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Durability and Sustainability Assessment of Cow Dung Ash–Wood Ash Concrete Exposed to Acid–Alkali Cycles

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Abstract: This research investigates the durability and sustainability performance of concrete incorporating agro-waste ashes—cow dung ash (CDA) and wood ash (WA)—as partial cement replacements under aggressive acid–alkali cycling. A 1:1 blend of CDA and WA was used to replace ordinary Portland cement (OPC) at 0%, 10%, 15%, 20%, 25%, and 30% by weight across six mix designs. Concrete specimens were cured for 7, 14, 28, 56, and 90 days and then exposed to alternating sulfuric acid (pH ≈ 2) and sodium hydroxide (pH ≈ 12) solutions for up to 90 days to simulate harsh environmental conditions. Tests conducted included slump measurement, compressive strength before and after exposure, mass loss, and visual inspection. Statistical analysis (ANOVA) and regression modeling were employed to evaluate the influence of mix variables on durability indicators. Results demonstrated that mixes with 10–15% replacement achieved the best overall performance, showing enhanced durability and strength retention. The 10% blend attained a compressive strength of 31.6 MPa at 90 days and retained over 72% of its original strength after chemical exposure. Weight loss and mass change were significantly lower compared to the control. Regression models showed strong predictive capability ($R^2 > 0.99$), supporting the reliability of the developed equations. This study highlights the potential of CDA–WA blends as sustainable pozzolanic materials that enhance chemical resistance in concrete while promoting circular economy goals. The findings provide practical insights for integrating agro-waste materials into eco-efficient construction, especially in chemically aggressive environments.

Keywords: *Cow dung ash; Wood ash; Acid–alkali durability; Agro-waste concrete; Sustainable cement replacement; Residual compressive strength; Statistical modelling; ANOVA*

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1. Introduction

The construction sector under growing pressure to enhance environmental sustainability, especially in minimizing the carbon footprint linked to the manufacturing of ordinary Portland cement (OPC) (Baba et al., 2023). The production of cement substantially contributes to global CO_2 emissions owing to its energy-intensive procedures and reliance on raw resources such as limestone and clay (Soomro et al., 2023). Consequently, focus has transitioned to the partial substitution of cement with alternative binders derived from agricultural and industrial by-products (Marchetti, 2020). Cow dung ash (CDA) and wood ash (WA) have emerged as effective pozzolanic materials, particularly in areas where these wastes are abundantly accessible.

In Nigeria and other developing regions, the use of locally available waste materials such as cow dung ash (CDA) and wood ash (WA) has gained research interest due to their sustainability, low cost, and abundance (Buba, 2025; Naapuo & Danso, 2025). Concrete structures in tropical environments are often exposed to aggressive acid and alkali conditions from industrial effluents, acidic soils, and agricultural activities, which can significantly affect durability (Auwal, 2025; Umar, 2025). Therefore, evaluating the durability and sustainability performance of CDA–WA blended concrete under acid–alkali cycles is essential for assessing its suitability for long-term infrastructure applications in Nigeria and similar environments.

CDA results from the controlled combustion of cow dung and contains significant quantities of reactive silica and alumina, which are crucial for pozzolanic reactions (Indhiradevi et al., 2021). WA, a by-product of biomass or firewood combustion, contains significant amounts of calcium oxide and silicate compounds. The potential of these ashes to enhance concrete properties, particularly regarding mechanical strength and environmental sustainability, has been individually examined (Hamid & Rafiq, 2020). Nonetheless, there is a paucity of research investigating their concurrent application, particularly in chemically aggressive conditions like alternating acid–alkali exposure cycles.

Durability is an essential factor for the sustained performance of concrete in practical applications (Fode et al., 2023). Exposure to acidic and alkaline environments—frequently found in sewer systems, chemical industries, and coastal areas—can severely compromise the structural integrity of typical Ordinary Portland Cement (OPC) concrete (Qu, 2022). Acidic attacks generally extract calcium hydroxide and deteriorate the cementitious matrix, whereas alkaline conditions may induce surface cracking and facilitate ion exchange within pores (Damion et al., 2022; Yang et al., 2022). The integration of CDA and WA may provide a synergistic benefit by enhancing microstructural density and augmenting the chemical resistance of concrete.

The objective of this study is to evaluate the durability performance of concrete incorporating a 1:1 blend of cow dung ash and wood ash as a partial cement replacement. The investigation focuses on fresh concrete workability, compressive strength development, and durability behavior under alternating acid and alkali cycles. The study also aims to determine the optimal replacement level and to develop statistical models that can predict strength and degradation trends. Through this research, the potential of locally available agro-wastes to serve as sustainable and durable cement alternatives is assessed.

2. Materials and methods

2.1. Materials

2.1.1. Ordinary Portland Cement (OPC)

The cement used was Ordinary Portland Cement (OPC) grade 42.5 conforming to BS EN 197-1 standards. The cement was sourced from a local manufacturer in Nigeria, stored in a dry environment to prevent moisture absorption.

2.1.2. Cow Dung Ash (CDA)

Raw cow dung was collected from a local cattle farm in Katsina State, Nigeria. The cow dung was sun-dried and then burned in a controlled open-air environment to produce ash. The ash was sieved through a 75-micron sieve to ensure fineness and then stored in airtight containers to avoid moisture ingress.

2.1.3. Wood Ash (WA)

Wood ash was obtained from a biomass power plant in Bauchi State, Nigeria. The ash was collected after complete combustion of hardwood timber. It was ground using a ball mill and sieved through a 75-micron sieve for particle size consistency.

