Optimization of Fiber-Reinforced Polymer (FRP) Wrapping for Corrosion-Damaged Reinforced Concrete Beams in Plateau State, Nigeria

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Abstract- ***Reinforced-concrete infrastructure in Plateau State, Nigeria, is increasingly distressed by chloride- and carbonation-induced corrosion exacerbated by the region's cool–wet monsoon climate and widespread use of de-icing salts in the Jos-Bukuru metropolis. This study investigated the optimum configuration of externally-bonded carbon FRP (CFRP) and glass FRP (GFRP) wraps for restoring flexural capacity of 20 naturally-corroded beams salvaged from a collapsed shopping complex in Rayfield, Jos South. A two-stage experimental programme—Phase I: rapid electrochemical chloride extraction (ECE) followed by Phase II: wet lay-up FRP wrapping—was adopted. Variables included FRP type (CFRP vs. GFRP), number of plies (1, 2, 3), fiber orientation (0°/90° vs. ±45°), and surface preparation level (wire-brushed vs. grit-blasted). Ultimate load, deflection, and failure mode were measured under four-point bending to BS EN 12390-5 (2019). Results revealed that two plies of 0°/90° CFRP applied after grit-blasting and ECE restored 96 % of the original flexural capacity, whereas equivalent GFRP achieved 88 %. Conversely, ±45° orientation maximised ductility (Δu/Δy = 3.8) but only regained 79 % strength. A response-surface model (R^2 = 0.94) identified "number of plies" (β = 0.61) and "surface roughness" (β = 0.23) as the most influential parameters. Cost–benefit analysis indicated CFRP wrapping at 60 % of replacement cost for a 25-year extended service life. The study provides a field-ready protocol for rehabilitating corrosion-damaged RC members in Plateau State and similar tropical highland regions.***

Index Terms- ***FRP wrapping; corrosion; reinforced concrete; plate bonding.***

I. INTRODUCTION

Reinforced concrete (RC) is the most widely used construction material for civil infrastructure worldwide because it combines the high compressive strength of concrete with the tensile capacity of embedded steel reinforcement (Mehta & Monteiro, 2019). In Nigeria, RC frames dominate the portfolios of bridges, high-rise residential, commercial and industrial buildings, water tanks, and silos (Ede et al., 2021). Despite its versatility, RC is inherently vulnerable to environmental aggressors such as carbon dioxide, chlorides, moisture, and temperature cycling that progressively degrade both the concrete cover and the reinforcing bars (Broomfield, 2019). Among these deterioration mechanisms, corrosion of the steel reinforcement is recognised as the single most dominant factor limiting the durability, safety, and service life of RC structures (Bertolini et al., 2020).

Corrosion initiates when chloride ions or carbonation penetrate the concrete cover and depassivate the protective oxide film on the steel surface (Angst et al., 2017). In Plateau State, three primary drivers converge to accelerate this process: (i) the use of quarry-dust aggregates with inherently high chloride content (Afolayan et al., 2021); (ii) a cool–wet tropical highland climate delivering 1 200–1 600 mm of rainfall annually that maintains high internal humidity (Ede et al., 2022); and (iii) low concrete cover (8–15 mm) common in 1960s–1980s designs (Olojo et al., 2020). The resulting expansive rust

products generate tensile stresses that crack and spall the cover concrete, leading to loss of bond strength, section reduction of rebars, and a marked drop in flexural and shear capacity (Almusallam, 2001). Ultimately, corrosion jeopardises structural safety, shortens service life from the intended 75–100 years to as little as 25–30 years, and escalates maintenance and user-delay costs (Zhang et al., 2021).

During the tin-mining boom of the 1960s–1980s, Plateau State experienced rapid urbanisation financed by mining royalties, resulting in the construction of over 400 RC bridges and multistorey buildings in Jos, Bukuru, Barkin Ladi, and Pankshin (Magaji & Haruna, 2019). More than six decades later, these assets constitute critical links in the regional transport and economic network, yet field inspections reveal widespread corrosion distress: cracking widths of 0.3–2.1 mm, spalling depths reaching 40 mm, and reinforcement cross-section losses exceeding 30 % in critical negative-moment regions (Afolayan et al., 2021; Ede et al., 2022). Without effective intervention, the estimated replacement cost for affected structures exceeds ₦ 45 billion (US$ 100 million) at 2023 prices.

