Research on Engineering Structures & Materials
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Research Article

Ascertaining the impact of locally sourced rice husk ash on the physical, mechanical, and sustainability performance of concrete

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Article Info

Article History:

Received 04 Apr 2026
Accepted 17 Aug 2026

Keywords:

C-S-H;
Concrete;
Materials;
Sustainability;
Ghana

Abstract

This study examined the physical, mechanical, and sustainability performance of concrete modified with locally sourced rice husk ash. Concrete specimens were prepared with Portland limestone cement partially replaced with rice husk ash (RHA) in proportions of 0%, 5%, 10%, 15%, and 20%. Tests conducted included XRF, slump, compressive, and flexural strength tests. The slump was a true slump, S2:50-90, indicating medium workability. Compressive and flexural strengths rose progressively to 15% optimum partial replacement levels at ages 7 days, 28 days, and 56 days, beyond which strength decreased. Compressive strength at 28 days was 22.10 N/mm^2, 23.74 N/mm^2, 24.37 N/mm^2, 25.53 N/mm^2, and 23.64 N/mm^2 for 0%, 5%, 10%, 15% and 20%, respectively. 20% RHA replacement level was found to be more sustainable, with a CO_2 reduction of 17.7% compared to the control. The maximum Pozzolanic activity index at 28 days was 115.52% and corresponds with 15% RHA replacement level. This study has established a mixed design that will guide civil and material engineers to optimize physical, mechanical, and sustainability performance of locally sourced RHA-modified concrete. The study promotes rice husk waste valorization and combating climate change as it finds an alternative for RHA in concrete.

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1. Introduction

Properties of concrete, such as the compressive strength, have made it a globally accepted and used material for civil infrastructure [1-3], including dams, buildings, and seawalls. A key component of concrete is cement [4], which accounts for about 10% of the carbon emissions in the world and contributes significantly, about 65%, to global warming and climate change with its effects in the world [3-6]. In the quest to reduce the cost of concrete, the carbon footprint of concrete, and to contribute to combating climate change in line with Sustainable Development Goal 13: Climate Action [7], some alternative cementitious materials, including locally sourced rice husk ash (RHA) [6], have been used within some national contexts such as Nigeria, India, Pakistan, and China [3, 8]. RHA is a pozzolanic material [9]. It is obtained after burning rice husks, an agricultural by-product, into ashes at a specific temperature [9]. Using RHA in concrete promotes rice husk waste valorization, reduces the cost and carbon footprint of concrete, and helps combat climate change and improves concrete performance [5,9,10]. However, the lack of a reference standard regulating

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DOI: http://dx.doi.org/10.17515/resm2026-1603me0404rs

the processing temperature in obtaining RHA, coupled with the origin and partial replacement level of RHA, has resulted in conflicting accounts of the chemical composition, sustainability, physical, and mechanical performance of RHA-modified concretes in existing literature. Hence, generalizing the sustainability performance, mechanical performance, and physical performance of RHA-modified concretes within some national contexts to be the same in Ghana is inaccurate. The lack of studies that have evaluated the impact of RHA on the sustainability, physical, and mechanical performance of concrete with Ghana as the focus makes this RHA study in Ghana geographically relevant. Empirically, it addresses the lack of literature within the context of Ghana on the performance of locally sourced RHA-modified concrete. Rice husk ash is obtained after recycling rice ash, an agricultural by-product [8]. Studies in the past have partially replaced cement with RHA in concrete in varying proportions: 5%, 7.5%, 10%, 12.5%, 15%, 20%, 30%, 40%, and 50%, and reported conflicting optimum replacement levels, which include 4%, 6%, 10%, and 15% (see [5,6,9,11]. Also, water-cement ratios vary, including 0.6 in Kenya according to Njagi et al. [11], 0.5 in Nigeria according to Agboola et al. [5], and 0.55 by Sathe et al. [6], equally limiting the generalizability of context-specific findings relating to the performance of RHA-modified concrete. As well, existing studies rarely give an empirical account of the pozzolanic activity index of pozzolans, even though it is a crucial indicator for ascertaining the activeness of pozzolans in the strength development of concrete, among others [6,12]. According to ASTM [12], pozzolans, in this case RHA-modified concrete, should have a pozzolanic activity index (PAI) not less than 75% for ages 7 days and 28 days [12]. Also, sustainability performance is rarely reported with empirical evidence (see [6, 8,11]). It is against this backdrop that this current study seeks to examine the physical, mechanical, and sustainability performance of concrete modified with locally sourced rice husk ash. The specific objectives that guided the study were:

- To assess the physical performance of concrete modified with locally sourced rice husk ash as a partial replacement for cement,
- To assess the mechanical performance of concrete modified with locally sourced rice husk ash as a partial replacement for cement,
- To assess the sustainability performance of concrete modified with locally sourced rice husk ash as a partial replacement for cement.

Mechanical performance assesses the performance of concrete when subjected to loading. It was evaluated using the compressive and flexural strengths [11]. Parameters for evaluating the physical performance of RHA-modified concrete included slump, density, and water absorption [11].

