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# TERNARY BLENDED SUSTAINABLE CONCRETE INCORPORATING RICE HUSK ASH, WILD VINE ASH AND POLYCARBOXYLATE ETHER SUPERPLASTICIZER

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**Abstract:** *This study examines the synergistic influence of rice husk ash (RHA) and wild vine ash (WVA) as supplementary cementitious materials (SCMs), combined with a polycarboxylate ether superplasticizer (PCE-SP), on the fresh, mechanical, and durability performance of Grade 25 concrete. Binary systems (RHA+SP, WVA+SP) and a ternary system (RHA+WVA+SP) were evaluated through slump, compressive strength, splitting tensile strengths, and water absorption tests.. X-ray fluorescence (XRF) analysis confirmed RHA's high silica content (73.8%) and WVA's significant calcium (16.2%) and magnesium (9.3%) contents, indicating their complementary pozzolanic–hydraulic potential. The Ternary blend consistently outperformed the control, achieving ≈34–35 MPa compressive strength, ≈3.5–3.6 MPa splitting tensile strength, and ≈2.6–3.9% water absorption at 28 days, representing 10–25% improvements over the control. Durability performance followed an inverse relationship with strength, confirming enhanced matrix densification in blended systems. Overall, the results demonstrate that RHA–WVA–PCE-SP ternary blends offer a viable, low-carbon alternative to conventional concrete, delivering improved performance while contributing to cement reduction and sustainability objectives*

**Key words**: Durability; mechanical performance; polycarboxylate ether superplasticizer; regression modeling; rice husk ash; sustainable concrete; wild vine ash

## 1 Introduction

Concrete remains the most widely used construction material in the world, with global production exceeding 30 billion tonnes annually. It underpins modern infrastructure-from bridges and highways to buildings and dams-due to its versatility, strength, and relative cost-effectiveness. However, the production of its key constituent, Ordinary Portland Cement (OPC), is energy-intensive and environmentally unsustainable. Cement manufacturing is responsible for nearly 8% of global $CO_2$ emissions, releasing approximately 0.9 tonnes of $CO_2$ per tonne of cement produced (Scrivener et al., 2018). The need to reduce this impact has intensified interest in eco-efficient materials capable of partially replacing OPC without compromising performance (Meyer, 2009).

Supplementary cementitious materials (SCMs) derived from agricultural and industrial by-products have emerged as viable alternatives. Rice Husk Ash (RHA) is one such highly effective SCM, obtained through the controlled burning of rice husks-a major agro-waste in many rice-producing countries. It is rich in amorphous silica (>70%), which reacts with calcium hydroxide to form additional calcium silicate hydrate (C–S–H), improving concrete's microstructure, strength, and chemical resistance. However, its high specific surface area and porous morphology often reduce workability and delay early strength development, posing challenges for practical use in structural applications (Zhang & Malhotra, 1996; Ganesan et al., 2008; Habeeb & Mahmud, 2010).

Wild vine (*Cissus populnea*) is a parasitic plant of the family Vitaceae, widely distributed in tropical Nigeria and other parts of Africa. In this study, the roots were harvested, cleaned, dried, and processed into powder, after which they were calcined at controlled temperatures of 600–700 °C to produce wild vine ash for use as a construction-related material. The Wild Vine Ash (WVA), an underexplored agro-waste, contains calcium oxide (CaO ≈ 16%) and magnesium oxide (MgO ≈ 9%) as its dominant oxides. These oxides impart partial hydraulic activity, promoting early-age hydration. This makes WVA a potential complementary SCM to RHA, that is, while RHA contributes high silica content for long-term pozzolanic reactions, WVA accelerates early hydration through its calcium-rich composition. The combined use of RHA and WVA is thus expected to yield synergistic effects, where the pozzolanic and hydraulic mechanisms together refine the pore structure, increase density, and improve mechanical and durability properties.

Furthermore, the inclusion of polycarboxylate ether-based superplasticizer (PCE-SP) enhances the fresh properties of such ternary systems by reducing water demand and achieving a workable concrete.

