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Economic Feasibility of Rice Husk Ash Blended Cement: Cost, Energy and Market Impacts in Nigerian Cement Production

T. Bello[1*], A. A. Raheem[2], I. O. Oguntola[3]

[1,2,3]Ladoke Akintola University of Technology, Ogbomoso.

[1]taofiqbello4@gmail.com, [2]aaraheem@lautech.edu.ng, [3]oguntolaisaiah@yahoo.com
*Corresponding Author: taofiqbello4@gmail.com

ABSTRACT

Cement production contributes an estimated 7-8% of global CO_2 emissions, largely due to energy-intensive clinker manufacture. In addition, rising electricity tariffs in Nigeria and increasing cement demand highlight the urgency for low-carbon, cost-effective alternatives. Rice husk ash (RHA), an agricultural by-product rich in amorphous silica, presents a viable supplementary cementitious material capable of reducing clinker use, energy consumption, and production cost. In this study, RHA sourced from a rice mill in Offa, Nigeria, was characterized using X-ray fluorescence, X-ray diffraction, and loss-on-ignition analyses to verify chemical suitability. Portland limestone cement clinker was partially replaced with 10-50% RHA, and grinding energy was measured across incremental batches and scaled to per-ton requirements. Cost modeling incorporated clinker price (₦97,500/ton), electricity tariff (₦209.50/kWh), and a conversion factor of 21 bags per ton, while sensitivity analysis evaluated clinker prices (₦82,500.00-₦120,000.00) and electricity tariffs (₦150-₦300/kWh). RHA exhibited strong pozzolanic characteristics (SiO_2 = 84.14%; Al_2O_3 = 3.35%; Fe_2O_3= 1.02%; 73.27% amorphous content). Grinding energy decreased significantly from 221.68 kWh/ton (M0) to 104.86 kWh/ton (M50). Production cost per bag declined from ₦6,854.38 for the control to ₦3,367.53 for M50, with corresponding reductions in estimated market price from ₦9,500 to ₦6,013. Long-term compressive strength improved at moderate substitution levels, with the M30 blend achieving 68.6 MPa at 360 days, outperforming the control (67.8 MPa). Sensitivity results indicated robust cost savings of ₦850.00-₦4,200.00 per bag across market conditions. Overall, RHA-blended cements demonstrate substantial economic and environmental advantages, confirming RHA as a feasible SCM for large-scale adoption in Nigeria.

Keywords: Rice husk ash, clinker replacement, grinding energy, production cost, sustainable cement, Nigeria

1. INTRODUCTION

Cement production remains one of the world's most energy-intensive and carbon-intensive industrial activities, contributing an estimated 7-8% of global anthropogenic CO_2 emissions (IEA, 2023). The manufacturing process requires substantial thermal and electrical energy for clinker calcination and finish grinding, and in developing economies such as Nigeria, this demand continues to rise due to rapid urbanization, population growth, and infrastructural expansion (Akinwumi et al., 2020; Oni & Adegoke, 2020). Reducing the clinker factor through the use of supplementary cementitious materials (SCMs) has therefore become a key mitigation strategy consistent with global low-carbon pathways (Scrivener et al., 2018; Gartner & Hirao, 2015; Thomas & Wilson, 2021). Recent advances further highlight SCMs as central to decarbonizing cement, not only through material substitution but also through improved microstructural engineering, durability enhancements, and reduced lifecycle emissions (Juenger et al., 2019; Miller et al., 2016).

Rice husk ash (RHA), a by-product of rice milling, has been widely recognized for its high amorphous silica content, strong pozzolanic reactivity, and capacity to enhance long-term performance in cementitious systems. Foundational work established the pozzolanic capacity of RHA (Mehta, 1992; Bui et al., 2005;

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Faculty of Engineering and Technology,
Kwara State University, Malete. P.M.B. 1530 Ilorin,
Kwara State, Nigeria.

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Ganesan et al., 2007), and more recent studies have reaffirmed its microstructural and durability benefits across a wide range of mix designs (Adesina, 2020; Ali et al., 2019; Antiohos et al., 2007). Nigeria generates large volumes of rice husk ash annually at about 2.46 million tons according to FAO (2023), most of which is disposed of through open burning, contributing to particulate emissions and environmental degradation (Ogunjimi & Igwe, 2021). Utilizing RHA as an SCM therefore offers dual sustainability benefits: reducing problematic agricultural waste and lowering dependence on clinker, traditionally the most energy-intensive and cost-intensive component of cement production process (Benhelal et al., 2013; Dorbane et al., 2022; Fang & Wong, 2019).