This study broadens the existing knowledge on RHA by providing a more comprehensive evaluation of RHA-modified concrete, as it integrates evaluation of its physical properties, mechanical performance, and sustainability characteristics in a single study. Unlike previous studies, this study evaluated the broader engineering and sustainability implications of using RHA-modified concrete. It also contributes to the chemical characterization of RHA, sourced locally from Ghana, using X-ray fluorescence (XRF) analysis. It provides an account of the optimal level of partial replacement of cement with RHA in the Ghanaian context, to guide construction practitioners and materials engineers on the use of RHA in RHA-modified concrete for optimal mechanical and sustainability performance. Also, the study promotes rice husk waste valorization by finding an alternative use for RHA locally sourced in Ghana as a supplementary cementitious material (SCM) in sustainable concrete production.

2. A Review of Literature on RHA-Modified Concrete in Existing Studies

2.1 Empirical Review

Agboola et al. [5] in Nigeria replaced cement partially with RHA in proportions of 0%, 5%, 10%, 15%, 20%, 25% and 30% in a concrete mix. The water-cement ratio was 0.5. The concrete specimens for compressive strength, tensile strength, and flexural strength at ages 7, 14, 21, and 28 days were prepared. Slump values ranged from 55mm for the control and 5% RHA level to 30mm for 30% RHA. Thus, as the percentage of RHA replacement increased, the slump value(workability) of concrete decreased. 0%, 5%, and 10% RHA replacement levels were

classified as S2 (50 mm- 90 mm), while 15%, 20%, 25% and 30% cement replacement were in the S1 classification (10mm – 40mm) as per BS EN 206-1:2000[13]. Normal-weight density concrete was produced, with the density of concrete increasing with the age of concrete. The optimum level of replacement was 10%, even though none of the compressive strengths exceeded the control [5]. The targeted compressive strength at 28 days was 25 N/mm^2. None of the compressive strengths exceeded the 0% RHA, even though the optimum level of replacement was 10%. Regarding tensile and flexural strengths, strength increased up to the optimum replacement level of 10% and thereafter decreased as %RHA increased [5]. The study was limited in computing the sustainability performance of RHA-modified concrete.

In a related study in Egypt by Salama et al. [10], concrete was produced with RHA partially replacing cement in proportions of 0%,4%,6%, and 8%. Although the optimum replacement level was recommended as 4%, none of the RHA-modified concrete exceeded the compressive strength of the control concrete. It was observed that compressive strength decreased as RHA percentage increased. The targeted compressive strength was 15 N/mm^2.Apart from the control and 4% RHA replacement, which recorded compressive strength values of 21.56 N/mm^2 and 16.11 N/mm^2, respectively, thus exceeding the targeted strength, the 6% and 8% RHA replacement levels recorded compressive strength values that were less than the targeted value. However, the study focused only on compressive strength and did not consider other mechanical and sustainability indicators in evaluating the performance of the concrete, hence making it highly non-comprehensive in characterizing the performance of concrete. Hence, the relevance of this current study in addressing this weakness.

In a related study by Kumar and Devi [14], cement was partially replaced with RHA at 0%, 5%, 7.5%, 10%, 12.5%, and 15%. Strength tests, such as tensile, compressive, and flexural, were performed at ages 7 and 28 days of curing. The study concluded that the optimum replacement level for RHA-modified concrete was 7.5%. The sustainability of concrete also improved when concrete was modified with RHA. However, this study was deficient in that long-term performance of concrete was not investigated.

In a study in Kenya by Njagi et al. [11], ordinary Portland cement was partially replaced with RHA in concrete in the proportions of 0%,10%,20%,30%,40%, and 50%. The water-cement ratio was 0.6. Slump increased up to the 10% RHA replacement level, after which any increase in the concentration of RHA resulted in a decrease in the slump value. None of the compressive strengths of the RHA-modified concrete exceeded that of the control at age 28 days. RHA-modified concrete was normal-weight concrete, and generally density decreased as the concentration of RHA in RHA-modified concrete increased. The optimum partial replacement level was 10%. Compressive strength increased up to 10% RHA replacement level and thereafter decreased with an increase in RHA concentration. Tensile strength increased progressively up to 10% RHA replacement level, and thereafter any increase in RHA resulted in a decrease in tensile strength [11]. However, the study was limited in that it did not consider the sustainability performance of the concrete, which this current study seeks to address.

In a related study by Sathe et al. [6], cement was partially replaced with RHA in proportions of 0%,5%,10%,15%, and 20%. RHA-modified concrete was tested at ages 7, 14, and 28 days. The water-cement ratio was 0.55. Concrete tests included slump, compressive strength, flexural strength, and tensile strength. Slump decreased continuously from 92mm (0%RHA) to 75mm (20%RHA). The targeted compressive strength was 30 N/mm^2.Optimum compressive strength, flexural strength, and tensile strength were at the 15% RHA partial replacement level for all the ages:7, 14, and 28 days. At ages 7, 14, and 28 days, compressive strength increased progressively when RHA concentration increased until it got to 15% RHA, and thereafter any increase in the percentage of RHA resulted in a decrease in compressive strength. The compressive strength for 5%,10%,15%, and 20% RHA exceeded the compressive strength of the control for ages 7, 14, and 28 days. A similar trend was observed regarding the tensile strength and flexural strength of RHA-modified concretes [6]. However, the study was limited in that it did not evaluate the density and water absorption performance of the RHA-modified concrete. The study also did not investigate the strength of the RHA-modified concrete beyond 28 days; thus, the long-term compressive

strength of RHA-modified concrete was not known. However, the long-term compressive strength of RHA-modified concrete is critical since strength development of pozzolanic materials, unlike hydraulic materials, takes a longer time [1]; thus, strength tends to develop well beyond the standard 28 days, according to Ranatunga et al. [1]. Also, the study by Sathe et al. [6] did not compute the pozzolanic activity index (PAI) for RHA-modified concrete, nor did it evaluate the sustainability performance of RHA-modified concrete. Hence, the relevance of this current study in addressing the weaknesses raised in the study by Sathe et al. [6].