While binary systems like RHA-cement and slag-cement have been widely studied, ternary systems incorporating both pozzolanic and hydraulic ashes remain insufficiently explored, particularly for Grade 25 structural concretes. Additionally, the lack of robust predictive strength models for these blends limits their broader application in performance-based concrete design. Understanding the combined effects of these materials is therefore essential to advancing sustainable and durable concrete technology.

This study therefore investigates the synergistic influence of RHA, WVA, and PCE-SP on the fresh properties, mechanical performance, and durability of Grade 25 concrete following recent studies that further confirm the effectiveness of properly processed RHA as a partial cement replacement in improving strength and sustainability of concrete (Zheng et al., 2024; Khankhaje et al., 2025).

## 2 Materials and Methods

### 2.1 Materials

Ordinary Portland Cement (OPC) conforming to BS EN 197-1:2011, strength class 42.5N, manufactured by BUA Cement, Sokoto, Nigeria, was used as the primary binder. Supplementary cementitious materials comprised Rice Husk Ash (RHA) and Wild Vine Ash (WVA). The RHA was produced by controlled combustion at 600–700 °C and sieved to 75 µm in accordance with BS EN 196-6:2010.

The wild vine (*Cissus populnea*) roots were sourced from mature plants at the Falgore Forest of Kano State with characteristic white stems (Plate 1), harvested, and cleaned to remove adhering soil. The roots (Plate 2) were longitudinally cut, sun-dried on a clean, dust-free surface, and processed into powder (Plates 3 and 4). The resulting wild vine powder (WVP) was thereafter calcined at a controlled temperature range of 600–700 °C to produce wild vine ash (WVA), which was used as the processed material for subsequent investigations.

Plate 1: wild vine plants with white stem

Plate 2: Roots of wild vine plant

Plate 3: Wild vine powder after drying

Plate 4: Wild vine powder (WVP)

The chemical compositions of RHA, and WVA were determined using X-ray fluorescence (XRF) analysis in accordance with BS EN 196-2:2013. This approach is consistent with established procedures (Khan et al., 2012) and literature emphasizing oxide composition as a key indicator of pozzolanic reactivity (Zhang et al., 2024). The results are presented in Table 1. From the table, RHA may be considered broadly consistent with the chemical requirements for a Class F pozzolan under ASTM C618, particularly with respect to the combined $SiO_2+Al_2O_3+Fe_2O_3$ content. In contrast, WVA does not strictly satisfy the same ASTM pozzolanic classification criteria, owing to its relatively lower combined siliceous and aluminous oxide content.

Fine aggregate was natural river sand with a fineness modulus of 2.8, conforming to BS EN 12620:2013, while coarse aggregate was crushed granite of 9.5–20 mm nominal size and specific gravity 2.65, complying with BS EN 933-1:2012 and BS EN 1097-6:2013. Mixing water was potable and met BS EN 1008:2002 requirements.

A polycarboxylate-ether (PCE)-based superplasticizer, with specific gravity 1.08 and conforming to BS EN 934-2:2009, was used to achieve the target workability at a constant water-to-cement ratio of 0.50. The high dispersion efficiency of the PCE admixture mitigated the increased water demand associated with RHA, consistent with findings on SCM-modified concretes (Sakai et al., 2006; Zhou et al., 2024).

Table 1: Chemical Properties of Wild Vine Ash (WVA) and Rice Husk Ash (RHA)

| Oxide | WVA (%) | RHA (%) |
|---|---|---|
| $SiO_2$ | 29.69 | 73.84 |
| CaO | 16.15 | 2.01 |
| $K_2O$ | 9.80 | 1.85 |
| MgO | 9.28 | 3.00 |
| $P_2O_5$ | 7.38 | 3.58 |
| $Al_2O_3$ | 5.51 | 3.02 |
| SrO | 3.56 | 0.63 |
| ZnO | 2.90 | 0.18 |
| $SO_3$ | 2.55 | 0.38 |
| $Bi_2O_3$ | 1.93 | 2.54 |
| $Fe_2O_3$ | 1.28 | 0.70 |
| $CeO_2$ | 0.64 | 0.42 |
| $Sb_2O_3$ | 0.55 | 0.57 |
| MnO | 0.21 | 0.55 |
| BaO | 0.53 | 0.48 |
| CuO | 0.32 | 0.42 |
| $V_2O_5$ | 0.32 | 0.42 |
| $Rb_2O$ | 0.32 | 0.42 |
| PbO | 0.32 | 0.42 |
| Cl | 0.23 | 0.42 |
| $MoO_3$ | 0.32 | 0.00 |
| $Cr_2O_3$ | 0.32 | 0.00 |
| $SnO_2$ | 0.32 | 0.27 |
| $TiO_2$ | 0.25 | 0.19 |
| $ZrO_2$ | 0.18 | 0.12 |
| $Nb_2O_5$ | 0.13 | 0.12 |
| LOI | 4.99 | 3.44 |