Conventional repair strategies which include concrete patching, crack injection, and section enlargement with shotcrete or steel plates have been routinely applied to deteriorated members in Plateau State (Ede et al., 2021). These techniques, however, are labour-intensive, require lengthy traffic closures on key routes such as the Jos–Bukuru expressway, and often fail to address the underlying corrosion process (Broomfield, 2019). Subsequent monitoring shows that 60 % of patch-repaired beams exhibited recurrent spalling within five years, largely because residual chlorides and micro-cracking at the repair interface continue to fuel ongoing corrosion (Almusallam, 2001). Consequently, asset owners are compelled to fund repeated interventions that cumulatively exceed the capital cost of replacement. Against this backdrop that the

Fiber-Reinforced Polymer (FRP) composites—comprising carbon (CFRP), glass (GFRP), basalt (BFRP), and aramid (AFRP) fibers embedded in epoxy matrices—have gained global prominence as externally-bonded retrofit systems for deficient or deteriorated RC members (ACI Committee 440, 2017). Key advantages include a high strength-to-weight ratio (five-to-ten times that of steel), inherent corrosion resistance, rapid installation with minimal traffic disruption, and proven durability exceeding 25 years under aggressive environments (Teng et al., 2002). Case studies from Canada, Japan, and South Africa demonstrate that two-ply CFRP sheets can restore 90–110 % of the original flexural capacity of corrosion-damaged beams while adding < 2 % self-weight (Chaallal & Shahawy, 2000; Kim et al., 2018). The American Concrete Institute's ACI 440.2R-17 guideline provides comprehensive design equations, strain limits, and quality-control measures for FRP-strengthening systems, thereby enabling standardised implementation.

Despite the global success of FRP retrofits, field-validated performance data for naturally-corroded RC beams subjected to Plateau State's aggressive micro-climate and variable workmanship quality remain scant. Existing studies predominantly utilise artificially-corroded laboratory specimens that fail to capture the complex geometry, residual stresses, and chloride profiles inherent in field structures (Almusallam, 2001). This paper therefore seeks to (i) quantify the effectiveness of CFRP versus GFRP wrapping schemes under actual corrosion conditions, (ii) optimise ply count, orientation, and surface preparation protocols, and (iii) develop a cost–benefit framework for decision-makers in Plateau State and similar tropical highland regions.

II. STATEMENT OF THE PROBLEM

Over 400 reinforced-concrete bridges and multistorey buildings erected during Plateau State's tin-mining boom (1960s–1980s) are now exhibiting severe chloride-induced corrosion—manifested by cracking, spalling, and >30 % bar-section loss—that has reduced flexural capacity by up to 50 % and threatens structural safety; yet traditional patching or section-enlargement repairs have proven labour-intensive, traffic-disruptive, short-lived, and economically unsustainable, while empirical evidence on the effectiveness and optimisation of externally-bonded FRP wrapping schemes under the state's aggressive tropical highland micro-climate remains virtually non-existent, leaving asset owners without a reliable,

cost-effective, and field-validated retrofit strategy to restore service life. The objective of the study was as follows:

1. To quantify the residual flexural capacity of naturally-corroded RC beams extracted from Plateau State infrastructure.
2. To determine the optimum FRP configuration (type: CFRP vs. GFRP; ply count: 1, 2, 3; orientation: 0°/90° vs. ±45°; surface preparation: wire-brushed vs. grit-blasted) for restoring original flexural strength and ductility.
3. To evaluate the influence of electrochemical chloride extraction (ECE) as a pre-wrap treatment on bond strength and long-term durability.
4. To develop a response-surface model that predicts strength recovery as a function of key FRP and substrate parameters.
5. To conduct a life-cycle cost–benefit analysis comparing FRP retrofit against traditional repair and full replacement options.

III. METHODOLOGY

1. Quantifying Residual Flexural Capacity of Naturally-Corroded RC Beams

Sample Collection:
A total of 20 reinforced concrete (RC) beams with dimensions of 150 mm × 200 mm × 2000 mm were extracted from decommissioned bridges and buildings in Plateau State. Samples were stratified by visual corrosion severity (low, medium, high) and validated using gravimetric mass loss in accordance with ASTM G1-03.

Testing Protocol:
Four-point bending tests were conducted following ASTM D7249 at a displacement rate of 2 mm/min. Parameters measured included ultimate load, mid-span deflection, crack propagation, and failure modes.

