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Valorization of Corn Cob Ash as a Sustainable Cement Substitute for Low-Carbon Concrete Block Production

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Abstract. The construction industry is one of the most vicious contributors to global GHG emissions, and the sector has a pivotal role to play in mitigating environmental degradation. This study examines the use of corn cob ash (CCA) as a partial substitute for cement in the production of concrete blocks. The study addresses the urgent need to identify and adopt sustainable alternative materials in the construction industry to mitigate greenhouse gas (GHG) emissions and promote environmental sustainability. CCA was used to partially replace OPC at 0%, 5%, 10%, 15%, and 20% by mass. The EDXRF, mechanical properties, embodied energy, global warming potential, and sustainability index of the composite materials were evaluated for each mix. The study found that the optimum mix of 15% CCA led to a 14.43% reduction in GHG emissions compared to the control sample. The study reveals a complex relationship between compressive strength and carbon footprint in concrete composites. The research provides empirical evidence supporting the valorization of CCA as a viable pozzolan in concrete block production. The adoption of CCA as a partial cement replacement leads to lower embodied energy, enhanced waste management benefits, and a reduced carbon footprint for masonry units.

1. Introduction

The construction industry is a significant contributor to global greenhouse gas (GHG) emissions, with substantial implications for environmental sustainability, resource efficiency, and climate change [1]. The GHG emissions challenge is particularly acute in developing countries like Nigeria, where the urgent demand for infrastructural development intersects with the imperative to decarbonize. In a multi-regional input-output (MRIO) analysis of 44 countries, [2] established that the built environment accounts for approximately 39% of global GHG emissions, with notable intensity in countries reliant on concrete and steel production. To mitigate GHG emissions, [3] suggests the adoption of green construction practices and robust policy frameworks.

Pozzolanic materials are either naturally occurring or artificially produced from agricultural or industrial waste. Natural pozzolanic materials include volcanic ash, diatomaceous earth, and calcined clays [4]. Pozzolans and pozzolanas improve the mechanical performance of concrete and enhance its durability properties [5], thereby reducing the environmental impact of cementitious composites and promoting more sustainable construction practices.

Despite the numerous benefits of CCA incorporation in concrete, CCA applications in cementitious systems are not without limitations. Excessive replacement levels (>15–20%) can impair workability, slow setting times, and reduce early-age strength due to insufficient calcium availability [6]. The variability in CCA's chemical composition due to source and combustion conditions poses a challenge to standardization [7], and it may not allow direct engineering

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application of corn cob ash from any region without thorough investigation. The research optimizes the application of CCA in block production and provides insights into the sustainability potentials of CCA in block production.

2. Materials and experimental procedures

The study utilized CCA, OPC, natural river sand, and water. The natural river sand used for producing the blocks has 80% of the particle size of less than 4.75 mm. The corn cob, CCA and concrete blocks produced are presented in Fig 1. Compressive and flexural strength tests were carried out on six samples of blocks produced with 0%, 5%, 10%, 15%, and 20% of corn cob ash replacement of ordinary Portland cement (OPC) by mass.

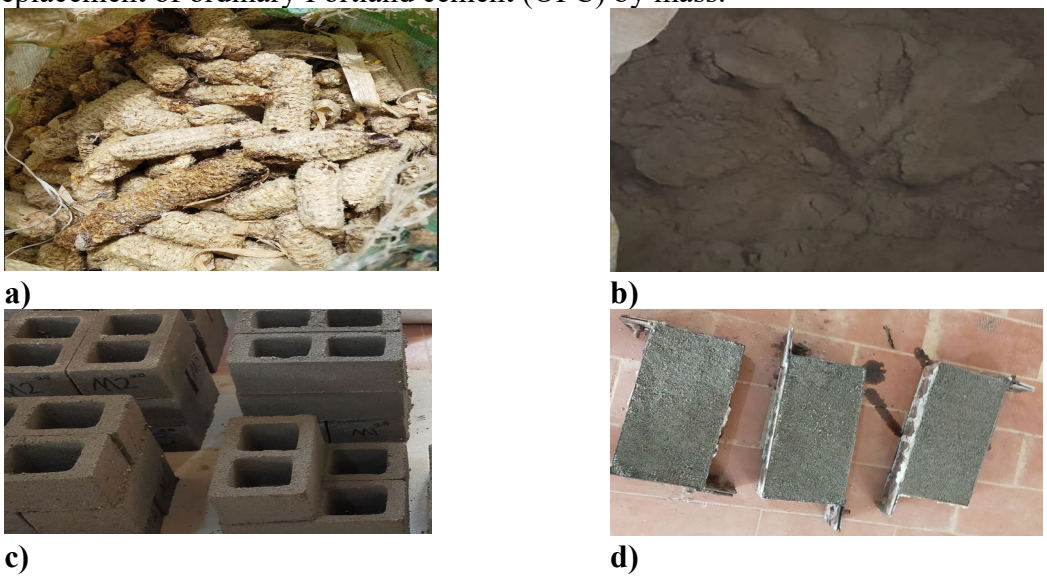


Fig 1: Corn cob ash production and samples prepare for testing: *a) Corn cob; b) Corn cob ash after calcination; c) CCA and OPC concrete blocks; d) CCA and OPC concrete prisms for flexural test*