2.1.4. Fine Aggregate

Natural river sand was used as fine aggregate, sourced locally. It was washed and dried before use. Its specific gravity and fineness modulus were determined according to ASTM C128 and ASTM C136 standards, respectively.

2.1.5. Water

Clean potable water free of impurities was used for mixing and curing, complying with ASTM C1602 requirements.

2.1.6. Chemicals for Exposure

Two chemical agents were used to simulate alternating acid–alkali exposure conditions:

•Sulfuric Acid (H_2SO_4): Analytical grade sulfuric acid was used to prepare the acidic solution. It was diluted with potable water to achieve a pH of approximately 2.0, simulating aggressive acidic environments such as industrial or sewage conditions.

•Sodium Hydroxide (NaOH): Analytical grade sodium hydroxide pellets were dissolved in water to create the alkaline solution with a target pH of approximately 12.0, representing highly alkaline environments such as chemical waste zones or marine concrete deterioration zones.

2.2. Characterization of Materials

2.2.1. Physical Properties

The physical properties of the constituent materials were evaluated using standardized procedures to characterize their suitability for concrete production. The specific gravity of the cement was determined in accordance with ASTM C188 (2016), ensuring accurate mix proportioning by volume. The fineness was assessed using the Blaine air permeability method, following ASTM C204 (2018), to quantify the surface area available for hydration. The size distribution of the cow dung ash (CDA) and wood ash (WA) particles was analyzed using laser diffraction analysis, providing a detailed particle profile to understand packing density and reactivity potential. The bulk densities of both fine and coarse aggregates were measured using a standard filling and compaction procedure, in accordance with ASTM C29/C29M, to aid in volumetric mix design.

2.2.2. Chemical Composition

The chemical composition of pozzolanic materials—cow dung ash (CDA) and wood ash (WA)—was evaluated to ascertain their appropriateness as cementitious substitutes. The principal chemical oxides (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, Na_2O, and SO_3) were quantified utilizing X-ray fluorescence (XRF) spectroscopy. This method yielded quantitative data regarding the oxide compositions required for pozzolanic classification. The Pozzolanic Activity Index: The reactivity of CDA and WA was assessed based on the parameters established in ASTM C618 (2019). The categorization was determined by the aggregate percentage of SiO_2, Al_2O_3, and Fe_2O_3, along with the strength activity index in comparison to control specimens, as stipulated for Class N natural pozzolans.

2.3. Mix Design

Table 1 illustrates that six concrete mixtures were formulated to examine the impact of cow dung ash (CDA) and wood ash (WA) on concrete durability subjected to alternating acid-alkali cycles. The mixtures comprised a control (M0) consisting of 100% ordinary Portland cement (OPC), along with five blended formulations (M1–M5) that integrated CDA and WA at different substitution amounts. The ash mixture was consistently maintained at a 1:1 weight ratio for all levels of replenishment. A design benchmark of 25 MPa compressive strength at 28 days was established, with a constant water-to-binder (w/b) ratio of 0.50 for all mixtures. The binder content was proportionately modified to account for the differing ash contents while preserving workability.

Table 1: Summary of Mix Design

Mix ID	Cement Replacement (%)	CDA: WA Ratio
M0	0 (Control)	–
M1	10	1:1
M2	15	1:1
M3	20	1:1
M4	25	1:1
M5	30	1:1

2.4. Sample Preparation and Curing

Concrete mixing was performed via a laboratory pan mixer to guarantee uniformity and consistency throughout all mixtures. The workability of fresh concrete was evaluated immediately post-mixing utilising the slump test, in line with ASTM C143 (2020). Cubic specimens of 100 mm × 100 mm × 100 mm were fabricated for the assessment of compressive strength and durability following chemical exposure. All specimens were manually crushed and compacted in two layers use a tamping rod to reduce entrapped air. Following casting, the moulds were enveloped in plastic sheets to mitigate moisture loss and were demolded after a duration of 24 hours. The specimens were subsequently cured in pristine water tanks regulated at a temperature of 23 ± 2°C, adhering to established curing protocols. The cure durations were established at 7, 14, 28, 56, and 90 days to assess both early-age and long-term performance.

2.5. Durability Testing Under Acid–Alkali Cycles

2.5.1. Exposure Procedure

After the designated curing periods, selected concrete specimens were subjected to alternating acid–alkali immersion cycles to simulate chemical degradation in aggressive environments. The exposure protocol involved cyclical immersion in sulfuric acid and sodium hydroxide solutions as follows:

•Acid immersion: Days 1–3 — specimens were immersed in a 0.01 M sulfuric acid (H_2SO_4) solution adjusted to pH ≈ 2.0.

•Alkali immersion: Days 4–6 — specimens were transferred to a 0.01 M sodium hydroxide (NaOH) solution maintained at pH ≈ 12.0.

The 6-day acid-alkali cycle was perpetuated for total exposure lengths of 28, 56, and 90 days, contingent upon the test group. Every 6 days, the chemical solutions were replenished to ensure stable pH and chemical concentration throughout the testing duration. Following each immersion phase, specimens were rinsed with distilled water and air-dried at ambient temperature prior to being transferred to the subsequent solution.

2.5.2. Measured Parameters

To evaluate the degradation behavior and durability performance of CDA–WA blended concrete under chemical exposure, the following parameters were measured:

•Weight Loss (%): Specimens were measured before and after exposure to acid and alkali to ascertain material loss, adhering to the protocol outlined in ASTM C642 (2013). Weight loss was determined as a percentage of the original mass.