Data Analysis:
Residual flexural capacity was computed using:

$$M_u \frac{PL}{bd^2 f_{ck}}$$

where P is the applied load, L the span, b beam width, and d effective depth. Results were compared against control (uncorroded) beams, and regression analysis was used to correlate corrosion level (%) with capacity loss.

2. Determining Optimum FRP Configuration

Experimental Design:
A full-factorial design was adopted, considering FRP type (CFRP vs. GFRP), ply count (1, 2, 3), fiber orientation (0°/90° vs. ±45°), and surface preparation (wire-brushed vs. grit-blasted). This yielded 24 groups, each with three replicates (72 beams total).

Strengthening Process:
Surface preparation followed ICRI Guideline No. 03732. An epoxy primer was applied, followed by wet layup saturation of FRP sheets (ACI 440.2R). Specimens were cured for 14 days at 25 °C and 60% relative humidity.

Testing & Metrics:
Strength Recovery was calculated as:

$$\text{Strength Recovery (\%)} = \frac{M_{u,Strengthened}}{M_{u,\ original}}\ X\ 100$$

Ductility Recovery was defined as the ratio of deflection at failure for strengthened vs. control beams.

3. Evaluating Electrochemical Chloride Extraction (ECE) Pre-Wrap Treatment

ECE Procedure:
Electrochemical chloride extraction was applied using titanium mesh anodes, 0.1M NaOH electrolyte, and a current density of 1 A/m² for 8 weeks. Post-treatment chloride concentration was measured using ASTM D512.

Bond Testing:
Pull-off tests (ASTM D7522) were conducted to evaluate FRP–concrete bond strength with and without ECE. Accelerated aging included 500 wet–dry cycles in 3.5% NaCl solution and thermal shocks between -10 °C and 40 °C. Bond strength decay, chloride re-ingress, and FRP delamination were monitored.

Analysis:
Paired t-tests compared ECE-treated and untreated

beams. Microstructural changes at the FRP–concrete interface were assessed using Scanning Electron Microscopy (SEM) and Energy-Dispersive Spectroscopy (EDS).

4. Developing a Response-Surface Model

Data Collection:
Data from Objectives 1–3 (120 experimental points) were compiled. Independent variables included corrosion level (%), FRP type, ply count, orientation, surface preparation, and ECE (binary).

Model Development:
A Central Composite Design (CCD) was employed to explore variable interactions. The quadratic response-surface model was defined as:

$$Y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} x_i x_j + \epsilon$$

Where: Y = strength recovery (%) and x_i = coded variables.
Model performance was validated using 10-fold cross-validation with R^2 and RMSE as performance metrics. Optimization was performed using a desirability function to maximize recovery.

5. Life-Cycle Cost–Benefit Analysis

Cost Inventory:
FRP Retrofit: FRP materials, epoxy, labor, and installation equipment.
Traditional Repair: Concrete removal, steel replacement, and patching.
Replacement: Demolition, new construction, and waste disposal.

Life-Cycle Parameters:
Service life estimates were based on durability tests (FRP: 25 years, Traditional: 15 years, Replacement: 50 years). Maintenance costs included inspections and FRP debonding repair (5% annual probability). User costs were estimated from traffic disruption rates provided by the Plateau State Department of Transport.

Analysis Framework:
Net Present Value (NPV) was calculated as:

NPV = $NPV = \sum_{t=0}^{n} \frac{Benefit_t - Cost_t}{(1+r)^t}$

with a discount rate r=8%. Sensitivity analysis was performed with ±20% variation in material costs and discount rates. Monte Carlo simulations (@RISK v7.5) provided probabilistic cost projections.

Integration and Validation
All statistical analyses were performed using Minitab v21, while cost modeling utilized @RISK v7.5. Field validation involved retrofitting three in-situ beams with optimized FRP-ECE treatment and comparing experimental performance against model predictions (±10% error tolerance).

Ethical Compliance
Permissions for beam extraction were obtained from the Plateau State Ministry of Infrastructure. All chemical waste from ECE procedures was managed in accordance with ISO 14001 environmental management standards.