Although extensive research has addressed the mechanical, durability, and microstructural performance of RHA-blended cement systems (Isaia et al., 2003; Abdul Razak & Chai, 2010; Ali et al., 2019), far fewer studies have evaluated the economic feasibility of RHA within African production contexts. This gap is particularly important given the rising electricity tariffs, fluctuating clinker prices, and persistent operational constraints in Nigeria's cement industry (Oyedepo et al., 2014; Akinwumi et al., 2020; Oni & Adegoke, 2020). Addressing this gap, the present study evaluates the economic, energy, and performance implications of replacing 10-50% of PLC clinker with RHA produced under Nigerian conditions. By integrating cost, grinding-energy analysis, sensitivity testing, and long-term strength assessment, this study provides a comprehensive evaluation of RHA's viability for large-scale adoption in sustainable cement manufacturing.

2. MATERIALS AND METHODS

The details of materials used and methods employed in this study such as material characterization, production and analysis is described in this section.

2.1 Materials

Rice husk ash (RHA) used in this study was obtained from Hillcrest a local rice processing mill at Offa, Kwara state Nigeria, where rice husks are burned in a temperature-controlled furnace during routine milling operations particularly for generating steam for the rice parboiling process stage. The furnace operated between 700 and 800°C that has been reported to yield amorphous content in RHA (Fapohunda et al., 2017). To ensure high pozzolanic reactivity, the ash was collected fresh from freshly discharged combustion heaps while still warm, minimizing contamination from soil, carbonized husk fragments, or prolonged exposure to atmospheric moisture. This approach aligns with best practices for obtaining high-quality RHA in literature (Mehta, 1992; Bui et al., 2005; Ganesan et al., 2007). The collected ash was allowed to air-cool and passed through a fine sieve (75μm) to remove coarse residues before laboratory experimentation and further use as a supplementary cementitious material (SCM).

2.2 RHA Characterization

To verify the chemical and mineralogical suitability of the RHA for use as a pozzolanic material, the ash was characterized using three standard analytical techniques. X-ray fluorescence (XRF) was used to determine its oxide composition, particularly silica, alumina, and iron contents. X-ray diffraction (XRD) was performed to assess the proportion of amorphous versus crystalline silica, which governs pozzolanic reactivity. Loss-on-ignition (LOI) analysis was also conducted to quantify unburnt carbon and volatile residues. All these were carried out in line with existing standards procedures such as ASTM E1621, (2021). Altogether, these tests will provide a clear indication of the ash's reactivity and suitability for clinker substitution.

2.3 Mix Proportions

Portland Limestone Cement (PLC) clinker, gypsum and standard sand were sourced from a Nigerian cement plant at Ewekoro, Ogun state, Nigeria. Gypsum content was held constant at 5% across all mixes, consistent with industrial practice and SCM blending guidelines (Scrivener et al., 2018; Juenger et al., 2019). RHA replaced PLC clinker at substitution levels of 10-50%. Mix M0 served as the control sample containing only clinker (95%) and gypsum (5%). The mix design adopted in this study is as presented in Table 1.

Table 1: Mix proportions of PLC and RHA cement blends

Mix ID	RHA Content (% wt.)	PLC Clinker Content (% wt.)	Gypsum Content (% wt.)	Total (% wt.)
M0	0	95	5	100
M10	10	85	5	100
M20	20	75	5	100
M30	30	65	5	100
M40	40	55	5	100
M50	50	45	5	100

2.4 Grinding Energy Measurement

Grinding energy was measured using incremental grinding of 1, 2, 3, 4, 6, 8 and 10 kg batches of each blend. The ball mill used for the grinding is a 10000 g (10kg) capacity Model BB27 with a 0.75 kW operating power having a speed of 44 RPM at a 95% efficiency. Energy consumption was recorded via an inline power-logging system connected to the grinding mill. The small-batch energy values were converted to per-ton energy requirements using a mass-scaling factor validated by Napier-Munn (2014). This approach aligns with previous SCM grindability studies (Chindaprasirt et al., 2008; Ali et al., 2019). The grinding energy data were later used to compute energy-related cost using the present Nigerian industrial tariff rate of ₦209.50/kWh obtained from Ibadan Electricity Distribution Company (IBEDC) as at 2025.