Thus, from the literature reviewed, the optimum replacement level varies, from as low as 4% RHA replacement level, according to Salama et al. [10] in Egypt, to a 15% RHA replacement level in the study by Sathe et al. [6]. Water-cement ratio also varies, including 0.6 in Kenya, according to Njagi et al. [11], and 0.5 in Nigeria, according to Agboola et al. [5]. The variation in the water-cement ratios, as well as the optimum level, is attributable to the lack of a reference standard to guide the use of RHA when used to partially replace cement, as well as the processing temperature and origin of RHA [9]. Thus, generalizing country- and context-specific findings regarding the mechanical, physical, and sustainability performance of RHA-modified concrete will be inaccurate. Also, the sustainability performance of RHA-modified concrete is rarely supported with empirical evidence, and likewise, the PAI of RHA-modified concrete. Hence, the need for this current study in Ghana as it gives a context-specific empirical account of the performance of RHA-modified concrete, primarily focusing on the physical, mechanical, and sustainability performance.

2.2 Theoretical Basis of The Study

2.2.1 Dilution Theory

This theory advances that partially replacing cement with SCM beyond a certain threshold results in a loss of clinker effect, which leads to a loss of cementitious binder, notwithstanding the gains from pozzolanic and hydraulic activities [33]. Hence, the optimum level of partial replacement is germane for RHA-modified concrete.

2.3 Synthesis of Literature

Based on the theoretical basis and empirical literature reviewed, this current study conceptualizes that partially replacing cement with RHA leads to an increase in the mechanical performance of concrete (compressive strength and flexural strength). However, beyond the optimum level of partial replacement, the mechanical performance of concrete decreases.

3. Materials and Methods

Portland Limestone Cement (PLC), CEM II/B-L, rated strength class 42.5 R, was used in this study. X-ray fluorescence (XRF) analysis was performed to determine the properties of the cement. Standard chemical composition requirements in accordance with BS EN 196-2:1995 included: CaO (Calcium Oxide), Al_2O_3 (Aluminum Oxide), SiO_2 (Silicon Dioxide), Fe_2O_3 (Iron (III) Oxide), SO_3 (Sulfur Trioxide), MgO (Magnesium Oxide), K_2O (Potassium Oxide), Na_2O (Sodium Oxide) [15]. Also, RHA was used as an SCM to replace the PLC partially. XRF analysis was also performed to determine the chemical composition of RHA and to compare it with PLC to ascertain its suitability as an SCM. Potable water, per BS EN 1008:2002, was used for the concrete specimens [16]. The sieve analysis test for aggregates was performed in accordance with BS EN 933-1:2012 and BS 1377-3:1990 to determine the particle size distribution of the aggregates for the concrete specimens [17, 18]. The rice husk was obtained from Ejura, Ghana. Guided by previous studies including Sathe et al. [6] and Njagi et al. [11], the husks were incinerated in a kiln at a controlled temperature of 600 °C for 4 hours to avoid the development of crystalline and less reactive ash [6, 11].

The sample was allowed to cool to room temperature for 2 hours to avoid thermal shock and was milled using electric mill. It was then sieved using a 75 μm sieve and stored in sealed bags. Similar protocols were followed in earlier studies, such as Sathe et al. [6] and Njagi et al. [11].

3.1 Development of RHA-Modified Concrete

A concrete mix design was developed to guide the process (see Table 1) following a laboratory trial mix. Firstly, the control concrete, which had 0% RHA, was prepared to achieve the targeted compressive strength of 20 N/mm^2 at 28 days of curing. In the design, the water-to-cement ratio was selected as 0.55. Then, PLC was partially replaced with RHA in proportions of 5%, 10%, 15% and 20%. A similar proportion was followed by Sathe et al. [6]. Concrete mixes were named RHA 0, RHA 5, RHA 10, RHA 15, and RHA 20, when RHA partially replaced cement (PLC) in proportions of 0%, 5%,10%,15%, and 20%, respectively. Three concrete specimens were tested at each of the ages, 7 days, 28 days, and 56 days, for compressive strength following BS EN 12390-3:2019 using a 150 mm x 150 mm x 150 mm mould [19], and flexural strength following BS EN 12390-5: 2019 using a 150 mm x 150 mm x 700 mm beam [20]. Concrete was mixed and cured in accordance with BS EN 12390-2:2000 [21]. Pozzolanic Activity Index (PAI) (%) was computed using the formula $PAI = \frac{f_p}{f_c} x100$.Where f_c is the compressive strength of the control mix at a particular age of curing, while f_p is the compressive strength of RHA-modified concrete at a particular curing age. According to ASTM [12], PAI should not be less than 75% at 7 days and/or 28 days of curing for classes N, F and C pozzolans [12].