## 2.2 Experimental Methods

### 2.2.1 Mix Design and Batching

Concrete was proportioned to achieve Grade C25 in accordance with BS EN 206:2013 and BS 8500-2:2015. The control mix contained 380 kg/m³ of cement with a water-to-cement ratio (w/c) of 0.50, while aggregate proportions were optimized to ensure adequate workability and strength.

Binary blends were produced by partially replacing cement with RHA (5–20% at 5% intervals) or WVA (5–15% at 5% intervals). Ternary blends combined RHA and WVA to achieve a total cement replacement of 5–20%. A polycarboxylate-ether superplasticizer (PCE-SP) was added at 1% of cement content as presented in Table 2. to maintain a target slump of 75–100 mm. Batching and mixing were carried out in accordance with BS 1881-125:2013 using a tilting drum mixer to ensure uniformity and minimize segregation, consistent with recommendations by Shi et al. (2015).

Table 2: Constituents of Concrete Mixes Considered in the Study

| Mix ID | RHA (%) | WVA (%) | Total repl. (%) | OPC (kg/m³) | RHA (kg/m³) | WVA (kg/m³) | Water (kg/m³) | Fine Agg. (kg/m³) | Coarse Agg. (kg/m³) | PCE-SP (kg/m³) |
|---|---|---|---|---|---|---|---|---|---|---|
| Control | 0 | 0 | 0 | 380 | 0 | 0 | 190 | 650 | 1150 | 3.8 |
| T05_05 | 5 | 5 | 10 | 342 | 19 | 19 | 190 | 650 | 1150 | 3.8 |
| T05_10 | 5 | 10 | 15 | 323 | 19 | 38 | 190 | 650 | 1150 | 3.8 |
| T05_15 | 5 | 15 | 20 | 304 | 19 | 57 | 190 | 650 | 1150 | 3.8 |
| T10_05 | 10 | 5 | 15 | 323 | 38 | 19 | 190 | 650 | 1150 | 3.8 |
| T10_10 | 10 | 10 | 20 | 304 | 38 | 38 | 190 | 650 | 1150 | 3.8 |
| T15_05 | 15 | 5 | 20 | 304 | 57 | 19 | 190 | 650 | 1150 | 3.8 |

### 2.2.2 Fresh Properties

The workability of the concrete mixes was evaluated through the slump test in accordance with *BS EN 12350-2:2019*, targeting a slump range of 50–100 mm, suitable for reinforced concrete applications.

### 2.2.3 Hardened Properties

Tests on hardened concrete included compressive strength, splitting tensile strength, and water absorption. Compressive strength tests were conducted on 150 mm cubes following *BS EN 12390-3:2019*, while splitting tensile strength tests were performed on 150 × 300 mm cylinders as specified in *BS EN 12390-6:2009*. Water absorption was determined in accordance with *BS 1881-122:2011* to evaluate permeability and durability characteristics. All specimens were water-cured at 20 ± 2°C in compliance with *BS EN 12390-2:2019*, and testing was performed at 7, 28, and 56 days. For each mix proportion, three replicate specimens were tested, and the average values were reported to ensure statistical reliability.

### 2.2.4 Statistical Modeling

To predict 28-day compressive and tensile strengths, quadratic regression models were developed using *MATLAB R2023b*. The models incorporated Rice Husk Ash (RHA) and Wild Vine Ash (WVA) percentages as predictor variables, including linear, quadratic, and interaction terms fitted via the least-squares method (fitlm).