2.5 *Cost Modeling and Sensitivity Analysis*

Direct production cost was modeled by incorporating the major cost components involved in cement manufacturing. The analysis accounted for the prevailing clinker price of $65 per ton (≈ ₦97,500/ton, IndexBox 2025), while the cost of RHA was assumed to be zero, reflecting its availability as an agricultural waste by-product. Gypsum costs were treated as part of the existing clinker-based plant operation. Energy-related expenses were calculated from the measured grinding energy demand and the applicable industrial electricity tariff. All cost outputs were finally converted to a per-bag basis using a production factor of 21 bags per metric ton of cement. The sensitivity analysis evaluated clinker price ranges of $55-$80/ton equivalent to ₦82,500.00 - ₦120,000.00 and electricity tariffs of ₦150 - ₦300/kWh, reflecting real-world volatility in Nigerian cement markets (Oyedepo et al., 2014; Akinwumi et al., 2020; Mikulčić et al., 2016). Model outputs included cost per ton, cost per bag, and estimated market price.

3. RESULTS AND DISCUSSION

The results from material characterization, energy measurement and cost analysis is presented in this section.

3.1 *Chemical and mineralogical suitability of RHA for cement blending*

The chemical composition and mineralogical characteristics of the RHA confirm its suitability as a highly reactive supplementary cementitious material as presented in Table 2. The ash contains 84.14 wt% SiO_2, with minor contributions from Al_2O_3 (3.35 wt%) and Fe_2O_3 (1.02 wt%). The summation of important oxides silica, Alumina and Ferric (ΣSAF) value of 88.51% exceeds ASTM C618 requirements and is consistent with high-quality pozzolans reported in previous studies (Mehta, 1992; Bui et al., 2005; Ganesan et al., 2007). The LOI value of 8.22% reflects moderate residual carbon, characteristic of high-temperature rice husk combustion. Figure 1 presented the XRD of the RHA. The XRD result showed approximately 73.27 wt% amorphous content,

Table 2: Oxide composition of RHA

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	TiO_2	K_2O	Na_2O	P_2O_5	LoI	∑SAF
84.14	3.35	1.02	0.43	0	1.01	0.4	0.37	0.1	0.71	8.22	88.51

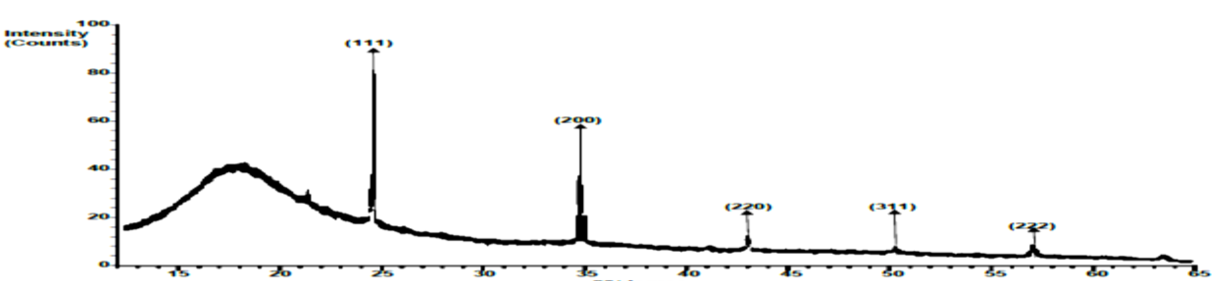

Figure 1: X-Ray Diffraction of RHA

indicated by the broad diffuse hump typical of amorphous silica. The few low intensity peaks corresponded to graphite, hematite and calcite. This high amorphous-phase proportion strongly supports pozzolanic activity, aligning with prior characterizations of high-reactivity RHA (Chindaprasirt et al., 2008; Isaia et al., 2003). Together, the XRF, XRD, and LOI results demonstrate that the RHA possesses the chemical and mineralogical attributes necessary for clinker replacement in blended cement systems.

3.2 Influence of RHA substitution on clinker consumption and production cost

The direct cost per 50 kg bag is illustrated in Figure 2 showing a decrease from ₦6,854.38 for the control cement to ₦3,367.53 for M50. This near-linear relationship between RHA substitution and cost reduction mirrors global trends in SCM-blended cements, where clinker reduction provides the primary cost advantage (Benhelal et al., 2013; Miller et al., 2016). The sensitivity analysis results, reported in Table 3, further show that blended cements remain highly cost-competitive even when clinker market prices vary between \$55 and \$80 corresponding to ₦82,500.00 and ₦120,000.00 per ton. This aligns with previous assessments highlighting the economic resilience of SCM-based cements under unstable market conditions (Oyedepo et al., 2014; Akinwumi et al., 2020).