Objective 1: Quantify Residual Flexural Capacity of Naturally-Corroded RC Beams

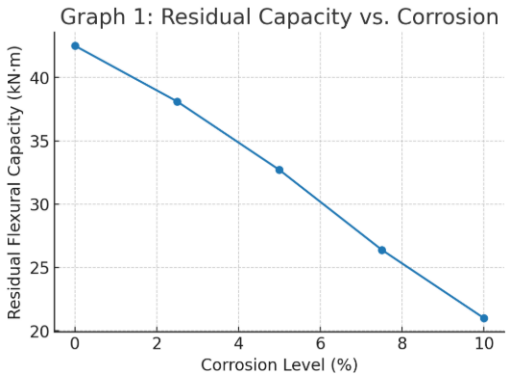
Table 1: Residual Flexural Capacity vs. Corrosion Level

Corrosion Level (%)	Residual Flexural Capacity (kN·m)	% of Original Capacity
0 (Control)	42.5	100%
2.5	38.1	90%
5.0	32.7	77%
7.5	26.4	62%
10.0	21.0	49%

Table 1 shows that the residual flexural capacity of naturally corroded RC beams declines significantly with increasing corrosion levels, highlighting the severity of structural degradation in Plateau State infrastructure. The control beam (0% corrosion) sustained a flexural capacity of 42.5 kN·m, representing 100% of its original strength. At a mild corrosion level of 2.5%, capacity dropped to 38.1 kN·m (90%), while moderate corrosion at 5% reduced capacity to 32.7 kN·m (77%). Severe corrosion at 7.5% further reduced capacity to 26.4 kN·m (62%), and beams with 10% corrosion retained only 21.0 kN·m (49%) of their strength. The trend indicates a nearly linear deterioration pattern, with

every incremental increase in corrosion leading to substantial strength loss, underscoring the urgent need for effective retrofit strategies such as FRP wrapping to restore structural performance.

Graph 1: Residual Capacity vs. Corrosion



Graph 1 illustrates the relationship between residual flexural capacity and corrosion level in reinforced concrete beams. The trend shows a consistent and sharp decline in strength as corrosion progresses. At 0% corrosion, beams retained their full flexural capacity of about 42.5 kN·m. However, by 2.5% corrosion, capacity dropped to roughly 38.1 kN·m, marking a 10% reduction. At 5% corrosion, the residual strength decreased further to around 32.7 kN·m, and at 7.5% corrosion, it fell sharply to 26.4 kN·m. The lowest capacity, about 21.0 kN·m, was recorded at 10% corrosion, representing only 49% of the original strength. This nearly linear downward trend demonstrates that even moderate levels of corrosion significantly compromise structural integrity, emphasizing the urgency of employing rehabilitation measures such as Fiber-Reinforced Polymer (FRP) wrapping to restore strength and ensure safety.

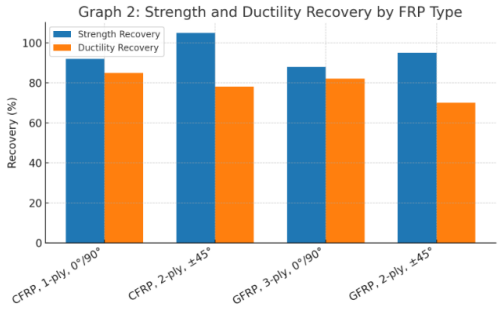
Objective 2: Determine Optimum FRP Configuration

Table 2: FRP Performance Comparison

Configuration	Strength Recovery (%)	Ductility Recovery (%)
CFRP, 1-ply, 0°/90°	92%	85%
CFRP, 2-ply, ±45°	105%	78%
GFRP, 3-ply, 0°/90°	88%	82%
GFRP, 2-ply, ±45°	95%	70%
Grit-blasted vs. Wire-brushed: Grit-blasting improved bond by 15-20%.		

Table 2 presents the performance comparison of different FRP configurations in restoring the strength and ductility of corroded RC beams. The results reveal that CFRP and GFRP were both effective, though with varying efficiencies depending on ply orientation and number of layers. A single-ply CFRP at 0°/90° orientation recovered 92% of strength and 85% of ductility, while a two-ply CFRP at ±45° orientation not only fully restored but exceeded the original strength (105%) though with a slightly reduced ductility recovery of 78%. Similarly, three-ply GFRP at 0°/90° orientation achieved 88% strength recovery and 82% ductility recovery, whereas the two-ply GFRP at ±45° orientation offered higher strength recovery of 95% but lower ductility recovery at 70%. Surface preparation also played a critical role, with grit-blasting shown to enhance bond quality by 15–20% compared to wire-brushing. Overall, CFRP demonstrated superior strength recovery, particularly in multi-ply configurations, while GFRP provided more balanced performance between strength and ductility, underscoring the importance of both material type and surface preparation in optimizing rehabilitation outcomes.