Embodied energy assessment, Global Warming Impact and Sustainability index

The energy intensity and embodied Carbon emission of the various materials employed in the production process of the concrete block are presented in Table 1, while material haulage distances are shown in Table 2. The Embodied energy of corn cob ash was determined using Equation (1)

$$EE = (1.20)\sum_{i=1}^{n}\left(m_w \times EE_f\right) \quad (1)$$

Where EE= Embodied energy (MJ/kg); m_w = mass of material (kg); EE_f = coefficient of embodied energy.

Table 1: Embodied energy and GHG emissions carbon equivalent coefficients

Materials	**Embodied energy coefficient, EEf (MJ/kg)**	**Embodied carbon equivalent, GWPf ($kgCO_2e/kg$)**	**Source**
Ordinary Portland Cement	5.85; 5.50	0.95	[8], [9]
Sharp sand	0.081	0.0048; 0.0051	[8], [10]
Water	0.01	-	[8]
Transportation, truck by road	2.4 MJ/tkm	0.15 $kgCO_2e$/tkm	[8]

Table 2: Material haulage distance

Material	Place of collection	Transportation distance (km)	Coordinates of location
OPC	Ibese	62.4	6.9528° N, 3.0388° E
River sand	Ota	7.5	6.6926° N, 3.2366° E
Corn cob	Ota	10	6.6888° N, 3.2265° E
Water	Bells University of Tech.	0	6.6859° N, 3.1711° E

Global warming impact is an environmental effect indicator that evaluates the combined impact of different GHG emissions that have the potential to alter the mean temperature of the atmosphere [11]. The global warming impact of utilizing corncob ash was assessed using the Inventory of Carbon and Energy (ICE) following [12]. The global warming potential (GWP) was computed as a function of the mass of material and the coefficient of the greenhouse gas emission in $KgCO_2$ eq/kg using Equation 3. The corn cob ash carbon equivalent coefficient was computed using Equation 2 [8], [10]. The carbon equivalent coefficient of corn cob ash is 5.88 x 10^{-4} $kgCO_2e/kg$. The embodied Carbon equivalent for sand and cement is 0.0051, and 0.95 $kgCO_2e/kg$, respectively [8].

$$EC = 0.021 \times EE \tag{2}$$

$$GWP = (1.15)\sum_{i=1}^{n}\left(m_w \times GWP_f\right) \tag{3}$$

Where EC is the embodied carbon equivalent coefficient in $kgCO_2e/kg$; EE is the embodied energy in MJ/kg; m_w is mass of material in kg; GWP_f is material embodied carbon equivalent coefficient in $kgCO_2e/kg$.

The sustainability index is the measure of the environmental impact of the concrete in relation to the characteristic compressive strength [13], [14]. Sustainability Index is expressed in two forms as the characteristic compressive strength compared to kg of Carbon dioxide equivalent emissions as presented in Equations 4 and 5 [13][14], [15], [16].

$$SI = \frac{\mathrm{f_{cu}}}{\mathrm{GWP}} \tag{4}$$

$$SI = \frac{GWP}{\mathrm{f_{cu}}} \tag{5}$$

Where SI in the Sustainability Index (N/mm^2.kgCO2e or $MPa/kgCO_2e$), f_{cu} is the characteristic compressive strength at 28 days (N/mm^2 or MPa); GWP is global warming potential ($kgCO_2e$).

3. Results and Discussions

Chemical characteristics of corn cob ash (CCA)

Energy Dispersive X-ray Fluorescence (EDXRF) analysis was performed to investigate the elemental and oxide constituents of corn cob ash (CCA) and Ordinary Portland Cement (OPC). The EDXRF spectrum of CCA indicated Zirconium Zr, and Strontium Sr, with a peak atom amount reaching 22000 cps/mA. Details of the principal constituent elemental oxides of the CCA and OPC measured in % weight as obtained in the EDXRF spectrum are shown in Table 3.