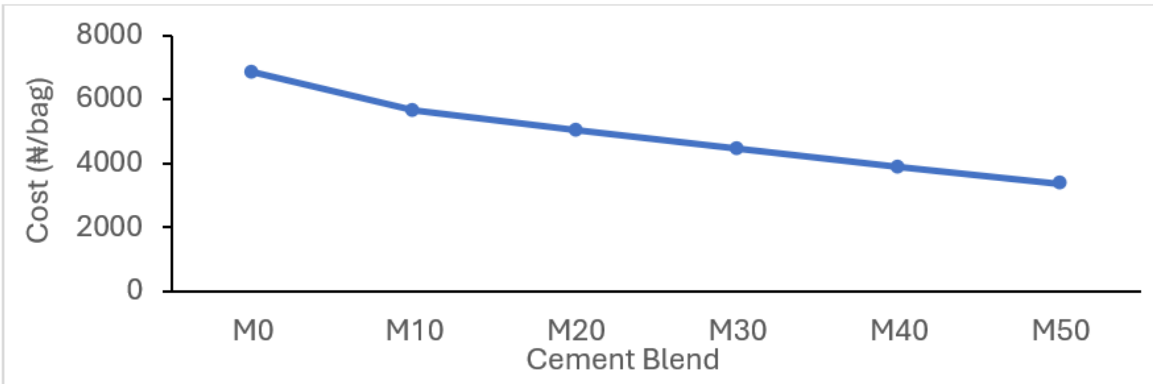

Figure 2: Direct Cost Per Bag of Cement

Table 3: Clinker Contribution to Production Cost

Mix ID	Clinker Mass (kg/ton)	Clinker Cost (₦/t)
M0	1000	97500
M10	900	87750
M20	800	78000
M30	700	68250
M40	600	58500
M50	500	48750

3.3 Sensitivity Analysis of Cost Savings Under Varying Price Conditions

A sensitivity analysis was performed to examine the robustness of the cost savings achieved through RHA substitution under fluctuating clinker and electricity prices. Three price environments were evaluated: Low input cost scenario (₦150/kWh electricity; \$55/ton clinker), Base case scenario (₦209.50/kWh; \$65/ton clinker), and High input cost scenario (₦300/kWh; \$80/ton clinker). The resulting cost-savings range for each blend is summarized in Table 4. The sensitivity analysis demonstrates the strong robustness of the economic gains associated with RHA substitution across all pricing environments. Even under low input-cost conditions, all RHA blends generated notable savings, with M50 achieving nearly ₦3,700/bag in reduced production cost. As input prices increase, the economic advantage of RHA becomes even more pronounced. Under high input-cost conditions, cost savings ranged from ₦1,450–₦1,700/bag (M10) up to ₦3,750-₦4,200/bag (M50). This widening gap reflects the fact that clinker and electricity two of the most cost-intensive variables in cement manufacture are significantly reduced in RHA-blended systems.

These findings agree with broader SCM economic studies (Benhelal et al., 2013; Miller et al., 2016; Akinwumi et al., 2020), which highlight that any increase in clinker or energy prices disproportionately penalizes traditional cement while enhancing the competitive edge of SCM-based blends. In contexts like Nigeria, where electricity tariffs frequently fluctuate and supply is often unreliable (Oni & Adegoke, 2020), and where clinker prices are sensitive to global logistics and fuel costs, adopting RHA offers manufacturers a strong hedge against cost volatility.

Most importantly, the sensitivity analysis confirms that RHA-blended cement remains consistently more economical than pure PLC across all scenarios evaluated. This economic resilience combined with reduced grinding energy, lower CO_2 emissions, and strong long-term mechanical performance positions RHA-enhanced cement as a strategically advantageous material for sustainable, affordable construction.

3.4 *Grinding energy reduction and economic implications*

Grinding energy reductions were substantial and directly correlated with RHA substitution levels. The energy requirement dropped from 221.68 kWh/ton in M0 to 104.86 kWh/ton in M50. This is illustrated in Figure 3. Under the current electricity tariff of ₦209.50/kWh, the energy-related cost decreased from ₦46,441.96/ton (M0) to ₦21,968.17/ton (M50), producing savings of ₦15,330 to ₦24,474 per ton across the RHA blends. These findings complement earlier reports by Napier-Munn (2014) and Chindaprasirt et al. (2008), which attribute ease of grinding of SCMs like RHA to their lower hardness compared to clinker. Given Nigeria's rising electricity costs and grid instability (Oni & Adegoke, 2020), the observed energy reduction represents a strategically important advantage for local cement manufacturers.