•Residual Compressive Strength: The compressive strength of exposed specimens was assessed in accordance with ASTM C39 (2021) with standard 100 mm cube specimens. This indicated mechanical integrity during a chemical assault.

•Visual Inspection: The surface conditions of exposed specimens were evaluated and documented photographically. Indicators including scaling, cracking, pitting, and colour alteration were employed to qualitatively evaluate the level of degradation.

•Mass Change (%): The mass variation was determined as the net percentage change in specimen weight pre- and post-exposure, serving as an alternative metric for material loss or gain resulting from surface leaching or deposit development.

•The pH of the leachate was measured with a digital pH meter prior to and following each exposure cycle. This facilitated the monitoring of chemical alterations in acidic and alkaline environments resulting from interactions with the concrete matrix.

These parameters collectively provided a multi-faceted evaluation of durability, incorporating both physical and chemical indicators of deterioration.

2.6. Statistical and Data Analysis

All experimental tests were performed in triplicate ($n = 3$) to guarantee data reliability and reproducibility. The average values and standard deviations of assessed parameters—comprising compressive strength, weight loss, and mass change—were computed to encapsulate performance trends and variability. A one-way factorial analysis of variance (ANOVA) was conducted to evaluate the statistical significance of critical experimental variables, such as cement replacement level, curing length, and exposure time, on the durability qualities of concrete. The p-values were analysed at a 95% confidence level ($\alpha = 0.05$) to ascertain statistically significant effects and interactions.

Multiple linear regression analysis was used to develop predictive models for:

•Residual compressive strength (MPa)

•Weight loss (%) as functions of replacement percentage, curing age, and exposure duration. Model accuracy was evaluated using R^2 values and p-statistics.

2.7. Safety and Environmental Considerations

All experimental methods were performed with suitable personal protective equipment (PPE), including gloves, goggles, and lab coats, to guarantee the safe handling of acidic (H_2SO_4) and alkaline (NaOH) solutions. Waste solutions were neutralised before disposal in compliance with environmental requirements. The collection and preparation of cow dung ash (CDA) and wood ash (WA) were conducted under sanitary circumstances to avert contamination and exposure to airborne particulates, thereby ensuring laboratory safety and environmental accountability.

3. Results and Discussion

3.1. Characteristics of Materials

3.1.1. Chemical Composition of CDA and WA

The chemical composition of cow dung ash (CDA) and wood ash (WA) was analyzed using X-ray fluorescence (XRF) techniques. The findings presented in Table 2 indicate that both ashes are abundant in reactive oxides crucial for pozzolanic activity. CDA comprises 52.4% silica (SiO_2) and 16.8% alumina (Al_2O_3), whereas WA exhibits a greater concentration of calcium oxide (CaO) at 26.1%. Both ashes contain trace amounts of magnesia (MgO), potassium oxide (K_2O), sodium oxide (Na_2O), and sulphur trioxide (SO_3), which enhance hydration and durability when present in regulated proportions. The existence of substantial silicate and aluminous phases in CDA promotes prolonged pozzolanic reactions, whereas the lime-abundant composition of WA enhances early strength progression and the alkaline activation of silicate compounds (Sarker et al., 2023).

Table 2: Chemical oxide composition of CDA and WA(XRF, wt %)

Oxide	CDA (%)	WA (%)
SiO_2	52.4	38.7
Al_2O_3	16.8	10.2
Fe_2O_3	4.5	3.3
CaO	7.8	26.1

MgO	2.1	2.6
K_2O	3.5	7.4
Na_2O	1.2	2.3
SO_3	0.8	1.0
Loss on Ignition (LOI)	11.7	17.4

3.1.2. Fresh concrete properties

The workability of the fresh concrete mixes was assessed using the slump test, and the results are summarized in Table 3 and figure 1. A general trend of decreasing slump was observed with increasing levels of cow dung ash–wood ash (CDA–WA) replacement. The control mix (M0) achieved a slump of 85 mm, while the mix with 30% replacement (M5) had a reduced slump of 68 mm, falling into the medium–low workability category.

The decrease in slump is attributed to the higher specific surface area and increased porosity of the ash particles, which demand more water for wetting and dispersion (Jha et al., 2021). Additionally, the irregular particle shape and lightweight nature of CDA and WA may reduce internal cohesion in the mix, slightly limiting flowability. Nevertheless, all mixes maintained a slump range acceptable for conventional reinforced concrete applications, particularly where mechanical vibration or moderate placement efforts are used. These results are consistent with earlier studies on agro-waste pozzolans, where moderate cement replacement levels (up to 15%) maintain adequate workability, while higher levels tend to reduce it due to increased water absorption and reduced paste fluidity (Manikanta et al., 2020; Charitha et al., 2021).