3.2 Assumptions for Carbon Footprint Calculation Based on the Mix Design

The calculation of the carbon footprint of the materials was based on the assumptions that, from cradle-to-gate, according to Abbas and Jabr [22], the carbon emission factor (kg CO_2e/kg) for Portland composite cement (PCC, CEM II) was 0.77[23]; sand was 0.004, crushed rock was 0.007, while water was 0.0003 [22]. The carbon emission factor of RHA was estimated as 0.06 kg CO_2e/kg based on electricity consumption during milling and transportation emissions [24]. In accordance with the carbon accounting principles of IPCC, biogenic emissions from biomass combustion were excluded [25]. Total carbon footprint for each mix ratio was computed using the formula:

$$Total\ CO_2\ foot\ print = \sum(Material\ mass \times Emission\ factor) \quad (1)$$

3.3 Determining the Properties of Materials for Concrete Production

3.3.1 X-Ray Fluorescence (XRF) Test: PLC, As Well As RHA

This is a non-destructive test. It was used to extract the chemical oxide composition of materials, including cement. X-ray fluorescence (XRF) considers the sum of all the elements in the material as the total weight of the material and gives the relative percentage of the elements present in the material [1]. XRF was carried out using the Rigaku NEX CG desktop XRF in this study. The device analyses from $_{11}$Na to $_{92}$U non-destructively. PLC and RHA samples were subjected to XRF to obtain major oxides and elemental constituents using the fundamental parameters method and double determination approach analysis. Four measurement conditions or secondary targets of Aluminum (Al), Molybdenum (Mo), Copper(cu), and Rigaku Crystal 9(RX9) were used to determine the elements and molecules in the samples. The following parameters were used: FP (fundamental parameters) method, an atmosphere of Helium at a flow rate of 0.660 l/min for powder/liquid samples, tube voltage = 50 kV, and tube current = 1.00 mA. The software used was Rigaku Profiling Fitting-Spectra Quant X(RPF-SQX).

3.3.2 Grading Test for Coarse Aggregate

The grading test for coarse aggregates for the concrete mix followed the procedures outlined in BS EN 933-1:2012[18]. The sieves used were: 22 mm, 20 mm, 19 mm, 14 mm, 12.5 mm,10 mm, 4.75 mm, and 2.36 mm.

3.3.3 Grading Test for Fine Aggregate (Sand) for Concrete

The grading test was done in accordance with BS EN 933-1:2012 [18] and classified following BS 882:1992 to belong to zone III (F): well-graded fine sands suitable for most concrete mixes [26,

27]. The sieves used for the grading test were: 5 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm, and 0.075 mm.

Table 1. Mix design for C20 RHA-modified concrete

Mix ID	RHA (Kg)	Cement (Kg)	Sand (Kg)	Crushed rock (Kg)	Water-cement ratio (0.55) (Kg)
(RHA 0)	0	1.51	2.26	4.53	0.84
(RHA 5)	0.08	1.43	2.26	4.53	0.84
(RHA 10)	0.15	1.36	2.26	4.53	0.84
(RHA 15)	0.23	1.28	2.26	4.53	0.84
(RHA 20)	0.30	1.21	2.26	4.53	0.84

4. Results and Discussions

4.1 Fine Aggregates

The fine aggregate for the RHA-modified concrete was classified as well-graded fine sands[18, 27, 28]. Also, with 57.33% passing through the 0.6mm sieve (see Figure 1), the fine aggregate falls within zone III: well-graded fine sands, with reference to BS 882:1992 [26-27];suitable for most concrete mixes [26-27].

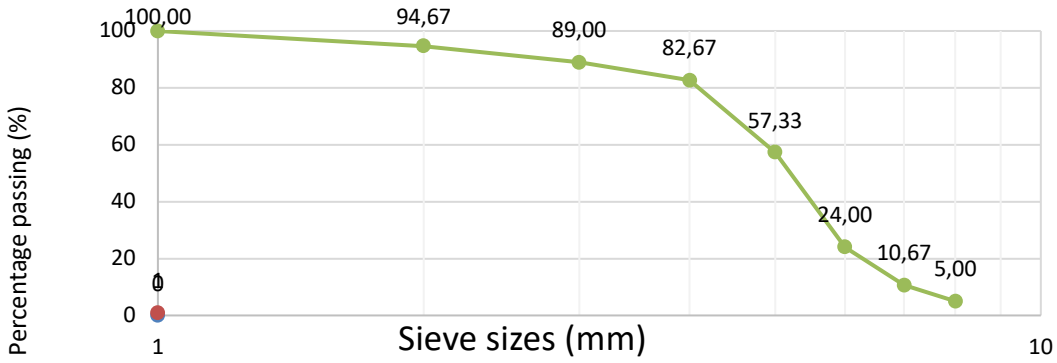


Fig. 1. Gradation curve for fine aggregate

4.2 Coarse Aggregate

The coarse aggregate was well graded with an upper limit not exceeding 20mm and a lower limit not exceeding 4.75mm (see Figure 2). The aggregate met the grading limits for 20mm coarse aggregate for coarse concrete [26-27], suggesting a well-graded coarse aggregate for a concrete mix.