Table 3: Chemical analysis of CCA and OPC

Constituents	SYMBOLS	OPC (%)	CCA (%)
Calcium Oxide	CaO	49.60	2.98
Strontium Oxide	SrO	9.70	9.70
Silica	SiO_2	13.13	47.29
Aluminium Oxide	Al_2O_3	2.57	13.70
Iron Oxide	Fe_2O_3	0.64	2.32
Magnesia	MgO	1.01	5.04
Sulphur Trioxide	SO_3	0.88	0.84
Phosphorus Pentoxide	P_2O_5	0.47	4.88
Potassium Oxide	K_2O	0.21	7.80

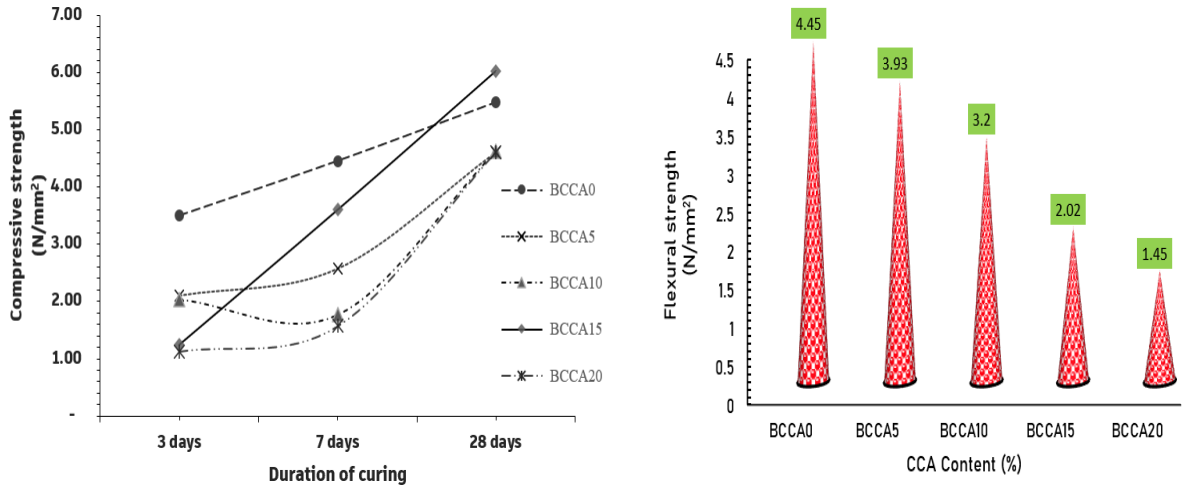
The Calcium Oxide (CaO) content in CCA and OPC is approximately 2.98% and 49.6%, respectively. The low CaO content in CCA suggests that CCA may not substantially contribute to early strength development. Thus, in an OPC and CCA binder blend, the OPC is responsible for the early development of strength.

Effect of corn cob ash on compressive and flexural strength of concrete blocks

The results of the compressive and flexural strength tests are presented in Fig. 2. From the figure, the compressive strength of all the concrete block samples increased with curing age, with the highest value for each sample at the 28-day test. This finding aligns with the results of [17], [18], which indicate that pozzolans enhance the compressive strength of concrete. The flexural strength test results show a steady decrease in flexural strength with an increase in CCA content (Fig. 4b).

Embodied energy, Global Warming Impact and Sustainability index

The result of the embodied energy of corn cob ash is presented in Table 4, while Table 5 and Fig. 3 show the embodied energy of the control concrete. The embodied energy is less than the 1.35 MJ/kg obtained for corn cob ash by Abubakar et al. [10] . This result is similar to the 0.97 MJ/kg provided for 1:5 mortar by Hammond and Jones [8] in the Inventory of Carbon and Energy (ICE). The result in Fig. 4 indicates a steady reduction in global warming potential (GWP) with the increase in CCA content reaching 19.23% at the 20% replacement of OPC.



a) **b)**

Fig. 2: Effect of corn cob ash on the strengths of concrete blocks: a) compressive strength; b) flexural strength