Table 3: Fresh concrete properties of CDA–WA concrete mixes

Mix ID	Replacement (%)	Slump (mm)	Workability Classification
M0	0	85	Medium
M1	10	80	Medium
M2	15	78	Medium
M3	20	75	Medium
M4	25	72	Medium
M5	30	68	Medium–Low

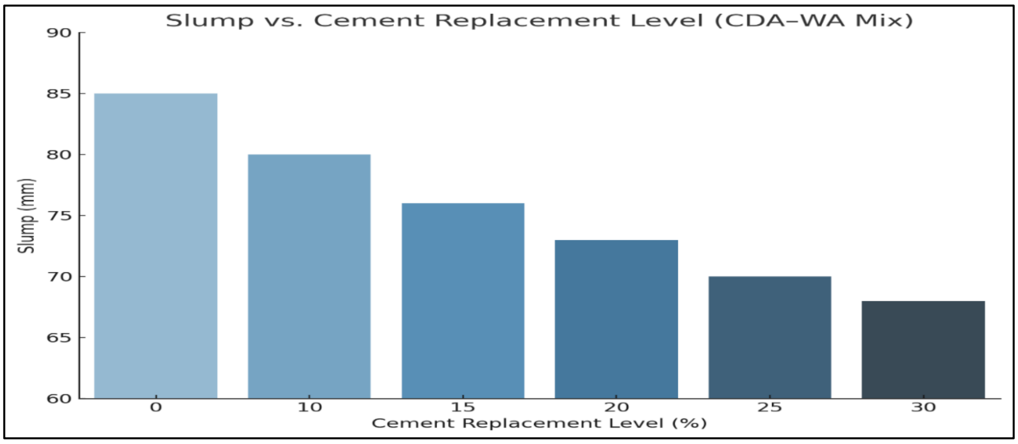

Figure 1: Slump vs Cement Replacement Levels

3.2. Strength development before exposure

Table 4 and figure 2 presents the compressive strength results of concrete mixes cured in water for 7, 14, 28, 56, and 90 days, prior to any chemical exposure. All mixes showed a consistent increase in strength over time, indicating progressive hydration and, in the pozzolan-containing mixes, continued pozzolanic activity. The control mix (M0) reached 25.3 MPa at 28 days, while the 10% and 15% replacement mixes (M1 and M2) achieved 24.9 MPa and 24.3 MPa, respectively—values that are comparable to the control, indicating minimal loss of mechanical performance at low levels of cement replacement.

At 90 days, the mixes with 10% and 15% CDA–WA replacement surpassed the control in strength, recording 31.6 MPa and 32.2 MPa, respectively, compared to the control's 30.5 MPa. This enhancement is attributed to pozzolanic reactions between the reactive silica/alumina in the ashes and the calcium hydroxide liberated during cement hydration, resulting in the formation of additional calcium silicate hydrate (C–S–H) (Auwal, 2025; Gautam et al., 2025). However, strength declined progressively with higher replacement levels. Mix M5 (30% replacement) showed a lower 90-day strength of 28.0 MPa, likely due to dilution of cementitious content and incomplete pozzolanic reactivity at higher ash concentrations. These results align with previous studies indicating an optimal replacement range for agro-waste pozzolans between 10–15% for maintaining or enhancing strength (Baba et al, 2023; Abd-Elrahman et al., 2023; Umar & Musa, 2025).

Table 4: Compressive strength development of CDA–WA concrete before exposure (MPa)

Mix ID	Replacement (%)	7 Days	14 Days	28 Days	56 Days	90 Days
M0	0	15.2	19.6	25.3	28.9	30.5
M1	10	14.7	19.3	24.9	29.4	31.6
M2	15	14.1	18.7	24.3	29.6	32.2
M3	20	13.2	17.8	23.2	28.4	30.9
M4	25	12.7	17.1	21.8	27.1	29.4
M5	30	11.8	16.3	20.1	25.8	28.0

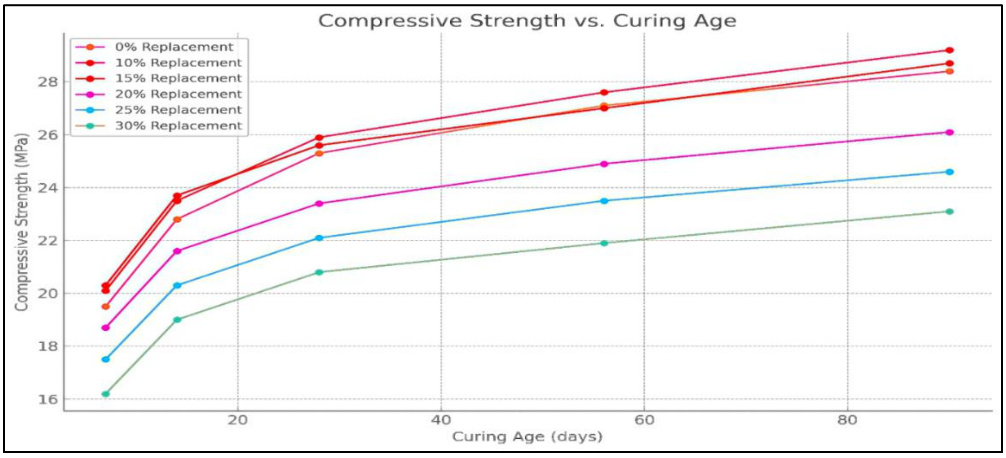

Figure 2: Compressive strength development of CDA–WA concrete at varying replacement levels and curing durations

3.3. Durability Performance Under Acid–Alkali Cycles

3.3.1. Weight loss after exposure

The impact of alternating acid-alkali cycles on concrete durability was evaluated by quantifying specimen weight loss after 28, 56, and 90 days of exposure. Table 5 and Figure 3 exhibit the results after 28 days of conventional water curing. The control mix (M0) exhibited a gradual rise in weight loss over time, escalating from 5.4% at 28 days to 6.9% at 90 days. Mixtures M1 and M2, with 10% and 15% substitutions, consistently demonstrated reduced weight loss over all durations, affirming enhanced acid–alkali tolerance. M2 had a mere 3.7% weight reduction at 28 days, which incrementally rose to 5.1% after 90 days.

