RHA in the concrete will reduce the primary slump, however, high water consumption occurs during the process [72].

iii. Drying Shrinkage

Drying shrinkage is defined as the process whereby the internal water in a concrete vanishes to harden the concrete. It is considered a durable property that causes tensile stress. The property is attributed to the cracking, internal deformation, and outer deflection that occurs before loading the concrete. Habeeb and Fayyadh [73], demonstrated that RHA-cement based concrete showed indistinguishable drying shrinkage when compared to control concrete and concrete blends produced at various curing ages. Overall, the findings showed that the addition of fine particles of RHA into concrete enhanced the drying shrinkage. This observation was attributed to the small particle sizes of RHA, which increases the pozzolanic activities through the action of pore refinement in the concrete blends. Other researchers have reported that the pore alteration of concrete through the addition of additives promotes higher shrinkage [31]. However, the studies by Zhang and Malhotra [60] and Chindaprasirt et al., [74] reported that the addition of pozzolanic materials such as RHA and Cassava peel ash as a replacement for cement reduced the drying shrinkage. According to Rizwan et al., [75], the contradicting report could be due to interpretational discrepancy based on dissimilar individuality and level of reactive pozzolanic material used in the studies. Conversely, the addition of up to 20% RHA can adequately absorb water to decrease the self-desiccated autogenous shrinkage.

IV. CONCLUSIONS

The paper presented an overview of the Potential Utilization of Rice Husk Ash (RHA) as Replacement for Cement in Concrete. Therefore, the Physical, Chemical, Mechanical, Fresh and Durability Properties of RHA-cement blended concretes were examined and highlighted. The findings of the reviewed literature demonstrated the suitability of utilizing RHA as a replacement for cement. The studies showed that the partial replacement of cement within the ranges of 5% to 30% of RHA would help attain the desired compressive strength, setting time (initial and final), Flexural strength and workability of the concrete. In addition, the RHA mix increases the initial and final setting time of cement pastes. This consequently extends the workability of fresh concrete and makes the available superior blending of concrete particularly for successive pours. Other studies showed that the RHA- cement mix concrete increases strength gradually at early curing age and distantly increases at a later curing age (90 days). Lastly, the reviewed studies showed that RHA possesses pozzolan properties, which could be effectively utilized for civil construction works, whilst reducing its environmental emissions/hazards and providing ample energy savings.

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