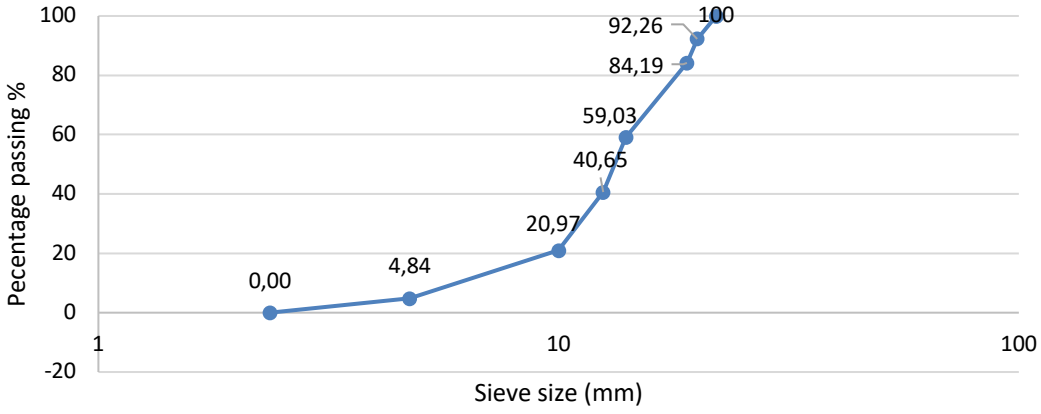


Fig. 2. Gradation curve for coarse aggregates

4.3 Chemical Composition of RHA And Portland Limestone Cement

Since RHA is a pozzolan, there is no universally accepted reference standard for classifying RHA; the provisions of ASTM C618:2019 for classifying Raw or calcined natural pozzolans were followed. ASTM [12] expressed the chemical composition of Raw or calcined natural pozzolans in oxide compounds to include CaO, SiO_2, Al_2O_3, and Fe_2O_3 [12]. The minimum requirement for the sum of (SiO_2+Al_2O_3+Fe_2O_3) should be 70%, and SO_3 should not exceed 4%. The sum (SiO_2+Al_2O_3+Fe_2O_3) of RHA was 94.74%, exceeding the minimum requirement of 70%; CaO concentration was 3.72%, and SO_3 was 0.04%, not exceeding the maximum requirement of 4%. Thus, the locally sourced RHA in Ghana met the requirements for class N and could be classified as a class N pozzolan. This classification is consistent with that of earlier studies, such as those by Umasabor and Okovido [8] and Raheem and Bello [29]. The presence of CaO and SiO_2 in the RHA will lead to the formation of calcium silicate hydrate during hydration, which is responsible for the strength development of concrete [1].

- Objective one: To assess the physical performance of concrete modified with locally sourced rice husk ash as a partial replacement for cement.

Table 2. Main chemical composition of RHA and Portland limestone cement

Material	Chemical composition (%)					
	CaO	Al_2O_3	Fe_2O_3	SiO_2	SO_3	MgO
Cement	51.40	5.89	3.70	25.40	4.01	3.99
RHA	3.72	0.89	1.80	92.05	0.04	0.42

4.4 Physical Performance of RHA-Modified Concrete

4.4.1 Slump of RHA-Modified Concrete

From Figure 3, the slump value decreased with a percentage rise in RHA, an indication of a decrease in workability as the RHA increases in an RHA-modified concrete mix. This affirms the position of Sathe et al. [6] that workability decreases with an increase in RHA concentrations in concrete. According to BS EN [13], BS EN 206-1:2000, true slump is ideal for a concrete mix, and it ranges from 10 mm to 220mm, and it could be further classified based on the level of workability as (S1: 10-40 mm slump: suitable for low-workability applications; S2:50-90: medium workability; up to S5: >220 mm slump, very high workability: suitable for specialized applications [13]. Thus, the level of workability for all concrete mixes were within the range of S2, indicating suitability for medium-workability applications.

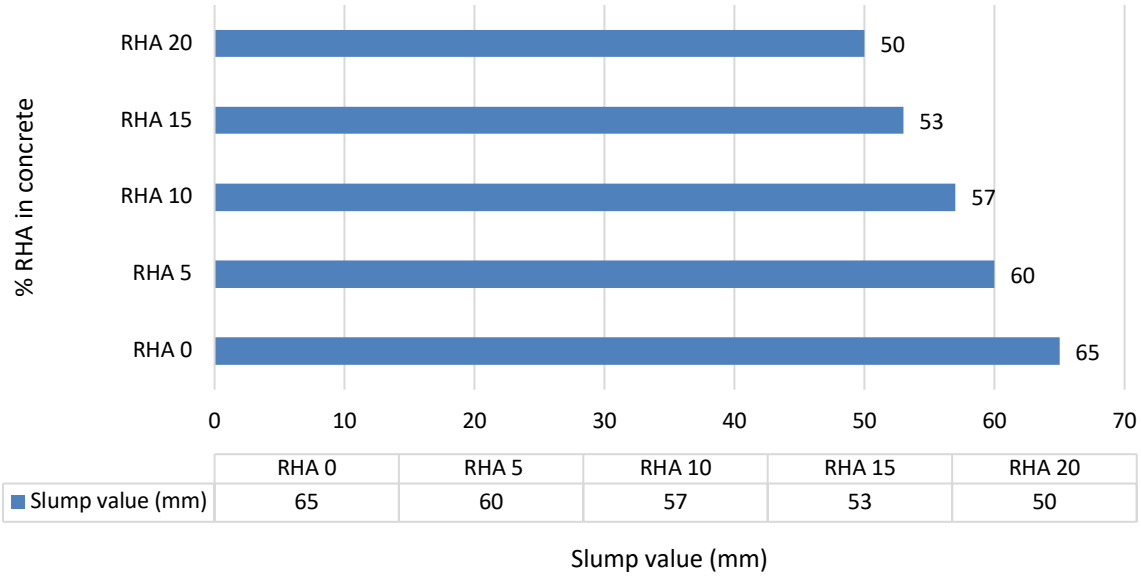


Fig. 3. Slump performance of RHA-modified concretes

4.4.2 Temperature of RHA-Modified Concrete

Thus, from Figure 4, the temperature of freshly mixed RHA-modified concrete ranged from 27 °C to 22 °C. The trend suggests that as RHA concentration increases, temperature decreases from 0% to 20%. This is attributable to the presence of RHA in the concrete mix, which reduces the heat generated during hydration, resulting in lowering the temperature [30,31]. According to the American Concrete Institute [32], the temperature for freshly mixed normal concrete typically ranges between 10 °C and 32 °C, with 20 °C–27 °C being considered the optimal range for normal concrete [32].