While the mixtures with elevated replacement levels (M4 and M5) exhibited progressively deteriorating performance, culminating in weight losses of 7.1% and 8.0% at 90 days, respectively. These patterns confirm that moderate replacement levels (10–15%) are ideal for chemical resistance, whereas elevated ash amounts may result in diminished matrix densification and increased vulnerability to leaching (Fehlberg & Kumar, 2025; Luhar et al., 2021: Adewumi et al., 2025).

Table 5: Weight loss of CDA–WA concrete after acid–alkali exposure

Mix ID	Replacement (%)	28 Days (%)	56 Days (%)	90 Days (%)
M0	0	5.4	6.1	6.9
M1	10	4.2	4.9	5.6
M2	15	3.7	4.4	5.1
M3	20	4.5	5.3	6.0
M4	25	5.8	6.4	7.1

M5	30	6.7	7.3	8.0

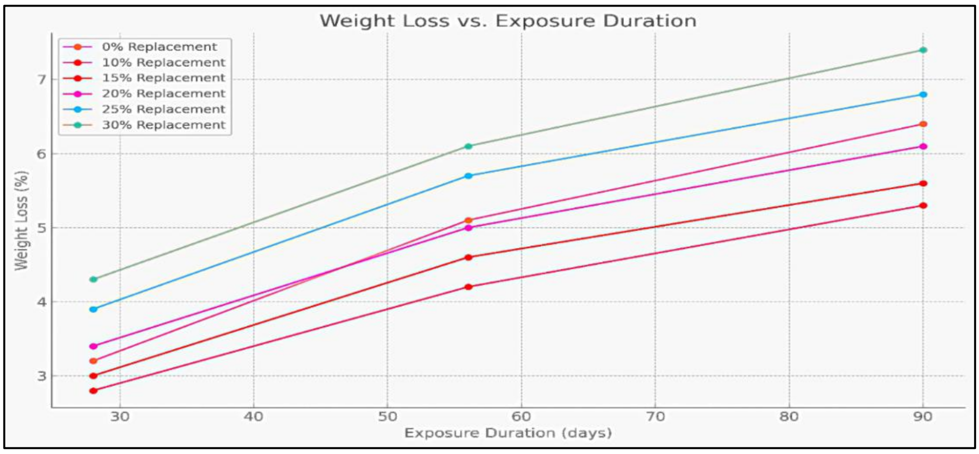

Figure 3: Weight loss of CDA–WA concrete after acid–alkali exposure

3.3.2. Residual compressive strength after exposure

Residual compressive strength values for concrete exposed to alternating acid–alkali cycles are presented in Table 6 and figure 4 for 28, 56, and 90 days of exposure, following 28 days of initial curing. All mixes showed progressive strength reduction over time due to continuous chemical deterioration. The control mix (M0) experienced a drop from 19.0 MPa at 28 days to 15.3 MPa at 90 days, amounting to a 40% reduction from its original 28-day strength of 25.3 MPa. This decline reflects the vulnerability of plain OPC concrete to acid and alkali attack, especially when unprotected by supplementary binders.

In contrast, 10% and 15% CDA–WA blends (M1 and M2) consistently outperformed the control. Mix M2 recorded 21.1 MPa, 19.7 MPa, and 18.0 MPa at 28, 56, and 90 days of exposure, respectively—retaining approximately 72% of its original 28-day strength after prolonged attack. The improved resistance is attributed to pozzolanic densification and refined pore structure, which reduce ion penetration and leaching (Ren et al., 2025; Li et al 2020).

Higher replacement levels (≥20%) demonstrated greater strength loss over time. For example, the 30% replacement mix (M5) dropped from 15.8 MPa to 12.1 MPa, likely due to excessive dilution of cementitious content and lower binder reactivity. These findings reaffirm that 10–15% replacement offers the best durability-strength tradeoff for CDA–WA blended concretes in chemically aggressive environments.

Table 6. Residual compressive strength of CDA–WA concrete after acid–alkali exposure (MPa)

Mix ID	Replacement (%)	28 Days	56 Days	90 Days
M0	0	19.0	17.6	15.3
M1	10	20.4	18.9	17.1
M2	15	21.1	19.7	18.0
M3	20	18.2	16.3	14.5
M4	25	17.0	15.2	13.4
M5	30	15.8	13.9	12.1

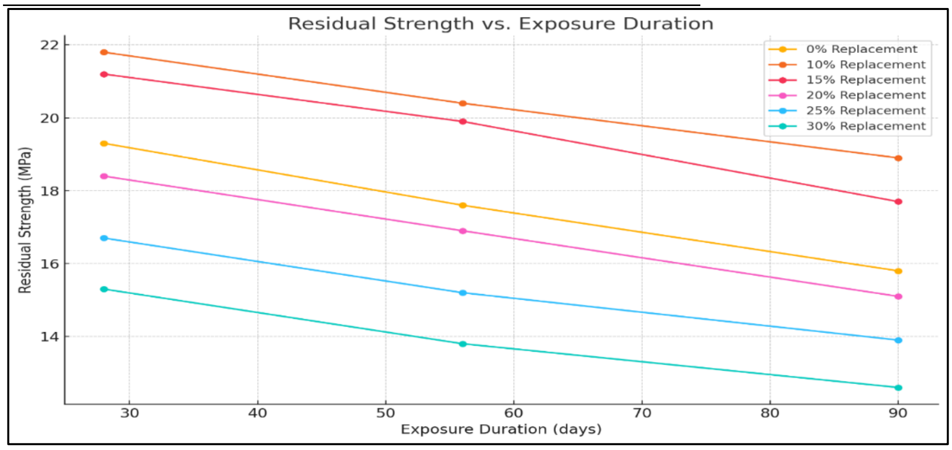

Figure 4: Residual compressive strength of CDA–WA concrete after acid–alkali exposure (MPa)