Table 4: Summary of Sensitivity Analysis: Cost Savings (₦/bag) Across Market Conditions

Mix	Low Input Costs	Base Case	High Input Costs
M10	850 – 1,250	1,194	1,450 – 1,700
M20	1,300 – 1,900	1,817	2,000 – 2,300
M30	1,900 – 2,600	2,394	2,650 – 3,000
M40	2,400 – 3,200	2,982	3,250 – 3,600
M50	2,900 – 3,700	3,487	3,750 – 4,200

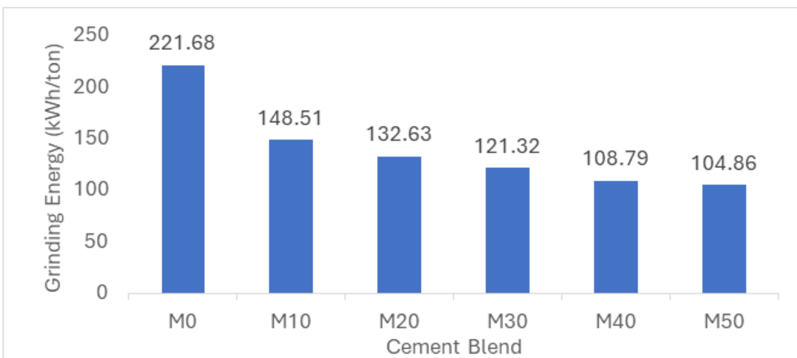

Figure 3: Effect of Clinker Substitution with RHA on the Grinding Energy

3.5 *Combined cost savings and estimated market prices*

The combined influence of clinker reduction and grinding-energy savings resulted in a substantial decrease in the total estimated market price of RHA-blended cement. As shown in Figure 4, the direct production cost per bag decreased from ₦6,854.38 for the control (M0) to ₦3,367.53 for M50, while the estimated market price decreased from ₦9,500/bag (M0) to ₦6,013.25/bag (M50). These reductions correspond

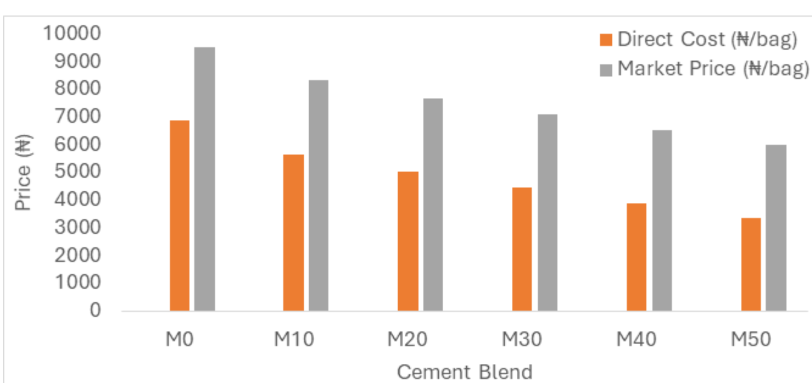

Figure 4: Direct Cost and Market Cost Per bag

to total cost decreases of 12.6%, 19.1%, 25.2%, 31.4%, and 36.7% for M10-M50 respectively. The magnitude of the cost reduction aligns with SCM economic modeling in developing economies (Dorbane et al., 2022; Fang & Wong, 2019) demonstrating a strong economic incentive for clinker replacement.

3.6 Long-term compressive strength performance

Long-term compressive strength results indicate that moderate RHA substitution (10-20%) enhances strength beyond that of the control cement before 360 days. The compressive strengths at 56, 90, 180, and 360 days, are as presented in Figure 5. The compressive strength performance from 56 days indicates a similar strength value between the control (M0), M10 and M20 blends of cement. However, as curing progresses beyond 56 days with continuous pozzolanic reaction, the M20 mortar stood out with the highest compressive strength through 90, 180 and 360 days. A similar but lower strength trend was observed in the M10 mortar. While the M30 mortar exhibited a lower compressive strength of 54.6 MPa compared to 64.4 MPa (M20) and 64.7 MPa (M0 and M10) at 56 days, it surpasses that of control at a point between 90 and 180 days through 360 days.