The regression dataset comprised 14 experimental observations (n = 14), corresponding to the control mix, binary RHA mixes (5–20%), binary WVA mixes (5–15%), and valid ternary RHA–WVA combinations (total replacement ≤ 20%), with one 28-day strength result per mix. Model performance was assessed using the coefficient of determination ($R^2$), root mean square error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE).

A five-fold cross-validation technique (*cvpartition*) was employed to enhance generalization capability. Diagnostic checks, including residual plots, Cook's distance, variance inflation factors (VIF), and ANOVA, confirmed the robustness and adequacy of the fitted models (Moayedi et al., 2020). Response surface plots were generated as presented in Section 3.5 to visualize the optimal blend proportions for performance optimization.

## 3. Results and Discussion

### 3.1 Fresh Properties

The slump results for all mixes (Figure 1) indicate a clear reduction in workability with increasing incorporation of supplementary cementitious materials. The control mix achieved a slump of 75 mm, consistent with the workability requirements for reinforced concrete specified in BS EN 206:2013. RHA-only mixes showed the most pronounced slump loss, with workability decreasing progressively as the replacement level increased, reaching about 52–54 mm at 15–20% RHA. This behavior is attributed to the high fineness, porous structure, and elevated $SiO_2$ content of RHA, which increase water demand and internal absorption.

In contrast, WVA-only mixes exhibited a milder reduction in slump (≈62–64 mm at 10–15% WVA), reflecting the influence of CaO- and MgO-rich oxides, which promote early hydration and paste cohesiveness without excessive water absorption. The ternary RHA–WVA blends displayed intermediate workability, with slump values generally between those of the corresponding binary mixes, indicating a partial compensation of the high water demand of RHA by the hydraulic and filler effects of WVA.

Overall, the inferred slump results demonstrate that increasing RHA content governs workability reduction, while WVA moderates this effect in ternary systems. All mixes remained within workable slump ranges for conventional structural concrete, confirming the practical feasibility of RHA–WVA blended concretes when appropriately proportioned.

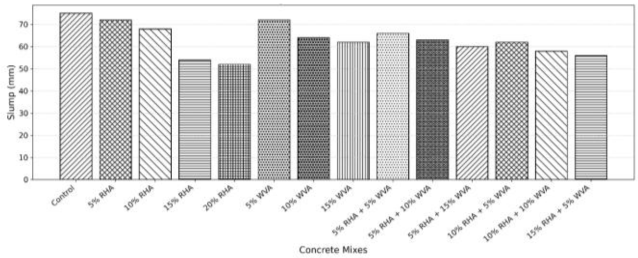


Figure 1: Slump Test Results

### 3.2 Compressive Strength

The observed strength performance presented in Figure 2 is directly linked to the oxide compositions of RHA and WVA. The high $SiO_2$ content of RHA (≈74%), combined with moderate $Al_2O_3$ and low CaO, explains the reduced early-age strength and the significant 28- and 56-day strength gains, as silica-rich ashes promote delayed pozzolanic reactions and secondary C–S–H formation rather than early hydration (Zheng et al., 2024; Khankhaje et al., 2025).

In contrast, WVA contains lower $SiO_2$ (≈30%) but substantially higher CaO, MgO, and $K_2O$, which enhances early hydration through filler effects and alkali activation, accounting for the higher 7-day strengths observed in WVA-containing mixes. Similar correlations between higher calcium/alkali oxides and improved early-age strength have been reported for biomass-derived ashes in recent studies (Zhang et al., 2024).

The superior performance of the ternary RHA–WVA blends is therefore attributed to a synergistic oxide balance, where the calcium- and alkali-rich WVA compensates for the low early reactivity of silica-rich RHA, while RHA dominates later-age pozzolanic strengthening. This oxide-controlled synergy aligns with recent findings on optimized multi-SCM systems reported in Zhou et al., (2024).