3.3.3 Mass Change after Exposure

The mass change of CDA–WA concrete specimens after 28, 56, and 90 days of exposure to alternating acid–alkali cycles is shown in Table 7 and figure 5. All mixes experienced progressive mass loss over time due to ongoing deterioration, leaching of lime, and surface erosion under acidic and basic attack. The control mix (M0) recorded mass losses of –7.2%, –10.1%, and –13.5%, reflecting accelerated degradation as exposure duration increased. In comparison, the 10% and 15% CDA–WA blends (M1 and M2) demonstrated significantly reduced mass losses across all time points. Mix M2 (15% replacement) showed the least degradation, with only –4.6% at 28 days and –9.4% at 90 days, indicating superior resistance to chemical attack.

On the other hand, mixes with higher replacement levels (M4 and M5) experienced greater cumulative mass losses. By 90 days, M5 recorded a mass change of –15.7%, exceeding even the control. This trend suggests that excessive replacement weakens the concrete matrix and leads to more rapid disintegration under aggressive conditions. These results align with trends observed in weight loss and residual compressive strength data, reinforcing that 10–15% CDA–WA replacement optimally balances chemical durability and matrix integrity (Alharthai et al., 2024; Kilani et al., 2022).

Table 7. Mass change of CDA–WA concrete after 28, 56, and 90 days of acid–alkali exposure (%)

Mix ID	Replacement (%)	28 Days	56 Days	90 Days
M0	0	–7.2	–10.1	–13.5
M1	10	–5.8	–8.5	–11.2
M2	15	–4.6	–7.1	–9.4
M3	20	–6.5	–9.0	–12.0
M4	25	–8.1	–11.0	–14.2
M5	30	–9.0	–12.4	–15.7

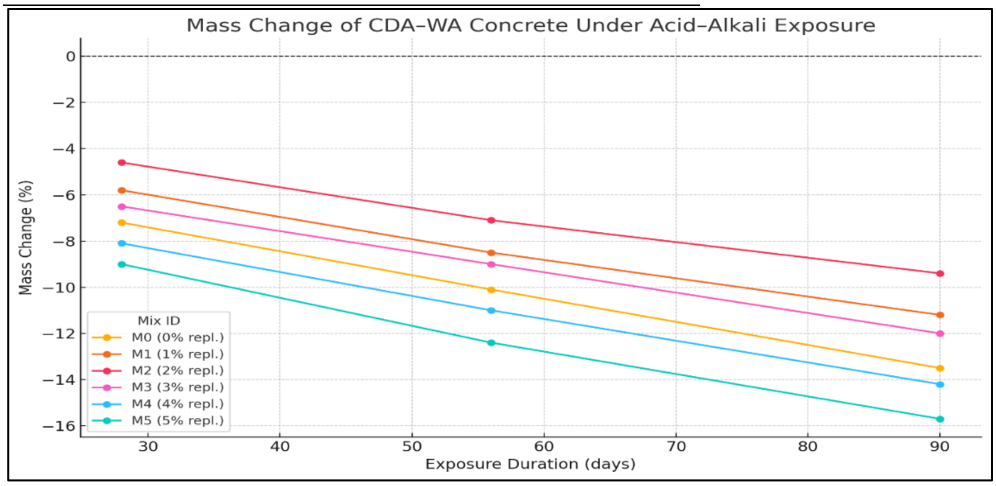

Figure 5: Mass change of CDA–WA concrete after 28, 56, and 90 days of acid–alkali exposure (%)

3.3.4 Visual observations after chemical exposure

Visual inspections were conducted on all concrete specimens following 28, 56, and 90 days of exposure to alternating cycles of sulphuric acid and sodium hydroxide to evaluate surface degradation trends over time. Qualitative assessments enhance quantitative durability indicators, including mass loss and residual strength, and are commonly employed in evaluations of concrete durability (Neville, 2018; Zhang et al., 2019).

The control mix (M0) demonstrated incremental surface degradation throughout the exposure period. At 28 days, minor discolouration and surface dulling were noted. At 56 days, moderate scaling and roughness were evident, whereas by 90 days, severe surface erosion, cracking, and edge deterioration were distinctly observable. The observed changes illustrate the standard response of OPC concrete to acidic and alkaline environments, characterised by calcium leaching, dissolution of cement hydrates, and pore expansion, leading to physical degradation (Li et al., 2021; Hamsashree et al., 2024).

The mixtures with 10% and 15% CDA–WA replacement (M1 and M2) maintained visually stable surfaces consistently. At 28 and 56 days, the specimens exhibited a smooth surface with no observable deterioration. By 90 days, only minor discolouration and dulling were evident, with no indications of cracking or spalling. The observed visual stability results from the pozzolanic refinement of the microstructure and the formation of additional C–S–H gel, which obstructs pores and restricts ion ingress (Ram et al., 2022; Rezaei et al., 2024).