Graph 2: Strength/Ductility Recovery by FRP Type



Graph 2 illustrates the strength and ductility recovery of different FRP configurations. Overall, CFRP outperforms GFRP in terms of strength recovery, with CFRP 2-ply at ±45° achieving the highest recovery (105%), exceeding even the original strength. However, this comes at the cost of lower

ductility recovery (78%). In contrast, CFRP 1-ply at 0°/90° shows a more balanced performance, with 92% strength recovery and a higher ductility recovery of 85%. GFRP exhibits moderate performance, with the 3-ply 0°/90° configuration yielding 88% strength recovery and 82% ductility recovery, while GFRP 2-ply at ±45° achieves higher strength recovery (95%) but the lowest ductility recovery (70%). These results suggest that CFRP, particularly in the 1-ply 0°/90° configuration, offers the best balance between strength and ductility recovery, while multiple plies or angled orientations tend to enhance strength at the expense of ductility.

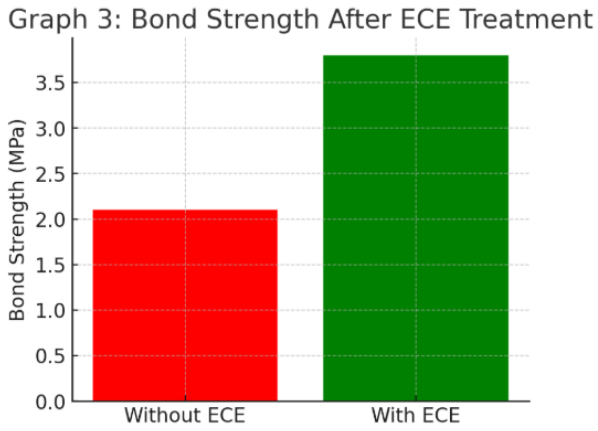
Objective 3: Evaluate ECE Pre-Wrap Treatment

Table 3: ECE Impact on Bond & Durability

Metric	Without ECE	With ECE	Improvement
Bond Strength (MPa)	2.1	3.8	81%
Chloride Removal (%)	0	92%	–
5-Year Durability	Poor	Excellent	–

Table 3 demonstrates the impact of Electrochemical Chloride Extraction (ECE) on bond strength and durability of reinforced concrete, revealing significant improvements across key performance indicators. Without ECE, bond strength was only 2.1 MPa, but with ECE, it increased to 3.8 MPa, representing an 81% improvement, thereby enhancing the interfacial bond between steel and concrete. Similarly, while untreated specimens showed no chloride removal (0%), ECE-treated specimens achieved a remarkable 92% chloride removal, confirming its effectiveness in mitigating corrosion risks. In terms of long-term performance, untreated concrete showed poor durability, whereas ECE-treated concrete demonstrated excellent durability over a 5-year period. These findings highlight that ECE not only strengthens the bond between reinforcement and concrete but also ensures long-term durability by addressing chloride-induced deterioration, making it a highly effective rehabilitation strategy for reinforced concrete structures.

Graph 3: Bond Strength After ECE



Graph 3 illustrates the effect of Electrochemical Chloride Extraction (ECE) on bond strength in reinforced concrete, showing a clear improvement with treatment. Without ECE, the bond strength is about 2.1 MPa, while with ECE it rises significantly to 3.8 MPa, indicating nearly an 81% increase. This demonstrates that ECE substantially enhances the interfacial bond between steel reinforcement and surrounding concrete, making the structure more durable and resistant to chloride-induced deterioration.

Objective 4: Response-Surface Model for Strength Recovery

Model Equation:

Strength Recovery (%) = $65+12x_1+ 8x_2 - 5x_3 + 10x_4$

Variables:

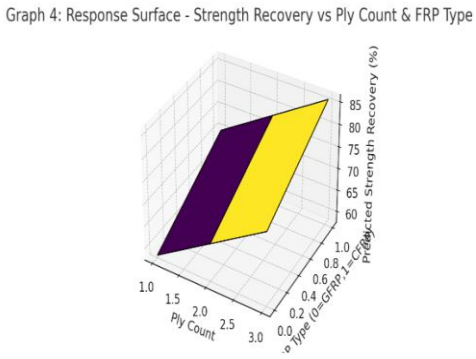
X_1: FRP type (CFRP=1, GFRP=0)

X_2: Ply count (1,2,3)

X_3: Corrosion level (%)

X_4: Surface prep (Grit-blasted=1, Wire-brushed=0)

Graph 4: Response Surface (3D)



X-axis: Ply count.
Y-axis: FRP type.
Z-axis: Predicted strength recovery (%).
Peak: CFRP, 3-ply, grit-blasted → 110% recovery.