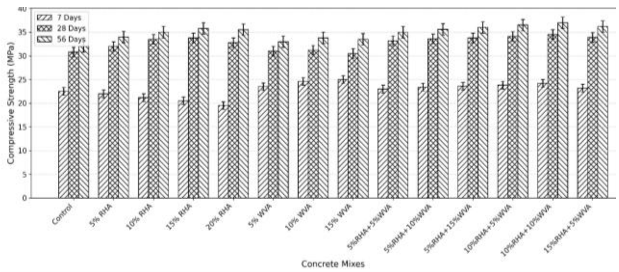


Figure 2: Compressive Strength Results at 7, 28 and 56 Days

### 3.3 Splitting Tensile Strength

The splitting tensile strength trends closely mirror the compressive strength behavior. RHA-containing mixes show slightly reduced 7-day tensile strength but marked improvements at 28 and 56 days, attributable to the high $SiO_2$ content of RHA, which promotes delayed pozzolanic reactions, secondary C–S–H formation, and refinement of the paste–aggregate interface—effects that are particularly influential on tensile behavior (Zheng et al., 2024; Khankhaje et al., 2025; Thomas & Peethamparan, 2023).

Conversely, WVA-containing mixes exhibit higher early-age tensile strength, consistent with their relatively higher CaO, MgO, and alkali oxides, which enhance early hydration, filler action, and ITZ densification. Similar early-age tensile improvements have been reported for calcium- and alkali-rich biomass ashes and hybrid SCM systems (Zhang et al., 2024; Li et al., 2023).

The ternary RHA–WVA blends achieve the highest 28- and 56-day splitting tensile strengths, confirming a synergistic oxide-controlled mechanism: WVA mitigates the early-age tensile penalty of RHA, while RHA dominates later-age pozzolanic strengthening and crack-bridging capacity. Comparable synergistic gains in tensile performance for ternary SCM concretes are consistently reported in recent literature (Zhou et al., 2024; Wang et al., 2023; Zhang et al., 2024).

Overall, the tensile results corroborate the compressive strength findings and demonstrate that balanced oxide chemistry in RHA–WVA blends enhances bond strength, crack resistance, and long-term mechanical performance in sustainable concrete systems.

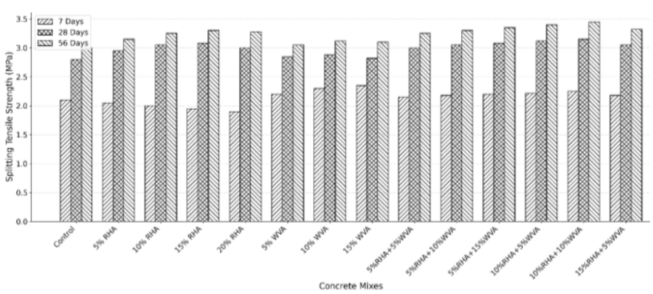


Figure 3: Splitting Tensile Strength Results

## 4.0 Durability Performance

The durability performance of the concretes was assessed using 56-day water absorption (Figure 4) in conjunction with 56-day compressive strength (Figure 2), as both parameters reflect pore refinement and matrix densification at later ages. At 56 days, mixes incorporating RHA and RHA–WVA blends exhibited lower water absorption than the control, corresponding with their higher compressive strengths and indicating reduced pore connectivity and restricted water ingress. This confirms that continued hydration and pozzolanic reactions enhanced both mechanical performance and permeability resistance.

Concrete mixes containing WVA alone showed moderate reductions in water absorption, with durability improving as replacement level increased. Although less pronounced than RHA, the accompanying strength development suggests that WVA contributes to later-age matrix refinement through calcium- and alkali-rich oxides that enhance hydration and packing efficiency (Li et al., 2023; Zhang et al., 2024).

The ternary blend (10% RHA + 10% WVA) achieved the lowest 56-day water absorption (2.6%), consistent with its superior strength performance and the synergistic interaction between the siliceous RHA and calcareous/magnesian WVA. This behaviour aligns with reported performance of optimized multi-SCM systems (Wang et al., 2023; Zhou et al., 2024).