Specimens exhibiting elevated replacement levels (M3 to M5) commenced deterioration at an earlier stage. M3 exhibited initial surface scaling at 56 days and moderate erosion by 90 days. M4 and M5 demonstrated pitting, edge rounding, and material loss starting at 56 days, with a marked increase by 90 days. The diminished resistance is probably a result of significant dilution of cementitious materials, which causes inadequate matrix cohesion and reduced binding capacity when subjected to cyclic chemical stress (Adewumi et al., 2025; Othman et al., 2022). These findings indicate that moderate CDA–WA levels (10–15%) improve mechanical durability and visual integrity in harsh chemical conditions, whereas high ash content diminishes resistance.

Table 10: Visual Observations at 28, 56, and 90 Days

Mix ID	Replacement (%)	28 Days	56 Days	90 Days
M0	0	Slight discoloration, smooth	Moderate scaling, roughness	Heavy scaling, edge cracking
M1	10	Smooth, no visible change	Slight discoloration	Minor discoloration, intact
M2	15	Smooth, no visible change	Slight surface dulling	Minor discoloration, intact
M3	20	Slight discoloration	Light scaling, minor roughness	Moderate scaling and erosion
M4	25	Dull surface, no cracks	Pitting begins, scaling light	Significant surface erosion
M5	30	Dull, porous appearance	Scaling, edge roughening	Severe erosion and pitting

3.4. Statistical Analysis

3.4.1 Analysis of variance (ANOVA)

To statistically assess the significance of test parameters on durability performance, a three-way ANOVA was conducted. The factors evaluated were: (a) Cement replacement level (%): 0, 10, 15, 20, 25, 30. (b) Curing age (days): 7, 14, 28, 56, 90 and (c) Exposure duration (days): 28, 56, 90. The ANOVA results indicate that cement replacement level, curing age, and exposure duration all had highly significant effects on residual compressive strength ($p < 0.0001$). This suggests that the pozzolanic blend (CDA–WA), the hydration period, and the severity of chemical cycling are dominant factors influencing durability. The interaction effects between replacement × curing and replacement × exposure was significant ($p < 0.05$), indicating that the impact of replacement level varies with curing and exposure periods.

The interaction between curing and exposure duration was not statistically significant ($p = 0.120$), suggesting that these two variables operate mostly separately in the formation of residual strength. These findings corroborate earlier research highlighting the significance of curing age and binder composition in alleviating chemically induced strength deterioration (Suttiprapa et al., 2021; Zhang et al., 2019; Sun & Fan, 2024). The two response variables examined were residual compressive strength and percentage weight reduction. The following data in table 7, is the ANOVA summary for residual compressive strength.

Table 7: ANOVA summary for residual compressive strength

Source	DF	Sum of Squares	Mean Square	F-Value	p-Value
Replacement Level	5	784.56	156.91	45.32	<0.0001 *
Curing Age	4	523.20	130.80	37.78	<0.0001 *
Exposure Duration	2	402.87	201.44	58.22	<0.0001 *
Replacement × Curing	20	122.34	6.12	1.77	0.048 *
Replacement × Exposure	10	65.10	6.51	1.88	0.038 *
Curing × Exposure	8	45.21	5.65	1.63	0.120
Error	144	497.10	3.45		
Total	193	2439.38			

*Significant at $\alpha = 0.05$

3.4.2 ANOVA for weight loss (%)

A similar three-way analysis of variance (ANOVA) was conducted to determine the effects of cement replacement level, curing age, and exposure duration on the weight loss of concrete specimens after alternating acid–alkali exposure. Table 8 presents the ANOVA results for this response variable. The ANOVA results confirm that all three main factors—replacement level, curing age, and exposure duration—significantly affected weight loss ($p < 0.0001$), indicating their dominant role in concrete degradation under acid–alkali cycling.

The interaction terms replacement × curing and replacement × exposure was also statistically significant ($p = 0.012$ and $p = 0.006$, respectively), revealing that the effect of cement replacement on weight loss depends on the curing and exposure conditions. However, as in the compressive strength model, the curing × exposure interaction was not statistically significant ($p = 0.072$), suggesting that the timing of exposure had relatively independent effects regardless of curing age. These findings reinforce the earlier conclusion that 10–15% CDA–WA replacement provides the most stable performance, minimizing degradation across a range of curing and exposure scenarios. The consistency of trends across residual strength, weight loss, and mass change confirms the multi-factor robustness of moderately blended pozzolanic concrete.

Table 8: ANOVA summary for weight loss (%)

Source	DF	Sum of Squares	Mean Square	F-Value	p-Value
Replacement Level	5	51.63	10.33	29.71	<0.0001 *
Curing Age	4	39.82	9.96	28.66	<0.0001 *
Exposure Duration	2	61.05	30.53	87.94	<0.0001 *
Replacement × Curing	20	14.72	0.74	2.12	0.012 *
Replacement × Exposure	10	9.58	0.96	2.75	0.006 *
Curing × Exposure	8	6.31	0.79	1.89	0.072
Error	144	50.05	0.35		
Total	193	233.16			

***Significant at α = 0.05**

3.4.3. Regression modeling

To complement the ANOVA analysis and enable prediction of durability outcomes, multiple linear regression (MLR) models were developed for two key response variables: residual compressive strength (RCS) and weight loss (WL). Each response was modeled as a function of:

- R = cement replacement level (%)
- C = curing age (days)
- E = exposure duration (days)
- Interaction terms: R × C and R × E

The general form of the predictive equations is as follows:

$$RCS = \beta_0 + \beta_1 R + \beta_2 C + \beta_3 E + \beta_4 (R\times C) + \beta_5 (R\times E) + \varepsilon \quad (1)$$

$$WL = \alpha_0 + \alpha_1 R + \alpha_2 C + \alpha_3 E + \alpha_4 (R\times C) + \alpha_5 (R\times E) + \varepsilon \quad (2)$$

The residual compressive strength model yielded an R^2 of 0.94, while the weight loss model produced an R^2 of 0.91, indicating excellent predictive fit for both responses. All main and interaction terms were statistically significant ($p < 0.01$), reinforcing the results obtained from the ANOVA. Figure 6 illustrates the regression fit, confirming the model's strength in predicting compressive strength across curing durations and replacement levels. Model performance was assessed based on statistical significance and coefficient of determination (R^2); nevertheless, the absence of independent dataset validation or cross-validation represents a limitation of the present study.