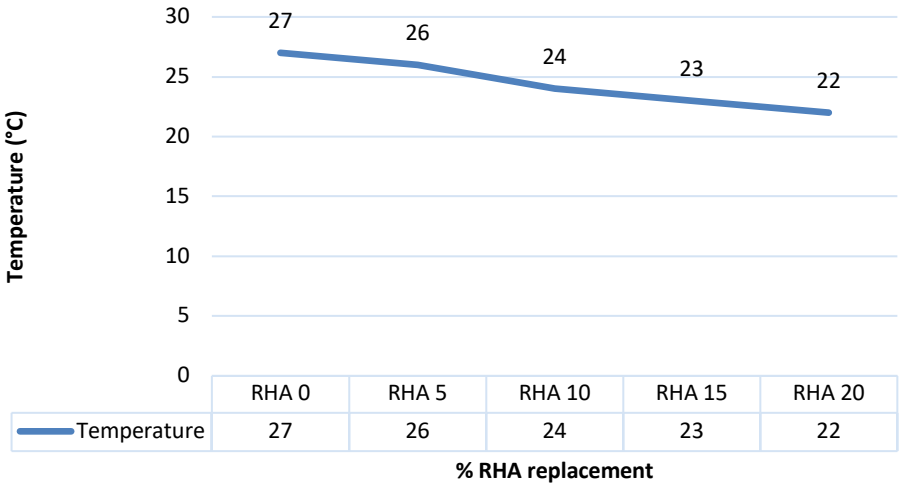


Fig. 4. Temperature of RHA-modified concrete

4.4.3 Density of Concrete

From Table 3, the density of RHA-modified concrete increased with curing age, while for each age of curing, density decreased with an increase in RHA concentration. A similar observation was made by Njagi et al. [11]. Also, the RHA-modified concrete was a normal-weight concrete in accordance with BS EN 206-1:2000, since the average oven-dry density values were more than 2000 kg/m^3 but less than 2600 kg/m^3 [13]. This finding is in congruence with Agboola et al. [5] and Njagi et al. [11]. This is attributable to the view that RHA is lighter in weight, and it is being used to replace cement, which is heavier in weight.

Table 3. Density of RHA-modified concretes

%RHA	7 days	28 days	56 days
	(kg/m^3)	(kg/m^3)	(kg/m^3)
RHA 0	2380	2413	2420
RHA 5	2375	2409	2415
RHA 10	2349	2392	2396
RHA 15	2343	2383	2388
RHA 20	2341	2380	2379

Table 4. Water absorption of RHA-modified concrete

Percentage of partial replacement	28 days (%)	56 days (%)
RHA 0	0.92	0.88
RHA 5	0.79	0.70
RHA 10	0.54	0.44
RHA 15	0.40	0.38
RHA 20	0.32	0.24

From Table 4, water absorption decreased with curing age, and it also decreased as %RHA increased. This is attributable to the presence of RHA, which improves the bonding characteristics of concrete. The reactive amorphous silica of RHA reacts with calcium hydroxide, Ca $(OH)_2$, which is produced during cement hydration. This generates additional calcium silicate hydrate (C–S–H) gel. The C–S–H gel fills voids and capillary pores within the cement matrix, leading to a denser and less permeable microstructure (see [1,5,14]).

- Objective two: To assess the mechanical performance of concrete modified with locally sourced rice husk ash as a partial replacement for cement.