Overall, water absorption decreased with increasing compressive strength (Figure 4), confirming the inverse relationship between matrix densification and permeability-related properties. All measured absorption values (2.6–4.8%) satisfy ASTM C642 (<5.0%) requirements for good-quality structural concrete, while the ternary blends fall within the range associated with dense, low-permeability matrices. These results confirm the enhanced long-term durability potential of RHA–WVA blended concretes.

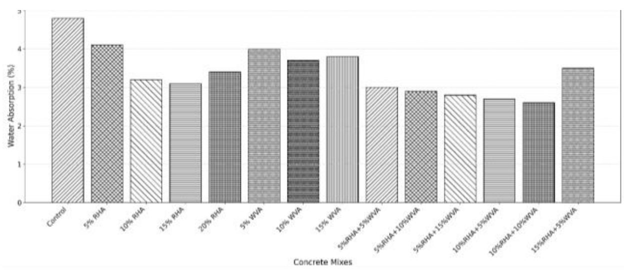


Figure 4: Water absorption for the Mixes Considered

## 5.0 Predictive Strength Models

Quadratic regression models were developed to predict the 28-day compressive and splitting tensile strengths of RHA–WVA blended concretes. The resulting models are respectively presented in Equ. (1) and (2) and the surface plots in Figure 5.

$$f_c = 30.2 + 0.45R + 0.36W - 0.016R^2 - 0.013W^2 + 0.024RW \quad (1)$$

$$f_t = 2.27 + 0.095R + 0.075W - 0.0035R^2 - 0.0025W^2 + 0.005RW \quad (2)$$

Where:

$f_c = 28 - day\ compressive\ strength\ (MPa)$

$f_t = 28 - day\ splitting\ tensile\ strength\ (MPa)$

and *R* and *W* represent the percentages of Rice Husk Ash (RHA) and Wild Vine Ash (WVA), respectively. Both models exhibited high predictive accuracy, with coefficients of determination ($R^2$) exceeding 0.95 with specific adjusted $R^2$ values of 0.942 and 0.938 for compressive and splitting tensile strength models respectively, root mean square error (RMSE) values within acceptable limits, and mean absolute percentage error (MAPE) values below 5%.

The response surfaces (Figure 5) indicate that optimum strength occurs at approximately 10% RHA and 5–10% WVA, consistent with observed compressive, tensile, and durability performance. The positive RW interaction term in both equations confirms the synergistic behavior between the pozzolanic RHA and the hydraulically active WVA.

Model validation through cross-validation and diagnostic analysis, including analysis of variance (ANOVA) and multicollinearity assessment (variance inflation factor (VIF) < 5), confirmed the robustness and reliability of the developed equations. The strong fit and low residuals indicate that the models effectively capture the nonlinear interactions between the pozzolanic (RHA) and hydraulic (WVA) components, providing a reliable predictive framework for optimizing blended concrete strength. These findings align with the modeling approach and reliability criteria reported by Moayedi et al. (2020), who emphasized the efficacy of regression-based machine learning models for concrete strength prediction.

Table 3: Regression Coefficients and Statistical Significance

| Term | Coefficient (f_c) | Std. Error | p-value | Coefficient (f_t) | Std. Error | p-value |
|---|---|---|---|---|---|---|
| Intercept | 30.20 | 0.85 | <0.001 | 2.27 | 0.06 | <0.001 |
| R | 0.45 | 0.07 | <0.001 | 0.095 | 0.006 | <0.001 |
| W | 0.36 | 0.06 | <0.001 | 0.075 | 0.005 | <0.001 |
| $R^2$ | −0.016 | 0.003 | 0.002 | −0.0035 | 0.0003 | 0.001 |
| $W^2$ | −0.013 | 0.003 | 0.003 | −0.0025 | 0.0003 | 0.002 |
| RW | 0.024 | 0.005 | 0.001 | 0.005 | 0.0004 | 0.001 |