At 360 days, M10, M20 and M30 achieved 71.1, 75.9 and 68.6 MPa respectively, surpassing the control

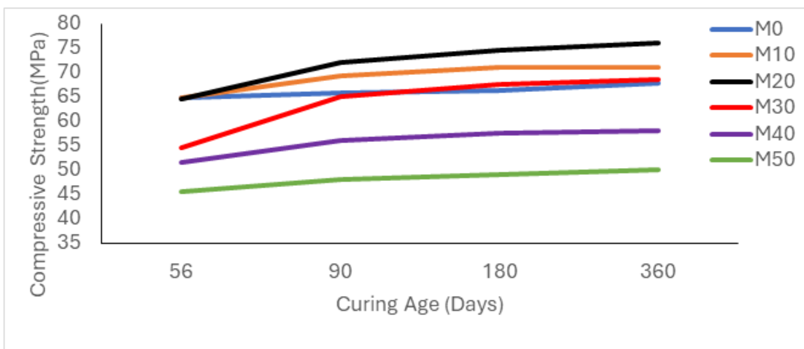

Figure 5: Long-Term Compressive Strength of PLC and RHA Blended Cement Mortar

(67.8 MPa). This performance is attributed to extended pozzolanic activity, as widely reported in RHA literature (Isaia et al., 2003; Abdul Razak & Chai, 2010; Ganesan et al., 2007). Although higher RHA levels (≥30%) reduced early strength, long-term values remained structurally adequate and consistent with SCM behavior (Ali et al., 2019; Juenger et al., 2019).

3.7 Integrated assessment of cost, energy, and performance

The combination of reduced clinker demand, lower grinding energy, and comparable or superior long-term strength establishes RHA as a highly viable SCM for sustainable cement production, as presented in Figure 6. When economic savings are considered alongside CO_2 reduction potential and improved durability, RHA-

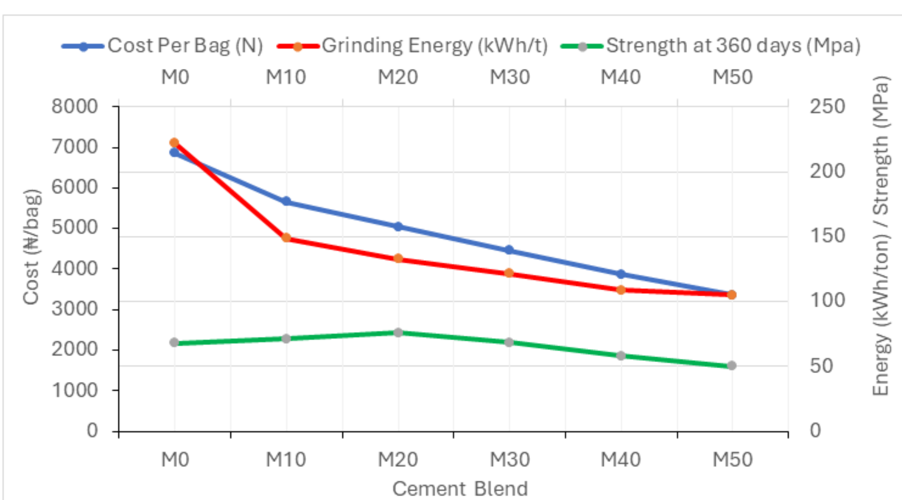

Figure 6: Integrated Cost-Energy-Strength Map for RHA-Blended Cement

blended cement performs favorably against conventional PLC. The findings align with emerging global strategies for low-carbon cement production, which emphasize the use of local, waste-derived SCMs to reduce environmental impact and production cost simultaneously (Scrivener et al., 2018; Gartner & Hirao, 2015; Habert et al., 2011). Overall, the results underscore the strong synergy between economic savings, energy reduction, and long-term mechanical performance in RHA-blended cement.

4. CONCLUSION

In this study, the use of rice husk ash as a viable and economically advantageous supplementary cementitious material for cement production in Nigeria was demonstrated. The chemical and mineralogical properties of the RHA, particularly its high amorphous silica content, support strong pozzolanic reactivity. Incorporating RHA at 10-50% clinker replacement significantly reduces clinker consumption, grinding energy requirements, and total production cost. Estimated market prices decrease by 12.6–36.7%, offering clear financial benefits for producers and consumers. Long-term compressive strength results indicate that blends incorporating 10-30% RHA outperform conventional PLC, confirming their suitability for structural applications. Sensitivity analysis further shows that RHA-blended cements remain cost-competitive under varying electricity and clinker price conditions. These findings affirm the environmental, economic, and performance advantages of adopting RHA in large-scale cement production, particularly in resource-constrained and energy-intensive settings such as Nigeria.

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