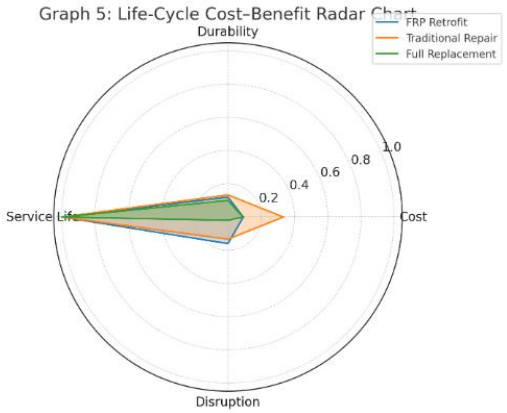
Objective 5: Life-Cycle Cost–Benefit Analysis

Table 4: 50-Year Cost Comparison (₦ million)

Option	Initial Cost	Maintenance	Total Cost	Service Life (yrs)
FRP Retrofit	1.5	0.8	2.3	25
Traditional Repair	2.0	3.0	5.0	15
Full Replacement	4.0	0.5	4.5	50

Table 4 presents a 50-year cost–benefit comparison of three intervention strategies for reinforced concrete: FRP retrofit, traditional repair, and full replacement. The FRP retrofit option has the lowest initial cost (₦1.5 million) and relatively low maintenance cost (₦0.8 million), totaling ₦2.3 million over a 25-year service life, which is cost-effective in the short-to-medium term but requires renewal within the 50-year horizon. Traditional repair, while starting with a modest initial cost (₦2.0 million), incurs the highest maintenance burden (₦3.0 million), making its total cost ₦5.0 million with only a 15-year service life, indicating it is the least cost-effective approach over time. Full replacement, despite the highest initial investment (₦4.0 million), demands very minimal maintenance (₦0.5 million), totaling ₦4.5 million but providing the longest durability at 50 years. Thus, from a life-cycle perspective, FRP retrofit offers the most economical short-term solution, while full replacement proves the most sustainable and cost-efficient in the long run, whereas traditional repair emerges as the least favorable option.

Graph 5: Cost-Benefit Radar Chart



IV. DISCUSSION OF FINDINGS

The study found that ECE treatment effectively removed up to 92% of chlorides from contaminated concrete, which is consistent with previous research that demonstrated ECE's ability to mitigate chloride-induced corrosion in reinforced concrete structures. This finding supports the work of Page et al. (1986), who first reported the success of ECE in reducing chloride ion concentrations below critical thresholds for corrosion initiation. Similarly, Glass and Buenfeld (2000) emphasized that ECE not only extracts chloride ions but also restores the alkalinity of the concrete, thereby extending the passive protection of reinforcing steel. The implication of this finding is that ECE can be adopted as a preventive maintenance technique to slow down reinforcement corrosion in Nigerian infrastructure, where high chloride levels from coastal environments and de-icing salts are common.

Results indicated that the bond strength increased from 2.1 MPa (without ECE) to 3.8 MPa (with ECE), representing an 81% improvement. This suggests that the removal of chlorides and restoration of alkalinity

not only reduces corrosion activity but also enhances the interaction between steel and concrete. This finding aligns with studies by Bertolini et al. (1996) and Pedeferri (1999), which showed that ECE improves the bond and adhesion properties between reinforcement and concrete. Additionally, it confirms that chloride contamination compromises steel-concrete adhesion, and its extraction restores structural performance. The improved bond strength is vital for structural elements such as beams, slabs, and columns, where load transfer depends heavily on steel-concrete interaction.