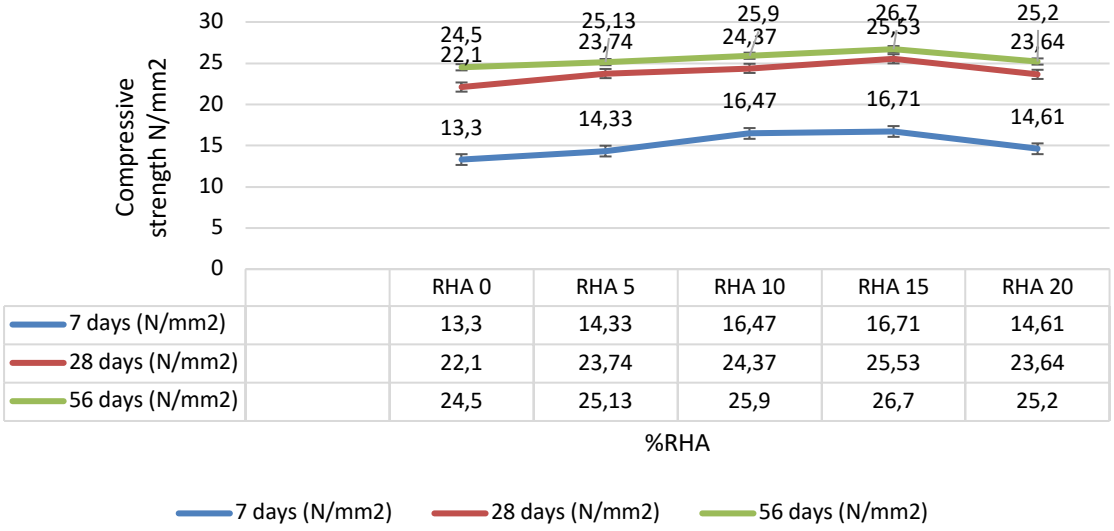


Fig. 5. Compressive strength of RHA-modified concretes

The targeted compressive strength at 28 days of curing was 20 N/mm^2. From Figure 5, for each of the days, compressive strength increased as RHA concentration increased from RHA 5 to RHA 15, and thereafter, any increase in RHA resulted in a drop in compressive strength. This effect is attributable to the dilution effect of concrete (see [33]). Thus, the optimal RHA replacement level was 15%. This value affirmed the 15% RHA replacement level advanced by Sathe et al. [6]; it is an improvement upon the 7.4 % optimum RHA reported by Kumar and Devi [14] and 10% by Agboola et al. [5] in Nigeria. Thus, variation in the optimum RHA replacement level is attributable to the lack of a reference material to guide the processing and use of RHA pozzolans. Again, compressive strength increased across ages, indicating a continuous pozzolanic reactivity as the RHA-modified concrete ages. This same trend was observed by Sathe et al. [6] and Salama et al. [10]. Contrary to the study by Njagi et al. [11] in Kenya, which reported that none of the RHA replacement levels recorded compressive strength values exceeding those of the control, this current study revealed that for all levels of RHA replacement, compressive strength values exceeded those of the control concrete. This could be attributable to the relative variation in the chemical composition of RHA in Ghana compared to Kenya, amidst the varying processing temperatures, among others. Thus, supporting the view by Agboola et al. [5] and Sathe et al. [6] that RHA characterization should be context-specific and generalization of findings will be inaccurate. More so, a one-way ANOVA was performed to ascertain if there is a statistically significant difference in mean compressive strength of RHA-modified concrete across the curing ages:7 days, 28 days, and 56 days. Prior to conducting the one-way ANOVA, the assumptions of normality and homogeneity of variances were evaluated. The Shapiro–Wilk test showed that the compressive strength data were normally distributed for all curing ages (7 days: $W = 0.973$, $p = 0.894$; 28 days: $W = 0.992$, $p = 1.000$; 56 days: $W = 0.990$, $p = 1.000$)). The Levene's test confirmed that the variances were homogeneous across the curing age groups ($F = 0.988$, $df_1 = 2$, $df_2 = 42$, $p = 0.381$), since $0.381 > 0.05$. Thus, the assumptions required for one-way ANOVA were satisfied, and the one-way ANOVA test was deemed appropriate. The ANOVA revealed a statistically significant effect of curing age on compressive strength, $F(2, 42) = 237.373$, $p < 0.001$.

Table 5. PAI at age 28 days

RHA (%)	Compressive Strength (N/mm²)	PAI (%)
RHA 0	22.1	-
RHA 5	23.74	107.42
RHA 10	24.37	110.27
RHA 15	25.53	115.52
RHA 20	23.64	106.97

Also, the Pozzolanic Activity Index (PAI) was computed at 28 days of curing. In accordance with the provisions of ASTM C618:2019, for a class N, PAI should exceed 75% for standard curing at 28 days [12]. From Table 5, the pozzolanic activity index at age 28 days for all levels of RHA replacement exceeded the minimum requirement of above 75% in accordance with ASTM [12], an indication of an excellent pozzolanic reactivity of RHA. The maximum PAI value was 115.52% and corresponds to a 15% RHA replacement level. This affirms the 15% optimum replacement level recorded in this study.

Table 6. Sustainability (carbon footprint reduction) performance evaluation of RHA-modified concrete

Mix ID	RHA (Kg)	Cement (Kg)	Sand (Kg)	Crushed rock (Kg)	Water-cement ratio (0.55) (Kg)	Total CO_2 (kg) (Cradle-to-gate)	CO_2 Reduction compared to Control (%)
RHA 0	0	1.51	2.26	4.53	0.84	1.20	0.0
RHA 5	0.08	1.43	2.26	4.53	0.84	1.15	4.7
RHA 10	0.15	1.36	2.26	4.53	0.84	1.10	8.6
RHA 15	0.23	1.28	2.26	4.53	0.84	1.04	13.6
RHA 20	0.30	1.21	2.26	4.53	0.84	0.99	17.7