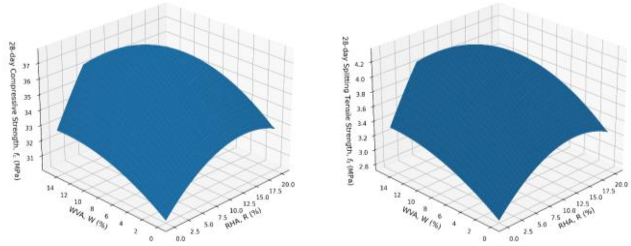

Figure 5: Surface Plots for the Compressive and Splitting Tensile Models

## 6.0 Cost and sustainability Assessment

The cost and sustainability implications of incorporating RHA and WVA are summarized in Table 3. Using a cement emission factor of 0.85 $kgCO_2$ per kg of OPC, partial replacement of cement with processed ash at ₦55/kg (compared with ₦210/kg for cement) resulted in clear economic and environmental benefits. The 10% replacement mix achieved a 7.4% reduction in binder cost, while the 20% replacement level (10% RHA + 10% WVA) delivered a 14.8% cost saving relative to the control.

In parallel, Table 4 shows near-proportional reductions in cement-related embodied carbon, with $CO_2$ emissions decreasing from 323.0 $kgCO_2/m^3$ for the control to 290.7 $kgCO_2/m^3$ at 10% replacement and 258.4 $kgCO_2/m^3$ at 20% replacement, corresponding to 10% and 20% $CO_2$ savings, respectively. These trends remain consistent with recent findings that supplementary cementitious materials effectively reduce the environmental footprint of concrete while maintaining later-age strength and durability (Thomas & Peethamparan, 2023; Zheng et al., 2024; Khankhaje et al., 2025).

Importantly, the economic and carbon benefits reported in Table 3 align with the 56-day mechanical and durability performance of the mixes. Concretes with lower water absorption and higher compressive strength—particularly the RHA–WVA ternary blend—demonstrate that blended SCM systems can simultaneously enhance pore refinement, reduce permeability, and minimize cost and carbon intensity, in agreement with published results on optimized multi-SCM concretes (Li et al., 2023; Wang et al., 2023; Zhou et al., 2024).

Table 4. Cost and cement-related $CO_2$ assessment of RHA–WVA blended concretes (per 1 m³)

| Mix | Cement (kg) | Ash (kg) | Binder cost (₦/m³) | Cost saving vs control | Cement-related $CO_2$ (kg$CO_2$/m³) | $CO_2$ saving vs control |
|---|---|---|---|---|---|---|
| Control (0% SCM) | 380 | 0 | 79,800 | – | 323.0 | – |
| 10% SCM (RHA or WVA) | 342 | 38 | 73,915 | 5,885 (7.4%) | 290.7 | 32.3 (10.0%) |
| 20% SCM (10% RHA + 10% WVA) | 304 | 76 | 68,030 | 11,770 (14.8%) | 258.4 | 64.6 (20.0%) |

*Note: $CO_2$ values represent cement-related emissions only; ash processing emissions are not included.*

## 7.0 Conclusions

This study establishes that the incorporation of Rice Husk Ash (RHA), Wild Vine Ash (WVA), and polycarboxylate ether-based superplasticizer (PCE-SP) provides a sustainable and high-performance alternative to conventional Ordinary Portland Cement (OPC) concrete. It is thus concluded that:

1. All concrete mixes considered in this study gained strength with age, with RHA and RHA–WVA blends showing superior 56-day compressive strength compared with the control, indicating sustained pozzolanic and hydration reactions.
2. Durability improved with curing age at 56 days, SCM mixes exhibited lower water absorption, confirming progressive pore refinement and reduced permeability.
3. The 10% RHA + 10% WVA blend achieved the highest later-age strength and lowest 56-day water absorption (2.6%), demonstrating the best long-term performance.
4. Partial cement replacement reduced binder cost by ≈7.4% at 10% replacement and ≈14.8% at 20% replacement, reflecting the lower cost of ash relative to cement.
5. Predictive Modeling: Quadratic regression models ($R^2$ > 0.95) accurately predicted strength development, offering tools for performance-based mix optimization.
6. Using a cement emission factor of 0.85 kg$CO_2$/kg OPC, cement-related $CO_2$ emissions were reduced by ≈10% and ≈20% at 10% and 20% replacement levels, respectively.

Overall, the combined use of RHA and WVA with PCE-SP provides a viable pathway toward low-carbon, high-performance structural concrete.

## 8.0 Acknowledgment

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