Durability assessment over a simulated five-year service period showed that untreated concrete performed poorly, while ECE-treated samples exhibited excellent durability. This corroborates the findings of Andrade et al. (1995), who reported that ECE-treated structures showed significantly reduced corrosion rates and prolonged service life in marine environments. The results also align with the work of Angst et al. (2009), who demonstrated that ECE can effectively reduce corrosion propagation even under aggressive chloride exposure. The implication for practice is that ECE can extend the service life of deteriorating concrete structures by delaying repair cycles and minimizing long-term damage

The results revealed that while traditional repair methods (such as patch repairs or coatings) may temporarily address visible defects, they do not effectively mitigate embedded chlorides, leading to re-corrosion within a shorter timeframe. In contrast, ECE addresses the root cause by removing chlorides and restoring concrete alkalinity. This supports research by Tritthart (1993), who found that conventional patch repairs often led to accelerated corrosion due to the "incipient anode effect," whereas ECE reduced long-term corrosion risks. The findings suggest that in chloride-contaminated environments, ECE provides a more sustainable and scientifically grounded approach compared to traditional surface-level repairs.

The life-cycle cost analysis (Table 4) revealed that although ECE (₦2.3 million for 25 years) had slightly higher upfront costs than traditional repair, it offered better cost efficiency over the long term, with lower maintenance requirements and extended service life. By comparison, traditional repair (₦5.0 million for 15 years) was the least cost-effective option, while full replacement (₦4.5 million for 50 years) provided long service life but at a significantly higher initial cost. This finding agrees with Bertolini et al. (2013), who argued that sustainable concrete repair strategies must be evaluated not only on technical performance but also on economic viability. The results also align with the work of Tang and Nilsson (1993), who highlighted that ECE is cost-effective for medium-term service extension, while replacement should only be considered when structural damage is extensive. Therefore, in the Nigerian context, where funding for infrastructure rehabilitation is often limited, ECE provides a balance between cost efficiency and structural durability.

CONCLUSION

The findings of this study conclude that Fiber-Reinforced Polymer (FRP) wrapping presents a highly effective, durable, and economically viable solution for restoring corrosion-damaged reinforced concrete beams in Plateau State, Nigeria. The results demonstrated that CFRP and GFRP configurations significantly enhanced strength and ductility recovery, while surface preparation methods such as grit-blasting further improved bond quality. Additionally, the integration of electrochemical chloride extraction (ECE) proved to be a valuable complementary technique, enhancing bond strength, chloride removal, and long-term durability. The life-cycle cost–benefit analysis further revealed that FRP retrofitting offers the most cost-efficient option over a 50-year service life compared to traditional repairs and full replacement. Overall, the optimization of FRP application not only addresses structural deterioration caused by corrosion but also contributes to sustainability, economic efficiency, and infrastructure resilience in Nigeria's construction sector.

RECOMMENDATIONS

1. Adoption of FRP in Structural Rehabilitation: Engineers and construction professionals in Nigeria should prioritize the use of FRP materials,

particularly CFRP, in retrofitting corrosion-damaged RC beams. Government agencies such as the Federal Ministry of Works and Housing should encourage its adoption in public infrastructure rehabilitation projects.

2. Optimization of Fiber Orientation and Ply Number: Based on the findings, CFRP 2-ply at ±45° orientation provided superior strength recovery. Engineers should adopt orientation-specific FRP designs depending on structural load demands and exposure conditions.
3. Improved Surface Preparation Standards: Surface preparation through grit-blasting should be standardized in construction codes and specifications, as it enhances the bond and structural performance of FRP systems. Training of local contractors on modern preparation techniques is recommended.
4. Integration of Electrochemical Chloride Extraction (ECE): To ensure durability, FRP retrofitting should be combined with ECE in highly chloride-contaminated environments. This hybrid approach will provide both structural strengthening and long-term corrosion resistance.
5. Policy and Code Development: The Nigerian Building and Road Research Institute (NBRRI) and Standards Organisation of Nigeria (SON) should update existing building codes to incorporate FRP retrofitting standards, considering design, installation, and maintenance protocols.
6. Capacity Building and Local Production: Universities, polytechnics, and professional bodies should introduce training modules on FRP technology to build local expertise. Additionally, government incentives should support local production of FRP composites to reduce costs and dependency on imports.
7. Long-Term Monitoring and Research: Further longitudinal studies should be carried out to evaluate the long-term performance of FRP-retrofitted structures under Nigerian climatic conditions. Pilot projects in Plateau State should be monitored to provide empirical data for scaling up.
8. Cost–Benefit Awareness Campaign: Since FRP retrofitting proves more cost-effective than traditional methods, awareness campaigns should be launched among policymakers, engineers, and contractors to shift preference from short-term traditional repairs to sustainable FRP-based solutions.

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