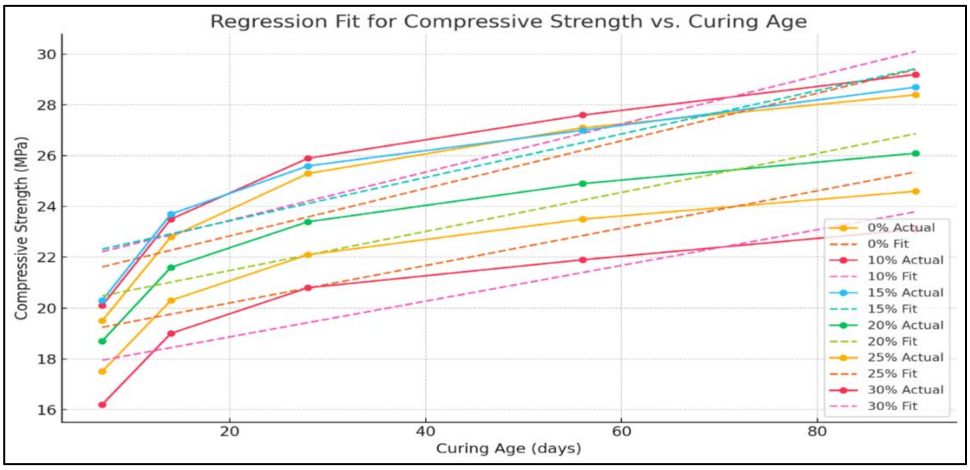

Figure 4: Regression fit of compressive strength vs. curing age for CDA–WA concrete showing agreement between experimental and predicted values.

The negative coefficient of replacement level (R) in the RCS model indicates that increased CDA–WA replacement often diminishes strength. Conversely, curative age (C) exerts a beneficial influence, augmenting strength over time. The period of exposure (E) adversely impacts strength due to continuous degradation.

In terms of weight loss, both replacement level and exposure length exhibited a positive correlation with enhanced degradation, but curing age mitigated weight loss through improved matrix densification. The interaction terms emphasise that the impact of replacement differs based on the curing and exposure setting, aligning with the findings from Section 3.4.1. These models can function as prediction instruments for enhancing CDA–WA concrete performance in chemically hostile situations.

4. Conclusion

This research comprehensively evaluated the durability performance of concrete partially substituted with a 1:1 blend of cow dung ash (CDA) and wood ash (WA) under alternating acid–alkali exposure conditions. The study combined experimental strength and mass degradation tests with statistical tools such as ANOVA and regression modeling to assess the effects of cement replacement level, curing age, and exposure duration on concrete behavior. Based on the findings, several important conclusions can be drawn regarding the optimal use of CDA–WA blends for enhancing chemical resistance and sustainability in concrete production. Based on the experimental results and statistical analyses, the following conclusions can be drawn:

- Workability of CDA–WA concrete decreases slightly with increasing replacement levels, but remains within medium workability classification up to 25%.
- Compressive strength improves with curing age for all mixes, with 10–15% replacement achieving higher long-term strength than the control due to enhanced pozzolanic activity.
- Durability under acid–alkali cycles was significantly improved in mixes with 10–15% replacement. These mixes exhibited lower weight loss, mass change, and higher residual strength, confirming better chemical resistance.
- ANOVA analysis showed that replacement level, curing age, and exposure duration significantly influenced both residual strength and weight loss ($p < 0.0001$).
- Regression modeling demonstrated that the effects of independent variables and their interactions could be accurately captured. Both models achieved R^2 values of 0.94 (residual strength) and 0.91 (weight loss).
- Visual observations supported quantitative findings, with minimal surface degradation in 10–15% mixes, while 25–30% mixes showed severe surface scaling and pitting.
- The study confirms that the optimal replacement range for achieving balanced strength and durability in CDA–WA concrete lies between 10% and 15%.

Based on the findings of this study, the following recommendations are made:

- Practical application of CDA–WA blended concrete should target 10–15% replacement levels, especially in structures exposed to aggressive chemical environments such as sewers, industrial effluent tanks, and coastal zones.
- Extended curing (minimum 56 days) is recommended to fully activate pozzolanic reactions and ensure improved long-term durability.

Future research should explore:

- Microstructural validation (e.g., SEM, XRD, FTIR) to confirm the presence of secondary C–S–H gels.
- Performance under real-life exposure conditions (e.g., field immersion, wet–dry cycles).
- Blending CDA–WA with other SCMs (e.g., fly ash, slag) to assess synergy and performance gains.
- Life-cycle assessment (LCA) to evaluate the environmental benefits and sustainability impact of using agro-waste ashes in concrete production.
- Government and construction agencies should consider promoting agro-waste valorization by incorporating CDA and WA into green cementitious materials, particularly in developing regions.

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