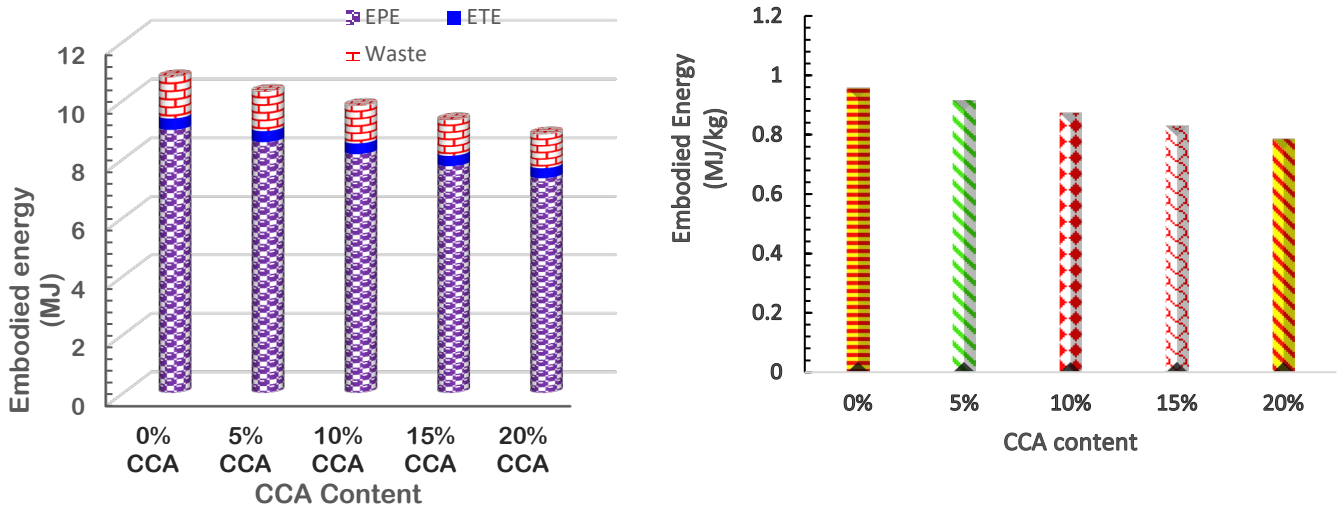
Table 4: Embodied energy of Corn cob ash

Materials	Mass (kg)	Energy Coefficient (MJ/kg)	Transportation distance	Transportation coefficient (MJ/tkm)	Energy sum (MJ)	20% waste (MJ)	Total
Corn cob	20	0.0	10	2.4	0.48	0.096	0.576
Thus, energy coefficient of Corn cob ash per kg							0.0288 MJ/kg

Table 5: Embodied energy of control concrete 0% corncob ash

Materials	Mass (kg)	Energy Coefficient (MJ/kg)	Transportation distance (km)	Transportation coefficient (MJ/tkm)	Energy sum (MJ)	15% waste (MJ)	Total (MJ)
Corn cob	0	0.0	0	2.4	0	0	0
OPC	1.5	5.5	62.4	2.4	8.47	1.27	9.74
River sand	9	0.081	7.5	2.4	0.891	0.134	1.023
Water	0.75	0.01	0	0	0.0075	0.0011	0.0086
Total	11.25				9.366	1.405	10.77
Thus, energy coefficient of concrete mix per kg (MJ/kg)							0.957

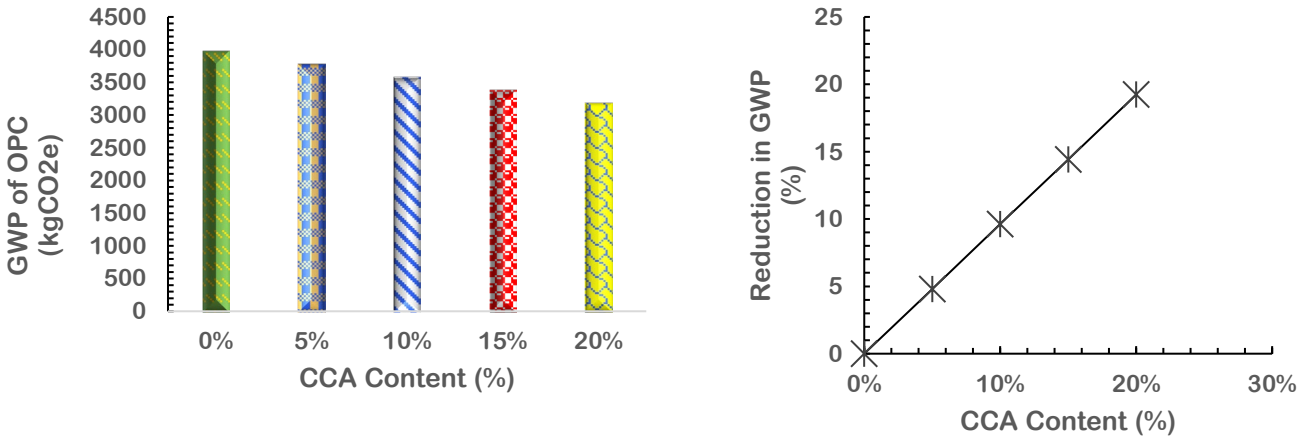
Sustainability Index serves as a pivotal metric in advancing eco-efficient concrete technologies. The Sustainability Index, SI, was assessed using the ISO 14064-1 [12]. The result of the analysis of sustainability Index is shown in Fig. 5.