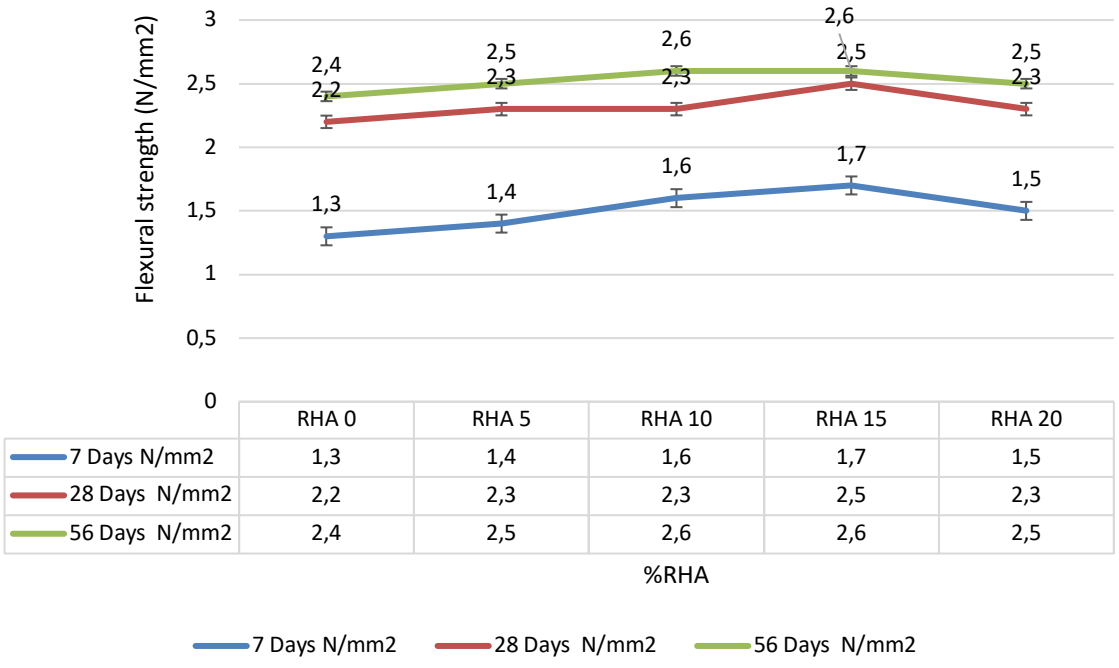


Fig. 6. Flexural strength of RHA-modified concretes

From Figure 6, flexural strength increased progressively up to an optimum level of 15% for ages 7, 28, and 56 days and thereafter decreased as RHA concentration increased. This was found to be consistent with the study by Sathe et al. [6], who also reported 15% RHA replacement level to be optimum, while it contrasts with the study by Agboola et al. [5] in Nigeria, who argued that the

optimum replacement level was 10%. This buttresses the opinion that RHA characterization is context-specific and generalization will be inaccurate owing to varying processing temperatures and the origin of material, among others [5,6]. Also, flexural strength increased progressively from age 7 through to 56 days for each of the RHA replacement levels, an indication of continuous pozzolanic reaction within the RHA-modified concrete as the concrete ages.

- Objective three: To assess the sustainability performance of concrete modified with locally sourced rice husk ash as a partial replacement for cement.

From Table 6, sustainability increased as the RHA concentration increased from RHA 0 to RHA 20. This trend supports the assertion by Kumar and Devi [14], which advanced that sustainability increases as RHA concentration increases. The RHA replacement that maximized sustainability was RHA 20, recording a CO_2 reduction of 17.7% compared to the control. The RHA replacement level that least contributed to sustainability was RHA 5, recording a 4.7% CO_2 reduction compared to the control.

5. Conclusions

The study sought to examine the physical, mechanical, and sustainability performance of concrete modified with locally sourced rice husk ash. The study found that RHA meets the requirements for a class N pozzolan, thus capable of being used as SCM. Also, the chemical composition of RHA revealed the presence of CaO and SiO_2 in the RHA, which are essential for the formation of calcium silicate hydrate during hydration (C-S-H), which is responsible for the strength development of concrete [1]. The slump of the RHA-modified concrete was a true slump, S2:50-90, indicating medium workability. The workability of the concrete decreased as the percentage of RHA replacement increased. The RHA-modified concrete was classified as normal-weight concrete since the average oven-dry density values were more than 2000 kg/m^3 but less than 2600 kg/m^3. Compressive strength and flexural strength of concrete rose progressively to 15% optimum replacement level, beyond which the dilution effect set in. This suggests a considerable potential for sustainable construction in Ghana using RHA. The chemical composition of RHA met the requirements for class N, thus classifying it as a class N pozzolan in accordance with ASTM [12]. In relation to sustainability performance, a 20% RHA replacement level was found to be more sustainable, with a CO_2 reduction of 17.7% compared to the control. The pozzolanic activity index at 28 days for all levels of RHA replacement exceeded the minimum requirement of at least 75% in accordance with ASTM [12], an indication of excellent pozzolanic reactivity by RHA. The maximum PAI value was 115.52% and corresponds to a 15% RHA replacement level, thus affirming the 15% optimum replacement level recommended by this study. The study found an alternative use for rice husks, which are otherwise an agricultural waste material, polluting the physical environment. RHA-modified concrete has the potential to reduce the cost of concrete and the carbon footprint of cement and concrete. Moreover, this study provides the basis for future studies on RHA-modified concrete. Empirically, it has established the chemical composition of RHA from Ejura, Ghana, which hitherto was not known; likewise, the mechanical, physical, and sustainability performance of RHA-modified concrete in Ghana. This study aligns with Sustainable Development Goal 13: Climate Action because partially replacing cement with RHA up to an optimum level of 15% RHA will reduce the demand for Portland cement concrete, with Portland cement known to have contributed to about 10% of carbon emissions in the atmosphere. Future studies could investigate the microstructure analysis of RHA-modified concrete by employing scanning electron microscopy (SEM). Also, since the chemical composition of RHA depends on processing temperature and origin of the rice husk, the findings may not be directly applicable to RHA produced in other regions and countries.

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