(a) Embodied energy constituents (MJ)

(b) Embodied energy per unit mass

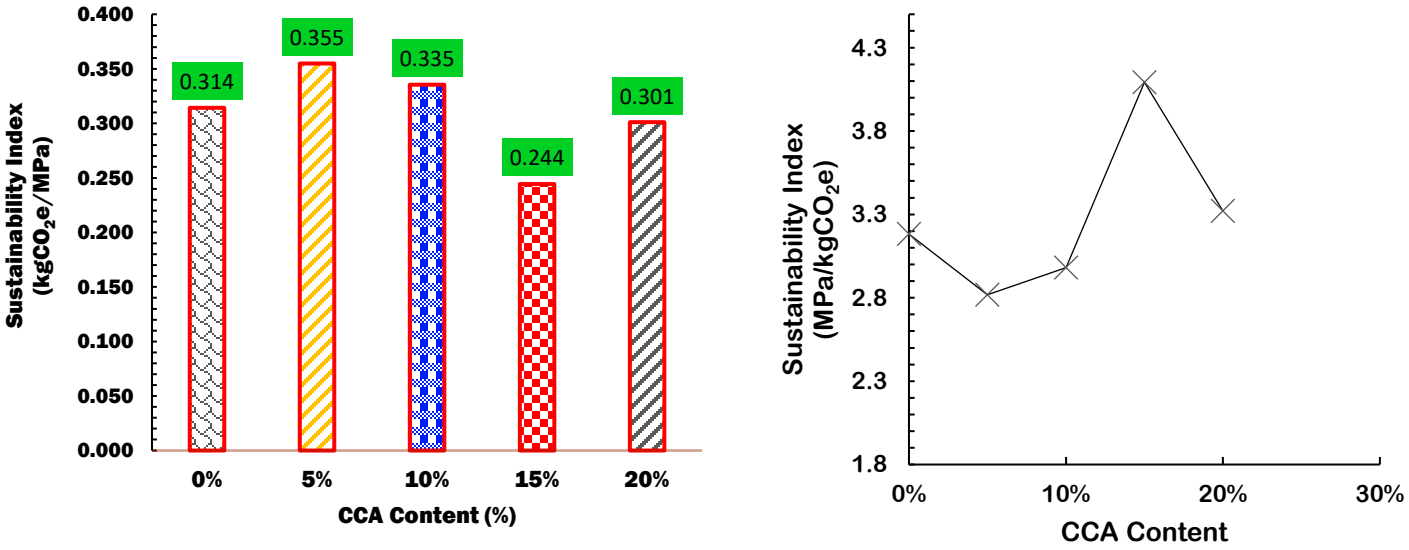
Fig. 3: Impact of corn cob ash on embodied energy of concrete



(a) Global warming potential (b) Percentage reduction in GWP

Fig. 4: Impact of CCA on global warming potential of concrete

The results highlight the complex relationship between compressive strength and the global warming potential (GWP) of concrete. The substitution of OPC with CCA initially led to a decline in the Sustainability Index at 5% and 10% replacement levels, indicating a reduction in carbon efficiency. However, at 15% replacement, the Sustainability Index improved significantly by 28.61%, suggesting that moderate inclusion of CCA can optimize both mechanical and environmental performance.



(a) GHG emission per unit MPa concrete (b) SI effect on strength gains per unit GHG

Fig. 5: Impact of CCA content on Sustainability Index.

Conclusion

This study explored the use of Corn Cob Ash (CCA) as a replacement for Ordinary Portland Cement (OPC) in concrete blocks. Chemical analysis revealed that CCA meets the requisite pozzolanic standards, with a significant content of silicon dioxide. CCA-based concrete exhibited initial strength retardation but showed enhanced strength at 28 days, with a 15% substitution, driven by secondary hydration resulting from CCA's pozzolanic properties. Additionally, increasing CCA content resulted in reduced energy consumption and a 14.43% decrease in global warming potential (GWP) at optimal levels. While lower substitution levels indicated a decline in

sustainability, a 15% replacement improved the sustainability index by 28.61%. The study emphasizes that utilizing agricultural waste, such as CCA, can effectively reduce the carbon footprint of concrete while maintaining its structural integrity, thereby promoting sustainable concrete design through innovative material utilization.

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